TÉCNICO LISBOA

# Assessing the Possibility of Using a Framo Electrical Generator for Marine Current Tidal Stream Technology

**Kirsten Elizabeth Storaker Kelly**

Thesis to obtain the Master of Science Degree in

## Energy Engineering and Management

Supervisors: Prof. João Carlos de Campos Henriques
B.Com. Kristine Biering

## Examination Committee

Chairperson: Prof. Duarte de Mesquita e Sousa
Supervisor: Prof. João Carlos de Campos Henriques
Member of the Committee: Prof. Luís Manuel de Carvalho Gato

**December 2021**

Acknowledgement

This master thesis is the result of the two-year master's degree Energy Engineering and Management, specialising in renewable energy, at Instituto Superior Técnico (IST). I am grateful for the opportunity I have been given by choosing this particular master's degree, for all the experience I have gained and friends I have made during my period in beautiful Lisbon.

I would like to thank João Carlos de Campos Henriques for being my supervisor from IST, for his guidance and help and all the theoretical material he has contributed with. Unfortunately, we never got the chance to meet in real life, but through mail and Zoom we could communicate between Norway and Portugal. Thank you to Kristine Biering for being my supervisor and contact person in Framo, and for every quick response to my concerns and doubts. A special thank you to Håkon Hystad in Framo Innovation for all his help and assistance, and for his patience with all of my questions. To Veslemøy and Dag for taking their time to read through my thesis, and give me their helpful feedback, I am very thankful for your points of view. I am really grateful for all the help and guidance I have been given throughout this process.

I would also take the opportunity to thank Thomas Størkson and Terje Ljones in Framo Innovation for giving me this thesis, which is for me a special chance to combine Framo equipment and renewable energy. Although this thesis may not be the breakthrough for Framo and tidal energy, I still believe in Framos green future within the renewable energy sector.

This year with the pandemic has been a big challenge for many, and as a student is has been so for myself included. I for one can say that it is not ideal to write a master thesis from your mothers dining room, far from fellow students and supervisors. I am still very grateful that I was able to travel back home from a unfamiliar and lonely Lisbon in lockdown, and I know for a fact that I am very privileged in many ways. I would like to thank my loving family and friends whom always watch out for me and for motivating me when it was hard to keep going. It has been a big challenge all together, but I am thankful for the experience and I know that it will be useful in my future personal life and working career.

# Resumo

Como as marés altas e baixas ocorrem com grande previsibilidade, o aproveitamento desta energia tem um grande potencial. A energia das marés pode ser dividida em duas tecnologias principais: as barragens de maré e as correntes de maré. O tema desta tese centra-se na avaliação da possibilidade de utilizar um gerador elétrico comercial da empresa Framo para a conversão da energia das correntes de maré.

Na tese é feita uma revisão do estado atual das tecnologias de conversão da energia das marés. São também apresentados os conceitos de custo nivelado da energia (LCOE), maturidade da tecnologia e curvas de aprendizagem, assim como é discutido as políticas energéticas públicas. Todos estes fatores são importantes para o desenvolvimento da energia das marés. É apresentado um modelo numérico para o cálculo do desempenho de uma turbina de correntes de maré, utilizando o número de Froude e a altura relativa como variáveis principais. Como a eficiência do gerador é um elemento importante na cadeia de conversão de energia, foi avaliado o desempenho de dois geradores da Framo para um local especificado.

A tecnologia das correntes de maré é ainda muito dispendiosa e, portanto, atualmente incapaz de competir com outras tecnologias economicamente viáveis. Os resultados desta tese mostram que, utilizando o local e parâmetros dados, um dos geradores sugeridos dá melhores resultados do que o outro, embora não seja a eficiência desejada. No entanto, a empresa Framo tem grande experiência e recursos para desenvolver um gerador de corrente de maré no futuro.



**Palavras chave:** energia das marés, energia das correntes marítimas, teoria do disco atuante, eficiência de geradores.

# Abstract

High and low tides occur with known predictability, and harnessing this energy has great potential. Tidal energy can be divided into two main technologies: tidal barrages and tidal currents. This thesis focuses on evaluating the possibility of using a commercial electric generator from the Framo company for the conversion of tidal current energy.

In the thesis, a review of the current state of tidal energy conversion technologies is given. The concepts of levelised cost of energy (LCOE), technology maturity and learning curves are also presented, as well as public energy policies. All these factors are essential for the development of tidal energy. The literature review of proven solutions can be used as a comparison for future developments. A numerical model for calculating the performance of a tidal current turbine is presented, using Froude number and relative height as primary variables. As generator efficiency is an important element in the energy conversion chain, the performance of two Framo generators was evaluated for a specified site.

Tidal stream technology is still very expensive and, therefore, currently unable to compete with other economically viable technologies. This thesis shows that using the given site and parameters, one of the suggested generators gives better results than the other, although not the desired efficiency. However, the Framo company has large experience and resources to develop a tidal current generator in the future.



**Keywords:** tidal energy, tidal stream technology, actuator disc theory, generator efficiency.

# Table of Content

# List of Figures

# List of Tables

# Abbreviations

| | |
|---|---|
| BEP | Best Efficiency Point |
| $CO_2$ | Carbon Dioxide |
| CAPEX | Capital Expenditure |
| DEVEX | Development Expenditure |
| DNV GL | Det Norske Veritas Germanischer Lloyd |
| EIA (US) | Energy Information Administration (United States) |
| EMEC | The European Marine Energy Centre |
| EU | European Union |
| EUR | Euro |
| IEA | International Energy Agency |
| IRENA | International Renewable Energy Agency |
| ISO | International Organisation for Standardisation |
| LACE | Levelised Avoided Cost of Energy |
| LCOE | Levelised Cost of Energy |
| LCOS | Levelised Cost of Storage |
| LMADT | Linear Momentum Actuator Disc Theory |
| LR | Learning Rate |
| NASA | National Aeronautics and Space Administration |
| NDC | Nationally Determined Contributions |
| NER | New Entrance Reserve |
| NOAA | National Oceanic and Atmospheric Administration |
| NOC | National Oceanography Centre |
| NOS | National Ocean Service |
| OPEX | Operational Expenditure |
| O&M | Operation and Maintenance |
| PTO | Power Take-Off |
| PV | Photovoltaic |
| REFIT | Renewable Feed-In Tariff |
| rpm | Revolutions per minute |
| R&D | Research and Development |
| SDG | Sustainable Development Goal |
| TLP | Tension Leg Platform |
| TSR | Tip Speed Ratio |
| UK | United Kingdom |
| UN | United Nations |
| UNFCCC | United Nations Framework Convention on Climate Change |
| US | United States |
| USD | United States Dollar |

# Chapter 1

# Introduction

## 1.1 Background

Tidal power is one of the most reliable and predictable energy sources in terms of renewable energy (O Rourke et al., 2010). The unique predictability of the high and low tides is possible during the day, as well as for a long-term perspective. The tides are reliant on the sun, the moon and the gravitational forces they contribute, and the tidal waves may in some places be affected by weather conditions such as temperature and wind (NOAA SciJinks, 2021). Nevertheless, there are no external obstacles that disturb or disrupt the tidal waves, and they may therefore be predicted in the far future. Thus, tidal power is an interesting source of energy for future development and investment.

## 1.2 Goals and objectives

This thesis aims to assess the possibility of using a novel electrical generator developed by Framo Innovation for tidal turbines without gearboxes. The thesis will explore possibilities (technological and geographical areas) and “proven” solutions for tidal power. Key parameters should be established to compare different solutions (e.g. unit power rating, size, weight, cost etc.) and evaluate them (e.g. units built, power produced etc.) This master thesis will mainly include tidal stream turbines' applications, presenting a numerical model for this application. The overall efficiency of the novel Framo electrical generator will also be examined and presented. Tidal barrages will be investigated briefly.

The research questions developed in dialogue with Framo Innovation, which will be answered in this thesis, are given as follows:

1. What are the advantages and disadvantages of tidal power compared to other renewable energies?
2. Is there a specific key parameter-target, e.g. kW/kg (investment) or kW/€ (total cost over 5/10 years), one should aim for?
3. What are the optimal tidal turbine parameters for the available Framo generators?
4. Are any of the Framo motors feasible for a tidal turbine?

The review of advantages and disadvantages can be helpful for weighing for and against the technology. The investigation of key parameters, and if there are any specific key parameters to aim for in the sense of investment or total cost over a period of time, can also be useful for to evaluate the feasibility of a future tidal power project. There are two Framo motors investigated in this thesis, which the final research question is regarding. The literature review and results in this thesis can be used to investigate the above research questions, and the motivation is to present an informative thesis on the topic of tidal power. This may be useful for Framo Innovation and possible future tidal energy development.

## 1.3 Structure of the thesis

The thesis is divided into six main chapters, which are arranged in the following order:

Chapter 1 – Introduction. In this chapter a short introduction to tidal power is presented. Goals and objectives as well as research questions are also introduced.

Chapter 2 – Literature Review. In this chapter, a literature review of the different tidal power technologies highlights important concepts and shows proven solutions to the technology.

Chapter 3 – Method. The mathematical model and theory regarding tidal stream technology are given in the methods chapter.

Chapter 4 – Results. The results chapter provides the results from the methods given in the methods chapter. Firstly, graphical results from the mathematical model are presented, and secondly, the findings regarding the generator efficiency are provided.

Chapter 5 – Discussion. In the discussion chapter the research questions will be linked to the methods chapter together with the results and findings.

Chapter 6 – Conclusion. The final chapter contains the conclusions drawn from the results given and the discussions regarding the research questions. Recommendations on further work are also suggested.

# Chapter 2

# Literature Review

## 2.1 Origin of tides

It is the gravitational forces from the sun and the moon, contributed with the rotational forces on the Earth, that make the tides rise and fall (National Oceanography Centre, n.d.). Bulges of water are placed on opposite sides of the Earth, where one bulge is where the Earth faces the moon, as the other bulge is directly on the opposite side of the Earth. These bulges are the high tides, and this explains why there are two high tides during the day. The pull of the bulges is knowns as the tidal force.

Gravity is one of the major forces for the occurrence of the tidal waves (US Department of Commerce, n.d.). Newtons law of attraction explains that any object attracts any other object with a gravitational force that is equal to the proportion of the objects masses, and inversely proportional to the distance between the objects, squared. The acceleration due to the rotation of the Earth is called the Coriolis acceleration (Coastal Wiki, 2020). The occurrence of this, strongly affects the oceans thus the tidal waves. The curving of the fluid on the Earth is caused by the Coriolis effect, where the force applied is called the Coriolis force (National Geographic, 2011). This effect in an influence on the tidal waves in the sense of rotation. In the Northern Hemisphere, the current flow follows a clockwise circulation as the opposite occurs in the Southern Hemisphere with an anticlockwise circulation (Water Encyclopedia, 2021). These circulation flows are also known as gyres.

The tidal forces results in rise and fall of the sea levels (Berg, 2020). The fall of sea level is commonly referred to as ebb tide, whiles rise of sea level is referred to as flood tide (US Department of Commerce, 2021a). The occurrence of ebb and flood happens twice daily per tide, with the first high tide being when the bulge on the Earth is closest to the moon. The time interval between each of the high tides is 12 hours and 26.5 minutes, where in-between the interval, approximately 6 hours and 13.25 minutes after the first high tide, there occurrence of a low tide also with the same interval (Henriques, 2020a). This leaves two high tides, and two low tides each day. A lunar day, meaning the time needed for the moon to rotate around its own axis thus the frequency of the tides, is 53 minutes longer than a solar day which is on 24 hours. This gives a 53-minute delay from tides from one day to the next.

Another phenomenon occurs during full or new moon, namely spring tides (US Department of Commerce, 2021c). These tides are slightly larger than the usual high tides. The occurrence of spring tide is due twice a month and occurs when the moon is aligned with the sun and the Earth. In addition and opposite action to the spring tide, is the occurrence of neap tide. Neap tide is significantly lower than low tide and occurs when the moon is at its first quarter or third quarter, and the moon is perpendicular to the sun. Syzygy is the straight-line configuration of three bodies, as in this case with the Earth, the moon and the sun (Henriques, 2020a).

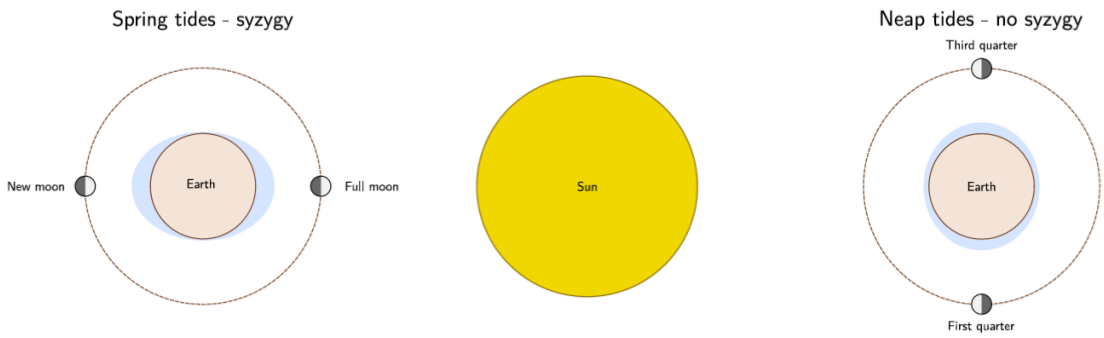


*Figure 1: Configuration of the Earth, the moon and the sun (Henriques, 2020a)*

The largest range of tides measured today is in the Bay of Fundy in New Brunswick and Nova Scotia in Canada (The Canadian Encyclopedia, 2010). The tidal range from ebb to flood tide is measured to 16.1 meters. The map of the world below illustrated the tides in the oceans of the world (Radar Altimetry Tutorial and Toolbox, 2001). As seen, the tides are strongest and largest in coastal areas, such as the western part of Europe, especially around the islands of Ireland and the United Kingdom (UK), eastern, as well as western part of Canada to mention some important areas.

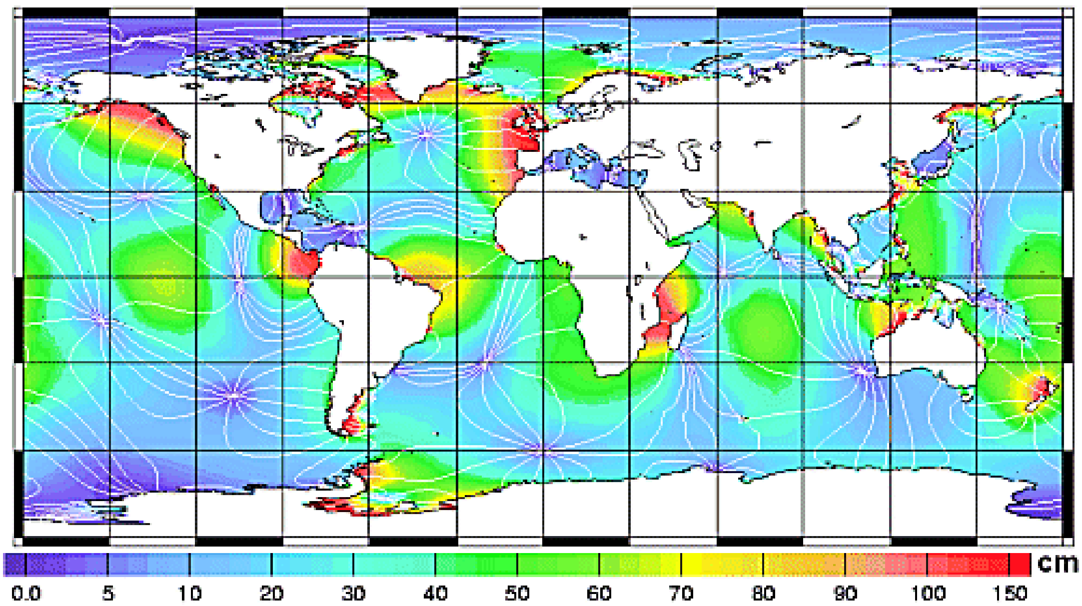


*Figure 2: Map of tides in the World (Radar Altimetry Tutorial and Toolbox, 2001)*

Due to the current climate change, there is a rising of the sea level, and this also therefore affects the level of the rise and fall of the sea water. The occurrence of larger flood tides than usual is predicted, and there is a real fear of floods at many locations in the world today. These large flood tides are also referred to as King tides, and can be seen up to once or twice a year, in certain areas (US Department of Commerce, 2021b). The damages that king tides and floods may bring are devastating both in materialistic terms, but most importantly in cases of life and death (EPA, 2011). With the knowledge of rising sea level and higher flood tides due to the climate changes, there are precautions today that must be taken. An example of this is whenever there is a case of infrastructure matter in coastal areas, future floods should be taken into account. At a later point of this thesis, flood control using tidal power technology will be discussed.

## 2.2 Tidal generation

The extraction of tidal waves is no new technology, and tidal ranges have been exploited since the middle ages with its tide mills (Neill et al., 2018). The potential differences in sea level between ebb and flood is called tidal range, and from this there are both potential and kinetic energy to capture. In some locations this range is larger than other locations, due to other factors like wind and weather conditions. As the tidal range is a frequent occurrence, and the predictability is so large, there is an opportunity to exploit this energy potential. That is why we discuss energy generation from tidal power.

There are two main different types of harnessing tidal power, namely tidal range and tidal stream (O Rourke et al., 2010). Tidal range power uses the potential of the tidal ranges from the ebb and flood tides, and the oscillating levels due to the tides. Tidal range power can often be built in dams and are also often referred to as tidal barrages. Tidal stream is the harnessing of the kinetic energy from a tidal current and may sometimes be referred to as tidal current or channel flows. The tidal range and tidal stream technologies are categorised under the group of Ocean Energy Technologies, together with wave energy, deep ocean currents, ocean thermal energy and salinity gradient technology (IRENA, 2014b). If not mentioned otherwise, this thesis will mainly focus on the tidal stream technology but will explain basic matters regarding the tidal range technology.

## 2.3 Tidal stream

Tidal stream power is the energy obtained in the tidal stream in a channel or river, or in the ocean (IRENA, 2014a). Utilizing the kinetic energy from the stream of water, tidal stream power can generate electricity. The capture of the kinetic energy of the tidal waves can be done by multiple technologies and many that are still under development.

There are different ways of harnessing the kinetic energy within tidal stream technology, including horizontal axis turbines, vertical axis turbines, oscillating hydrofoils, helix screws, enclosed tips and tidal kites (Røkke & Nilssen, 2013). For the technology of horizontal axis turbines, there is also the choice of different types of floating and fixed structures, submerged or partially submerged. The choice of the different technologies and the different mooring types all depend on the location of where the turbine will operate. Factors like water depth, wave exposure and sea bed conditions play an important role in the decision making (O Rourke et al., 2010). Also, the type of regulation, configuration and power take-off (PTO) are measures to evaluate.

For tidal stream, the demand of a current at 2-3 m/s is given for a location to make the generation economically viable (Bell, 2002). This makes tidal stream generation very limited to locations where only certain areas are fitted for this application. The horizontal axis tidal current turbine technology is similar to the wind technology. As the density of water is much larger than the density of air, there are obvious differences from a turbine under water to a wind turbine. The density of water is approximately 832 times larger than the density of air. Therefore this results in the forces on the tidal turbine being larger than the forces applied on a wind turbine (O Rourke et al., 2010). This also means that a tidal turbine can be much smaller than a wind turbine. For comparison, a 1 MW wind turbine requires a 60 meter rotor diameter, whereas a tidal turbine rotor only needs a diameter of 20 m approximately, and, 1 m/s of water has the same kinetic energy as 9 m/s of air (Bell, 2002). To compare further, due to the higher water density of water than of air, a tidal turbine is applied with a greater thrust (Houlsby & Vogel, 2017). A greater thrust applied to the turbine also implies for a stronger and more robust structure even though it can have a smaller characteristic length.

The first turbine connected to the grid was the Andritz Hydro Hammerfest turbine, for Hammerfest Strøm in 2004 (Røkke & Nilssen, 2013). With its horizontal axis 3 bladed turbine with variable pitch and a synchronous machine connected to the gearbox, the current project of MeyGen is built on the same turbine technology as the Hammerfest project (SIMEC Atlantis Energy, 2021)(Andritz Hydro, 2019).

### 2.3.1 Current status

The main trend for today's development is horizontal axis turbines and vertical axis turbines. In contrast, according to the International Renewable Energy Agency, IRENA, 76 % of tidal turbines are horizontal axis, being a large superiority of the tidal stream technologies (IRENA, 2020a). In the figure below taken from IRENA's technology outlook from 2020, planned capacity, planned projects and developers of tidal stream energy are visualized. It is clear to see that horizontal axis turbines are trending in all categories. Throughout this thesis, horizontal axis turbines will be the main concern regarding tidal stream technology if not mentioned otherwise.

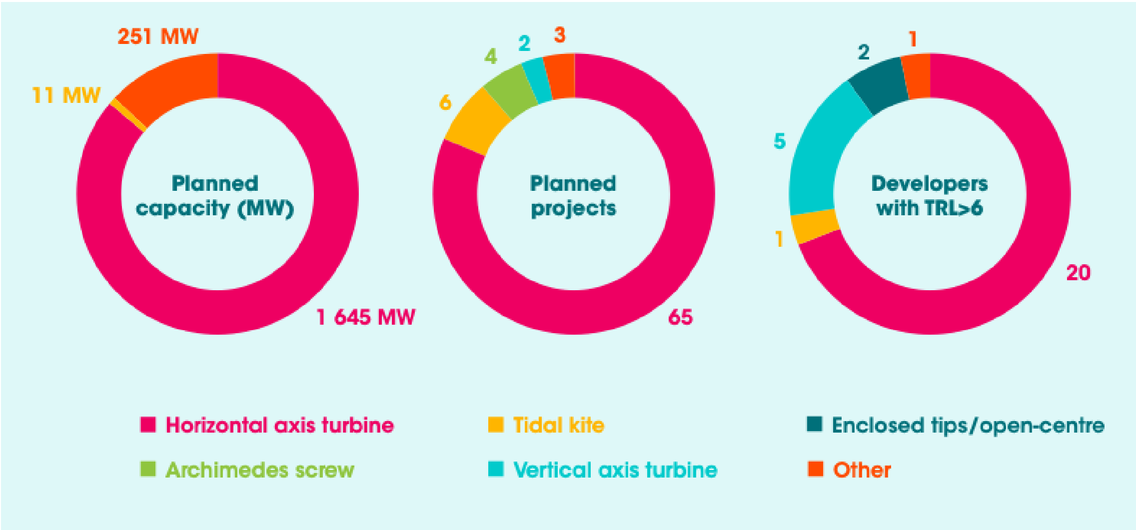


*Figure 3: Tidal stream projected capacity, planned projects and number of project developers by technology readiness level (TRL) (IRENA, 2020a)*

As the costs for both research and development, as well as the operational and production costs, it is an expensive technology to have interests in. Small scale projects and prototypes have been developed and are under development, but there is still a lack of large-scale projects due to the high costs that this brings. The need for subsidies and funds are vital in the development of this technology, and this is not an easy case. Nonetheless, the tidal stream is considered a good option within the ocean energy technologies, also compared to the tidal range, set aside the costs. These cases will be investigated in this thesis.

The Simec Atlantic Energy project named MeyGen tidal stream project, is currently the largest tidal stream project both in terms of cost and capacity (Noonan, 2019). The project, located in the channel between mainland Scotland and the island for Stroma, is planned to generate power up to 398 MW (SIMEC Atlantis Energy, 2021). The project's first phase is to install 4 bottom fixed, 1.5 MW turbines with 16 meters rotor turbine, weighing around 150-350 tonnes, and a maximum rotational speed of 20 rpm. The turbine types are of Atlantis Resource AR1500 and Andritz Hydro Hammerfest AH1000 MK1, and can be placed at a minimum depth of 30 meters, with a clearance of 8 meters between turbine blades and sea surface (MeyGen, 2012). The project cost is more than £420 million, and the Scottish Government has supported the project (SIMEC Atlantis Energy, 2021). The project is also supported by the innovative low-carbon technology EU program New Entrance Reserve (NER) 300 (Noonan, 2019).

*Figure 4: Construction of the MeyGen tidal turbine (SIMEC Atlantis Energy, 2021)*

The European Marine Energy Centre (EMEC) Ltd is a test and research centre located in the Orkney Islands, designed to develop further tidal and wave energy converters (EMEC: European Marine Energy Centre, n.d.). With its open water test facilities and grid-connection test sites, EMEC motivates for further tidal energy development. EMEC stated that there are more than 120 different tidal project, from prototypes to commercial stages (Røkke, 2017). As the UK has great potential for tidal stream development, it is forecasted that 10 % of the electricity demand can be gained from tidal stream, with 29 TWh per year (Houlsby & Vogel, 2017).

### 2.3.2 Technical overview

As for other technologies, there are various ways and types of designs of the ultimate turbine for the specific case on a plant or a project. Not only in terms of size or capacity but also technical details and decisions are needed to be made. In the table below, IRENA list some of the different classifications and technical specifications for tidal stream turbines (IRENA, 2014b).

*Table 1: Tidal stream classifications and trends (IRENA, 2014b)*

| Classification | Trend |
|---|---|
| Status | Active, unactive, unknown |
| Application | River hydrokinetic, ocean current system |
| Device type | Horizontal axis turbines, vertical axis turbines, oscillating hydrofoils, helix screws, enclosed tips and tidal kites |
| Configuration details | Multiple rotors, ducting |
| Regulation | Pitch, yaw, stall, no regulation |
| Power Take-Off (PTO) | Variable speed, direct driven permanent magnet, direct-drive hydraulic, undefined/other |
| Support structure | Fully submerged, monopile, rigid connection, moorings |

As the status explains at which stage the development is at, the application describes if the developers are also interested in applications such as river hydrokinetics or ocean current systems (IRENA, 2014b). The next classifications are regarding the equipment itself, starting with the device type. As mentioned earlier, there are multiple types of devices, being the horizontal axis and vertical axis the most common. For horizontal axis turbine, 3 blades are also often most used, as for horizontal axis wind turbines (Resen, 2018). Other configuration details are regarding the utilization of multiple rotors and the phenomenon of ducting (IRENA, 2014b). For the case of multiple rotors, they may have the advantage of contra-rotating rotors compared to a single rotor but also brings extra costs. For the control of the turbine itself and the blades, there are different types of control. Pitching is the regulation of the blades angle to obtain the optimal power output (*Wind Turbine Control Methods*, 2020). There is always an optimal blade angle of attack, to maximize the turbine power output or a maximum attack angle required to operate the electrical generator with its maximum rated power. Yaw is the control mechanism that ensured that the turbine is aligned with the flow.

The choice of PTO, it depends on the type of technology. There are different types of generators in use for horizontal axis turbines, in terms of geared and direct driven (no gears), and synchronous and asynchronous generators (Røkke & Nilssen, 2013). As for direct driven generators, permanent magnets (PM) are often used. This trend is also seen in wind energy technology, and for tidal energy is it a good solution regarding O&M.

Finally, to the structural support. These structures depend not only on the where the placement of the turbines will take place but also on the sea bed conditions, water depth and wave exposure. The tidal turbines may have the placement of fixed or floating. Fixed turbines, most often gravity-based structures, are more optimal for shallow waters. Floating structures can be classified into monopile, semi-submersible, spar and tension leg platform (TLP), and the mooring technologies are classified as spread mooring and single point mooring (*EUREC MSc in Renewable Energy - Ocean Energy - Master in Energy Engineering and Management: Mooring and Anchoring System - Introduction*, n.d.). The floating structures are structures suited for deeper waters. As seen for wind turbines, the development of floating turbines is very attractive, also referred to as tidal power. Cost-wise, floating structures have the advantage in the O&M stage (Røkke & Nilssen, 2013). An example of a floating tidal power structure is the Orbital Marine Power Ltd.´s O2, 2 MW tidal turbine with 2 rotors, both of with 2-bladed rotors, placed offshore of the Orkney Islands and will be connected to the EMEC test site and connected to the national grid (Orbital Marine, 2021)(EMEC: European Marine Energy Centre, 2021).

As an example, this next paragraph will be using the active MeyGen project with the AR1500 turbine, rated at 1500 kW (MeyGen, 2012). The project is utilizes horizontal axis turbines of monopile type structure, with a 3 carbon fibre bladed rotor (Atlantis Resources, 2016). Blade pitch is possible to 10°, and a yaw drive system is available. The cut-in speed, the speed at which the turbine starts to generate electricity, is on 0.5 m/s, and cut-out speed, the speed at which the turbine is shut down, is 4.5-5 m/s, whereas the rated operational speed is on 3 m/s.  The rotational speed is in a region of 8-20 rpm, but typically 14 rpm (MeyGen, 2012). The gearbox is of type two stage planetary flexi-pin, and the generator is a permanent magnet generator (Atlantis Resources, 2016).

As an overview, the figure below shows a summary of some of the options of classifications for a tidal stream turbine (IRENA, 2014b).

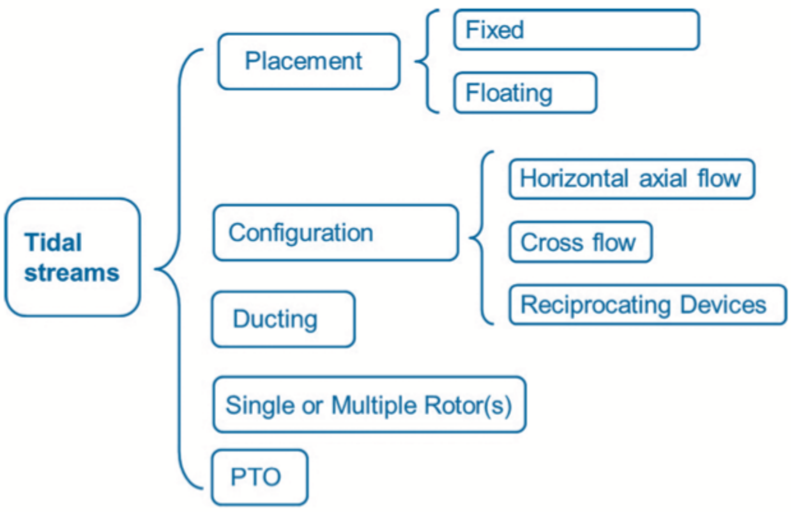


*Figure 5: Tidal stream turbine options of classifications (IRENA, 2014b)*

### 2.3.3 Tidal arrays

As for wind turbines, also tidal turbines can be connected through arrays (Vennell et al., 2015). This means multiple tidal stream turbines placed in the same channel or tidal stream connected to the same grid, taking advantage of the energy potential in the certain channel. Therefore, with this technology, it is possible to use multiple smaller turbines, preferably over one large turbine to generate the same amount of electricity. In terms of power available per turbine, the larger the number of turbines the larger the power available (Houlsby & Vogel, 2017). Installing rows of turbines in parallel, increases the blockage ratio, *B*, maximizing the power available. The blockage ratio is an important term for tidal turbines which will be discussed later in this thesis. Nevertheless, installing multiple turbines in a channel may also lead to a reduction in the current, where worst-case scenario is a choked flow (Garrett & Cummins, 2005). Therefore it is important to analyse the costs of building an array versus the output production and income for it to be a sustainable array.

Tidal turbines wake effect is the downstream area of the flow, which may cause disturbance (Jump et al., 2019). The cause of the wake behaviours can be related to turbulence, waves, geographical location of turbine and shear profile of the channel, amongst others. This may bring behaviours like velocity deficit, wake swirl and tip vortices may occur.

Array design is very complex and is dependent on the channels size and flow (Vennell et al., 2015). Again the output of the turbines depend on the number of turbines placed in the array and how they are placed. Arrays can be divided into large and small arrays. A large array is specified as an array where the turbines in the array take advantage of the duct effect due to the multiple turbines. The duct effect, a duct of water formed around the turbines, may improve the turbine performance. Another characteristic of large arrays is that the cross-sectional area of the channel can have a blockage ratio of 2-5 %. Large arrays may be divided into subcategories such as “moderately-large”, “very-large”, and “extremely-large”, all with different properties and array effects. Below, 8 array effects are listed. All 8 effects are relevant for large arrays, whiles the last effect listed is related to a small array. These array effects are important for understanding the tidal power production using large arrays, and to achieve a feasible array design. The array effects are listed as (Vennell et al., 2015):

1. Free-stream flow in the channel is reduced due to interaction between the array and the power extraction
2. Increasing drag coefficient and power production to gain maximum power extracted
3. Individual tuning to make sure that all turbines interact with each other, and that turbine wake impacts other turbines
4. Optimal tuned versus isolated tuned
5. Power return
6. Diminishing power return
7. Loads and costs are related to the power output of each turbine
8. Boost output by adjusting relative position

For now, the development of the array of MeyGen is still ongoing with its initial 4 turbines. With maximum of 86 turbines and 398 MW planned, being the largest tidal array yet to be built (MeyGen, 2012)(Noonan, 2019).

## 2.4 Tidal range

As previously mentioned, a tidal barrage is the technology used to harness the potential energy from the tidal waves. In other words, they are using the tidal range to generate electricity. Another name frequently used is the tidal range, and as the name implies, this technology uses the tidal range potential energy to capture the energy (IRENA, 2014a). Tidal barrages are often dams or barriers with turbines placed in the foundation, similar to hydropower technology. Tidal range generation is no new technology, and has been generating electricity on a large scale since 1966 in France, making the tidal range the most mature ocean energy technology (IRENA, 2014b).

The average tidal range on a worldwide basis is calculated to approximately 0.6 meters (Henriques, 2020a). The below formula shows the calculation of the average tidal range, whereas $\Delta h$ is the height difference between high and low tide

$$\Delta h\left(\theta = \frac{\pi}{2}\right) = \frac{3}{2}\left(\frac{1}{81.5}\right)\left(\frac{6371}{384000}\right)^3 (6371 \times 10^3) = 0.56\, m \tag{2.1}$$

For an economically viable tidal range power plant, a tidal range of 5 meters is required (Bell, 2002). Due to this, and other reasons like cost and environmental issues, there are limitations to implying tidal range and barrages. Although, research and development are still ongoing to find smart solutions for a technology that is limited in many ways. Even though the costs are high, the tidal range is an ocean energy technology that has shown economically viable and reliable projects. The tidal range of the Earth's oceans is shown in the figure below (IRENA, 2014b).

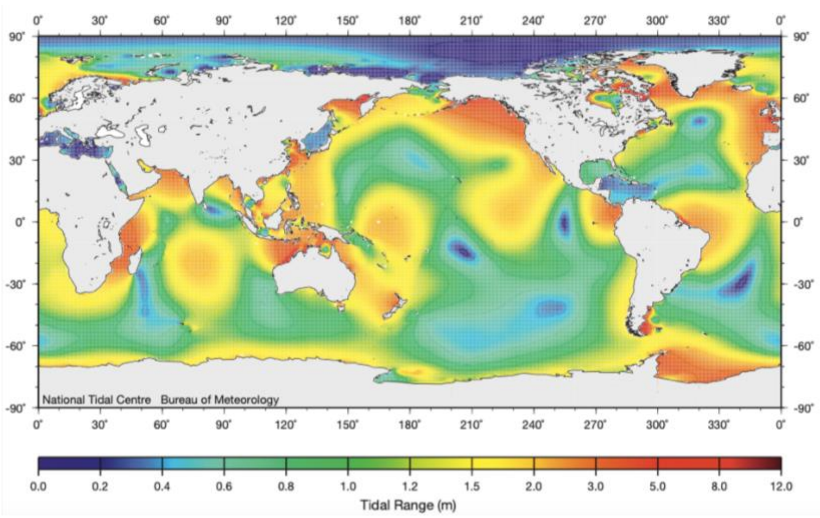


*Figure 6: Tidal range World map (IRENA, 2014b)*

As for tidal streams, there are also for tidal range different types of technical configurations and ways of harnessing the tidal range potential (O Rourke et al., 2010). For a single basin barrage, meaning one basin or reservoir connected to a bay or estuary, there are three different methods of operation for the tidal barrage technology. The different operation methods depend on the type of tides and at what point the turbine starts generating electricity. Single-way ebb generation is the principle of a barrage generating electricity from the water stored in the basin back to the original source. The filling of the basin happens during the flood tide, and the sluices are opened again during the ebb tide, which is where the name is from. To gain a sufficient hydrostatic head, the sluices and turbine gates are not opened until the ebb tides are at an optimal point, minimum head, $h_{min}$. The flow through the turbines can keep on for several hours, around 4 hours per day, before the turbines are stopped and the filling of the basin may start again (IRENA, 2014a). Ebb-generation is the preferred option based on cost, as it has the lowest unit cost for the generation (Bell, 2002).

In a single-way flood generation, the generation starts during the flood tides, in opposite to the ebb-generation (O Rourke et al., 2010). The filling of the basin happened during ebb tides. When the highest level of water is gained during flood tides, maximum head $h_{max}$, the sluices and gates are opened and water passes the turbines into the basin.

The final method of a single-basin barrage is the two-way generation, where both principles of ebb-generation and flood-generation occur. In a two-way generation barrage, the reversible turbines in the barrage can operate 4 hours daily, meaning double the time than for one of the other operation methods (IRENA, 2014a). Therefore, this method is more optional in the sense of operating time and costs of generation (O Rourke et al., 2010). There is also the method of double-basin, where the name implies, two basins are needed. Whereas for a single-basin, the water goes back and forth from the source to the basin, a double-basin has an extra basin for storage. Using the ebb-generation method, water is pumped into the second basin during the ebb tide. With the storage possibility, this method of generation can be more reliable than the other methods in cases of higher electricity demand. On the other hand, the method is not feasible in terms of large constructions and low efficiency.

Besides the barrages, there are also other ways of generating electricity using the tidal range, namely tidal lagoons, tidal fences and tidal reefs (IRENA, 2014a). Whereas barrages are more developed, these technologies are still being considered. Hybrid solutions are also thought solutions for the tidal range technology to be combined with infrastructure. By combining renewable energy sources into new infrastructure near the coast, like integrating tidal turbines with floating bridge constructions or submerged tunnels (Christophersen, 2012).

### 2.4.1 Current status

As previously mentioned, tidal range technology has been used since the 1960s, with the plant La Rance Tidal Power Station, located in the river Rance in Brittany, France (Tethys, 2019b). La Rance is still to this day operating, with its 24 reversible turbines on 10 MW, giving a total of 240 MW. With a net output of 480 GWh/year, La Rance was known to be the largest full-scale tidal range power plant in the world, until 2011 when the operation of the Sihwa Lake Tidal Power Station started. Sihwa Lake is located in the Gyeonggi Bay in South Korea, and with 10 turbines of 25.4 MW with an annual generation of 552 GWh/year (Tethys, 2019a).

For newer development, the tidal range technology is currently and consecutively under development and new innovations are still emerging. For the case of tidal lagoons, the 320 MW project of Swansea Bay Tidal Lagoon in Wales shows the real potential for a technology under development (Tidal Lagoon Power, 2021) (Clarke, 2016). The project is still under development, but if built, this means that 1 year of generation can produce electricity for around 150 000 Welsh homes. The report “The role of Tidal Lagoons” written by the previous Minister of State for Energy and Climate Change in the British Government, Charles Hendry, was published in 2016 and is also known as the Hendry review (Hendry, 2016). In this report, Hendry proposes that the United Kingdom should invest in new, green energy, like tidal lagoons, with the project of Swansea Bay in mind. Investing in these projects may not only lead to reduced $CO_2$ emissions but also economic benefits, jobs and prosperity, and export opportunities.

“*Tidal range energy resource and optimization – Past perspectives and Future challenges*” state that, assuming maximum water depth of 30 meters and minimum annual energy yield of 50 kWh/m$^2$, across 11 different coastal countries the global annual energy potential is 25880 TWh (Neill et al., 2018). For the tidal range technology, there are specifically 5 countries that take up 90 % of the potential energy in the world, whereas Australia alone makes up 30 % globally. The other countries are Canada, France, the UK and the US, with respectively 23 %, 13 %, 13 % and 11 % of the global resources.

### 2.4.2 Technical overview

For a tidal range power plant, there are four main components, namely the embarkment, the turbines, openings and locks (Neill et al., 2018). Coastally attached structures or offshore structures are options to choose between for tidal range power. Barrages and tidal lagoons, respectively, are examples of these two structure types. For a two-way generator barrage, reversible turbines are needed for the generation during both ebb and flood tides. A reversible turbine is a turbine that operates in both directions of the flow, bi-directional. Uni-directional turbines are turbines working in one direction, as for a one-way generation in ebb-generation or flood-generation (O Rourke et al., 2010). Bulb turbines, as used for low head hydropower, are most used for tidal range technology (Andritz Hydro, n.d.) (O Rourke et al., 2010). There are also alternatives to the straflo or rim turbines, amongst others. A bulb turbine is a form of horizontal Kaplan turbine with higher load capacity and higher full-load efficiency (NPTEL, n.d.). With the regulation of pitch angle, variable speed and adjustable guide vanes, is it a good solution for low head tidal range technology (Neill et al., 2018). The operation projects of La Rance and Sihwa Lake both utilize bulb turbines in different power ranges.

## 2.5 Maturity and Technology Readiness Level

### 2.5.1 Maturity

Maturity is a concept used on how well developed and advanced a state or form is (Camebridge Dictionary, 2021). The maturity of a technology may be measured and showed in a Technology Life Cycle (TLC) curve (Gao et al., 2013). The curve shows the different states of a technology life cycle, and is also referred to as an S-curve concept. The curve starts with an emerging, new technology. As the technology emerges, the technical stage changes to growth and the state of a pacing technology. As the technology matures, it might eventually saturate or even decline (Costa, 2019). For the technology of tidal power, the tidal range is seen as a mature technology, whilst tidal stream is less mature but growing to be one (IRENA, 2020a).

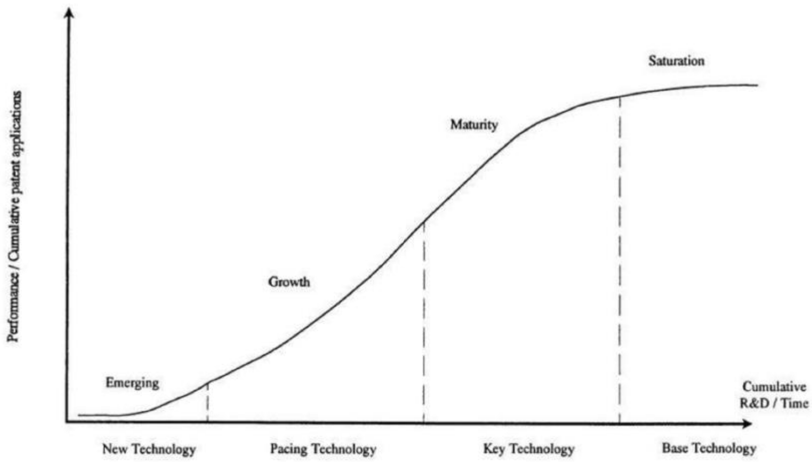


*Figure 7: Maturity graph/technology life cycle S-Curve (Costa, 2019)*

### 2.5.2 Technology Readiness Level

Technology Readiness Level (TRL) is a measurement of the maturity of the technology, often rated from the level TRL 1 to TRL 9, where 1 is the lowest level of maturity and 9 is the highest level of maturity (IRENA, 2014b). This scale was developed by NASA in the 1970´s, and has in later years been implemented in the International Organisation for Standardisation (ISO) in the standard ISO 16290:2013 regarding Space Systems (Tzinis, 2015)(ISO, 2013). The European Union also uses the system on the 2020 Horizon program (European Commission, 2014).

Based on Det Norske Veritas Germanischer Lloyd (DNV GL) data from 2014, the tidal stream is classified between TRL 7 and TRL 8, whereas tidal range has a classification on TRL 9 (IRENA, 2014b). The reasoning for the lower classification on tidal stream is due to the lack of tidal stream turbines in an array and the development of this. Currently, there is installed tidal stream array, namely the MeyGen tidal energy project with 4 turbines commissioned in 2016 and additionally 86 more turbines planned, being the largest tidal energy plant operating (SIMEC Atlantis Energy, 2021). Therefore, it is worth considering the technology readiness level of the tidal stream is forecasted to increase.

The table below is taken from WavEC and presents the maximum TRL, from 2015, on different tidal technology types (Mascarenhas et al., 2015).

*Table 2: Technology type and technology readiness level (Mascarenhas et al., 2015)*

| Technology type | Technology Readiness Level |
|---|---|
| Tidal barrage | 9 |
| Horizontal axis turbine | 8 |
| Vertical axis turbine (cross flow) | 5 |
| Oscillating hydrofoil | 5 |
| Enclosed tips/venturi | 8 |
| Archimedes screw | 5 |
| Tidal kite | 5 |

Tidal wave energy is 15 years behind the wind power technology in terms of development, which can also be a promising measure (O Rourke et al., 2010). The maturity graph explains and means is that developing technologies can learn and gain experience from the more mature technologies. And for tidal power, and especially tidal stream turbines, there is much knowledge to gain from wind turbine development.

As the technology of tidal power is said to be a mature technology, it still has large challenges (IRENA, 2014b). Firstly, the technology is largely dependent on specific locations of operation and cannot be located at any random location to generate electricity. Secondly, these specific locations are subsea and maybe offshore, and often in difficult conditions. Therefore, both the installation and maintenance of the equipment of tidal power generation may be costly, which again shows that the maturity level for marine tides are lagging behind other renewable energy technologies. This means that for tidal power to become economically viable and to be able to compete with other energy sources, it is a need to cut costs in both stages of development and operation and maintenance.

*Table 3: Stages in tidal current development (EMEC, 2021)*

| Stage | Tidal current development protocol |
|---|---|
| Stage 1 | Formulation of conversion concept |
| Stage 2 | Intermediate test of subsystem, dynamic and finite element analysis, fluid dynamics computation |
| Stage 3 | Large scale test of subsystem |
| Stage 4 | Full-scale prototype tested at sea |
| Stage 5 | Commercial demonstrator tested at sea |

In the table above, EMEC defines stages in the development of tidal current technology, collected from their task report 02-2-2 (EMEC, 2021). Whereas for wave energy, the levels of TRL is also defined, this is still unclear from a tidal energy point of view.

### 2.5.3 Learning rate

As an addition to the S-curve for the Technology Life Cycle, there is also the concept of a learning curve. In basic terms, it is similar to the concept of maturity, whereas the further the technology has gained in experience and knowledge, the more developed the technology (Zhou & Gu, 2019). The learning curve also focuses on costs reduction. As the name implies, it is about learning, and also learning from other, maybe more developed, technologies. As mentioned earlier, tidal turbines take much learning from wind energy technology which is in a more developed and commercialised stage. As for many times in life, the term learning-by-doing is also applicable for the development of new technologies.

Learning rate is a measure of change of costs over time, cost reductions, measured as a percentage of the fall of production costs with each doubling of the units produced (Allan et al., 2011). As an example of a learning rate of 10 % implies that the second unit will have a price reduction of 10 % to the first unit produced (Callaghan, 2006). Similarly to Levelised Cost of Energy (LCOE) presented in the next chapter, learning rates can then be compared to other technologies and the same technology over time to track the level of cost and cost reduction.

There is still not insufficient data on tidal power, as with other ocean energy technologies, as it is in such early stages of development. Nevertheless, learning rates are reported from different sources to lie around 3-15 % (European Commission. Joint Research Centre., 2018). Tidal stream estimated learning rates from Catapult are 19 % of OPEX and 13 % for CAPEX (Smart & Noonan, 2018). The graphic below shows the learning rates for tidal, wave and unspecified, and it is clear that for tidal, the information is poor (European Commission. Joint Research Centre., 2018).

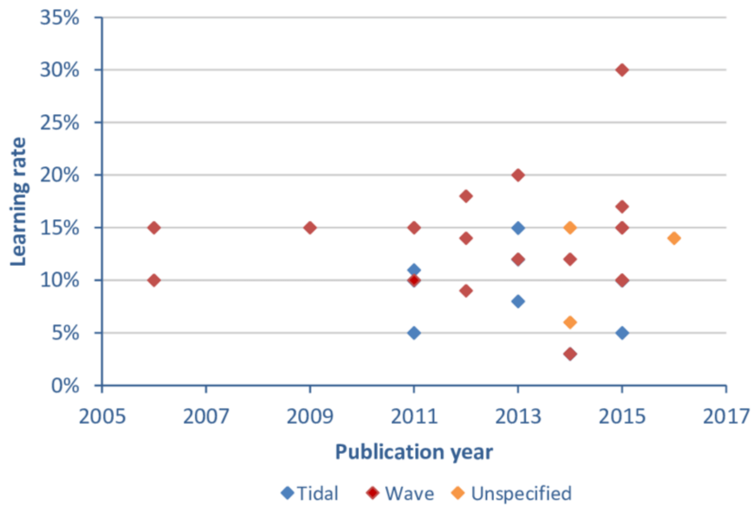


*Figure 8: Learning rates (European Commission. Joint Research Centre., 2018)*

Using the learning rate method, cost reduction can be calculated using the following formula (European Commission. Joint Research Centre., 2018)

$$Cost_t = Cost_0 \left(\frac{C_d}{C_0}\right)^{\varepsilon} . \tag{2.2}$$

The learning rate can be calculated using

$$LR = 1 - 2^{\varepsilon} , \tag{2.3}$$

where $Cost_t$ is the unit cost in year t, $Cost_0$ is the unit cost at t=0, $C_d$ is the cumulative deployment, $C_0$ is the cumulative deployed capacity, $\varepsilon$ is the experience parameter and $LR$ is the learning rate.

These concepts of maturity and learning also play an important role in the costs of the technologies. The more developed the technology, the cheaper the production and operation costs may occur.

## 2.6 Cost of Energy

Levelised Cost of Energy (LCOE) is a measurement used to calculate the cost of energy for a certain energy plant generating electricity over a period of time so that it is possible to compare different energy technologies up against each other (Ueckerdt et al., 2013)(Solarity, 2019). As well as the ability to compare different technologies with different bases and costs, the estimated LCOE of an energy technology is also a useful tool for decision making in going forward with a chosen project. LCOE is a simplified method used for any energy project. It is a much used method and can be used for a power plant regardless of the size, costs and lifetime. It is also important to mention that the LCOE measurement has its limitations. Several contributing factors are not measured using LCOE alone, such as risks (Shah & Bazilian, 2020). Other assisting concepts can be adopted such as Levelised Cost of Storage (LCOS) and Levelised Avoided Cost of Energy/Electricity (LACE) as suggested by the United States Energy Information Administration (EIA) (EIA, 2021).

LCOE is calculated in price per kilowatt or megawatt-hour, for example EUR/kWh or USD/MWh, by overall costs over the energy produced, all over the lifetime of the project. In other words the Capital expenditure (CAPEX) and operational expenditure (OPEX) over the energy production from the power plant or system. CAPEX are fixed costs expenses such as investment costs and other expenses on equipment to be used long term (Ross, 2021). OPEX are variable expenses and costs related to the short term and on a daily basis, namely taxes, wages, fuel costs, research and development (R&D) and operation and maintenance (O&M) costs.

LCOE can be calculate using following formula (Office of Indian Energy, 2015)

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+k)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \ , \tag{2.4}$$

where $I_t$ is the investment in year t, $M_t$ is the operation and maintenance in year t, $F_t$ is the fuel costs in year t, $E_t$ is the electricity generation is year t, $k$ is the discount rate and $n$ is the lifetime of the system.

Figure 9 illustrates different renewable energy technologies and the LCOE from 2010 up to 2019 for each technology, respectively (IRENA, 2020b). The global weighted average LCOE is illustrated in the lines drawn within each technology. The light grey box indicated the fossil-fuel cost range and is, therefore, the region for renewable energies that want to be within and below. The figure shows that LCOE for solar power and wind energy has decreased during these years, being attractive power generation technologies. Tidal power is not shown in this figure as it is not on the same level of commerciality.

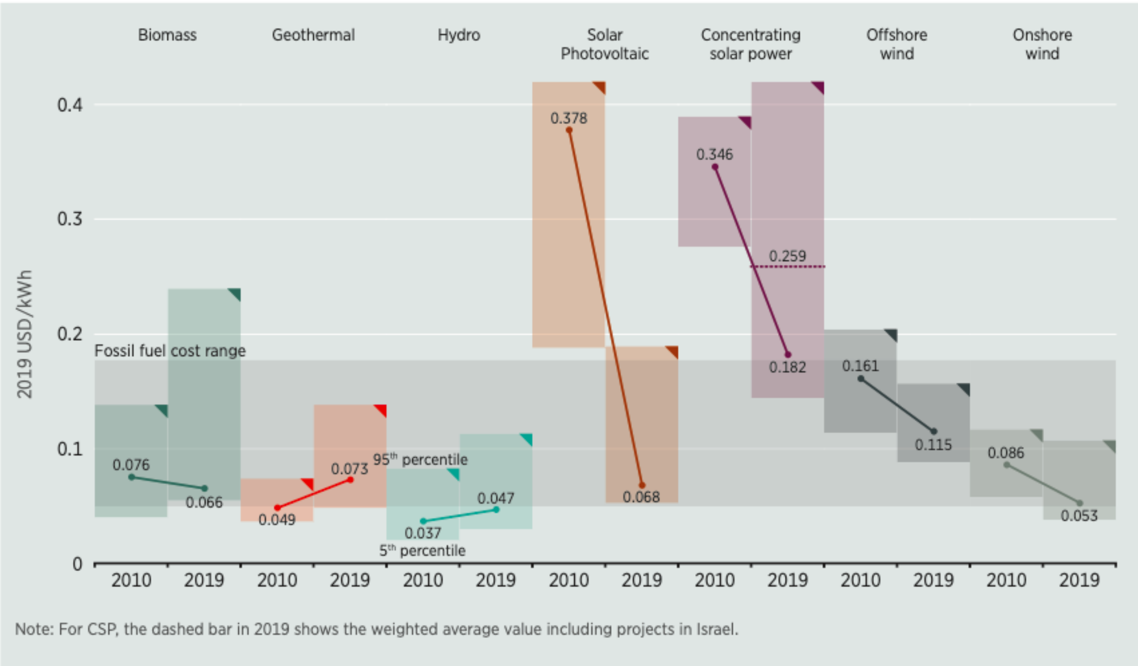


*Figure 9: Renewable energy LCOE 2010-2019 (IRENA, 2020b)*

### 2.6.1 LCOE tidal power

LCOE is a common and well-used method to compare the different renewable energy sources against the more conventional energy sources such as oil, gas and coal, in terms of energy cost. For renewable energies, the costs are higher than the costs for the conventional energy plants, where other expenses are less or even neglected. Renewable energy sources are clean and do not emit toxic gases into the atmosphere due to their technology not burning coal or oil. Thus, there are no fuel costs for renewable energy, and therefore there is one factor less in the calculations and evaluation of LCOE. On the other hand, renewable energy plants and arrays tend to have higher investment costs and higher operation and maintenance costs. In the case of tidal energy, both these costs are currently high, even compared to other renewable energy sources. This is also related to the degree of maturity and TRL of tidal power, and the development of the tidal energy devices and generators.

For the MeyGen project, the initial LCOE was given as 0.423 USD/kWh (£300/MWh) (Snieckus, 2020). In June 2020, Simec Atlantis Energy chief executive Tim Cornelius could say that costs were cut and that the LCOE was now around 0.14 USD/kWh (£100/MWh). These values are still high and not competitive in the total market compared to other sources. For tidal power in the US, the LCOE forecast for first commercial-stage projects is somewhere between 130-280 USD/MWh (Office of Efficiency & Renewable Energy, 2019). Anticipated cost reductions are on 61 % due to cost reduction over the long term due to experience. According to the European Commission the target for 2025 is on 0.165 USD/kWh (0.15 EUR/kWh) and 0.11 USD/kWh (0.10 EUR/kWh) for 2030 (IRENA, 2020a). Comparing with figure 9, the predicted values for the LCOE are somewhere in the upper region of the fossil fuel cost range and still higher than the more optimal LCOEs, like solar photovoltaic (PV) and onshore wind. In contrast, also these technologies have lower predicted LCOEs in the future (IRENA, 2019).

Currently, the LCOE for tidal power is higher than for other technologies, and therefore not competitive against cheaper sources (IRENA, 2014b). To obtain a commercial and competitive technology, the LCOE needs to be reduced to meet other technologies costs of energy. Reducing costs and improving reliability are large challenges and must be solved for the technology to survive in the market.

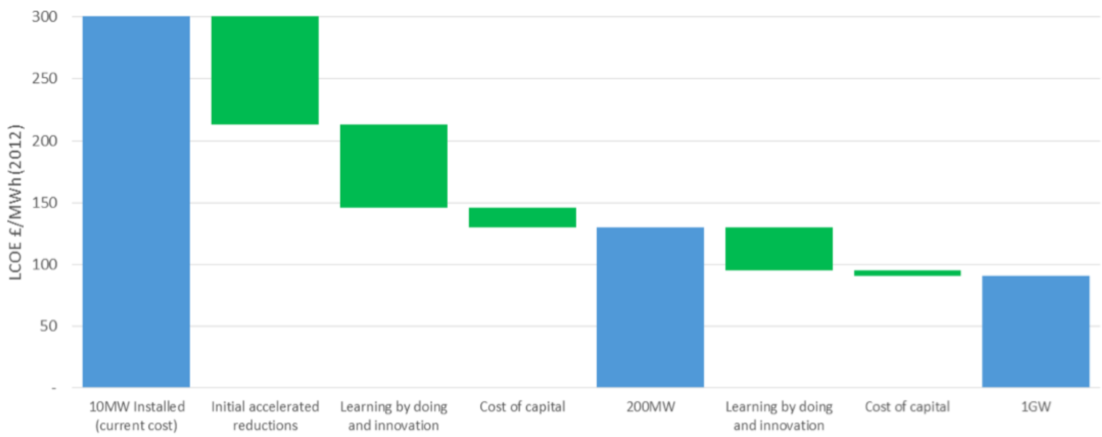


*Figure 10: LCOE reduction for tidal stream (Smart & Noonan, 2018)*

The above figure, figure 10, shows how cost reductions can be made for tidal stream technology through accelerated reductions, innovation and learning by doing, and finally cut the cost of capital (Smart & Noonan, 2018). The graphic illustrates current costs in blue boxes, and cost reduction in green boxes. As the installed capacity increases, the costs and total LCOE are predicted to decrease, as experience will gain by learning, new innovations will continue to emerge, and the capital costs may decrease.

Figures 11 and 12 are pie charts illustrating the breakdown of capital cost and LCOE for the tidal stream, respectively. Figure 11 illustrates that the breakdown of capital costs indicates two main components: the structure and the mechanical and electrical costs, which count for almost 80 % of capital costs (Callaghan, 2006).

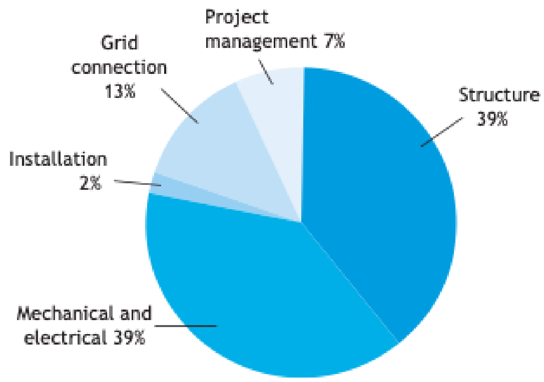


*Figure 11: Tidal stream farm capital cost breakdown (Callaghan, 2006)*

The pie chart below, figure 12, is taken from a pre-commercial, early-stage tidal project, and illustrates the breakdown of the LCOE (Noonan, 2019). The cost of capital, including all the costs from the previous chart, is the largest expense for a tidal project. Followed by O&M and turbine costs, these three shares cover 80 % of all costs. Therefore, the priorities of costs are listed in the correct order as cost of capital, O&M, turbine costs, electrical costs, installation costs, foundation and moorings, and finally development expenditure (DEVEX) and other CAPEX.

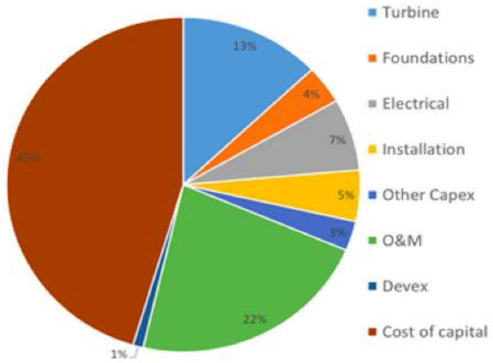


*Figure 12: LCOE breakdown (Noonan, 2019)*

## 2.7 Tidal power market

As previously explained, tidal power extraction is limited to its locations (O Rourke et al., 2010). Coastal areas with conditions matching the needs and requirements are limited making the tidal power market more narrow than other renewable energy sources. Nevertheless, there are still opportunities to harness tidal energy, and there are locations that meet the requirements, like in the UK, France, Canada, Portugal, USA, Indonesia and other coastal countries. More specific sites are listed below (O Rourke et al., 2010):

- Skagerrak-Kattegat
- Bay of Fundy
- Gibraltar
- English Channel
- Gulf of Mexico
- Sicily
- Artic Ocean

Energy potential from tidal energy is calculated to be up to 21 TWh in Europe and between 1000 and 1200 TWh/year on a world basis (Røkke, 2017)(IRENA, 2020a). On a global scale and in the global market, it is forecasted for tidal power to produce up to 101 GW by the year 2050 (Smart & Noonan, 2018). The International Energy Agency (IEA) graphic below shows the evolution of ocean power generation from 2005 and through 2020 and a predicted scenario until 2030 (Chowdhury et al., 2020).

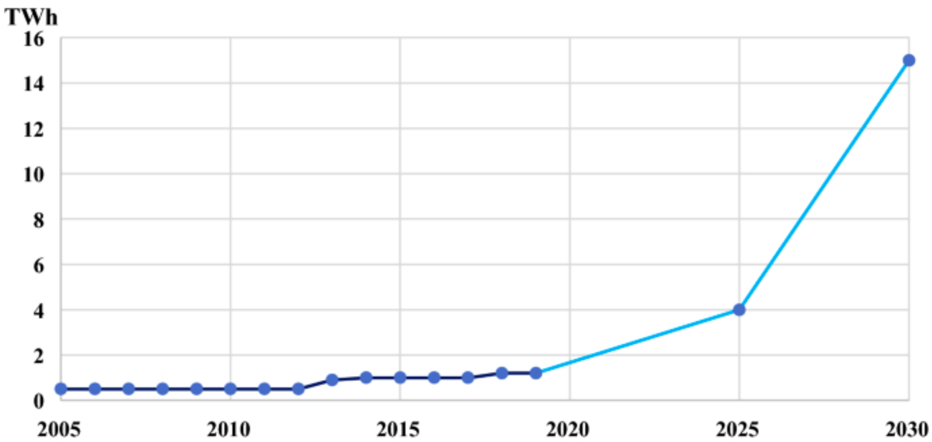


*Figure 13: Ocean power generation 2005-2030 (Chowdhury et al., 2020)*

## 2.8 Government support/subsidies/policies

High investment and operational costs make any tidal energy project an expensive project to invest. Therefore there are often needs for external funding and financial support to carry through the project. At the same time, tides are a natural resource that contributes to the renewable energy sector. As sustainability goals and targets are needed to be reached, and the energy demand is increasing, tidal energy is a reliable and carbon-neutral energy source that can contribute to meet these goals (UN, 2021e). The United Nations (UN) and its 193 member countries are cooperating on fighting the climate changes that are currently occurring (UN, 2021a). The secretariat of the United Nations Framework Convention on Climate Change (UNFCCC), operating since 1992, consisting of experts from all over the world, negotiates and treats the information regarding climate change and is also the parent treaty of the Paris Agreement (UNFCCC, 2021a). The Paris Agreement is the framework to limit the global warming to 1.5 degrees Celsius (UNFCCC, 2021c). Besides the Paris agreement, the EU have also set on a long-term strategy to become carbon neutral by 2050.

The UN's 17 Sustainable Development Goals (SDG) consists of targets, publications, events and actions to secure sustainability (UN, 2021e). SDGs number 7 is accurate and applicable for renewable energy and tidal power in focus, namely *Affordable and clean energy* (UN, 2021c). SDG7 indicates that renewable energies need to gain more effort to reach the target. SDG14 regarding sustainable use of the water resources, *Conserve and sustainable use the oceans, sea and marine sources for sustainable development*, is also relevant and important for ocean energy such as tidal power (UN, 2021d, p. 14).


*Figure 14: SDG7 – Affordable and clean energy (UN, 2021c)*

On individual stages, there are targets and goals for each country nationally. Nationally Determined Contributions (NDC), as named by the UN, are voluntary plans with action to fulfil to reach the target (UNFCCC, 2021b). For many countries, especially countries with tidal power development, clear policies and guidelines are defined regarding further development on tidal power.

To reach these above goals, it is fundamental for $CO_2$ emissions to decrease and for green, carbon-free technologies to enter the market on a full scale. For the case of tidal power, it is the costs and the commercial stage that limit the technology. To develop and eventually become commercial, there are certain mechanisms to help, including the above renewable energy targets.

1. Financial and tax incentives
2. Research and development funding
3. Feed-in-tariffs
4. Carbon taxes
5. Renewable energy targets
6. Improvements in planning processes

The above lists point out multiple solutions to help the tidal technology to develop and commercialize (O Rourke et al., 2010). Financial and tax incentives mean reducing costs and the risks related to investing in tidal energy projects. Other incentives are feed-in-tariffs, where suppliers buy electricity at prices set by energy policies above market price. Feed-in-tariffs are often used on renewable energies and are a great advantage for the technologies, such as tidal energy, to stabilize the long-term market. The tariffs are set by the energy policy of the specific country and may therefore vary from market to market. In 2010, D. Jackson and T. Persoons investigated the varying and fixed renewable feed-in-tariffs (REFIT) in regards to different tidal energy projects in Ireland, and the findings where that tidal energy will become economically feasible in 15 years, with an increase of generator scale and incentives given (Jackson & Persoons, 2012).

Research and development (R&D) funding is another way of reducing the costs (O Rourke et al., 2010). Research and development on tidal energy are often carried through by private companies, universities and other institutions, which is vital for the technology to grow. Tidal power, a renewable energy source, also benefits from the carbon taxes and renewable energy targets set to reduce the carbon footprint of today's technologies. This involves the different markets today that must contain a certain share of renewable power, a significant advantage for these technologies, including tidal power. The final mechanism listed is regarding the planning processes related to tidal power. Therefore there is raised awareness at the local and national levels about the challenges regarding strategic planning.

All in all, the UK has the best tidal energy policies, which also shows in the development of this technology in the UK (Røkke & Nilssen, 2013). This proves that for the development of tidal energy, it is at this stage vital to have tidal energy policies for a sustainable future of the technology (O Rourke et al., 2010).

### 2.8.1 COVID 19

From late 2019 until this day, a global pandemic has dominated the world in many ways, also in the sense of demand and supply of energy and electricity (IRENA, 2020c)(IEA, 2020). Thus, there has been an effect of COVID-19 on renewable energy and tidal energy. Although lockdowns, social distancing and business closures, renewable energy did show signs of reliability and stability during this period of time. Data also shows that renewable energies accelerated installation activities. While recovering from the pandemic, the energy sector needs to keep in mind the ongoing pace for renewable energies, and renewable energy sources are essential now more than ever to keep the energy supply as demanded and the security in providing jobs worldwide.

## 2.9 Energy power potential

### 2.9.1 Tidal stream

The energy produced by the tidal stream power generator is crucial to calculate and determine whether it is feasible to harness the energy using a tidal power turbine, as is the turbine in a channel flow. Energy production from moving water, meaning the power available, is calculated using the formula (Røkke, 2017)

$$P = \frac{1}{2}\rho u^3 A C_P \tag{2.5}$$

#### *2.9.1.1 Linear momentum actuator disc theory*

The linear momentum actuator disc theory (LMADT) is a mathematical method to derive the maximum upper limit of power that may be extracted from a fluid (Henriques, 2020b). Carried out by replacing a turbine in a certain flow with an ideal actuator disc, followed by analysing the passing flow. For wind power, this method is frequently used, whereas the Lanchester–Betz limit of 59.3 % is the power extraction limit (Pereira et al., 2020)

$$Betz\ limit = C_{Pmax} = \frac{P_{max}}{\frac{1}{2}\rho u^3 A} = \frac{16}{27} = 0.593 = 59.3\ \% \tag{2.6}$$

Derived by the scientist and physicist Frederick Lanchester and Albert Betz in 1915 and 1920, it is still applicable today (Henriques, 2020b). In practice, it means that the maximum energy harnessed from wind energy is 59.3 % with an ideal actuator disc. If the tidal turbines operated the channels where the blackage factor is not negligible, the Lanchester–Betz limit may be exceeded. Nevertheless, it is still possible to extended the actuator disk theory for this case to find the maximum limit for a tidal current stream, as the models used by Chris Garrett and Patrick Cummins (Houlsby & Vogel, 2017).

The Froud number

$$Fr = \frac{u}{\sqrt{gh}}\ , \tag{2.7}$$

is a dimensionless number related to the flow characteristics and how gravity influences the fluid (Encyclopaedia Britannica, 2016). $Fr$ is given by the speed of the flow divided by the square root of gravitational acceleration and static head (Houlsby & Vogel, 2017). This quantity is an important factor in terms of calculating the available power given by tidal waves, using the LMADT.

The blockage ratio,

$$B = \frac{Area\ of\ turbine}{Cross - sectional\ area\ of\ channel} = \frac{A}{bh}\ , \tag{2.8}$$

is the ratio of the area of the turbine and the cross-sectional area of the channel flow (Houlsby & Vogel, 2017). The more turbines in a flow, the larger the power available, and the blockage ratio increases. High blockage on turbines is more efficient than lower blockage. Thus, the blockage ratio plays an important role in determining the power achieved by a turbine. Other important factors are the torque,

$$T = \rho g(\Delta h)A, \tag{2.9}$$

the power coefficient,

$$C_P = \frac{P}{\frac{1}{2}\rho u^3 A}, \tag{2.10}$$

as shown above used to obtain the Betz limit, and thrust coefficient

$$C_T = \frac{T}{\frac{1}{2}\rho u^2 A}. \tag{2.11}$$

These factors are important in further modelling of the tidal stream (Garrett & Cummins, 2005).

### 2.9.2 Tidal barrages

For the case of tidal barrages and tidal range technologies, the power generated can be calculated using the formula (Neill et al., 2018)

$$P \propto Ah^2 \tag{2.12}$$

Thus, the energy available for tidal barrages, is approximately proportional to the square of the tidal range, meaning the potential difference of water level, times the surface area (Bell, 2002).

## 2.10 Tidal power advantages and disadvantages

### 2.10.1 Tidal power advantages

This next chapter will summarize the benefits by extracting energy from both of the tidal power technologies, whether using tidal turbines in channels, or turbines in barrages.

Tidal power is a carbon-neutral, renewable energy and exhaustible source with the ocean as its resource. Renewable energies are often also put in context with sustainability. With the drastic climate changes, and the need for the entire world society to cut their $CO_2$ emissions, at the same time as the electricity demand is increasing, renewable energy sources are more critical than ever. As the market is changing, the attraction for renewable energy is enormous. Likewise, for investors, renewable energy sources are more attractive to invest in compared to traditional energy sources like oil, gas and coal. Nevertheless, there is a big competition for tidal power in wind energy and solar power especially. Another solution may be to combine the different technologies to create an optimal technology. One examples is to couple offshore wind energy with tidal stream technology, to take advantage of both wind and the tidal stream at the same time (Lande-Sudall et al., 2018). Another example can be to couple tidal barrages with infrastructure, like floating bridge structures (Christophersen, 2012).

Tidal power is very reliable and predictable, in the sense of the continuous rise and fall of the water levels (IRENA, 2020a). In this case, tidal energy has a significant advantage compared to both wind and solar power. The phenomenon of tides will is not be stopped nor slowed down by any external factors.

Any renewable energy, it may also bring an economic opportunity with it (UN, 2021b). This presupposes a good LCOE to start with, but a project may bring economic benefits to the surrounding environment on both a local and national scale. Another advantage that new technology and development brings is the opportunity for new jobs. As the phasing out oil and gas may become a fact, the need for jobs will also be a real issue. The new development will therefore make an important impact on the job market.

In particular, for the tidal stream technology, it is common to compare the technology up against wind energy. One big advantage of tidal power is that the flow of water is bidirectional, compared to the wind, which is multidirectional (Bell, 2002). This leads to tidal turbines needing less space than wind turbines. As tidal turbines also may be much smaller than wind turbines, this again shows the fact that less area is required and, therefore, a smaller encroachment on the environment. As tidal turbines are placed under the water surface, there is also the advantage of the aesthetic sense, whereas most of the technical equipment is “hidden” underwater.

For barrages, there are other main advantages. As the past has shown, there are already full-scale projects operating to this day. If the costs and location allows it, this proves that the technology is well developed and may be a sustainable investments.

Similarly to hydropower stations and hydropower dams, tidal barrages may also be advantageous in creating storage (IRENA, 2014b). Also, the creation of dams and smaller or larger lakes may be used by the public and hikers as an outdoor area or park. As turbines are placed in a barrage, the technology is also suitable for flood control and water quality management in certain areas, such as areas that are struggling with large floods.

The IRENA figure below, figure 15, summarizes the advantages and benefits that tidal energy has, where tidal energy plays a big part in ocean energy.

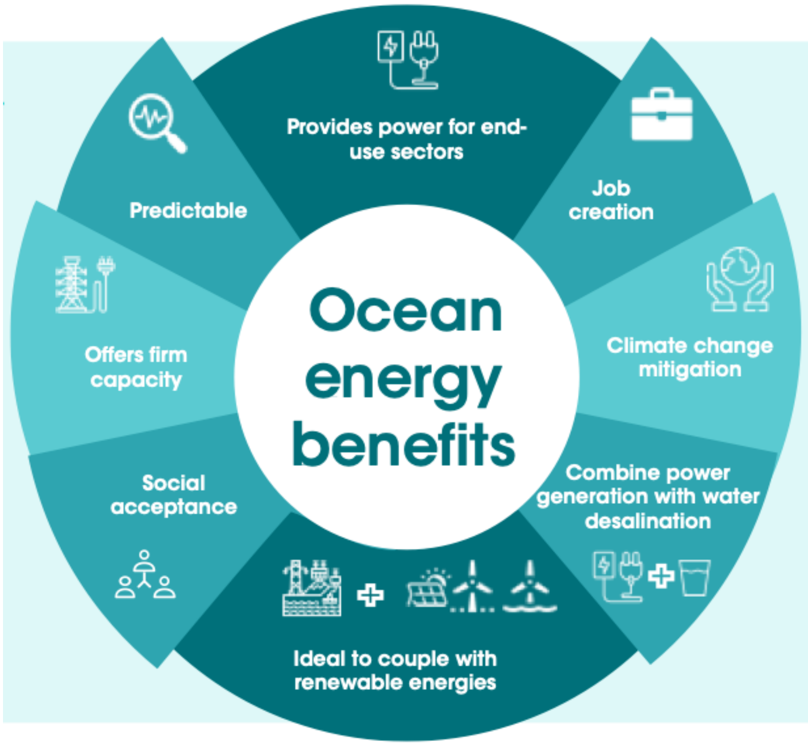


*Figure 15: Ocean energy benefits (IRENA, 2020a)*

### 2.10.2 Tidal power disadvantages

On the contrary to advantages, there are possible disadvantages and hurdles to overcome for the tidal power technologies. IRENA has listed four main challenges for tidal power: technical, economic, the environmental and social, and infrastructural (IRENA, 2014b).

Starting with the biggest challenge for the technology is for the costs related to all stages of the development of tidal power. For tidal power to be a compatible source on the market, the costs regarding installation, operation and maintenance must be lower than the income of electricity (Røkke & Nilssen, 2013). If government support and policies are given, the potential for tidal power will be significant. As the technology is growing in the sense of maturity, and the more produced and the more business, the cost will decrease.

Tidal power is a predictable and reliable source due to the occurrence of the ebb and flood tides, though it also has its restrictions in terms of energy harnessing. Since the tides only happen four times a day, the energy is intermittent, and cannot produce electricity all day and night around.

As discussed in the previous chapter, where an underwater technology is an advantage, there is also a backside to this. For the technology to be submerged, there are high costs of installation and maintenance. Underwater is a harsh environment, and equipment installed underwater needs to withstand these surroundings for a long time. When need for maintenance, which also may occur regularly due to its environment, this is a demanding and costly process.

Another challenge to mention is regarding ecological, social and environmental issues. Tidal power constructions and equipment are in close contact with water and aquaculture, and there is a risk to consider. The large construction that tidal range technologies bring will impact on the environment due to the impoundment of seawater (Houlsby & Vogel, 2017). Aspects that interfere with the well-being of marine species such as noise, collisions, electromagnetic fields and transport of sediment are important to consider before installing of any tidal energy technology and monitoring after installation (Chowdhury et al., 2020). Especially for the construction of barrages, environmental issues have been discussed. The barrage infrastructure can be large constructions and may take up large space of nature. As for tidal turbines in a channel, they are easier avoided for living creatures than for the turbines in a barrage (O Rourke et al., 2010). Tidal stream has a lower environmental footprint than tidal barrages in terms of infrastructure, but as the technology is maturing, there is still a lack of data.

As many times previously mentioned, there is a certain similarity between tidal turbines and wind turbines. One large disadvantage for tidal turbines being placed underwater, it the possible occurrence of cavitation (Wimshurst et al., 2018). This limits the reduction of load, tip speed ratio (TSR) and therefore also costs.

## Chapter 3

# Methods

## 3.1 Framo generator

For a Framo generator, the key properties to consider are namely low speed/velocity, high load and high torque due to high water density. The Framo motors to investigated if they are feasibile for tidal power, are the two following generators/motors with respective optimal parameters:

*Table 4: Parameters for SR2000 and SR2000E*

| Parameters | SR2000 | SR2000E |
|---|---|---|
| Diameter, $D$ [mm] | 1700 | 8000 |
| Rotational speed, $N$ [rpm] | 130 | 20 |
| Torque, $T$ [Nm] | 4407 | 28600 |
| Power, $P$ [kW] | 60 | 60 |
| Weight, $W$ [kg] | 1000 | 1500 |

Framo's SR2000, illustrated in the figure below, is currently used within the aquaculture sector as a flow generator for fish farms with lice skirts (Framo Innovation, n.d.). The solution is installed within the net pens and provides and distributes continuous flow of fresh water at an optimal water temperature for the fish. The motor utilizes permanent magnets and is rim-driven, gear- and shaftless, which are optimal factors for large volume of water and low pressure conditions.

*Figure 16: Framo Innovation´s SR2000 (Framo Innovation, n.d.)*

Whereas the SR2000 has an internal rotor, the motor SR2000E has similar characteristics, though with an external rotor and blades outside the rotor. Thus, the diameter of this solution will be much larger than the SR2000. Therefore, significant differences in speed can be seen in the two specs.

## 3.2 The relationship between the inertia and the kinetic rotational speed

The turbine/generator set is given by

$$I\dot{\Omega} = T_{turbine} - T_{generator}, \quad (3.1)$$

where $I$ is the inertia of rotating parts and $\Omega$ is the rotational speed (Henriques, 2021a). Multiplying both sides of equation by the rotational speed $\Omega$ we get

$$\frac{d}{dt}\left(\frac{1}{2}I\Omega^2\right) = P_{turbine} - P_{generator}, \quad (3.2)$$

where $\frac{1}{2}I\Omega^2$ is the kinetic rotational energy. For tidal waves, and the occurrence of ebb and flood tides, the time interval is known as the hours between each tide. Thus, we are discussing large periods of time, which means that the inertia is small.

To maximizes the power, the turbine should work at a point where the tip speed ratio (TSR) and $C_P$ are at the optimal point, called the best efficiency point (BEP). The TSR is the ratio between the velocity in the tip of the blade, and the fluid velocity and is defined as:

$$TSR = \lambda = \frac{\Omega R}{u} \quad (3.3)$$

The following graphic explain the above relationships closer, with $C_P$ on the y-axis, and TSR on the x-axis. Figure 17 is illustrated for large wind turbines but is also relevant for tidal stream turbines. A common value for tidal turbine TSR is between 4 and 6, whereas the TSR for wind turbines is higher, and known to be between 7 and 11 (Wimshurst et al., 2018).

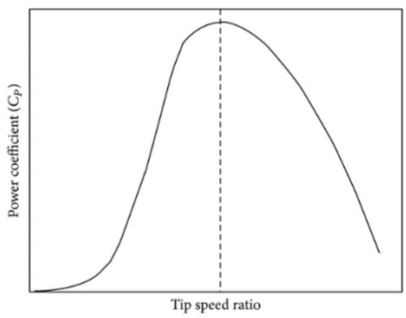


*Figure 17: Power coefficient vs. tip speed ratio (TSR) (Kjellin et al., 2013)*

The graph below shows an example of the relationship between power, on the y-axis, and velocity, on x-axis. Until cut-in speed, $u_{ci}$, meaning speed of the fluid which the starts the turbine generating electricity, power is equal to 0. After cut-in speed, the curve follows a cubic curve until it reaches rated velocity, $u_{rated}$. From here and until cut-out speed $u_{co}$, the velocity of which the turbine is stopped generating, the curve is linear and at constant value. The area between cut-in and rated speed is where the power coefficient is at its best efficiency point.

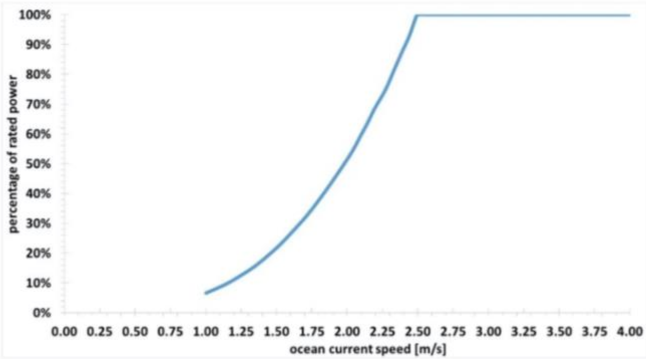


*Figure 18: Power curve - rated power vs. speed (Boretti, 2020)*

In an ideal turbine, $u_{ci}$ would be equal to 0 and $u_{co}$ would be infinite, which would always lead to maximum $C_P$. For a real turbine, $u_{ci}$ is always larger than 0, and $u_{co}$ is a finite value, giving typical values for $C_P$ equal to 0.35 – 0.50 as seen in the figure below (Henriques, 2021/2021a).

The following and final example is an illustration of the relationship between $C_P$ and velocity. With velocity still on the x-axis, power coefficient is on the y-axis, here named eta. This graphic shows that between 0 and $u_{ci}$, turbine is not operating. Between $u_{ci}$ and $u_{co}$ turbine is operating and power of generator should follow the power of the turbine, following a linear curve. In the area between $u_{rated}$ and $u_{co}$ the power of the generator should operate at rated power. If rotational speed decreases, pitching the blades may increase the rotational speed to maintain constant rotational speed. The curve in this area follows an inverse cubic curve. At $u_{co}$ generator is not operating.

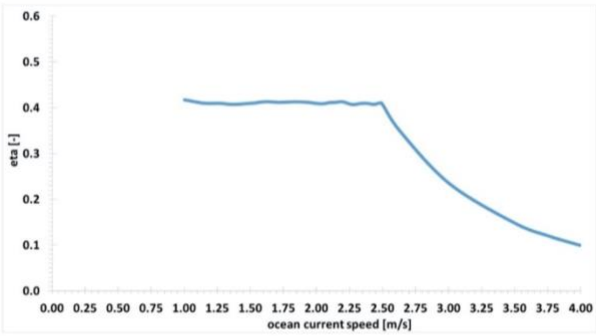


*Figure 19: Power coefficient vs. velocity (Boretti, 2020)*

## 3.3 Energy production in a tidal stream turbine

The instantaneous power at shaft is given by (Henriques, 2021/2021a)

$$P(t) = \frac{1}{2}\rho U(t)^3 A C_P(t). \tag{3.4}$$

In general $P(t)$ is smaller than rated power. The unit power is the following

$$P_u(t) = \eta_t P(t), \tag{3.5}$$

and the energy produced by one single unit, can be calculated by

$$E(t) = \int_0^t P_u(t)\,, \tag{3.6}$$

where $t$ is time, and one year is $t = 8760\ h$. $\eta_t$ is the efficiency of the powertrain and generator, and for a typical tidal stream turbine lies somewhere between 0.92 and 0.95 (Henriques, 2021/2021a). To calculate the annual energy yield, following formula can be used

$$energy\ yield = number\ of\ hours\ per\ year \times installed\ power \times capacity\ factor. \tag{3.7}$$

A common unit used for the energy yield is $GWh/year$. The capacity factor is the dimensionless ratio, often given as a percentage, of annual energy yield over the energy at 100 % rated power and is

$$capacity\ factor = \frac{E}{E_{rated}}, \tag{3.8}$$

$$0 \le capacity\ factor \le 1, \tag{3.9}$$

$$E_{rated} = P_{rated} t. \tag{3.10}$$

## 3.4 Modelling the tidal stream turbine

Using the LMADT, and assuming an inviscid and impressible flow in a frictionless, free surface channel, the following numerical model has been concluded (Houlsby & Vogel, 2017). The model is a simplification of the formulation of Garrett and Cummins theories, and Houldsby and Vogel, and was carried out by professor João Carlos de Campos Henriques (Henriques, 2021/2021b).

Using the Froud number and the relative height as main variables, it is possible to obtain a dimensionless result from solving multiple equations, giving one valid and one invalid solution (Henriques, 2021/2021b). A version of this model is presented below.

The figure below shows the stream channel boundaries (Henriques, 2020b). The core flow is the fluid streaming through the disc, and the bypass flow is the flow passing by the disc (Houlsby & Vogel, 2017). Upstream is defined as the flow before the turbine, and downstream as the flow after the turbine.

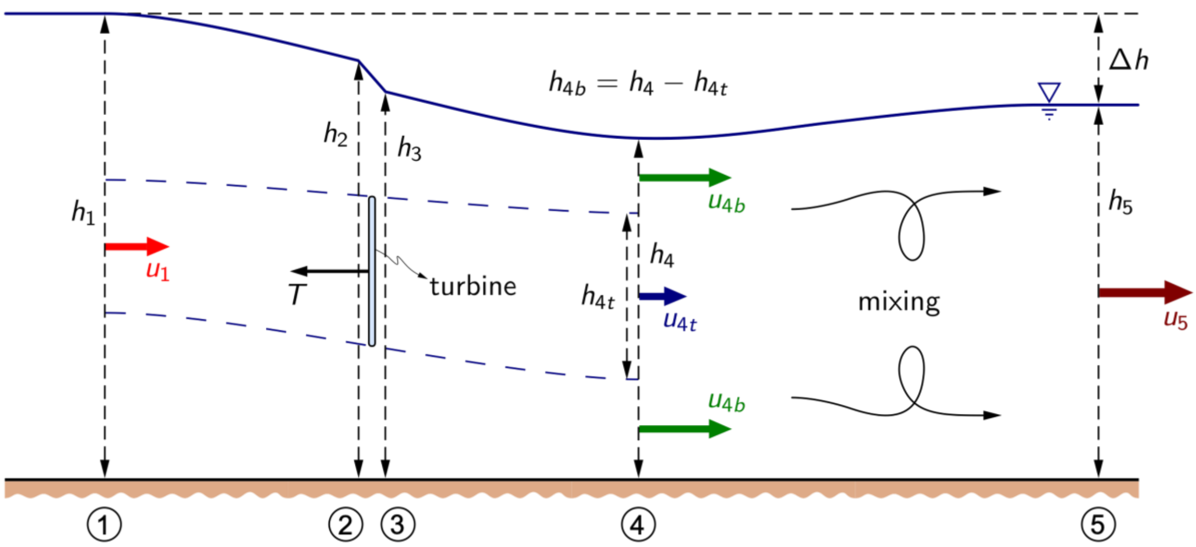


*Figure 20: Channel stream boundaries (Henriques, 2020b)*

The subscript *t* is for the turbine, *b* is for the by-pass flow, and 1-5 is the channel cross-section position.

Firstly, defining the dimensionless depth $\zeta_i$, with reference to $h_1$, as

$$\zeta_i = \frac{h_i}{h_1}. \tag{3.11}$$

The Froud number is defined as

$$Fr = \frac{u}{\sqrt{gh}}. \tag{3.12}$$

The local Froud number for the reference height $h_1$ is defined as

$$Fr_1 = \frac{u}{\sqrt{gh_1}}. \tag{3.13}$$

Starting with applying Bernoulli's equations on the flows, we get

- By-pass flow:

$$h_1 + \frac{1}{2}\frac{u_1^2}{g} = h_4 + \frac{1}{2}\frac{u_{4b}^2}{g}. \tag{3.14}$$

- Upstream:

$$h_1 + \frac{1}{2}\frac{u_1^2}{g} = h_{2t} + \frac{1}{2}\frac{u_{2t}^2}{g}. \tag{3.15}$$

- Downstream:

$$h_{3t} + \frac{1}{2}\frac{u_{3t}^2}{g} = h_4 + \frac{1}{2}\frac{u_{4t}^2}{g}. \tag{3.16}$$

Using the factors, $\zeta_i$ and $Fr$, results in the following dimensionless forms

- By-pass:

$$1 + \frac{1}{2}Fr_1^2 = \zeta_4 + \frac{1}{2}Fr_{4b}^2. \tag{3.17}$$

- Upstream:

$$1 + \frac{1}{2}Fr_1^2 = \zeta_{2t} + \frac{1}{2}Fr_{2t}^2\,. \tag{3.18}$$

- Downstream:

$$\zeta_{3t} + \frac{1}{2}Fr_{3t}^2 = \zeta_4 + \frac{1}{2}Fr_{4t}^2. \tag{3.19}$$

Continuing on to the forces working on the turbine, we have (see Figure 21)

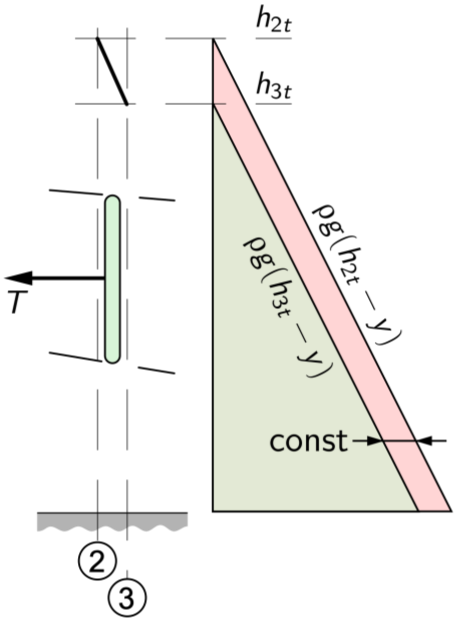


*Figure 21: Forces between sections 2 and 3 (Henriques, 2020b)*

- The thrust:

$$T = \rho g(h_{2t} - h_{3t})A_t, \tag{3.20}$$

where the turbine area is given by $A_t$.

- Thrust coefficient:

$$C_T = \frac{2}{Fr_1^2}(\zeta_{2t} - \zeta_{3t}), \tag{3.21}$$

$$\frac{C_T Fr_1^2}{2} = \zeta_{2t} - \zeta_{3t}. \tag{3.22}$$

- Power coefficient:

$$C_P = C_T \frac{u_{2t}}{u_1}. \tag{3.23}$$

Knowing that:

$$u_{2t} = u_{3t}, \tag{3.24}$$

$$Fr_{2t} = Fr_{3t}, \tag{3.25}$$

gives:

$$C_P = \frac{C_T Fr_{2t}}{Fr_1} \tag{3.26}$$

and the following relationship is obtained:

$$\frac{Fr_{4b}^2}{2} - \frac{Fr_{4t}^2}{2} = \zeta_{2t} - \zeta_{3t}, \tag{3.27}$$

$$C_T Fr_1^2 = Fr_{4b}^2 - Fr_{4t}^2. \tag{3.28}$$

Mass balance between stations 1 and 4 gives

$$h_{4b}u_{4b} + h_{4t}u_{4t} = h_1u_1, \tag{3.29}$$

$$Fr_{4b}\zeta_{4b} + Fr_{4t}\zeta_{4t} = Fr_1. \tag{3.30}$$

Momentum balance yields

$$M_{4b} + M_{4t} - M_1 = F_{p1} - F_{p4} - T, \tag{3.31}$$

$$-\rho bh_1u_1^2 + \rho bh_{4b}u_{4b}^2 - \rho bh_{4t}u_{4t}^2 = -\frac{A_tC_T\rho u_1^2}{2} + \frac{\rho bgh_1^2}{2} - \frac{\rho bgh_4^2}{2}, \tag{3.32}$$

$$Fr_{4b}^2\zeta_{4b} + Fr_{4t}^2\zeta_{4t} - Fr_1^2 = -\frac{B(Fr_{4b}^2 - Fr_{4t}^2)}{2} - \frac{\zeta_4^2}{2} + \frac{1}{2}. \tag{3.33}$$

Specifying

$$0 \le B \le 1, \tag{3.34}$$

$$Fr_1 = \frac{u_1}{\sqrt{gh_1}}, \tag{3.35}$$

$$Fr_{4b} > Fr_1, \tag{3.36}$$

$$\zeta_4 = \frac{Fr_1^2}{2} - \frac{Fr_{4b}^2}{2} + 1, \tag{3.37}$$

$$\zeta_{4t} + \zeta_{4b} = \zeta_4, \tag{3.38}$$

We get the following system of equations

$$Fr_{4b}^2\zeta_{4b} + Fr_{4t}^2\zeta_{4t} - Fr_1^2 = -\frac{B(Fr_{4b}^2 - Fr_{4t}^2)}{2} - \frac{\zeta_4^2}{2} + \frac{1}{2}, \tag{3.39}$$

$$Fr_{4b}\zeta_{4b} + Fr_{4t}\zeta_{4t} = Fr_1, \tag{3.40}$$

$$\zeta_{4t} + \zeta_{4b} = \zeta_4. \tag{3.41}$$

Solving system of equations for $Fr_{4t}^2$, we obtain

$$Fr_{4t}^2 = \frac{-Fr_{4b}\zeta_{4b} + Fr_1 - B\sqrt{B^2Fr_{4b}^2 + 2BFr_{4b}Fr_1 - 2BFr_1^2 + B\zeta_4^2 - B + Fr_{4b}^2\zeta_4^2 - 2Fr_{4b}Fr_1\zeta_4 + Fr_1^2}}{2}, \tag{3.42}$$

gives a valid solution

$$Fr_{4t} = \frac{C_1 + \sqrt{C_2}}{B}, \tag{3.43}$$

and an invalid solution

$$Fr_{4t}^{inv} = \frac{C_1 - \sqrt{C_2}}{B}, \tag{3.44}$$

where

$$C_1 = Fr_1 - Fr_{4b}\zeta_4, \tag{3.45}$$

and

$$C_2 = B^2Fr_{4b}^2 + B(2Fr_1(Fr_{4b} - Fr_1) + \zeta_4^2 - 1) + C_1^2. \tag{3.46}$$

Solving for $\zeta_{4b}$ and $\zeta_{4t}$ we obtain

$$\zeta_{4b} = \frac{-Fr_{4t}\zeta_4 + Fr_1}{Fr_{4b} - Fr_{4t}}, \tag{3.47}$$

$$\zeta_{4t} = \frac{Fr_{4t}\zeta_4 + Fr_1}{Fr_{4b} - Fr_{4t}}. \tag{3.48}$$

It is not difficult to prove that $Fr_{4t}^{inv}$ is invalid since

$$u_1 h_1 = u_{4b} h_{4b} + u_{4t} h_{4t}, \tag{3.49}$$

$$u_{4b} > u_{4t}, \tag{3.50}$$

$$u_1 h_1 = u_{4b} h_{4b} + u_{4t} h_{4t} < u_{4b} h_4. \tag{3.51}$$

Dividing by $\sqrt{gh_1}h_1$ we get

$$\frac{u_1}{\sqrt{gh_1}} - \frac{u_{4b}}{\sqrt{gh_4}}\frac{h_4}{h_1} < 0, \tag{3.52}$$

$$Fr_1 - Fr_{4b}\zeta_4 < 0, \tag{3.53}$$

or equivalently

$$C_1 < 0. \tag{3.54}$$

This implies that

$$Fr_{4t}^{inv} < 0, \tag{3.55}$$

as $\sqrt{C_2} > 0$. This gives a solution which is always negative, and it is therefore clear that $Fr_{4t}^{inv}$ is an invalid solution and there is only one correct solution for $Fr_{4t}$.

# Chapter 4

# Results

The results will be divided into two chapters. First, graphical results from the mathematical model is presented. In chapter 4.2, the results regarding the efficiencies of the two respectful Framo motors are shown.

## 4.1 Graphical results from mathematical model

The following graphical results can be obtained using the mathematical model from chapter 3.4 (Henriques, 2021/2021c). The results of the tidal stream model will be given by three graphs, namely $C_P$ versus $C_T$, $\frac{Q_i}{Q_1}$ versus $C_T$ and lastly $Fr$ versus $C_T$. All three graphs are shown three times, with different parameters.

The first three graphics use blockage ratio $B = 0.1$. The first graphic shows the relationship between $C_P$ and $C_T$, using the values of $B = 0.1$ and $Fr_1 = 0.1$. Seen in this graphic is that maximum value of $C_P$ equals approximately 0.78, with a value of $C_T$ at around 1.3.

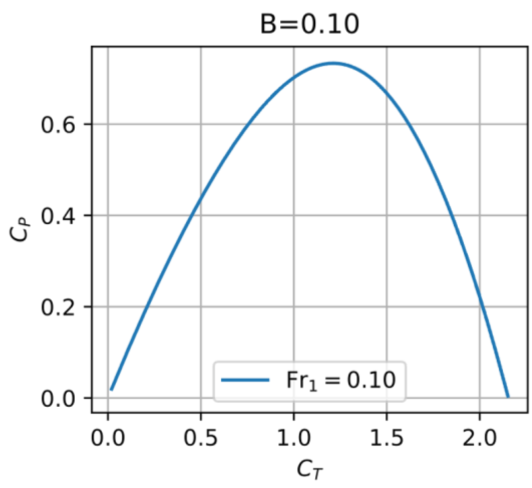


*Figure 22: $C_P$ vs. $C_T$ with $B = 0.1$ and $Fr_1 = 0.1$*

Also using the blockage ratio of $B = 0.1$, figure 23 represents the curves of $\frac{Q_{4b}}{Q_1}$ and $\frac{Q_{4t}}{Q_1}$. The curves mirror each other with $\frac{Q_{4b}}{Q_1}$ curving in positive direction, as $\frac{Q_{4t}}{Q_1}$ curves in negative direction. The $\frac{Q_{4b}}{Q_1}$ curve is the relationship between the downstream bypass flow and inlet flow of the system boundary, whiles $\frac{Q_{4t}}{Q_1}$ represents the relationship between downstream turbine flow and inlet flow of system boundary.

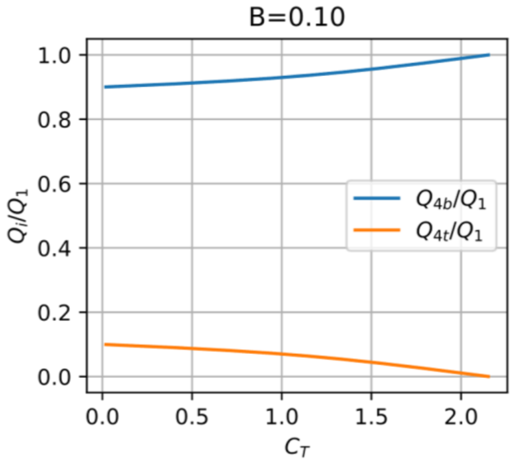


*Figure 23:* $\frac{Q_i}{Q_1}$ *vs.* $C_T$ *with* $B = 0.1$ *and* $Fr_1 = 0.1$

Figure 24 illustrates the relationship between the Froud number and the thrust coefficient, with a blockage ratio of 0.1 and $Fr_1$ of 0.1. In this graph, the curves of $Fr_{2t}$, $Fr_{4t}$ and $Fr_{4b}$ are shown. As $Fr_{4b}$ curve in a positive direction from starting point $Fr_1 = 0.1$, the two other curves of $Fr_{2t}$ and $Fr_{4b}$ curve in negative direction. This shows that downstream the turbine the trust coefficient increases as the Froud number decreases.

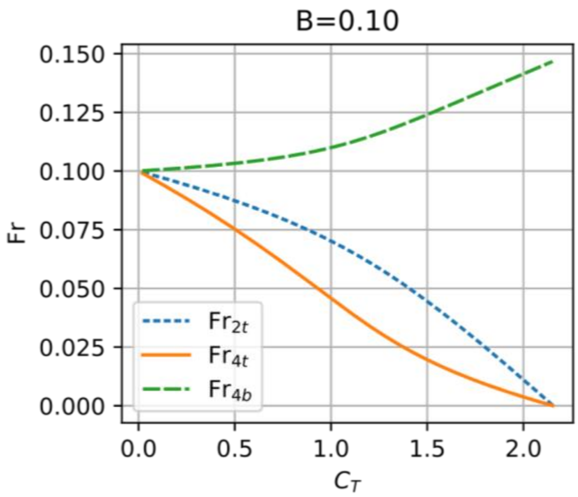


*Figure 24:* $Fr$ *vs.* $C_T$ *with* $B = 0.1$ *and* $Fr_1 = 0.1$

The three following graphics, uses $B = 0.1$ and value of $Fr_1$ from 0.1 up to 0.5. The first of the three, figure 25, again illustrates the relationship between $C_P$ and $C_T$. Compared to figure 22, where only one curve, $Fr_1 = 0.1$, is shown, figure 25 describes how $C_P$ and $C_T$ change by increasing $Fr_1$. What is clear to see is that by increasing $Fr_1$, $C_P$ and $C_T$ also increase. As also shown figure 22, maximum $C_P$ equals approximately 0.78, with a value of $C_T$ at around 1.3 with $Fr_1 = 0.1$, where maximum $C_P$ is approximal 0.81 with $C_T = 1.5$, for $Fr_1 = 0.5$.

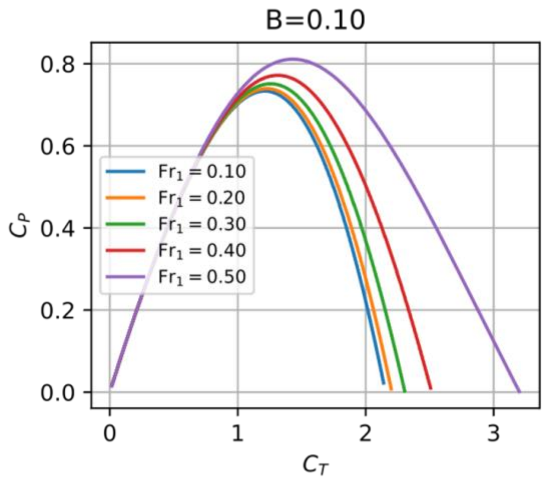


*Figure 25: $C_P$ vs. $C_T$ with $B = 0.1$ and variable $Fr_1$*

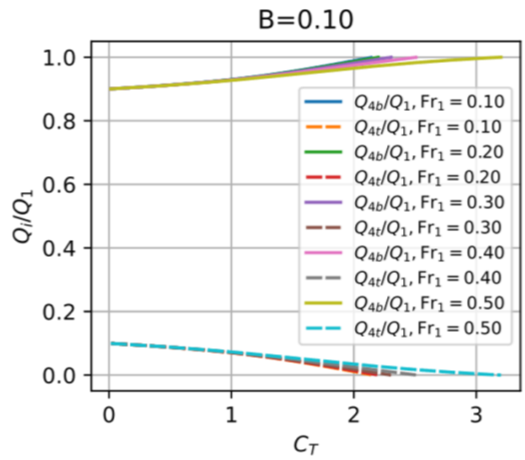


*Figure 26: $\frac{Q_i}{Q_1}$ vs. $C_T$ with $B = 0.1$ and variable $Fr_1$*

Figure 26 also show multiple curves with $Fr_1$ varying between 0.1, 0.2, 0.3, 0.4 and 0.5. As for the previous graph, figure 25, it is not as clear to see the differences between each curve, as the differences are minor. This means that changing the value of $Fr_1$ does not have much effect on the downstream flow relationships of $\frac{Q_{4b}}{Q_1}$ and $\frac{Q_{4t}}{Q_1}$.

As for figure 24, figure 27 below illustrated multiple curves of $Fr_{2t}$, $Fr_{4t}$ and $Fr_{4b}$ with the variance of $Fr_1$. As the Froud number increases, so does the value of thrust coefficient.

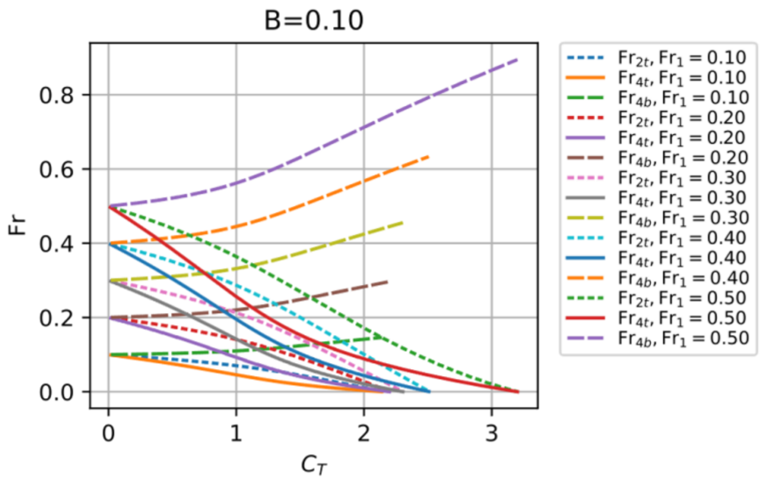


*Figure 27: $Fr$ vs. $C_T$ with $B = 0.1$ and variable $Fr_1$*

The final three graphics illustrate the three graphics with values of $Fr_1 = 0.2$ and the blockage ratio varying from 0.05 to 0.20, with an interval of 0.05. Starting with figure 28 which is similar to figure 22 and figure 25, but with different values for both $Fr_1$ and $B$. The orange curve illustrates the same curve as in figure 22, with an 0,1 increase of $Fr_1$. Whereas maximum value of $C_P$ was approximately 0.78 it shows that the increase of $Fr_1$ does have little effect on the maximum $C_P$. Nevertheless, the increase of blockage ratio also increases bot maximum $C_P$ and $C_T$.

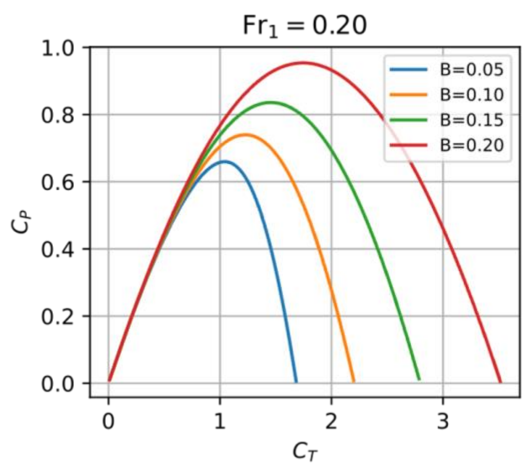


*Figure 28: $C_P$ vs. $C_T$ with $Fr_1 = 0.2$ and variable $B$*

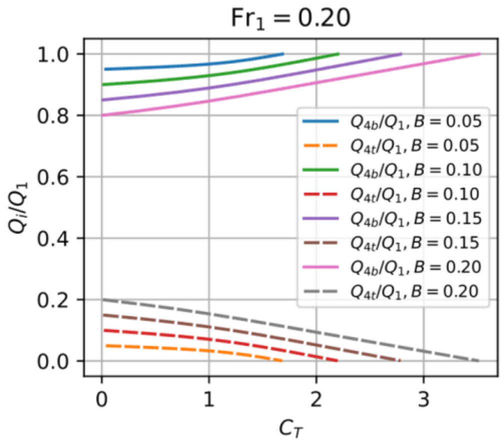


*Figure 29:* $\frac{Q_i}{Q_1}$ *vs.* $C_T$ *with* $Fr_1 = 0.2$ *and variable* $B$

Compared to figure 26, it is clearer to see in figure 29 the differences in the flow curves with the increase of $Fr_1$, and the increase and decrease of the blockage ratio. For $\frac{Q_{4b}}{Q_1}$, increasing the blockage ratio means increasing the value of $\frac{Q_i}{Q_1}$, whereas the opposite occurs for $\frac{Q_{4t}}{Q_1}$.

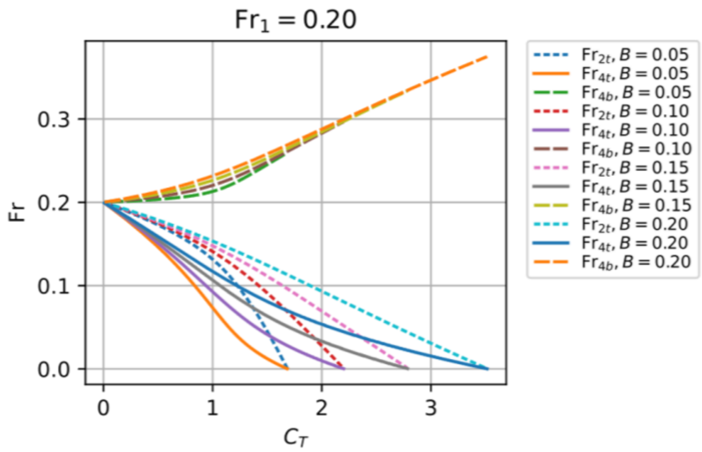


*Figure 30:* $Fr$ *vs.* $C_T$ *with* $Fr_1 = 0.2$ *and variable* $B$

Finally, figure 30 illustrates $Fr_{2t}$, $Fr_{4t}$ and $Fr_{4b}$ with the increase of $Fr_1$ and varying blockage ratio. The figure shows a less clear spread between the curves of $Fr_{4b}$ with the varying values of $B$. The spreading of $Fr_{2t}$ and $Fr_{4t}$ is larger, and the values of $C_T$ increases in line with the increasing of the blockage ratio.

## 4.2 Generator efficiency

The generator efficiency is an excellent indicator on how well the generator will operate. The efficiency may be shown in a efficiency chart, as a result of the speed and power of the generator. Using a python code, developed by Henriques referred to as (Henriques, 2021b, p. 200) and (Henriques, 2021c, p. 200), it is possible to obtain several results regarding the power curve and efficiency. The values regarding velocity and bins, are taken from a specific location with given time series of velocities, which are then implemented in the python code. The location will not be specified further, but it is important to mention that values will vary from location to location, and so will the results. It may now be possible to discuss the final research question; are any of the Framo motors feasible for a tidal turbine?

The below efficiency plot is given by Framo and illustrates the efficiency region of a given motor to be used for the SR2000E. The span of shaft power, given in 1e5 watts (100 kW), is from 0 to 120 kW (0 to 1.2 1e5 W), and the speed varies from 0 to 30 rpm. The colour codes are shown on the right side of the plot where 93 % is given as highest efficiency. It is important to mention that this plot is not a general plot, but an ideal and specific plot for a generator design with speed between 4 and 20 rpm, and power between 0 and 60 kW, focused on the rated point of 60 kW and 20 rpm. Mechanical and hydraulic losses will are not included in these results obtained in the plot. Other generator designs may therefore differ from this current plot.

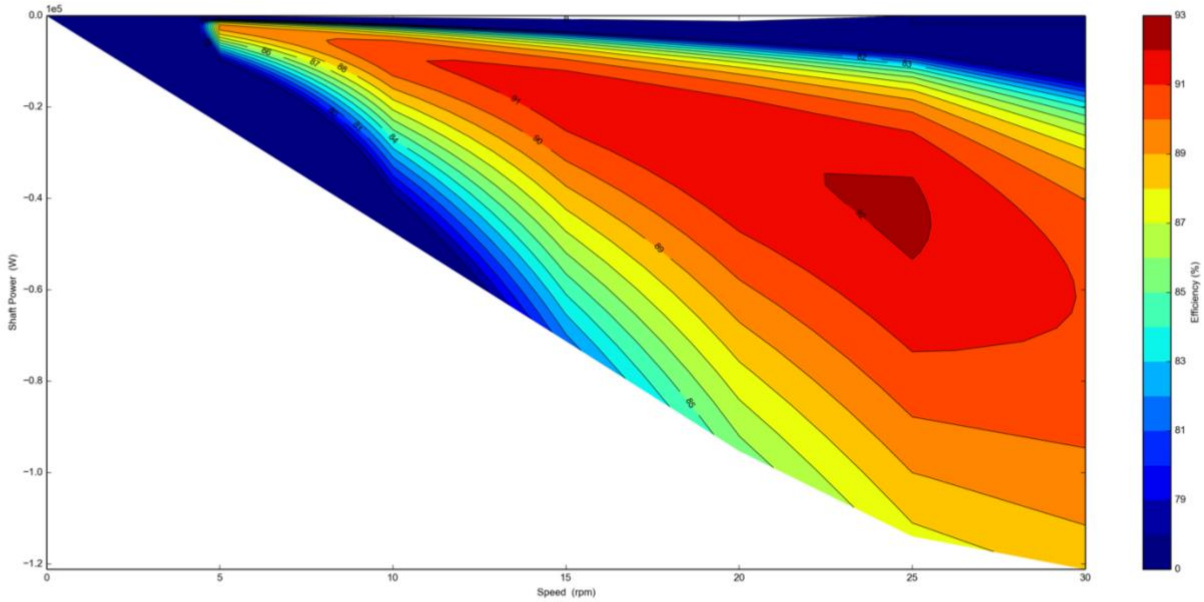


*Figure 31: Generator efficiency plot*

Python code for SR2000 is referred to as (Henriques, 2021b, p. 200), and (Henriques, 2021c, p. 200) for SR2000E. Using the python code with the given data from Framo regarding the motors SR2000 and SR2000E, the below results can be made. Whereas the radius for each of the two generators will vary, the following parameters are used in both cases:

*Table 5: Coding parameters*

| Parameters | Value |
|---|---|
| Rated power, $P_{rated}$ [kW] | 60 |
| Maximum rotational speed, $N_{max}$ [rpm] | 20 |
| Cut-in velocity, $u_{ci}$ [m/s] | 0.4 |
| Power coefficient, $C_P$ [-] | 0.48 |
| Sea water density, $\rho$ [kg/m$^3$] | 1025 |

The first step in the code is to calculate the number of bins, and number of hours in each of these bins. In this specific case, the total hours of 4387 hours are divided into 14 bins. The velocities are on given from a spectre starting from 0.1 and ending at 2.7 with an interval of 0.2 between each velocity.

The bins are spread over the velocities as seen in the figure below:

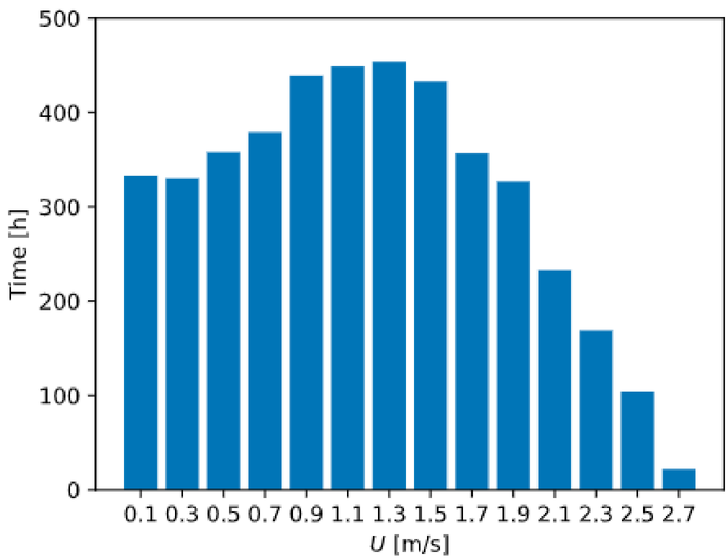


*Figure 32: Distribution of bins*

### 4.2.1 SR2000 efficiency

Starting with the SR2000, using the above parameters and speed of 20 rpm, the following two graphs can be presented, starting with the power curve, $P$ versus $U$, and lastly $C_P$ versus $U$. The two graphs above are the same as the graphs presented previously in the thesis, figure 18 and 19, and can therefore also be compared to these graphs.

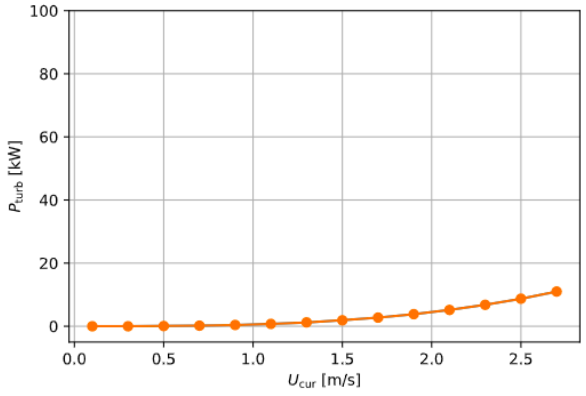


*Figure 33: Power curve SR2000*

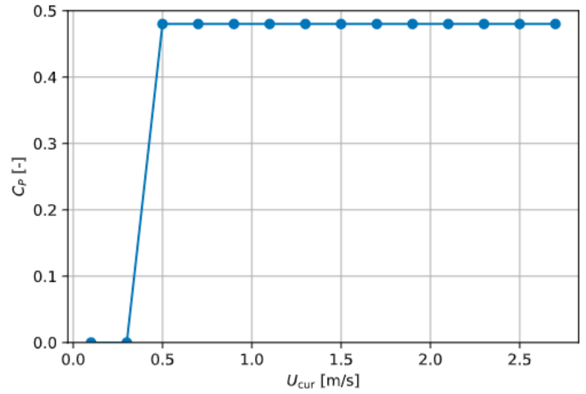


*Figure 34: Power coefficient curve SR2000*

What can be seen in figure 33, is the very low power produced by the turbine, with a maximum of 10 kW, and that the turbine never reached the rated power of 60 kW. Figure 34 show how the maximum and constant $C_P$ of 0.48 is obtained at 0.5 m/s. These relatively poor results may also be seen in the table below, table 6.

The following table obtained from the python code illustrate the 14 bins, the current velocity and how many hours each bin contains. Followed by power curve and speed, the generator efficiency was possible to obtain from Framo data. Generated power and annual power is then calculated by multiplying the power curve by the efficiency, and power produced per bin is generated power times number of hours in the given bin. The total annual power production with the given parameters is 7716.7kWh.

*Table 6: Coded values SR2000*

| | Ucur [m/s] | bins [h] | Power Curve[kW] | Speed [rpm] | Generator Efficiency [%] | Generated Power [kW] | Power Production per bin [kWh] |
|---|---|---|---|---|---|---|---|
| **0** | 0.1 | 333.0 | 0.000000 | 0.742003 | 0.00 | 0.000000 | 0.000000 |
| **1** | 0.3 | 330.0 | 0.000000 | 2.226008 | 0.00 | 0.000000 | 0.000000 |
| **2** | 0.5 | 358.0 | 0.069796 | 3.710013 | 0.00 | 0.000000 | 24.987101 |
| **3** | 0.7 | 379.0 | 0.191521 | 5.194019 | 1.76 | 0.003371 | 72.586551 |
| **4** | 0.9 | 439.0 | 0.407052 | 6.678024 | 43.67 | 0.177760 | 178.696020 |
| **5** | 1.1 | 449.0 | 0.743192 | 8.162029 | 60.23 | 0.447624 | 333.693101 |
| **6** | 1.3 | 454.0 | 1.226741 | 9.646035 | 67.75 | 0.831117 | 556.940424 |
| **7** | 1.5 | 433.0 | 1.884502 | 11.130040 | 75.41 | 1.421103 | 815.989377 |
| **8** | 1.7 | 357.0 | 2.743277 | 12.614045 | 77.69 | 2.131252 | 979.349738 |
| **9** | 1.9 | 327.0 | 3.829866 | 14.098051 | 81.92 | 3.137427 | 1252.366341 |
| **10** | 2.1 | 233.0 | 5.171074 | 15.582056 | 83.17 | 4.300782 | 1204.860139 |
| **11** | 2.3 | 169.0 | 6.793700 | 17.066061 | 85.19 | 5.787553 | 1148.135232 |
| **12** | 2.5 | 104.0 | 8.724546 | 18.550066 | 85.99 | 7.502237 | 907.352827 |
| **13** | 2.7 | 22.0 | 10.990416 | 20.000000 | 87.73 | 9.641892 | 241.789148 |

To show the relationship between the tidal current speed and the generator efficiency, a plotted efficiency map for SR2000 is shown below. The map is plotted with all 14 points, showing the respectively efficiency for the given velocities.

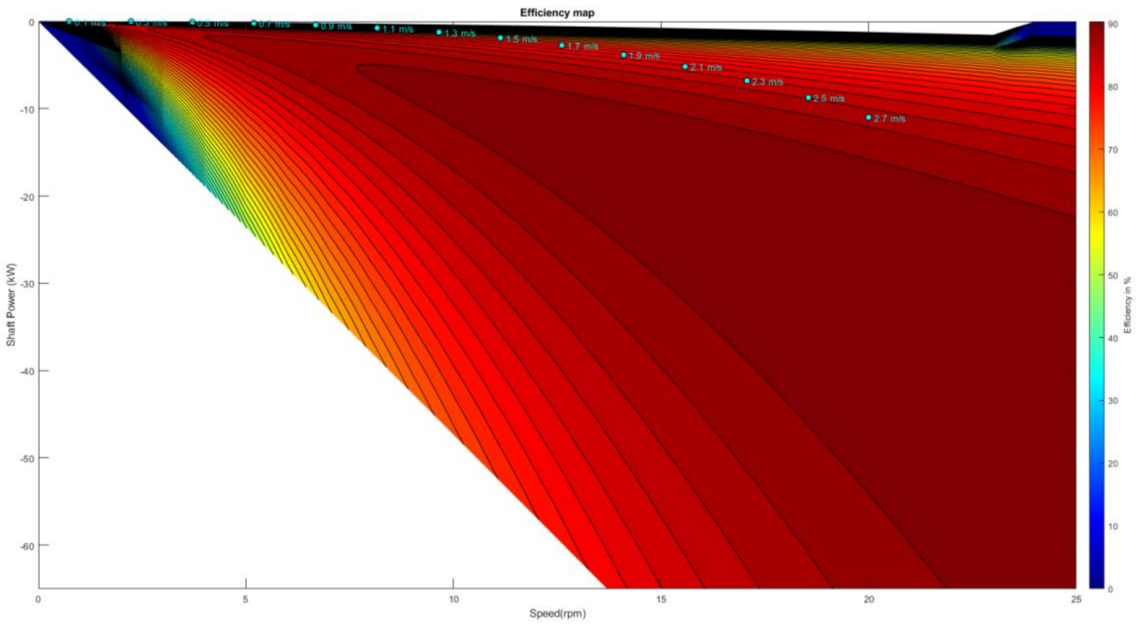


*Figure 35: Efficiency map SR2000*

### 4.2.2 SR2000E efficiency

For the case of SR2000E, the resulting graphics are much better than for SR2000. The power curve, figure 36, describe much better conditions than for the SR2000 where at 1.9 m/s the turbine power reaches 60 kW. The blue curve in figure 36 is the ideal power curve.

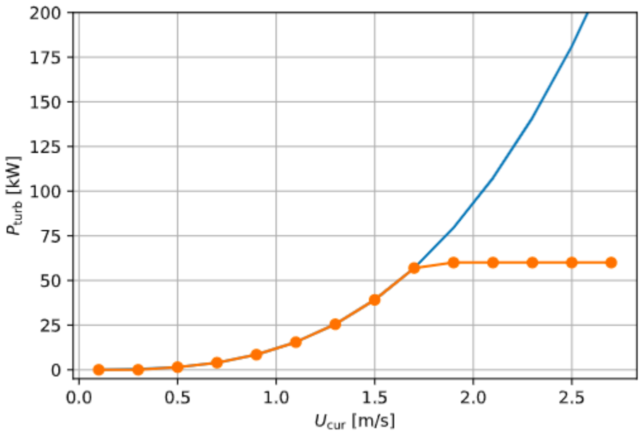


*Figure 36: Power curve SR2000E*

For the second curve, figure 37, also this curve is of better results compared to SR2000. $C_P$ is constant from cut in speed at 0.5 m/s, and stays constant until approximately current speed of 1.7 m/s, before it decreases until cut-out speed, $u_{co}$.

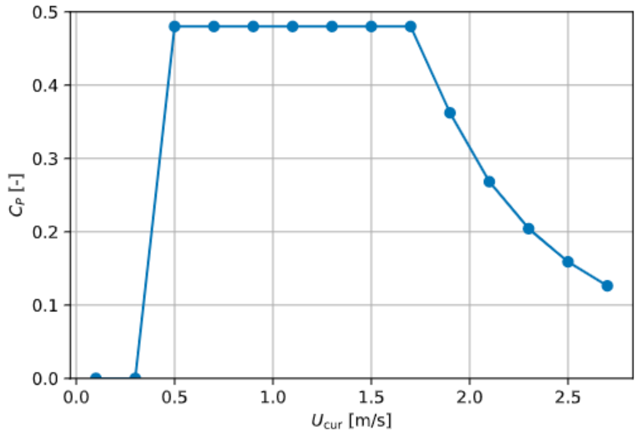


*Figure 37: Power coefficient curve SR2000E*

As for SR2000, the code also gives a table for SR2000E, as can be seen below. For the case of SR2000E, the table also show better results than for SR2000. Whereas SR2000 did not reach efficiency over 80 % until 1.9 m/s, SR2000E reaches almost 90 % at already 0.5 m/s. This also increases the generated power as well as the power production. The total annual power production for the SR2000E with the given parameters at the given location is 112799.8kWh. The highest point of production is at 1.7 m/s with 20332.5 kWh.

*Table 7: Coded values SR2000E*

| | Ucur [m/s] | bins [h] | Power Curve[kW] | Speed [rpm] | Generator Efficiency [%] | Generated Power [kW] | Power Production per bin [kWh] |
|---|---|---|---|---|---|---|---|
| **0** | 0.1 | 333.0 | 0.000000 | 0.742003 | 0.00 | 0.000000 | 0.000000 |
| **1** | 0.3 | 330.0 | 0.000000 | 2.226008 | 0.00 | 0.000000 | 0.000000 |
| **2** | 0.5 | 358.0 | 1.449060 | 3.710013 | 88.37 | 1.280534 | 518.763341 |
| **3** | 0.7 | 379.0 | 3.976220 | 5.194019 | 88.19 | 3.506628 | 1506.987218 |
| **4** | 0.9 | 439.0 | 8.450916 | 6.678024 | 88.07 | 7.442721 | 3709.951972 |
| **5** | 1.1 | 449.0 | 15.429587 | 8.162029 | 85.20 | 13.146008 | 6927.884448 |
| **6** | 1.3 | 454.0 | 25.468672 | 9.646035 | 84.95 | 21.635637 | 11562.776966 |
| **7** | 1.5 | 433.0 | 39.124610 | 11.130040 | 81.36 | 31.831782 | 16940.955918 |
| **8** | 1.7 | 357.0 | 56.953839 | 12.614045 | 85.83 | 48.883480 | 20332.520512 |
| **9** | 1.9 | 327.0 | 60.000000 | 14.098051 | 82.12 | 49.272000 | 19620.000000 |
| **10** | 2.1 | 233.0 | 60.000000 | 15.582056 | 85.86 | 51.516000 | 13980.000000 |
| **11** | 2.3 | 169.0 | 60.000000 | 17.066061 | 87.15 | 52.290000 | 10140.000000 |
| **12** | 2.5 | 104.0 | 60.000000 | 18.550066 | 89.06 | 53.436000 | 6240.000000 |
| **13** | 2.7 | 22.0 | 60.000000 | 20.000000 | 89.75 | 53.850000 | 1320.000000 |

For the efficiency map of SR2000E, all point except 0.1 and 0.3 m/s have an efficiency between 80 and 90 %. After 1.9 m/s the efficiency increases as the velocity increase.

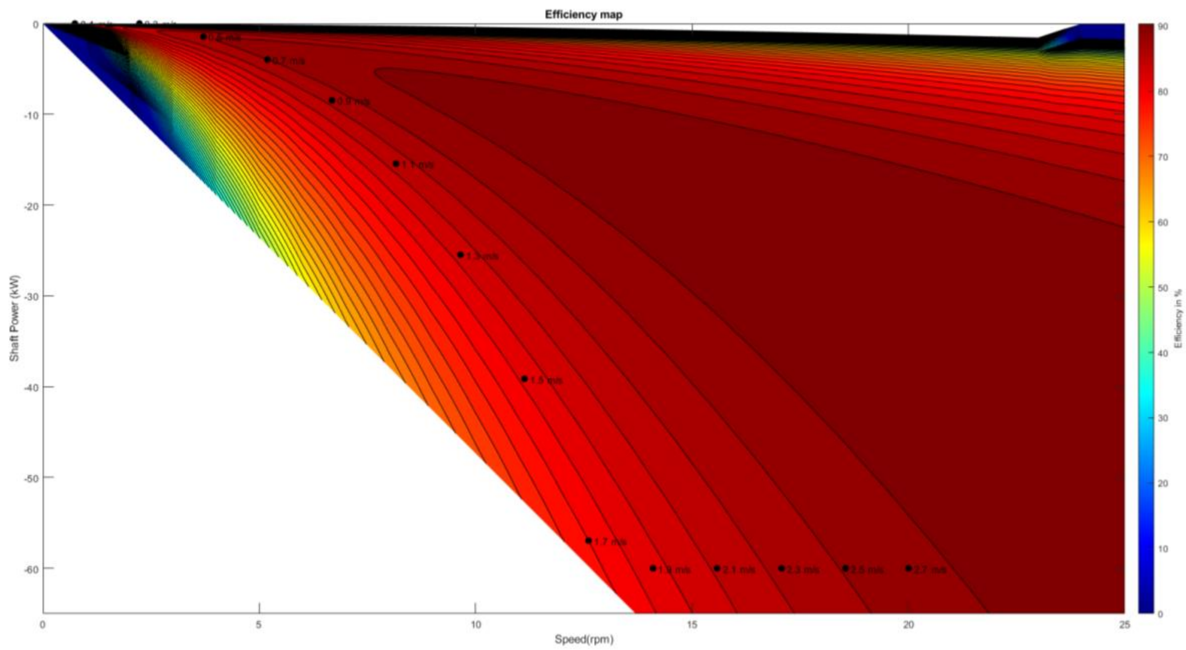


*Figure 38: Efficiency map SR2000E*

# Chapter 5

# Discussion

Investigating the research questions and reviewing what has been presented above, the issues asked in the introduction may be answered more closely. If not mentioned otherwise, tidal stream technology will be the main focus regarding the research questions, and the MeyGen project and O2 project will be used as examples and for comparison.

## Research question 1

What are the advantages and disadvantages for tidal power compared to other renewables?

*Table 8: Tidal power advantages and disadvantages*

| Advantages | Disadvantages |
|---|---|
| Predictable, reliable and continuous | Time restricted due to variability of the tidal waves, intermittent technology |
| Renewable, green resource | Construction, operation and maintenance costs |
| Jobs | Environmental issues such as magnetic field and noise |
| Less need for space compared to wind power (tidal stream) | Large infrastructure (barrages) |
| Submerges technology, aesthetically pleasing | Submerged technology, cavitation |
| Coastal protection such as flood protection and water management | Location restricted |
| Economical profit | Low commercial success until now, with mostly prototypes |

Table 8 is a summary of listed tidal power advantages and disadvantages from chapter 2.10. There are great advantages to harvesting tidal energy. However, there are also disadvantages to consider before deciding on a tidal energy project. As with many technologies, there will always be challenges and hurdles to overcome, and the importance is that the technology is more advantageous than anything else. Discussing the advantages and disadvantages of tidal energy technologies in 2021, the one must separate the two main technologies namely tidal stream and tidal range. The technology seem to be on hold for tidal range, as the environmental and infrastructure challenges are in such a scale that they outweigh the advantages. For the case of tidal stream, it is mainly the large capital costs involved in the development of the technology that is a big challenge. Nevertheless, as discussed in previous chapters, with innovation and maturity gained, these costs may decrease in the coming years, making the tidal stream a mainly promising technology, in the renewable energy market.

For these reasons, only tidal stream turbines was discussed and investigated further as an alternative for a Framo tidal generator.

### Research question 2

Is there a specific key parameter-target, e.g. kW/kg (investment) or kW/€ (total cost over 5/10 years), one should aim for?

In terms of parameters for tidal power and which targets to aim for, the LCOE can be used as a tool for indication. As discussed, the current LCOE for tidal power is high compared to other technologies, therefore not competitive in the energy market. Nevertheless, the LCOE is predicted to decrease, and for Europe, the predicted tidal stream LCOE for 2025 is 0.15 euro/kWh, and therefore new projects should strive for similar values. Investment and capital are large expenditures for the projects, making a large part of the LCOE, and reducing these expenses may lower the LCOE.

Evaluating current optimal tidal power solutions, the MeyGen projects can be used as an example. This project can used to compare to eventual future investment, as a Framo project. As discussed in this thesis, the more developed a technology, the more mature the technology is. Maturity may also be gained by learning from other projects. MeyGen is planning large capacity and relatively small turbines. MeyGen utilizes the turbine type AR1500, used as a horizontal axis turbine, which also dominated most of today's development within tidal power (Atlantis Resources, 2016). The turbine is equipped with three lightweight, carbon- fiber blades which withstand the large loads from the flow and turbulence of the fluid. As for windmills, the three blades have been operating for a long time, and have been the optimal number of blades due drag, balance, angular momentum and the power coefficient (Resen, 2018). Although, there have been developments of turbines with multiple blades, such as the Open Hydro turbine (EMEC: European Marine Energy Centre, 2018). Open Hydro also had internal blades, blades pointing inside of the turbine. The Open Hydro solution was, unfortunately, terminated in 2018 after years of significant investments. Therefore, the utilization of multiple blades is possible, but with careful calculations to maintain the optimal power coefficient as with a 3-bladed turbine.

Another matter of concern in the tidal stream is the turbine gearbox. MeyGen turbines are equipped with an integrated gearbox and permanent magnet generator type (Atlantis Resources, 2016). This combination is optimal over a wide speed range and operates at high efficiency.  The main advantage of solutions with gearboxes is that it is a way to reduce the size of the generator and the weight (Røkke & Nilssen, 2013). This means that direct-drive, non-gear generator solutions are more expensive and larger than generators with gearboxes. There is also the disadvantage of loss of reliability of the generator without gears. Nevertheless, there are also advantages with this solution. A direct-drive generator is a more reliable power train than a generator with a gearbox. As the AR1500 uses a permanent magnet type generator, it is also a trend for direct drive solutions to combine with permanent magnet motors. For Framo, with their expertise and specialization in direct drive, permanent magnet motors, it is a good starting point for a future tidal stream generator.

On to the topic concerning foundation and turbine support structure (TSS), and the question regarding bottom fixed or floating structures. Bottom fixed, or seabed mounted structures are often called first-generation tidal devices, as floating structures are known as second-generation tidal devices (Røkke, 2017). For the MeyGen turbines, these are bottom fixed to the seabed on a monopile type structure (MeyGen, 2012). The O2 turbine is the leading star in floating tidal turbines technology (Orbital Marine, 2021). Whereas seabed mounted structures are suitable for shallow water depths, floating structures are used for deeper waters. Floating structures can be a solution to cut costs related to O&M, as floating structures are easier to access, and can also reduce the yaw mechanism as the structure self-adjusts due to the pull of the tides (Røkke & Nilssen, 2013). Although there are both advantages and disadvantages with both support structures, the type of support structure mainly depends on the sea bed structure, foundation and the depth of placement of the turbines.

For the geographical possibilities and discussing the suitable locations for the tidal stream, Europe will be used as an example. UK and Ireland both have great tidal resources, and it is also here where the MeyGen project have their main location, in the channel between the mainland of Scotland and the island of Stroma. Other locations further north in Europe are Skagerrak-Kattegat and Saltstraumen.

Regarding the unit power rating of a tidal stream turbine, the previously developed turbines are of power sizes around 1-2 MW per turbine. MeyGen with their 1.5 MW turbines, and the floating Orbital Marine turbine, O2, with its 2 MW generated by its two rotors, being 1 MW per turbine. These are the largest rated power of tidal turbines so far in the development. To the author's knowledge, there is no upper or lower limit to the rated power of the unit in terms of feasibility. Still, the feasibility is more related to the specific geographical sites and the tidal current velocity. This must be higher than 2 m/s to be encountered economically viable. Nevertheless, and as mentioned previously in the feasibility case study for Ireland, the generation needs to scale up for tidal energy to become economically feasible (Jackson & Persoons, 2012).

The above turbines differ in technology and also in size, weight and costs. The MeyGen turbines weight around 150 tonnes and have a turbine length of 12 meters, whereas the O2 turbine has a length of 72 meters. To the authors knowledge, there is no further information on the weight of the structure, although the Orbital Marine prototype SR2000 is of the same capacity and includes a turbine mass of 500 tonnes (Scott, 2019). These values of new development will also depend on the deployment location, how many turbines, and which capacity is planned on the specific site. In terms of costs, this brings us back to the critical parameter of LCOE.

As discussed in the chapter regarding tidal arrays there are still no large arrays built. MeyGen have installed four and are planning an additional 86 units, whereas O2 have installed one unit. The power capacity of both are 13.8 GWh and around 3 GWh, respectively (SIMEC Atlantis Energy, 2020) (EMEC: European Marine Energy Centre, 2019).

For the more developed and mature technology of tidal barrages, there are the projects of La Rance, Sihwa Lake and the planned tidal lagoon project, Swansea Bay, with its turbine units of 24, 10 and 16 respectively, and power produced yearly of 480GWh, 552 GWh and around 530 GWh (Tidal Lagoon Power, 2021).

### Research question 3

What are the optimal tidal turbine parameters for the available Framo generators?

### Research question 4

Are any of the Framo motors feasible for a tidal turbine?

As well as comparing to proven tidal stream solutions, further discussion is based on the findings in the results chapter. These findings are useful for the two final research questions. Starting with the graphical results from the mathematical model. Using values of blockage ratio between 0.05 and 0.2, and varying the inlet Froud number at point 1, $Fr_1$, from 0.1, 0.2, 0.3, 0.4 and 0.5. The model shows factors and variables which all are important for modelling a tidal stream turbine.

The efficiency maps and related tables can be discussed with the efficiency of the two given Framo generators,. It is important to specify that the above results are from a particular location with the provided properties, and that other location may give different results.

The power curves and the power coefficient curve of the two potential generators reflect the results on the power for each of the generators. As seen, the power curve for SR2000 only reaches around 10 kW at the final velocity of 2.7 m/s, whereas SR2000E reaches 60 kW at 1.9 m/s and continues throughout the velocity points. From the power coefficient curve, the curve for SR2000E follows the curves as seen in figure 19, where $C_P$ decreases when rated power is reached, whereas $C_P$ for SR2000 follow a constant value of 0.48 due to the rated power never being reached.

For the given locations and the relating bins and number of hours, the result shows that from 0.7 to 1.7 m/s, most of the hours take place. With SR2000E, which showed the best results, the generator does not necessarily generate the most power at exactly these velocities. The highest point of production occurred at 1.7 m/s, whereas the highest efficiencies occurred at 2.5 and 2.7 m/s, where the hours in the bins are only 104 and 22 hours, respectively. The efficiency curves and the plotting of velocities in the map illustrate the efficiency at the velocity points. Also, here it is seen that there is potential in shifting the curve so that the efficiency increases.

Both generator models SR2000 and SR2000E prove to be efficient for the studied application. A smaller turbine needs a higher speed than a larger turbine, so increasing the rotational speed could be a way to increase the performance of SR2000. As in the spec, the optimal rated speed for SR2000 is 130 rpm. Increasing the speed would nevertheless affect other factors again, also in the sense of the environment. Therefore, low-speed turbines are more optimal for tidal power.

For research questions number 3 and 4, the results chapter show that using the given parameters from table 5 for the SR2000E gives the best results for the efficiency of the two generators. And compared to the SR2000, the SR2000E is the better option for a tidal stream turbine with the given parameters and the given location. Nevertheless, it is also seen that it is hard to maintain good efficiency over a big spectre of speed. Also, for the given location, the generator never reaches an efficiency above 90 %, and therefore lies below the efficiency of a typical tidal stream turbine of 92-95 %.

## Chapter 6

# Conclusion

This master thesis aims to assess the possibility of using a Framo generator for tidal stream power. Including presenting a mathematical model, efficiency chart regarding two Framo motors, proven solutions have also been discussed. A literature review was necessary to provide answers to the research questions developed in cooperation with Framo Innovation. The literature review explained essential concepts of tidal energy, including the different tidal energy technologies, LCOE, maturity and learning, policies and subsidies. Proven solutions, such as the MeyGen project, were used to present full-scale solutions and a possible new innovation from Framo Innovation. Based on the literature review, methods and final results and findings, this final chapter will conclude on the main questions of this thesis.

Parameters to aim for are in particular regarding cost and an LCOE close to what is being predicted at a certain time. All in all, for the project to be feasible and competitive, whether over a 5 or a 10 year period, the costs regarding installation, operation and maintenance must be lower than the electricity income. And at this current time, government subsidies and large investors are necessary in many cases. In terms of investment and comparing to already proven solutions, this depends on the technology of tidal stream power and from project to project. As the O2 is of large structure and mass, MeyGen utilizes smaller turbines in terms of capacity and size. The cost will be thereafter, and as the goal is to reduce structural costs, it is more feasible to aim for small structured turbines.

Changing the values of the blockage ratio and Froude number, the mathematical model presented allowed us to plot and graphically present the relationships between $C_P$ and $C_T$, $\frac{Q_i}{Q_1}$ and $C_T$ and $Fr$ and $C_T$. The graphs, figure 20 through to figure 30, further show that increasing the blockage ratio increases both power coefficient and thrust coefficient, which proves that a higher blockage ratio on turbines is more efficient than lower blockage ratios.

With the unique experience Framo has with submerged equipment, permanent magnet motors and pumping solutions, it is possible for Framo Innovation to develop a tidal stream turbine. From the two generators evaluated with the given parameters and at the given location, SR2000E show the best results. Although these results should improve, it may be possible to present a generator with an efficiency of over 90 %, which a tidal generator should hold. Throughout the study, horizontal axis turbines were considered best option for tidal stream, based on the current status and development, as well as the advantages, of exactly this technology.

Tidal energy is a reliable and trustworthy renewable energy source with many advantages, although the technology also has downsides. Disadvantages such as location restrictions and intermittent time restrictions may be the most critical disadvantages related to costs. The LCOE for tidal stream energy at this current time is well above other competitive energy sources. There are multiple ways of reducing costs, and as the LCOE for tidal stream energy is predicted to fall, so are the LCOEs for competing technologies. The tidal stream energy may take some time to reach the level of competitiveness of the mature renewable energy technologies such as wind. Consequently, it is not economically feasible to invest in tidal stream technologies today due to the need for investors and external subsidies and funding. Whether or not a Framo generator is feasible, is therefore strongly related to the costs of a future project. Nevertheless, as mentioned previously in this thesis, tidal stream energy is said to be 15 years behind wind energy development, so with gained experiences, the future might hold promising opportunities for tidal stream energy.

As renewable energies are more important than ever, tidal energy can play an important part in reducing greenhouse gasses and reaching the goals and targets of the Paris Agreement, SDG7 and SDG14. As tidal power alone has its advantages and disadvantages, further investigation on merging the different renewable energy sources, hybrid solutions may solve challenges regarding tidal stream technology restrictions.

## 6.1 Further work

Based on the findings and experiences made during this thesis, the following recommendations can be suggested:

- Evaluating the development and operational costs against income.
- Investigating if costs are possible to cut based on methods given in this thesis.
- Increasing the efficiency of SR2000E with other parameters and different location.
- Testing the smaller turbine, SR2000, with increased speed and measure the efficiency of this turbine.

# References

Allan, G., Gilmartin, M., McGregor, P., & Swales, K. (2011). Levelised costs of Wave and Tidal energy in the UK: Cost competitiveness and the importance of “banded” Renewables Obligation Certificates. *Energy Policy*, *39*(1), 23–39. https://doi.org/10.1016/j.enpol.2010.08.029

Andritz Hydro. (n.d.). *Hydro News 29—ANDRITZ HYDRO Bulb Turbine Technology*. Retrieved 22 May 2021, from https://www.andritz.com/hydro-en/hydronews/hydro-news-29/hy-news-hn29-13-bulb-turbines-hydro

Andritz Hydro. (2019). *ANDRITZ HYDRO Hammerfest—Renewable energy from tidal currents*. 12.

Atlantis Resources. (2016). *AR1500 Tidal Turbine*. https://simecatlantis.com/wp-content/uploads/2016/08/AR1500-Brochure-Final-1.pdf

Bell, I. (2002). *Turning the tide: Power from the sea and protection for nature*. 189.

Berg, I. (2020). *Tides explained—On the origin of a global ocean phenomenon*. Belt Of Orion. https://beltoforion.de/en/tides/index.php#idStart

Boretti, A. (2020). State-of-the-art of MW-level capacity oceanic current turbines. *Nonlinear Engineering*, *9*(1), 361–369. https://doi.org/10.1515/nleng-2020-0022

Callaghan, J. (2006). *Future Marine Energy*. https://discomap.eea.europa.eu/map/Data/Milieu/OURCOAST_093_UK/OURCOAST_093_UK_Doc1_FutureMarineEnergy.pdf

Camebridge Dictionary. (2021). *Maturity*. https://dictionary.cambridge.org/dictionary/english/maturity

Chowdhury, M. S., Rahman, K. S., Selvanathan, V., Nuthammachot, N., Suklueng, M., Mostafaeipour, A., Habib, A., Akhtaruzzaman, Md., Amin, N., & Techato, K. (2020). Current trends and prospects of tidal energy technology. *Environment, Development and Sustainability*, *23*(6), 8179–8194. https://doi.org/10.1007/s10668-020-01013-4

Christophersen, E. B. (2012). *Technology Survey or Renewable Energy Integrated to Bridge Constructions—Statens Vegvesen* (No. 112; p. 84).

Clarke, K. (2016). *The New Power Cost League Table: A clear view of the consumer cost of new build power stations*. Tidal Lagoon Power. http://www.tidallagoonpower.com/wp-content/uploads/2016/09/New_Power_Cost_League_Table_2016.pdf

Coastal Wiki. (2020, December 17). *Coriolis acceleration—Coastal Wiki*. http://www.coastalwiki.org/wiki/Coriolis_acceleration

Costa, T. (2019). *Forecasting the Cost of Electricity Generated by Offshore Wind Turbines*. https://doi.org/10.7275/14154953

EIA. (2021). *Levelized Costs of New Generation Resources in the Annual Energy Outlook 2021*. 25.

EMEC. (2021). *Technology Readiness Levels: EMEC: European Marine Energy Centre*. http://www.emec.org.uk/services/pathway-to-emec/technology-readiness-levels/

EMEC: European Marine Energy Centre. (n.d.). *EMEC: European Marine Energy Centre: About us*. Retrieved 5 June 2021, from http://www.emec.org.uk/about-us/

EMEC: European Marine Energy Centre. (2018, July). *Open Hydro: EMEC: European Marine Energy Centre*. http://www.emec.org.uk/about-us/our-tidal-clients/open-hydro/

EMEC: European Marine Energy Centre. (2019, August 14). *Press release: Orbital O2 to be built by TEXO Group in Dundee : EMEC: European Marine Energy Centre*. http://www.emec.org.uk/press-release-orbital-o2-to-be-built-by-texo-group-in-dundee/

EMEC: European Marine Energy Centre. (2021, April 26). *Press release: Orbital O2 tidal turbine arrives in Orkney : EMEC: European Marine Energy Centre*. http://www.emec.org.uk/press-release-orbital-o2-tidal-turbine-arrives-in-orkney/

Encyclopaedia Britannica. (2016). *Froude number | physics | Britannica*. https://www.britannica.com/science/Froude-number

EPA. (2011). *King Tides*.

*EUREC MSc in Renewable Energy—Ocean Energy—Master in Energy Engineering and Management: Mooring and Anchoring System—Introduction*. (n.d.).

European Commission. (2014). *HORIZON 2020 WORK PROGRAMME 2014 – 2015*.

European Commission. Joint Research Centre. (2018). *Cost development of low carbon energy technologies: Scenario based cost trajectories to 2050, 2017 edition.* https://data.europa.eu/doi/10.2760/490059

Framo Innovation. (n.d.). *Pumping systems for fish farming*.

Gao, L., Porter, A. L., Wang, J., Fang, S., Zhang, X., Ma, T., Wang, W., & Huang, L. (2013). Technology life cycle analysis method based on patent documents. *Technological Forecasting and Social Change*, *80*(3), 398–407. https://doi.org/10.1016/j.techfore.2012.10.003

Garrett, C., & Cummins, P. (2005). The power potential of tidal currents in channels. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *461*(2060), 2563–2572. https://doi.org/10.1098/rspa.2005.1494

Hendry, C. (2016). *THE ROLE OF TIDAL LAGOONS*. 183.

Henriques, J. C. C. (2020a). *Marine Current and Tidal Energy—The origin of the tides*.

Henriques, J. C. C. (2020b). *Marine Current and Tidal Energy—Channel Flows*.

Henriques, J. C. C. (2021a). *Lecture note on inertia and kinetic rotational speed*.

Henriques, J. C. C. (2021b). *SR2000 Code*. https://colab.research.google.com/drive/1NHhHM5qWL0T_sYB7Ef5_zvJVbN3dZdP2#scrollTo=Dupy2ge3TPrv

Henriques, J. C. C. (2021c). *SR2000E Code*. https://colab.research.google.com/drive/1VDpXc0UuqSNnv29Y78gNq74aWcgYxKx9#scrollTo=JJD1kPhbUUsL

Henriques, J. C. C. (2021a). *Histograms For Energy Production, Energy Production V07—Joaochenriques/MCTE_2020_2021* [Jupyter Notebook]. https://github.com/joaochenriques/MCTE_2020_2021/blob/39b6c0e8b572623d8ad78ce351e0256a6e6bf368/HistogramsForEnergyProduction/EnergyProduction_V07.ipynb (Original work published 2021)

Henriques, J. C. C. (2021b). *Disk Actuator—Joaochenriques/MCTE_2020_2021* [Jupyter Notebook]. https://github.com/joaochenriques/MCTE_2020_2021/blob/39b6c0e8b572623d8ad78ce351e0256a6e6bf368/DiskActuator/DiskActuator.ipynb (Original work published 2021)

Henriques, J. C. C. (2021c). *Disk Actuator Sensitivity Analysis* [Jupyter Notebook]. https://github.com/joaochenriques/MCTE_2020_2021/blob/39b6c0e8b572623d8ad78ce351e0256a6e6bf368/DiskActuator/Sensitivity_Analysis.ipynb (Original work published 2021)

Houlsby, G. T., & Vogel, C. R. (2017). The power available to tidal turbines in an open channel flow. *Proceedings of the Institution of Civil Engineers - Energy*, *170*(1), 12–21. https://doi.org/10.1680/jener.15.00035

IEA. (2020). *Covid-19 and the resilience of renewables – Renewables 2020 – Analysis*. IEA. https://www.iea.org/reports/renewables-2020/covid-19-and-the-resilience-of-renewables

IRENA. (2014a). *Tidal Energy—Technology Brief (3)*. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2014/Tidal_Energy_V4_WEB.pdf

IRENA. (2014b). *Ocean Energy—Technology Readiness, Deployment Status and Outlook*. http://biblioteca.olade.org/opac-tmpl/Documentos/cg00171.pdf

IRENA. (2019). *Future of Wind*. 88.

IRENA. (2020a). *Innovation outlook: Ocean energy technologies*. 112.

IRENA. (2020b). *Renewable power generation costs in 2019*. 144.

IRENA. (2020c). *Call to Action in Response to COVID-19: Renewable Energy is a Key Part of the Solution*. 3.

ISO. (2013). *ISO 16290:2013(en), Space systems—Definition of the Technology Readiness Levels (TRLs) and their criteria of assessment*. https://www.iso.org/obp/ui/#iso:std:iso:16290:ed-1:v1:en

Jackson, D., & Persoons, T. (2012). *Feasibility study and cost-benefit analysis of tidal energy: A case study for Ireland*.

Jump, E., Wills, T., & Macleod, A. (2019, September 1). *Review of tidal turbine wake modelling methods—State of the art*.

Kjellin, J., Eriksson, S., & Bernhoff, H. (2013). Electric Control Substituting Pitch Control for Large Wind Turbines. *Journal of Wind Energy*, *2013*, 1–4. https://doi.org/10.1155/2013/342061

Lande-Sudall, D., Stallard, T., & Stansby, P. (2018). Co-located offshore wind and tidal stream turbines: Assessment of energy yield and loading. *Renewable Energy*, *118*, 627–643. https://doi.org/10.1016/j.renene.2017.10.063

Mascarenhas, P., Bald, J., Menchaca, I., O'Hagan, A. M., & Simas, T. (2015). *RiCORE Project Novel Technology Selection*. 64.

MeyGen. (2012). *MeyGen Tidal Energy Project Phase 1: Environmental Statement*. 544.

National Geographic. (2011, August 17). *Coriolis Effect*. National Geographic Society. http://www.nationalgeographic.org/encyclopedia/coriolis-effect/

National Oceanography Centre. (n.d.). *The Double Tidal Bulge*. Retrieved 8 March 2021, from https://noc.ac.uk/files/documents/business/Double-Bulge-Explanation.pdf

Neill, S. P., Angeloudis, A., Robins, P. E., Walkington, I., Ward, S. L., Masters, I., Lewis, M. J., Piano, M., Avdis, A., Piggott, M. D., Aggidis, G., Evans, P., Adcock, T. A. A., Židonis, A., Ahmadian, R., & Falconer, R. (2018). Tidal range energy resource and optimization – Past perspectives and future challenges. *Renewable Energy*, *127*, 763–778. https://doi.org/10.1016/j.renene.2018.05.007

NOAA SciJinks. (2021, May 27). *What Causes Tides? | NOAA SciJinks – All About Weather*. https://scijinks.gov/tides/

Noonan, M. (2019). *TIDAL STREAM: OPPORTUNITES FOR COLLABORATIVE ACTION*. 21.

NPTEL. (n.d.). *Fluid Machinery*. Retrieved 22 May 2021, from https://nptel.ac.in/content/storage2/courses/112104117/chapter_7/7_14a.html

O Rourke, F., Boyle, F., & Reynolds, A. (2010). Tidal energy update 2009. *Applied Energy*, *87*(2), 398–409. https://doi.org/10.1016/j.apenergy.2009.08.014

Office of Efficiency & Renewable Energy. (2019). *Powering the Blue Economy: Exploring Opportunities for Marine Renewable Energy in Maritime Markets: Appendices*. 14.

Office of Indian Energy. (2015). *Levelized Cost of Energy (LCOE)*. 9.

Orbital Marine. (2021). O2. *Orbital Marine*. https://orbitalmarine.com/o2/

Pereira, R. S., Baltazar, J., & Henriques, J. C. C. (2020). *Offshore Wind Energy—MCOES, MCTE*.

Radar Altimetry Tutorial and Toolbox. (2001). *6.2.4 Tides*. http://www.altimetry.info/thematic-use-cases/ocean-applications/tides/

Resen, A. (2018). *Why is usually three of blades on a wind turbine instead of say 5 or more?* ResearchGate. https://www.researchgate.net/post/Why_is_usually_three_of_blades_on_a_wind_turbine_instead_of_say_5_or_more

Røkke, A. (2017). *Permanent Magnet Generators for Marine Current Tidal Turbines*. NTNU.

Røkke, A., & Nilssen, R. (2013). Marine Current Turbines and Generator preference. A technology review. *Renewable Energy and Power Quality Journal*, 336–341. https://doi.org/10.24084/repqj11.299

Ross, S. (2021, March 30). *CAPEX vs. OPEX: What's the Difference?* Investopedia. https://www.investopedia.com/ask/answers/112814/whats-difference-between-capital-expenditures-capex-and-operational-expenditures-opex.asp

Scott, A. (2019, April). *Orbital Marine Power presentation*. https://www.marineenergywales.co.uk/wp-content/uploads/2019/04/3.-Andrew-Scott-Orbital-Marine-Power.pdf

Shah, S., & Bazilian, M. (2020). *LCOE and its Limitations*.

SIMEC Atlantis Energy. (2020, January 27). *MeyGen Operational Update*. SIMEC Atlantis Energy. http://simecatlantis.com/2020/01/27/4036/

SIMEC Atlantis Energy. (2021). MeyGen | Tidal Projects. *SIMEC Atlantis Energy*. http://simecatlantis.com/projects/meygen/

Smart, G., & Noonan, M. (2018). *TIDAL STREAM AND WAVE ENERGY COST REDUCTION AND INDUSTRIAL BENEFIT*. 21.

Snieckus, D. (2020, January 28). *Corporate deals for world's first ocean-powered data centre 'within weeks' | Recharge*. Recharge | Latest Renewable Energy News. https://www.rechargenews.com/transition/corporate-deals-for-worlds-first-ocean-powered-data-centre-within-weeks/2-1-745493

Solarity. (2019, September 8). What does LCOE mean? *Solarity*. https://solarity.cz/blog/what-does-lcoe-mean/

Tethys. (2019a, July 30). *Sihwa Tidal Power Plant | Tethys*. https://tethys.pnnl.gov/project-sites/sihwa-tidal-power-plant

Tethys. (2019b, August 27). *La Rance Tidal Barrage | Tethys*. https://tethys.pnnl.gov/project-sites/la-rance-tidal-barrage

The Canadian Encyclopedia. (2010, July 8). *Bay of Fundy and Gulf of Maine | The Canadian Encyclopedia*. https://www.thecanadianencyclopedia.ca/en/article/bay-of-fundy-and-gulf-of-maine%20

Tidal Lagoon Power. (2021). Key Statistics. *Tidal Lagoon*. http://www.tidallagoonpower.com/projects/swansea-bay/key-statistics/

Tzinis, I. (2015, May 6). *Technology Readiness Level*. NASA; Brian Dunbar. http://www.nasa.gov/directorates/heo/scan/engineering/technology/technology_readiness_level

Ueckerdt, F., Hirth, L., Luderer, G., & Edenhofer, O. (2013). System LCOE: What are the costs of variable renewables? *Energy*, *63*, 61–75. https://doi.org/10.1016/j.energy.2013.10.072

UN. (2021a). *About Us*. United Nations; United Nations. https://www.un.org/en/about-us

UN. (2021b). *Energy | Department of Economic and Social Affairs*. https://sdgs.un.org/topics/energy

UN. (2021c). *Goal 7 | Department of Economic and Social Affairs*. https://sdgs.un.org/goals/goal7

UN. (2021d). *Goal 14 | Department of Economic and Social Affairs*. https://sdgs.un.org/goals/goal14

UN. (2021e). *Home | Sustainable Development*. https://sdgs.un.org/

UNFCCC. (2021a). *About the Secretariat | UNFCCC*. https://unfccc.int/about-us/about-the-secretariat

UNFCCC. (2021b). *Nationally Determined Contributions (NDCs) | UNFCCC*. https://unfccc.int/process-and-meetings/the-paris-agreement/nationally-determined-contributions-ndcs/nationally-determined-contributions-ndcs

UNFCCC. (2021c). *The Paris Agreement | UNFCCC*. https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

US Department of Commerce, N. O. and A. A. (n.d.). *Tides and Water Levels, What Causes Tides, NOS Education Offering*. Retrieved 10 March 2021, from https://oceanservice.noaa.gov/education/tutorial_tides/tides02_cause.html

US Department of Commerce, N. O. and A. A. (2021a). *Tides and Water Levels: NOAA's National Ocean Service Education*. https://oceanservice.noaa.gov/education/tutorial_tides/tides01_intro.html

US Department of Commerce, N. O. and A. A. (2021b, February 26). *What is a King Tide?* https://oceanservice.noaa.gov/facts/kingtide.html

US Department of Commerce, N. O. and A. A. (2021c, February 26). *Why do we have spring tides in the fall?* https://oceanservice.noaa.gov/facts/springtide.html

Vennell, R., Funke, S. W., Draper, S., Stevens, C., & Divett, T. (2015). Designing large arrays of tidal turbines: A synthesis and review. *Renewable and Sustainable Energy Reviews*, *41*, 454–472. https://doi.org/10.1016/j.rser.2014.08.022

Water Encyclopedia. (2021). *Tides—Building, river, sea, depth, oceans, effects, important, largest, system*. http://www.waterencyclopedia.com/St-Ts/Tides.html

Wimshurst, A., Vogel, C., & Willden, R. (2018). Cavitation limits on tidal turbine performance. *Ocean Engineering*, *152*, 223–233. https://doi.org/10.1016/j.oceaneng.2018.01.060

*Wind Turbine Control Methods*. (2020, May). https://www.ni.com/en-no/innovations/white-papers/08/wind-turbine-control-methods.html

Zhou, Y., & Gu, A. (2019). Learning Curve Analysis of Wind Power and Photovoltaics Technology in US: Cost Reduction and the Importance of Research, Development and Demonstration. *Sustainability*, *11*(8), 2310. https://doi.org/10.3390/su11082310

# Appendices

Appendix 1: Tidal_power.xlsx