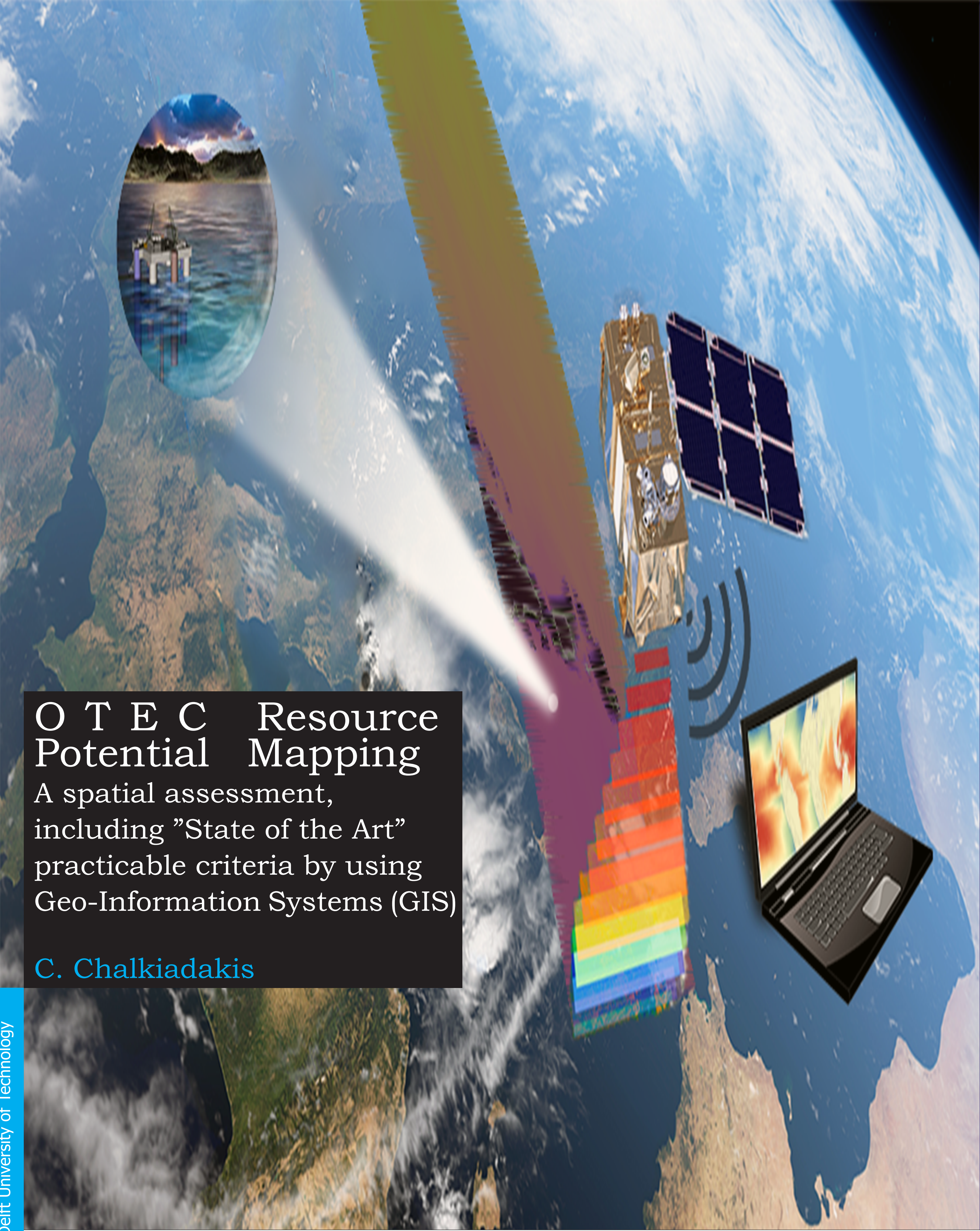


OTEC Resource Potential Mapping

A spatial assessment, including ”State of the Art” practicable criteria by using Geo-Information Systems (GIS)

C. Chalkiadakis

Delft University of Technology

Delft University of Technology

Challenge the future

OTEC RESOURCE POTENTIAL MAPPING

A SPATIAL ASSESSMENT INCLUDING "STATE OF THE ART" PRACTICABLE CRITERIA BY USING GEO-INFORMATION SYSTEMS (GIS)

OTEC RESOURCE POTENTIAL MAPPING

A SPATIAL ASSESSMENT INCLUDING "STATE OF THE ART" PRACTICABLE CRITERIA BY USING GEO-INFORMATION SYSTEMS (GIS)

by

Charalampos CHALKIADAKIS

Thesis Dissertation

to obtain the degree of,
Master of Science in Industrial Ecology,
at Delft University of Technology,
under the authority of,
Professor dr. Kornelis Blok,
to defend publicly on 20th November 2017 at 12:00 p.m.

Faculty of Technology Policy and Management,
Delft University of Technology, Delft, the Netherlands

and

Faculty of Science, Institute of Environmental Sciences,
Leiden University, Leiden, the Netherlands.

This thesis has been approved by the

Supervisor: prof. dr. K. Blok
Co-supervisor: prof. dr. E. Voet

Composition thesis committee:

Prof. dr. K. Blok,	Technical University of Delft
Ing. M. van 't Zelfde	GIS Specialist in Leiden University
B.J. Kleute	CTO and co-founder of Bluerise

Keywords: OTEC, mapping, spatial, potential, locations, Industrial Ecology

Printed by: Chalkiadakis Charalampos

Front & Back: Beautiful cover art that captures the entire content of this thesis in a single illustration.

An electronic version of this dissertation is available at
http://repository.tudelft.nl/.

Nature uses only the longest threads to weave her patterns,
so that each small piece of her fabric reveals the organization of the entire tapestry.

Richard P. Feynman

Contents

LIST OF FIGURES

List of Symbols

Mathematical Symbols:

η_{max} : Thermodynamic Carnot Efficiency, an absolute number
P_{net} : OTEC Net Power Density, in Watts/m^2
TP : Total OTEC Power, in Watts
T : Temperature, in degrees of Celsius or Kelvin
ΔT : Temperature Difference, in degrees of Celsius or Kelvin
α_{gross} : OTEC gross overall efficiency of a typical plant, an absolute number
w_{cw} : OTEC cold seawater pump flow rate per unit of area, in m/yr
c_p : Specific heat of seawater, in Joules/Kilogram*Kelvin
ρ : Seawater density, in Kilogram/m^3
ϵ : Turbo-generator efficiency, an absolute number
A_{OTEC} : OTEC implementation Area, in m^2
Q_{cw} : OTEC cold seawater pump flow rate, in m^3/s
Δ_x : OTEC spacing distance, in meters
Δ_x^2 : Area that occupies one OTEC plant, in m^2
V_{EW} : East to West Velocity in 1km depth, in m/s
V_{NS} : North to South Velocity in 1km depth, in m/s
Δ_z : Thickness of the cold water utilization layer, in meters

Abbreviations:

AEG: Africa's Electricity Grid
AFD: Agence Française de Development
CMEMS: Copernicus Marine Environment Monitoring Service
EEZ: Exclusive Economic Zones
GIS: Geographical Information Systems
NetCDF: Network Common Data Form
OGCM: Ocean General Circulation Model
OTEC: Ocean Thermal Energy Conversion
PPD: Practicable Power Density
PoD: Population Density
R.& D.: Research and Development
SEDAC: Socioeconomic Data and Applications Center
SWAC: Sea Water Air-Conditioning
ThPD: Theoretical Power Density
TPD: Technical Power Density
TPD_EEZ$_{polygon}$: Technical Power Density within EEZ boundaries

Acknowledgements

After discussing with Bluerise and specifically with B. Kleute, the idea of using GIS software was proposed for such a demanding spatial assessment. Thereafter, Leiden University through Maarten van't Zelfde contributed on providing significant guidance on the spatial part of this work which was required for the extrapolation of the results. In the end, Delft University of Technology along with Bluerise were responsible for the theoretical basis and the interpretation of the resulting potential.

This thesis project was established through the Masters program of Industrial Ecology in Leiden University and Delft University of Technology in the Netherlands and the research was carried out for approximately 7 months. During this time many people contributed significantly towards this research. In specific, I would like to thank Maarten van't Zelfde from Leiden University, who provided numerous times his excellence and expertise on examining and interpreting the data using the ArcGIS software. His explicit guidance, especially towards the examination of the last details of this work, was more than helpful in order to present a proper visual outcome.

Secondly, I would like to thank B. Kleute for sharing his knowledge and his advice on the latest OTEC estimates and also for the discussions around OTEC designs and projects. Lastly, from Delft University of Technology, I want to thank Professor Kornelis Blok and Jaco Quist for the patience and eagerness that showed and the guidance that provided me in order to advance in this research topic.

Professor Gerard Nihous in the School of Ocean and Earth Science and Technology at the University of Hawaii at Manoa, also assisted further on understanding and managing the temperature profiles of this study and therefore I would like also to show him my explicit appreciation. Last but not least, I would like to thank from heart my family and friends who offered me direct and indirect continuous support throughout this entire time.

SUMMARY

"A global agenda for change". This was the urgent expectation of the Brundtland Commission of the United Nations in 1987. In this direction, Ocean Thermal Energy Conversion (OTEC) resources could cover the electricity demand of the entire world, if only large-scale operations within specific limitations, are realized. Consequently, explicit attention is being put on spatial aspects while identifying prosperous OTEC locations, since the nature of these resources (Thermal Energy) depends significantly on location-based indicators. So, the reasonable question that arises is: What is the resource potential for OTEC installations and how many locations worldwide can be identified for the development of a realistic short-term OTEC deployment scenario? Thus, this study's objective includes the examination of pragmatic criteria for deployment that establish a realistic potential scenario, which in extent could be used to create short-term implementation agendas.

Extensive information is also presented, regarding previous estimates of OTEC (worldwide) resources and for some interesting local case studies (Chapter 2). Initially, the technical aspects of an OTEC plant are described where a detailed assessment regarding the current Research and Development (R.&D.) status of the technology, is being carried out. In specific, the different thermodynamic designs (Closed-Cycle, Open-Cycle, Hybrid-Cycle) are represented with their potential applications and related benefits along with the different possible platform configurations. In addition, local-based assessments that served as examples for OTEC resource estimates, are further examined. In addition, professor Nihous' latest resource calculations in an Ocean General Circulation Model (3-D OGCM), are offering a fundamental literature base for comparisons with this present GIS assessment. Lastly, "the state of the art" practicable criteria are described and analyzed in detail in order to derive a realistic OTEC follow-up agenda.

Additionally, in Chapter 2, essential information can be found regarding explicit maritime regions (such as EEZ, Distance Proximity, Population Density, etc), which is important for underlying a realistic OTEC potential. Moreover, the methods and the relevant tools needed while conducting a spatial distribution analysis of that magnitude are listed in chapter 3. Resource potential studies require the collection and management of a vast amount of data. ArcGIS software offers the opportunity to examine such spatial information, find patterns and extrapolate results. In detail, seawater velocities and bathymetry data combined with the ocean temperature profile provide the basis of this OTEC assessment.

The distribution analysis in Chapter 4 in the contrary, is dividing the resource potential in a distinguishable manner in order to offer a clear understanding related to the resulting estimates. Firstly, the theoretical and technical resources are examined and all

the associated processes and tools involved are described in detail. Afterwards, the practicable potential is analyzed, where most of the advanced criteria are applied including Exclusive Economic Zones (EEZ), Population Densities (PoD) and the Africa's Electricity Grid (AEG). In the end, the onshore and offshore potential is depicted with respect to spacing considerations. The important aspect described in this chapter, is also the additional benefit of using ArcGIS software that provides the ability to reproduce the results within a modeling environment. Therefore, the analysis in Chapter 4 is structured and organized properly with the help of the "model builder" function.

Subsequently, all the resulting OTEC estimates are presented and listed in Chapter 5, where explicit attention is being put on the determination of the "Realistic" OTEC deployment scenario. Regarding the main research question above, this study identifies 72 countries that show prosperous offshore and onshore OTEC resources with 100 km distance from population densities greater than 500 people/km^2. The total potential, in this case, reaches the value of 4.4 TW, which according to similar studies will not cause any thermal disruptions within the ocean. The "Aggressive" implementation scenario shows a different behavior where OTEC plants are deployed in locations even outside the EEZ boundaries of each country. This scenario is considered as the least sustainable and therefore the least probable since such "Aggressive" deployment would cause significant thermal changes in the ocean.

Figure 1: Number of countries that have Adequate OTEC Offshore Resources within 100 km away from the coast

Regarding the "Realistic" OTEC deployment scenario, there have been 6 Continents identified that show adequate thermal resources. Elaborately and as it can be seen from the picture 1 above, Africa has 16 territories where OTEC potential could be explored in the future, with Madagascar, Mozambique, and Seychelles showing up to 175 GW of adequate Offshore resources. The American population in the contrary could benefit with additional electricity generation of about 5.7 million GWh/year which is way beyond the value of 4,079 GWh that the United States alone produced at utility scale facilities in the year 2016. Remarkable results also show locations in Brazil with 169.57 GW (and 45,000 km^2 of total OTEC implementation area) and the nations of Dominican Republic and Mexico with just above 55 GW of maximum prosperous electricity output.

On the other side of the planet, all Oceanic countries appear to have onshore resources, a fact which is from one perspective noteworthy and from another reasonable, since there is deep enough water within a very close proximity to their shorelines. Papua New Guinea is the "front-runner" with 75 coastal locations and a total power generation of just above 4 million GWh/yr. However, European nations also show considerable OTEC potential with a total of 2.4 million GWh/yr but only 3 nations appear to have thermal resources, located in African, American and Oceanic territories.

Lastly, Asia shows an exceptional amount of OTEC resources distributed over only 13 coastal nations. An expected outcome since the temperature difference in these regions reaches much greater values in comparison with the rest of the world. Hence, the total OTEC power production in Asia, would be almost double (10 million GWh/yr) with just half the amount of countries compared to deployments in North and South America.

In the concluding Chapter, explaining the scientific and technical implications of such research findings is becoming essential after interpreting the resulting resource estimates. In specific, the aim of this chapter is to answer the research questions proposed during the introduction and list the additional results derived from the analysis. Thereafter, a critical view of the insights driven by the sensitivity analysis is depicted. Towards this direction, the offshore and onshore total power estimates show that OTEC could cover more than 1.4 times the current total amount of electricity generated, around the world. This represents a remarkable electricity production of about 35,000 TWh/year, which would be accessible by 72 coastal countries around the world.

PREFACE

In the present global scenario of a fossil fuel based economy, excessive use of non- renewable resources, such as petroleum, coal and natural gas has resulted in global warming, extreme weather events, and biodiversity loss. Therefore, the need for social, environmental and economic change is still dominant around the world and many places including the Netherlands, are proposing different alternatives to mitigate the increasing anthropogenic impact.

Our Oceans with thermal energy basins covering more than 70% of our planet's surface are noticeably the largest solar collector. Ocean Thermal Energy Conversion (OTEC) technology provides the means of harvesting this vast potential to offer a steady baseline power generation for coastal cities and regions where most of the World's population is currently living. Nonetheless, since the nature of OTEC resources depends significantly on location-based indicators, an explicit focus has been put on this study towards the collection and examination of spatial information.

Nevertheless, cold water availability in 1 km depth, constraints the total amount of electricity that could be extracted by OTEC operations. For this reason, an advanced analysis below is performed which redefines the magnitude of the resources for the development of a realistic OTEC deployment scenario which can still cover the entire electricity demand of the world.

In total, the Offshore and Onshore OTEC power produce can reach up to 4.4 TW with a deep seawater flow rate of w_{cw}=175 m/yr without causing any thermal disruptions in the ocean. Therefore, countries such as Indonesia, Papua New Guinea, Dominica, Mozambique, U.S., Indonesia, etc that have a great abundance of OTEC resources, could even exchange this power produce through a symbiotic relationship to uplift their economy and make a step closer towards the forthcoming renewable energy transition.

Charalampos Chalkiadakis
Delft, November 2017

1

INTRODUCTION

How inappropriate to call this planet Earth
when it is clearly Ocean.

Arthur C. Clarke

1

1.1. CLIMATE CHANGE MITIGATION

At present, Climate Change consequences oppose severe mitigation challenges and risks for the developed and developing nations around the world. Developing countries especially, need to focus attention on creating mitigating strategies and in parallel compete with larger economies in the midst of pressing development needs. Nevertheless, countries differ enormously in which of these elements they emphasize and policymakers direct the attention on different sustainable development goals depending on the financial, social and environmental standards of each region.

However, these mitigation agenda's share the same problem origins that implies the consideration of multiple establishment requirements, in a short period of time. In specific, the increased population results in an enlarged need for electrification, especially in coastal regions and Delta's. In addition, the demand for clean and affordable energy is more than dominant in small islands and remote regions around the world which predominately use fossil fuel supplies.

In the contrary though, most of the renewable sources of energy are intermittent and therefore, a clean technology that offers baseload power production is becoming an inevitable necessity. Towards this direction, Ocean Thermal Energy which is the largest thermal recoverable basin in the world offers a unique opportunity for heat and electricity exploitation.

1.2. OCEAN THERMAL ENERGY RESOURCES

The immense size of the thermal resources of our planet enclosed within the oceans was firstly introduced by d'Arsonval in 1881 [12]. The oceans, one of the least explored sources of power, contain energy in the form of heat and movement that is enough

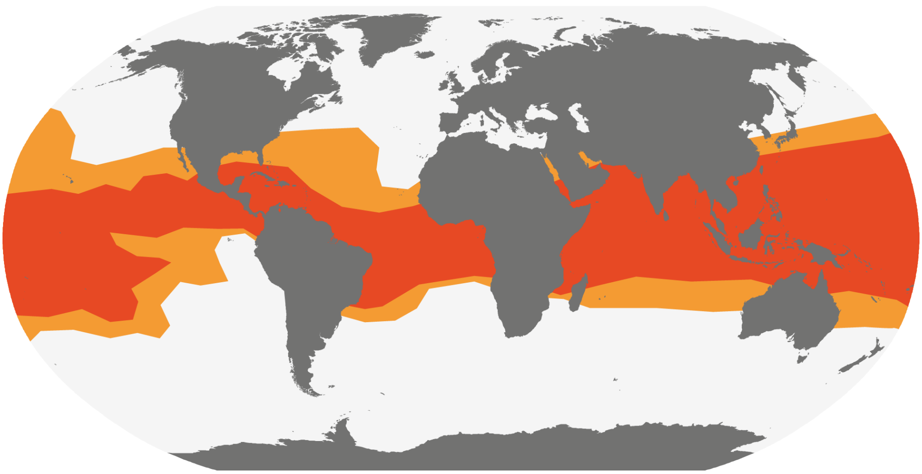


Figure 1.1: Temperature differences higher than 20^{o}C between the surface of the ocean and 1000m depth. The locations marked with red indicate much greater potential (Large ΔT) [4]

to power the entire world. In reality, Ocean thermal energy has the largest recoverable potential in comparison with all the other renewable sources [36]. Ocean Thermal Energy Conversion (OTEC) is the technology that aims to take advantage of that abundance that can cover the projected electricity demand of the world.

In detail, OTEC is a renewable source of energy that uses the temperature difference between the surface and the depth of the oceans around the equator, in order to produce electricity with a capacity factor of up to 100%. Specifically, within the tropics, the surface temperature can reach up to 25-29°C while at 1000 meters mark below sea surface level, temperatures are reaching values of around 4-6°C (see figure 1.1). This will result in temperature differences of between 20°C and 26°C for most locations nearby the equator. Therefore, this reliable and predictable behavior of OTEC resources continuously draws positive attention by the market and academic environment.

In the contrary, temperature differences lower than 20°C, cannot ensure an economically viable power output from OTEC installations. After consulting the thermodynamic aspects of such a design it is obvious that OTEC's sequential thermodynamic processes are nearly identical to an ideal Rankine power cycle [48]. Nevertheless, due to the thermodynamic irreversibilities that occur in reality, OTEC's turbogenerator, is assumed to be 85% efficient. Therefore, the overall gross efficiency of a typical OTEC unit can be approximated as: $\alpha_{gross} \approx \epsilon_{tg} \times \Delta T/2T = 2.85\%$, with a surface temperature of 25°C or 298 Kelvin and $\Delta T = 20°C$ (as indicative values) [48].

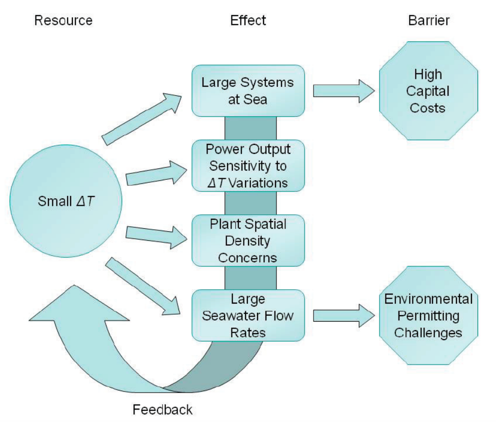


Figure 1.2: Barriers and concerns for OTEC deployment. OTEC plants work with a small temperature difference that necessitates large physical plants with high seawater flow rates [10]

Undoubtedly, the example above shows that deriving power from an OTEC unit is a rather ineffective thermodynamic process. Due to OTEC efficiency's strong dependence on the temperature difference, a $\Delta T = 11°C$ results in almost zero net power output, on standard thermodynamic conditions [48]. As a direct consequence, the power derived from the OTEC plant will be used only to drive the 3 associated pumps (parasitic electricity). The real challenge for OTEC deployment, lies not in alternative thermodynamic processes but advancing the existing performance of the present cycles and at the same time put specific attention on spatial considerations as the figure 1.2 illustrates. Therefore, locating the ocean thermal resources which are at some extent inexhaustible and renewable, should be the dominant priority.

The low thermodynamic efficiency of OTEC (approximately 3%) therefore, directs the focus on finding the proper locations for deployment. The technical feasibility related to positioning of the OTEC units is the parameter that affects directly the development of these alternative sources of energy, as mentioned also above [33]. In other words, the OTEC plant spatial density determines in some degree, the resulting power output in a specific area. In addition, physical and practicable criteria for deployment should also be considered as important factors for mapping a realistic resource potential. Thus, there are many steps to be taken towards the realization of ocean technologies, including the identification of a practicable OTEC resource potential and the selection of proper locations for offshore and onshore installations [39].

1.3. RESEARCH OBJECTIVE

According to Professor Gerard Nihous in the School of Ocean and Earth Science and Technology at the University of Hawaii at Manoa, harnessing this global potential from the ocean can reach the limits of a few TW (values that still exceed the current total electricity production) without causing thermal degradation [48],[46]. In detail, the early studies indicate that the global resource potential is estimated to be in the range of 5-10 TW. Nevertheless, after examining the ocean's complex parameters in a three dimensional Ocean General Circulation Model (3-D OGCM), the professor came to the conclusion that worldwide OTEC resources could exceed the above-mentioned threshold [50]. How realistic, a deployment scenario of this magnitude can be, is a reasonable question to propose. It is thus important to mention that, this distribution might cause significant thermal changes within the ocean, disrupt the thermal equilibrium and in extent put at risk the marine aquatic life and the performance of deployed plants.

A more sophisticated approach is used throughout this study which includes positioning aspects essential for deployment. Thus, it is important to take into account populated regions with sufficient need for electricity. Furthermore, the Exclusive Economic Zones (EEZ) of each maritime nation, will be also taken into consideration in order to re-define each country's potential and the onshore/offshore locations will be identified based on specific OTEC spacing ranges. Therefore, for the clarity of the analysis, the promising resources will be distinguished in Theoretical, Technical, Practicable, Onshore and Offshore Resource Potential for OTEC installations. Therefore, the objective of this study is to use these potential estimates as a stepping stone towards the creation of a realistic short-term deployment scenario, including "State of the Art" practicable criteria.

Specifically, the main research question that arises is:

What is the resource potential for OTEC installations and how many locations worldwide can be identified for the development of a realistic short-term OTEC deployment scenario?

In order to answer the main research question above, subsequent steps need to be followed towards that direction. In specific, it is reasonable to look for the theoretical potential with the initial temperature profile and the refined technical potential that corresponds to a $\Delta T \geq 20°C$. Subsequently, the coursed questions need to be answered in the following order as listed below:

- What is the current Technical resource potential of OTEC technology worldwide?
- Which countries have practicable locations for OTEC installations and how much is this total resource potential?
- How much is the Onshore and Offshore resource potential of OTEC technology after taking spacing considerations into account?
- Which countries have adequate Onshore and Offshore realistic resource potential for OTEC installations?
- In which way is it possible to alter the assumptions of the analysis, in order to offer reproducible outcomes in future studies?

GIS software offers the tools needed to examine such spatial data and visualizes information into the format of geographical maps and therefore, it is used extensively in this present study. The software offers also the opportunity to reproduce all the results by anyone who has access and sufficient knowledge of the software capabilities. Nonetheless, It is more than important to point out that this is the first (identified) attempt to utilize data for global OTEC resource mapping, by using the means that GIS software offers. Hence, it would be more than essential at the end of this study, to reflect upon the functionality of such a software, within this specific spatial context.

1.4. RESEARCH COMPOSITION

UNder this section, the research arrangement of this study is described in order to properly organize the information around this particular topic. In Chapter 2, the GIS software is initially introduced and all the relevant methods, tools, and data used throughout the entirety of this project, are respectively analyzed. To continue with, Chapter 3 is used as a literature basis where the OTEC technology's research and development status is described. Additionally, localized OTEC assessments are presented along with the global resource potential estimates for further utilization. The latter is accomplished in accordance with the decision framework that is composed for the selection of the "State of the Art" practicable criteria.

Moreover, in Chapter 4 the spatial distribution analysis is taking place, where all the processes and models used are represented and described in detail. Afterwards and in Chapter 5, the spatial results are represented through annotated geographical maps and an action plan is composed for the creation of valuable insights. Moreover, a sensitivity analysis is taking place for the determination of a refined onshore and offshore resource potential after altering the cold seawater pump flow rates (w_{cw}) in OTEC installations. In the end, the results from the spatial analysis will be combined with the literature study for the development of a realistic short-term OTEC deployment scenario. In addition, different scenarios are presented for the OTEC potential wherever a diverged assessment was used during the analysis. A complete overview of this thesis project is recognized in the illustration 1.3 below.

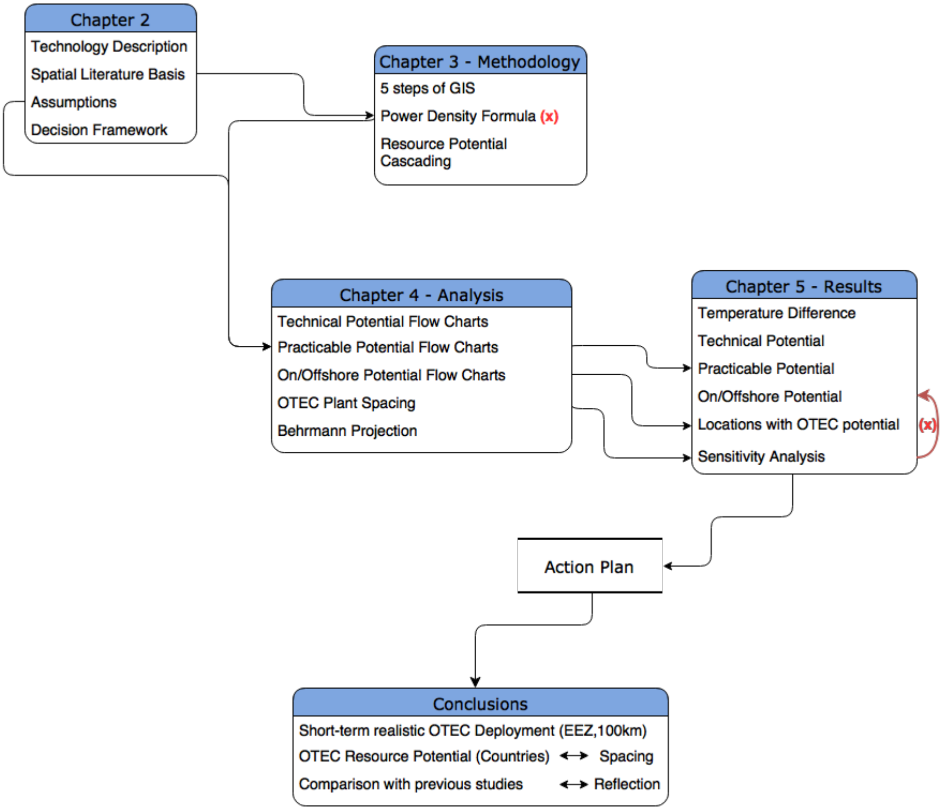


Figure 1.3: Total overview of the research steps for the composition of the thesis project

This research was conducted over twenty-six weeks by a single master's student in partial fulfillment of the thesis requirements of the master's program Industrial Ecology at Leiden University and Delft Technical University (TU Delft). The project was supervised by Professor Dr. Kornelis Blok of the Department of Technology, Policy and Management at TU Delft and Associate Professor Dr. Ester van der Voet at the Faculty of Environmental Studies in Leiden University. Ing. Maarten van't Zelfde, GIS Specialist in Leiden University, offered additional but exceptional guidance as an external supervisor. Lastly, Berend Jan Kleute, CTO and co-founder of Bluerise, provided his valuable feedback on the distribution results and offered a different perspective in relation to the associated spatial criteria.

2

OTEC RESOURCE MAPPING

This Chapter is dedicated to the development of the theoretical literature basis for this thesis project. Initially, the technical aspects of an OTEC plant are described where a detailed elaboration is executed for the current Research and Development (R & D) status of the technology. In specific, the different thermodynamic designs are presented with their potential applications and related benefits (Closed-Cycle, Open-Cycle, Hybrid-Cycle) along with the different possible platform configurations. To continue with, local-based assessments related to OTEC mapping are showing a significant potential for the technology in remote and isolated regions around the world. In addition, professor Nihous the past 10 years, is performing an on-going research on global OTEC resource mapping. His latest estimates of 7 TW of technical resource potential in an Ocean General Circulation Model (3-D OGCM), are offering a fundamental base for comparisons with this present GIS assessment in Chapter 5. Lastly, "the state of the art" practicable criteria used later during the GIS analysis, are presented and described in detail, composed in a structured manner within a Decision Framework that guides this resource assessment.

2

2.1. TECHNOLOGY DESCRIPTION

By the beginning of the 19th century Watt had already up to 500 designs of the heat engine dedicated to irrigation, energy and metal production purposes. As the years went by, other engineers such as Newcomen, Woolf, and Cornish tried to increase the efficiency of the steam engine for better performance. At that time, the efficiency of the heat engine was measured by the amount of water that could be pumped to a specific height per unit of coal burned [2]. Only after the year 1824, a French engineer, Sadi Carnot, published a scientific paper where he mentions that the production of work by the thermal expansion of a liquid is related directly to the heat transfer from a source at one temperature (T_1) to a sink at a lower temperature (T_2) [2]. Then Carnot showed that the theoretical maximum of such a process is derived by the formula depicted below:

$$\frac{Work\ Performed}{Heat\ Consumed} = \eta_{max} = \frac{T_1 - T_2}{T_1} = \frac{\Delta T}{T_1}$$

The Carnot equation (or the Carnot's principle) nowadays is also expressed as the 2nd law of Thermodynamics. It appeared a lot of time before the recognition of the 1st law and the mathematical expression of entropy Nowadays, the latter is still a valid equivalent to the current version of the second law of thermodynamics which indicates the limitations of the performance of any heat engine where the Carnot limits are derived in accordance to the two temperatures mentioned above.

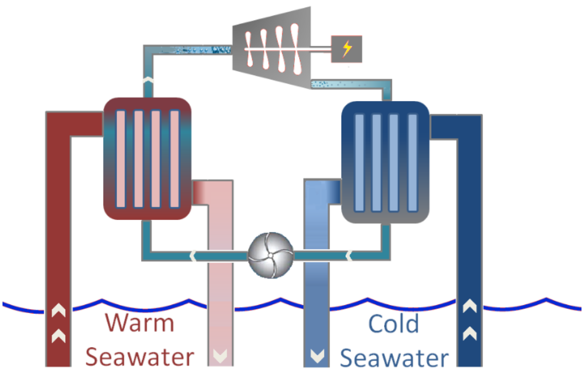


Figure 2.1: Schematic representation of a closed-cycle OTEC system and its components [3]

Furthermore, after the passing of many decades, engineers also focused on how to extract electrical power derived from low temperature heat sources. This knowledge marked the beginning of Ocean Thermal Energy Conversion (OTEC) technology. This concept was proposed by D'Arsonval as a heat engine that can produce a significant amount of electrical power with a ΔT difference between the boiler and the condenser as low as 15°C [12]. According to D'Arsonval (1881), there are many available heat sources and sinks in the nature that could be utilized according to this principle. He pointed out that the ocean waters around the equator offer a suitable temperature difference between the surface water and the cold water of 1 km depth (with $T_{cold} \simeq 4-6°C$) [12].

Hereafter, the heat engines could be designed in a manner that uses that ocean surface water to warm up organic working fluid (which has a very low boiling point) such as Ammonia, hydrocarbons, etc. The deep cold water is used to condense the fluid and thereafter provide the suitable pressure differential for a steady operation as it is shown in figure 2.1 above. The past few years, the offshore engineering industry offers many options for a safe and reliable unit deployment ensuring efficient electricity production at lower costs. Subsequently, it is more than evident that the state of the OTEC technology surpassed the stage of research and development [3].

2.2. STATE OF THE OTEC TECHNOLOGY

THere are only 3 types of OTEC technical system designs that have been tested so far; The Open-Cycle, the Closed-Cycle and the hybrid systems which are designed based on a combined configuration of both cycles. The main advantage of the latter configuration is that it can produce power in a closed-cycle and desalinated water in an open-cycle with a combined seawater and working fluid circulation [45]. Below, each cycle is analyzed with a description of the advantages and disadvantages of each unit system design and additionally, the OTEC platform configurations are presented in order to understand the physical aspects of the offshore plantship.

2.2.1. CLOSED-CYCLE

The principle of a Closed-Cycle OTEC system is based on the principles that D'Arsonval first described in 1881 [2]. The OTEC plant pumps the warm sea surface water and evaporates the working fluid by taking advantage its low boiling point. Subsequently, the working fluid will expand creating a pressure differential which will be translated to power in the turbo-generator as it is shown in figure 2.2 below [44]. Eventually, the working fluid will be condensed by the cold seawater and it will follow its path towards another "closed-loop" cycle for continuous operation.

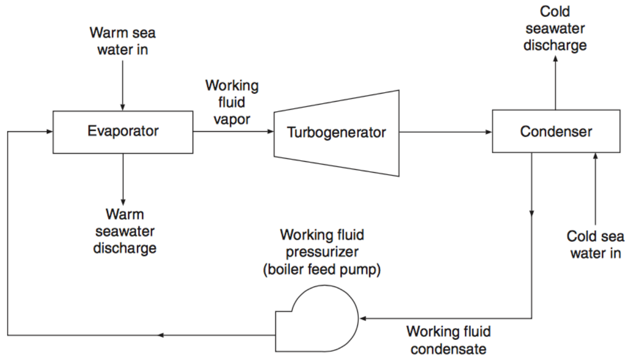


Figure 2.2: Schematic representation of a Closed-Cycle OTEC configuration [44]

In addition, Closed-Cycle systems are the most common configurations deployed in off-shore installations. The most common working fluids, on the other hand, are Ammonia and some fluorocarbon refrigerants. Both could potentially pose further environmental attention in case of a leakage since the first one is toxic and the fluorocarbon refrigerants destroy the stratospheric ozone [44]. However, the safety measures of such systems nowadays is quite advanced and therefore, it eliminates any risks of contamination.

2.2.2. Open-Cycle

The student of D'Arsonval, Claude, concerned about the high cost of such a configuration and by taking into account the danger of fouling the Heat Exchangers, he proposed an Open-Cycle configuration as it is shown in figure 2.3 [44]. In Open-Cycle OTEC systems, warm surface water is the working fluid which is flash evaporated inside a partial vacuum (in the evaporator). The vapor is expanding through the turbine and it is condensed with the cold seawater coming from 1km depth. Furthermore, the Open-Cycle configuration has an advantage over the closed-cycle since the design has one less heat exchanger to employ. The difference in this configuration though is the platform, which is double the size in order to deliver the same electrical output. The other disadvantage of such a system is the low performance derived from the low system operating pressures [44].

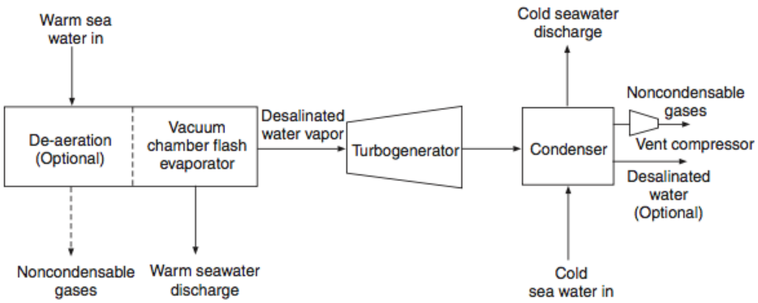


Figure 2.3: Schematic representation of a Open-Cycle OTEC configuration [44]

Nevertheless, the Open-Cycle systems provide additional benefits including the possibility for desalination. Moreover, in the Open-Cycle systems the cold water that is used for condensation can be also utilized afterwards for cooling purposes in a Sea Water Air-Conditioning (SWAC) system [39]. These installations have already been commissioned in many cases around the world where the costs for conventional cooling are significant.

2.2.3. OTEC Platform Configurations

Both Open-Cycle and Closed-Cycle systems are used in on-shore installations where the additional benefits of SWAC can also be exploited. The Closed-Cycle systems can be installed Offshore or on the top of a submerged platform (see figure 2.4). One important information here is that the most reasonable and economically viable option is to deploy onshore OTEC units within a distance from the source of approximately 4 km.

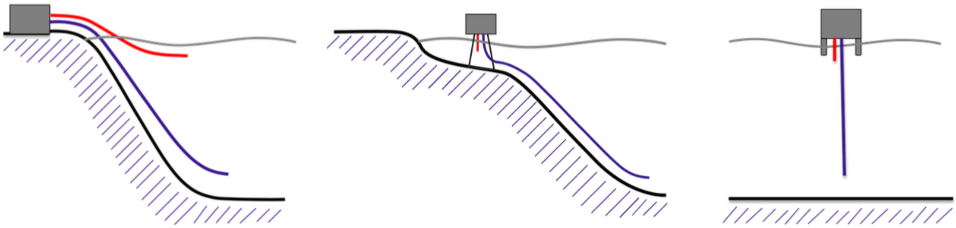


Figure 2.4: Schematic Representation of Different OTEC platform configurations [5]

Regarding the shelf-mounted units, it is more likely that these configurations will be used depending on the slope and the seabed profile of the chosen location. In the resource potential analysis below in Chapter 4, the distance used to define the onshore potential is approximately 9km which covers both configurations in most cases. Therefore in this resource mapping study, the onshore potential (see Chapter 4 and 5) will represent both the onshore and shelf-mounted designs. In the contrary, previous studies related in specific to resource potential mapping, should be initially examined before reaching a decision about the proper criteria important for the analysis.

2.3. OTEC Localized Mapping Case Studies

In many countries that are located in places such as: Africa, America, and the Indian or Pacific ocean, there is a vast amount of OTEC resources. The team with Hinicio as a leader researched up to 66 locations in 28 Latin American countries and Caribbean territories for potential attractive sites for district Cooling, SWAC and OTEC projects [26]. A small overview of such studies can be identified below in the subsequent sections.

2.3.1. OTEC in Caribbean Sea, Atlantic Ocean

The vast amount of the resource potential in the Caribbean Sea is mentioned thoroughly in the literature [26] and it clearly offers a clean and renewable alternative solution for the developing states of that region. The Agence Française de Development (AFD) funds a feasibility study for SeaWater Air-Conditioning (SWAC) in 8 regions in the Caribbean including Dominican Republic (Puerto Plata, Santo Domingo, Aeropuerto Internacional Las Américas), Jamaica (Kingston, Montego Bay and Ocho Rios), Guadalupe (Basse Terre) and Martinique (Fort-de-France).

Martinique is a French sovereignty located in the Atlantic ocean nearby Venezuela. The island being close to the equator receives enough sunshine throughout the year to maintain an average ocean surface temperature. Martinique island in specific has an average yearly surface temperature close to 25°C. Lastly, it has infrastructure present and a developed electricity grid needed for integration which makes it a suitable location for OTEC installations.

2.3.2. OTEC IN REUNION ISLAND, INDIAN OCEAN

Reunion island is another overseas French territory located in the Indian ocean south-west of Mauritius. A ten-year study on ocean surface temperatures at a coastal location in Reunion island found that the ocean surface temperature ranges from 23.4^{o}C to 28^{o}C with a mean temperature of 25.7^{o}C. The annual amplitude of temperature variation is 4.6^{o}C with daily variations ranging from 0.25-0.74^{o}C depending the season [9]. From 2011 and onwards, many contacts were carried out with technology providers for the realization of various projects in the Reunion island. Therefore, OTEC, micro-algae and SWAC units were also commissioned, some for the data collection phase and some for the prototype phase (CETO PELAMIS & OTEC Prototype) [27].

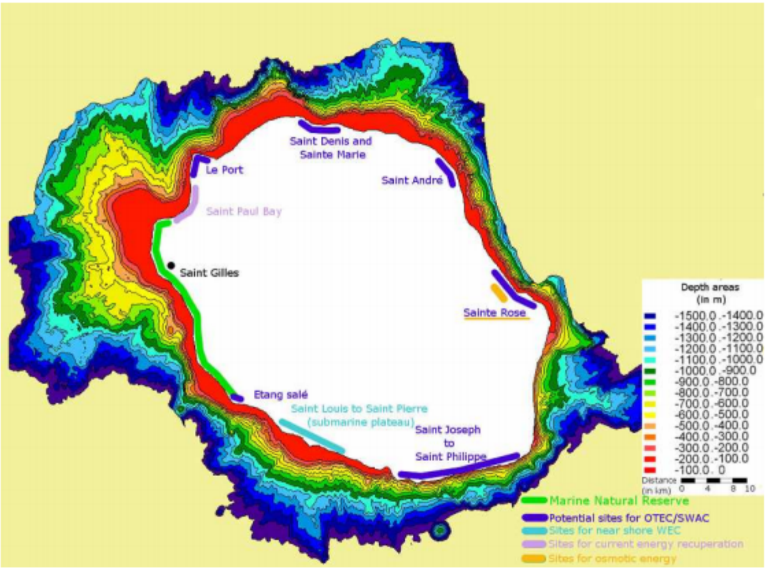


Figure 2.5: OTEC Resource Potential Mapping in Reunion Island [28]

By just assessing the bathymetry map of the Reunion island it is evident from figure 2.5 that the eastern coast has a lot of potential sites for onshore OTEC and SWAC. In addition, a small stretch on the western coast is also suitable for near shore OTEC development [28]. The visual assessment as illustrated in figure 2.5 therefore, provides a valuable qualitative and quantitative spatial overview which becomes necessary during the decision-making process while commissioning an OTEC project.

2.3.3. OTEC IN PHILIPPINES

A research derived from the Philippine Sea in the tropical zone with $\Delta T \geq 20°C$ provides additional reasons for exploring this resource potential. As it can be identified by the figure 2.6 below, there are at least 14 potential locations for OTEC installations which are suitable according to the temperature profile, the extreme weather conditions and the sea state; the surface and subsurface current velocity and their directions along with the wave spectrum, and the speed of the wind [61]. In detail, the study of Uehara (1988) showed that 10 sites from the entire maritime regions available (see figure 2.6) are suitable for off-shore OTEC and 4 sites for on-shore installations. This "State of the Art" local assessment can become the stepping stone for developing a location-based framework for local OTEC resources in the future.

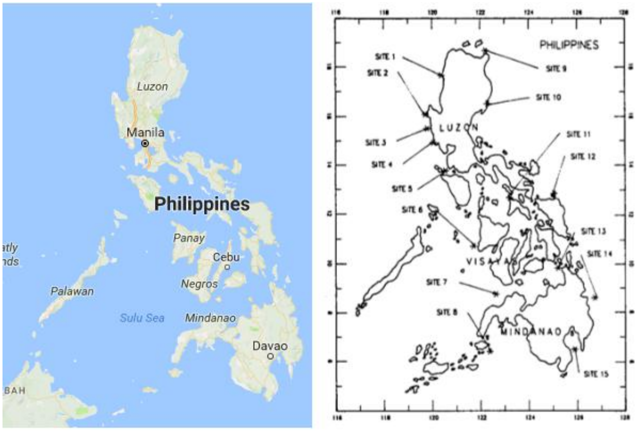


Figure 2.6: Map of the Philippines showing 15 locations with OTEC resource potential [61]

In addition, the government in the Philippines is interested in assessing the resource potential of OTEC in order to identify more potential ocean areas for deployment and at the same time create and maintain an extensive database on ocean energy resources of the country [41]. According to the same source, the government also developed an Ocean Energy Sector Roadmap for the years 2011–2030 which also includes a total target installed capacity of additional 10MW of electrical produce by 2030.

Figure 2.7: Philippines Map showing potential OTEC locations depending on the electrical grid connectivity [34]

Similarly, in figure 2.7 there is also an assessment from a GIS analysis which identifies the suitable OTEC locations for deployment by taking into account the electricity grid connection possibilities. Finally, the UNDP-assisted project by OCEANOR conducted a better investigation on the potential of ocean energy in the Philippines by visiting attractive locations such as Batanes, Cagayan and Polilio Islands and Bolinao [34]. The goal, in the end, was to determine the feasibility of ocean energy projects such as wave, tidal and OTEC systems in the country.

2

2.3.4. OTEC IN AFRICA

What matters the most is not how much an OTEC installation will cost but how much a country is willing to earn back (social, economic and environmental benefits) by switching to "clean" energy sources [14]. This quote is showing that even in the case of developing countries in Africa, it is a matter of governmental willingness to how many non-polluting resources will be introduced to the energy mix of a country. African waters have actually some of the best sites for OTEC which are positioned in the southern part of Africa including locations nearby Tanzania and Mozambique [15].

A more detailed investigation of the Western South part of Africa by Hammar et al.(2012), shows locations that are suitable for OTEC installation as the figure 2.8 indicates below. The criteria for such an analysis are including a maximum distance of 25 km from the coast, the deep sea currents' speed and other physical criteria that allow safe mooring [29].

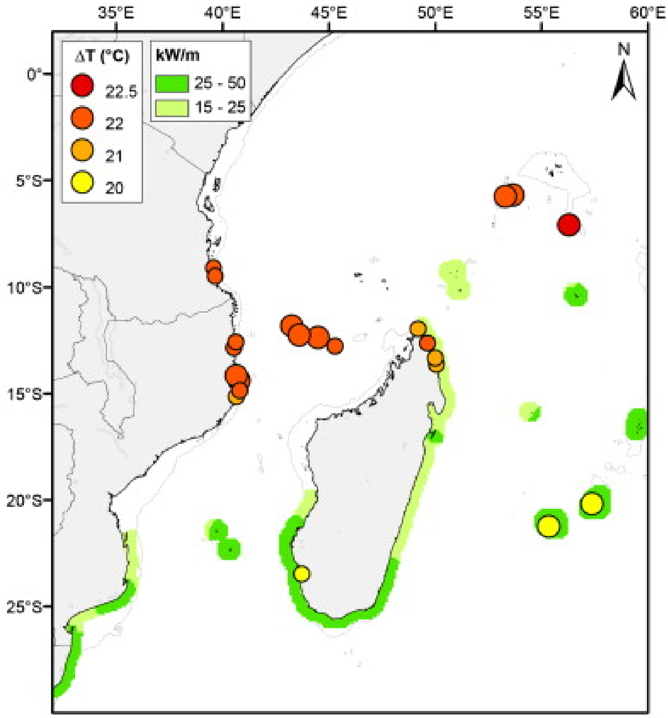


Figure 2.8: Circles mark locations with $\Delta T \geq 20°C$ within 5 km (large circles) and 10 km (small circles) from shore [29]

However, according to the same source, the resource availability must be in parallel with the need for energy, especially in such countries that do not have access to other resources [29]. According to the results of that study, such deployments could be established in the small island states of the Western Indian Ocean (WIO), and also in some remote regions of the mainland of Africa.

On the other hand, there are some additional observations that have to be taken into account in terms of the resource potential of OTEC around Africa. More specifically, along the West Coast of South Africa, there are strong cold currents that affect the temperature profile and thus keeping the tropical coastal temperatures below 20°C [59]. In addition, a seasonal drop of the seawater temperature in African waters is also observed due to the upwelling of deep sea water which is taking place [59]. In conclusion and according to the same source, the seasonal variations might affect significantly the performance of OTEC modules and therefore a careful assessment of the local climatic conditions is important.

2.3.5. AN OVERVIEW OF HAWAII ISLANDS, OTEC IN THE PACIFIC OCEAN

Hawaii islands are one of the most popular tourist destinations in the world. The energy demand in Hawaii is considered high due to the continuous activity of the tourist industry throughout the entire year. The luxurious hotels and resorts contribute a significant percentage to the electricity consumption in these islands. In fact, in 2014, around 68% of the electricity was produced from burning oil and 14% was produced from coal combustion [30].

Since the fossil fuels have to be imported from US mainlands or from other countries, the cost of electricity production is large in these islands. The electricity prices in Hawaii are almost double compared to the average US electricity price [30]. This has been the driving force for the switch towards renewable energy sources. Even though there is a significant increase in power delivered by wind and solar projects, the intermittent nature of these sources prevents them from making a significant change in the generation portfolio. Finally, the costs of power production in Hawaii are almost equal to the levelized cost of electricity of OTEC technology which can serve as a base load and help Hawaii islands achieve the ambitious aim of being 100 % energy independent by 2045.

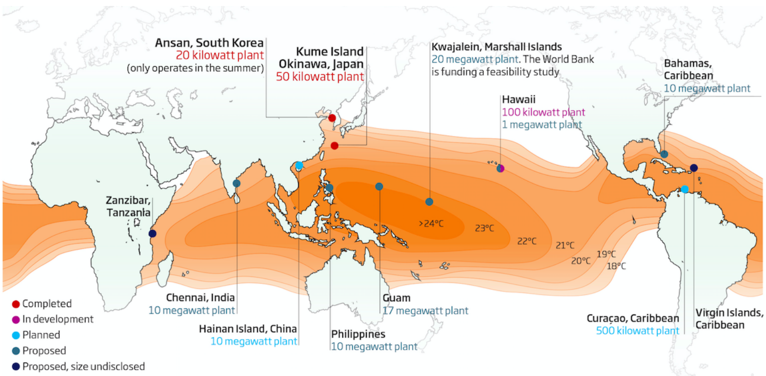


Figure 2.9: OTEC operational and demonstration plants around the world: Geographical overview

A better geographical overview of some of the OTEC installations worldwide is also shown above in the figure 2.9 where it is evident that Hawaii islands have significant potential for OTEC technology. Operational plants are already deployed in the island where one of them serves as a pilot project for further research and development, installed by Lockheed Martin Naval Facility Engineering [33].

The School of Ocean and Earth Science and Technology at the University of Hawaii at Manoa also carries significant efforts for the development of OTEC on the island. As it follows below in the next subsection, the leader of the research group at Manoa, Professor Gerard Nihous, is investigating the global OTEC resources for more than 10 years and his work has been reviewed by many researchers around the world. Therefore, it is more than interesting to describe and present some of his publications below.

2.4. OTEC Global Resource Mapping

2.4.1. Order of Magnitude Potential Estimates

Nihous (2005) in his study, estimates the theoretical resource potential of OTEC to be represented by a wide range of values, from 10 till 1000 TW, as an order of magnitude [48]. Moreover, the researcher shows the past estimates of OTEC resources and he presents a total literature overview which can be found below in table 2.1. Analytically, most of these results are based only on the amount of solar energy that the ocean can absorb without addressing several physical and practicable limitations. In reality, 51% of the heat input into the ocean is used only for evaporation which starts when the air over the ocean is unsaturated with moisture (evaporative flux in W/m^2). Therefore, if only the evaporative flux is taken into account, the range of power estimates reaches unrealistic thresholds and when limitations are introduced, the OTEC power estimates are limited to less than 100 TW.

In detail, the first two potentials in table 2.1 above, represent theoretical resource estimates (incident solar radiation values) but the rest which show much lower power maxima under environmental constraints, could be interpreted as technical resource estimates. Professor Nihous within his first publications though, offers a "state of the art" primary analysis of the vertical structure of oceanic temperature, in order to derive a realistic interpretation of OTEC resources around the world. He suggests that the OTEC installations worldwide can reach a final net electrical power of about **$3*10^9$ kW = 3 TW** of steady-state operations at the most [48]. Nevertheless, the model of the oceanic circulation that he utilizes in the first place, is based on a one-dimensional (1-D) analysis which does not take into account the potential future arrangements from convective horizontal currents [48].

On the other hand, according to a later study of professor Nihous where a resolution of one-degree-by-one-degree is achieved, the maximum of steady-state OTEC power is adjusted to the value of **5 TW** [46]. Under this 1-D study, a dynamic analysis was also part of the objectives where OTEC net power is gradually implemented for large-scale operations. Long-term power losses indicate that even with a higher spatial resolution model, the sustainability of OTEC resources at large enough scale could be at stake [46].

In specific and if we take into account the significant cold water flow rates, important for large-scale OTEC installations, a long-term warming of the waters around the tropics will occur according to Nihous's calculations [46]. These massive flow rates can disrupt the vertical thermal structure of the oceanic water column and in extent cause a brief cooling of the mixed layer. This phenomenon degrades the performance of OTEC units and at the same time causes thermal imbalances with unknown consciousnesses to the marine environment. Undoubtedly, these predictions have to be further investigated, through a three-dimensional model which takes also into consideration the convective horizontal currents.

2

2.4.2. LATEST POTENTIAL ESTIMATES

The latest resource potential estimates thereafter, are including predictions of OTEC resources under broad geographical constraints using an Ocean General Circulation Model (3-D OGCM) [49],[50]. These studies, by investigating the horizontal transport phenomena in a 3-D model, reach to higher OTEC maximum for much greater cold water flows and small effects in the oceanic thermal equilibrium. These results are expected since the horizontal transport processes dictate their vertical counterparts [50]. In the contrary, earlier estimates indicated that "...any significant degradation of OTEC net power production would occur at smaller OTEC flow rates in such a limited modeling context"

Table 2.1: OTEC power limits derived by the technical literature [48]

Source	**OTEC Power Limit (TW)**
Incident solar power over 60 million km^2 (tropical oceans): 250 billions barrels of oil equivalent (boe) daily [44][53]	$366^{a,b} - 610^{a,b,c}$
Evaporative flux over all oceans 370 million km^2 and 3% OTEC conversion efficiency [64]	$180^{a,b} - 1000$
Limited by the rate of formation of deep water (no details) [59]	50 – 150
Environmentally safe OTEC production density: 190 kW/km^2 (no details) [2]	19^{c}
Continuous, renewable OTEC production with no detrimental effect on the oceanic thermal structure (no details) [54][11]	10
Projected OTEC production of 60 TW deemed safe [68][69]	> 60
Projected OTEC production of 0.2 TW over 1 million km^2 not sustainable [43]	> 20

[a] 1 boe is 6 million BTU, or 6.326*10^{-3} TJ
[b] net OTEC conversion efficiency of 2% was applied (Standard OTEC Process described in Section 2)
[c] area of 100 million km^2 was used

according to Nihous and Rajagopalan (2013).

Therefore, the complexity of more sophisticated oceanic circulation models is opposing a significant challenge on identifying a "sustainable" OTEC resource potential. In reality, the transport of heat within the ocean results from vertical diffusion and advection forces [46]. In this current modeling context, the coefficients that describe these processes; the vertical eddy diffusion coefficient (K in m^2/s) and the OTEC equivalent deep seawater vertical velocity (w_{cw}), are kept constant throughout the entire analysis (Static 1-D model). In any other case (with three-dimensional K coefficients), the modeling context would be much more complicated with a significant computational power necessary to extrapolate results (60 processors running the model for several days [50]).

Therefore, during the calculations later in Chapter 4, it is evident that only the static temperature field is examined in a 1-D model for the calculation of the power density since a constant value of the vertical eddy diffusion coefficient is used. Thus, the formula (3.1) is used for the calculation of the power density along with a small and "permitted" value of w_{cw}= 5 m/yr (the calculations in detail follow at the Appendix C). This will result in a total worldwide net power of a few Terra Watts (TW) in contrary with the **30 TW** of Nihous and Rajagopalan's (2013) estimates within a 3-D OGSM model [50] (with w_{cw}=60 m/yr as illustrated in figure 2.10).

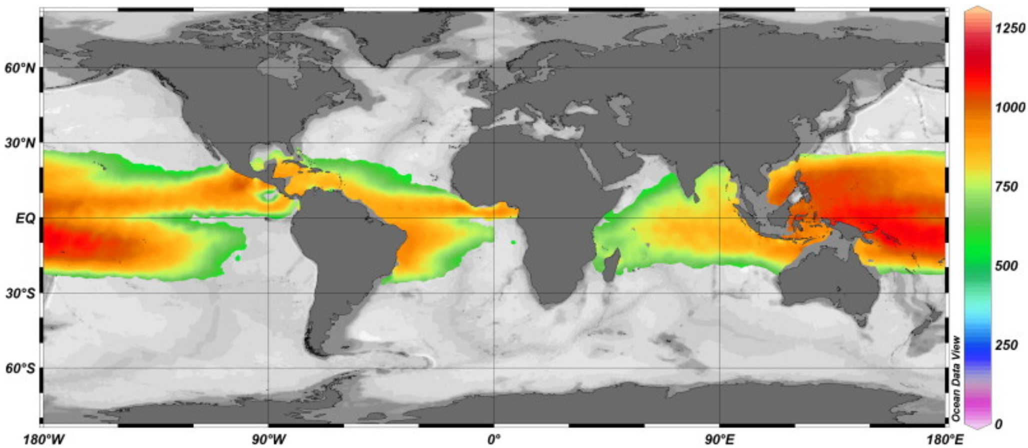


Figure 2.10: Annual OTEC net power density if no change of the ocean's thermal structure occurred when w_{cw}=60 m/year [50]

However, from figure 2.10 it is obvious that the tropical islands in the Atlantic, Pacific and Indian ocean have remarkable potential for both onshore and offshore OTEC installations. The figure corresponds to the maximum net power density with w_{cw}=60 m/yr as described above. Additional results from this study indicate that extracting thermal energy with this w_{cw} and without taking spacing considerations into account, would have undesirable effects on the oceanic temperature profile of the oceans worldwide.

In reality and according to figure 2.11, with w_{CW}=60 m/yr, the change occurring in the annual mean temperature, would be significant. Elaborately, in some locations within the OTEC region boundary (Japan, Indonesia, Caribbean Sea, etc), there would be an increase in temperature of about 2.5°C, in 1km depth. This would cause considerable degradation of the total OTEC power maxima while triggering remarkable ecosystem alterations [50].

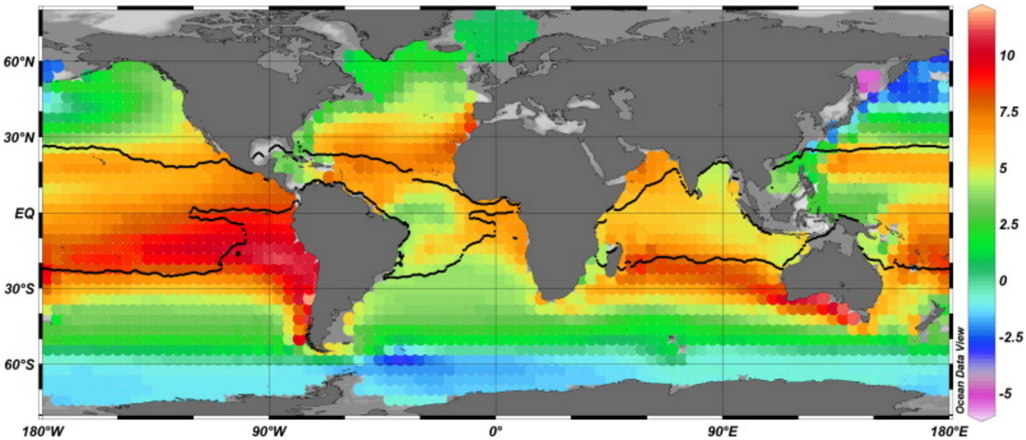


Figure 2.11: Occurring changes in the annual mean temperature of the OTEC seawater intake layer (at 1km) when the total power produce is maximum (w_{CW}=60 m/year): The black line is the OTEC region boundary [50]

Nihous and Rajagoplan in this publication conclude that unit deployments of up to 7 TW with w_{CW}= 5 m/yr, would not cause alterations even in an unperturbed case as such which behaves similarly with the sophisticated 3-D OGCM model (graph 2.12 below) [50].

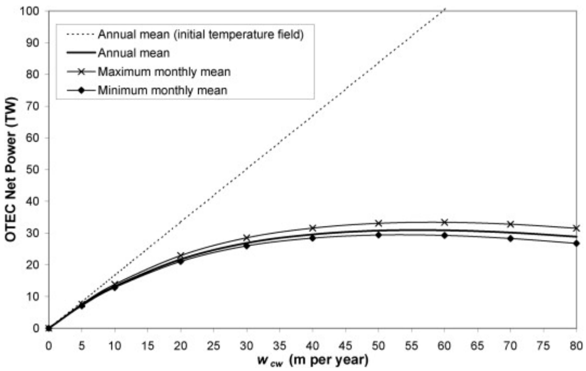


Figure 2.12: Global OTEC net power as a function of w_{CW} [50]

Therefore, the objective of this thesis project is to use this small value for the OTEC cold water flows as a sustainable and "permitted" basis, in order to perform the spatial distribution analysis. Later on and during the sensitivity analysis in chapter 5, the cold water availability in 1km depth will be considered which determines the OTEC plant spacing (density of deployed units along the ocean). Consequently, the w_{CW} values will be adjusted accordingly to correspond to rather greater OTEC power maxima, though sustainable and within 100 km away from the coast (similar work to Nihous' very last publication [49]).

Clearly, w_{cw} is the variable that tunes the total technical power produce as shown in the graph 2.12 (over 100 million km^2 of OTEC area). It represents the OTEC cold water flow rate that the plant uses from 1km depth, per unit of area:Q_{cw}/A_{OTEC}. This variable determines how much will be the change in the OTEC net power (TW) worldwide as it is shown in the graph 2.12 and in extent the magnitude of the thermal degradation that could occur as shown in figure 2.11 above.

The initial (static) temperature field with dots, as shown in the figure above, is the linear approximation of the technical power as a function of w_{cw} (see formula (3.1)). Since the present modeling environment is limited to only one dimension and without taking into account the advection and diffusion forces, it is more than reasonable to use the value of w_{cw}= 5 m/yr which is closer to the realistic estimates of the extended modeling environment present in the literature, as described above. A decision to choose higher cold water flow rates for an OTEC unit in the contrary, would result in an amplified but not realistic resource potential in a static modeling context as such.

To summarize, it is evident from the literature above that physical constraints related to OTEC deployment, are concerning other researchers around the world. There are also limited case studies identified where an advanced local assessment took place with practicable criteria. Thus, the decision framework along with the resource potential categorization below, offer a progressive development of estimates in a distinguishable manner.

2.5. Decision Framework

Ocean thermal energy resources are site-specific dependent and the advantages or disadvantages of different but limited locations must be considered before taking a final decision. The main factors to be contemplated for selecting an OTEC site are environmental conditions like ocean surface temperature and water depth. Additionally, there are many other factors that affect the deployment of such a unit and consequently the decision-making process during commissioning. All these "state of the art" practicable criteria are listed and described in detail below.

There are mainly 5 different practicable criteria that are used throughout the entire analysis and are listed and illustrated below (see also figure 2.13):

1. OTEC Plant Spacing
2. Cold Water Resource Availability
3. Distance to Shore (AC/DC cable)
4. Need for Energy (Population Density and Africa's Electricity Grid)
5. Exclusive Economic Zones

As it is shown in figure 2.13, all the above-mentioned criteria affect the technical performance and the economic feasibility of such a project. In further detail, the operational capacity and the resource availability are the topmost important sub-interests and the cost of components along with the operation & maintenance costs, are a secondary priority. In reality, the Distance to Shore criterion is connected with all the sub-interests and it provides essential insights on whether the cable should deliver electricity in the form of AC (Alternative Current) or DC (Direct Current) from such an installation.

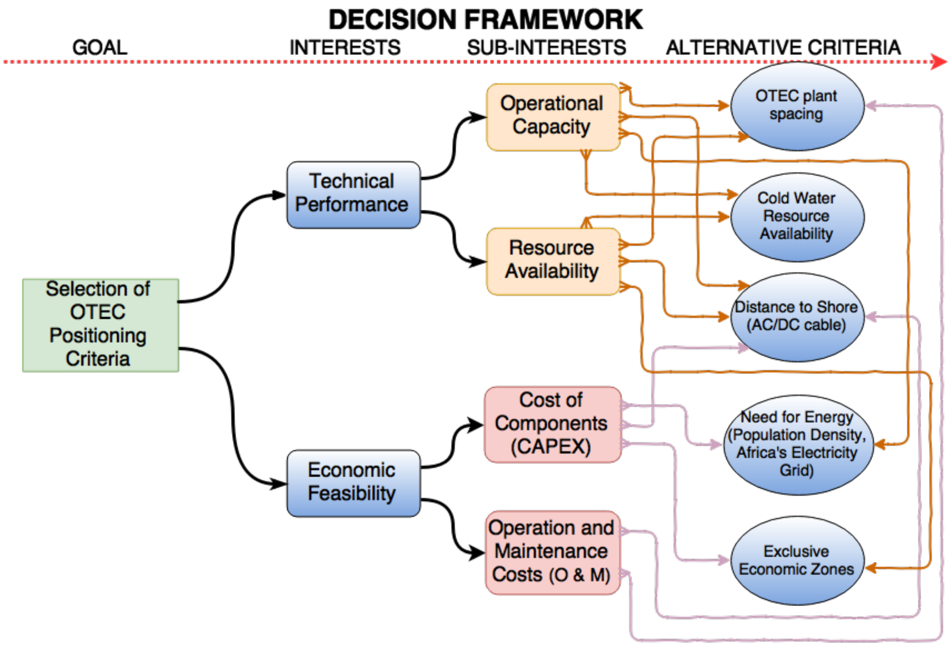


Figure 2.13: Decision Framework for the Practicable Assessment Criteria

In addition and after consulting the associated literature, power transmission with high voltage AC cable for distances greater than 70km is not an economically viable decision [65],[1]. A different solution in this case, is to transmit electricity with a DC submarine cable. According to Olivier Angoulevant, Sales Manager–Wind at Nexans, for distances greater than 70 km, only DC cable is expected to work, since AC is constrained by the amount of reactive power required to energize the circuit [57]. In addition, when there is a need to transfer power rated at 100 MW, medium voltage AC is used for 15 km distance and high voltage AC for distances smaller than 70 km [57]. Therefore, in the analysis and results section in Chapters 4 and 5, the cable type will be specified accordingly while executing the proximity calculations.

Another critical aspect of the viability of an OTEC installation is the plant spacing considerations in the case of a large onshore or offshore OTEC farm. In the former case study (Onshore), the distance between the plants should exceed at least the value of 4km

2

in order to prevent thermal degradation and in extent further decrease in OTEC performance within these regions. Moreover, in the case of Offshore OTEC units, the cold water availability at 1062m needs to be considered [37]. As described above in the previous section, the sustainability of OTEC resources hinges on the amount of thermal degradation that occurs and in extent on the limits of the cold water availability.

Meanwhile, the OTEC cold water usage is limited by the production of cold seawater in the polar areas and therefore there would be practically very small margins of time for ocean circulation to recover it [37]. As a result, Lockheed Martin Corporation (2012) which addresses the question of cold water reservoir attenuation, provides important tools to calculate different spacing ranges for the offshore OTEC unit locations, that can be found below.

In detail, the OTEC cold water pumping that occurs in a specific region is directly related to the amount of water transported into that region by oceanic circulation. If a steady-state process is considered, the cold water flow rate ($F_c \equiv Q_{cw}$) identified in figure 2.14, should be equal to the amount of incoming water in 1062 meters depth in that region [37] as pointed out in the formula (2.1) below.

$$F_c \equiv Q_{cw} = V_{in} \times \Delta z \times \Delta x \quad [m^3/s] \tag{2.1}$$

In more detail, the parameter Δz is the thickness of the cold water utilization layer and the Δx^2 represents the area that occupies one OTEC plant as illustrated in figure 2.14. Additionally, the parameter V_{in} is depicted using the Pythagorean theorem and the East to West (EW) and North to South (NS) water velocities in 1062 meters depth ($V_{in} = \sqrt{V_{EW}^2 + V_{NS}^2}$) obtained by Copernicus Marine Database (see Chapter 3).

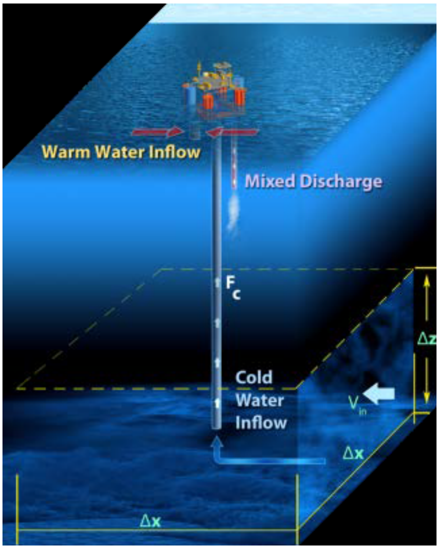


Figure 2.14: Schematic of Cold Water Usage by a single OTEC plant [37]

Thereafter, typical values for OTEC cold water flows, the utilization layer thickness, and the OTEC unit spacing, are obtained using a mathematical analysis. A cold water flow rate typical value of 357m^3/s (in a 100MW plantship [37]) is used, along with an average value of V_{in}=0.05m/s, in order to calculate a typical spacing Δx. In reality, one single unit will occupy a region with: $Area = D^2 = 4 \times R^2$ where the distance between 2 units is defined as $\Delta x = D = 2R$ as shown in the associated schematic in figure 2.15 below.

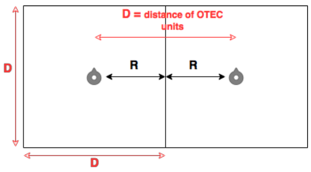


Figure 2.15: Schematic for OTEC plant spacing calculation

As a result, the average value of the parameter Δx is used for the calculation of an average utilization layer thickness Δz. In the end, this value serves as an input for the calculation of the overall OTEC spacing as the formula (2.2) below indicates [37] (see also Chapter 4).

$$\Delta x = \frac{357}{0.05 \times \Delta z \times V_{in}} \quad [km] \tag{2.2}$$

Of course according to Lockheed Martin Corporation (2012), "...as the global OTEC estimate is refined or modified over time..." this methodology remains well founded and it can be used with the adjusted resource potential values of every future study.

In specific and without any loss of generality, it is possible to assume that the resulting 11.8 TWe resource potential estimates from the technical analysis formulated in chapter 5, are utilized by 100 MW OTEC plants. In reality, there will be 118,000 virtual OTEC plantship units, appeared to be evenly distributed throughout the globe. Therefore, the formula (2.2) is used to calculate the spacing ranges as indicated in the subsequent steps below:

- Calculating the typical $\Delta x = D = 2R$ values as shown in figure 2.15:
  1 OTEC unit occupies an area: $Area = D^2 = 4 \times R^2$
  118,000 OTEC units will occupy an area: $Area = 118,000 \times 4 \times R^2 \Rightarrow$
  ' $\Rightarrow R = \sqrt{Area/(4 * 118,000)} = \sqrt{120 * 10^6/(4 * 118,000)} \Rightarrow R = 16km$ and therefore, $D = 2R = 32km$
- Calculating the typical utilization layer thickness Δz: $\Delta x = \frac{357}{0.05 \times \Delta z \times V_{in}} \Rightarrow \Delta z = \frac{357}{0.05 \times \Delta x \times V_{in}} = \frac{357}{0.05 \times 32 \times V_{in}} \Rightarrow \Delta z = 22cm$

After performing the calculations above, it is evident that the average OTEC spacing has the following form:

$$\Delta x = \frac{1.62}{V_{in}} \quad [km] \tag{2.3}$$

These results are in the same order of magnitude with the outcome present in the study of Lockheed Martin (2012) [37]. The formula (2.3) above therefore, is used predominately along with the spatial analysis (Chapter 4) in order to extract the OTEC spacing map found in chapter 5.

On the other hand, in order to define the OTEC implementation area and the practicable potential of each country, the Exclusive Economic Zones (EEZ) are used as an indication. In addition, the population density applies a selection process related to where exactly OTEC could offer sufficient electrical supply. In the contrary and for the sensitive case study of Africa, since electricity grids are not always present in populated regions, the distance to the electricity transmission lines of the continent will be used as

2

an actual indicator (described also in chapter 3).

Nevertheless, the alternative criteria presented above might affect specific economic indicators (Capital and Operational Costs) but they are not offering any insights related to executive economic decisions. These aspects are prone to a Cost and Benefit Analysis which is not the objective of this study. To summarize, the criteria mentioned above are distributed throughout the different resource potential categories that follow below. In the end, they are also used during the distribution analysis in chapter 4, in order to extrapolate the refined OTEC power maxima for all the locations around the world in chapter 5.

2.6. Resource Potential Categorization

The discussion around the resource categorization is identified in numerous studies in the past but only until recently Lopez et al. (2012) developed a more unified framework [38]. In general, potential resources are the ones of which we have insufficient knowledge or we do not have the technology or infrastructure to exploit them at present. Renewable resources like OTEC, show conditional behavior and therefore the long-term sustainability of these resources is subject to possible ecological disruption.

Therefore, the resource potential categorization is becoming more than essential since the sustainability of the resource "...hinges on the avoidance of excessive thermal degradation (among other constraints)" according to Professor Nihous. As a result, this categorization present in the figure 2.16 above, indicates some of the alternative options for OTEC deployment while considering several physical and practicable limitations. Specifically, the analysis in this thesis work is focused on 5 main criteria categories (see figure 2.16). This type of categorization is necessary to avoid any confusion related to the resource potential definitions, in the first place and finally, the data will be organized in a proper manner for a better understanding to make the study also reproducible.

Therefore, the following resource groups will be taken into account and will be analyzed thoroughly in Chapter 4:

1. **Theoretical Resource Potential** which is the energy that is contained in the entire resource. The theoretical potential includes the power derived by the static temperature field for locations in all longitudes and latitudes around the world.

2. **Technical Resource Potential** which represents the proportion of the theoretical potential that is technically feasible to exploit. In the case of OTEC, this proportion is related to the minimum requirement of $\Delta T \geq 20°C$ which is the current threshold proposed for a viable installation.

3. **Practicable Resource Potential** which is the proportion of energy that is extracted after the removal of impracticable locations for installation. Practicable OTEC locations are within the EEZ maritime zones and within 100 km distance from grid cells with population densities of more than 500 people/km^2. The later assumption is derived by a similar worldwide resource assessment that Professor Kornelis

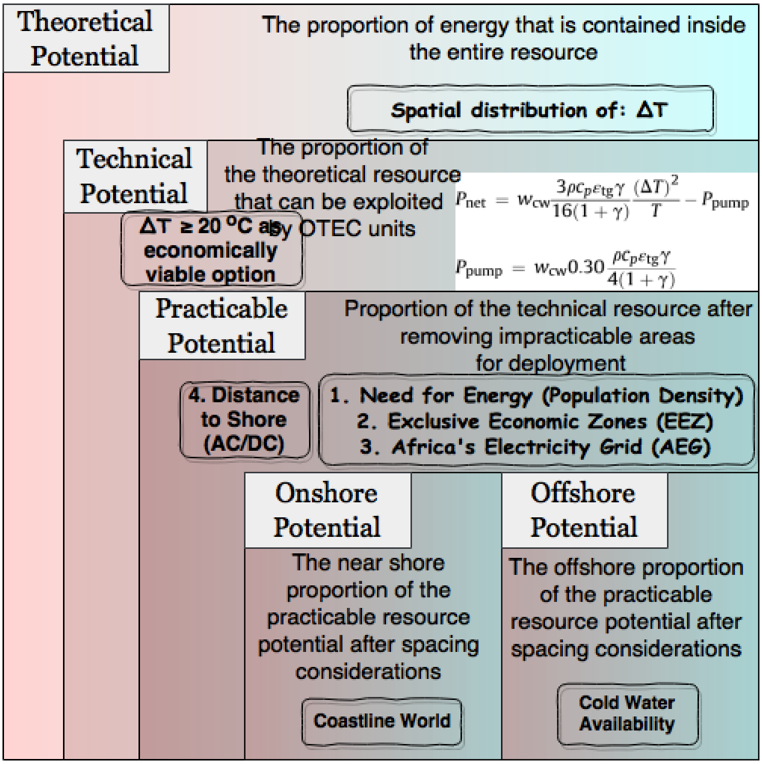


Figure 2.16: Resource Potential Cascading (Theoretical>Technical>Practicable>On/Off-shore)

Blok recommended [13]. In addition, the electricity grid of Africa will be used since in that case, population does not match the need for energy as described above. In the end, the distance proximity to the shorelines is also examined in order to derive a decision on the cable type deployment (AC/DC).

4. **Offshore Resource Potential** which appears as the offshore part of the practicable resource potential after applying spacing considerations. Nevertheless, the spacing aspect is more complex in this case since the cold water availability needs to be taken into account as discussed above.

5. **Onshore Resource Potential** which represents the near shore resource potential after the units are spaced properly. OTEC units require a distance of at least 4 km to be apart in order to prevent thermal energy degradation. In contrary, distances smaller than this, will lower the performance of both units.

Categories like the above mentioned, are like labels or tags that provide an extra level of hierarchy. In numerous renewable energy studies, this kind of resource cascading is very important since most of these sources are intermittent (solar, wind, etc).However, OTEC technology, offers a stable electricity production with a capacity factor of up to

100%, but it strongly depends on other physical and spatial density aspects. These aspects therefore are examined and evaluated through the unified decision framework and the resource categorization above.

undoubtedly, this study is the first (identified) attempt towards organizing properly the OTEC resources, in the direction of discovering potential locations for deployment. Therefore, the chapter below establishes a distinguishable spatial methodology, following the resource hierarchy proposed above in this section.

3

METHODOLOGY

The methods and the relevant tools needed while conducting a spatial distribution analysis are presented thoroughly in this chapter. Resource potential studies require the collection and management of a vast amount of information. ArcGIS software offers the opportunity to manage such spatial information, find patterns and extrapolate results. In detail, seawater velocities and bathymetry data combined with the ocean temperature profile provide the basis of this OTEC assessment. In addition, information related to maritime regions (such as EEZ, Distance Proximity, Population Density, etc) is also necessary for underlying the practicable potential of OTEC around the world. However, it is evident that also other factors might affect a project's feasibility related to the location of an OTEC unit and therefore they are equally investigated in this study.

3.1. Research Scope & Methods

To begin with, the research approach is discussed in this section where the scope and the methods of this study are presented. In specific, the relevant literature review conducted beforehand, offered significant guidance for composing this thesis research project. The literature review includes information that is necessary for the OTEC technology description and the resource potential "state of the art" studies. In addition, scientific papers and reports on successful OTEC case studies that were reviewed focused also on demonstration and early-stage projects. In other words, the above-developed overview of various results related to estimates for mapping OTEC resources, provided essential insights towards the composition of the research scope of this study.

3.1.1. Research Scope

A number of scientific articles was used to describe the different OTEC resource assessment studies which was used as input for the theoretical decision framework in chapter 2. This framework is guiding the quantitative analysis of this study where the subsequent criteria classes are described and used for the resource potential categorization (see Chapter 2 figure 2.16). Both original articles and more recent literature references are becoming a necessity for this step. Moreover, the research boundaries of this study are the deltas and all the coastal, remote and isolated regions of our planet. Locations outside the Exclusive Economic Zones (EEZ) of these regions, could be also used as desalination, methane, and hydrogen production facilities serving more than one country at the same time. This scenario though is sensitive to thermal degradation as described in the previous section, and therefore, it is considered as the least probable for the deployments in the near future.

3.1.2. Research Methods

The research methods used in general are an extensive literature review (see chapter 2), the discussion with the Professor Nihous and a quantitative spatial approach. The literature review is essential for exploring the existing written knowledge about a specific scientific topic. During this research, published papers along with books are utilized properly in order to describe the alternative approaches discovered so far. Professor Gerard Nihous, has been publishing advanced (worldwide and localized OTEC) resource assessments related to OTEC for more than 10 years (The assessments are present in: [46], [47],[48],[49],[50]). In addition, research for OTEC technology's present status ([44], [62], [2]) and supplementary information around OTEC potential resources ([37],[39],[63],[55]) will be also used for additional support on the research findings.

However, this study takes also into account the aspects that could affect the OTEC sustainability in case of large-scale operations. While most similar studies show explicit attention on the resource estimates with the overall long-term effects that follow large-scale operations, this study provides a spatial methodology through a flexible interface, essential for evaluating local potential resources in the near future. This aspect along with the ability to reproduce any of the results by altering the assumptions is an exceptional element that this research provides.

Finally, modeling the technical, practicable, onshore and offshore resource potential in ArcGIS software, is the direct methodology used predominantly. In more detail, the modeling procedure below is following the resource potential categorization developed in the previous section (see figure 2.16). Thereafter, the objective is to develop a market expansion scenario using the results from the spatial distribution analysis and in the end, define a follow-up agenda to stimulate even further research in this field. Subsequently, the following section with the proposed spatial approach introduces the quantitative methodology that guides this assessment.

3.2. INTRODUCTION TO GIS & REMOTE SENSING

THE GIS initials stand for Geographical Information System which is used as a useful tool needed for the examination of spatial information. ArcGIS in specific offers a distinctive set of instruments which enclose many capabilities for an advanced location-based assessment [16]. The software was developed in the late 70's and nowadays it is used for a wide variety of applications including urban planning, natural hazard analysis, geological and mining engineering, ocean surface flux analysis, etc [31]. Spatial Data refers to where things belong, or perhaps, where they were in the past or will be in the future. To be more precise, the outcome of a study that utilizes spatial information would be the effective management of the geographical space relative to the Earth's surface [31].

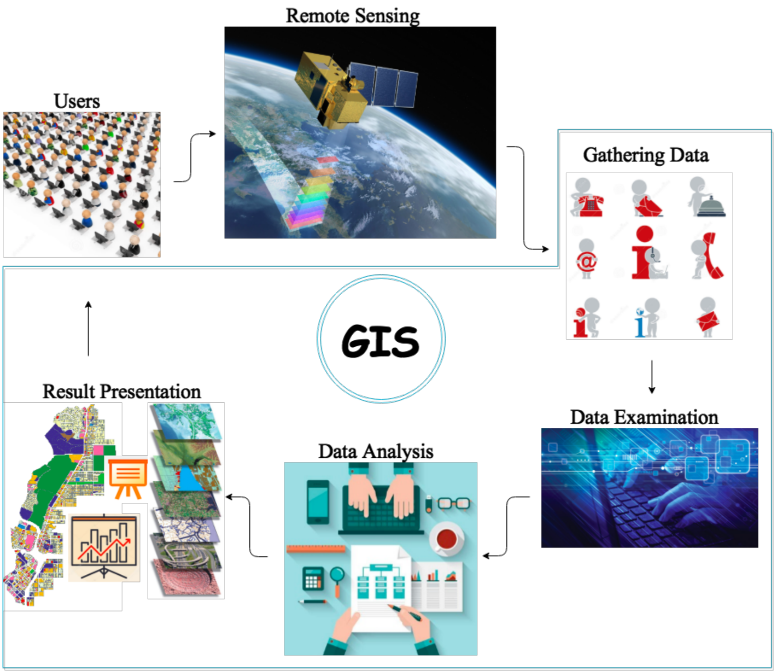


Figure 3.1: Processing steps of Geographical information from a GIS software. Accessed and adapted from Kartalis and Fidas (2013) [35]

ArcGIS software is used predominately throughout this research for the purpose of calculating and mapping the resource potential for OTEC. In other words, the software is necessary for such an analysis since OTEC deployment requires location-based indicators which raise spatial density concerns (Chapter 1, figure 1.2). The software's package also provides spatial query tools built into ArcGIS's interface for analyzing spatial data layers. In more detail, a geo-spatial software such as ArcGIS, collects and confirms the quality of information, examines and stores it in the form of databases or maps, updates and changes while managing and exchanging information with other users and eventually it compiles and presents the combined results in an advanced interface (see figure 3.1).

Within the last years, these tools have become more sophisticated turning the raw data into a high-quality end product. ArcGIS offers access to the world's largest imagery collection in parallel with advanced modeling in order to accommodate satellite imagery, lidar information, and 3-D spatial models. It is a sophisticated tool that manages spatial information and therefore, uplifts the exploration of geographical data while increasing our knowledge regarding our planet's behavior [16]. This information can be connected in such a way that allows deeper spatial understanding while offering explicit mapping results.

Therefore, the spatial step by step approach as presented below is chosen as the framework that guides the analysis of this research, for a proper spatial classification during the data management and analysis steps. This framework is also identified in the guiding manual of Maarten van't Zelfde and Dr. Niels Raes which is accessed through the university's informational system [67].

3.3. Spatial Approach

The following 5 steps of the Geographical Approach that are used throughout the entirety of this project include [25] (see figure 3.2):

1. Ask-Problem Definition
2. Data Acquisition/Collection
3. Data Management/Examination
4. Spatial analysis and modeling
5. Act

3.3.1. Ask-Problem Definition

The problem as it is also mentioned in Chapter 1 is to identify the possible OTEC locations for installation which are under specific technical and practicable criteria while using the ArcGIS software. The locations investigated for this analysis (spatial boundary) are all the countries that have a viable potential for exploring OTEC resources. These countries are within the tropical waters spreading from the equatorial line to, respectively, 20°N and 20°S [63]. These countries including major industrialized nations such as the USA and Australia have a considerable resource potential within their Exclusive Economic Zones (EEZ). Additionaly, an extensive list dated from the 1980's is present in the Appendix A in figure 1, with all the nations and territories which have adequate OTEC resources [63].

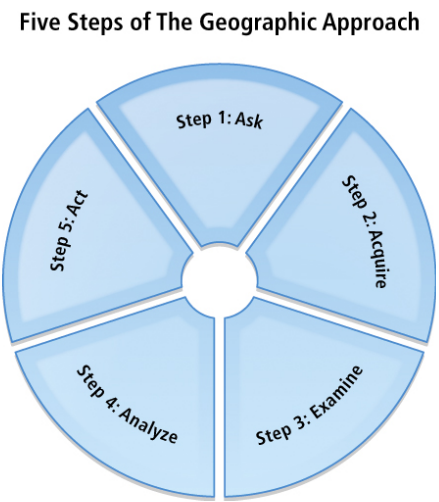


Figure 3.2: 5 steps of Geographical Information Systems [25]

Moreover, the nations that have adequate thermal resources, have the ability through this study, to explore this clean and renewable source of energy and in extent de-carbonize their industries. Many countries around the equator have prosperous resources in a very close proximity to their shore and therefore, the exploitation of this stable energy could provide affordable electricity to these coastal communities. In the end, nearby locations could potentially benefit from such installations through a symbiotic relationship with countries that show excessive OTEC electricity output.

As a conclusion, the stakeholders directly involved in this thesis dissertation are the Leiden University, the Delft University of Technology and Bluerise B.V. The later partner was also responsible for providing any further databases or tools which could bring additional value to this study. The closest cooperation nevertheless, was with the GIS expert of Leiden University; Maarten van 't Zelfde. Some additional and quite credible information was also provided by the Associate Professor Gerard Nihous who is investigating OTEC potential resources worldwide for many years. Therefore, his expertise on this topic was more than valuable on proceeding with the data collection, examination and analysis.

3.3.2. DATA ACQUISITION/COLLECTION

The data requirements include tasks such as the identification of regions with an adequate depth of 1062m, locations with adequate temperature difference and locations that are subject to appropriate practicable criteria. Therefore, the location criteria are organized in a manner that allows the distinction between the theoretical, technical and practicable potential of OTEC resources around the world. In detail, the theoretical and technical potential requires temperature profile data and the practicable potential requires the application of offshore marine zones and population density estimates. This information which is discussed below in further detail is present online without any restrictions.

TEMPERATURE PROFILE DATA

Initially, information is needed for the temperature profile of the ocean at approximately 30 and 1060 meters depth. This information is present in the databases of Copernicus Marine Environment Monitoring Service (CMEMS) [7]. CMEMS updates the core reference data on the state of the physical oceans and regional seas frequently and systematically. The dataset preferred for this spatial analysis is the one that: covers all the oceans around the world, has high-resolution values and adequate depth level information and it is thoroughly updated for at least the last 10 years. The search engine of CMEMS product catalog found 12 products matching the above-mentioned criteria [8].

In more detail, one of the products;"GLOBAL_ANALYSIS_FORECAST_PHY_001_024", offers a set of aggregated analysis updated daily with information regarding, salinity values, potential temperature and speed currents for different depth layers of the global ocean [52]. The horizontal resolution is at 1/12°=0.083 degrees (≃9km) and the vertical resolution is at 8km, ensuring a better consistency between the statistics of the different regions and higher quality of analysis. The resolution with a grid size of 4320x2041 was the highest among the rest of the products. For a better understanding regarding the climate modeling resolution, information can be found in Appendix B in figure 2.

Moreover, the datum coverage used is between 01/01/2007 and 01/01/2016 (10 years) which increases the accuracy of the analysis. The potential temperature profile downloaded, holds information for two ocean depth levels: 29.44 meters and 1062.44 meters which are the depth layers interesting for an OTEC resource assessment [52]. Lastly, for the extrapolation of the OTEC spacing map in chapter 4 and in extent the refined offshore and onshore potential (sensitivity analysis in chapter 5), seawater velocities are used at 1062.44 meters depth, represented by a 2-year average (2007-2008, Copernicus).

For the technical potential, it is essential and elegant to calculate the power density for the OTEC locations that reach higher temperature differences. Since OTEC's thermodynamic efficiency is quite low, temperature differences of: $\Delta T \geq 20°C$ are chosen as the limit of economically viable installations. Therefore, the power density serves as a "groundwork" model for calculating all the potentials for OTEC resources (Technical, Practicable, Onshore and Offshore potential). As a result, the formula (3.1) below will guide the distribution analysis and it is useful during the table calculation within the software in Chapter 4. This formula is identified in many research papers in previous studies including professor's Nihous publications ([49],[50]).

$$P_{net} = w_{cw}\,\rho\,\epsilon_{tg}\,c_p \left\{ \frac{\Delta T^2}{8T_{surf}} - \frac{1}{20} \right\} \quad [MW/km^2] \tag{3.1}$$

The potential power density of OTEC is depending on the temperature difference ΔT and the seawater surface temperature T_{surf} in degrees Kelvin, the water volume flow rates per year w_{cw} in meters/year, the specific heat of seawater c_p in Joules/Kilograms*Kelvin, the seawater density ρ in kilograms/m^3 and the turbo-generator efficiency ϵ_{rg}, an absolute number. The pump consumption of the OTEC unit has also been taken into account as 30% of the total in the formula mentioned above [51]. Finally, these values will be also used for assessing the total potential by multiplying them with the total OTEC implementation area each time and then add all these values to extract the total power output.

SUPPLEMENTARY SPATIAL DATA

Regarding the practicable potential (see figure 2.10), it is essential to find alternative information which produces better decisions related to the potential of OTEC technology. For example, OTEC regions within the Exclusive Economic Zones (EEZ) of each country should become the first priority for deployment. In addition, the population density can also provide an initial estimate on where OTEC could offer sufficient electrical supply. In the case of Africa however, it is not always certain that the population density follows the need for energy. Therefore, for the African countries which have sufficient OTEC resources, the electricity grid is used instead of the population density.

In more detail, the population density database is accessible through NASA's Socioeconomic Data and Applications Center (SEDAC) without any restrictions [58]. Furthermore, the Exclusive Economic Zones (EEZ) polygon file of all maritime nations can be found also online in Marine Regions which is an integration of the VLIMAR Gazetteer and the VLIZ Maritime Boundaries Geodatabase [42].

Regarding the onshore and offshore potential of OTEC, which is also the last step of the analysis, spacing aspects need to be taken into consideration. In the case of onshore OTEC deployment, the units are spaced at approximately 4km away from each other in order to prevent thermal degradation of the potential OTEC farm (with 0.075 m/s current speed) [6]. Furthermore, the distance from the shoreline to the resource potential is set to 9 km. In other words, this distance is derived if half the resolution of the present study -which is approximately 9 km- is added to the maximum length of the installed cold water pipe which theoretically (based on economic indicators) should not exceed 4 km away from the coastline ($0.5\times$ Resolution + 4km (Length of pipe) $\simeq 4.2+4 \simeq 9km$). In the case of offshore resources, the spacing range is regulated according to the availability of deep cold water resources. Likewise, in the report of the U.S. Department of Energy [37], there is a specific attention to this aspect which appears to have significant importance for OTEC's sustainability.

In fact, the methodology described in the previous study is being utilized for the extrapolation of a power output of 100 MW spaced plants, in accordance with the deep seawater velocities. Details related to the exact spacing values and the availability of the cold water basin are mentioned in chapters, 3, 4 and 5 where the sensitivity analysis also takes place for the calculation of a refined offshore and onshore resource potential.

Finally, the files are formatted into points (spacing, onshore and offshore potential), polygons (countries, potential, OTEC offshore distance, exclusive economic zones), poly-lines (coastlines, Africa's electricity grid) and NetCDF files (the temperature profiles and the seawater velocities). Thereafter, these different formats are managed and structured in an organized manner within several personal geo-databases, for the accessibility of the data and the modeling procedures.

3.3.3. DATA MANAGEMENT/EXAMINATION

The nature of the data downloaded from the Copernicus Marine geo-database creates a few first-to-order challenges. However, the ArcGIS software has the associated tools to manage this type of data format, commonly known as NetCDF files. The NetCDF (Network Common Data Form) files are a set of libraries or machine-independent data formats that offer the creation and the accessibility of array-oriented scientific data [56]. In reality, NetCDF files are quite useful and flexible formats that can be utilized for advanced scientific research. In the end, the storing of the data, after transforming them to raster layers, is taking place in several geo-databases (.gdb) for efficient recall and management. More details for this project's geo-databases will follow in Chapter 4.

The rest of the data created or found online, will be stored respectively in shapefiles, raster layers, points as databases, map files (.mxd, .tiff) and excel file (.xls). The conversions that are needed are mainly transforming a raster to a polygon, a point to a raster, attribute join by location or spatial join, raster calculations such as cell statistics, overlay, mask and clip. An adequate description of these tools will also follow in Chapter 4 and in the respective appendices.

3.3.4. SPATIAL ANALYSIS

The spatial distribution analysis is described in this section but a more elaborated segment of this project is employed to describe the modeling procedure. In the spatial analysis in Chapter 4, detailed flow charts will indicate all the steps towards the development of the resource potential assessment. It is now evident that each resource category has its own flow chart processes and associated tools. Moreover, a simplified chart as the one below in figure 3.3, is helpful for understanding the entire project flow.

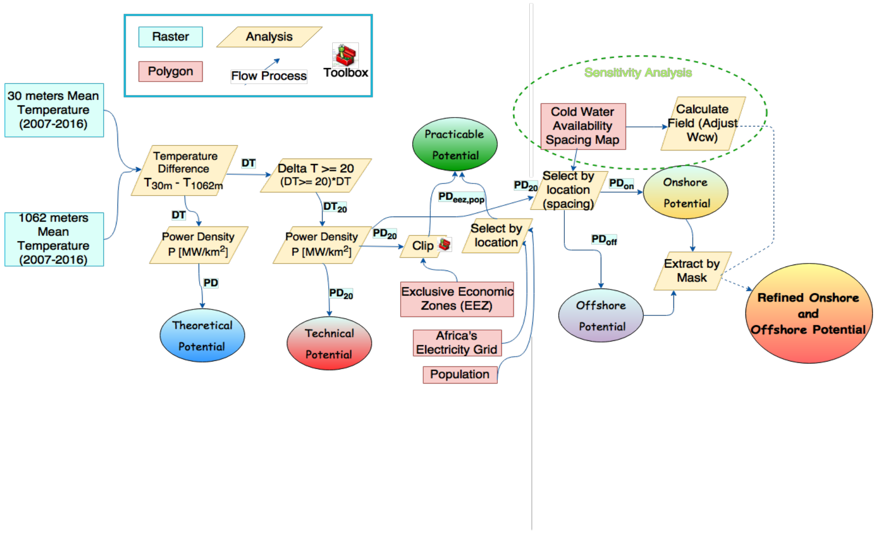


Figure 3.3: Simplified Analysis Flow Chart

In detail, the spatial distribution analysis incorporates processes such as limiting the resource potential (with "Clipping" and "Masking" GIS tools) and executing spatial join, wherever is necessary. In addition, the application of constraints derived from the data requirements above is essential, along with the determination of the power produce of OTEC resources (calculating the net power density with the formula (3.1) above and the tool "Calculate Field"). In the end, spatial join with the countries that have potential for OTEC is executed for extrapolating the Onshore and Offshore potential.

In the end, spacing estimates are analyzed with the help of another function in ArcGIS ("Create Fishnet" tool) which creates evenly spaced points for the determination of the adjusted offshore and onshore potential. This modeling process is taking place in the sensitivity analysis in chapters 4 and 5. Labeling the maps and preparing it with the proper annotations are some of the last details, where the latter is useful to extract remarkable visual elements. Lastly, the tables with the resulting OTEC resource estimates of each country are present in the subsequent sections in Chapter 5.

3.3.5. Act

Finally, a follow-up agenda is vital in order to represent and utilize further the outcomes of this study. Initially, the objective is to compose several resource potential scenarios (Worldwide, 100km, Onshore, etc) derived by the spatial analysis which in the end will reveal additional insights regarding the development of a short-term deployment plan. This step should not be neglected since it is a crucial part of the analysis and it should reflect in the best way, the outcomes of such a visual project.

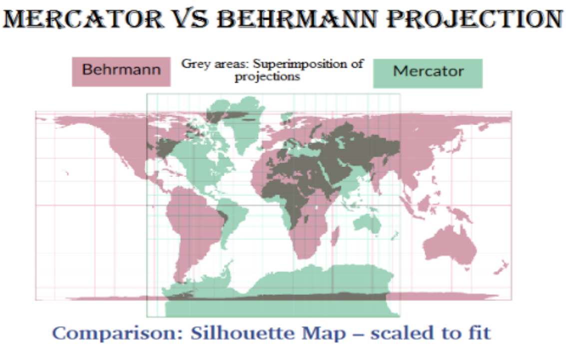
4

DISTRIBUTION ANALYSIS

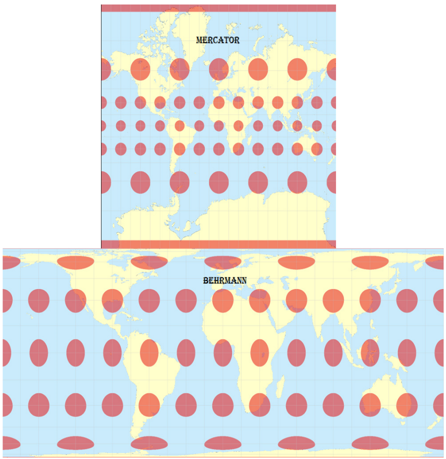
This Chapter is dedicated to the spatial distribution analysis of OTEC resources that are organized in a distinguishable manner for a better understanding and decision making. Initially, the theoretical and technical potential is analyzed and all the associated processes and tools involved are described in detail. Afterwards, the practicable potential will follow, where "state of the art" criteria are used including Exclusive Economic Zones (EEZ), Population Densities (PoD) and Africa's Electricity Grid (AEG). However, the most important objectives of the GIS analysis is the ability to achieve higher accuracy and reproducibility. Reproducibility is the ability of an entire analysis of an experiment or study to be duplicated, either by the same researcher or by someone else working on the same experimental configuration. Therefore, the analysis is structured within the "model builder" function of ArcGIS in order to reproduce the results and higher accuracy is achieved by applying the Behrmann projection for the calculation of OTEC implementation areas.

4.1. QUEST FOR ACCURACY WITH BEHRMANN PROJECTION

ONe of the exceptional features of this study, is the use of a different map projection which brings higher accuracy to the resulting estimates. The current data projection (WGS_84) stretches and in extent distorts the areas especially along the equator where most of the data points of this OTEC analysis belong. It represents, the typical version of the worldwide 2-D map found present almost everywhere in the literature. In reality, it is not feasible to prevent these deformations but it is possible to minimize them by choosing a different projection that comes in parallel with the needs of a project. The quest of a projection that will bring higher accuracy within the corresponded OTEC areas, had consequently just begun.



(a) Differences between Mercator and Behrmann Projection System based on a scale to fit basis [40]



(b) Differences between Mercator and Behrmann Projection System based on the Tissot Indicatrix, 30° [40]

Figure 4.1: Differences between Mercator and Behrmann Projection System

Map coverage is essential for performing any type of important and valid queries in several GIS practices. Generally, there are 3 type of projections: Conformal, Equal-Area and Equidistant. When performing a spatial analysis similar to this which requires "strict" area calculations, the Equal-Area Projection is more than reliable and therefore necessary in order to reduce the amount of distortion [66]. According to the same source, the Equal-Area projections which are useful for increasing the area calculation accuracy, are divided into three "ideal" projections: Albers, Behrmann and Sinusoidal. Unfortunately, many GIS users disregard these important details and in extent ignore the area distortions probably due to their lack of awareness. The Mercator projection used as default in many cases has differences with the Behrmann projection that can be also identified above in figures 4.1a, 4.1b. This offers a better understanding on how the area calculations may significantly deviate.

In fact, during the analysis below, the data was projected using the Behrmann projection for the OTEC area calculations. In comparison with the other two projections mentioned above, it offers the most accurate results with the least area distortions according to the same publication. These figures can be also identified in the illustration 4.1b above with the Tissot Indicatrix. In cartography, a Tissot's indicatrix is a mathematical contrivance presented by French mathematician Nicolas Auguste Tissot in 1859 and 1871 in order to characterize local distortions due to map projection [40]. In detail, Behrmann projection is always suggested for analyzing regions of up to 500 km^2 and it preserves the area calculation differences under 500 m^2 [66]. In the case of OTEC, the implementation area is far larger than 500 km^2 and therefore it provides better estimates in comparison with the Mercator projection.

4.2. THEORETICAL POTENTIAL ANALYSIS

SIte conditions as described above, are considered to be one of the most important factors regarding OTEC installations, especially if the theoretical resource potential (ΔT distribution), is taken into account. It is this temperature difference between the ocean surface and 1km depth that drives this potential and therefore, it is the key to identify it as well. Therefore, the initial modeling procedure is presented below along with the associated charts that indicate the flow of the process.

The initial temperature field used for this analysis is representing a 10 year average (2007-2016) in order to arrive in a better estimate for the potential OTEC resources. The first flow chart in figure 4.2, is dedicated only on transforming the current data format (NetCDF into raster layers) and identifying the mean temperature values and differences. For the next step, it is necessary to utilize the formulas within the ArcGIS environment. In specific, the spatial analyst tool "Cell Statistics" and "Raster Calculator" are predominantly used along with the "Make NetCDF Raster Layer" tool. In detail, the "Raster Calculator" tool is a calculus interface which performs map algebra expressions derived by the user. On the other hand, the "Cell Statistics" tool calculates a per-cell statistic from multiple raster layers. This is also the final objective of this first step: A 10 year averaged temperature raster layer with embedded spatial information.

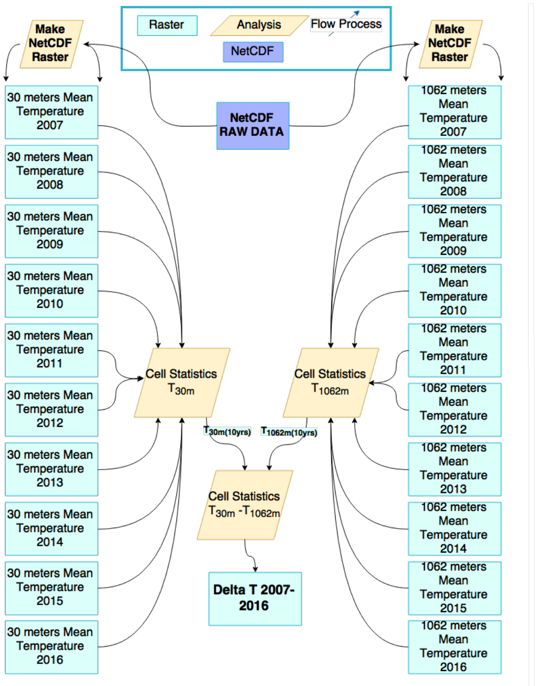


Figure 4.2: Analysis Flow Chart to calculate the 10 year temperature average (2007-2016)

Going further within the modelling of the resource potential, calculating the Theoretical Power Density becomes an inevitable necessity. Particularly, the formula (3.1) in Chapter 3 is used for the determination of the net power density where each cell of the resulting raster represents the power that can be extracted from each area in Watts per square meter (W/m^2) (the calculations and the assumptions used in detail, follow at the Appendix C). Consequently, this calculation results in a map (geographical grid), which consists of a matrix of cells (or pixels) organized into rows and columns, where each cell contains a power density value.

Next and in order to extract further information from the raster layers (raster power density), it is important to convert it into a more manageable format. A polygon format is able to store data with discrete geographical boundaries. This is achieved with the ArcGIS tool "Raster to Polygon", a spatial conversion that accepts only an integer type raster. This is the reason for calculating the Integer Power Density beforehand (see figure 4.3 below). Within the power density polygon file ($\text{ThPD}_{\text{polygon}}$), the data are organized in feature classes which are tables with special fields that comprise supplementary information about the geometrical properties of the features ("Attribute Tables") [24]. Now, it is possible to add and calculate additional information within the attribute table of the polygon file, by using specific ArcGIS functions ("Add Field" and "Calculate Field").

The above mentioned ArcGIS capability, provides a unique opportunity to calculate the total power of OTEC resources for each geographical area. In detail, this is achieved by multiplying the power density value with the implementation area field of each polygon, within the attribute table. Afterwards, a useful ArcGIS function is utilized, in order to aggregate all the features based on definite attributes ("Dissolve" tool). In other words, this tool is used to collapse all those values in one single row which will represent the aggregated OTEC power estimates (in Terra Watts). Lastly, the attribute table can be extracted as an excel file (see figure 4.3 above), in order to obtain the overall net power produce along with the total OTEC implementation area.

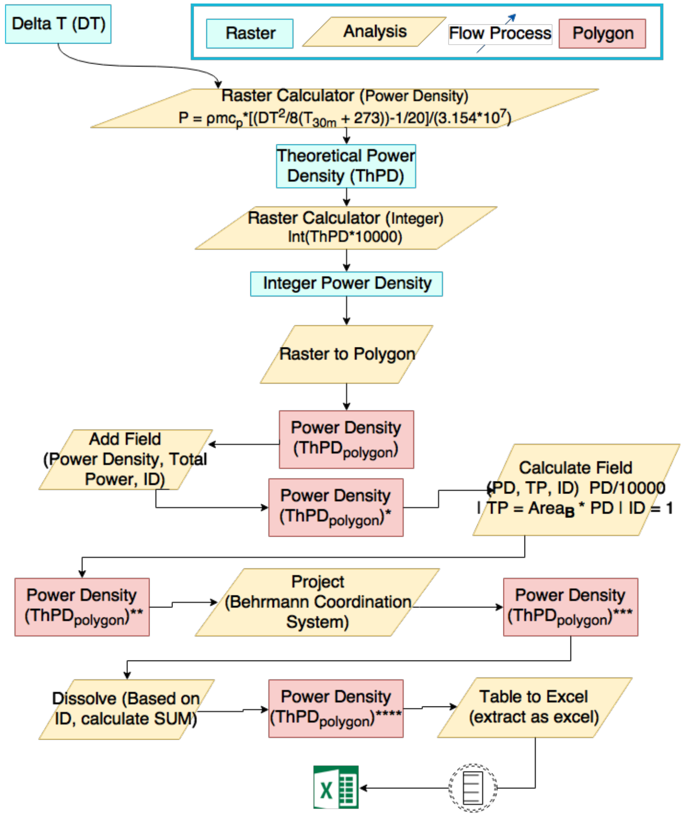


Figure 4.3: Analysis Flow Chart for the calculation of the Theoretical Power Density (ThPD)

4.3. TECHNICAL POTENTIAL ANALYSIS

Likewise, the Technical Power Density is derived in a very similar way following the same strategy, with the only disparity to be, the refinement of the temperature difference ΔT. Technically, it is only viable to extract energy from temperature differences of $\Delta T \geq 20°C$ since in any other case, the OTEC engine efficiency will drop below 3% making the resource unreliable [50]. As mentioned explicitly in chapter 2, a temperature difference of $\Delta T = 11°C$ will drop the net power density to almost zero. Therefore, the OTEC implementation areas are expected to be more limited in comparison with the results of the theoretical power density above.

Under this study, the ΔT value that was decided to represent the technical potential is just above 20°C. Beginning from the upper part of the flow chart in figure 4.4, the ΔT raster layer is used as the initial input, for all the following power and area calculations. Thereafter, the same function is used as before in order to constrain the temperature difference at $\Delta T \geq 20°C$ ("Raster Calculator" tool). In detail, the threshold is created by performing a "Conditional Evaluation" (via Spatial Analyst) which manages the output value for each cell based on whether the cell value is evaluated as true or false in a specified conditional statement [18]. In this case, this tool examines each cell's location and based on the ΔT value, controls if the cell is assessed as a true or a false statement (Is the $\Delta T \geq 20°C$ in that cell?) and in extent keeps or discards the cell during execution. Nonetheless and as discussed explicitly in chapter 2, the 20°C limit for the OTEC resources is not a "strict" condition. In reality, other thresholds could be depicted in the future as the technological development of the heat engines, continues to evolves.

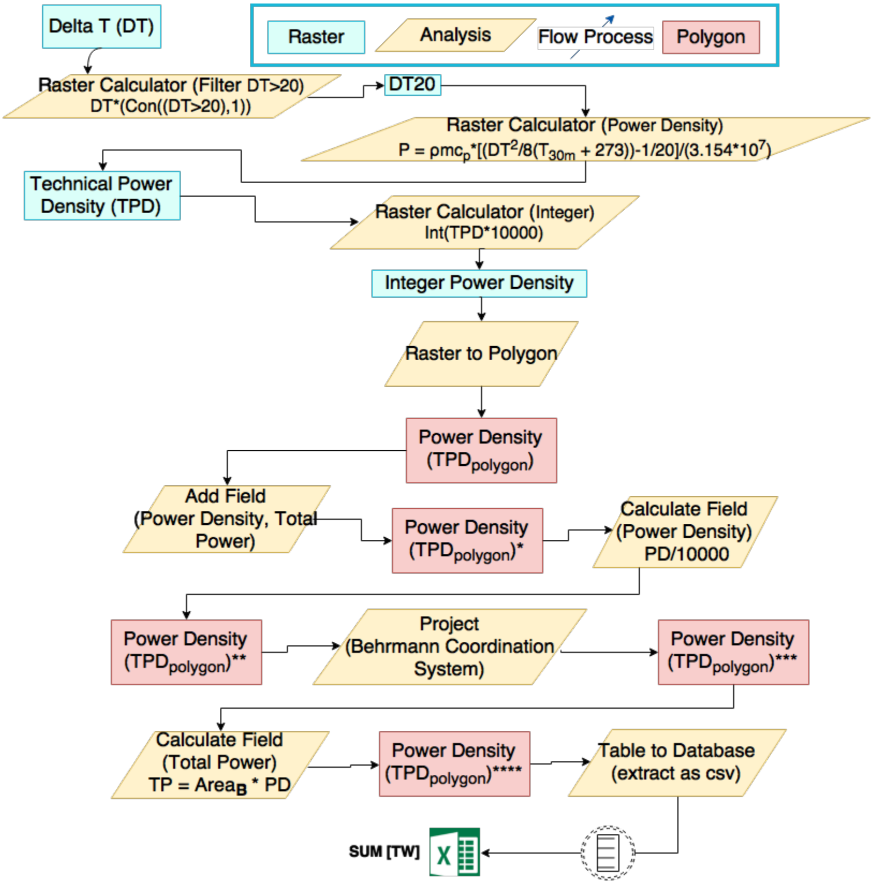


Figure 4.4: Analysis Flow Chart for the calculation of the Technical Power Density (TPD)

The rest of the procedure is exactly the same as executed during the theoretical potential calculations above. The Technical Power Density (TPD) is calculated in accordance to equation (3.1), the raster is transformed into a polygon and the total power field is added to the Attribute Table. Likewise, the Attribute Table is extracted as it is shown in figure 4.4 as an excel or csv file, for the calculation of the technically feasible net power produce.

4.4. PRACTICABLE POTENTIAL ANALYSIS

Several studies in the past use alternative criteria to develop a local resource assessment for the regions that are practically feasible for deployment. As it is also mentioned before (see Chapter 2), the criteria used for this study, offer an advanced and pragmatic analysis. In summary, the additional information (data layers) used for the extrapolation of the results are: The Exclusive Economic Zones (EEZ) polygon, the Population Density (PoD) raster, the Africa's Electricity Grid (AEG) polygon and the Shore's polyline. It is important to point out that the complexity of the calculations increases at this point and therefore, the projected flow charts that are following below, are more indicative rather than detailed.

In specific, the complex flow chart (in figure 4.5 below) is guiding the analysis in this section where the practicable criteria are used in accordance to the assumptions below:

1. Regions within the Exclusive Economic Zones (EEZ) of each country,
2. Regions with 100 km distance from Population Densities (PoD) of at least 500/km^2,
3. Regions in Africa within 200 km distance from Africa's Electricity Grid (AEG),
4. Regions with distance from potential smaller than 15 km ⇒ Low Voltage AC cable,
5. Regions with distance from potential of 15-70 km ⇒ High Voltage AC cable,
6. Regions with distance from potential greater than 70 km ⇒ High Voltage DC cable

These assumptions are essential for developing a realistic short-term scenario while in parallel ensuring a stable and reliable performance of the deployed units. Lastly, the AC/DC cable decision will affect the OTEC installation costs and the infrastructure conditions and therefore, it is an important aspect for the determination of the near-shore or offshore resource potential.

Regarding the structure of the flow chart in figure 4.5, the Technical Power Density (TPD) raster is used as the primary input for this modeling procedure while the EEZ boundaries are restricted to the OTEC implementation area for a faster execution ("Extract by Mask" tool). This function is used to extract only a proportion of the Technical Power Density raster layer that can be found within the EEZ boundaries of each country. In reality, it provides an output raster layer outlined by a mask or a cover [22]. Thereafter, a similar technique is used as above, in order to transform the raster to a polygon layer ($TPD\_EEZ_{polygon}$). Moreover, the ArcGIS data management tool "Make Feature Layer" which offers additional modeling properties, is an inevitable step essential for the continuation of the process.

Furthermore the model proceeds with the selection of the potential that has 100 km distance from population densities of at least 500 people/km^2. The ArcGIS tool "Select Layer By Location", chooses the features from a layer depending on a specific spatial relationship that two or more layers share [23]. In this case, the spatial relationship is be-

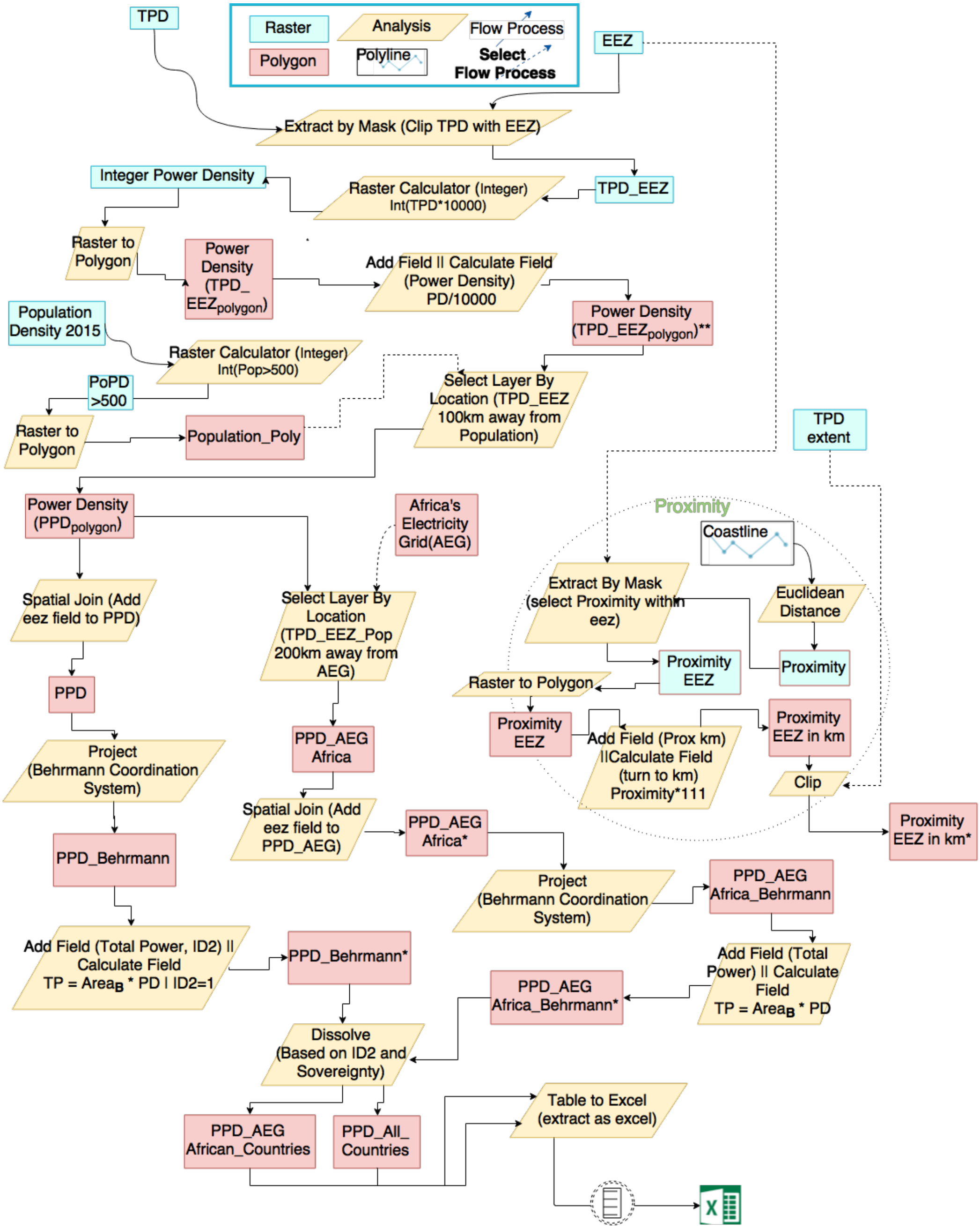


Figure 4.5: Analysis Flow Chart for the calculation of the Practicable Power Density (PPD)

tween the Population Density (PoD) and the polygon layer TPD_EEZ$_{\text{polygon}}$ (illustrated in figure 4.5). Later, the same tool is used once more for the selection of features that show power density values, only within 200 km distance away from Afica's Electricity Grid (AEG). In the end, a similar process is used for the calculation of the OTEC implementation areas and the total OTEC power output. The extraction of the practicable resource potential for the whole world and for the case of African countries is taking place separately, by using similar tools as above ("Dissolve" and "Table to Excel" tool), where the latter exports the tables from the feature layers as excel files.

ARCGIS ADDITIONAL TOOL ANNEX

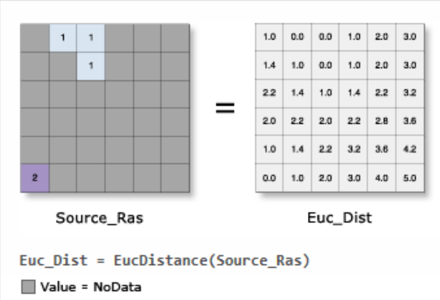


Figure 4.6: Understanding the ArcGIS tool "Euclidean Distance" through an illustration [21]

As described also above, an additional element present in this study, is the classification of the electricity cable that is proposed for the OTEC energy transfer. Therefore, as it is shown in figure 4.5 above, the proximity calculations are more than necessary for making such a decision. In detail, the coastlines of the world are employed as an input for this process and an ArcGIS function is used to append a specific distance ("Euclidean Distance" tool [21]). While in execution, this tool reports each cell's relationship to a source depending on a straight-line distance as it is shown in the adjacent image 4.6.

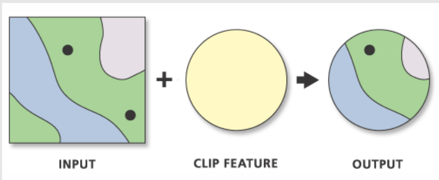


Figure 4.7: Understanding the ArcGIS tool "Clip" through an illustration [17]

However, the ArcGIS tool above provides proximity values for all the cells within the map (inside and outside the coastlines of the world). As a result, it is reasonable to only keep the proximity values that fall outside the shoreline and discard the ones that are located inshore. For this reason, a practical ArcGIS tool ("Clip") is used along with the ocean polygon as an input, in order to choose only the offshore proximity values. The tool is applied predominately in various GIS applications and it is useful for cutting a piece of a feature layer by using one or more features from another layer [17]. The figure 4.7 offers a detailed illustration on how the tool functions. In the end, the same tool is used additionally to clip the practicable power density map with the offshore proximity and thus, provide distance information for the area of interest (see Chapter 5).

4.5. OTEC PLANT SPACING ANALYSIS

THE importance of the cold water availability in the assessment of positioning properly the offshore OTEC units, is increasing since the risk of thermal degradation is explicitly considered by previous studies. In this direction, the study carried out by Lockheed Martin (2012) as mentioned before in chapter 2, is establishing an advanced methodology for determining a practicable spacing range [37]. This method is used during the sensitivity analysis for the extrapolation of a spatial map that defines the proper offshore OTEC spacing, based on the cold water availability in 1062m depth.

To continue with, the seawater velocities at 1062m depth are used in a similar way as the mean temperature values were calculated above, representing a 2 year average. In reality, the deep sea water velocity values do not appear to have significant deviations and therefore, the resulting accuracy is sufficient. Thereafter, the formula $V_{in} = \sqrt{V_{EW}^2 + V_{NS}^2}$ is utilized with another ArcGIS function ("Raster Calculator"), in order to calculate the proper velocity vector values with the help of the Pythagorean theorem. Next, the raster layer is transformed into a polygon and a new field is added as shown in the flow chart below.

In the end, the Δx values are calculated in order to classify the final spacing ranges (flow chart 4.8). For this step, the formula (2.3) in chapter 2 is used to append one unique spacing value for each cell. Then, the spacing ranges are derived for the extraction of the proper distribution map depending the cold water availability in 1062m depth. This is also the final step towards the development of a refined offshore power density that follows in the sensitivity analysis in chapter 5.

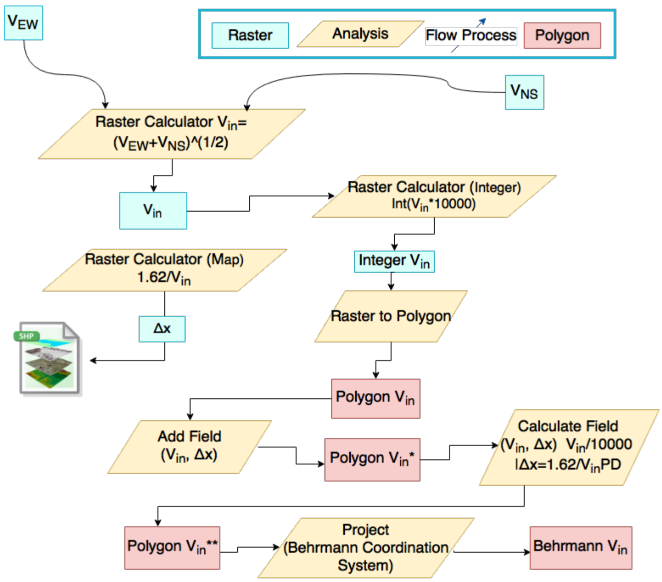


Figure 4.8: Analysis Flow Chart for the determination of the OTEC spacing map

4.6. OFFSHORE POTENTIAL ANALYSIS

Continuing further with the distribution analysis, the offshore potential along with the corresponded spatially spaced points are being determined after following the modeling procedure in this subsection. As it is evident from the flow chart below (see figure 4.9), everything begins with the the use of the cold water availability polygon layer. In specific, this map holds information about which locations correspond to greater or less cold water availability in 1km depth by providing OTEC unit spacing estimates. These estimates are divided into 6 subsequent categories:

1. Locations where the spacing between OTEC units should be between 0-50 km,
2. Locations where the spacing between OTEC units should be between 50-100 km,
3. Locations where the spacing between OTEC units should be between 100-150 km,
4. Locations where the spacing between OTEC units should be between 150-200 km,
5. Locations where the spacing between OTEC units should be between 200-250 km,
6. Locations where the spacing between OTEC units should be greater than 250 km

In reality, the objective in this section, is also similar to the previous modeling processes: The identification of the offshore power density (OffPD) and in extent the determination of the total offshore power output. For this purpose, the raster layer Technical Power Density (TPD) calculated above is used as a process input. However, the Practicable Power Density (PPD) restricts the potential within the EEZ boundaries while in reality the OTEC units could be also deployed outside these zones in the distant future. Thus, this aspect is been neglected, since the general objective of this study is the determination of a short-term realistic deployment scenario (OTEC resources with a realistic distance from the shoreline).

As it is shown in figure 4.9 below, a useful ArcGIS function provides the evenly spaced offshore points ("Create Fishnet" tool). Specifically, this data management tool is a set of cells where label points are given depending the cell's size, width and height [19]. Obviously, the tool is been used up to 6 times within the model, in order to alter the spacing aspect for each range. In further detail and for the 1st category mentioned above, the distance used is 0.2 degrees which is approximately 20 km and $0.6° \simeq 65km$, $1.1° \simeq 120km$, $1.6° \simeq 175km$, $2.1° \simeq 230km$, $2.6° \simeq 285km$ for the rest of the categories, respectively. Note that the distinction between different spacing criteria is more than essential in order to ensure the vital recovery of the deep cold waters and the minimal disruption of the oceanic profile.

Proceeding further with the modeling process, an another ArcGIS tool splits all the points that correspond to each spacing category ("Clip" tool). Then, another GIS tool ("Select Layer by Location") is applied to intersect each spacing range with the technical power density polygon as indicated below. As a result, 6 different power density layers have been created to correspond to a different spacing range. Thereafter, for the extraction of the spaced units as point layers, an additional ArcGIS function is utilized ("Copy

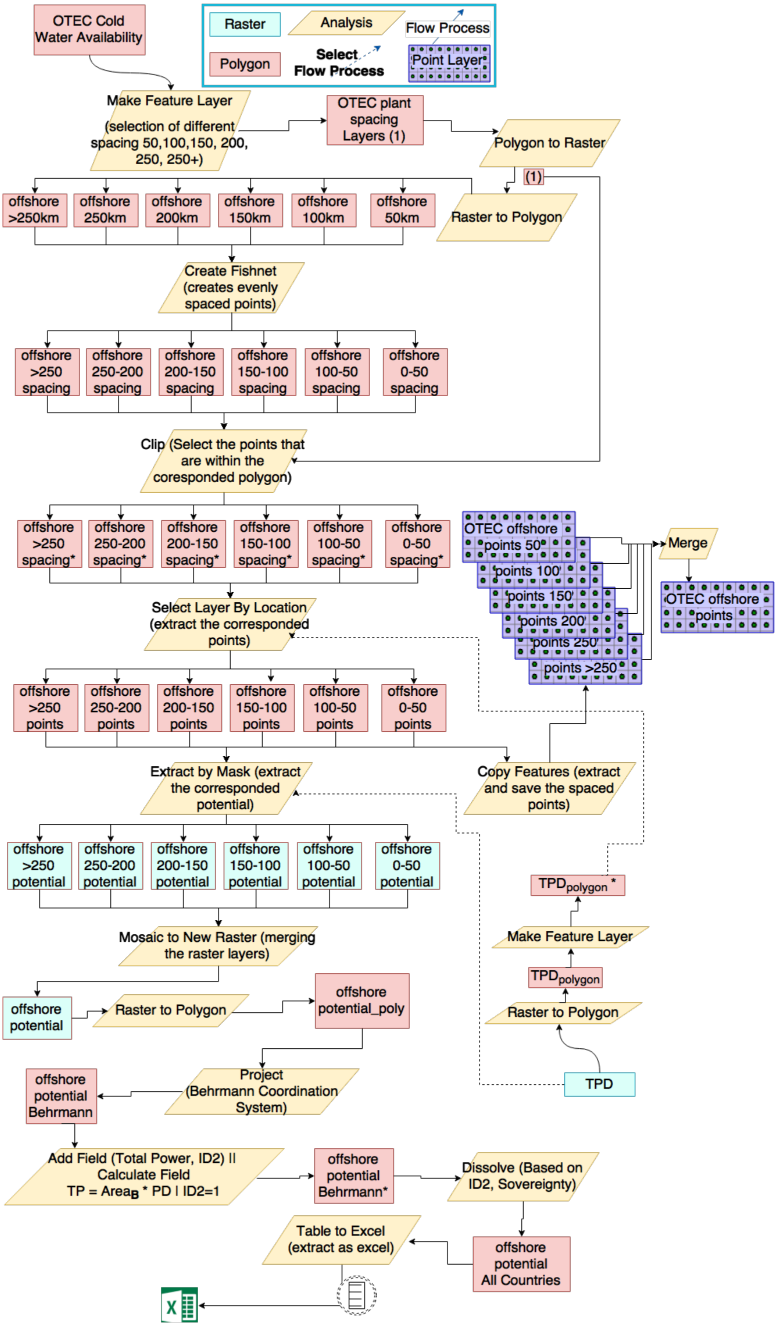


Figure 4.9: Analysis Flow Chart for the calculation of the Offshore Power Density (OffPD) and for the determination of the exact offshore OTEC locations

Features" tool). Lastly, the ArcGIS tool "Merge" is used in order to combine all the layers together in one single map.

In conclusion, similar strategy is applied as before in order to determine the offshore potential. An additional field is added in the attribute table (Total Power) and the Behrmann projection is used for the calculation of the implementation areas. In the end, the potential for every spaced polygon is calculated separately. This is achieved by applying another tool in the ArcGIS environment. In specific, the "calculate field" function is used which in reality, provides calculation capabilities for the user. In the end, the OTEC cold water flow rates should be adjusted in accordance to the different spacing ranges to correspond to greater power maxima since the OTEC plant density has been significantly decreased (Sensitivity Analysis in Chapter 5).

4.7. ONSHORE POTENTIAL ANALYSIS

THE calculation of the onshore potential on the other hand, is a straightforward procedure which requires similar ArcGIS functions as the above. The objective of this subsection is to identify the Onshore OTEC locations as points and determine the Onshore potential found in 9km distance away from the shoreline. In this direction, the ArcGIS tool that selects a layer according to its spatial relationship with a feature layer ("Select Layer By Location"), is utilized several times within this modeling context. Additionally, the Onshore OTEC units should be at least 4 km apart from each other to prevent thermal degradation of the resource and in extent long-term unstable performance.

In the beginning, the Coastlines of the world are used as the primary modeling input. Then an online ArcGIS tool is utilized to construct point features along a polyline ("Create Points Along Lines" [20]). The distance interval used is $0.036° \simeq 4km$. This is the actual distance that the two onshore OTEC units should have away from each other in order to prevent any thermal degradation of the local resources. In addition, the "Select Layer By Location" tool is used to select the points that are within 9km distance from the Practicable Power Density (PPD) Layer calculated above. This selection is essential since the OTEC seawater pipes are critical parts of an OTEC design and their length could determine the viability of the project.

In the end, the points are extracted with the help of the function "Copy Features" and the potential is calculated in accordance with the Behrmann projection. The Onshore power density (OnPD-Behrmann) in figure 4.10 is used afterwards for the extraction of the potential for all the countries one by one around the world. The only small difference in this section is that the modelling procedure above will be used twice: One time for the calculation of the Onshore Potential of all the countries excluding Africa and one time for the African countries (The PPD_AEG is used as an input in this case). These results though are illustrated later in the following chapter where all the outcomes are presented separately (chapter 5).

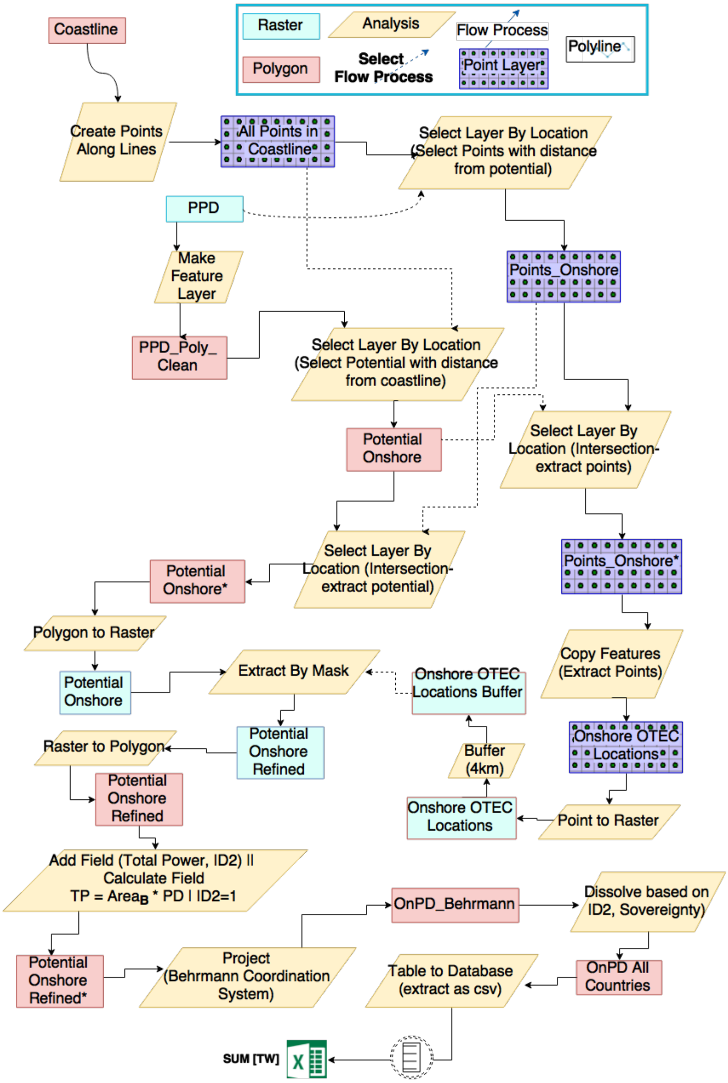


Figure 4.10: Analysis Flow Chart for the calculation of the Onshore Power Density (OnPD)

5

Results and Action Plan

Towards the development of far more realistic estimates, the resulting OTEC potential is presented below in chapter 5. In detail, 72 countries show prosperous OTEC resources within 100 km distance from adequate population densities. The total potential in that case reaches the value of 4.4 TW which according to similar studies will not cause any thermal disruptions within the ocean. On the other hand, the "Aggressive" implementation scenario shows a different behavior. Nevertheless, this scenario is considered as the least sustainable and therefore the least probable, since OTEC deployments in that magnitude could cause significant thermal changes within the ocean. Later on in this chapter, a sensitivity analysis is taking place in order to adjust the total offshore and onshore potential (the 4.4 TW mentioned above) in regards to the spacing considerations that have been previously proposed.

5.1. SPATIAL RESULTS

During the distribution analysis, the spatial layers were examined in accordance to the practicable criteria for every resource potential category. Finally, the present results coming from chapter 3 will be displayed combined with the maps and tables below for a better overview. The theoretical and technical resource potential results offer initial insights comparable to previous studies and the refined offshore and onshore estimates provide a realistic interpretation of the OTEC unit deployment within 100km distance from the shore. Therefore, the focus is directed on the sensitivity analysis and the development of a short-term deployment scenario, with the adjusted resource potential estimates.

5.1.1. THEORETICAL POTENTIAL

The static temperature field between 30m and 1062m depth of the ocean, for an average of 10 years (2007-1016), is illustrated below in figure 5.1. This is the theoretical proportion of the entire resource potential enclosed within the oceans. It represents the solar absorption of the oceans in two different depth levels and it has been estimated many times already in the past by previous researchers.

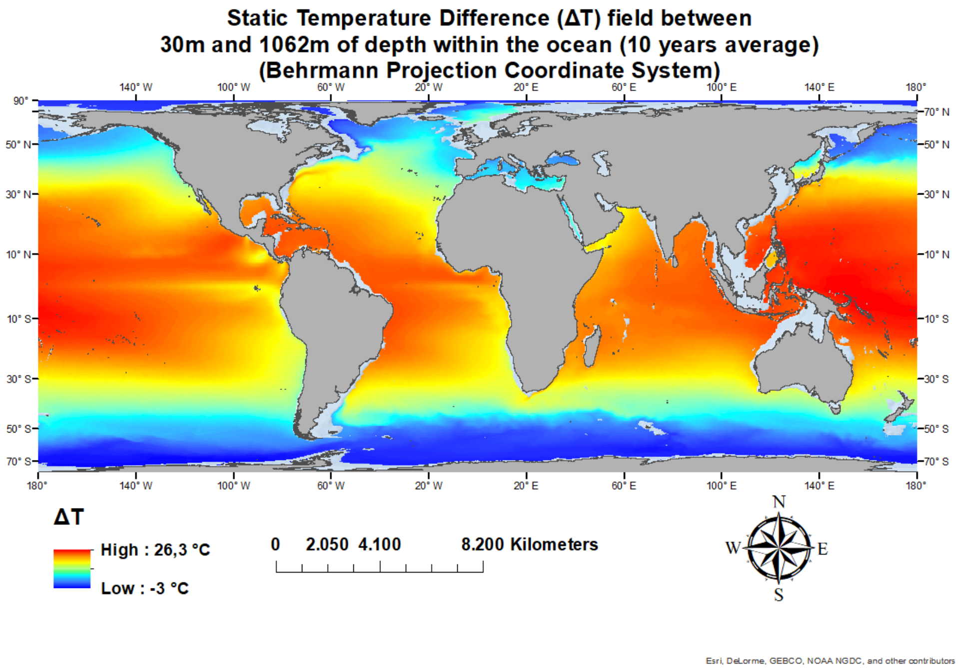


Figure 5.1: Temperature Difference between 30 meters and 1062 meters deep in the ocean (2007-2016 Average)

In detail, as it is also evident in the graph 2.12, the choice of a greater cold water flow rates (as for example w_{cw}= 60 m/yr) would result in an unrealistic technical estimate of approximately 100 TW. This is derived by the fact that in a static modelling environment as such, convective horizontal currents and the mixing processes within the ocean have not been considered and therefore the power density estimates follow a linear approximation and (the doted line in figure 2.12). Nevertheless, in this case with the choice of w_{cw}= 5 m/yr, there are very little differences between the dynamic and static modeling results and therefore this is the value that was selected for the calculation of the power density.

Table 5.1: OTEC total power estimates of the theoretical potential under the Behrmann Coordinate System

Resource Potential	Total Power (TW)	Total OTEC Area (km^2)
Theoretical	17.8	319×10^6

In total, the maximum theoretical power produce for the entire thermal resource of the planet, can reach more than 30 TW according to professor Nihous. The 3-D OGCM model uses a much smaller OTEC implementation area but massive cold water flow rates of w_{cw}= 60 m/yr. Nonetheless, as mentioned explicitly also earlier in chapter 2, this scenario causes significant warming in 1km depth and in extent excessive thermal degradation.

5

In the contrary, this study identifies an upper theoretical limit of 17.8 Terra Watts (TW) with w_{cw}= 5 m/yr. The critical assumption here nevertheless, is the amount of cold water flow rates as described above. It is therefore more than obvious, the dependence that w_{cw} has as a function of the power density. In the case of the theoretical upper limit of the total power produce (17.8 TW, see below in table 5.1), the value of w_{cw}= 5 m/yr was used to represent a more sustainable option that is not far from the 3-D OGCM predictions of Nihous and Rajagoplan (2013) [50].

However, this publication along with the latest one of Professor Nihous [49], allow a range of only 5-7 TW of OTEC unit deployment without causing thermal degradation. Therefore, it is important to proceed to a quest of a more sustainable option than the one shown in the table 5.1 above. This includes considering technical limitations of this theoretical upper limit after taking into account the temperature differences that could allow economically viable installations.

5.1.2. TECHNICAL POTENTIAL

The thermal resources within the ocean, can be exploited only if there are adequate temperature differences due to the low thermodynamic efficiency of the OTEC units. In specific, it is not economically viable to extract energy from locations that do not have at least $\Delta T \geq 20°C$. This value could be also redefined as the technology evolves making locations with $\Delta T \geq 18°C$ adequate for OTEC resources (It can be also found in Nihous and Rajagoplan study [50]). Nonetheless, in case of temperature differences of 11°C the net OTEC power produce approaches the value of 0. On the other hand, the present study focuses in the first threshold that was mentioned above with the technical power density of OTEC resources (w_{cw}=5m/yr) to be illustrated below in figure 5.2, where the ΔT

intervals define different subsequent zones in the ocean.

Table 5.2: OTEC total power estimates of the technical potential under the Behrmann Coordinate System

Resource Potential	Total Power (TW)	Total OTEC Area (km^2)
Technical	11.8	127×10^6

The results show that the total OTEC implementation area is about 20% greater in comparison with the one that Nihous used in one of his initial publications [48]. In specific, Professor Nihous used an area of A_{OTEC}=100 million km^2 while in this case the total OTEC implementation area for $\Delta T \geq 20°C$ is $A_{OTEC\_Behrmann}$ = 127 million km^2 which in extent represents an increased total technical power. Namely, this area is represented by latitudes between 30^o North and 30^o South in the Behrmann projection system.

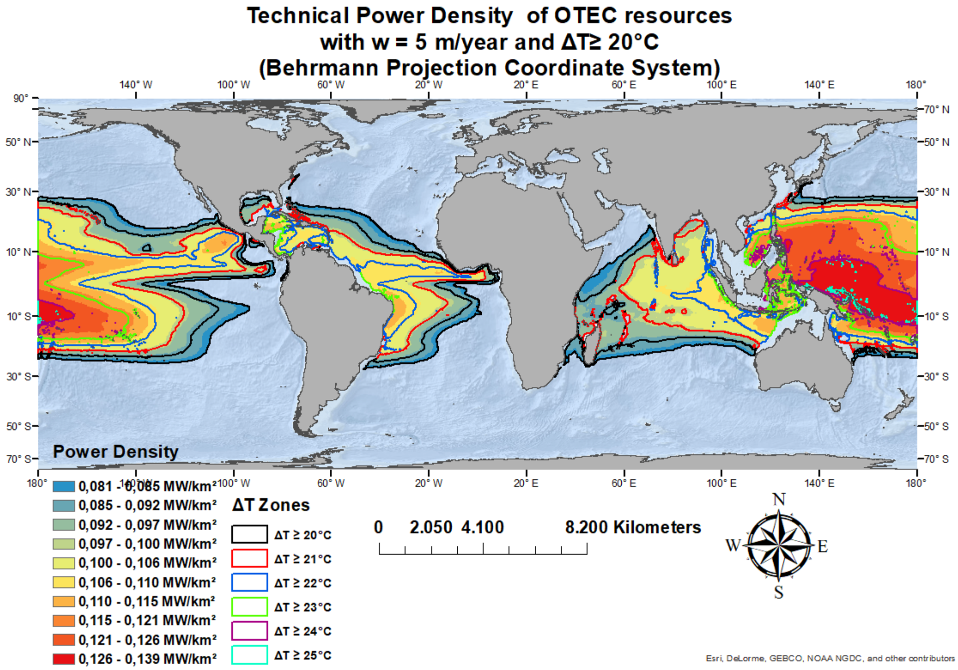


Figure 5.2: Technical Power Density with $\Delta T \geq 20°C$ (2007-2016 Average)

The total power resource estimates for a technically constrained OTEC implementation area reach the limit of 11.8 TW with a w_{cw}=5m/yr (Table 5.2). The power density distribution within the ocean is in parallel with the expectations of this project and the results of the previous studies. In detail, the average value identified is as high as 105 GW/Km^2 and the maximum reaches the value of 140 GW/Km^2. Undoubtedly and as it was mentioned numerous times above, the OTEC maxima can reach larger values if the value of w_{cw} is adjusted accordingly.

However, even in this case, this range of power estimates does not represent a sustainable OTEC deployment scenario according to the literature (5-7 TW sustainable deployment [49]). Therefore, the exploration of additional criteria is following in the next subsection, where only practicable locations are considered for OTEC deployment.

5.1.3. PRACTICABLE POTENTIAL

Proceeding to the removal of impracticable locations for deployment where selection criteria apply, the practicable power density of OTEC resources has been depicted (see figures 5.3 and 5.5). As instructed above, the Exclusive Economic Zones (EEZ) criterion is thoroughly applied and only for the sensitive case study of Africa, a minimum distance of 200km from the electrical supply grid (AEG) was used. In addition, population densities that exceed values of 500 people per square kilometer are also represented in the map below, annotated with the red color.

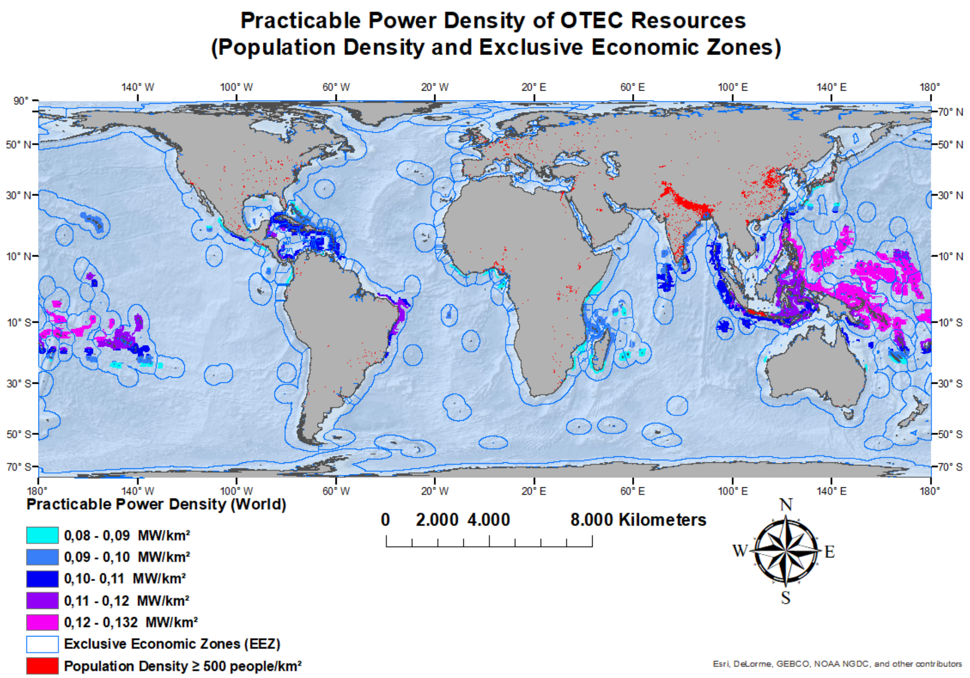


Figure 5.3: Practicable Power Density with Exclusive Economic Zones (EEZ) and Population Density (PoD) selection criteria applied

There is a large visual differentiation between the present results and the previous studies since the spatial resolution used reaches much greater values. Under this study, there is a significant amount of detail evident in the maps, in consideration of a representative refinement of each cell's area (0.083 degrees x 0.083 degrees), even in comparison with former localized assessments.

Additionally, the enlarged resolution along with the flexibility of ArcGIS interface allows a collection of multiple localized assessments. In this direction, the image 5.4 below offers a closer glimpse of the practicable locations for deployment in the Caribbean Sea. Apparently, the maximum power density (0.11-0.12 MW/km^2) values, stretch just outside the coast of Belize, Honduras and Costa Rica.

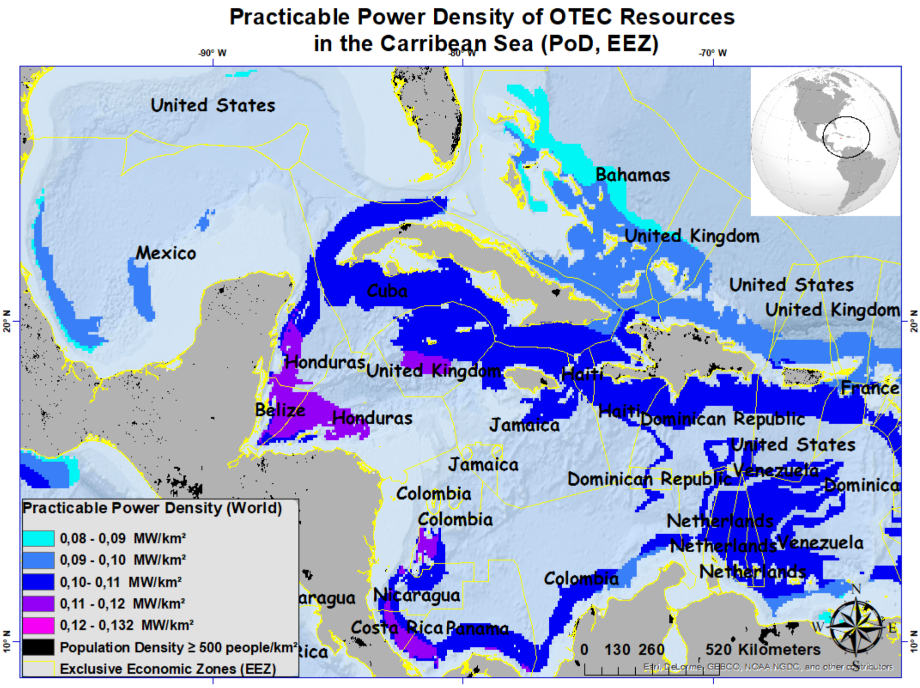


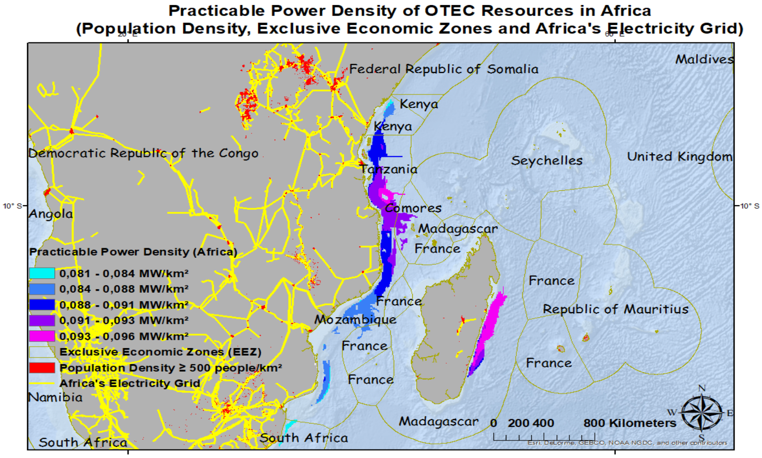
Figure 5.4: Practicable Power Density of Caribbean Sea (EEZ, PoD applied)

Table 5.3: OTEC total power estimates of the practicable potential under the Behrmann Coordinate System

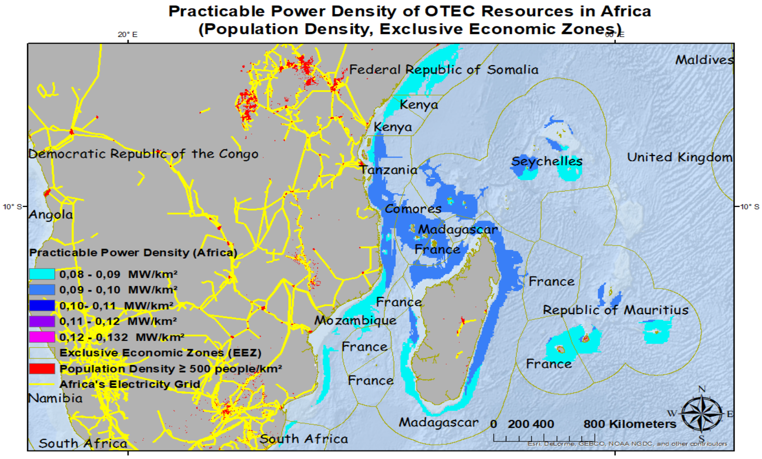
Resource Potential	Total Power (TW)	Total OTEC Area (km^2)
Practicable (World)	1.6	15.2×10^6
Practicable (Africa EEZ, PoD)	0.110	1,227,716
Practicable (Africa EEZ, PoD, AEG)	0.038	421,262

AFRICA'S CASE STUDY (AEG CRITERION INCLUDED)

Under this section, the Africa's case study is treated separately where an alternative analysis was used due to the lack of electricity providers in these regions. In reality, OTEC resources of the African countries are appeared to be limited, if only the resource potential locations which are 200 kilometers away from AEG are appraised. Therefore, a map for the case of Africa particularly, is extracted in order to derive a more realistic but debatable estimate (see figure 5.5). However, the limited resource estimates are raising further questions regarding the validity and accuracy of the AEG spatial layer.



(a) EEZ, PoD, AEG



(b) EEZ, PoD

Figure 5.5: Practicable Power Density of Africa with different criteria applied: (a) Exclusive Economic Zones, Population Density, Africa's Electricity Grid, (b) Exclusive Economic Zones, Population Density

After examining the differences between the two cases in Africa, it is evident that AEG limits the practicable locations for OTEC deployment. There are 18 countries identified with adequate resources in comparison with the 15 countries found while applying the AEG criterion. In detail, there is a 65% difference between the two OTEC implementation zones and in extent between the two total potentials as it is evident in the tables 5.3 above and 5.4. Moreover, the total overview of the African nations with adequate practicable potential (including the AEG criterion) is present above in table 5.4. Comprehensively, Mozambique is the nation which shows the largest practicable potential with 12.56 GW/yr while the total power output of all the African territories reaches the value of 37.74 GW/yr with a total OTEC implementation area of 421,262 km^2.

Table 5.4: Africa's OTEC total power estimates of the practicable potential (Sovereignty Overview)

#	Sovereignty (Africa)	Total Power (GW)	OTEC Impl. Area (km^2)
1	Benin	0.63	7,315
2	Comores	3.97	42,921
3	Equatorial Guinea	0.49	5,890
4	Ghana	0.84	9,964
5	Ivory Coast	0.32	3,668
6	Kenya	1.25	14,419
7	Liberia	1.93	22,047
8	Madagascar	5.75	61,108
9	Mozambique	12.56	142,168
10	Nigeria	1.37	15,401
11	Sao Tome and Principe	0.48	5,810
12	Sierra Leone	0.99	11,461
13	South Africa	0.47	5,609
14	Tanzania	6.38	69,906
15	Togo	0.31	3,575
#15	**Total (EEZ, PoD, AEG)**	**37.74 GW**	**421,262 km^2**

In general, the total practicable power density of the entire world is reaching the value of 1.6 TW with 15.2 million km^2 which represents only a 12% proportion of the (technical) total OTEC implementation area. Therefore, the amount of OTEC resources is limited to the geographical extent of each country's EEZ boundaries. In the end, in order to obtain a better geographical overview of this potential, the entire list of all countries' practicable resources (distinguished into different continents), can be found in the tables 1,2,3 of the Appendix D.

However, the analysis above might have reached limited OTEC power maxima that allow sustainable deployment but the cold water availability in 1km depth finally determines the vital recovery of the deep seawater, necessary for OTEC operations. Therefore, the map in figure 5.6 created below shows the path towards the proper OTEC unit spacing that ensures stable performance before depicting the offshore and onshore proportion of the total power produce.

5.1.4. OTEC PLANT SPACING MAP

After estimating the OTEC plant spacing based on the methods described in chapters 3 and 4, the spatial distribution map with 6 different distance ranges is presented below (see figure 5.6). This map will serve as a basis for the extraction of the offshore power density in the next section and the offshore adjusted resource potential while perform-

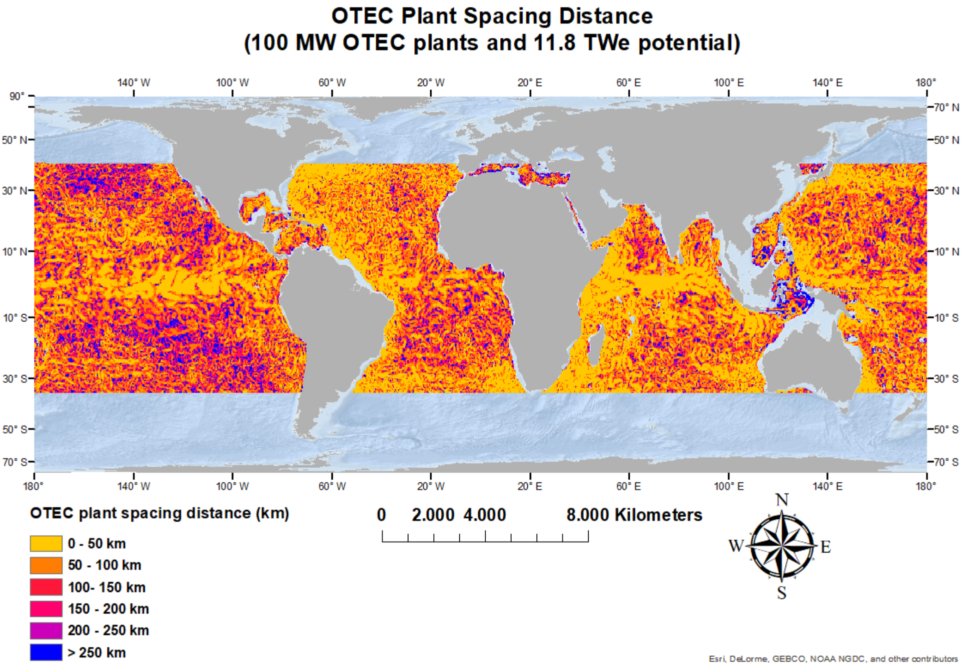


Figure 5.6: OTEC plant minimum spacing map (Δx distribution) for 100 MW distributed units over 11.8 TWe Resource Potential

ing the sensitivity analysis. In reality, it represents 6 OTEC spacing ranges that need to be followed for a vital cold water recovery in 1km depth.

Subsequently and after examining the distribution map above, it is more than evident that the dominant spacing distance is on the range of 0-50 km (92% of the total OTEC implementation area). In the contrary, the locations that show the highest spacing range (>250km) are indicated with the blue color corresponding to much lower area (0.1% of the total OTEC area). Specifically, in locations of the Pacific and Atlantic ocean that correspond to very small current velocities, a fast cold water recovery is not feasible. Therefore, in order to avoid excessive thermal degradation the OTEC units need to be spaced in accordance to the spacing map above, in order to reach into a realistic resource potential scenario.

5.1.5. OFFSHORE AND ONSHORE POTENTIAL

To begin with, under this section, the offshore and onshore proportion of the OTEC resources worldwide is represented, after taking into account the spacing considerations from the previous section. In reality, OTEC resources are highly dependant on the cold water availability in 1km depth. This fact implies a reasonable limitation which restricts the offshore power density in a way that can be illustrated below in figure 5.7. As it is obvious, the potential of OTEC has been evenly spaced and therefore, the OTEC spatial density has been significantly decreased.

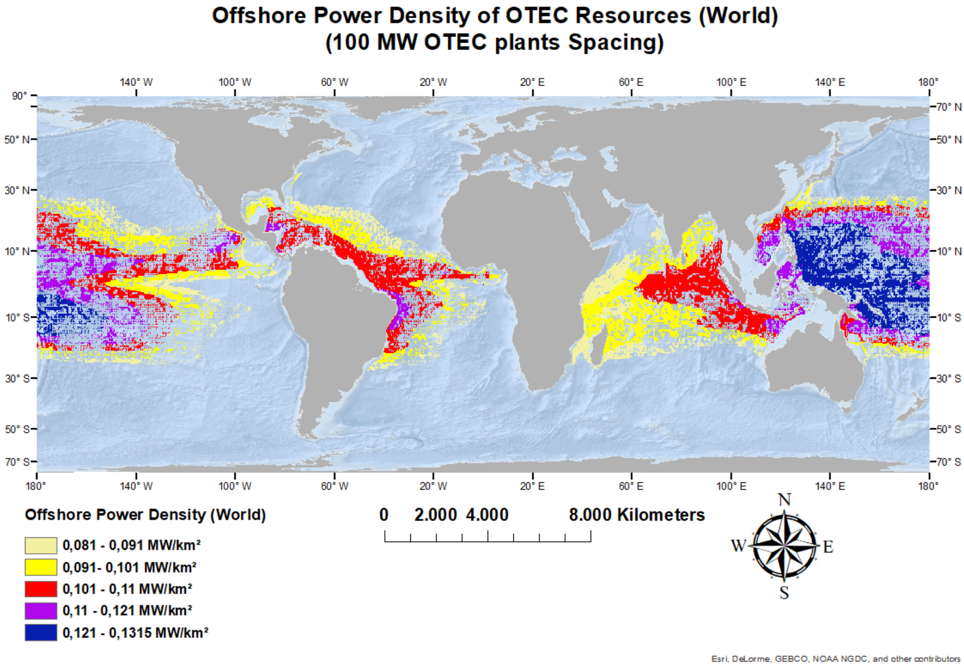


Figure 5.7: Offshore potential of OTEC resources after spacing considerations (100 MW plants)

In total, offshore resources are estimated to be at around 0.84 TW with 8.1 million square kilometers of total OTEC implementation area (with w_{cw}=5m/yr). It represents only 6.75% of the total (technical) OTEC implementation region calculated above and therefore the risk of excessive thermal degradation is minimized. Additionally and in regards of the other results present in the table 5.5 below, interesting outcome is the limited onshore resources worldwide with a threshold of just below 6 GW (which is almost the same amount of resources that are present offshore just for the case of Africa) and the large values of the Offshore EEZ resource potential (0.15 TW).

Table 5.5: OTEC total power estimates of the offshore and onshore potential under the Behrmann Coordinate System

Resource Potential	Total Power (TW)	Total OTEC Area (km^2)
Offshore (World)	0.84	8.1×10^6
Offshore (World, EEZ)	0.15	1.3×10^6
Offshore (Africa EEZ, PoD, AEG)	0.006	63,603
Onshore (World, EEZ, PoD)	0.006	49,783
Onshore (Africa EEZ, PoD, AEG)	0.00004	335

After consulting the spacing ranges and deriving the offshore and onshore locations for 100MW OTEC plants, the fact that becomes apparent is the extreme limitation of the world's OTEC resources. By taking into account the low cold water flow rates (w_{cw}=5m/yr) in formula 3.1, it is evident that the total power output (Offshore and Onshore) would be tremendously minimized (see table 5.5). It is therefore important to point out that the cold water flow rates (w_{cw}) need to be adjusted accordingly in order to: firstly, correspond to the 100MW plant spacing and secondly, in order to provide the opportunity to the limited OTEC units, to accommodate additional thermal resources from the nearby adjacent cells. For this reason, a sensitivity analysis is performed in the next section in order to attain a pragmatic onshore and offshore resource potential and the associated model that have been used for that purpose can be found in Appendix G in figure 6.

5.2. SENSITIVITY ANALYSIS

Regarding the offshore and onshore OTEC resources, a sensitivity analysis is executed in order to produce an adjusted power density based on the OTEC plant spacing map from above. Sensitivity analysis is the study of how the uncertainty in the output of a modeling process (quantitative or qualitative) can be allocated to different sources of uncertainty in its inputs. In this study, the uncertainty of the results arises due to the cold water availability constraints in 1km depth and in extent the nature of the resource itself (reservoirs of thermal energy).

In order to perform properly the sensitivity analysis, it is important to consider initially the OTEC plant spacing map. Suppose that the "After" scenario in the figure 5.8 below is the offshore power density as calculated above. Consider also that the "Before" scenario represents the technical resource potential where the OTEC units are located at the center of each cell, spaced approximately 10km away from each other. It is now obvious that the OTEC implementation Areas that correspond to the potential, are considerably different in each scenario ($Area_1$ and $Area_2$). The crucial assumption that arises is to use the total technical potential calculated above to adjust the offshore (including only the practicable locations) potential with different values of w_{cw} each time. In other words the desirable outcome would be (Total $Power_{Technical}$=Total $Power_{Off.Practicable}$ or Total $Power_1$=Total $Power_2$) and therefore:

$$TP_1 = TP_2 \Rightarrow PD_1 * Area_1 = PD_2 * Area_1 \Rightarrow$$
$$\Rightarrow w_1\,\rho\,\epsilon_{rg}\,c_p \left\{\frac{9\left(\Delta T\right)^2}{80\,T_{surf}} - \frac{9}{200}\right\} * Area_1 = w_2\,\rho\,\epsilon_{rg}\,c_p \left\{\frac{9\left(\Delta T\right)^2}{80\,T_{surf}} - \frac{9}{200}\right\} * Area_2 \Rightarrow$$
$$\Rightarrow w_1 * Area_1 = w_2 * Area_2 \Rightarrow w_2 = w_1 * \frac{Area_1}{Area_2}$$

In more detail, the calculation above is directing the analysis on identifying the proper OTEC vertical flow rate per unit area (w_{cw}) for each different spacing range. Therefore, 6 different values of w_{cw} are resulting based on the formula above and the area values of each zone.

- for 0-50 km OTEC spacing: w_{cw}=175 m/yr (representing 92% of the total OTEC implementation area)
- for 50-100 km OTEC spacing: w_{cw}=2,459 m/yr (representing 6.8%)

- for 100-150 km OTEC spacing: w_{cw}=7,289 m/yr (representing 0.9%)
- for 150-200 km OTEC spacing: w_{cw}=18,838 m/yr (representing 0.15%)
- for 200-250 km OTEC spacing: w_{cw}=26,845 m/yr (representing 0.05%)
- for >250 km OTEC spacing: w_{cw}=27,504 m/yr (representing 0.1%)

In reflection of the calculations above, the deep seawater flow rate per unit area (w_{cw}) is reasonably reaching much greater values. This is especially the case for the OTEC units that are spaced in distances longer than 100km. There, most of the w_{cw} values reach an order of magnitude way larger than the typical values mentioned in the literature by G. Nihous. But in reality, the dominant OTEC spacing range (0-50km is 92% of the sample) is the one that shows the lowest value of w_{cw} of 175m/yr, which according to the latest publication of professor Nihous, is a reasonable and sustainable value to use [49].

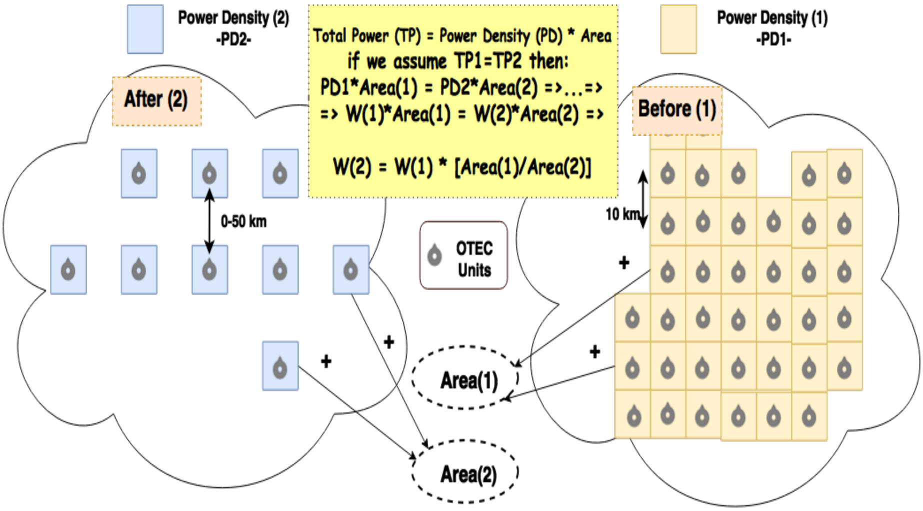


Figure 5.8: Sensitivity Analysis: Adjusting w_{cw} values with the Total Power$_{\text{Technical}}$=Total Power$_{\text{Offshore Practicable}}$

In reality, there would be no limitation in the deep seawater cold flow rates, if the decision to only deploy OTEC units within the EEZ zones is taken into consideration. Therefore, the procedure above, can be interpreted as an allocation of all possible thermal resources of the ocean towards the determination of a refined practicable offshore and onshore potential (which also includes PoD, EEZ and spacing criteria). However, for the determination of a refined potential, ArcGIS modeling have been used once again and therefore, the final and adjusted resource estimates are presented below for 100 MW evenly spaced OTEC plants, with w_{cw}=175 m/yr and with distance of 100km away from the population of 500 people per km^2.

5.2.1. OFFSHORE AND ONSHORE POTENTIAL 100KM (ADJUSTED)

After adjusting the cold water flow rates per unit area values, the spatial distribution of the offshore and onshore power density, can be found below in figure 5.9. However the resource potential is difficult to recognize since it is limited to approximately 100km away from the coast (Distance to Population Density=100km). Moreover, since most of the cells (92%) represent values of w_{cw}=175m/yr (0-50km OTEC spacing), the power output mainly ranges between 2.5 and 5 MW/km^2, a much higher estimate in comparison with the previous results.

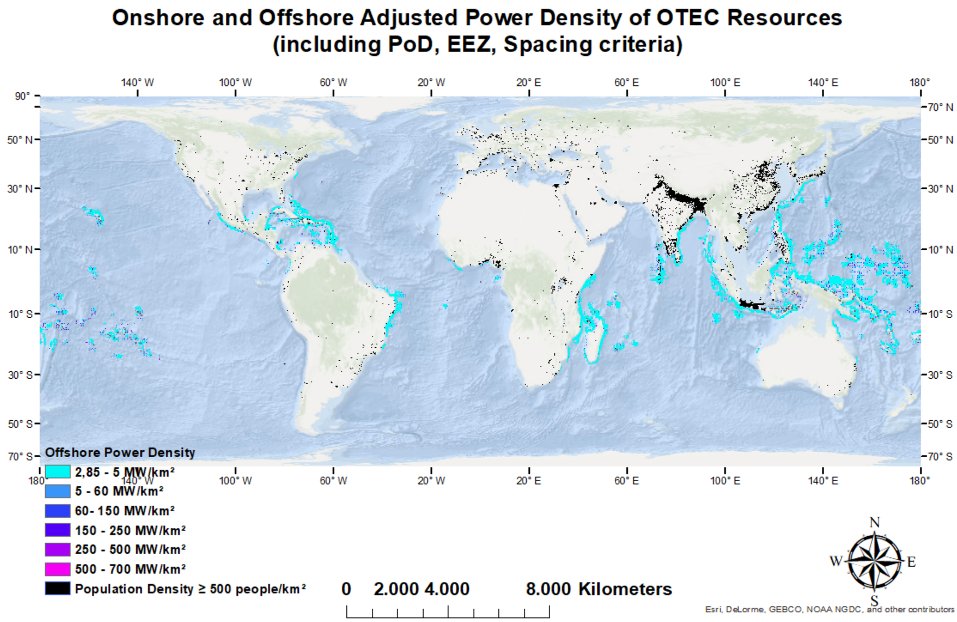


Figure 5.9: Adjusted Onshore and Offshore OTEC Resource Potential with EEZ, PoD and spacing criteria applied

Regarding the results from the sensitivity analysis, the offshore potential enclosed only within the EEZ boundaries, shows a large maximum of about 10.6 TW with 8 million square kilometers of total implementation area. Nevertheless, the sensitivity analysis was performed also with the selection criteria applied (100km) which yields approximately 4.4 TW with a total of only 50,000 km^2 of OTEC implementation area. The maximum electricity generation in that case, is approaching the threshold of up to 35,000 TWh/yr. All the results with the onshore and offshore potential of OTEC resources can be found in the table 5.6 below.

There are 72 countries in total that show prospective OTEC resources within their exclusive economic boundaries and within 100km away from adequate population density. In comparison with other studies this number is smaller but far more realistic.

Table 5.6: OTEC total power estimates of the offshore and onshore potential (adjusted)

OTEC Resource Potential (Sensitivity Analysis)	Total Power (TW)	Total Power Gen. (TWh/yr)	Total OTEC Area (km^2)
Offshore Adjusted (World EEZ, Spacing)	10.6	83,492	8,091,197
Offshore Adjusted (World EEZ, PoD, Spacing)	4.2	33,113	1,186,904
Onshore Adjusted (World EEZ, PoD, Spacing)	0.2	1,577	50,041
Offshore and Onshore Adjusted (EEZ, PoD, Spacing)	4.4	34,690	1,233,361
Offshore Onshore Intersected	0.02	158	3,584

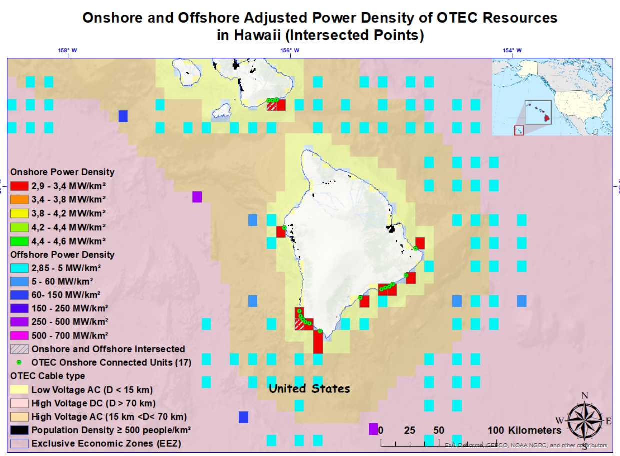


Figure 5.10: Adjusted Onshore and Offshore OTEC Resource Potential in Hawaii with Cable type specification

In addition, If we assume 90% availability for OTEC operations per year then the total amount of time that the unit will operate is: 7,884 hours/year. This is the value that is being multiplied with the respective resource potential each time in order derive the total electricity generation output. This means that the total power output will be expressed in different units which are more comparable with other sources of energy.

Moreover, since there was a different methodology applied each time for calculating the onshore and the offshore potential respectively, there are some locations that intersect with each other. In reality, those locations can be interpreted as areas where both onshore and offshore installations are likely to be feasible. In respect to this analysis which can be also found in Appendix G in associated models, the map in figure 5.10

above serves as an example illustration for identifying the intersected location. To summarize, in the same figure it is possible to recognize the spatial results related to the cable type that should be utilized depending the distance to the shore (Distance< 15 km Low voltage AC, 15 km <Distance< 70 km High Voltage AC, Distance> 70 km High Voltage DC).

It is difficult to identify from the map in figure 5.9 the resources of each country and for this reason, every continent's potential is presented below along with the correlated local resource maps. In addition, below there is also the geographical overview of OTEC resources for each country (see tables 5.7, 5.8, 5.9, 5.10, 5.11 below). In these tables there is information for the onshore and offshore total power output, the electricity generation per year for both and the total OTEC implementation area of each country.

AFRICA

The OTEC resources of Africa, outreach a maximum power output of 412.5 GW with a total implementation area of 135,313 km^2. In more detail, Madagascar and Seychelles show a strong resource potential just few km away from theirs coastlines as illustrated in figure 7. The illustration 5.11, provides a closer estimate of the Madagascar's OTEC resources which exceed a power output of 120 GW in total. This location also shows the highest implementation area values (just below 39,000 km^2) among the rest of the African countries which reveals a prosperous OTEC resource in that location.

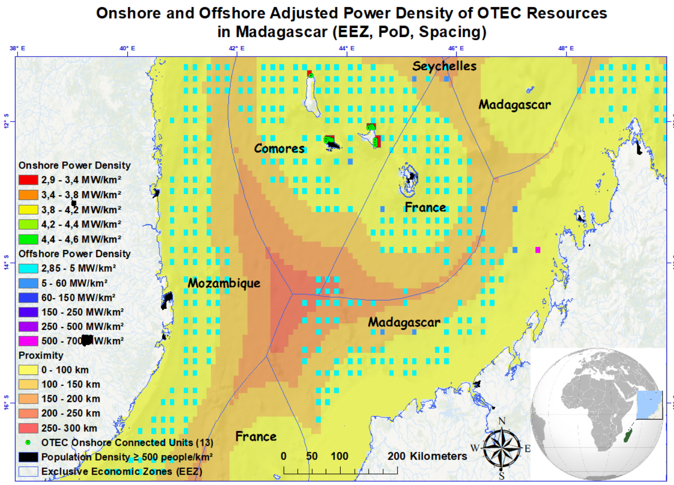


Figure 5.11: Adjusted Onshore and Offshore OTEC Resource Potential in Madagascar with EEZ, PoD and spacing criteria applied

The illustration with the local resources of Africa above shows remarkable detail, in comparison with the amount of features present in figure 2.8. The study derived from the theoretical literature, only shows the adequate temperature differences of that region. In addition, this research publication also points out the importance of the AEG criterion as an actual indicator. Specifically, the study mentions that the availability of OTEC resources should be in parallel with the demand for energy in order to attract the interests of stakeholders in that region.

However, in the last stage of the sensitivity analysis above, the AEG criterion has not been taken into account since there were substantial resource limitations present. In

Table 5.7: Africa's OTEC total power estimates of the adjusted Offshore and Onshore potential (Sovereignty Overview)

#	Sovereignty	Total Power (Off)-GW	Total Power (On)-GW	Total Power Gen. (GWh/yr)	OTEC Area (km^2)
#16	**Africa (EEZ, PoD, spacing)**	**409.31**	**3.18**	**3,252,071**	**135,313**
1	Benin	1.51	-	11,905	595
2	Comores	36.23	1.87	300,380	12,138
3	Equatorial Guinea	0.01	-	79	85
4	Ghana	0.51	-	4,021	341
5	Ivory Coast	0.51	-	4,021	171
6	Kenya	11.74	-	92,558	4,013
7	Liberia	7.12	-	56,134	2,387
8	Madagascar	121.23	-	955,777	38,952
9	Mozambique	73.98	-	583,258	24,134
10	Nigeria	0.23	-	1,813	170
11	Republic of Mauritius	36.07	-	284,376	12,255
12	Sao Tome and Principe	7.39	0.25	60,234	2,906
13	Seychelles	79.53	1.06	635,372	26,224
14	Sierra Leone	2.31	-	18,212	849
15	South Africa	1.53	-	12,063	528
16	Tanzania	29.41	-	231,868	9,565

fact, the resources of Madagascar would be 4 times less when the AEG criterion is applied which implies the fact that even an African nation (see table 5.4) should have better access to electricity with 50 million people populating that region (which implies an outdated or insufficient data source for the AEG criterion). In addition, there are other countries that show adequate OTEC resources in Africa. These nations' coasts are facing the Atlantic ocean on the other hand, and their potential is illustrated in figure 8 in Appendix I. Lastly, the total geographical overview of the African countries can be found above in the table 5.7 where the associated onshore and offshore resources are properly distinguished for each sovereignty.

AMERICA

The American continent in general, has the largest amount of countries that can benefit from an OTEC installation. In specific, there are 26 nations in total which could have access to nearly 730 GW of OTEC electricity resources in the near future. In the contrary, the total onshore resources reach the limit of 27 GW which implies longer distances from the coast in the case of the American shores. Specifically and as the table 5.8 indicates below, the American population could benefit with additional electricity generation of about 5.7 million GWh/year which is way beyond the value of 4,079 GWh that United States alone produced at utility scale facilities for the year 2016 [32].

In America, remarkable results show the territories of Brazil with 169.57 GW and the

Table 5.8: America's OTEC total power estimates of the adjusted Offshore and Onshore potential (Sovereignty Overview)

#	Sovereignty	Total Power (Off)-GW	Total Power (On)-GW	Total Power Gen. (GWh/yr)	OTEC Area (km^2)
#26	**America**	**702.72**	**26.74**	**5,751,063**	**220,146**
1	Antigua and Barbuda	11.28	-	88,932	3,341
2	Bahamas	67.35	0.77	537,058	22,176
3	Barbados	23.33	-	183,934	6,497
4	Belize	9.92	-	78,209	2,617
5	Brazil	169.57	-	1,336,890	45,398
6	Colombia	11.31	-	89,168	3,879
7	Costa Rica	8.17	-	64,412	2,448
8	Cuba	36.97	13.19	395,461	14,913
9	Dominica	4.51	0.59	40,208	1,568
10	Dominican Republic	55.44	0.59	441,741	16,385
11	El Salvador	2.28	-	17,976	918
12	Grenada	7.12	-	56,134	2,006
13	Guatemala	0.01	-	79	166
14	Guyana	8.07	-	63,624	2,191
15	Haiti	17.44	2.38	156,261	5,751
16	Honduras	14.11	-	111,243	3,850
17	Jamaica	16.56	-	130,559	4,885
18	Mexico	59.40	1.44	479,663	20,012
19	Nicaragua	9.93	-	78,288	2,763
20	Panama	2.27	0.25	19,868	1011
21	S. Kitts & Nevis	0.30	-	2,365	164
22	Saint Lucia	7.66	-	60,391	2,076
23	S. Vincent & Grenadines	8.40	-	66,226	2,410
24	Trinidad & Tobago	10.20	-	80,417	2,766
25	United States	119	7.53	997,563	43,125
26	Venezuela	22.12	-	174,394	6,830

nations of Dominican Republic and Mexico with just above 55 GW of maximum prosperous electricity output. Brazil also owns just above 45,000 km^2 of potential locations which makes it an explicit territory for offshore OTEC deployment. Lastly, the visual results for the case study of the Caribbean Sea in total and the example case study of Hawaii, can be viewed in considerable detail in figures 9,10 in Appendix I.

ASIA

Asia shows an exceptional amount of OTEC resources since the temperature differences in these locations reach much higher values in comparison with the rest of the world. Asia and Oceania together, literally embody the "heart" of the thermal resources of this planet. Comprehensively, the Asian nations could derive all together a total OTEC produce of about 10,000 GWh/year within 350,000 km^2. A visual overview of other Asian nations with adequate OTEC resources can be found in figure 11 in Appendix I.

Table 5.9: Asia's OTEC total power estimates of the adjusted Offshore and Onshore potential (Sovereignty Overview)

#	Sovereignty	Total Power (Off)-GW	Total Power (On)-GW	Total Power Gen. (GWh/yr)	OTEC Area (km^2)
#13	**Asia**	**1,203.39**	**66.90**	**10,014,966**	**352,356**
1	Brunei	1.74	-	13,718	425
2	China	1.53	-	12,063	492
3	East Timor	11.11	7.96	150,348	5,235
4	India	131.20	1.16	1,043,526	41,033
5	Indonesia	543.03	45.05	4,636,423	157,525
6	Japan	90.65	0.72	720,361	29,966
7	Malaysia	3.17	-	24,992	767
8	Maldives	121.85	0.62	965,554	35,914
9	Myanmar	5.92	-	46,673	2,197
10	Philippines	229.81	10.85	1,897,363	59,828
11	Sri Lanka	43.84	-	345,635	13,146
12	Taiwan	18.91	0.54	153,344	5,580
13	Vietnam	0.63	-	4,967	248

5

In specific, Indonesia alone has a vast amount of OTEC resources that reaches up to 600 GW of onshore and offshore potential with a $\Delta T \geq 20°C$ and w_{cw}= 175 m/yr. Remarkably, Indonesia has approximately all the American OTEC resources concentrated just in one nation. Moreover, a better orientation on where exactly this explicit basin of thermal energy is located could be acquired, after consulting the illustration 5.12.

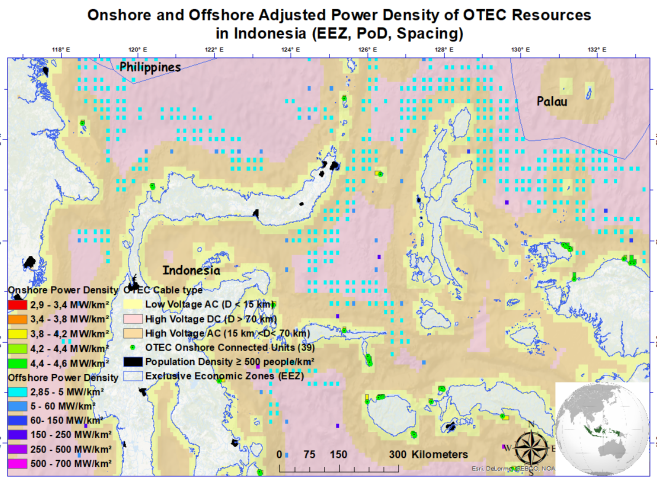


Figure 5.12: Adjusted Onshore and Offshore OTEC Resource Potential in Indonesia with EEZ, PoD and spacing criteria applied

According to the same illustration, it is possible to identify multiple OTEC locations that can produce up to 50

MW/km^2. The grid cells that are not in the dominant output range of 2.85-5MW/km^2, are spaced in longer distances from each other as expected by the sensitivity analysis above. Additionally, the same illustration provides important information related to the proximity to the shore. Specifically for these locations, since there are many different nations with their exclusive economic boundaries very close to each other, the proximity to shore along with EEZ spatial information, becomes essential for the avoidance of competing use conflicts.

EUROPE

In the contrary, Europe shows the least amount of feasible OTEC installations since only 3 nations appear to have an adequate proportion of thermal resources. In reality, European countries are located outside the geographical extent that OTEC installations become viable. Only few nations including France, the Netherlands and the United Kingdom, show OTEC potential which is pinned in the coastlines of the Caribbean Sea or in other African domains.

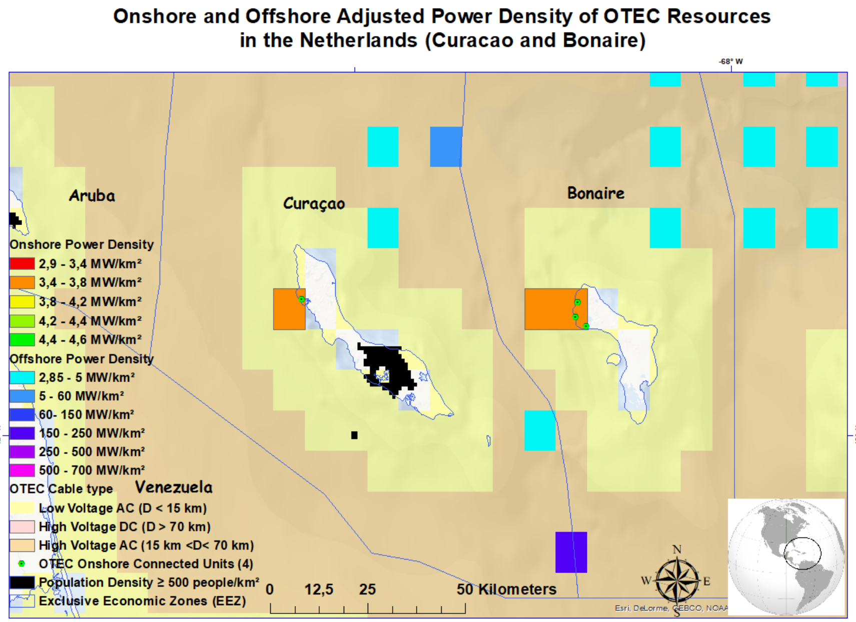


Figure 5.13: Adjusted Onshore and Offshore OTEC Resource Potential with EEZ, PoD and spacing criteria applied

In specific, Curacao and Bonaire, the two Dutch overseas locations in the Caribbean, show a maximum of 36,500 GWh/year of prosperous electricity output over a region of around 1,700 km^2. Moreover, in order to provide an additional step for this visual assessment, the cable type was also specified in accordance with the distance from the coastline of the Dutch areas, as illustrated in detail in figure 5.13 above. To summarize, the total resources accounted for the case of all European territories is reaching the threshold of 300 GW with just below 100,000 km^2 of overall OTEC implementation areas as pointed out in the power estimates table below (table 5.10).

Table 5.10: Europe's OTEC total power estimates of the adjusted Offshore and Onshore potential (Sovereignty Overview)

#	Sovereignty	Total Power (Off)-GW	Total Power (On)-GW	Total Power Gen. (GWh/yr)	OTEC Area (km^2)
#3	**Europe**	**273.42**	**27.26**	**2,370,561**	**98,370**
1	France	216.60	23.64	1,894,052	79,476
2	Netherlands	3.72	0.92	36,582	1,666
3	United Kingdom	53.10	2.70	439,927	17,228

OCEANIA

5

The countries that belong to Oceania are also appeared to have high yields of ocean thermal energy. Hence, as it can be identified by the figure 12 in Appendix I, Oceania possesses more than 430,000 km^2 that could be used for OTEC installations within the exclusive economic zones of each Oceanic nation. Moreover, with more than 14 countries sharing the above mentioned OTEC implementation area, Oceanic nations have the ability to explore up to 1,700 GW of the prosperous onshore and offshore resources, according to the analysis above (see table 5.11).

Table 5.11: Oceania's OTEC total power estimates of the adjusted Offshore and Onshore potential (Sovereignty Overview)

#	Sovereignty	Total Power (Off)-GW	Total Power (On)-GW	Total Power Gen. (GWh/yr)	OTEC Area (km^2)
#14	**Oceania**	**1,614.8**	**71.23**	**13,292,661**	**430,760**
1	Australia	101.90	0.63	808,347	30,234
2	Fiji	-	3.44	27,121	897
3	Kiribati	41.20	10.20	405,238	14,132
4	Marshall Islands	173.20	2.54	1,385,534	47,115
5	Micronesia	302.51	2.61	2,405,566	78,206
6	Nauru	43.36	1.49	353,597	10,768
7	New Zealand	46.43	1.24	375,830	16,211
8	Palau	114.57	2.22	920,772	27,476
9	Papua New Guinea	504.04	21.93	4,146,748	125,081
10	Samoa	5.12	2.91	63,309	2,582
11	Solomon Islands	203.69	15.71	1,729,750	52,296
12	Tonga	30.44	0.28	242,197	9,262
13	Tuvalu	-	2.29	18,054	1,015
14	Vanuatu	48.34	3.74	410,599	15,485

The illustration 5.14 below is helpful for understanding the magnitude of the resources in the Papua New Guinea region. In specific, the nation could prospect onshore installations in more than 75 coastline locations and the power produce in that case would reach up to 22 GW. Additionally, all Oceanic countries appear to have adequate onshore resources which is from one point of view remarkable and from another perspective reasonable, since the waters are deep enough in a very close proximity to the shoreline. To summarize, Papua New Guinea appears to have OTEC resources of about 4.2 million GWh/year and along with Micronesia and Solomon Islands, it could potentially cover the entire electricity demand of the nearby Oceanic nations.

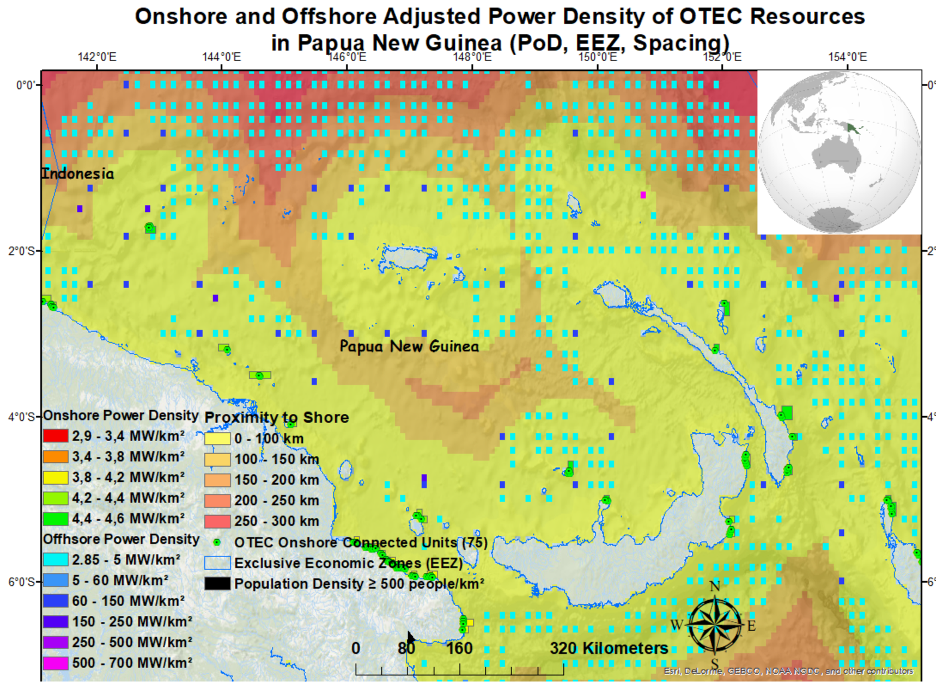


Figure 5.14: Adjusted Onshore and Offshore OTEC Resource Potential in Papua New Guinea with EEZ, PoD and spacing criteria applied

5.3. ACT

UNdoubtedly, with the potential organized in a structured manner for each country, it is now possible to compose a viable and realistic plan for the future of OTEC resources. The results above provide a clear guideline on which countries show OTEC potential valuable enough to explore and in which of these locations, this type of investment would be advantageous. In detail, due to the large estimated deployment costs of ocean technologies, the investment capacity appears to be limited. Therefore, a viable short-term scenario is created below, in order to prioritize the steps towards OTEC installations that show large electricity yields within a close proximity to their coastlines.

5.3.1. SCENARIO DEVELOPMENT

Ocean Energy, whether it is expressed as Tidal, Wave, Salinity or Thermal gradient, it is still at the very early stages of development and commercialization. In other words, one of the barriers and challenges for OTEC's "aggressive" market expansion will be to ensure the creation of a highly advanced resource agenda for prosperous demonstration and pilot projects. Towards this direction, the table 5.12 below is used to show the development of scenarios that reflect the OTEC resource assessment above and eventually, it assists on answering the research questions proposed in the introduction.

Table 5.12: Presentation of OTEC deployment scenarios based on the results of the resource potential analysis

OTEC Deployment Scenarios			
Scenario	**Resource Potential**	**Total Power**	**# Countries**
"Aggressive" Deployment (World)	**Offshore + Onshore (Adjusted)**	**10.8 TW**	**<100**
"Realistic" Deployment (100 km)	**Offshore + Onshore (Adjusted)**	**4.4 TW**	**72**
"Onshore" Deployment	**Onshore (Adjusted)**	**0.2 TW**	**35**

Firstly, the table above provides essential information about the results of this research which are useful for comparison with the latest potential estimates as described in chapter 2. Within a particular publication of Nihous and Rajagoplan (2013), the maximum total power of 6-7 TW from OTEC operations in all of the scenarios, would be considered as sustainable [49]. In addition, only the exceptional case of the Atlantic scenario (America's continent in this study) would be limited to 3 TW according to the simulations. Nevertheless, in this high resolution (1^{o}x1^{o}) Ocean General Circulation Model (OGCM), the actual OTEC power maxima are estimated to be up to 12-14 TW for all cases including the EEZ geographical restrictions. However, as it was also wisely pointed out by professor Nihous during our discussions, this would require massive cold water flows rates that would most likely disrupt the oceanic structure and trigger temperature changes elsewhere in the ocean [49].

This is the reason why the "Aggressive" Deployment scenario above is considered as the least sustainable and therefore the least probable, since it behaves very similar with Nihous and Rajagoplan outcomes for the unconstrained case. In the contrary, the 100km deployment scenario with the spatial criteria applied above, is at a close range with Nihous estimates, with just below 4.5 TW of total power output and w_{cw}=175m/yr. This "Realistic" estimate represents the short-term and viable market expansion plan for OTEC operations around the world. In detail, this would result in approximately 35,000

TWh/year of electricity generation accessible by 72 countries. This could cover up to 1.4 times the current total year-round electricity and heat production of the whole world [32].

The result above, is depicted with a value of cold water flow rates of w_{cw}=175m/yr and an OTEC deployment spacing range of approximately 20 km (which is 92% of the total OTEC implementation area). This result shows a remarkable similarity with professor Nihous' latest publication where a value of 180m/yr results in similar total power estimates [49]. Therefore, the accuracy of this study is even in a static environment as such was kept at satisfactory levels.

In the end, The "Onshore" scenario which is on the range of 0.2 TW of total power, could serve as a low-cost short-term solution for about 35 developing and developed countries around the world. In these locations, OTEC units could serve additional purposes such as desalination and air-conditioning with Sea Water Cooling (SWAC).

Admittedly, in general there are significant modeling differences between this study and the publication mentioned above. This study focuses on a much higher resolution (0.083^o x 0.083^o) visual assessment with a static temperature field (steady-state) while Nihous executes dynamic simulations with an OGCM which require significant computational strength. Nevertheless, the advanced criteria used above with the spatial capabilities of ArcGIS together, provide significant advantages towards the development of supplementary localized OTEC estimates, which will make the OTEC commercial transition possible in the near future.

6

CONCLUSION

This is a concluding chapter explaining the scientific and technical implications for the society of this research findings in considerable detail. In specific, this section's objective is to answer the research questions proposed during the introduction and list the additional results from the spatial analysis above. Thereafter, a critical view upon the insights derived during the sensitivity analysis, is opposed. Towards that direction, the offshore and onshore total power estimates are compared with results from previous studies. In the end, a preliminary discussion on the possibilities that this resource study offers is also taking place and the supplementary benefits of using a spatial software as such are briefly outlined.

An analysis with 100 MW deployed OTEC units spaced properly (at 20 km along 92% of the total OTEC region) across extensive oceanic locations, was performed through a high resolution (0.083^o x 0.083^o) steady state temperature model. This project is the first identifiable attempt of modeling worldwide OTEC resources that encloses such explicit practicable criteria, including the cold water availability that defines the proper OTEC spacing distribution. While most similar studies, show explicit attention on the resource estimates with the overall long-term effects that follow large scale operations, this study provides spatial capabilities through a flexible environment for assessing local potential resources in the near future.

However, this study took also into consideration the aspects that could affects the OTEC sustainability in case of large scale operations. Specifically and in regards to the first sub-question that was opposed in the introduction, the total technical resource potential found to be 11.8 TW for the whole world with w_{cw}=5m/yr. In addition and regarding the nations that show practicable locations for OTEC deployment, there are 72 countries identified installations after enclosing the potential within the exclusive economic zones and by taking into consideration the 100km distance from population densities of 500 people/km^2.

6

Proceeding to the next challenge of this study and after taking into account the sensitivity analysis, the total Onshore and Offshore potential-including the practicable criteria-reaches the values of 4.4 TW power output (with w_{cw}=175m/yr for 92% of the total OTEC locations). Similar studies as mentioned above have shown almost identical results but with different modeling procedures. Nevertheless, the present study also reveals onshore potential for 35 countries that are listed in the tables above which reaches a maximum of 0.2 TW of total electricity output.

Additional benefit from this research, is the ability to reproduce any of the results above and redefine the analysis by altering the assumptions and thus answering the last sub-question of this study. The model builder function within the ArcGIS software, provides the opportunity to model all the desired processes while accommodating a large list of spatial tools and queries. Hence, these models could be useful for further research if greater focus could be put on the geographical overview of each country, for several advanced local assessments.

The main research question proposes the quest of a pragmatic OTEC resource potential and the identification of locations where short-term deployments could be feasible. Regarding this issue, a realistic short term deployment scenario would be the one that takes into account the listed aspects: The need for energy considering a realistic population density, the exclusive economic interests of each sovereignty and the distance to the shore that defines the cable type (AC/DC) that should be preferred in OTEC installations. In that direction, the total output that 100MW OTEC units could generate would be 34,690 TWh/year in order to provide to over 1 billion people electricity supplies and possibly cover entirely the total electricity demand around the world.

Similar to other studies, during the procedure of examining and interpreting the results, additional outcomes may be discovered. That was also the case in this thesis project, where the quest for accuracy leaded to the choice of an equal area projection (Behrmann). Moreover, for the sensitive case study of Africa, not many insights have been depicted since a better overview of the continent's electricity grid is needed. The results in that case excluded many locations which show very large population densities but no access to electricity grids. Therefore, careful assessment is always necessary for a valid interpretation of results in this magnitude.

In conclusion, the 4.4 TW of total power output of 100MW evenly spaced OTEC plants, show a tremendous resource potential which should be investigated and explored in the near future. The thermal resources of our ocean show the most recoverable and therefore renewable behavior among all the other sources of energy. Therefore after also taking into account the potential of studies such as the above, it is becoming more than necessary to increase the efforts towards harvesting such a prosperous source of energy.

7

DISCUSSION

To begin with, during the discussions with Professor Nihous, there was an explicit attention on the importance of the cold water availability and the thermal disruption that may occur within the ocean, in case of excessive OTEC operations. The present models, do not examine the fact that if the OTEC units are installed in such a magnitude, which long term effects would occur in the overall oceanic thermal structure. Nevertheless, specific attention was put on developing a spacing map based on the cold water availability in 1km depth; an analysis that increased the accuracy of the results. Therefore, the estimates of this study, reflect a realistic deployment scenario that comes in parallel with previous estimates as discussed previously.

In addition, as implied also in the conclusion, the Africa's electricity grid was not taken into account while estimating the adjusted onshore and offshore power density. It is not certain whether these countries have access to electricity which questions the results of such an analysis. By discussing the outcomes with another researchers therefore, the transparency among the community increases and the validation process of the results becomes more reliable.

At this point, it is also important to point out the significance of the iteration processes that followed during the calculations within the ArcGIS software. The model builder function is providing the opportunity to model all the processes and change the assumptions of the analysis in a flexible manner. However, this procedure requires few iteration steps that need to be considered for the proper evaluation of the results. In specific, the ArcGIS interface is a flexible visual tool that can be further used to eradicate the spatial results and perform the calculations again, if the visual outcome does not reach the expectations. This capability would be exceptional if a localized OTEC assessment needs to be realized.

In addition, there are many supplementary barriers that need to be considered during the commissioning of an OTEC plant. Permitting issues and environmental aspects are becoming nowadays more important and an investment as such can reach the limits of hundreds of billion euros for the realization of a 100MW OTEC unit. Also the mix of electricity generation units in an island or an isolated region could determine the level of integration of additional renewable technologies and in extent the investment decisions that follow.

In the contrary though, OTEC's ability to provide all year round electricity supplies, its flexible behavior while combined with other renewables and the long-term viability of the technology, are more than enough reasons to choose such a reliable source of energy. In this direction, this study reveals the tools and methods that are necessary for a spatial assessment which includes pragmatic criteria. The ability to reproduce its results as mentioned previously in the concluding remarks, is an additional step towards the development of highly advanced local OTEC assessments.

In the end, as also professor Nihous wisely pointed out, defining the term "sustainability" for the case of OTEC resources, depends on the avoidance of excessive thermal degradation within the ocean. With the criteria being introduced above, deployment of OTEC units that explores resources located nearby the coastline (100km) would ensure a sustainable future for OTEC technology with little effects on the oceanic thermal structure. Consequently, there would be very little restrictions related to the realization of the first OTEC farm in the near future.

8

Recommendations for Further Research

Results as the above, are based on a spatial assessment including EEZ boundaries, population densities, proximity and spacing considerations. Nevertheless, there are additional elements that could be incorporated in this present study. Modeling processes can become more extensive and a dynamic interpretation can be depicted in future studies.

A dynamic adaptation of the models in this thesis project could be examined as a solution for a further increase in the accuracy and predictability of the resulting outcomes. Under this study, a 1-D steady-state temperature field was adopted for the calculation of the OTEC resource potential. Other studies indicate that horizontal transport phenomena and their vertical counterparts affect significantly the temperatures within the ocean. Therefore, utilization of other facilities that could increase the computational power, would assist towards a dynamic interpretation of the results above.

Moreover, a useful recommendation would be to utilize these results and redefine the assumptions in order to reach into an even more realistic short-term deployment scenario. However, the results of this study could be also used for local assessments and provide a variety of insights. In this direction, this study provides the transitional methodology that fuses together global and local estimates. Consequently, the next step would be the local identification of the resources of each country that have adequate potential according to this assessment and the creation of short-term scenarios that will increase the interest of even more stakeholders around the OTEC community.

Another additional research that could be carried out deals with the possibility of exporting the OTEC produce to other islands. OTEC integration with other renewables is considered a stable and viable electricity generation mix which could make those regions energy neutral. Therefore, criteria as shipping routes and additional electricity grid information should be considered essential towards this direction. Lastly, there is also the possibility to use this study's methods and tools to derive additional insights in symbiotic installations with a combination of a Sea Water cooling (SWAC) technology, Hydrogen production facilities and desalination plants or offshore fisheries.

Concluding, as satellite technology and remote sensing evolves, the availability of more local criteria (such as other country's electricity grids) will grow along with the modeling options of the available spatial software. Thus, the accuracy of the results will further increase and more eradicated local examples will be generated. Therefore, the possibilities that a spatial analysis offers are unlimited and on that account, they should not be neglected. Therefore, further research perpetrated towards the development of supplementary ArcGIS functions and tools, would uplift and elevate such spatial assessments.

Bibliography

[1] Ardelean, M. and Minnebo, P. *HVDC Submarine Power Cables in the World*. http://publications.jrc.ec.europa.eu/repository/bitstream/JRC97720/ld-na-27527-en-n.pdf. [European Commission, The Netherlands]. 2015.

[2] Avery, W. and Wu, C. *Renewable Energy from the Ocean: A Guide to OTEC*. New York: Oxford University Press, 1994.

[3] Aydin, H. *Performance analysis of a closed cycle Ocean Thermal Energy Conversion system with solar preheating and superheating*. University of Rhode Island. 2013.

[4] Bluerise. *Ocean Thermal Energy*. http://www.oceanpotential.com/ocean-thermal-energy/index.html. [Online; Accessed on 29-August-2017]. 2017.

[5] Bluerise. *Ocean Thermal Energy Conversion – OTEC*. http://www.bluerise.nl/technology/ocean-thermal-energy-conversion/. [Online; Accessed on 05-March-2017]. 2015.

[6] B.V., Bluerise. *Ocean Thermal Energy: Renewable Energy from the Ocean*. https://blackboard.tudelft.nl/bbcswebdav/pid-2908120-dt-content-rid-10037687_2/courses/41455-161702/11b_OE44075_OTEC_2016.pdf. [TU Delft Information System; Accessed on 10-February-2017]. 2017.

[7] (CMEMS), Copernicus Marine Environment Monitoring Service. *About Your Copernicus Marine Service*. http://marine.copernicus.eu/about-us/about-your-copernicus-marine-service/. [Online; Accessed on 18-August-2017]. 2017.

[8] (CMEMS), Copernicus Marine Environment Monitoring Service. *Copernicus Marine Service Online Catalogue*. http://marine.copernicus.eu/services-portfolio/access-to-products/. [Online; Accessed on 18-August-2017]. 2017.

[9] Conand, F. et al. “A Ten-year Period of Daily Sea Surface Temperature at a Coastal Station in Reunion Island, Indian Ocean (July 1993 – April 2004): Patterns of Variability and Biological Responses”. In: *Western Indian Ocean Journal of Marine Science* 6.1 (2007), pp. 1–16. DOI: 10.4314/wiojms.v6i1.48222.

[10] Council, National Research. *An Evaluation of the U.S. Department of Energy’s Marine and Hydrokinetic Resource Assessments*. Washington, DC: The National Academies Press, 2013.

[11] Daniel, T. H. “Ocean Thermal Energy Conversion: An Extensive, Environmentally Benign Source of Energy for the Future”. In: *Sustainable Development International* 3 (2000), pp. 121–125. DOI: 10.1023/A:1026062531405.

[12] D’Arsonval, A. “Utilisation de forces naturelles”. In: *Revue Scientifique* 370.2 (1881).

[13] Deng, Y. et al. "Quantifying a realistic, worldwide wind and solar electricity supply". In: *Global Environmental Change* 31 (2015), pp. 239–252. DOI: 10.1016/j.gloenvcha.2015.01.005.

[14] Dessne, Petter. "OTEC Africa and the University of Boras: Working for a sustainable future". In: *Presentation for the 3rd international symposium on OTEC*. Kuala Lumpur: University of Boras, 2015, pp. 1–22.

[15] Dessne, P. et al. *OTEC Matters*. http://www.otecafrica.org/OTECMatters.aspx. [Online; Accessed on 25-December-2016]. 2015.

[16] (ESRI), Environmental Systems Research Institute. *About ArcGIS*. http://www.esri.com/arcgis/about-arcgis. [Online; Accessed on 14-August-2017]. 2017.

[17] (ESRI), Environmental Systems Research Institute. *Clip*. http://pro.arcgis.com/en/pro-app/tool-reference/analysis/clip.htm. [Online; Accessed on 01-August-2017]. 2017.

[18] (ESRI), Environmental Systems Research Institute. *Conditional evaluation with Con*. http://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/conditional-evaluation-with-con.htm. [Online; Accessed on 22-July-2017]. 2017.

[19] (ESRI), Environmental Systems Research Institute. *Create Fishnet*. http://pro.arcgis.com/en/pro-app/tool-reference/analysis/clip.htm. [Online; Accessed on 01-September-2017]. 2017.

[20] (ESRI), Environmental Systems Research Institute. *Create Points From Lines*. https://www.arcgis.com/home/item.html?id=. [Online; Accessed on 10-September-2017]. 2017.

[21] (ESRI), Environmental Systems Research Institute. *Euclidean Distance*. http://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/euclidean-distance.htm. [Online; Accessed on 01-August-2017]. 2017.

[22] (ESRI), Environmental Systems Research Institute. *Extract by Mask*. http://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/extract-by-mask.htm. [Online; Accessed on 27-July-2017]. 2017.

[23] (ESRI), Environmental Systems Research Institute. *Select Layer By Location*. http://desktop.arcgis.com/en/arcmap/10.3/tools/data-management-toolbox/select-layer-by-location.htm. [Online; Accessed on 23-August-2017]. 2017.

[24] (ESRI), Environmental Systems Research Institute. *Support: Attribute Table*. http://support.esri.com/en/other-resources/gis-dictionary/term/attribute%20table. [Online; Accessed on 30-August-2017]. 2017.

[25] (ESRI), Environmental Systems Research Institute. *What Is The Geographic Approach?* http://www.esri.com/news/arcnews/fall09articles/what-is-geographic.html. [Online; Accessed on 14-August-2017]. 2017.

[26] Foundation, OTEC. *Vast potential for Ocean Thermal Energy in the Caribbean.* http://www.otecnews.org/2015/08/vast-potential-for-ocean-thermal-energy-in-the-caribbean/. [Online; Accessed on 05-March-2017]. 2015.

[27] Gautret, L. and Labat, M.C. *Reunion Island/Indian Ocean, a French experimental key laboratory for Ocean Energy.* http://www.arer.org/IMG/pdf/583_ICOE2010-REUNION-ISLAND.pdf. [Online; Accessed on 01-February-2017]. 2010.

[28] Gautret, L. and Nicet, J.B. "0 to 1000 m Deep Ocean Water Characterization for OTEC and SWAC Applications, Reunion Island, Indian Ocean". In: *Proceedings of the 2nd International Conference on Ocean Energy (ICOE 2008).* (Oct. 15–17, 2008). Spain, Bilbao: 2008, pp. 1–5.

[29] Hammar, L. et al. "Renewable Ocean Energy in the Western Indian Ocean". In: *Renewable and Sustainable Energy Reviews* 16.7 (2012), pp. 4938–4950. DOI: 10.1016/j.rser.2012.04.026.

[30] (HSEO), Hawaii State Energy Office. *Hawaii Energy Facts & Figures.* . [Hawaii State Energy Office, USA]. 2016.

[31] Huisman, O. and Rolf, A. *Principles of Geographic Information Systems: An introductory textbook.* Enschede, The Netherlands: The International Institute for Geo-Information Science and Earth Observation (ITC), 2009.

[32] (IEA), International Energy Agency. *Electricity and Heat Generation for the year 2015 (World).* http://www.iea.org/statistics/statisticssearch/report/?country=WORLD&product=electricityandheat&year=2015. [Online; Accessed on 29-August-2017]. 2017.

[33] (IRENA), International Renewable Energy Agency. *Ocean Thermal Energy Conversion.* [Technology brief]. 2014.

[34] Joy, M.A. et al. "Ocean renewable energy in Southeast Asia: A review". In: *Renewable and Sustainable Energy Reviews* 41 (2015), pp. 799–817. DOI: 10.1016/j.rser.2014.08.016.

[35] Kartalis, K. and Fidas, C. Αρχές και Εφαρμογές Δορυφορικής Τηλεσκόπησης *(Greek) [On: Principles and applications of Satellite Remote Sensing].* Athens, Greece: Tziolas Publications, 2013.

[36] Lewis, A. et al. *Ocean Energy. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlomer, C. von Stechow (eds)].* http://ipcc.ch/pdf/special-reports/srren/Chapter%206%20Ocean%20Energy.pdf. [Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA]. 2011.

[37] Lockheed Martin, Corporation. *Ocean Thermal Extractable Energy Visualization Report.* https://energy.gov/sites/prod/files/2013/12/f5/1055457.pdf. [Online; Accessed on 10-February-2017]. U.S. Department of Energy, Wind, Water Power Program, Office of Energy Efficiency, and Renewable Energy, Oct. 2012.

[38] Lopez, A. et al. *U.S. Renewable Energy Technical Potentials: A GIS-Based Analysis.* http://www.nrel.gov/docs/fy12osti/51946.pdf. [Online; Accessed on 10-February-2017]. 2012.

[39] Magagna, D. and Uihlein, A. *JRC Ocean Energy Status Report.* https://setis.ec.europa.eu/sites/default/files/reports/2014-JRC-Ocean-Energy-Status-Report.pdf. [Online; Accessed on 21-December-2016]. 2015.

[40] Map Projections, Comparison Platform. *Compare Map Projections.* http://www.map-projections.net/compare.php. [Online; Accessed on 10-September-2017]. 2017.

[41] Marasigan, M.C. *Philippine Government Policies for OTEC Development.* http://hinmrec.hnei.hawaii.edu/wp-content/uploads/2013/09/1.6-M.-Marasigan_-Philipines-OTEC-Roadmap.pdf. [Online; Accessed on 25-February-2017]. 2013.

[42] Marine Regions, databases. *Exclusive Economic Zones Boundaries (EEZ).* http://www.marineregions.org/downloads.php. [Online; Accessed on 20-July-2017]. 2017.

[43] Martin, P.J. and Roberts, G.O. "An Estimate of the Impact of OTEC Operation on the Vertical Distribution of Heat in the Gulf of Mexico". In: *Proceedings of the 4th Annual Conference on OTEC.* (). 1977, pp. 26–34.

[44] Masutani, S. M. and Takahashi, P. K. *Ocean Thermal Energy Conversion (OTEC).* University of Hawaii at Manoa, Honolulu, HI, USA: Elsevier, 2001.

[45] Muralidharan, S. *Assessment of Ocean Thermal Energy Conversion.* Massachusetts Institute of Technology. 2012.

[46] Nihous, G. "A Preliminary Assessment of Ocean Thermal Energy Conversion Resources". In: *Journal of Energy Resources Technology* 129.1 (2007), pp. 10–17. DOI: doi:10.1115/1.2424965.

[47] Nihous, G. "An estimate of Atlantic Ocean thermal energy conversion (OTEC) resources". In: *Ocean Engineering* 34 (2007), pp. 2210–2221. DOI: doi:10.1016/j.oceaneng.2007.06.004.

[48] Nihous, G. "An Order-of-Magnitude Estimate of Ocean Thermal Energy Conversion Resources". In: *Journal of Energy Resources Technology* 127.4 (2005), pp. 328–333. DOI: doi:10.1115/1.1949624.

[49] Nihous, G. and Rajagopalan, K. "An assessment of glonal Ocean Thermal Energy Conversion resources under broad geographical constrains". In: *Journal of Renewable and Sustainable Energy* 127.1 (2013), pp. 063124–11. DOI: doi:10.1063/1.4850521.

[50] Nihous, G. and Rajagopalan, K. "Estimates of global Ocean Thermal Energy Conversion (OTEC) resources using an ocean general circulation model". In: *Journal of Renewable Energy* 50 (2013), pp. 532–540. DOI: doi:10.1016/j.renene.2012.07.014.

[51] Nihous, G.C., Syed, M.A., and Vega, L.A. "Design of a Small OTEC Plant for the Production of Electricity and Fresh Water in a Pacific Island". In: *Proceedings of the Annual Conference on Ocean Energy Recovery OTEC*. (). 1989, pp. 207–216.

[52] Nouel, L. *PRODUCT USER MANUAL For the GLOBAL Ocean Sea Physical Analysis and Forecasting Products (GLOBAL_ANALYSIS_FORECAST_PHY_001_024)*. http://cmems-resources.cls.fr/documents/PUM/CMEMS-GLO-PUM-001-024.pdf. [Online; Accessed on 10-March-2017]. 2016.

[53] Penney, T. R. and Bharathan, D. "Power from the Sea". In: *Scientific American* 256.1 (1987), pp. 86–92.

[54] Penney, T.R. and Daniel, T.H. *Energy From the Ocean: A Resource for the Future, Year Book for 1989*. Encyclopedia Britannica, 1989.

[55] Quirapas, M. et al. "Ocean renewable energy in Southeast Asia: A review". In: *Renewable and Sustainable Energy Reviews* 41 (2015), pp. 799–817. DOI: doi:10.1016/j.rser.2014.08.016.

[56] Rew, R. et al. *The NetCDF Users Guide*. http://www.unidata.ucar.edu/software/netcdf//old_docs/docs_4_1_2/netcdf.pdf. [Online; Accessed on 18-August-2017]. 2011.

[57] Schachner, S. *Power Connections for Offshore Wind Farms*. Delft University of Technology, Netherlands and University of Leoben, Austria. 2004.

[58] (SEDAC), NASA Socioeconomic Data Applications Center. *UN-Adjusted Population Density, v4 (2000, 2005, 2010, 2015, 2020)*. http://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-density-adjusted-to-2015-unwpp-country-totals/data-download. [Online; Accessed on 20-July-2017]. 2017.

[59] Seymour, R.J. *Ocean Energy Recovery: The State of the Art*. New York: American Society of Civil Engineers, 1992.

[60] (UCAR), University Corporation Atmospheric Research. *Climate Model Resolution*. https://www.vets.ucar.edu/vg/Climate_Model_Resolution%20%20/index.html. [Online; Accessed on 18-August-2017]. 2002.

[61] Uehara, H., Dilao, O.C., and Nakaoka, T. "Conceptual design of Ocean Thermal Energy Conversion (OTEC) power plants in the Philippines". In: *Solar Energy* 41.5 (1988), pp. 431–441. DOI: 10.1016/0038-092X(88)90017-5.

[62] Vega, L. *Encyclopedia of Sustainability Science and Technology*. Hawaii Natural Energy Institute, School of Ocean, Earth Science, and Technology, University of Hawaii at Manoa, Honolulu, HI, USA: Springer, 2012.

[63] Vega, L. *Ocean Thermal Resource and Site Selection Criteria*. http://hinmrec.hnei.hawaii.edu/wp-content/uploads/2010/01/Ocean-Thermal-Resources-and-OTEC-Site-Selection-Criteria.pdf. [Online; Accessed on 01-March-2017]. 2011.

[64] Vega, L.A. *Ocean Thermal Energy Conversion: Encyclopedia of Energy Technology and the Environment*. New York: Wiley, 1995.

[65] Williams, A. *HVDC vs. HVAC cables for offshore wind*. http://newenergyupdate.com/wind-energy-update/hvdc-vs-hvac-cables-offshore-wind. [Online; Accessed on 29-August-2017]. 2017.

[66] Yildirim, F. and Kaya, A. "Selecting Map Projections in Minimizing Area Distortions in GIS Applications". In: *Sensors* 8.12 (2008), pp. 7809–7817. DOI: doi:10.3390/s8127809.

[67] Zelfde, M. and Raes, N. *Introduction to ArcGIS 10 Part 1: Plotting species distributions on a map*. https://blackboard.tudelft.nl/bbcswebdav/pid-2917724-dt-content-rid-10116777_2/courses/41550-161703/Manual_ArcGIS_10.2_course_Master_IE_CML_part1_v1_2.pdf. [TU Delft Information System; Accessed on 10-February-2017]. 2012.

[68] Zener, C. "Solar Sea Power". In: *Physics Today* 26 (1973), pp. 48–53.

[69] Zener, C. "The OTEC Answer to OPEC: Solar Sea Power". In: *American Journal of Mechanical Engineering* 99.12 (1977), pp. 26–29.

APPENDIX A

GEOGRAPHICAL AREA	MAINLAND		ISLAND	
AMERICAS	Mexico	Guyana	Cuba	Guadeloupe
	Brazil	Suriname	Haiti	Martinique
	Colombia	French Guiana	Dominican Rep.	Barbados
	Costa Rica	Nicaragua	Jamaica	Dominica
	Guatemala	El Salvador	Virgin Is.	St. Lucia
	Honduras	Belize	Grenada	St. Kitts
	Panama	United States	St. Vincent	Barbuda
	Venezuela		Grand Cayman	Montserrat
			Antigua	The Grenadines
			Puerto Rico	Curacao
			Trinidad & Tobago	Aruba
			Bahamas	
AFRICA	Nigeria	Gabon	Sao Tome & Principe	
	Ghana	Benin	Ascension	
	Ivory Coast	Zaire	Comoros	
	Kenya	Angola	Aldabra	
	Tanzania	Cameroon	Madagascar	
	Congo	Mozambique		
	Guinea	Eq. Guinea		
	Sierra Leone	Togo		
	Liberia	Somalia		
INDIAN/PACIFIC OCEAN	India	Australia	Indonesia	American Samoa
	Burma	Japan	Philippines	Northern Marianas
	China	Thailand	Sri Lanka	Guam
	Vietnam	Hong Kong	Papua New Guinea	Kiribati
	Bangladesh	Brunei	Taiwan	French Polynesia
	Malaysia		Fiji	New Caledonia
			Nauru	Diego Garcia
			Seychelles	Tuvalu
			Maldives	Wake Is.
			Vanuatu	Solomon Is.
			Samoa	Mauritius
			Tonga	Okinawa
			Cook Is.	Hawaii
			Wallis & Futuna Is.	

Figure 1: List of Nations with adequate OTEC resources within their EEZ [63]

APPENDIX B

The discussion about the resolution of data is holding quite large significance. It is a vital aspect in modeling and especially in climate modeling. A map canvas is organized with a specific number of grid cells. Spatial resolution refers to how large are those grid cells and how many will they be accordingly [60]. This can be measured in degrees of latitude and longitude or miles or kilometers. Typical changes in resolution can be found below in the images which ensures a better understanding on this topic.

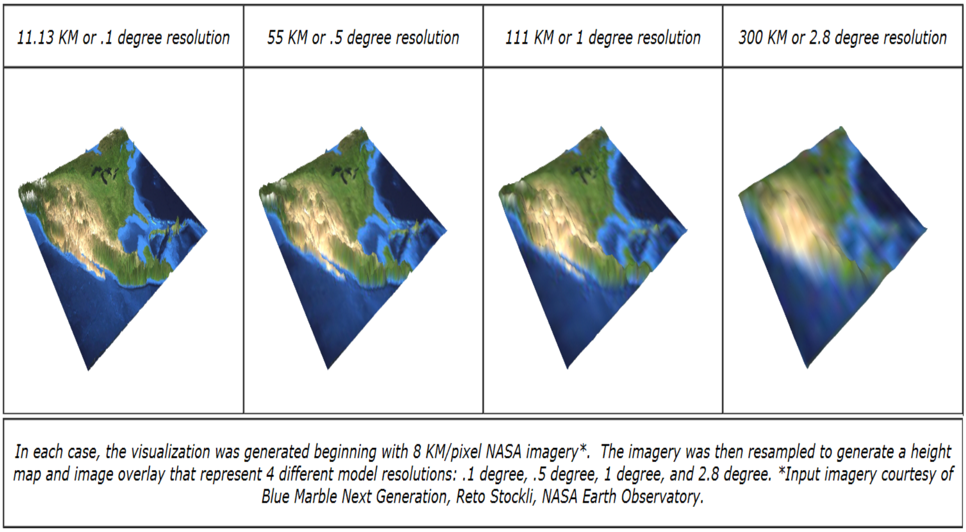


Figure 2: The images above were created to help illustrate the differences in climate model resolutions [60]

APPENDIX C

The assumptions that follow the distribution analysis for the calculation of the power density are listed below:

- The specific heat of seawater is: $c_p = 4000\, J/kgK$,
- The water volume flow rates per year $w_{cw} = 5\, m/yr$,
- The seawater density $\rho = 1025\, kg/m^3$,
- The turbo-generator efficiency $\epsilon_{tg} = 0.75$,
- The cold water pump volume flow rate Q_{cw},
- The warm water pump volume flow rate Q_{ww},
- The seawater surface average temperature and the temperature difference in Kelvin,
- 1 year is 3.154*10^7 seconds.

Therefore, if for example we choose a temperature difference of 20°C and a surface temperature of 25°C the power density is calculated as below:

$$P_{net} = w_{cw} \frac{3\rho\epsilon_{tg} c_p \gamma \Delta T^2}{16(1+\gamma)\, T_{surf}} - w_{cw} \frac{0.3\rho\epsilon_{rg} c_p \gamma}{4(1+\gamma)} \xrightarrow[\gamma=2]{\gamma=\frac{Q_{cw}}{Q_{ww}}}$$

$$\Rightarrow P_{net} = w_{cw}\, \rho\, \epsilon_{tg}\, c_p \left\{ \frac{\Delta T^2}{8T_{surf}} - \frac{1}{20} \right\} \Rightarrow$$

$$\Rightarrow P_{net} = 15,375 \times 10^6 \times \left\{ \frac{400}{2384} - 0.05 \right\} J/m^2 yr \Rightarrow$$

$$\Rightarrow P_{net} = 15,375 \times 10^6 \times \frac{(0,168-0.05)}{3.154\times10^7} J/(s\, m^2) \Rightarrow P_{net} = 0,057\, W/m^2\ or\ MW/km^2$$

Therefore, the results from Chapter 5 must be (and they are) in the order of magnitude of the power density value as calculated above. There is no difference in deriving the unit in W/m^2 or MW/km^2 since both Mega (M) and Kilo squared (K^2) are 10^6.

APPENDIX D

Table 1: Africa's OTEC total power estimates of the practicable potential (Sovereignty Overview)

#	Sovereignty	Total Power (GW)	OTEC Area (km^2)	Population (e or c)*
#18	**Africa (EEZ,PoD)**	**110.00**	**1,227,716**	**497,630,715**
1	Benin	0.63	7,315	10,872,298 (2016e)
2	Comores	11.89	128,766	795,601 (2016e)
3	Equatorial Guinea	0.55	6,573	1,221,490 (2016e)
4	F. Republic of Somalia	8.56	103,401	14,317,996 (2016e)
5	Ghana	0.84	9,964	27,043,093 (2014e)
6	Ivory Coast	0.32	3,668	23,740,424 (2016e)
7	Kenya	2.19	25,437	48,655,760 (2017e)
8	Liberia	2.46	28,016	4,503,000 (2015e)
9	Madagascar	28.00	303,051	24,894,551 (2016e)
10	Mozambique	13.27	150,624	28,829,476 (2016e)
11	Nigeria	1.37	15,401	185,989,640 (2016e)
12	Republic of Mauritius	9.94	111,869	1,262,132 (2016e)
13	Sao Tome and Principe	4.29	49,641	199,910 (2016e)
14	Seychelles	17.52	193,269	94,228 (2016e)
15	Sierra Leone	1.00	11,631	7,075,641 (2015c)
16	South Africa	0.47	5,609	54,956,900 (2015e)
17	Tanzania	6.38	69,906	55,572,201 (2016e)
18	Togo	0.31	3,575	7,606,374 (2016e)

* c: Population Census
e: Population Estimate

Table 2: America's OTEC total power estimates of the practicable potential (Sovereignty Overview)

#	Sovereignty	Total Power (GW)	OTEC Area (km^2)	Population (e or c)*
#27	**America**	**258.94**	**2,577,848**	**836,953,671**
1	Antigua and Barbuda	2.34	24,202	100,963 (2016e)
2	Bahamas	16.29	177,763	391,232 (2016e)
3	Barbados	6.37	61,089	277,821 (2010c)
4	Belize	3.29	29,439	387,879 (2017e)
5	Brazil	40.80	370,873	208,064,000 (2017e)
6	Colombia	8.50	87,989	49,364,592 (2017e)
7	Costa Rica	4.96	50,043	4,857,274 (2016e)
8	Cuba	18.64	177,646	11,239,224 (2016e)
9	Dominica	1.86	17,910	73,543 (2016e)
10	Dominican Republic	13.10	129,142	10,800,857 (2017e)
11	Ecuador	0.37	4,443	16,385,068 (2016e)
12	El Salvador	0.70	7,929	6,344,722 (2016e)
13	Grenada	1.84	17,292	107,317 (2016e)
14	Guatemala	1.10	11,901	16,582,469 (2016e)
15	Guyana	0.47	4,467	773,303 (2016e)
16	Haiti	5.43	51,907	10,847,334 (2016e)
17	Honduras	2.82	25,245	9,112,867 (2016e)
18	Jamaica	6.45	59,942	2,881,355 (2016e)
19	Mexico	27.06	284,292	119,530,753 (2015e)
20	Nicaragua	2.15	20,002	6,167,237 (2012c)
21	Panama	5.53	50,967	4,034,119 (2016e)
22	S. Kitts and Nevis	0.48	4,589	54,821 (2016e)
23	Saint Lucia	1.67	15,776	178,015 (2016e)
24	S. Vincent and the Grenadines	1.83	16,990	109,643 (2016e)
25	Trinidad and Tobago	2.46	23,311	1,353,895 (2016e)
26	United States	73.89	770,768	325,365,189 (2017e)
27	Venezuela	8.54	81,931	31,568,179 (2016e)

* c: Population Census
e: Population Estimate

Table 3: Asia's, Europe's and Oceania's OTEC total power estimates of the practicable potential (Sovereignty Overview)

#	Sovereignty	Total Power (GW)	OTEC Area (km^2)	Population (e or c)*
#14	**Asia**	**414.00**	**5,438,860**	**3,603,974,772**
1	Bangladesh	0.18	1,854	162,951,560 (2016e)
2	Brunei	1.03	8,847	417,200 (2015e)
3	China	0.86	8,344	1,403,500,365 (2016e)
4	East Timor	4.30	1,649,934	1,167,242 (2015c)
5	India	41.41	416,172	1,324,171,354 (2016e)
6	Indonesia	225.51	2,036,156	261,115,456 (2016e)
7	Japan	23.83	257,960	126,740,000 (2017c)
8	Malaysia	1.02	8,634	31,694,000 (2017e)
9	Maldives	31.00	303,372	427,756 (2016e)
10	Myanmar	3.38	33,970	51,486,253 (2014c)
11	Philippines	62.65	526,643	100,981,437 (2015c)
12	Sri Lanka	10.08	102,698	21,203,000 (2016e)
13	Taiwan	5.94	57,421	23,550,077 (2017e)
14	Vietnam	2.81	26,855	94,569,072 (2016e)
#3	**Europe**	**209.03**	**660,526**	**149,755,281**
1	France	175.57	298,549	66,991,000 (2017e)
2	Netherlands	10.24	129,217	17,116,281 (2017e)
3	United Kingdom	23.22	232,760	65,648,000 (2016e)
#14	**Oceania**	**574.80**	**5,314,236**	**39,942,269**
1	Australia	30.95	298,549	24,684,200 (2017e)
2	Fiji	20.46	185,849	898,760 (2016e)
3	Kiribati	60.31	521,879	110,136 (2015c)
4	Marshall Islands	75.52	303,372	821,928 (2016e)
5	Micronesia	84.79	1,188,324	523,167 (2016e)
6	Nauru	8.22	65,805	10,084 (2011c)
7	New Zealand	49.81	480,125	4,825,470 (2017e)
8	Palau	10.90	118,531	21,503 (2016e)
9	Papua New Guinea	113.67	1,081,079	7,059,653 (2011e)
10	Samoa	6.52	52,175	192,342 (2016c)
11	Solomon Islands	66.34	521,212	599,419 (2016e)
12	Tonga	8.80	86,910	103,036 (2011c)
13	Tuvalu	10.91	164,851	10,640 (2012c)
14	Vanuatu	27.60	245,575	81,931 (2016e)

* c: Population Census
e: Population Estimate

APPENDIX E

Table 4: Africa's OTEC total power estimates of the offshore potential (Sovereignty Overview)

#	Sovereignty	Total Power (GW)	OTEC Area (km^2)
#15	**Africa(EEZ, PoD, AEG)**	**5.74**	**63,603**
1	Benin	0.05	595
2	Comores	0.39	4,119
3	Equatorial Guinea	0.01	117
4	Ghana	0.07	767
5	Ivory Coast	0.02	171
6	Kenya	0.28	3,243
7	Liberia	0.17	1,960
8	Madagascar	0.98	10,406
9	Mozambique	2.42	27,384
10	Nigeria	0.02	170
11	Sao Tome and Principe	0.01	85
12	Sierra Leone	0.07	849
13	South Africa	0.04	528
14	Tanzania	1.21	13,209
15	Togo	0.09	85

Table 5: America's OTEC total power estimates of the offshore potential (Sovereignty Overview)

#	Sovereignty	Total Power (GW)	OTEC Area (km^2)
#26	**America**	**25.22**	**238,861**
1	Antigua and Barbuda	0.39	4,072
2	Bahamas	2.05	22,561
3	Barbados	0.74	7,080
4	Belize	0.32	2,861
5	Brazil	6.10	55,611
6	Colombia	0.40	4,216
7	Costa Rica	0.31	2,957
8	Cuba	1.23	11,945
9	Dominica	0.17	1,650
10	Dominican Republic	1.81	17,857
11	El Salvador	0.11	1,253
12	Grenada	0.24	2,256
13	Guatemala	0.02	166
14	Guyana	0.47	4,467
15	Haiti	0.54	5,187
16	Honduras	0.47	4,176
17	Jamaica	0.55	5,130
18	Mexico	2.10	21,793
19	Nicaragua	0.36	3,349
20	Panama	0.10	926
21	S. Kitts and Nevis	0.02	164
22	Saint Lucia	0.23	2,159
23	S. Vincent and the Grenadines	0.32	2,998
24	Trinidad and Tobago	0.49	4,614
25	United States	4.80	41,092
26	Venezuela	0.88	8,321

Table 6: Asia's, Europe's and Oceania's OTEC total power estimates of the offshore potential (Sovereignty Overview)

#	Sovereignty	Total Power (GW)	OTEC Area (km^2)
#14	**Asia**	**44.43**	**405,175**
1	Bangladesh	0.18	1,863
2	Brunei	1.03	8,847
3	China	0.05	492
4	East Timor	0.36	3,206
5	India	4.98	50,033
6	Indonesia	19.46	169,229
7	Japan	3.05	33,029
8	Malaysia	0.15	1,276
9	Maldives	4.72	45,896
10	Myanmar	0.32	3,179
11	Philippines	7.93	66,145
12	Sri Lanka	1.52	15,435
13	Taiwan	0.64	6,131
14	Vietnam	0.04	414
#3	**Europe**	**10.64**	**105,671**
1	France	8.58	85,069
2	Netherlands	0.17	1,580
3	United Kingdom	1.89	19,022
#12	**Oceania**	**59.66**	**470,701**
1	Australia	3.89	36,438
2	Kiribati	1.93	16,503
3	Marshall Islands	6.42	52,934
4	Micronesia	11.66	91,955
5	Nauru	1.75	14,016
6	New Zealand	2.39	19,748
7	Palau	4.00	32,058
8	Papua New Guinea	17.51	139,196
9	Samoa	0.30	2,416
10	Solomon Islands	6.93	54,487
11	Tonga	1.11	10,950
12	Vanuatu	1.77	15,898

Appendix F

Table 7: Africa's OTEC total power estimates of the onshore potential (Sovereignty Overview)

#	**Sovereignty**	**Total Power (GW)**	**OTEC Area (km^2)**
#2	**Africa(EEZ, PoD, AEG)**	**0.04**	**335**
1	Mozambique	0.02	166
2	Tanzania	0.02	169

Table 8: America's, Asia's, Europe's and Oceania's OTEC total power estimates of the onshore potential (Sovereignty Overview)

#	Sovereignty	Total Power (GW)	OTEC Area (km^2)
#8	**America**	**0.78**	**7,415**
1	Bahamas	0.02	237
2	Cuba	0.38	3,602
3	Dominica	0.02	165
4	Dominican Republic	0.02	163
5	Haiti	0.07	646
6	Mexico	0.04	484
7	Panama	0.01	85
8	United States	0.22	2,033
#8	**Asia**	**1.96**	**17,236**
1	East Timor	0.23	2,029
2	India	0.03	335
3	Indonesia	1.29	11,201
4	Japan	0.02	232
5	Maldives	0.02	171
6	Philippines	0.31	2,697
7	Taiwan	0.02	157
8	Vietnam	0.04	414
#3	**Europe**	**0.79**	**7,154**
1	France	0.68	6,164
2	Netherlands	0.03	251
3	United Kingdom	0.08	739
#14	**Oceania**	**2.18**	**17,643**
1	Australia	0.02	168
2	Fiji	0.10	897
3	Kiribati	0.29	2,392
4	Marshall Islands	0.14	1,103
5	Micronesia	0.08	594
6	Nauru	0.04	342
7	New Zealand	0.04	325
8	Palau	0.06	508
9	Papua New Guinea	0.63	5,102
10	Samoa	0.08	665
11	Solomon Islands	0.45	3,542
12	Tonga	0.01	81
13	Tuvalu	0.13	1,015
14	Vanuatu	0.11	909

APPENDIX G

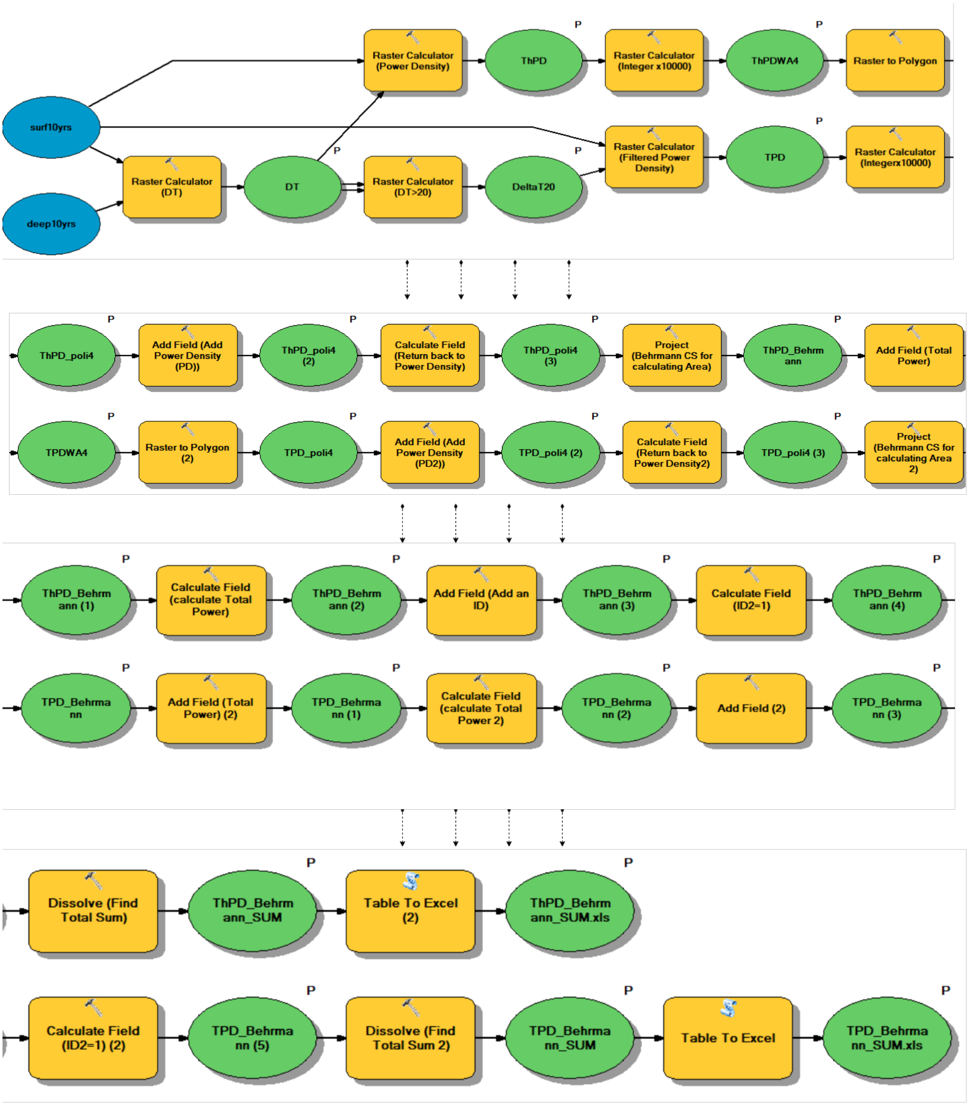


Figure 3: Theoretical and Technical Potential Model Builder Flow Charts

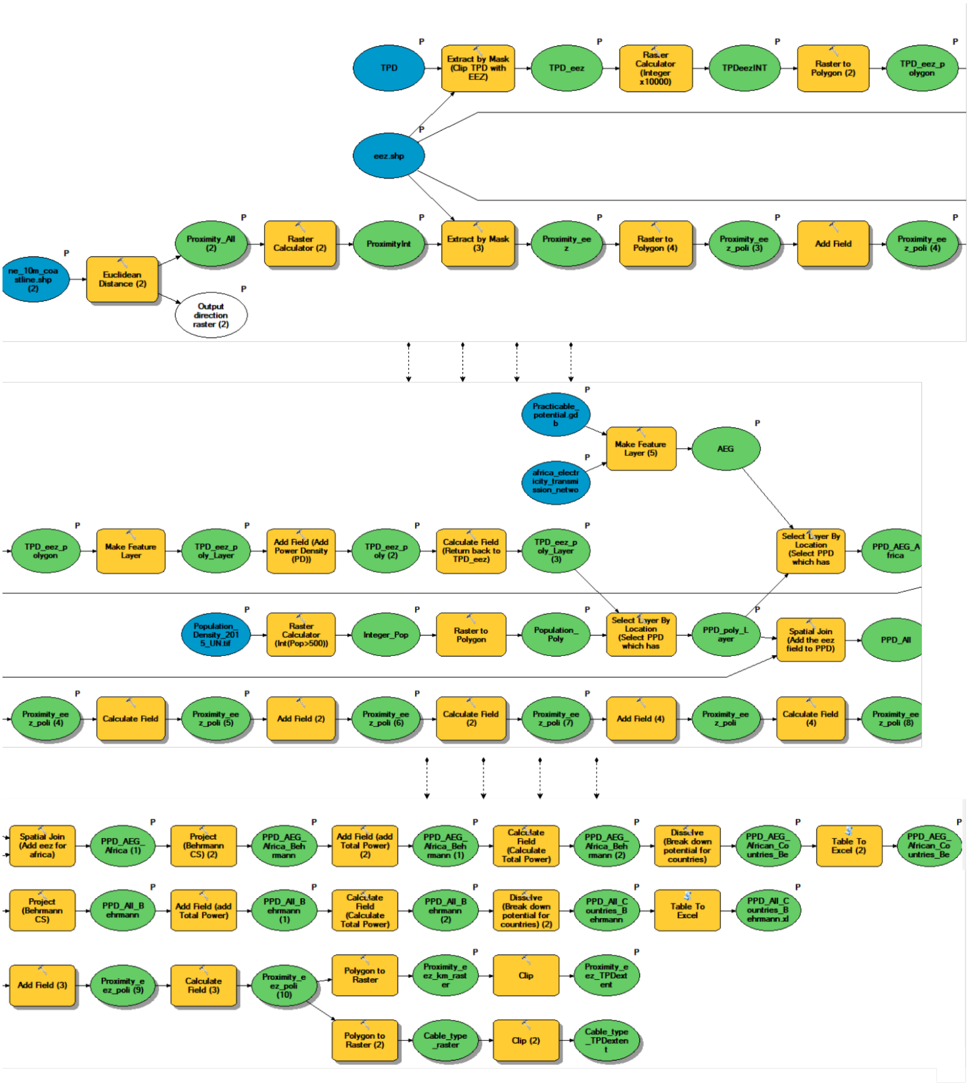


Figure 4: Practicable Potential Model Builder Flow Charts

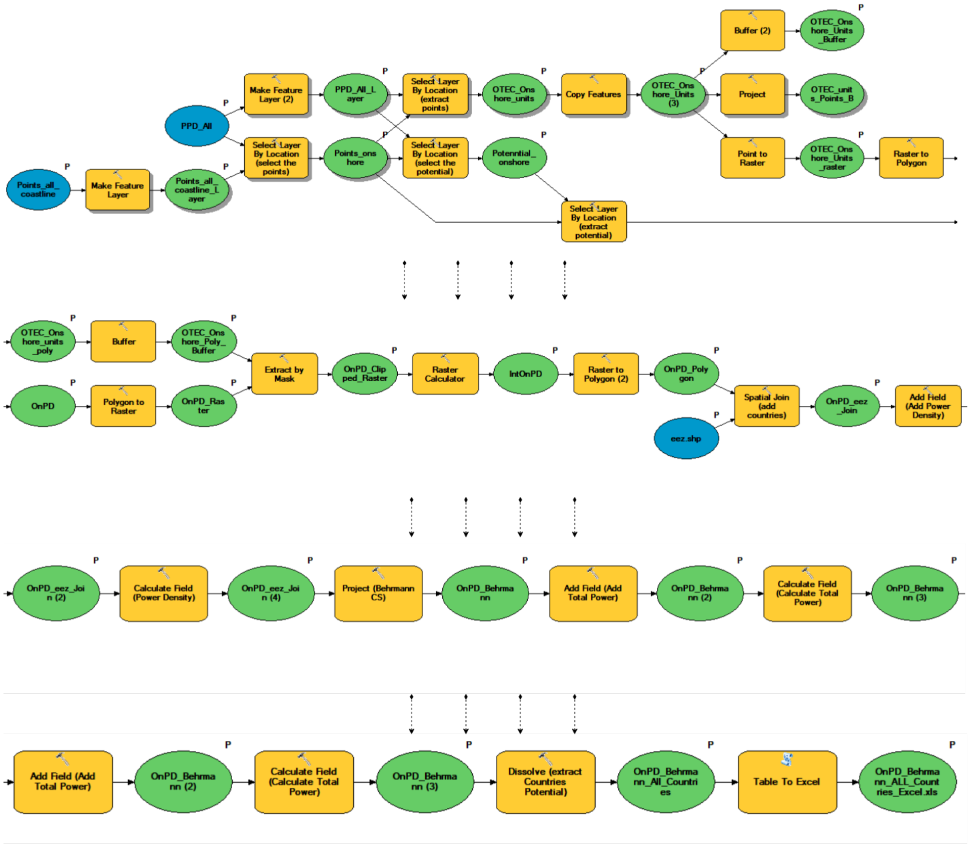


Figure 5: Onshore Potential Model Builder Flow Charts

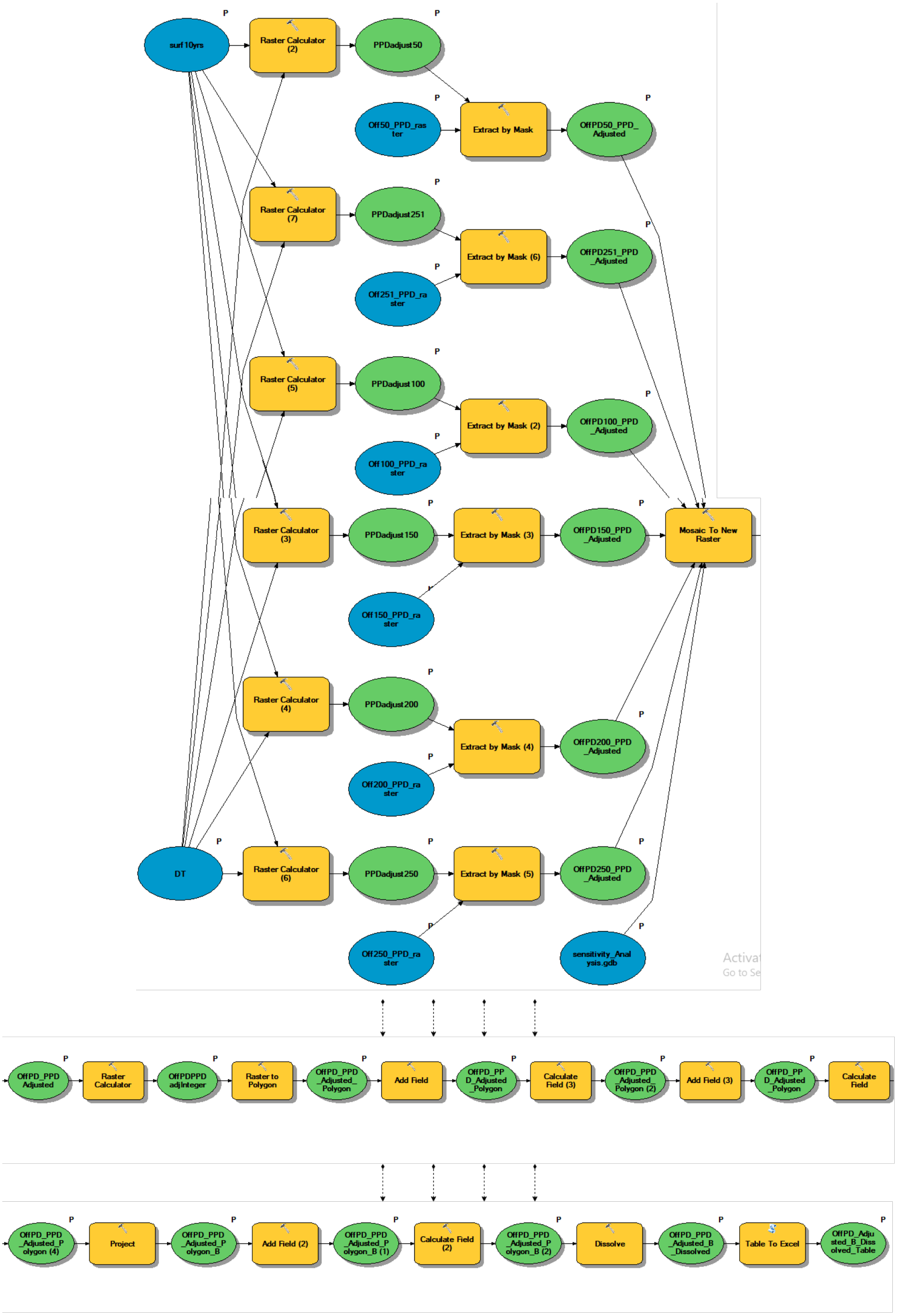


Figure 6: Offshore (Adjusted) Potential Model Builder Flow Charts

APPENDIX I

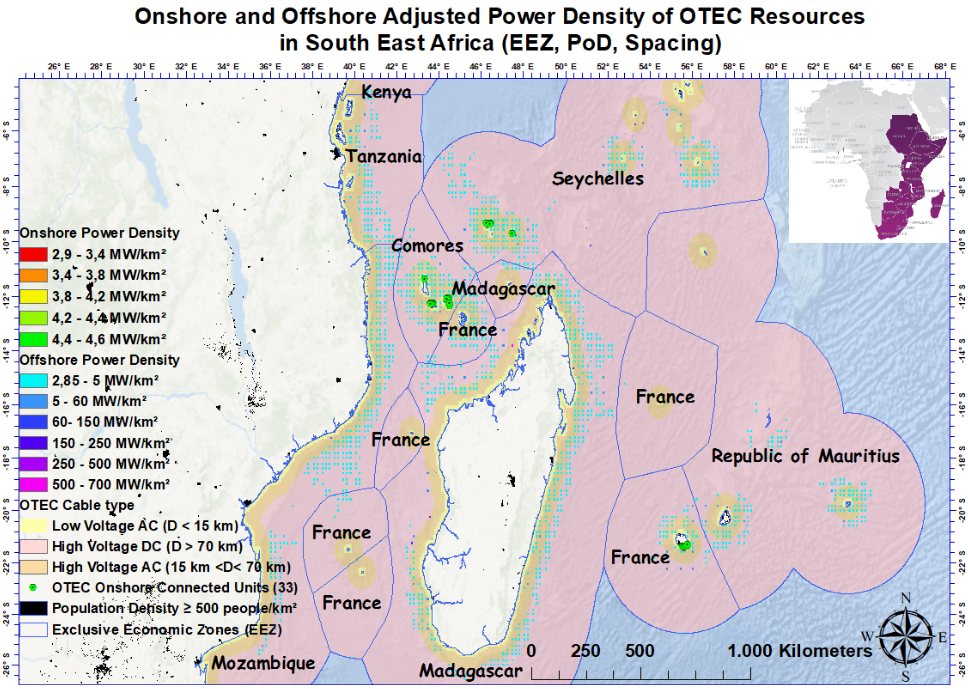


Figure 7: Adjusted Onshore and Offshore OTEC Resource Potential in Africa with EEZ, PoD and spacing criteria applied

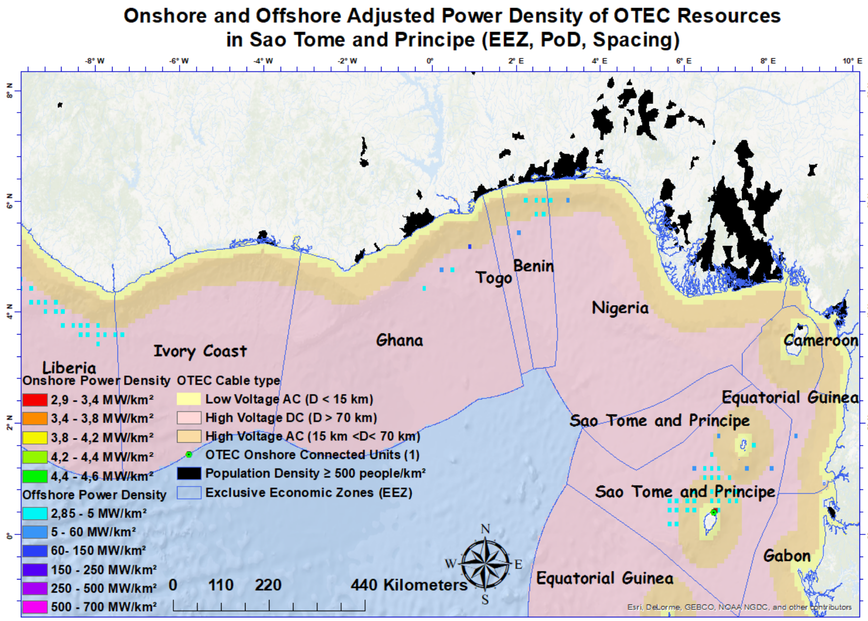


Figure 8: Adjusted Onshore and Offshore OTEC Resource Potential in Sao Tome and Principe with EEZ, PoD and spacing criteria applied

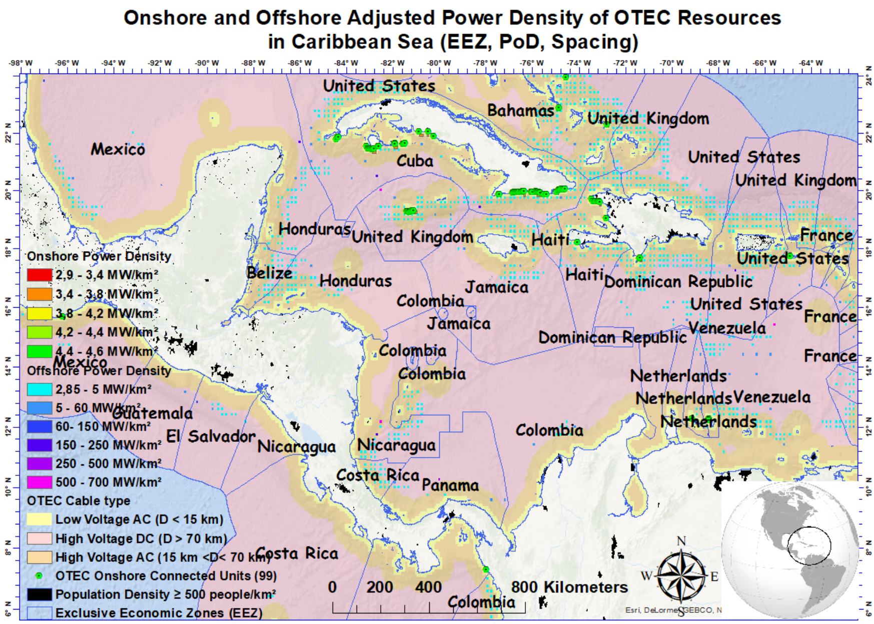


Figure 9: Adjusted Onshore and Offshore OTEC Resource Potential in Caribbean Sea with EEZ, PoD and spacing criteria applied

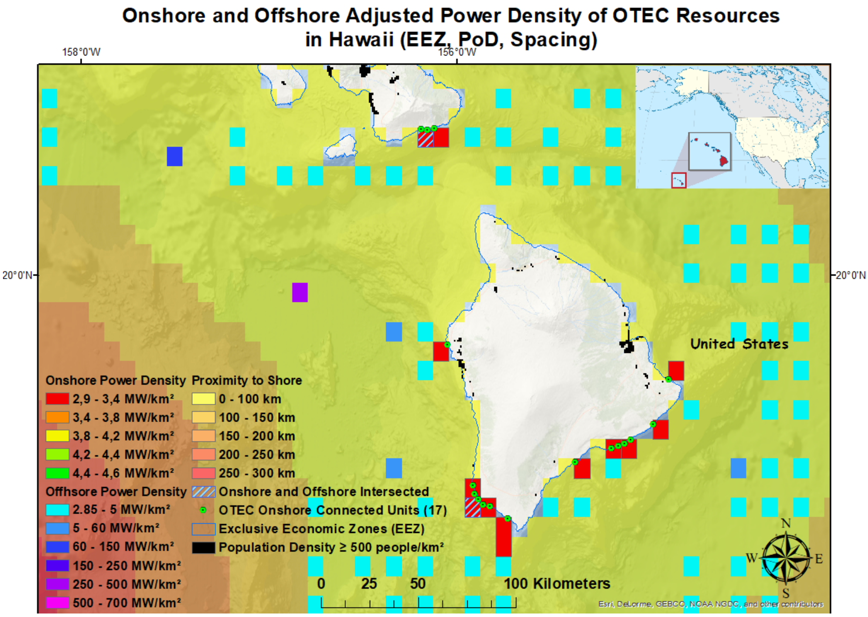


Figure 10: Adjusted Onshore and Offshore OTEC Resource Potential in Hawaii with EEZ, PoD and spacing criteria applied

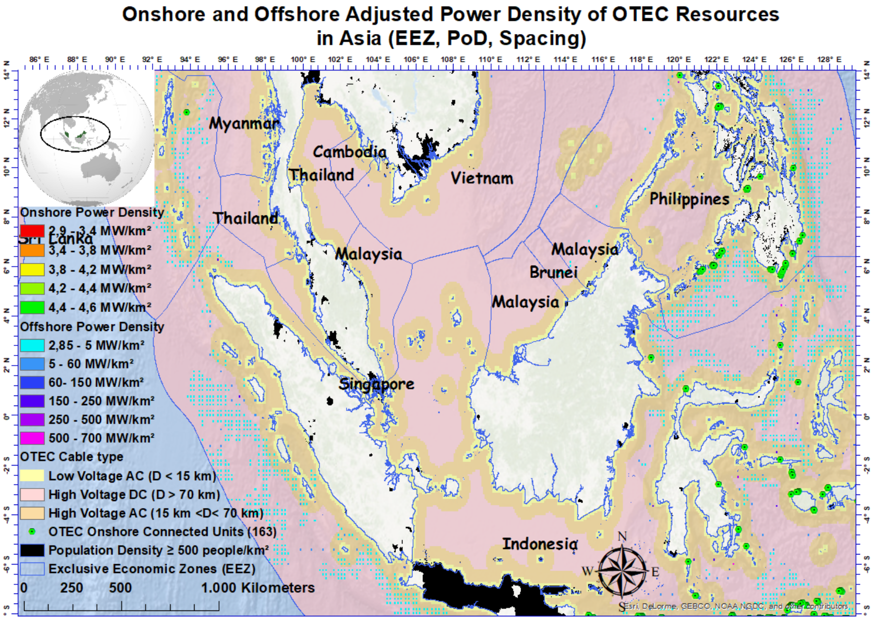


Figure 11: Adjusted Onshore and Offshore OTEC Resource Potential in Asia with EEZ, PoD and spacing criteria applied

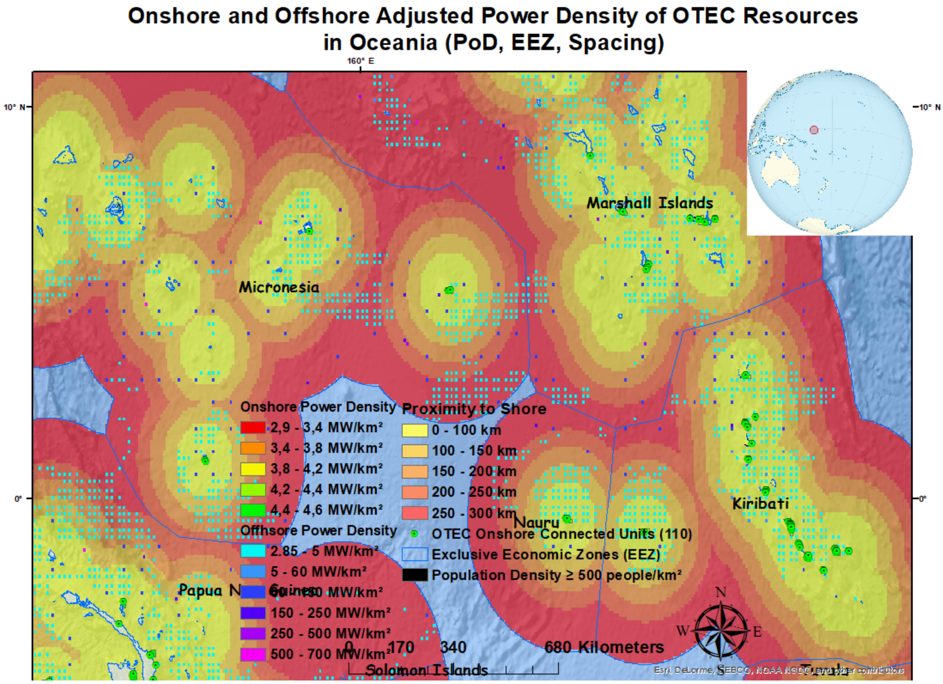


Figure 12: Adjusted Onshore and Offshore OTEC Resource Potential in Oceania with EEZ, PoD and spacing criteria applied