National and Global Projection of the Economic Potential of Ocean Thermal Energy Conversion and Development of Implementation Scenarios

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National and Global Projection of the Economic Potential of Ocean Thermal Energy Conversion and Development of Implementation Scenarios

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Für meine Mutter, die mir das Leben schenkte und mich wie kein anderer Mensch geprägt hat.

Für A.A.C.R.S., mein Fels, mein Kompass, mein Gegenpol, meine beste Freundin, meine Liebe.

Executive Summary

Extreme weather phenomena like the devastating hurricane season of 2017 prove once more how anthropologic climate change commences to exert its unsettling effects upon global flora and fauna and that a transition to cleaner, more renewable energy sources is necessary. One option for this is Ocean Thermal Energy Conversion (OTEC) which could potentially provide over 30 TW of clean and continuous energy. But although such potential sounds intriguing, OTEC's contribution to the global energy transition has been marginal to non-existent and the technology's journey to commercialisation reprobates to an odyssey of cancelled, delayed and failed pilot projects. As it turns out, the 30 TW above are merely the theoretical potential of OTEC and the practicable potential is considerably lower with only 4.4 TW. However, little is known about the economic potential of the ocean technology. Hence, this thesis for the M.Sc. Course "Sustainable Energy Technology" at TU Delft endeavours to tackle this problem by projecting the economic potential of OTEC on a national, international and global scope with and without the consideration of learning effects. Furthermore, hypothetical experience curves are designed based on a set of implementation scenarios with variables and parameters observed from similar technologies like offshore wind power.

The literature study in chapter 2 revealed a total of four knowledge gaps. First, there are no studies on the economic potential of OTEC in general. Second, the discount rate used in contemporary assessment of OTEC's economics are negligently or not argued for. Third, deep financial and economic data remain predominantly unaddressed and fourth, there are no detailed elaborations on experience curves and learning effects of OTEC. Moreover, there are strong discrepancies of scholars and industry within and beyond the niche of OTEC, i.e. regarding the capital expenses (CAPEX). Based on these conflicts, the results are not presented as precise values, but as ranges of best-, base- and worst-case projections. By this, the study maintains an unbiased point of view and strives to find a balance with academic and industrial research on OTEC.

The methodology employed in this thesis is presented in chapter 3. The construction of supply curves based on the LCOE is perceived as the most suitable modus operandi to perform the activities mentioned above. The economic potential of moored, closed-cycle OTEC is analysed with a discount rate of 10 and 18 %, respectively, and refers to five different scales of capacity, namely 2.5, 10, 20, 50 and 100 MW. With two layers of reference costs, worst- and best-case values are determined which form a range of conceivable economic potentials. Before the analysis commences, a set of suitable tropical islands is selected by contrasting them to a total of five selection criteria, namely (1) geography, (2) climate, (3) fossil fuel import dependency, (4) final electricity consumption and (5) electricity demand distribution. This results in a host of 29 islands, whose economic potential is first determined on a solely national, then international scope. The impact of changes in discount rate on the results is investigated by means of a sensitivity analysis. The insights of these supply curves are then used to extrapolate them to a global level. To generate more understanding about possible roadmaps for OTEC

implementation and their effects on the economic potential of OTEC, four implementations scenarios are designed on whose bases experience curves are plotted. Additionally, it is possible to project distinct implementation phases and to indicate them on the global supply curves.

In chapter 4, the economic potential of OTEC at 29 tropical islands is computed and aggregated to a total range of 0 – 390.1 GW for a discount rate of 10 % and 0 – 381.7 GW for 18 %, respectively. A sensitivity analysis elucidated the considerable impact of the discount rate on the shape of supply curves, at least for worst- and base-case cost estimations. Another striking peculiarity is the starkly heterogenous distribution of the economic potential across the 29 islands. Indonesia, Papua New Guinea and the Philippines already comprise around 61.5 % of the aggregate potential, while it is merely 9.8 % for the second-best hotspot consisting of Cuba and the Dominican Republic. The observed trends in LCOE and real energy output are used to extrapolate the supply curves to a global level. For a discount rate of 10 %, a global potential of 0 – 645 GW is computed, which reduces to 0 – 633 GW for a discount rate of 18 %.

According to the results of chapter 5, OTEC's impact on global electricity system is going to be marginal in the near- to mid-term future with a proportion of just 0.91 % at an annual installation growth rate of 40 % after 24 years. In such a scenario, merely 3.58 % of the previously determined economic potential would be harnessed. To employ 99.9 %, it would take 35 years at the same growth rate, after which OTEC could theoretically cover over 20 % of global electricity consumption. With progressing implementation of OTEC, the effects of economies of scale are offset by the deterioration of the quality of possible deployment locations. However, even a low learning rate of 6 %, combined with economies of scale, can neutralise the cost increases due to low-quality locations. To sustainably push the dynamic global supply curves below a reference cost of 20 $ct./kWh, high growth rates, strong learning and public participation are required.

Chapters 6, 7 and 8 reflect upon the work performed in the previous chapters by means of a discussion, recommendations and a conclusion, respectively. Although this thesis succeeded in filling three of the four detected knowledge gaps, with results being in line with literature, many of the limitations of this study boil down to a lack of empirical data on OTEC and oceanography in general. Furthermore, the global scope of the analysis lead to technical, economic and geographic generalisations which could be avoided by choosing a more spatially limited scope. These drawbacks are addressed by recommendations for future research, but also by a remark on the indisputable necessity and urgency of pilot plants and explicit implementation strategies to render OTEC's development prosperous. Chapter 8 answers the sub research questions directly and elaborates on the main research question on a meta level.

Table of Contents

List of Figures

List of Tables

1. Introduction

Harvey, Irma, Maria. The *enfant terribles* made international news in the late summer of 2017 when they wreaked havoc across the Caribbean Sea and the Gulf of Mexico. Destruction and calamity ensued wherever the trio hit land, as they caused billions of dollars of damage and claimed the lives of hundreds of people[1]. Eventually, Harvey would vanish into thin air, then Irma, then Maria, never to be seen again (NOAA, 2017). They were not human beings. They were hurricanes.

There is strong evidence that climate change is the string-puller of these events. As the rise of seawater temperature due to global warming fosters the emergence of such extreme weather phenomena, scientists indicate that the happenings of Summer 2017 were not just coincidences, but a foretaste of what might become gruesome routine in the future (Sneed, 2017). This unsettling notion is only one of myriad reasons why decision makers worldwide are galvanised to mitigate climate change and to embrace sustainability as their new leitmotif. One dogma of this school of thought is the reduction of greenhouse gases and concomitantly a more frugal use of fossil fuels, whose combustion produces these very pollutants. Since global energy systems still mainly foot on these fuels, a transition from conventional to sustainable energy sources is a *sine qua non* to render climate change mitigation successful.

Tropical island countries take this challenge rather serious. Particularly affected by the consequences of climate change, they are motivated to break the clutches of fossil fuels and to become a paradigm of sustainability. Their endeavours are epitomised by some of the world's most audacious targets for renewable energy implementation (Dornan & Shah, 2016). Not only are tropical island states repelled by the implications of fossil fuel deployment, but also by the resource itself. As most of these countries do not possess own reservoirs, they are bound to import them for staggering and highly volatile prices (Niles & Lloyd, 2013).

One technology which could aid tropical island countries in establishing more sustainable energy systems is Ocean Thermal Energy Conversion (OTEC). OTEC utilises the temperature difference between surface water and deep ocean water at a depth of around 1000 m to generate electricity (Fujita et al., 2012; Vega, 2012). In recent years, computer simulations resulted in a global OTEC potential of up to 30 TW of net power output (Rajagopalan & Nihous, 2013). Putting this figure into perspective, this potential would exceed the global net electricity generation in 2015 by almost a twelvefold (EIA, 2017). However, although tropical islands meet the stringent oceanographic and climatic requirements for OTEC deployment, its contribution to the proclaimed energy transitions is yet marginal to non-

[1] The National Oceanic and Atmospheric Administration (NOAA) reported 65 deaths by Hurricane Maria, 97 deaths by Hurricane Irma and 89 deaths by Harvey. The costs of damages were estimated at US$ 90.9, 50.5 and 126.3 billion (2017 values).

existent. Instead, the technology has been lingering in a niche existence for decades, with alternatives like photovoltaic and wind power being preferred.

One might wonder why the power of the ocean has predominantly remained untapped despite OTEC's vast potential? It seems that semantics are both the origin and the resolution of this conundrum as the shape and the scope of a potential depends on its definition. Concerning energy technologies, literature distinguishes certain levels of potential, which gradually descend from theoretical to more and more practical values (Angelis-Dimakis et al., 2011; Blok & Nieuwlaar, 2016; de Vries, van Vuuren, & Hoogwijk, 2007). Therefore, while a potential of 30 TW of net OTEC power provides the fabric for catchy power point presentations, it does not necessarily reveal what proportion can actually be deployed under real-life conditions.

As it turns out, the 30 TW above are merely a projection of what is *theoretically* viable without the consideration of technical constraints. If these are taken into account, like a minimum temperature difference of 20 °C and a cold seawater depth of 1000 m, respectively, a *technical* potential is computed which is already considerably lower vis-à-vis its theoretical predecessor. Charalampos Chalkiadakis (from now abbreviated as Chalkiadakis in the main text), a graduate from TU Delft and Leiden University, went even further and estimated the *practicable* potential of OTEC. By adding even more constraints like distance to shore, population density and many others, he concluded that approximately 4.4 TW of OTEC are practicably deployable across the globe (Chalkiadakis, 2017). But is this an ultimate representation of OTEC's "real" potential?

Unfortunately, it is not. While Chalkiadakis' thesis forged understanding about the practicability of OTEC, it does not address barriers erected by economic and financial constitutions. In fact, the *economic* potential of OTEC is barely covered in current literature at all, mostly limited to qualitative estimations and references to future research. While there are cost analyses of individual OTEC projects and models, none of these publications frame their insights into the bigger picture of the technology itself. Thus, current literature fails to display to which extent OTEC can be implemented economically on a national and global level. For the former, it remains unclear how OTEC performs under the light of regional and national wholesale electricity prices and how the technology performs economically based on geographic and climatic conditions. For the latter, no insights are provided on what impact OTEC could make on global energy systems in an economically sound way and how its future implementation might be shaped. Important aspects like cost reductions by learning and its implications on the economic potential of OTEC in the short-, medium- and long-run are predominantly neglected hitherto.

This thesis for the M.Sc. course "Sustainable Energy Technology" at TU Delft strives to tackle the prevailing knowledge gaps by projecting the economic potential of OTEC on a national and global level with and without learning effects. Based on the deficiencies in contemporary OTEC research, the following main research question is articulated consisting of multiple sub questions.

What is the national and global economic potential of OTEC and what are conceivable trajectories of global OTEC implementation under consideration of learning effects?

1. *How is the economic potential of renewable energy technologies determined in current literature and which methodology is suitable for the evaluation of OTEC and its economics?*
2. *Which tropical islands are the most suitable for OTEC deployment in terms of geography, demography and electricity demand?*
3. *What is the range of economic potential of OTEC for the selected host of tropical islands and how can the economic potentials be translated from a national to a global level?*
4. *What are conceivable implementation scenarios for OTEC and how do they affect its future economic potential based on global experience curves?*

To answer the research questions above, this study follows a modelling approach. Unfortunately, there are no commercial OTEC plants or even pilot plants at sufficient scale as of today in summer 2018, which impedes the availability and application of empirical OTEC data. In lieu, proxies are determined based on contemporary literature and observations in comparable renewable energy niches, such as offshore wind. Therefore, the deliverable of this thesis are not prognoses based on hard, empirical OTEC data, but hypothetical projections of conceivable trajectories for OTEC development under the fulfilment of certain premises.

The thesis is structured as followed. After the introduction in chapter 1, a literature study is performed in chapter 2 to detect knowledge gaps in contemporary literature on which the research questions foot. Subsequently, the methodology employed to answer these questions is presented in chapter 3. There, it is explained how national and global supply curves are modelled and which data is used. It is also elaborated how the host of suitable island countries and territories is determined based on multiple selection criteria. Furthermore, the methods to design implementation scenarios and experience curves are explained and how their results are integrated into the supply curves. The corollaries of the economic analysis are then presented in chapter 4 in the form of national and international supply curves, which are extrapolated to a global level. Chapter 5 shifts the thesis from a static to a dynamic point of view and contrasts these supply curves to the effects of learning by means of global experience curves. These curves are shaped based on a total of four implementation scenarios which also provide insights about conceivable roadmaps for OTEC development. The methods and results are discussed in chapter 6 and shortcomings elaborated there are addressed in chapter 7 with recommendations for future research and development of OTEC. The final chapter answers the main and sub research questions and provides a concluding remark. Figure 1.1 illustrates the roadmap through this thesis.

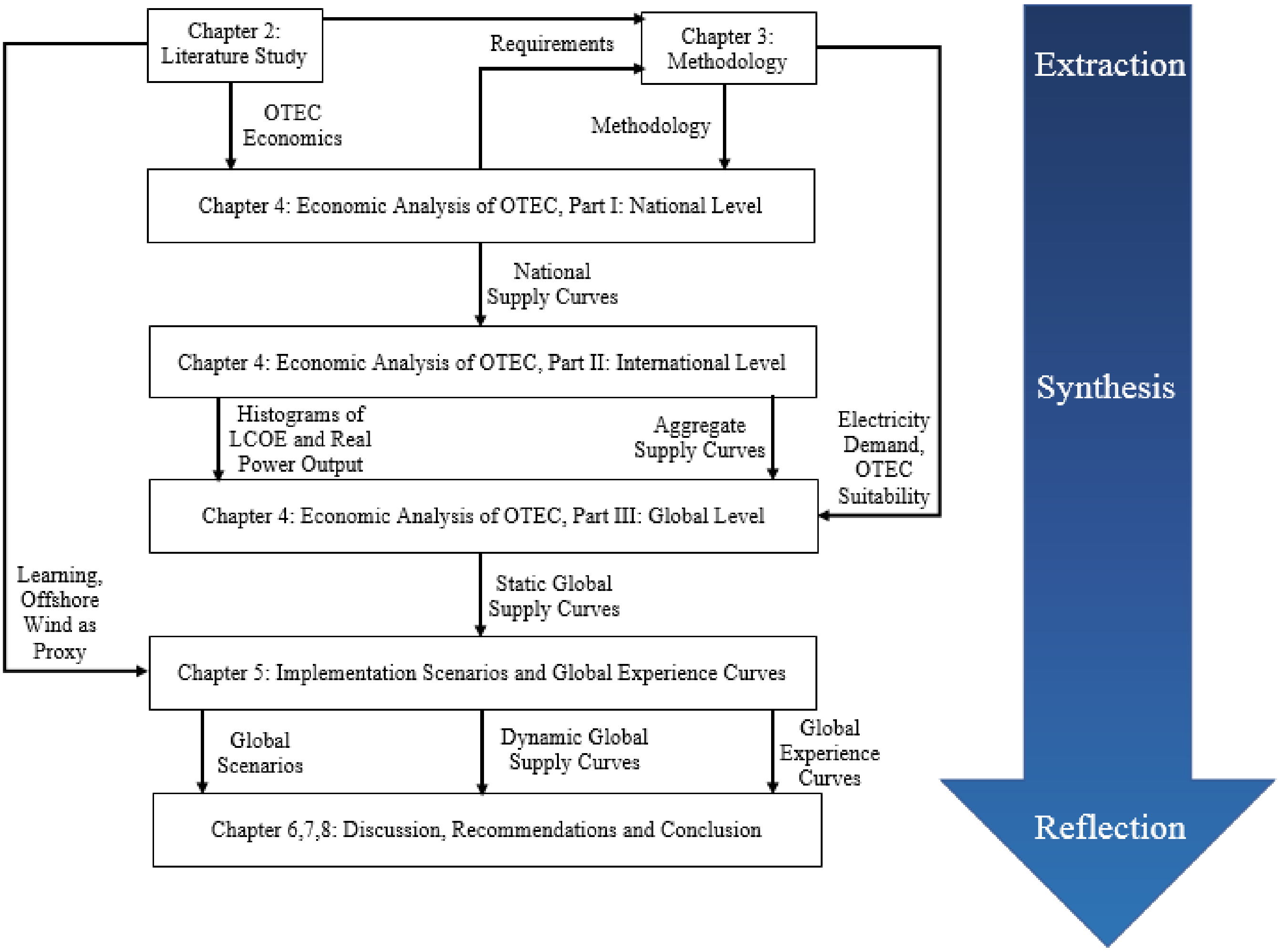

Figure 1.1 Roadmap Through Thesis (Own Illustration).

2. Literature Review

In this chapter, the results of the literature study are presented which focussed on how the economic potential of renewable energies are generally determined, the state of the art of OTEC economics and the effects of learning on the costs of energy technologies. A whole set of research tools is mobilised to extract and process a decent amount of publications. First, studies are traced by using search engines like ScienceDirect, Scopus, google and google scholar as well as the web presence of the TU Delft Library. Among myriad others, search terms include “economic potential”, “economics”, “Ocean Thermal Energy Conversion”, “renewable energy”, “energy” and combinations of the mentioned expressions. Preferred literature is published in peer-reviewed journals in English language within the last 10 – 15 years. Older publications are also included given that the content is still relevant today. Snowballing – obtaining literature from the reference list of a paper – is performed as well, but only to a certain level to avoid redundancy. After the references are extracted from the internet, they are stored via Mendeley in different folders to make them easily accessible for future use.

2.1. The Determination of Economic Potential of Renewable Energies

The first part of the literature study predominantly dealt with the methods applied in academia to determine the economic potential of renewable energies. The key insights of the literature review are that (1) OTEC is barely covered in contemporary literature regarding economic potentials, therefore revealing a knowledge gaps and that (2) the construction of cost-supply curves is the dominant method in literature to obtain the economic potential of renewable energies (Bidart, Fröhling, & Schultmann, 2013; de Vries et al., 2007; Liu, Wang, & Zhu, 2017; McElroy et al., 2009; Mercure & Salas, 2012; Nagababu, Kachhwaha, & Savsani, 2017; van Vuuren, van Vliet, & Stehfest, 2009). The details of the reviewed papers unrelated to the methodology will not be mentioned here, but interested readers are invited to consult section A in the appendix.

In most cases, the construction of supply curves is relatively straightforward and comprises the following steps. First, locations suitable for the implementation of a technology are mapped within the proclaimed spatial boundaries, i.e. by using geographic information systems. Subsequently, the costs and the revenues of the technology are calculated for each determined location. Based on these, the individual levelized costs of electricity (LCOE) are generated. The LCOE is the minimum average price at which electricity needs to be sold to reach parity with all expenditures of a project at the end of its useful lifetime (IEA, 2015; Visser & Held, 2014). Endowed with both the energy output and the LCOE at each location, it is then possible to construct a supply curve by arranging the LCOEs from smallest to largest and to plot them against the cumulative electricity supply. When the supply curve is contrasted to a reference cost, say the local wholesale price of electricity, one can distinguish the fractions of the supply curve which are economically viable vis-à-vis the ones which are not. The parts of the plot *below* the reference cost are considered as economically sound and aggregate to a total economic potential. Figure 2.1 below visualises the methods described above with a qualitative supply curve.

Since locations eligible for OTEC deployment were already mapped by Chalkiadakis on a global level, the construction of supply curves represents the logical continuation of his research and is therefore the most suitable modus operandi for this thesis. The next sub sections of this literature review systematically address all variables, parameters needed for the supply curves. Starting with the calculation of the LCOE itself, light is shed on the choice of *Discount Rate* (DR) and on the state of the art of OTEC economics. Then, the chapter moves on with the review of learning effects and experience curves which will be of great pivot in later chapters.

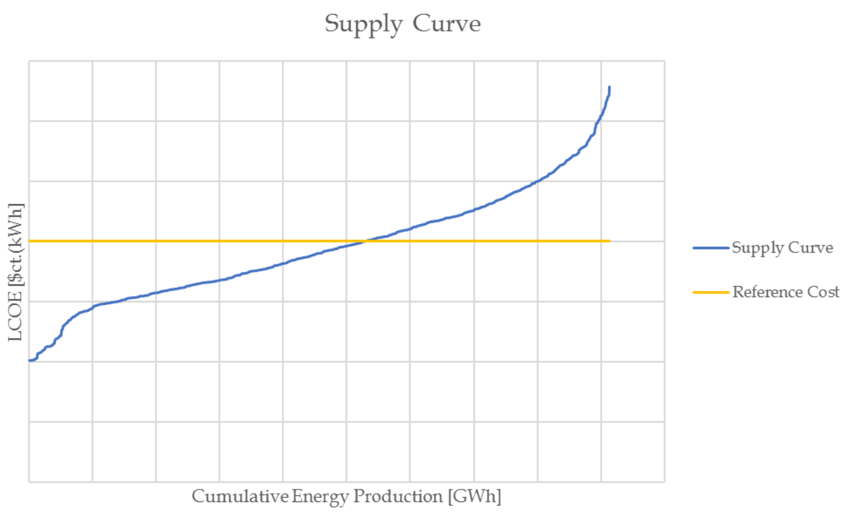

Figure 2.1 Qualitative Visualisation of a Supply Curve (Own Illustration based on Bidart et al., 2013).

2.2. Supply Curve Modelling

2.2.1. Levelized Cost of Electricity (LCOE)

The first variable looked upon in more detail is the LCOE itself. It is widely acknowledged throughout academia and industry as an effective tool to compare different energy technologies and, thus, to help at investment decisions (Henbest et al., 2015; Visser & Held, 2014). The essential equation used in this thesis is shown below in equation (1).

$$LCOE = \frac{\sum_{t=1}^{N} \frac{CAPEX_t + OPEX_t}{(1+DR)^t}}{\sum_{t=1}^{N} \frac{E_t}{(1+DR)^t}} \tag{1}$$

Basically, the LCOE as computed above consists of the *capital expenses* (CAPEX), *operational expenses* (OPEX) and the amount of energy E_t produced in the years t over a technical lifetime N. Usually, there would also be fuel costs as in the case of coal and gas plants. But since OTEC's "fuel", if it can be even called as such, is abundant seawater, fuel costs are considered as zero and fall out of the equation. Cash flows occurring in the future are adjusted for present values using a *discount rate* (DR). The reader is expected to have a basic understanding of economics and the concept of discounting. If this is not the case, an explanation can be found in Appendix B. Instead of a discount rate, some scholars use a *Capital Recovery Factor* (CRF) to calculate the LCOE. Both methods compute the same result and equation (1) and a more detailed explanation of CRF can be found in Appendix B as well.

When calculating the LCOE, a critical junction is the extent of which advanced financial and fiscal data is used, for instance cost of capital, taxes, depreciation and many more. In this regard, there is no black or white in current literature, as the level of inclusion varies over the whole spectrum. While some scholars fully neglect deep financial aspects (Magesh, 2010; Oko & Obeneme, 2017; Straatman & van Sark, 2008; Vega, 2012), others ameliorate their computations by considering corporate and value added tax, interest payments, debt-to-equity ratio, depreciation, tax deductibility and even tax credits (Comello, Glenk, & Reichelstein, 2017; Darling et al., 2011; Liu et al., 2017; McElroy et al., 2009; Purohit & Purohit, 2017). Who are those scholars that limit their calculations to the bare, financial minimum?

As it happens to be, they all belong to the research field of OTEC and this reduction entails both benefits and drawbacks. On the one hand, it renders economic assessments rather straightforward. It is extraordinarily suitable for preliminary and general cost evaluations, especially for technologies whose financing is yet unknown, as in the case of OTEC. Thus, the negligence of deep financial data in OTEC literature is acceptable considering the technology's financial ambiguity and immaturity. On the other hand, simplifications come at the price of precision and credibility. Consequently, there is the ubiquitous risk of fostering inadequate hopes and expectations due to oversimplifications distorting the actual profitability of the technology. Regarding the OTEC niche, merely a technical report drafted by the company Lockheed Martin from 2012 provides sophisticated considerations regarding corporate and project finance of OTEC (Martel et al., 2012). Regarding academia, though, a second knowledge gap in current OTEC literature is unveiled.

Whether this gap ought to be tackled or not depends on the objective of the study. This thesis focusses on a large host of tropical island states with distinct financial and fiscal environments. In many cases, these differences are great enough to significantly curb the space for generalisations. Thus, the economic analyses here will follow the approach of contemporary literature and merely perceives CAPEX and OPEX as the only cost factors. Nevertheless, the inclusion of financial and fiscal data, especially for analyses on a regional level, is strongly advocated for in future research. For this, a *Discounted Cash Flow Analysis* (DCF) would be an appropriate method. A detailed elaboration on DCF can be found in Appendix C.

2.2.2. Determination of Private and Public Discount Rates

Some of the most fundamental questions which arose during the literature study on the LCOE revolved around the discount rate. How is it determined? Are there certain rules and guidelines? Or is it selected arbitrarily? The last question might sound absurd, but in fact there are publications in which the choice of discount rate is not or negligently argued for, i.e. (Blechinger et al., 2016; Fath et al., 2015). Considering the stark sensitivity of the discount rate, such opaqueness might pose adverse impacts on the robustness of economic studies. Therefore, this section deals with the peculiarities and complications involved in finding a commensurate discount rate, first for private and then for public projects.

2.2.2.1. Weighted Average Cost of Capital

The capital of a company consists of debt and equity. While the former requires an annual repayment of a principle plus interest, the latter expects a certain return on the total equity invested (Henbest et al., 2015). The capital, therefore, comes at a certain cost. The cost of debt and cost of equity, when weighted for their proportions, amalgamate to a *Weighted Average Cost of Capital* (WACC), which is commonly used as a discount rate for private projects by companies. The WACC incorporates a confluence of different risks entailed by a project, for instance regarding the company, technology, implementation country or the underlying project. Hence, it matters decisively *who* implements *what*, *where* and *how* (Henbest et al., 2015; IEA, 2015; Noothout et al., 2016). A precise calculation of the WACC surpasses the scope of this thesis by far and interested readers are referred to advanced literature. And even if it was the scope of this work, myriad complications arise. First, there is neither profound financial data on OTEC projects nor companies, as commercial OTEC is yet unprecedented (Edenhofer, Pichs Madruga, & Sokona, 2012). Per se, it is possible to calculate country-specific WACCs without project data, i.e. via the guidelines provided by the executive board of the *Clean Development Mechanism* (CDM) from the United Nations (UNFCCC, 2011). Their framework has also been applied in literature (Ondraczek, Komendantova, & Patt, 2015). But even the authors themselves deploying it conceded that the accuracy is severely hampered by simplifying assumptions, with results that do not necessarily reflect real conditions appropriately for some countries.

With all those question marks blocking the way, resourcefulness seems to be the virtue of demand. In fact, obtaining an appropriate discount rate for every tropical island could be the work of a whole research circle, but not of this thesis. Instead, a private discount rate is chosen based on other ocean technologies, i.e. floating wave energy. This technology also lingers at a pre-commercial stage and comprises high investment risks, just like OTEC (Edenhofer et al., 2012). For floating wave energy, a discount rate of 18 % is estimated in literature and adapted for this thesis as a WACC (Oxera Consulting Ltd, 2011). However, the discount rate might be alleviated over time, as risks are curtailed with rising experience. The change in discount rate over time is acknowledged but not further pursued here.

This value stands in strong contrast with discount rates employed by OTEC literature, which oscillate between 7.4 – 13 % (Avery, 2003; Magesh, 2010; Muralidharan, 2012; Oko & Obeneme, 2017; Straatman & van Sark, 2008; Vega, 2012). Although such rates might be appropriate for public projects, as explained later in this section, OTEC scholars do not specify that and based on their argumentation, it must be assumed that they predominantly perceive private OTEC projects. While many scholars use the interest on bank loans as their discount rates, one needs to question their validity.[2] For whom are these lending rates designed, prime borrowers or high-risk clients? Do these interest rates reflect the inherent risks connected to OTEC? Do those discount rates include costs of equity? These are objections which barely find attention in current OTEC literature and therefore draw a deceptive picture of OTEC. Consequently, the use of oversimplified discount rates is detected as a deficiency in contemporary OTEC literature. A real discount rate of 18 % also defies the methodology proposed by CDM's executive board, which could result in a WACC as low as 3.7 % (for Japan) for *any* technology, (Ondraczek et al., 2015) which needs to be discarded as unreasonable.

It is acknowledged that a one-size-fits-all discount rate for every analysed country in this thesis is generalising and ignoring country-specific peculiarities. But the rate adapted here originally regarded to developed countries and is therefore rather generous towards less developed sovereignties, which would most likely face noticeably higher WACCs in practice. The impact of the choice of discount rate on the LCOE will be analysed in detail later in this thesis by means of a sensitivity analysis.

2.2.2.2. Social Discount Rate

Alas, things are even more complicated for public projects. Compared to their private counterparts, public ventures bear a far higher social responsibility. Taxpayers want to see their money well-spent and aspects like social welfare, apposite utility distribution and sustainability are key factors to be considered. Thus, while the societal impact of a project is a rather elastic concept in the accounts of private corporations, they are essential for public decision making. This also reverberates in the *Social Discount Rate* (SDR) applied for public undertakings and policy decisions (Palinko & Szabo, 2012).

Obviously, the WACC introduced above is not suitable as an SDR, since it does not appreciate societal factors accordingly. But unfortunately, this is where the consensus among scholars ends. Contrarily, when it comes to the SDR and the methods to calculate it, not only theory, but also practice could hardly differ more, with reconciliation not in sight (Zhuang et al., 2007). Resorting to economics, one way to look at the SDR is from the demand side. According to the *Marginal Social Rate of Time Preference* (STP), people prefer social benefits rather sooner than later and the discount rate ought to reflect the extent of this preference. On the other hand, one could also adopt an attitude towards the supply side and interpret the SDR as the rate of return of foregone investments, or *Social Opportunity*

[2] Merely Bluerise (2014) and Muralidharan (2012) use the WACC as a discount rate. Others like Vega (2012), Oko & Obeneme (2017) and Upshaw (2012) explicitly state bank loans as their sole basis.

Cost (SOC). Note that in a perfect market, the SDR would equal to an equilibrium market rate independent of whether STP or SOC is applied (Spackman, 2016; Zhuang et al., 2007). But due to market distortions, real markets are not perfect and thus the SDR is affected by the method employed (Boardman et al., 2010).

Where there is conflict, there is also diplomacy, and besides STP and SOC, there are also hybrid methods combining the best of both approaches. Some countries and agencies do not use any of the methods above directly at all, and in lieu draw on their costs of borrowing, avoiding the feud between STP and SOC. Putting all these options into perspective, there are neither inter- nor intranational trends observable of which technique is applied by which country or region (Spackman, 2016). Unsurprisingly, these complications render many decision makers scratching their heads in confusion.

To console the reader, the situation is not completely hopeless as there are at least some general trends independent of the method. First, the social discount rate is less stringent vis-à-vis their private counterparts. This is because the risks accompanied by a project is hedged over far more people, namely the taxpayers of a country or region. Additionally, the focus of public undertakings are not as much focussed on short-term returns as in the case of private projects, since they strive for benefits unfolding not only over months and years, but also decades and even generations (Boardman et al., 2010; Palinko & Szabo, 2012). Second, developing countries generally use higher SDR than developed countries. The former articulate their rates in accordance to recommendations of international development banks like the World Bank and the Asian Development Bank, comprising 10 – 12 % (Harrison, 2010; Zhuang et al., 2007). In contrast, the latter varies between 3 – 6 %. This is reasonable, as developing countries are much more concerned with projects generating short-term benefits, such as the establishment of stable food and water supplies (Spackman, 2016).

Due to a lack of available data on country-specific social discount rates, the SDRs in this thesis are adapted from the recommendations of the World Bank and the Asian Development Bank. Since the vast majority of tropical islands linger in an underdeveloped or emerging state, this results in a public discount rate of 10 % for all perceived islands (Zhuang et al., 2007). Again, a thorough sensitivity analysis will study the implications of different SDR on the economic potential of OTEC.

2.2.3. State of the Art of OTEC Economics

As the discount rates for the economic analysis are determined, the literature study moves on to the state of the art of OTEC's economics. There are many different OTEC concepts, based on closed, open and hybrid cycles, being land-based, moored or grazing plants, et cetera. An elaboration of the functional principle of OTEC is omitted. Instead, interested readers are invited to consult the works of other TU Delft students (Chalkiadakis, 2017; Fuchs Illoldi, 2017; Salz, 2018).

Scholars concur that there are distinct markets OTEC could penetrate in the future. While large-scale, closed-cycle OTEC with a net power output of at least 50 MW are most suitable for industrialised countries, *Small Island Developing States* (SIDS) are eligible for small-scale, open-cycle plants of 1 – 10 MW. The advantage of open-cycle plants is the production of desalinated water, which could generate additional streams of revenue such as drinking water (Banerjee, Musa, & Jaafar, 2017; Muralidharan, 2012; Vega, 2012). But since relevant economic data is only obtainable for moored, closed-cycle OTEC, any other configurations are excluded for the remainder of this work. This also affects land-based systems, which indeed already exist today in the form of pilot projects, but struggle with fundamental technical, economic and ecological drawbacks which vindicate its abolishment.

In contemporary literature, the focus is predominantly set on moored and to some extent grazing systems instead of land-based OTEC for two reasons. First, although a land-based system would not require a platform and mooring, these cost savings are offset by staggering pipe costs. While a floating system only requires a *cold water pipe* (CWP) of one kilometre reaching to the bottom of the sea, the CWP of a land-based plant would also have to be lead from the coast to the operational site. Considering that the diameter of large-scale plants is roughly 8 to 12 meters, this would pose tremendous costs. From a technical point of view, a longer pipe reverberates in larger pressure drops and a lower efficiency, further hampering the system's profitability. Second, land-based OTEC precipitates larger disruptions with marine ecosystems. Not only has the CWP to be extended to further distances, but also the outlet water pipes. To avoid severe thermal degradation of the sea water, these outlets would also have to reach to the site of water extraction, leading again to economic and technical inefficiencies (Upshaw, 2012).

Although there are economic assessments covering OTEC plants of varying scale, most of them are strongly simplified or foot on outdate sources from the last century. Under the light of technological progress, the literature study performed here only considers economic assessments of OTEC from the last ten years to maintain a sufficient relevance and quality of research. Interested readers, nevertheless, are redirected to the works of Upshaw (2012) and Muralidharan (2012) for further insights on historic economic assessments of OTEC.

In the following paragraphs, current literature is studied with close attention to aspects like economies of scale, CAPEX, OPEX, project lifetime as well as real net power output of closed-cycle, moored OTEC systems. It is strongly emphasised that the costs presented here are merely *projections*. No commercial OTEC plants, let alone markets, exist yet and its implementation merely comprises a couple of pilot plants in the range of some kW to 1 MW at locations like Hawaii, Nauru or Martinique (Edenhofer et al., 2012; Magagna & Uihlein, 2015). Leapfrogging to commercial scales of 100 MW and above as widely proposed in literature seems like a bold venture, as many of these pilot plants could not satisfy the high expectations. Some of them were even abandoned before they could deliver any results at all due to technical, financial or administrative issues (CAG, 2008; IRENA, 2014; Upshaw, 2012). If upscaling poses so many struggles, why endeavouring it in the first place?

2.2.3.1. *Economies of Scale*

Because of economies of scale. OTEC comprises significant potential for cost reductions by the mere upscaling of power output. This is a clear advantage over alternatives like offshore wind, which is suspected to have no or even diminishing returns to scale (Dismukes & Upton, 2015). In the case of OTEC, economies of scale can be accomplished in manifold ways and mainly depends on the individual cost component. For example, while cost factors like heat exchangers scale linearly with capacity, the same cannot be said about other aspects like power cables. While the scale factors of most components can be deduced from similar industries, things get more intricate for items for which there is no experience hitherto, such as the OTEC platform and mooring. Here, scholars resort to rough back-of-the-envelope estimations and underline the necessity of empirical data to corroborate their potential for economies of scale. Table 2.1 below illustrates the behaviour of cost factors for increasing capacities.

Component	100 MW	200 MW	400 MW	α for 100 -> 200 MW	α for 200 -> 400 MW
Cold Water Pipe	61	117	229	0,94	0,97
Platform Structure	190	253	400	0,41	0,66
Side Spar Structure	141	202	297	0,52	0,56
Mooring	66	94	145	0,51	0,63
Deployment	73	109	145	0,58	0,41
Condensers	185	364	721	0,98	0,99
Evaporators	186	367	725	0,98	0,98
Heat Exchanger Connections	54	106	210	0,97	0,99
Ammonia Piping and Storage	5	10	20	1,00	1,00
Ammonia Pumps	7	14	29	1,00	1,05
Warm Water Pumps	50	100	200	1,00	1,00
Cold Water Pumps	38	63	113	0,73	0,84
Turbines	37	73	146	0,98	1,00
General Topsides	84	109	162	0,38	0,57
Power Cable to Shore	69	90	156	0,38	0,79
Design, Permitting, Management	30	51	88	0,77	0,79
Programmatic Costs[3]	255	424	757	0,73	0,84

Table 2.1 Scale Coefficients for Different Cost Components (Costs Depicted in US$ Million and Based on Martel, et al. (2012)).[4]

The information on costs are retrieved from a feasibility study on 100, 200 and 400 MW systems by Lockheed Martin (Martel et al., 2012). Whether the costs C of a component scale linearly or not can be determined by calculating the individual scale coefficients α for the upscaling of capacity Q from 100 to 200 MW and 200 to 400 MW, in accordance to equation (2) (Tribe & Alpine, 1986; W. Whitesides,

[3] It is not elaborated in the report what "Programmatic Costs" exactly are and it remains unclear what is meant by that.

[4] The costs in Martel et al's report were rounded off to the nearest thousand. This explains the minor differences in scale factors for linearly scaling components like ammonia pumps.

2012). If the two obtained coefficients for a component are similar or same, its upscaling is perceived as (quasi) linear; if the differences are significant, it is non-linear.

$$\frac{C_1}{C_2} = \left(\frac{Q_1}{Q_2}\right)^{\alpha} \tag{2}$$

Unfortunately, validating the scale coefficients in Table 2.1 is not that easy. Besides the reports by Lockheed Martin, detailed, relevant insights on the scale effects of individual components are scarce in contemporary literature and not rarely are publications from the 1970's and 80's found in their respective reference lists. Often these authors analyse OTEC's economics from a macro perspective without elaborating the costs of individual components at all, like (Magesh, 2010; Oko & Obeneme, 2017; Vega, 2012). If individual cost components are included, they do not match the thoroughness of Martel et al.'s (2012) analysis. More on these shortcomings in OTEC literature is discussed in the next section.

Furthermore, the costs of each component depend on the design of the system. Take the cold water pipe (CWP) for example. If the length of the pipe remains constant, its costs are defined by the linear correlation of its circumference, expressed as $\pi * d$, where d is the diameter of the pipe. However, the volumetric flow of whatever species through the pipe does not change linearly since it depends on the cross-sectional area $\frac{\pi}{4} * d^2$. Hence, if the diameter of a pipe is doubled, its costs double as well, while the volumetric flow is increased by a fourfold. For OTEC, as the volumetric flow of water is directly connected to the power output, the doubling of power output stipulates the increase of CWP diameter by a factor of $\sqrt{2}$ (Martel et al., 2012). However, the volumetric flow through the pipe is also determined by its velocity. Depending on the dimensions of the pumps and the overall system design, the desired volumetric water flows can be achieved not only by changes in pipe diameter, but also other variables. For example, depending on whose elaborations to believe in literature, a CWP with a diameter of roughly 8 m could be used in a 20 MW system (Upshaw, 2012), but maybe also in a 50 MW (Asian Development Bank, 2014) or 100 MW plant, respectively (Oko & Obeneme, 2017).

Lockheed Martin did not only analyse the feasibility of large-, but also small-scale OTEC systems. Albeit not as extensive as for the former, they analysed the economics of a 2.5 MW plant upgradable for commercial use (Lockheed Martin, 2011). Comparing the cost estimates for 2.5 and 100 MW in both reports, one notices significant distinctions. Due to differences in system design, the costs of individual components for the small-scale system do not match with the large-scale versions anymore; in fact, not even for items which scale linearly. This predicament is illustrated in Table 2.2 which contrasts the variations in scale coefficients for a selected host of components, which ought to scale linearly with a (nearly) constant α.

Due to the limited comparability of scaling effects in academia and industry, it is conceded that a micro perspective on the individual costs components of OTEC might not be the most suitable course to follow. Instead, this thesis follows the practices in contemporary literature and perceives the costs of

OTEC on a macro level, which summarises the individual cost factors to one overarching value. Merely the cable costs are analysed separately, but more on that in the next section.

Component	2.5 MW	100 MW	200 MW	400 MW	α for 2.5 -> 100 MW	α for 100 -> 200 MW	α for 200 -> 400 MW
Cold Water Pipe	5,48	61	117	229	0,65	0,94	0,97
Condensers	10,72	185	364	721	0,77	0,98	0,99
Evaporators	7,8	186	367	725	0,86	0,98	0,98
Warm Water Pumps	1,04	50	100	200	1,05	1,00	1,00
Turbines	2,1	37	73	146	0,78	0,98	1,00

Table 2.2 Scale Coefficients for Various Scales in Different Publications. Despite its Linear Behaviour, the Scale Coefficients Between 2.5 and 100 MW Do Not Match, Highlighting the Problems in Comparability Between Different Publications (Costs in US$ Million for 2.5 MW Based on (Lockheed Martin, 2011), Costs for Other Scales Based on (Martel et al., 2012)).

2.2.3.2. Capital Expenses

The complications described above did not deter scholars to analyse the costs of OTEC on a macro level. Luis A. Vega, a venerable vanguard of ocean technologies, studied the outcomes of economic assessments made by his contemporaries and blended them into a graph as shown in Figure 2.2 (Vega, 2012). The costs represented there resemble the total, accumulated CAPEX of all components combined and do not elaborate the changes in costs for individual items.

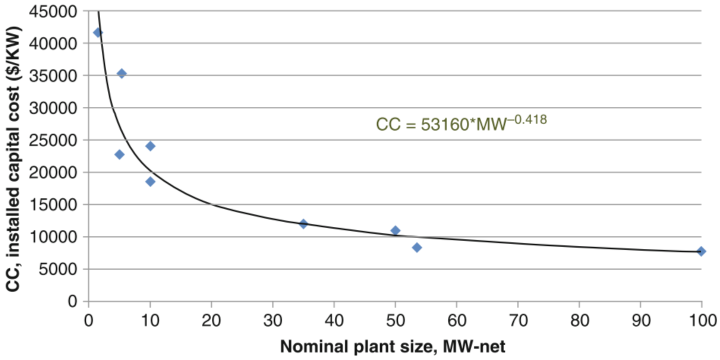

Figure 2.2 Correlation between Capital Costs and Nominal Plant Size of OTEC (Vega, 2012).

Both the graph and the respective equation in Figure 2.2 are frequently referred to in literature (IRENA, 2014; Muralidharan, 2012; Oko & Obeneme, 2017). Notwithstanding its simplicity in application, there are some limitations. First, it only applies for OTEC plants assembled and installed in the United States, with equipment acquired from the U.S., Europe or Japan. The plot might provide decent cost projections for OTEC entrepreneurs situated in these regions, but for any corporates outside these spatial boundaries, say China for example, there might be discrepancies.

Second, Vega draws on many references originating from the early 1990's. Although the corollaries of a study on OTEC from 1992 was updated by Vega in 2010, the plot in Figure 2.2 still incorporates these past references (Vega, 1992, 2010). Hence, it is unclear to which extent the CAPEX of a state-of-the-art OTEC plant differs from Vega's calculations, with the impacts of technological change over time in mind.

Third, some of the values embedded in the graph foot on simplifications and assumptions of varying gravitas. Generally, literature discerns six main types of capital costs connected to OTEC, namely the (1) platform and mooring, (2) cables, (3) power generation system, (4) water ducting system, (5) heat exchangers and (6) deployment & installation (IRENA, 2014; Muralidharan, 2012; Upshaw, 2012). In publications regarding OTEC economics, it is not clear whether and to which extent these six domains were included. For example, some scholars do not explicitly mention whether the costs of platform, CWP and cables are considered (Upshaw, 2012). Recollecting Table 2.1, the negligence of platform costs, for example, would entails considerable implications, since it occupies roughly 12 % of the total CAPEX. Thus, it is uncertain which of these cost factors moulded Vega's plot. Then again, three of Vega's sources resort to land-based OTEC, which do not require offshore platforms and mooring. Although it is reasonable to abolish these costs in such cases, Figure 2.2 needs to be perceived cautiously, bearing in mind which costs in the graph refer to land-based or moored OTEC.

A fourth problem is the ambiguity of the cost factors themselves. It is agreed upon that the range of probable costs of a component depends on its maturity and adaptability for OTEC. Well-known and easily adaptable components for OTEC, such as heat exchangers and power generators comprise a lower uncertainty than constituents specifically designed for OTEC, such as CWP. It is estimated that the aggregated uncertainty of total CAPEX ranges between ± 20 – 30 % (Avery, 2003; Muralidharan, 2012).

The graph seen in Figure 2.2 is merely a trend line born by previous cost estimations, which in some cases differ vastly from each other. For example, at a nominal size plant of 5 MW, there are two estimates of 22.500 and 35.000 $/kW. Whether these discrepancies arose due to differences in assumptions and simplifications or uncertainties of cost factors could not be determined. The upper cost is supposed to originate from a publication by Vega & Nihous in 1994. Despite their shrewd elaboration on the engineering aspects of a nominal, floating 5 MW OTEC plant, no insights are provided about the composition of its costs (Vega & Nihous, 1994), leaving their cost estimation unjustified. The lower value originates from a study by Wenzel from 1995, for which Vega does not provide a detailed reference. It was not possible to trace this publication.

Instead of using Vega's plot, this thesis designs its own scale curves as described in the next chapter. Therefore, the cost estimations of both academia and industry are used. In the following paragraphs, estimations on the CAPEX of 2.5 and 100 MW OTEC made by Lockheed Martin are presented and contrasted to the values determined by both academia and other OTEC companies.

OTEC is not going to come cheap if Lockheed Martin's cost estimations hold true. Under nominal conditions, Lockheed Martin estimates a total CAPEX of roughly US$ 1.5 billion for a 100 MW plant at the reference site in Hawaii. Under this light, OTEC companies need to argue extraordinarily well for their technology to convince any decision maker of their technology. Interestingly, a CAPEX of US$ 1.5 billion exceeds the estimation made by Vega significantly, who projects total capital expenses of roughly US$ 780 million for the same capacity (Vega, 2012). If this discrepancy is not intriguing enough, some scholars argue for a CAPEX of as low as US$ 420 million (year of dollar value not stated) (Magesh, 2010). However, many of the CAPEX in literature are not or insufficiently argued for must therefore not necessarily be taken at face value. But even if these rather optimistic estimations apply, the gargantuan CAPEX is probably going to be one of the largest hurdles to surmount for OTEC. To put it into perspective, a 90 MW offshore wind farm, 19 km away from shore, costed merely € 181 million in 2007, which equals to US$ 265.45 million (2010 value) (Gonzalez-Rodriguez, 2017). Yes, compared to other renewable energies, OTEC has some unique benefits like continuous operation, but would customers be willing to pay hundreds of millions, or billions, for it? It seems inevitable that OTEC's costs must be starkly reduced to mitigate its disagreeable position against other market competitors. For an overview of CAPEX estimations in literature, see Table 2.3 at page 20.

How does the CAPEX of a small-scale OTEC plant compete against other technologies? For a 2.5 MW system, Lockheed Martin estimates a total CAPEX of US$ 133.5 million (2011), which includes a pilot phase of two years and a subsequent upgrade to commercial use by exchanging a load emulator with a grid connection (Lockheed Martin, 2011). The wind farm mentioned above consists of 25 wind turbines with a capacity of 3.6 MW each (Gonzalez-Rodriguez, 2017). If the total CAPEX of the 90 MW wind farm is translated into 2011 values and then divided by the number of turbines, this results in an expenditure of US$ 10.8 million per turbine. Hence, if one would choose offshore wind over OTEC, s/he would obtain 44 % more power output for 91.9 % less costs. Before the economic analysis even begins, it is already fair to say that OTEC's profitability strongly depends on its capacity.

The reader might already have noticed that Lockheed Martin's cost estimations are far higher vis-à-vis the ones in contemporary literature. As precious as Lockheed Martin's studies are, it is obvious that there is another side of the story. Certainly, sceptics might argue that these low estimations originate from academic scholars which are not or not as in-touch with industry. But a striking revelation is that the cost estimates of other OTEC companies concur with academia. For example, Bluerise, an OTEC company situated in the Netherlands, computed a CAPEX of roughly € 120 million (2013 value) for 10 MW plant (Bluerise, 2014). It is one thing if multiple independent academic scholars disagree with the projections by Lockheed Martin, but it is a whole different story if even other industrial contemporaries do. Figure 2.3 shows two trendlines for conceivable scale curves of OTEC, representing the estimations by Lockheed Martin and the projections by academia as well as other OTEC companies.[5] The literature

[5] All cost estimations are converted to 2018 US$ values.

on which the latter curve draws is illustrated in Table 2.3, which summarises the insights of the literature study on OTEC economics.

Curiously, the plot shaped by the estimations by scholars and other OTEC companies are akin to Vega's plot in Figure 2.2. So, was he right after all? No one can tell for sure. As seen for 20 MW, the costs can vary between roughly 8.000 and 30.000 US$/ kW, which would imply an uncertainty of almost 70%. Curiously, this wide range of costs was obtained by a single publication by Upshaw (2012), who foots his results on the inherent uncertainty of OTEC literature, notwithstanding the outdatedness of his sources (many of his references originate from 1979). Hence, it is reasonable to assume that the true costs of an OTEC system must lie somewhere in between the blue and the grey scale curves in Figure 2.3. But until there is an actual commercial system, any projection of capital expenses is enveloped in a mist of ambiguity. In this thesis, the estimations by Lockheed Martin are perceived as the most trustworthy since they are the best and most detailed argued for.

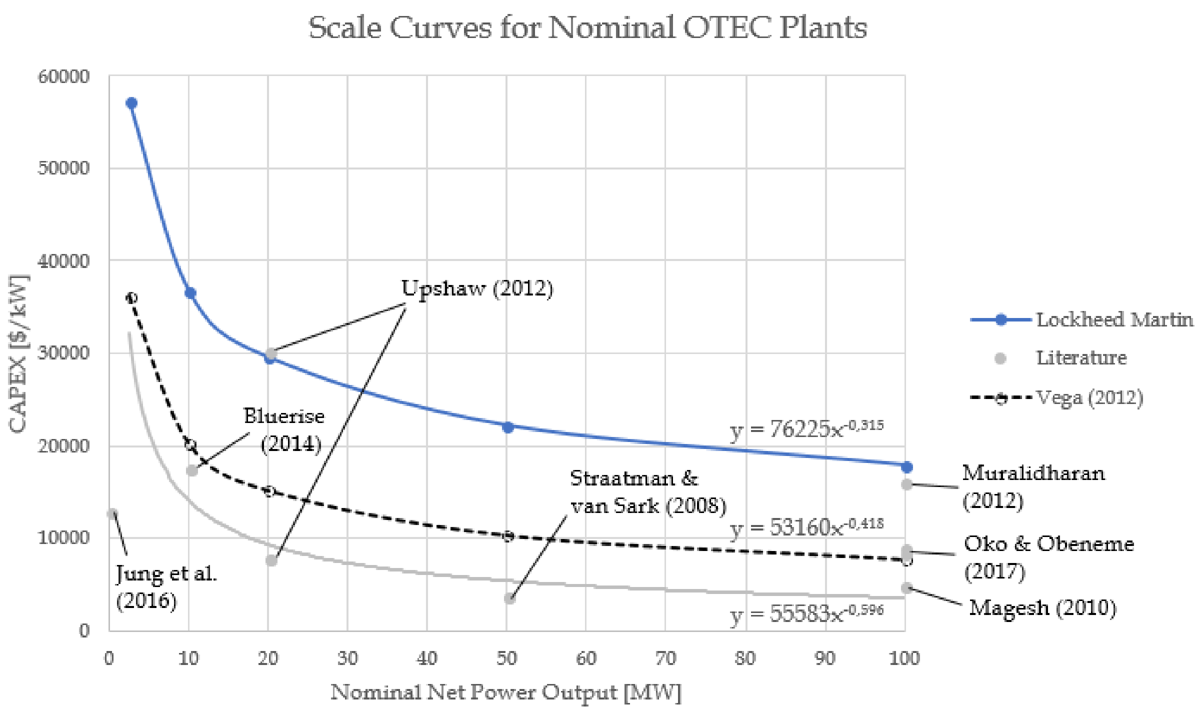

Figure 2.3 Scale Curves of OTEC The Blue Plot Represents Cost Estimations by Lockheed Martin; the Grey Plot the Ones by Academia and Other OTEC Companies. The Black, Dashed Curve Shows Vega's Projections for Comparison (Own Illustration).

Author (Year)	Currency (year)	Power Output [MW]	LCOE [currency/kWh]	Discount Rate [%]	CAPEX [mil.]	OPEX [% of CAPEX]	Life-time [y]	Capacity Factor [%]
Jung et al (2016)	US$ (N.A.)	0.02	0,363 $/kWh	5 (nom)	0,248	7	20	91,3
Lockheed Martin (2011)	US$ (2011)	2.5	-	-	133,46 (pilot+up-grade)	-	-	-
Bluerise (2014)	€ (2013)	10	0,19 €/kWh	8 (real)	123,1	2 - 3	30	95
Upshaw (2012)	US$ (2009)	20	0,13-0,65 $/kWh	10 N.A.	144 – 553,4	5	20	70-90
Straatman & van Sark (2008)	€ (N.A.)	50	0,04 €/kWh	8-10 (real)	110	1,4	30	90
Vega (2012)	US$ (2010)	100	0,18 $/kWh	8 (nom)	780	5	20	92,3
Oko & Obeneme (2017)	US$ (2015)	100	0,11 $/kWh	13 (nom)	795	2	25	100
Magesh (2010)	US$ (N.A.)	100	0,07 $/kWh	10 (real)	420	1	30	N.A.
Muralidharan (2012)	US$ (2010)	100	0,194 $/kWh	7,4 (real)	1400	3,2	30	95-97
Banerjee & Blanchard (n.d.)	£ (N.A.)	100 gross	0,029 p/kWh	8 (nom)	128,8	1,5	30	80
Martel et al. (2012)	US$ (2010)	100, 200, 400	0,177, 0,149, 0,122 $/kWh	4 (real)	1506, 2494, 4044	3	30	92

Table 2.3 Insights from Recent Literature on OTEC Economics (Ordered by Ascending Power Output).

2.2.3.3. *Operational Expenses and Project Lifetime*

As in the case of the CAPEX, estimations on OPEX are embroiled in a web of ambiguity and uncertainty. When perceived as a fraction of the CAPEX, the OPEX ranges from 1.4 % (IRENA, 2014; Straatman & van Sark, 2008), 2 % (Oko & Obeneme, 2017) and 3.2 % (Muralidharan, 2012) to 5 % (Asian Development Bank, 2014; Upshaw, 2012; Vega, 2012). In this regard, these assumptions foot on shaky ground, since many of these scholars do not or not sufficiently elaborate what these operational expenses consist of. For example, Upshaw (2012) elucidates the choice of an OPEX of 5 % but concedes that some operational costs like salaries were determined arbitrarily. Concerning the latter, Vega analyses personnel requirements and respective wages in more detail, but still leaves out additional, valuable details as seen later (Asian Development Bank, 2014). In contrast, Muralidharan's (2012) list of O&M costs is surprisingly rich in detail. However, the aspects he enumerated seemed strangely familiar and a scrutiny of his list of references confirmed this intuitive sentiment. His explications draw on the technical reports of Lockheed Martin.

Again, the company made substantial efforts to provide a list of operational expenses as holistic as possible. For example, while scholars only mention the salary of OTEC personnel, if mentioned at all, the technical report goes further beyond and includes training, crew transport, personnel safety and accommodation. Moreover, other factors comprise ongoing environmental monitoring, spare parts as well as maintenance and overhaul (Martel et al., 2012).

It is common practice in literature to assume the OPEX to unfold in the shape of constant, annual payments. Eventually, Lockheed Martin would also use an average, levelized OPEX to calculate the LCOE, but before that, they provide an ample schedule of operational costs over the life of the project. They distinguish minor maintenance due on an annual basis, interim maintenance every ten years and a major overhaul after half of the projects lifetime, which comprises over 50 % of the total OPEX. Over the lifetime of 30 years, the 100 MW plant is estimated to produce operational costs of approximately US$ 1.41 billion excluding inflation. This almost equals the CAPEX and results in an OPEX of roughly 3 % of total capital costs when averaged over the system's lifetime (Martel et al., 2012). As this value concurs with contemporary literature, a reasonable objection arises whether such a detailed scrutiny of OPEX is necessary for this study.

From a pragmatic point of view, it is probably not. This might feel unappreciative or even blunt, but under the light of the gargantuan capital costs associated with OTEC, the impact of O&M costs on the LCOE is relatively small. Of course, a detailed assessment of OPEX is essential for any project to be rendered successful and sustainable. But for the sake of economic calculations as performed in OTEC literature and here, such simplifications are acceptable.

Regarding the lifetime of an OTEC plant, there are slight differences in literature. While some scholars rely on a period of 20 years for their calculations (Edenhofer et al., 2012; Jung et al., 2016), others use 30 years (Banerjee & Blanchard, n.d.; Bluerise, 2014; Magesh, 2010; Martel et al., 2012; Muralidharan, 2012; Straatman & van Sark, 2008). Some variations in literature include 15 years (Asian Development Bank, 2014) and 25 years (Oko & Obeneme, 2017). This thesis argues for a lifetime of 30 years to ensure clean and sustainable electricity as long as possible.

2.2.3.4. Annual Real Net Power Output and OTEC Siting

The last OTEC-specific value required for the economic analysis is the annual, real net power output. Until now, little attention has been paid to the terminology of power output, although there are distinctions to be considered. What does it mean when an OTEC plant generates a nominal net power output of 100 MW? Basically, it is the power available under standard conditions after power flows for the operational preservation of the plant are subtracted from the gross power output (Martel et al., 2012). The term "standard condition" means that a nominal 100 MW OTEC plant only produces this output under specific premises, which, for OTEC, are perceived to be met at the coast of Kauai, Hawaii; not only according to Lockheed Martin, but also to scholars like Vega. Thus, if a plant is exposed to an environment diverging from the standard, its performance adapts to *real* conditions. (Lockheed Martin, 2011, 2012; Martel et al., 2012; Vega, 2012). These environmental influences mainly comprise the temperature difference between surface and deep ocean water as well as cold water availability. The latter however is not included in economic analyses on OTEC at all. Therefore, it is not discussed here, and its omission is vindicated in the next chapter.

Although not every scholar explicitly mentions the impact of ocean water temperature differences, it is overtly articulated by others, i.e. (Asian Development Bank, 2014; Straatman & van Sark, 2008). Both academia and industry agree that there is a linear correlation between temperature difference and real OTEC power output. Nevertheless, there are inconsistencies between theory and practice. For example, Vega mentions a standard temperature difference of 20 °C in a report for the Asian Development Bank (Asian Development Bank, 2014) vis-à-vis 21.6 °C used by Lockheed Martin (Lockheed Martin, 2011, 2012; Martel et al., 2012). There are also slight differences between the changes in power output. According to Vega, a change in 1 °C of temperature difference leads to a linear change of 15 MW for a nominal 100 MW plant. Lockheed Martin, on the other hand, resorts to 13.6 MW. The linear correlation between temperature difference and net power output holds independent of the scale of the plant and the slopes merely have to be adjusted to the power output. Figure 2.4 illustrates the linear correlation between temperature difference and power output.

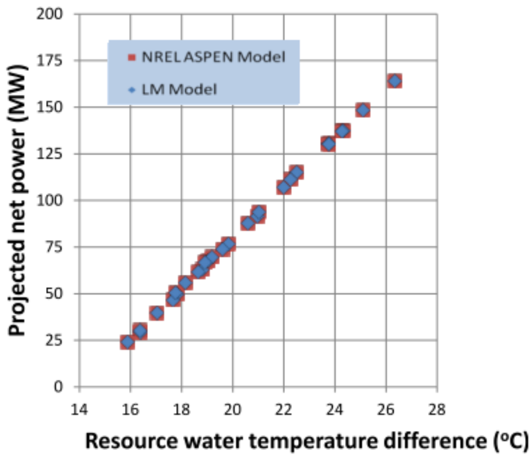

Figure 2.4 Correlation Temperature Difference versus Net Power Output(Lockheed Martin, 2012).

Suspicion might emerge to which extent local temperature differences within a region are incorporated by OTEC studies. After all, if the temperature profile of a certain location is heterogeneous, that implies that some spots are more suitable for implementation than others. However, the site at which the system is supposed to be situated is mostly predetermined in literature, for example Hawaii (Lockheed Martin, 2011; Vega, 2012), Nigeria (Oko & Obeneme, 2017), Guam (Martel et al., 2012) or South Korea (Jung et al., 2016). Other publications do not include a specific OTEC site at all, limiting their notional models to a general scope (Banerjee & Blanchard, n.d.; Muralidharan, 2012; Upshaw, 2012). This is curious, since such an approach might induce inefficient decision making and poor investments. Instead, the choice of a specific site for OTEC might be justified considerably easier if comparative data on the economic suitability of different locations was available. There are silver linings upon the cloudy realm of OTEC literature, though, which partly address the spatial predeterminism. For example, Vega contrasts the effective net power output of different countries, albeit without further elaboration on regional differences within these countries (Asian Development Bank, 2014). Furthermore, Lockheed Martin took formidable efforts to map the technical potential of OTEC worldwide (Lockheed Martin, 2012). But while their comprehensive models cannot be reproduced here within the given timeframe, this study resorts to the outcomes of Chalkiadakis' work instead, whose results and model are easily accessible via the TU Delft depository.

If a 100 MW system would operate continuously throughout the whole year, it would generate a total of 876 GWh of electricity. But such an output does not include the hours of downtime due to maintenance or malfunction. However, OTEC's operation is relatively stable compared to other renewable energies and therefore embodies a reasonable choice for baseload power production (Fujita et al., 2012; Vega, 2012). Ipso facto, most publications apply a capacity factor of at least 90 % for their calculations and go as far as 95 – 97 % (Muralidharan, 2012) or even 100 % (Oko & Obeneme, 2017). Occasionally, there are also rather conservative estimates like 80 % to be found in literature (Banerjee & Blanchard, n.d.).

There is another aspect affecting the real net power output which is ignored throughout academia, namely the transmission losses from plant to shore. Usually, the distances to shore assumed in literature are so small that they are not further elaborated. But since practicable OTEC plants as mapped by Chalkiadakis can be as far away as 370 km from shore, cable losses are a significant obstruction not be underestimated. Lockheed Martin also thought about that, with cable efficiencies for both 60 kV and 132 kV AC cables being displayed in Figure 2.5. The underlying functions are reproduced and extrapolated for distances beyond 200 km. After multiplied with the real net power output of the OTEC plant, one obtains the effective power at the coast. Evidently, the impact of cable losses increases with rising distance and thus exerts adverse effects upon the economic feasibility of offshore OTEC.

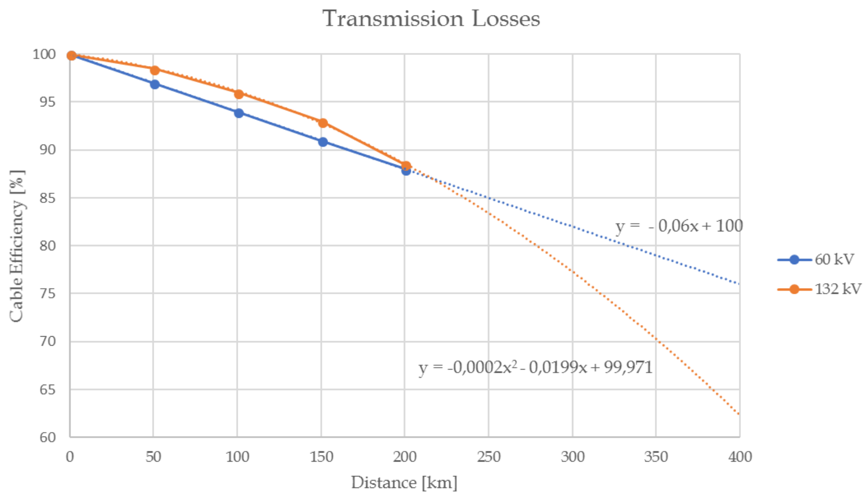

Figure 2.5 Cable Efficiency versus Distance to Shore (Solid Lines Based on (Martel et al., 2012), Extrapolations (Dashed Lines) and Functions Added for this Study).

A peculiar detail in Figure 2.5 is the nonlinear behaviour of the efficiency for 132 kV cables and the linearity for 60 kV. Lockheed Martin does not provide further details on the assumptions shaping the graphs as they are, curtailing the comprehension of the applied methods. The transmission losses are expected to be linear in accordance to ohmic, reactive and skin losses, but it is possible to back up the nonlinear behaviour of the 132 kV with literature, although the underlying phenomena remain undiscussed (Rodrigues, 2016). In contrast, it cannot be explained why the linearity changes for different cables. If the 132 kV cables behave linearly as well, the economic profitability of large-scale systems using these cables is undervalued in this thesis. However, the impact on the results of this thesis are small, since this predicament only affects large-scale systems and plants far from shore. The efficiencies shown and used here are rather conservative values and this shortcoming is acknowledged.

2.3. Cost Reduction by Learning and Experience Curves

2.3.1. General Concepts

From *homo erectus* learning how to control fire to young, ambitious guitarists avidly practising to become the next Jimmy Hendrix, learning is an essential part of every living being's life. Learning enables us to master activities, which originally started as awkward and clumsy attempts. Unless blessed with extraordinary talents, no one is born a musician, marathon runner or theoretical physicist, but we acquire the skills to become them by continuous extraction, synthesis and reflection of information. Technology poses no exemption to this process. There, learning is an essential vehicle to streamline processes, broaden and deepen its network and, especially, to reduce costs.

In general, cost reductions can be achieved by economies of scale and learning. While the former is already discussed in section 2.2.3.2, the latter is reviewed here. Figure 2.6 illustrates how these two phenomena cooperate to reduce a technology's cost.

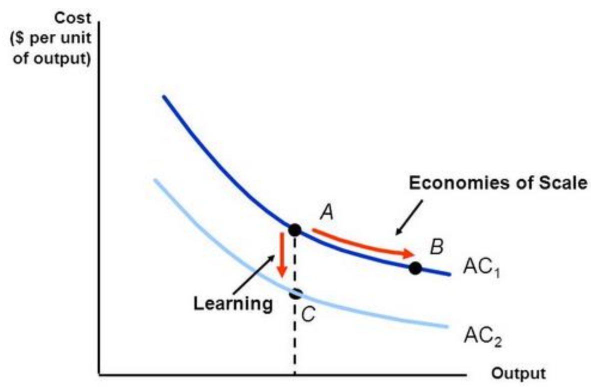

Figure 2.6 Economies of Scale versus Learning (Manning, 2016).

Learning occurs on different levels and can be discerned between labour, capital and organisational learning (Nemet, 2006). Besides learning-by-doing, other learning activities comprise Research & Development (R&D), standardisation, automation and knowledge spill-over from other industries (Junginger, Faaij, & Turkenburg, 2005; Weiss, 2009). If the effects of learning are plotted in a graph, one obtains a *learning curve* which illustrates the unit cost of a good or service versus its cumulative output. If reductions in manufacture costs are included as well, the learning curve becomes an *experience curve* (Nemet, 2006). If all learning efforts are summarised as one factor, the learning coefficient, the cost reduction by learning can be expressed as shown below.

$$C_t = C_0 * \left(\frac{q_t}{q_0}\right)^{-b} \tag{3}$$

$$PR = 2^{-b} \tag{4}$$

$$LR = 1 - PR \tag{5}$$

C is the unit cost, q is the quantity of output, while b is the learning coefficient. PR and LR are the *progress* and *learning ratio*, respectively. The latter tells by how much the costs can be lowered when the output of a good or service is doubled; the higher LR, the higher the cost reductions by learning. There are also two-factor experience curves, which segregate the effects of learning-by-doing and R&D, but these are neglected in this study due to complexity and lack of applicability (Junginger et al., 2005).

Regarding the unit cost C, there are discrepancies found in literature. While some scholars use the capacity-specific costs, expressed in [$/kW] (Dismukes & Upton, 2015; Junginger et al., 2005; Nemet, 2006), some others resort to the net energy production costs in [$/kWh] (Van der Zwaan et al., 2012; Williams et al., 2017). The latter argue that technological innovation, for example an increase in hub height and capacity factor for wind power, can reduce the LCOE despite the simultaneous stagnation or rise in CAPEX (Williams et al., 2017). This might also apply for OTEC. After all, its annual energy production depends on the cable length and capacity factor. Both are highly uncertain and therefore, it proves beneficial if experience curves would include their inherent ambiguity. Hence, this thesis uses the net energy production costs for the experience curves designed later.

The concept of single-factor experience curves offers many advantages but is also not free of shortcomings. On the one hand, it is a simple approach, which has already been applied in a multitude of studies, encompassing both energy supply and demand technologies (Weiss, 2009). Furthermore, most experience curves foot on empirical data and are conversely backed by empirically determined trends, rendering them relatively reliable. On the other hand, these curves are highly sensitive to the inputs used to calculate it. Not only deviations in technology-specific, but also market-related values can change the shape of the experience curve markedly. Another disadvantage is the exclusion of discontinuity as it is assumed that the learning rate of a technology stays constant regardless of its stage of development and rate of implementation (Nemet, 2006). This aspect, however, is contested by some scholars, who argue that learning does not slow down even for technologies converging maturity (Junginger et al., 2005). Therefore, this thesis studies learning effects for both finite and infinite learning and considers the predicament of discontinuity accordingly.

The reader might object how an experience curve can be plotted for a technology which virtually has none. True. OTEC also fails to meet any of the data requirements posed by Junginger et al. (2005) to design trustworthy experience curves, which are (1) price information from competitive markets, (2) no time inconsistencies, (3) internationally orientated markets and (4) sufficient availability. Any of these four points can be waved off by pointing to the absence of commercial OTEC. Also true. But given the precarious cost profile of OTEC, it can be extremely helpful to give at least projections of what could be possible if certain premises are fulfilled. Maybe the gargantuan capital expenses are merely a necessary evil to enjoy the benefits of OTEC in the future with strongly reduced costs via learning. Then again, if these cost reductions prove unfruitful for the technology's profitability, the whole OTEC niche would be jolted to reflect upon themselves and their doing. In such a case, the high costs would not be a temporary inconvenience, but an everlasting stigma severely jeopardising OTEC's preservation. In this regard, the absence of both theoretical and practical experience curves of OTEC is perceived as another knowledge gap in OTEC literature.

Even though there is indeed no empirical data on commercial installation growth or learning rates of OTEC, both variables could be adapted from similar cases. But when it comes to energy technologies, there is stark inconsistency among scholars. For example, the learning rate for wind power is estimated to oscillate between -3 and +33 % (Williams et al., 2017). In a more general scope, PhD graduate Martin Weiss conducted a comprehensive study of the learning rate of not one, but multiple energy technologies resulting in an average learning rate of 16 ± 9 %. Curiously, the rate assumed by OTEC literature falls out of this range with merely 7 % (Martel et al., 2012; Vega, 2012). What might be reasons for such a low learning rate?

First, OTEC literature argues that the technology partly relies on already mature technologies like turbines and generators, which curb the potential of further learning. In fact, Lockheed Martin states that learning is finite and cost reductions via learning stop after the 4^{th} or 5^{th} doubling of power output (Martel et al., 2012). But if learning is an infinite process as implied above, that is not really a convincing argument. Consequently, this is a clash between two opposing forces which needs attention when designing implementation scenarios later.

Second, OTEC is an offshore technology and therefore faces challenges unknown to technologies analysed by Weiss. Since there is no empirical data on any ocean technology, they were comprehensibly neglected in his analysis. For offshore wind it is not specified whether and to which extent it is included. Merely one of his references studies the cost reduction prospects of offshore wind, but it was published in 2004 and its validity 14 years later needs to be questioned. Generally, it is questionable to which extent Weiss' results could hold as a proxy for OTEC. To gain more understanding, it proves worthwhile to contrast OTEC to a similar technology, such as offshore wind power. Both comprise relatively high capital expenses which are affected by location-specific factors like cable and structural costs. Both struggle not only with economic, but regulatory and political issues hampering their implementation (Rodrigues et al., 2015). Based on the insights obtained from the offshore wind niche, it is possible to argue better for a range of conceivable learning rates of OTEC.

2.3.2. Trends in Implementation and Learning of Offshore Wind Power

Not many people could have anticipated the development offshore wind power took over the last years. After initial pilot projects in 1991 and its commercial lift-off in the early 2000's, offshore wind has been growing at an annual rate of 25 – 40 % (Dismukes & Upton, 2015; Rodrigues et al., 2015; Takami & Lidington, 2017). As of 2015, there were over 70 projects spread over ten countries, comprising an installed capacity of around 7.5 GW with further wind farms waiting just around the corner (Rodrigues et al., 2015).

Nevertheless, worrying trends have been observed which do not give much reason for celebration. There is growing suspicion that learning has low to insignificant effects on the specific costs of offshore wind over time. Multiple studies concluded that learning rates range between 3 to 5 % at best, with CAPEX gradually increasing (Dismukes & Upton, 2015; Rodrigues et al., 2015; Van der Zwaan et al., 2012). The problem is not a lack of learning itself, but external disturbances offsetting learning effects, i.e. the scramble for decent offshore locations. As described earlier, a further distance to shore reverberates in higher cable and mooring costs as well as larger transmission losses. Therefore, any cost reductions by learning are counteracted by cost increases due to scarcity of proximate implementation areas. Other reasons for limited cost reductions are soaring commodity prices for steel and copper as well as tight markets for offshore wind turbines (Dismukes & Upton, 2015; Van der Zwaan et al., 2012). However, the latter aspects might only be temporary, with the possibility of plummeting commodity prices and relaxing markets in the future. In such cases, the cost reductions by learning would be more distinct than as they are now.

One might argue that these factors cannot be that severe yet, since offshore wind is a relatively novel technology from a commercial perspective. Nevertheless, there is already tangible evidence that offshore wind projects not only tend to be located further from shore (with distances of over 120 km) at deeper sea grounds, but that the average CAPEX of these ventures also increased in recent years. If the future of offshore wind looks so sombre, why does its expansion proceed so rapidly, with no end in sight? This is where the learning effects take place. Even though the rate itself is low, there is still technological progress, epitomised by a surge in scale of power output, hub height and capacity factor among others. Thus, although the CAPEX of an offshore wind farm tends to rise, its power output does as well, resulting in lower net energy production costs (Rodrigues et al., 2015; Williams et al., 2017). As long as these progressions veneer the adverse trends above, there is a strong impetus to further implement this technology.

All these observations apply to OTEC to some extent as its CAPEX strongly depends on its offshore location. If it also struggles with high commodity prices and tight markets, it is reasonable to assume that a learning rate of 3 – 5 % might become reality.

2.4. Conclusion of the Literature Study

On the grounds of the literature study performed in this chapter, a total of four deficiencies in contemporary literature were detected. First, no publication was found which assesses the national and global economic potential of OTEC. Instead, evaluations merely encompass the economics of individual, notional projects. Second, these analyses predominantly neglect advanced financial and fiscal data due to the immature state of the technology. Third, the choice of discount rate foots on oversimplification and does not reflect the aggravated business conditions a high-risk technology like OTEC faces. Fourth, there are no projections on global experience curves of OTEC and current economic analyses on the technology do not take into account cost reductions via learning.

The literature review revealed the construction of supply curves as the method of choice among contemporary scholars. There, the Levelized Cost of Electricity (LCOE) is calculated for a host of possible implementation locations, ordered from smallest to largest values and then plotted against the cumulative energy output to form a supply curve. The part of the curve which is underneath a reference cost, i.e. the wholesale electricity price, is perceived as the economic potential. The calculation of the LCOE can be as simple or sophisticated as desired. Since OTEC is an immature technology with scarce economic and financial data available, the second knowledge gap is not addressed in this thesis and deep financial aspects like tax expenses are excluded. The third knowledge gap is tackled by consolidating the choice in discount rate by practices observed in literature and industry as well as public decision making. For private projects, a WACC of 18 % is adapted from the floating wave energy niche, while for public projects, a SDR of 10 % based on the recommendations of the World Bank and Asian Development Bank.

Concerning the economics of OTEC, considerable discrepancies were encountered in literature. First, it is not possible to comprehend and compare the cost reductions of individual components by the upscaling of capacity found in different OTEC studies, due to differences in system design and external, environmental parameters. Hence, this thesis follows the approach common in literature and perceives the costs of an OTEC plant from a macro perspective without the consideration of the costs of individual components (expect for cable costs). Second, cost estimations on the CAPEX of OTEC differ vastly. On the one hand, there is the U.S. company Lockheed Martin which did extensive research on the technology and its economics, resulting in very detailed elaborations, but also rather high cost estimations. On the other hand, there are academia and other OTEC companies whose cost projections are not as detailed and, in most cases, considerably lower than the ones made by Lockheed Martin. However, the estimations made by Lockheed Martin are still perceived as the most trustworthy since (1) barely any economic analysis in academia comes close to the detailedness and transparency of Lockheed Martin's and (2) they are partly backed by individual academic sources as well. Regarding (1), some scholars do not or insufficiently elaborate the sources and references of their cost estimates which render their results opaque and irreproducible. In any case, OTEC's monumental costs, both for estimates made by Lockheed Martin and academia, pose a major hurdle in the technology's development. If OTEC endeavours the successful competition with other technologies like offshore wind, considerable cost reductions by economies of scale and learning are required. The real power output of an OTEC plant is not only determined by its design, but also by its environment. However, the literature study revealed that many academic studies do not explicitly consider external factors like the change in seawater temperature difference. Therefore, their results remain notional and have a limited relevance on a local level.

When it comes to learning, OTEC literature breaches with contemporary customs. The former argues that learning proceeds at a rate of 7 % and eventually stops after the 4^{th} or 5^{th} doubling of output. In contrast, learning is widely perceived in literature as an infinite, continuous process which is not limited by the doubling of output. Moreover, the learning rates found in literature for other energy technologies are predominantly higher than the ones found in OTEC publications. Since there is no empirical data on OTEC implementation, nothing can be said about practical learning effects within the OTEC niche. Therefore, to design experience curves in later chapters, the offshore wind niche serves as a proxy and provides values for conceivable learning rates. The review of the trends observed there in the recent years serve as the foundation of the implementation scenarios presented later.

Perceiving the knowledge gaps and discrepancies in OTEC literature, this thesis endeavours to tackle most of these deficiencies and to contribute to the body of research being performed on the technology. By assessing the economic potential of OTEC on various spatial scopes with and without learning effects, this study is the logical continuation of previous work and conversely, paves the way for future research which can draw on the results presented here.

3. Methodology

3.1. Objects of Investigation, Boundary Conditions and General Assumptions

In the previous section, it is revealed that the costs of an OTEC plant are determined by its system design and the environment in which it operates. Since these peculiarities severely exacerbate the analysis of the change of components costs during upscaling, this thesis adheres to the practices of contemporary literature which predominantly assesses the costs OTEC from a macro perspective. Due to a lack of relevant literature and data, only moored, closed-cycle systems will be analysed.

3.1.1. Scale Curves and CAPEX of OTEC

Although there are scale curves in literature illustrating the capital costs of OTEC depending on its capacity, they comprise several shortcomings and need to be perceived critically. Based on the findings in the previous chapter, own scale curves are designed which reflect the outcomes of contemporary analyses on the economics of OTEC. Regarding the scale curve based on Lockheed Martin's cost estimates, they only provide publicly accessible reports for 2.5 and 100 MW systems. Based on them, the costs for capacities in between are interpolated, namely for 10, 20 and 50 MW, using the trendline function in Microsoft® Excel.[6] The scale curve for cost projections by academia and other OTEC companies are designed analogously. The reader is invited to consult Table 3.1 at page 35 for all cost functions and CAPEX used in this thesis.

For a 100 MW system situated 20 km from shore, Lockheed Martin estimates the cable costs to be US$ 111 million (2010 value), comprising the costs for the cable itself as well as variable and fixed installation costs of US$ 3.6 million/km, US$ 0.65 million/km and US$ 26 million, respectively. After the location-specific costs have been multiplied with the assumed cable length *d*, the cable costs are then added to the CAPEX of the other OTEC components, which is US$ 1.459 billion (Martel et al., 2012). Thus, the total CAPEX is calculated using equation (6) below.

$$CAPEX_{tot} = CAPEX_{w/ocable} + CAPEX_{fix.inst.} + d * (CAPEX_{var.inst.} + CAPEX_{cable}) \qquad (6)$$

[6] The method of using Microsoft® Excel to obtain scale curves for Lockheed Martin originates from an early stage of the master thesis. Only shortly after the greenlight meeting months later was the analysis of scale coefficients performed as presented in section 2.2.3.1, which would have been a more coherent way to obtain the scale curves. However, the impact of a different methodology on the results presented here is expected to be minimal, ranging around ± 5 – 10 % for small scale systems.

For 2.5 MW, a little bit more preparation is required. As already mentioned, Lockheed Martin proposes a pilot phase of two years, before the system is modified for commercial operation, with the load emulator being replaced by cables connecting the system to the grid. In this thesis, the first step is skipped, and the plant operates commercially right from the start. Therefore, the costs associated with the 2.5 MW plant need to be adjusted to reflect the immediate commercial operation. For example, the pilot plant operates with a 3-leg mooring system, which is upgraded to a 9-leg version for commercial operation, entailing additional acquisition and installation costs. Here, the 3-leg mooring system is excluded, since the plant immediately deploys a 9-leg mooring version. All adaptions result in a total CAPEX of US$ 127.41 million (2011 values). Unfortunately, the report on 2.5 MW OTEC did not crack down the cable costs as presented for the 100 MW system, but only lists the total cable costs as US$ 18.18 million (2011 values) (Lockheed Martin, 2011). For simplicity, it is assumed that the proportions of the three cable cost factors found in the report on 100 MW OTEC are constant for any scale of power output. The total CAPEX of a 2.5 MW plant is then computed analogously to the 100 MW version with equation (6). Note, that the costs of the 100 MW and 2.5 MW plants are denominated in different dollar values (2010 vs. 2011). Consequently, they are not comparable yet and need to be adjusted to real 2018 dollars later.

Based on the availability and credibility of cost estimations in literature, this thesis studies the economic potential of five different scales of OTEC, namely 2.5 MW, 10 MW, 20 MW, 50 MW and 100 MW, respectively. Due to the vast differences in cost estimations found between Lockheed Martin vis-à-vis academia and other OTEC companies, it is argued here that both sides must be considered to maintain as much objectivity as possible. If Lockheed Martin's work is neglected, the economic potential of OTEC might be overvalued, fostering wrong hopes and expectations. Vice versa, if the projections in literature are discarded, the resulting potential might be undervalued, drawing an inadequately sombre picture of OTEC's profitability. Lockheed Martin's results are used as base values, since their cost analysis is by far more transparent than any other publication analysed in this thesis. However, the projections made by academia and other OTEC companies serve as the lower boundary of uncertainty. The lower range of uncertainty varies with the scale of the OTEC plant and is enumerated in Table 3.1. In contrast, the upper range of uncertainty is held constant independent of the system's scale, namely at 30 % of the total CAPEX. The costs might also be higher than claimed by Lockheed Martin due to the uncertainty inherent in some cost components as described below.

For both Lockheed Martin reports, Hawaii was chosen as a reference location, with OTEC plants being situated 20 km away from shore. This study adapts Hawaii as a reference as well and adjusts location-dependant variables accordingly. While the costs of most components are assumed to be independent of the plants location relative to the shore, this is not the case for two cost factors, namely marine cables and mooring. The length and the costs of a cable increase with the distance between the OTEC system and shore (Martel et al., 2012), while the costs of mooring correspond to the depth of the ocean underneath the plant. Regarding the former, one aspect to keep in mind is that the airline from plant to shore does not represent the actual length of the cable, as it is conducted below the surface as shown in Figure 3.1.

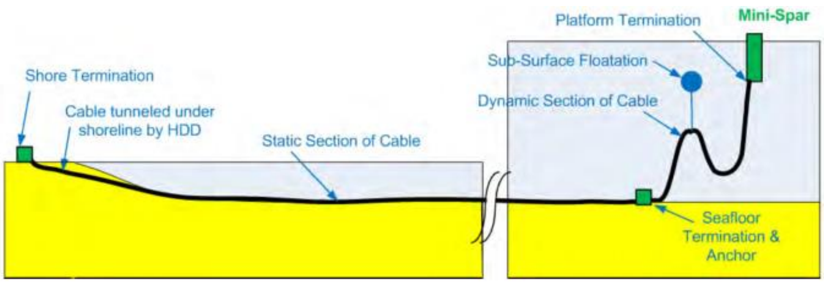

Figure 3.1 Cable Management of Grid-Connected OTEC Plant (Lockheed Martin, 2011).

There are publications which establish a correlation between cable costs, airline distance, and subsea distance to shore, i.e. (Nagababu et al., 2017). In fact, Chalkiadakis did consider the impact of cable costs as well when he mapped practicable locations for OTEC deployment. But the calculation of cable *lengths* for each practicable OTEC location would require a bathymetry of ocean grounds worldwide, which surpasses the scope of Chalkiadakis' and this thesis. This is also the reason why location-specific mooring costs cannot be determined. To address these shortcomings, it is assumed that an uncertainty of + 30 % of total CAPEX includes the derivations in cable and mooring costs in addition to the inherent uncertainty of other cost components like platforms. Although this value might be perceived as overestimated, it follows the elaborations in literature (Avery, 2003; Muralidharan, 2012). The appropriateness of such an upper boundary is discussed in later chapters.

3.1.2. OPEX and Operational Lifetime

The previous chapter described how it is common practice in OTEC literature to assume the OPEX as a fixed proportion of the total CAPEX. Although this approach is reasonable, it cannot be directly applied here. This study is innovative as it calculates the LCOE of OTEC in dependence of its location. Since these locations vary in distance to shore, they also vary in cable costs, which influence the CAPEX of the project. Thus, with rising capital costs for systems further away from the coast, the OPEX would increase as well if a fixed percentage is chosen. This seems intuitive and agreeable at first. It would make sense to assume that a longer cable would result in higher maintenance costs; and a longer distance to shore would mean increased expenses and efforts to transport personnel to the plant. But curiously, Lockheed Martin explicitly states that the cables do *not* need maintenance. Instead, they ought to persist throughout the plant's lifetime and merely pose marginally higher monitoring costs. It is also assumed that the crew can reach the plant within one day by a regular motor boat independent of the system's location and that spare parts ought to be transported with the crew on the same boat, incorporating their transportation costs (Martel et al., 2012). Whether to believe the report's elaborations or not seems to depend on personal judgement. Without empirical evidence, any argument for or against them is a shot in the dark and, therefore, of limited aid.

In this thesis, Lockheed Martin receives the benefit of the doubt and every 100 MW OTEC plant, independent of its location, faces O&M costs of US$ 47 million per year in the base case (2010-dollar value). This equals to a proportion 3 % of total CAPEX for a nominal plant situated in Hawaii. Hence, the OPEX is determined as a fixed fraction of the nominal CAPEX and is then held constant for all other systems independent of their location. The OPEX for all capacities are deduced accordingly based on the blue scale curve in Figure 2.3. The same boundaries of uncertainty for OPEX are analogically adapted from the uncertainties of CAPEX as displayed in Table 3.1. Regarding the operational lifetime of the OTEC plant, this study strikes an accord with literature and applies a lifespan of 30 years.

3.1.3. Annual Real Net Energy Output

As discussed in the previous chapter, the real power output of an OTEC system depends on external factors, such as the seawater temperature difference and cold water availability. In this thesis, the assumptions Lockheed Martin are adapted, who proclaim a change in power output of 13.6 MW/°C of a 100 MW plant at a reference temperature difference of 21.6 °C, prevailing at the coast of Hawaii, USA. These values are preferred over the ones found in academic literature as Lockheed Martin's values foot on empirical evidence, while academia's figures are drawn from theoretical, mathematical models, i.e. by Nihous (2010). In this study, the required temperatures are adapted from Chalkiadakis, who recorded global temperature differences based on ten-year averages. Since the change in real power output scales linearly with capacity, the values above are adapted by interpolating them to the analysed scales. For example, the real power output changes only by 6.8 MW/°C for a 50 MW, which is half of the value for a 100 MW version. The values for the remaining scales can be found in Table 3.1. Equation (7) shows the calculation of the annual real net energy output., with β being the change in real power output.[7] The transmission efficiency from plant to demand centre and the capacity factor are included by η_{Cable} and c_f, respectively.

$$E_t = (P_{nom} + (\Delta T - \Delta T_{nom}) * \beta) * \eta_{Cable} * c_f * 8760 \frac{h}{a} \tag{7}$$

In this thesis, standardised OTEC systems are analysed whose dimensions do not change in respect to its deployed location. This is vindicated by the amount of individual locations analysed in later

[7] There is no conventional letter representing the change in real power output. The letter β is chosen arbitrarily.

chapters. In total, over 8.000 suitable locations with different temperature profiles are considered. It is acknowledged that practical OTEC plants would be specifically designed for a certain location, adapting the dimensions of components like condensers and evaporators to the temperature of the extracted water. However, it is not possible within the timeframe and the workload of this thesis to design over 8.000 individual OTEC systems with varying cost structures. For the sake of simplicity and comparability, the standardisation of OTEC plants and their components holds.

Another criterion affecting the real power output of an OTEC plant is the availability of cold, deep sea water. In contrast to warm surface water, the access to cold water depends on global seawater currents and the cold water flow rate of the system (Lockheed Martin, 2012). Hence, one would require a global model of deep sea currents to compute the impact on the real power output of every practicable OTEC location. This surpassed the scope Chalkiadakis thesis by far and was abandoned, since such a model requires highly sophisticated hard- and software. As this thesis foots on the results of Chalkiadakis, the inflow of deep ocean water is omitted here as well. Nevertheless, its consideration would ameliorate the insights of both Chalkiadakis and this study noticeably and are, therefore, possible objects of further research. This thesis also adapts the assumptions made by Chalkiadakis regarding the spacing of individual OTEC plants from each other. In order to curtail disruptions in the marine ecosystem, the systems are separated by at least 9 km.

One of OTEC's major benefits is its continuous operation and higher availability compared to other renewable energy technologies. This thesis employs an availability of 92 %, which equals to a downtime of four weeks per year and stands in good agreement with literature (Asian Development Bank, 2014; IRENA, 2014; Jung et al., 2016; Martel et al., 2012; Straatman & van Sark, 2008). Notwithstanding, an uncertainty of unscheduled downtime of - 5% of the capacity factor is included as well, which influences the capacity factor and, consequently, the annual electricity supply of probable OTEC locations.

Regarding transmission losses from power plant to shore, this thesis draws on the efficiencies calculated by Lockheed Martin (see Figure 2.5). The efficiency function for 60 kV cables are applied for 2.5, 10 and 20 MW, while 132 kV cables are deployed for 50 and 100 MW plants in accordance to Lockheed Martin's instructions (Lockheed Martin, 2011; Martel et al., 2012).

	OTEC Configurations Based on Lockheed Martin				
Nominal Net Power [MW]	2.5	10	20	50	100
CAPEX w/ cable [US$ million (year)]	109,23 (2011)	NA	NA	NA	1459 (2010)
Cable Cost [US$ million (year)]	4,26+(0,59+0,11)*d (2011)	NA	NA	NA	26+(3,6+0,65)*d (2010)
OPEX [US$ million (year)]	3,82 (2011)	NA	NA	NA	47 (2010)
Real CAPEX w/ cable [US$ million (2018)][8]	122,94	328	535	1022	1669
Real Cable Cost [US$ million (2018)][8]	4,79+(0,66+0,12)*d	9,50+(1,32+0,24)*d	13,44+(1,86+0,33)*d	21,12+(2,92+0,53)*d	29,74+(4,12+0,74)*d
Real OPEX [US$ million (2018)][8]	4,3	11,05	17,77	33,36	53,76
Power Output Change per 1°C [MW/°C]	0,34	1,36	2,72	6,8	13,6
Cable Type	60 kV	60 kV	60 kV	132 kV	132 kV
Lifetime (year)	30	30	30	30	30
Capacity Factor [%]	92	92	92	92	92
	Cost Estimations Based on Academic Literature and Other Companies				
Nominal Net Power [MW]	2.5	10	20	50	100
Real CAPEX (with cable) for d = 20 km [US$ million (2018)][89]	80,48	140,9	186,45	269,98	480,44
Real OPEX [US$ million (2018)	2,41	4,23	5,59	8,1	14,41
Uncertainty CAPEX and OPEX [%]	43,8	61,7	68,5	75,7	73,2

Table 3.1 OTEC Configurations Analysed in this Thesis Based on Literature. (Own Illustration)

[8] US$ values are translated from nominal to real values with CPI Inflation Calculator (Bureau of Labor Statistics, 2018)
[9] If costs were given in €, they were first converted to US$ using historic currency exchange rates. Subsequently, the US$ value was adjusted for 2018 value.

3.2. Selection of Suitable Tropical Islands and OTEC Cells

As a result of his master thesis, Chalkiadakis enumerated a set of 72 countries with practicable potential for OTEC, which unfolds to over 95 when some countries are cracked down to their territories. For example, while countries such as the Netherlands and France themselves are technically unsuitable for OTEC, their territories like Aruba and Martinique are. However, since tropical islands embody the theme of the first part of the economic analysis, not every sovereignty of Chalkiadakis' collective fits into the context of this study. In the following sections, selection criteria are introduced and applied to obtain a refined and more exclusive set of tropical islands for which the economic potential of OTEC is determined. Note, that by the term "island", island countries are meant and not sub islands of archipelagos. If an archipelago is called island, all of its sub islands are addressed.

3.2.1. Determination of Tropical Islands Eligible for Economic Assessment

3.2.1.1. Criteria Deduced from Geography and Climate

Tropical island countries. If this term is disintegrated into its essential components, one obtains two simplistic, but no less effective criteria of *"Which of the countries and territories are islands?"* and *"Which of these islands are tropical?"*. The dependency on fossil fuel imports, price instability and myriad other struggles as mentioned in the introduction of this thesis epitomise enough justification for the first question.

The second one, on the other hand, does not relate as much to the struggles of island countries as to the ones of OTEC itself. The average seawater temperature difference in subtropical islands tends to be cooler vis-à-vis tropical ones. While values of merely 20 °C are common for subtropical countries like Japan and Australia, they are rather exceptional for tropical countries, for example island countries along the East-African coast. Thus, most OTEC plants in the subtropics would require larger components to generate the same amount of power compared to systems in the tropics and vice versa, the same plant would generate less electricity for the former than for the latter. One pervasive argument of OTEC proponents for the technology is the ostensible production of steady, non-intermittent electricity, thus engendering balance in energy systems perforated by volatility (Fujita et al., 2012; Vega, 2012). Alas, a lot of the vigour of this assertion is somewhat lost by the word *ostensible*. What many champions of OTEC tend to conceal – willingly or not – is the fact that the technology is intermittent as well. The seasonal changes of seawater temperature are both the poison and the antidote of OTEC power and either enhance or undermine the technical and, consequently, economic performance of a system. In this regard, subtropical areas are more prone to stark, seasonal temperature differences than tropical ones. For example, while the real power output of a nominal 100 MW plant stays constant throughout the year at a real power output of roughly 150 MW for the Northern parts of Indonesia and Papua New Guinea, the performance in Japan would vary between roughly 100 MW in June and less than 50 MW in December (Lockheed Martin, 2012).[10] Hence, it is argued that the abolishment of subtropical islands curtails the uncertainty inherent in the temperature profiles of scrutinised countries.

After filtering the initial set of sovereignties for island countries within a geographical range of tropical climate between 23.44°N and 23.44°S, only 56 islands remained. Some of the continental countries leaving the party are Brazil, Colombia, Tanzania, Ghana, China and Malaysia, while others like Australia, New Zealand and Japan are eliminated due to their subtropical climate (n.a., 2018; National Geographic, 2018; United Nations, 2018). Concerning the first criterion, even if a continental country contains islands, it is omitted, as solely non-continental countries are of interest in the first part of the economic analysis.

3.2.1.2. Criteria Deduced from Electricity Demand

While the first two criteria adjust the set of countries for the geographical and climatic frame of this thesis, they do not address the economic suitability of OTEC. Hence, as simple as these aspects are, they only scratch the surface of the matter and call for more sophisticated, supplementary criteria. As of right now, OTEC can be supplied to 56 tropical islands. But as a yin needs a yang, a supply needs a demand. Without perceiving its compliment, the economically feasible supply of OTEC might be examined for islands which do not need it in the first place and, conversely, might neglect islands which urgently do. Thus, the following criteria take a closer look at the energy sectors of the remaining countries and territories, namely *fossil fuel import dependency* and *final electricity consumption*.

As already mentioned throughout this work, most tropical islands lack access to fossil fuel. With no own reservoirs at hands, they are bound to import them from global markets, with high transportation costs and instable prices (Dornan & Shah, 2016; Niles & Lloyd, 2013). Then again, exemptions confirm the rule and two countries in particular, Brunei Darussalam and Trinidad & Tobago, stand out as net fossil fuel exporters. One quick glance at their energy statistics is enough to exclude them from any further consideration. Abound in domestic fossil fuel, electricity in Brunei and Trinidad & Tobago can be as cheap as 7.6 and 4 $ct./kWh, respectively (Department of Electrical Services, 2012; Energy Transition Initiative, 2015a). Against such odds, OTEC's economic potential is probably minuscule to non-existent, at least without state intervention. With further depletion of fossil fuels, however, such countries might consider looking into OTEC in the future.

[10] Values estimated with a global heatmap in (Lockheed Martin, 2012).

The fourth criterion encompasses the final electricity consumption on the islands. The logic behind it is that whenever an OTEC plant is installed, its power output replaces the output of another plant and ultimately covers a part of the island's electricity demand. If the power output of one OTEC plant already surpasses the total demand within the country or territory, there is little impetus to embark on its implementation, as the local overproduction of electricity would entail plummeting prices and considerable profit squeezes upon OTEC operators. Thus, the final power consumption of every island is documented and then compared to the annual energy output of 2.5, 10, 20, 50 and 100 MW OTEC plants with an availability of 92%. Moreover, the final electricity consumption of each island is obtained for the year 2015 from the energy balances provided by the United Nations and the World Factbook of the CIA (Central Intelligence Agency, 2018; United Nations, 2015). The final electricity consumption of the analysed island countries can be found in Table 4.1 at page 57.[11] Under this line of reasoning, an island is omitted if one small-scale OTEC plant already produces more power than its population consumes.

But what if the island's electricity consumption is slightly higher than the plant's output? Is the island still suitable? At least to the author's attention, no national energy system on this planet relies solely on one power plant. Not only would the people and their consumption patterns be subjected to the seasonal intermittency inherent in OTEC, but they would also be utterly susceptible to outages due to unscheduled maintenance or malfunction. Thus, this thesis assumes that an island is suitable if one small-scale OTEC plant only covers a maximum of 30 % of the final power consumption. This percentage is loosely based on the proportion of baseload energy production by sources like coal and nuclear energy in the United States in 2015 (Squalli, 2017). By no means it is argued that the proportions of baseload production and baseload consumption within a country are the same – they are not – but for the sake of simplicity, this assumption is accepted. Hence, if 30 % of an island country's demand is lower than the annual energy production of 20.1 GWh of a 2.5 MW plant, it needs to be discarded from further consideration, at least until future electricity demand grows beyond this threshold.

As it turns out, 15 islands are not suited for baseload OTEC power, five of which consume less energy within a year than produced by a standard 2.5 MW OTEC plant, amongst them Tuvalu and Kiribati. Considering that the formidable, practicable OTEC potential of over 60 GW encompassed by the latter, this is a rather curious, but also sobering insight (Chalkiadakis, 2017).

Even after considering the demand for different scales of OTEC, there is still a large group of islands in the game. This might ensue a great horizontal quality of the research, but also an enhanced workload. These concerns are surely not expressed to shy away from long days (and nights) in front of the laptop, but it needs to be questioned if such a strain is adequate. Although the documentation of the thesis progresses linearly, its methodological execution did not. For example, the first back-of-the-

[11] The table was placed in chapter 4 to avoid redundancy in later chapters.

envelope calculations on the economic potential of OTEC already took place during the process of country selection. The result is not a step-by-step, but more an iterative approach in which the methodology was adjusted based on preliminary economic modelling. This prophylactic modus operandi proved highly fruitful, since it showed the absence of *any* economic potential for 2.5 MW OTEC. Even at the most promising locations, which happen to be Indonesia and Papua New Guinea, the LCOEs of such plants just scratch on the surface of competitiveness. These insights are illustrated in more detail later, but of course the reader is warmly invited to already peek into the results in chapter 4.1. Consequently, although a 2.5 MW OTEC system could commensurately cover the electricity demand of many tropical islands, it is highly unlikely that this could ever happen under economic boundaries. Therefore, any islands suitable for 2.5 MW, but not for the next biggest scale, are omitted as well, eliminating an additional group of 13 islands.

With energy-specific criteria, the selection of countries becomes more relevant. By contrasting the output of an OTEC plant to the total power consumption within an island, one learns if there is a general demand for the technology. But what if the population, and consequently the demand, is spread over countless isolated sub islands? Countries like the Maldives, Federated States of Micronesia or Marshall Islands are vast archipelagos, with some sub islands more populated than others. For the former, most people reside in its capital Malé, while most of the remaining hundreds of sub islands linger in a more or less rural state of development (van Alphen, van Sark, & Hekkert, 2007). Therefore, while there might be sufficient demand for OTEC in some densely populated areas of an island country, this might not be the case for smaller, scarcely populated ones. This vindicates the examination of the *demand distribution* within islands, which embodies the fifth selection criterion.

Tackling this aspect turns out to be a little bit more complicated. One of the boundaries of Chalkiadakis' models was a population density of at least 500 people per km² along the coast of a country, thus accounting for a sufficient energy demand. While this assumption was fairly effective for the tasks of his thesis, it cannot be adapted for this study directly. During the analysis of Chalkiadakis' dataset, it was noticed that countless islands were labelled as practicably suitable although they were either uninhabited or only comprised a handful of residents. It stands to reason that his model perceives all sub islands of an archipelago as practicably suitable for OTEC as soon as one of them meets the boundary of 500 people per km².

Therefore, only islands with distinct demand centres are analysed in this thesis. If the population and electricity demand of an archipelago is spread over too many tiny sub islands, like in the case of the British Virgin Islands, it is excluded from further consideration. For a city or region to be considered as a demand centre, it needs to fulfil several premises. First, the population within a centre should be at least 15.000 people. For this, the largest populated cities within a country are gathered using databases like geonames.org. Then, the location of these cities is tracked by using google maps. If commensurately populated cities are within a range of 50 km to each other, they are summarised as one regional demand centre. For larger island countries like Indonesia or the Philippines, the population threshold was lifted to 100.000 to maintain a feasible amount of demand centres. One could object that the energy consumption of island countries is not high enough to justify the deployment of OTEC, especially of island developing states. For example, Haiti's per capita consumption in 2014 was only 39 kWh according to the World Bank. Thus, a 10 MW plant, providing 80.6 GWh per year, could provide electricity to over two million people per annum. Why using a population threshold of 15.000 then? Many of the analysed countries, especially Haiti, struggle with energy poverty, or the inaccessibility of electricity. Thus, the energy consumption statistics can be deceptive because they do not consider the latent demand of isolated communities bereft of accessible electricity. OTEC could be a tangible solution to electrify these regions and a less stringent population threshold is justified.

Based on the five selection criteria, namely (1) geography, (2) climate, (3) fossil fuel import dependency, (4) final electricity consumption and (5) electricity demand distribution, a final set of 29 countries and territories is obtained and enlisted in Table 3.2. A table displaying the number and location of every demand centre for each country can be found in Appendix D.

3.2.2. Cataloguing of Suitable OTEC Grid Cells

In chapter 2.2.3, it was revealed that the costs and revenues of an OTEC plant depend on the seawater temperature difference and the distance from plant to shore. While the former determines the real power output of the system, the latter not only shapes the capital expenditures, but also the power losses due to cable inefficiencies. Thus, each site suitable for OTEC comprises a different quality, depending on its relative location. In this section, a catalogue of OTEC units is generated for each of the 29 tropical islands, enumerating both the temperature difference and closest distance to demand centres.

Again, the corollaries of Chalkiadakis' thesis serve as the foundation. His objects of investigation were both onshore and offshore 100 MW OTEC systems for which he mapped practicable OTEC cells spread across the world. A strongly simplified depiction of such cells is shown in Figure 3.2 below for a notional island. The cells are not evenly distributed due to the boundary conditions in Chalkiadakis' model which comprise among others a sufficient sea water temperature difference of at least 20 °C, a sea depth of at 1.000 m the location within *Exclusive Economic Zones* (EEZ). Onshore cells are coloured yellowish and abide by the same boundary conditions. The green dots represent the grid connection at the coast. Although the term "onshore" implies that the plants are land-based, they are not, but situated exactly 9 km away from shore. Therefore, the term "near shore" would maybe be more appropriate. Notwithstanding, this thesis adapts the terminology of Chalkiadakis and perceives onshore cells as cells being situated 9 km from shore.

Country	10 MW	20 MW	50 MW	100 MW
Barbados	x	x	-	-
Cuba	x	x	x	x
Dominican Republic	x	x	x	x
Fiji	x	x	-	-
Haiti	x	-	-	-
Indonesia	x	x	x	x
Jamaica	x	x	x	x
Madagascar	x	x	-	-
Maldives	x	-	-	-
Marshall Islands	x	x	-	-
Papua New Guinea	x	x	x	x
Philippines	x	x	x	x
Republic of Mauritius	x	x	x	-
Saint Lucia	x	-	-	-
Seychelles	x	-	-	-
Sri Lanka	x	x	x	x
French Polynesia	x	x	-	-
Guadeloupe	x	x	x	-
Martinique	x	x	x	-
Mayotte	x	-	-	-
New Caledonia	x	x	x	x
Reunion	x	x	x	x
Aruba	x	x	-	-
Curacao	x	x	-	-
Cayman Islands	x	x	-	-
Guam	x	x	x	-
Hawaii (USA)	x	x	x	x
Puerto Rico	x	x	x	x
U.S. Virgin Islands	x	x	-	-

Table 3.2 List of Countries Suitable for the Economic Analysis of OTEC Coloured Cells Represent Territories. Blue: France; Orange: The Netherlands; Red: United Kingdom; Green: USA. (x) Marks Suitability; (-) Marks Ineligibility.

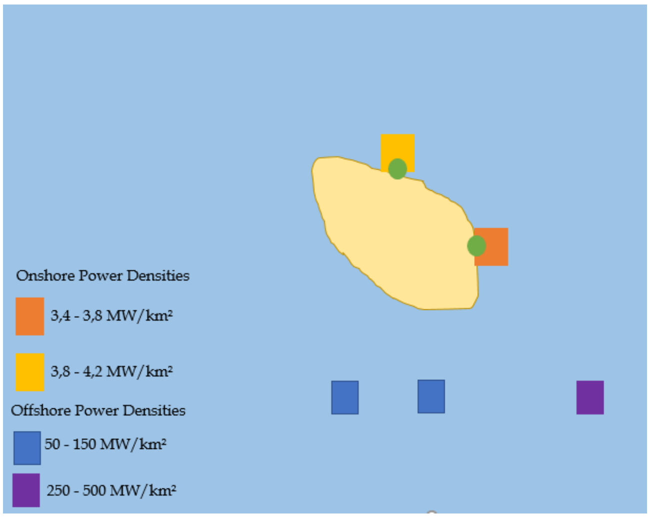

Figure 3.2 Practicable OTEC Locations for a Notional Island (Power Density Values and Colours for Cells are Directly Adapted From Chalkiadakis (2017).

Figure 3.2 above provides an appreciable indication of the practicable potential of OTEC. Nevertheless, some modifications are necessary to deploy its results commensurately for this thesis. As of right now, the potential of each OTEC unit is expressed in power densities in [MW/km²]. To calculate the absolute power one cell could produce, the power density needs to be multiplied with the area it occupies. But exactly here lies the problem. What is the area of one OTEC plant? Generally speaking, it is the area of cold water which is siphoned off by the cold water pipe of the system. The computation of this area is a highly theoretical concept and foots on rather simplifying assumptions in literature (Lockheed Martin, 2012). Therefore, it is considerably more convenient to calculate the power output of each cell without the OTEC area by analysing the seawater temperature difference prevailing there instead. If each OTEC unit is characterised by its specific temperature difference rather than its power density, it is easily possible to catalogue their real power output and, therefore, to streamline the economic analysis. The cataloguing of the seawater temperature differences at each cell is rather straightforward as the geographical information of Chalkiadakis' model is merely converted to a Microsoft® Excel sheet.

The choice of seawater temperature differences over power densities can be further consolidated by comprehending how Chalkiadakis calculated the latter. One of the most important values in this process was the cold water flow rate w_{CW} which is the proportion between the volumetric cold water flow and the area of cold water extracted from underneath the OTEC plant.[12] Depending on how it is defined, it affects the dimension of power output considerably. Chalkiadakis used a w_{CW} of 175 m/year to compute a practicable potential of 4.4 TW and thereby accords with contemporary research (Rajagopalan & Nihous, 2013). But it cannot be denied that there are inconsistencies between the values

[12] A more detailed elaboration on w_{CW} and its impact on the power output of an OTEC plant can be found in Chalkiadakis (2017) and Lockheed Martin (2012).

utilised in academia and industry. For example, Lockheed Martin's 100 MW system siphons off a volumetric cold water flow of around 360 m^3/s (Lockheed Martin, 2012). Based on this, a cold water area of 64 km² would be required to obtain a w_{CW} of 175 m/year. But how are those values realised? The only two options are to either increase the volumetric cold-water flow or to decrease the area of cold water channelled into the system. While the former is on the short side of technical feasibility, the latter is either out of human's reach or simply paradoxical. Controlling the cold water area in a natural way is impossible, since its availability depends on complex, global deep sea currents. If the area of extracted cold water is to be altered artificially, intuition would suggest curbing the volumetric water flow through the cold water pipe. After all, less water being extracted would concomitantly mean a smaller area. But then again, a smaller area would be offset by a lower volumetric cold water flow which reduces the w_{CW}. Vice versa, increasing the volumetric water flow to boost w_{CW} would intuitively increase the area of cold water lead into the system, offsetting the increase of extraction.

Therefore, this thesis strongly argues against a w_{CW} of 175 m/year, on which Chalkiadakis' results foot. Perceiving Figure 3.2, some of the grid cells shown there comprise a power density of between 2.85 and 5 MW/km², which are rather mediocre values in Chalkiadakis' dataset. But if one would multiply this range with an area of 64 km², one would obtain a real power output of 182.4 – 320 MW. That would be an increase of 82.4 – 220 % of power output compared to a nominal value of a 100 MW plant! Based on these contemplations, Chalkiadakis' results might inherently overestimate the practicable potential of OTEC.

It was not possible to obtain the distances from OTEC cell to demand centre from Chalkiadakis directly. In his thesis, an optimisation tool was used to determine to shortest distance of each cell to the coast. But in this study, not only the distance to shore is important, but also to demand centres. Therefore, the distance between OTEC cell and demand centre is calculated by analysing their geographic coordinates and by applying trigonometry, as shown in Figure 3.3. The underlying formulas and assumptions can be found in Appendix D.

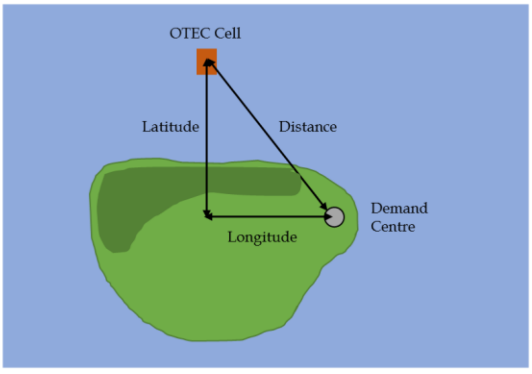

Figure 3.3 Determination of Distances between OTEC Cell and Demand Centre , Difficult Terrain Depicted in Dark Green (Own Illustration).

Figure 3.3 highlights the discrepancies between Chalkiadakis' approach vis-à-vis the one elaborated here. The distance calculated here is noticeably longer than the perpendicular, optimal distance to the shore. But is the latter always desirable? Maybe, the perpendicular route leads to difficult terrain. This is not far-fetched. Some of the largest cities in Madagascar are sealed-off from both the Eastern and Western coast by thick stripes of rain forest, which render them unsuitable as OTEC demand centres despite its dense population. Of course, power lines could be installed through these forests, but then objections might arise due to economic (and ecologic) costs of deforestation and soil excavations. These disruptions in local flora and fauna might be avoided by considering other energy technologies. Thus, a striking benefit of this method is not only the definition of demand centres, but also the accessibility of OTEC to these hot spots.

One must recall that these distances are supposed to represent the length of a submarine cable. When the distances are calculated as described above, this would mean that some of these cables would breach across the coast line onto shore. This and the concomitant surge of cable costs could be conceived as a major drawback of this approach. But maybe also not. First, if a cable, whether submarine or not, is bound to cover a long distance on land just to reach a location with sufficient demand, OTEC's suitability for this island is generally questionable. In this case, it would be reasonable to reject OTEC for other alternatives like onshore wind power or photovoltaic. Second, it was already discussed in chapter 2.2.3.2 that the distances from OTEC plant to shore do not represent the actual length of the cables. Recollecting Figure 3.1, the cables travel towards the coast along the seafloor. From this perspective, the distances to demand centres do not overestimate cable lengths, but in lieu counteract the inherent underestimation of cable lengths due to previous simplifications. However, whether the marine cable lengths are over- or underestimated depends on local criteria, i.e. grid connection along the coast, and require further attention in more spatially specialised analyses.

Of course, one island might have more than just one demand centre. Then, the distances between one OTEC cell and each demand centre are calculated and compared for the smallest value. By doing so, one does not only obtain the shortest distance to an area of high demand, but also the area's exact location. Considering that this thesis mostly comprises a national and global approach, such regional and provincial precision is a remarkable feature, since it is then possible not only to argue which countries, but also which cities, provinces, counties, etc. are most suitable for OTEC deployment. Although this method might not compare to the in-depth quality of solely provincial assessments, it still provides helpful suggestions and might serve as a preliminary guideline for such studies. It might also remove the subjective bias inherent in the methods described here. The decision whether a region is perceived as a demand centre or not foots on personal judgement over information like total population and electricity consumption. However, the author of this thesis neither set a foot on any of the analysed countries nor is familiar with the social customs prevailing there. Hence, although the scope of this thesis is comprehensive with 29 islands to be analysed, it comes at a cost of country-specific relevance. It is acknowledged that there is a pervasive risk of determining a demand centre which might not be one and, conversely, neglecting areas which in fact are.

3.3. Modelling of National Global Supply Curves

After the set of suitable island countries and territories is determined, the LCOE at each OTEC cell previously mapped by Chalkiadakis is calculated using equation (1) shown in chapter 2.2.1, namely.

$$LCOE = \frac{\sum_{t=1}^{N} \frac{CAPEX_t + OPEX_t}{(1+DR)^t}}{\sum_{t=1}^{N} \frac{E_t}{(1+DR)^t}} \tag{1}$$

Depending on which capacity of OTEC can be deployed at a specific island, the CAPEX, OPEX and energy output and their boundaries of uncertainty refer to either 2.5, 10, 20, 50 or 100 MW systems. All economic calculations are performed for two discount rates associated with privately and publicly funded projects. For the former, a WACC of 18 % is used as a discount rate, while the latter draws on a social discount rate of 10 %. For the remainder of the thesis, the terms “private” and “public” regard to a discount rate of 18 and 10 %, respectively. After the LCOEs are ordered from smallest to largest value, a total of three supply curves are produced, a blue base curve based on Lockheed Martin, a grey curve for cost estimations by academia and other OTEC companies as well as an orange curve which adds an upper boundary of uncertainty to the base values. To determine the economic potential of OTEC for the analysed island, the supply curves are contrasted to yellow reference lines which ought to resemble local wholesale electricity prices. In total, there are two reference lines ranging between 20 and 40 $ct./kWh.

The reference values are merely estimations, since it was not possible to retrieve any actual wholesale prices for the analysed countries. The values were chosen based on the recommendations of thesis committee member Professor Dr.ir. Kornelis Blok and the observations made for retail energy prices on small islands. Due to their remoteness, retail prices of electricity are far higher than for continental regions and larger islands. At the U.S. Virgin Islands for example, residential prices were roughly 47 $ct./kWh in 2015 (Energy Transition Initiative, 2015b). Of course, wholesale prices are considerably lower than retail prices but since no specific values for the former could be found, this thesis resorts to the range proclaimed by the yellow lines. This ambiguity is a clear shortcoming and could be addressed in future research by means of more local scopes of investigation. It is acknowledged that the wholesale prices for larger islands like Indonesia and continental countries as discussed later are considerably lower than the thresholds used here. While these reference values are decent estimates for most of the 29 island countries analysed in this chapter, their validity declines with the extension of the spatial scope and the inclusion of larger countries.

Neither the supply curves of OTEC nor the reference costs to which they are contrasted are specific values, but instead ranges of possible outcomes. In the worst case, the orange curve is contrasted to the lower range of reference costs, being 20 $ct./kWh; in the best case, the grey curve to the upper range of 40 $ct./kWh. For the remainder of the thesis, these scenarios are abbreviated as “worst case” and “best case”, respectively. The ranges of worst- to best-case economic potentials at each island refer to the highest capacity deployable there. For example, since Indonesia is eligible for 100 MW, every grid cell will be occupied by such a capacity and its economic potential is solely determined by such systems. In practice, this would not be the case and there would be a mix of various scales. Furthermore, one cell could also be occupied with multiple smaller plants, i.e. two 50 MW systems instead of one 100 MW. These considerations are acknowledged, but the assumptions here are accepted for the sake of simplicity.

After the economic potential of OTEC is determined for each of the 29 islands, their supply curves are amalgamated to form an aggregated, international supply curve revealing the range of economic potential for all analysed islands combined. The sensitivity of the discount rate on the shape of the plots is analysed for a range 3 to 18 % and an interval of 3 %. With the aggregated supply curves, it is also possible to observe statistical trends which are needed to extrapolate the results to a global level. These observations are among others epitomised by histograms depicting the proportion of economically eligible OTEC cells, the probability of certain values for real energy output and LCOE as well as the coverage of energy demand by economically viable OTEC.

3.4. Implementation Scenarios and Global Experience Curves

3.4.1. General Constitution of the Implementation Scenarios

Contriving reasonable implementation scenarios tends to be a tightrope act, especially for a niche technology like OTEC. As already discussed earlier, there are no commercial OTEC plants as of today, so it is not possible to resort to preceding patterns of deployment or learning. Therefore, the scenarios presented here should not be perceived as predictions, but as rough indications of what might happen under certain conditions. It is impossible to know what trajectory OTEC might pursue if it was actually implemented, so the best what this thesis can do is to rely on trends seen in other, comparable niches, like offshore wind power. There, installation growth rates have been astonishing with annual rates of 25 – 40 % in the last two decades (Takami & Lidington, 2017).

These growth rates act as the foundation of the first three implementation scenarios elaborated here, epitomised by (1) *Modest Growth* with an installation rate of 20 %/year, (2) *Fast Growth* with 30 %/year and (3) *Rapid Growth* with 40 %/year. Every scenario is contained within a time frame of 24 years, which resembles the period at which wide-spread offshore wind implementation commenced.

Given that only a marginal fraction of the economic potential of OTEC might be covered under these premises, a fourth scenario encompasses the (4) *Superaggressive Expansion* of the technology. Here, virtually all OTEC cells analysed in chapter 4 are deployed at a growth rate of 40 %/year, which leads to a time frame of 35 years in this case.

Each of the four scenarios employs various learning rates. Besides the absence of learning, other cases comprise learning rates of 6, 12 and 18 %. A relatively low learning rate of 6 % is vindicated by both OTEC literature and experiences within the offshore wind niche. On the other hand, a learning rate of 18 % might also be reasonable in accordance to the comprehensive elaborations by Weiss (2009). The value of 12 % is not backed by literature and merely serves as a buffer between the other two learning rates to make trends visible more easily. Additionally, the scenarios are analysed for infinite and finite learning to address the disparity within literature (see section 2.3.1).

The scenarios ought not only to give insights on how much of the economic potential found in chapter 4 can be covered within a certain time frame, but also how much of the global electricity demand can be met. Note, that “global” in this thesis refers merely to the over 90 countries and territories suitable for OTEC, not the entire world. It is assumed that the global electricity demand rises at an annual rate of 1.15 % in accordance to the estimations found in the *World Energy Outlook 2017* by the IEA (IEA, 2017).

Before the results of the scenarios are presented, it is important to elucidate the logic behind OTEC implementation. During the economic analysis in chapter 4, small-scale 2.5 MW systems are discarded as hopelessly unprofitable. However, it is argued that they are still required during the pilot phase to gather valuable operational data. Therefore, these systems are implemented at the very beginning of each scenario, but eventually excluded later.

3.4.2. Global Experience Curves

As insightful as the supply curves in chapter 4 are, they still lack essential information, for example the impact of learning on the LCOE. Instead of projecting OTEC’s profitability *over time*, the supply curves assume every OTEC cell to be occupied *overnight*. Thus, while the total host of economic potential can be determined by them, the supply curves do not reveal how to implement these cells and how their profitability changes over time; the supply curves remain static. The first step in tackling this shortcoming is the construction of implementation scenarios as described in the previous section. The next step is the construction of experience curves based on these scenarios. According to the scenarios, each year a specific number of OTEC cells are deployed depending on the annual growth rate of installed capacity. Logically, the first units are realised at high-quality locations with high seawater temperature differences very close to a demand centre. Over time, the quality of the available locations gradually declines and OTEC implementers have to resort to more and more inferior alternatives. If the LCOEs of the utilised OTEC units are plotted against the cumulative energy production and ordered by the time of their implementation, experience curves are obtained which reflect the profitability of the technology under the light of deployment. Hence, experience curves are the compliment to present a more holistic picture of OTEC's economic potential. Figure 3.4 shows an example of an experience curve. It is custom in contemporary literature to use logarithmic axes and this thesis complies to it as well.

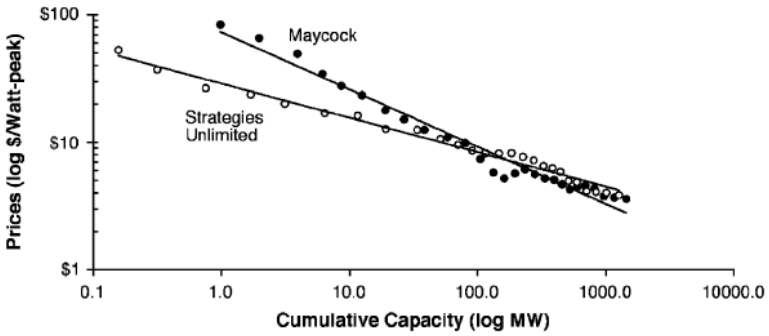

Figure 3.4 Example of an Experience Curve (Nemet, 2006).

For each scenario and learning rate, experience curves are modelled which ought to shed light on the implications of different aspects like economies of scales as well as the intensity and continuity of learning. Regarding the latter, it is assessed how the experience curves are shaped if cost reductions via learning stop after the 4th to 5th doubling of output as argued by OTEC literature. It is also assessed how the experiences differ depending on the base cost estimates and their worst- and best-case deviations.

3.4.3. Integration of Experience Curves into Supply Curves

As already mentioned above, the supply curves designed in chapter 4 do not take into account cost reductions via learning. However, this changes as soon as the insights from the experience curves are integrated into the supply curves. If the LCOEs of the OTEC units deployed during a scenario are arranged from smallest to largest value, one obtains dynamic global supply curves which abide by the effects of both economies of scale and learning. To avoid confusion, it is important to highlight the differences between the experience curves and the supply curves discussed here. Table 3.3 enumerates the major distinctions between the two concepts, while Figure 3.5 illustrates how the insights of the experience curves can be integrated into the supply curves and vice versa.

Criterion	Experience Curves	Supply Curves
Time Dependency	Yes, implementation follows schedule	Not explicitly, implementation occurs overnight
Ordered by	Time of implementation	Lowest to highest LCOE
Deliverable	Development of costs over time including learning effects	Economic potential at a fixed point in time

Table 3.3 Differences Between Experience and Supply Curves (Own Illustration).

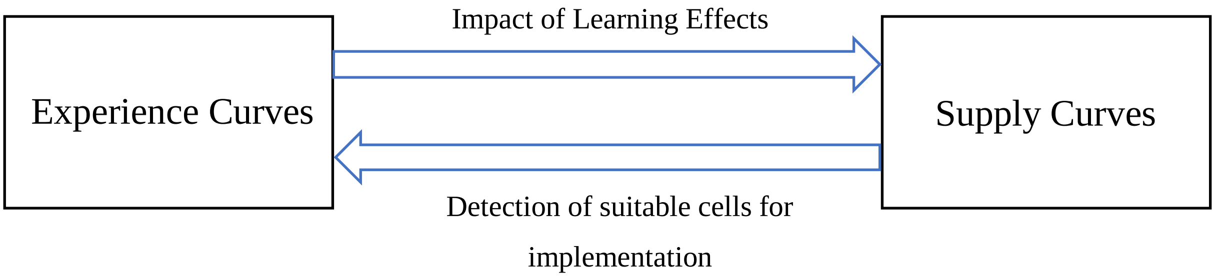

Figure 3.5 Interaction Between Experience and Supply Curves (Own Illustration).

The two illustrations above underline that experience and supply curves must not be confused. The economic analysis performed in chapter 4 produces supply curves revealing which OTEC cells are generally economically profitable and suitable for implementation. The experience curves generated in chapter 5 analyse how the costs of these OTEC units change over time by learning effects. This is an important thing to remember. Supply curves do not incorporate time explicitly; they merely reflect the LCOE of OTEC plants implemented *overnight*. By integrating the experience curve into the supply curves, the circle closes and it is uncovered how the amount of economically suitable OTEC cells and their costs change under the consideration learning effects. Thus, these dynamic global supply curves demonstrate how the economic potential of OTEC would look like if all available cells would be implemented *overnight* with learning effects. Even if the term “dynamic” might imply otherwise, these dynamic supply curves still do not explicitly represent the implementation of the OTEC cells, but only the total economic potential under the consideration of both economies of scales and learning effects.

Nevertheless, it is possible to observe patterns which give a hint on where to find certain development stages in these dynamic supply curves, like pilot and commercialisation phases. The last section of chapter 5 elaborates qualitatively how to interpret the supply curves as a roadmap for OTEC deployment.

3.5. Conclusion of Methodology

The construction of supply curves based the LCOE is perceived as the most suitable methodology for this study. The economic potential of moored, closed-cycle OTEC is analysed for private and public projects with a discount rate of 10 and 18%, respectively, and refers to five different scales of capacity, namely 2.5, 10, 20, 50 and 100 MW. Based on two layers of reference costs, worst- and best-case values are determined which form a range of conceivable economic potentials. Before the analysis commences, a set of suitable tropical islands is selected by contrasting them to a total of five selection criteria, namely (1) geography, (2) climate, (3) fossil fuel import dependency, (4) final electricity consumption and (5) electricity demand distribution. This results in a host of 29 islands, whose economic potential is first determined on a solely national, then international scope. The impact of changes in discount rate on the results is investigated by means of a sensitivity analysis. To enhance the relevance of the study, the insights of these supply curves are then used to extrapolate them to a global level, also including continental and subtropical countries. To generate more understanding about possible roadmaps for OTEC implementation and their effects on the economic potential of OTEC, four implementations scenarios are designed on whose bases experience curves are plotted. These measures enable a shift from a static to a dynamic perspective and reflect OTEC profitability under the light of learning effects and economies of scale. Additionally, it is possible to project distinct implementation phases and to indicate them on the global supply curves. Finally, the results are reflected by means of a discussion, recommendations and conclusion chapter.

4. Results and Discussion of the Economic Analysis of OTEC

It is now time to present the first results of this study. The foundation of this analysis are the corollaries of Chalkiadakis' thesis. He mapped the practicable potential of OTEC in the form of 15.295 offshore and 599 onshore grid cells, which in aggregate provide around 4.4 TW of power worldwide. Since merely the cells belonging to the 29 tropical islands are analysed in detail, they have to be extracted from the global set of data first. As a result, the conglomerate of islands consists of 8049 offshore and 405 onshore cells, which are then examined for their closest distance to a demand centre as defined earlier.

This chapter is structured as followed. First, the results of the national analysis are shown and discussed with Indonesia as a representative case. The standardised Microsoft® Excel Sheet used in this thesis is presented in Appendix E. Besides the supply curves for public 2.5 and 100 MW OTEC, it is illustrated how values like seawater temperature difference, distance to demand centre and LCOE are correlated. After the results are compared to the practicable potential computed by Chalkiadakis, the next section shows the aggregate supply curve of all 29 islands. A sensitivity analysis then examines how the change in discount rate affects the shape of the aggregate supply curves. Finally, the last section transcends to a global scope. Based on the previous work, the aggregate supply curves are extrapolated to represent every country worldwide economically suitable for OTEC.

The economic analysis elaborated in this chapter generated hundreds of graphs. For example, every of the 29 islands produces up to ten supply curves for five scales of power output and two discount rates. To maintain clarity, this chapter only presents the results of *public*[13] projects regarding either 2.5 or 100 MW. Appendix F and G list a comprehensive catalogue for all scales, discount rates and islands.

4.1. Supply Curve Modelling for Individual Islands

In the following, the economic potential of OTEC is described for Indonesia. The archipelago is chosen as an example since it is the country with the largest amount of OTEC grid cells among the 29 islands by far, even after peripheral cells beyond 370 km are removed. Curiously, merely 1.028 of the originally 1.851 cells are close enough to one of the 20 demand centres of Indonesia. This is a two-edged sword. On the one hand, one of Chalkiadakis boundary conditions could be responsible for the large proportion of drop outs. In fact, Indonesia consists of hundreds and thousands of islands of varying size and population, so there is a ubiquitous chance of some OTEC cells regarding to small sub islands

[13] In this thesis, the term "public" refers to a discount rate of 10%, "private" regards to a discount rate of 18%.

which do not have a demand for the technology in the first place. On the other hand, it might also be a shortcoming of the methods applied here. The risk of not defining a commensurate number of demand centres within a country is already mentioned in chapter 3.2.2 and Indonesia is a perfect example for this conflict. To leave the reader rest assured, it helps to mention that islands like Indonesia, Papua New Guinea, French Polynesia and Seychelles are rather exemptions and that the proportion of drop outs is minute for most other islands.

After the range of LCOEs is calculated for each of the 1.028 suitable cells of Indonesia, they are ordered from smallest to largest to form a bandwidth of supply curves, as shown in Figures 4.1 and 4.2 for 2.5 and 100 MW, respectively.

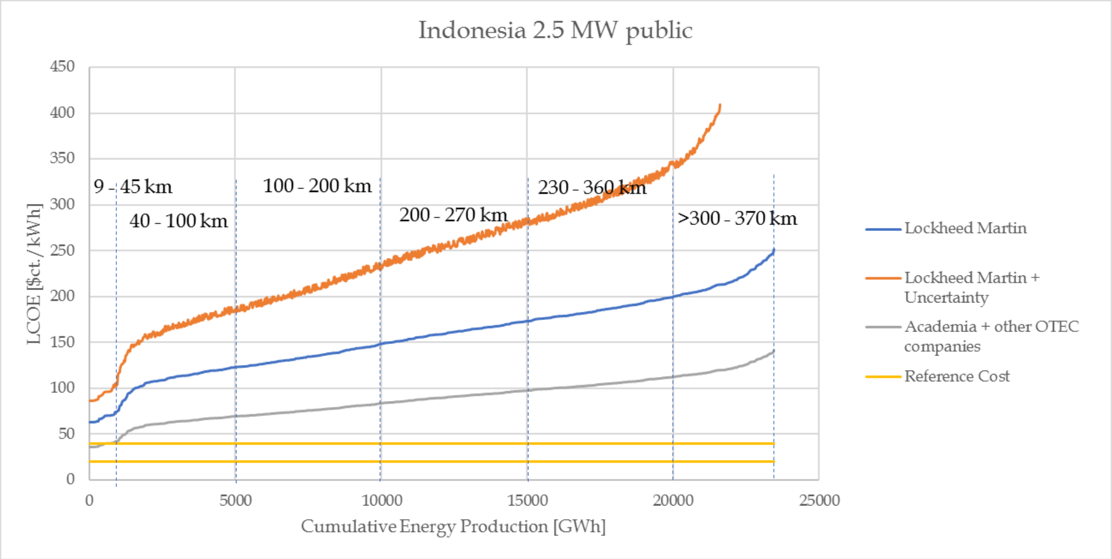

Figure 4.1 Supply Curve for 2.5 MW OTEC in Indonesia. Discount Rate 10% (Own Illustration).

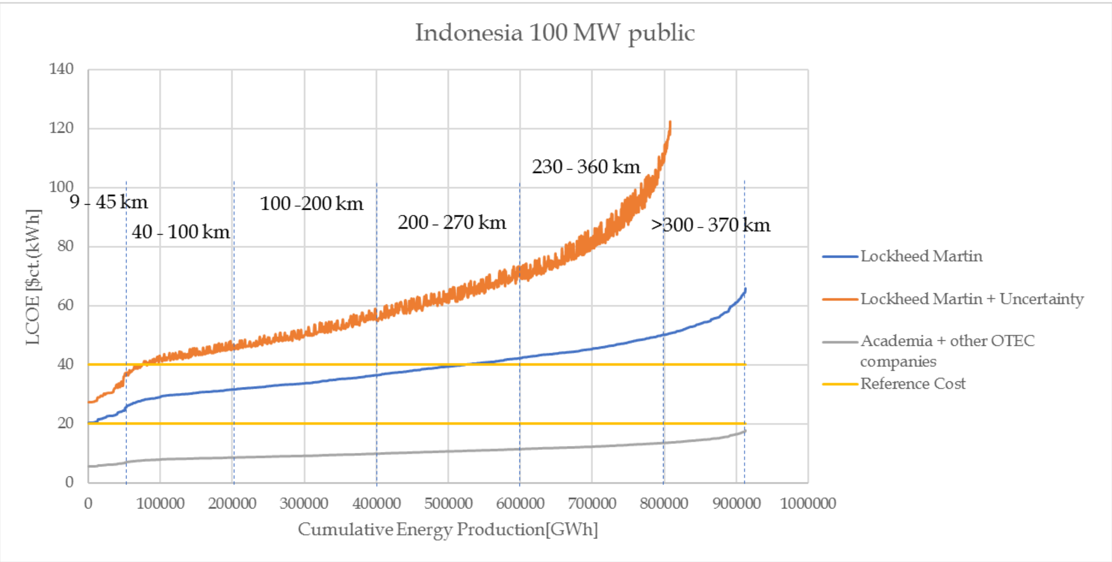

Figure 4.2 Supply Curve for 100 MW OTEC in Indonesia. Discount Rate 10% (Own Illustration).

The blue plots in Figures 4.1 and 4.2 are the base lines, with costs adapted from Lockheed Martin, whereas the grey lines resemble the more optimistic view of academia and other OTEC companies. The orange graphs represent the costs of Lockheed Martin plus the upper layer of uncertainty. The yellow, horizontal lines are the range of possible wholesale electricity prices (from now abbreviated as wholesale prices) prevailing at the 29 islands.

A remarkable feature in the figures above is the shape of the orange curves. While the blue and grey curves smoothly run from left to right, the orange curves start to oscillate at some point. The effects not only intensify with rising cumulative electricity supply, but also with increasing scale, since the "fuzziness" of the orange curve is more distinct in Figure 4.2 than Figure 4.1. As it turns out, the culprits are the uncertainties in cable length and capacity factor, which directly affect the net power output. These aspects are also the reason why the final cumulative supply of the orange graph is not the same as for the blue and grey plots (i.e. 800.000 GWh vs. 900.000 GWh in Figure 4.2). After all, a smaller capacity factor and higher transmission losses due to longer cables reduce the net amount of available energy at the demand centre.

Every analysed cell comprises a base LCOE and two variations for the lower and upper boundary of uncertainty, respectively. If the base LCOEs are ordered from smallest to largest, the corresponding values are reassembled accordingly. In the case of the lower uncertainty, the grey curves do not show any oscillations, which implies that the disruptions caused by smaller CAPEX and OPEX do not influence the general order of the cells. Contrarily, not only the CAPEX and OPEX, but almost all inputs of the LCOEs are adjusted for the upper uncertainty in the orange plot, which does not follow the order from smallest to largest anymore.

Figures 4.1 and 4.2 also contain rough indications on the distances between plants and demand centres, which is engendered by the strong correlation between distance and LCOE as shown below in Figure 4.3. Then again, Figure 4.4 reveals a weak to non-existent correlation between seawater temperature difference and LCOE. The latter is the reason why it is not feasible to indicate rough estimations for temperature differences in Figures 4.1 and 4.2. The weak correlation of seawater temperature difference and LCOE can be explained by the grave impact of the cable length. Even if a location contains a large seawater temperature difference, the gains in power output can be offset by transmission losses if the location is too far away from a demand centre.

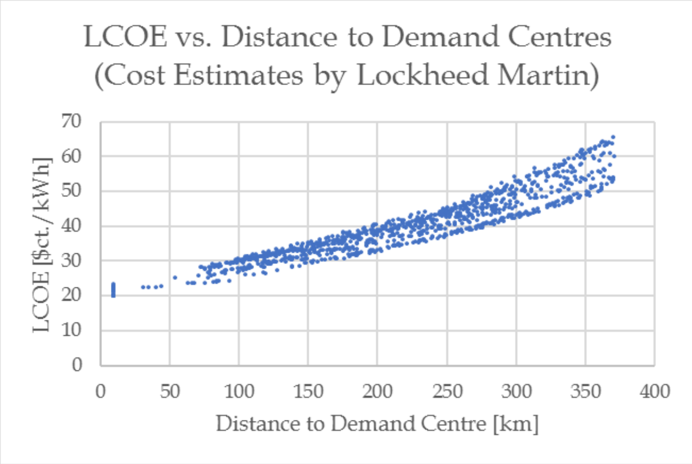

Figure 4.3 Correlation Between Distance to Demand Centre and LCOE (Own Illustration).

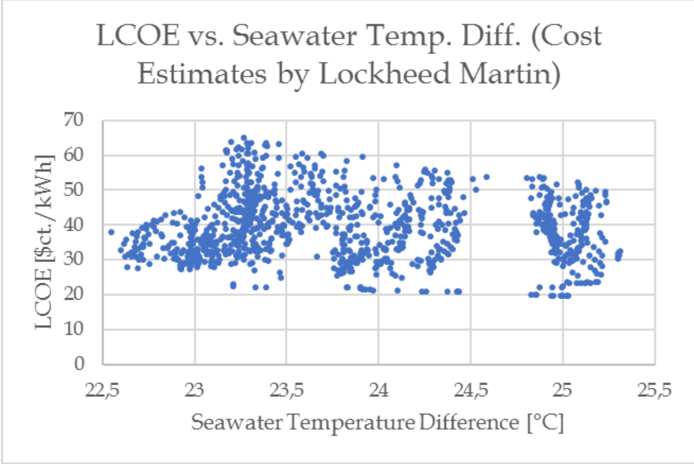

Figure 4.4 Correlation Between Seawater Temperature Difference and LCOE (Own Illustration).

Figures 4.3 and 4.4 refer to public 100 MW systems in Indonesia, but the general shape of the figures does not change regardless the scale, discount rate or island. Thus, these plots are not shown for any other island in this thesis. One might notice the strong incline in LCOE in Figure 4.3. From 100 to 200 km, the average LCOE increases by 25 % from roughly 28 $ct./kWh to around 35 $ct./kWh. Compared to offshore wind literature, that is quite a lot, which merely stipulates an increase of 6.6 % for the same range of distance (from 21.4 to 22.8 $ct./kWh) (Myhr et al., 2014).[14] The main reason for this is the exclusion of transmission losses in the latter case, while being a pivotal part of the calculations performed here. With increasing distance, more power is dissipated which adversely affects the LCOE. Another argument might be that the offshore wind LCOEs regard to monopile structures with a maximum depth of around 30 m, while OTEC operates at seawater depths of 1.000 meters. Consequently, the cable of an OTEC plant must be at least around 1 km longer than for an offshore system. However, at a distance of 100 to 200 km with corresponding cables, this is not expected to make an impact high enough to justify the noticeable differences in cost increases for OTEC and offshore wind.

What do Figures 4.3 and 4.4 mean for OTEC producers? When choosing a location for OTEC deployment, the economic analysis demonstrated that its quality is more determined by the distance to a demand centre than by the seawater temperature difference. But then again, it also proves fruitful to consider locations further away from the island. Despite its deceptively weak correlation with the LCOE, the seawater temperature difference is still a pivotal aspect to be considered. To fully grasp the competitive edge over other OTEC producers, one should not solely rely on the distance and instead resort to the well-balanced combination of both variables.

The most important insights of Figures 4.1 and 4.2 have not been discussed, yet. Based on the graphs above, what is the economic potential of OTEC in Indonesia? This is a tricky question, since there is no precise answer. Not only the supply curves, but also the reference costs are distributed over

[14] Values were given in €/MWh (2014) for a discount rate of 10% and converted to $ct./kWh (2018).

ranges of likelihood. For 2.5 MW systems, the situation is quite sombre. Even in the best case, only some grid cells undercut a wholesale price of 40 $ct./kWh. With Indonesia being one of the most promising locations worldwide due to its favourable seawater temperature profile, it is fair to say that 2.5 MW systems will not be economically viable *at all*. Instead, the country would be well-advised to resort to larger, more profitable systems.

Figures 4.1 and 4.2 outstandingly underline the effects of scaling up the power output on the LCOE. Nevertheless, none of the analysed scales can breach a wholesale price of 20 $ct./kWh in the worst case. Due to Indonesia's extraordinary conditions, it is expected that no other island can do so either. It becomes clear that the upper range of uncertainty is a red-flag which must be avoided by any means. Additionally, Figure 4.2 displays that the blue base curve is just shy from penetrating the lower layer of reference cost, resulting in a **base economic potential of 0 GW**. This is a rather unpleasant result at first, but at least there is hope that cost reductions by learning might push the curve below 20 $ct./kWh.

Based on Figure 4.2, **the economic potential of OTEC in Indonesia ranges between 0 – 913 TWh or 0 – 113 GW for a scale of 100 MW and a discount rate of 10 %**. This is rather ambiguous, since it implies that OTEC's economic potential could be nearly all or none of available OTEC locations. While the upper layer of uncertainty obliterates any profitability even at large capacity, the lower boundary even allows the profitable deployment of OTEC at ostensible "junk" cells. However, OTEC's greatest burden, its vast capital expenses, underlines perfectly that an economic potential as above, as promising as it might appear, must be taken cautiously. If the entire best-case potential was to be implemented overnight, it would amount to a total CAPEX of US$ 756.2 billion (2018 value), which would be 77.3 % of Indonesia's GDP in 2016 (converted to 2018 values) (countryeconomy, n.d.). The good news is that these costs are rather small for OTEC's standards. If the same potential was implemented for the worst case, it would amount to overnight costs of US$ 3.67 trillion. Thus, as formidable as an economic potential of 113 GW sounds, it does not provide any realistic insights about its implementation, but more on that in chapter 5.

Unfortunately, almost all islands analysed in this study show the patterns described above, with either all or no OTEC cells being economically attractive. This is the crux when the ranges of uncertainty are too broad as in the case of this study. But rather being a flaw of the methodology applied here, this is more of a major shortfall of the OTEC niche itself. No one knows how much a commercial OTEC plant will cost and no one knows for sure how the costs behave in the case of scaling up the power output. Again, it is emphasised that the results here are only projections. None of the graphs depicted here should be taken literally, but instead as a rough sketch of what might happen if certain conditions are fulfilled.

In any case, the economic potential of OTEC only covers a small proportion of what could practicably be deployed. If the 113 GW of economically viable OTEC in Indonesia would be implemented, it would only be around one fifth of what Chalkiadakis computed as practicable. Curiously, a proportion of 20 % is rather decent compared to other islands. For instance, only 0.2 % of the practicable potential in Seychelles could be economically realised. How can that be?

First, in contrast to this study, Chalkiadakis only mapped the global potential of OTEC for one scale, namely 100 MW, without regard to local electricity demands. That this has far-reaching consequences is perfectly demonstrated by the Federal States of Micronesia. According to Chalkiadakis, Micronesia is one of the most promising regions for OTEC deployment with a stunning practicable potential of 305.12 GW. But its minute electricity consumption does not even vindicate a 2.5 MW plant (United Nations, 2015). The sub islands are just too small and too far away from each other. So even though there is a practicable potential of 305.12 GW, the economic potential is ultimately zero. In this thesis, merely eleven out of 29 islands are suitable for 100 MW OTEC and those are the ones converging the closest to the practicable potential. Then again, islands only suitable for smaller systems, such as Seychelles, leave much of their practicable OTEC potential untouched. Second, Chalkiakis' values foot on a cold water availability w_{CW} of 175 m/year which is already argued against in chapter 3.2.2.

Table 4.1 contrasts the economic potential of each tropical island with the practicable potential computed by Chalkiadakis. All economic potentials refer to the best-case values and the assumptions holds that each island implements OTEC systems of the highest possible scale. Furthermore, Chalkiadakis' values are adapted to a capacity factor of 92 % for this study. Originally, he resorted to a factor of 90 %. An interesting feature of Table 4.1 is the starkly heterogeneously distribution of economic potential among the 29 tropical islands. Indonesia, Papua New Guinea and the Philippines, all located in the Pacific Ocean, occupy around 61.5 % of the aggregate economic potential of OTEC. Thus, these country's cooperation is imperative for OTEC to be implemented on a large scale. The next best hotspot can be found in the Caribbean Sea with the Dominican Republic and Cuba, which combined hold 9.8 % of the aggregate economic potential.

Even though only a small part of the practicable potential of OTEC can be economically harnessed, there is still an impetus to endeavour its development. At each of the 29 analysed islands, the economic potential of OTEC exceeds their respective final electricity consumption by a manifold (United Nations, 2015). Thus, OTEC could still be a conceivable option to cover future energy demands in the long-term.

Country	OTEC Scale [MW]	Elect. Cons. [GWh]	Pract. OTEC Pot. [GWh]	Eco. Pot. Disc. Rate 10% for Best Case [GWh]	Eco. Pot. Disc. Rate 18% for Best Case [GWh]	Pro-portion 10%	Pro-portion 18%
Barbados	10	933	188.021	13.623	13.623	7,2%	7,2%
Cuba	100	16.160	404.250	144.765	144.765	35,8%	35,8%
Dominican Republic	100	15.578	451.557	157.853	157.853	35,0%	35,0%
Fiji[15]	20	826	27.724	31.821	30.746	114,8%	110,9%
Haiti	10	411	159.733	5.496	2.113	3,4%	1,3%
Indonesia	100	212.767	4.739.454	912.659	912.659	19,3%	19,3%
Jamaica	100	3.008	133.460	55.494	55.494	41,6%	41,6%
Madagascar	20	1.195	977.017	36.519	12.936	3,7%	1,3%
Maldives	10	349	987.010	19.211	3.432	1,9%	0,3%
Marshall Islands	20	580	1.416.324	84.765	73.576	6,0%	5,2%
Papua New Guinea	100	3.664	4.238.897	379.086	379.086	8,9%	8,9%
Philippines	100	67.808	1.939.527	600.669	600.669	31,0%	31,0%
Republic of Mauritius	50	2.506	290.695	21.833	21.072	7,5%	7,2%
Saint Lucia	10	338	61.733	2.251	1.274	3,6%	2,1%
Seychelles	10	324	649.491	1.413	-	0,2%	0,0%
Sri Lanka	100	11.741	353.315	122.397	122.397	34,6%	34,6%
French Polynesia	20	637	1.936.142	199.366	190.437	10,3%	9,8%
Guadeloupe	50	1.504					
Martinique	50	1.441					
Mayotte	10	275					
New Caledonia	100	2.881					
Reunion	100	2.657					
Aruba	20	778	37.395	1.509	720	4,0%	1,9%
Curacao	20	664					
Cayman Islands	20	602	449.703	12.121	11.620	2,7%	2,6%
Guam	50	1.600	1.019.731	341.413	341.413	33,5%	33,5%
Hawaii (USA)	100	10.000					
Puerto Rico	100	19.350					
U.S. Virgin Islands	20	700					
Σ		381.276	20.461.179	3.144.264	3.075.885	15,4%	15,0%

Table 4.1 Comparison Between Practicable and Economic Potential of OTEC (Own Illustration).

[15] In Chalkiadakis (2017), it is stated that the offshore potential of OTEC in Fiji is zero. However, in his set of raw data, a total of 160 offshore cells where found, out of which all are within the defined spatial boundaries. Therefore, the absence of offshore potential for Fiji in Chalkiadakis' thesis must be an editorial hiccup which explains the unrealistic proportions found in Table 4.1 for Fiji.

4.2. Aggregate Supply Curve of all Analysed Islands

The focus of the economic analysis now shifts from a national to an international scope. If the economic potential of each of the 29 islands is aggregated and compared to the practicable potential computed by Chalkiadakis, one sees that merely 15.4 % of the practicable potential is economically viable in the best case. According to Figure 4.5, the aggregate economic potential of all 29 analysed islands ranges between **0 – 3.144 TWh or 0 – 390.1 GW**, respectively (for a discount rate of 10 %). Indonesia is vindicated as a decent proxy of the analysed countries, since the base economic potential, indicated by the blue curve, is still zero if compared against a wholesale price of 20 $ct./kWh. The aggregate supply curves for each individual scale of OTEC, as well as the graphs regarding private projects, are listed under Appendix H.

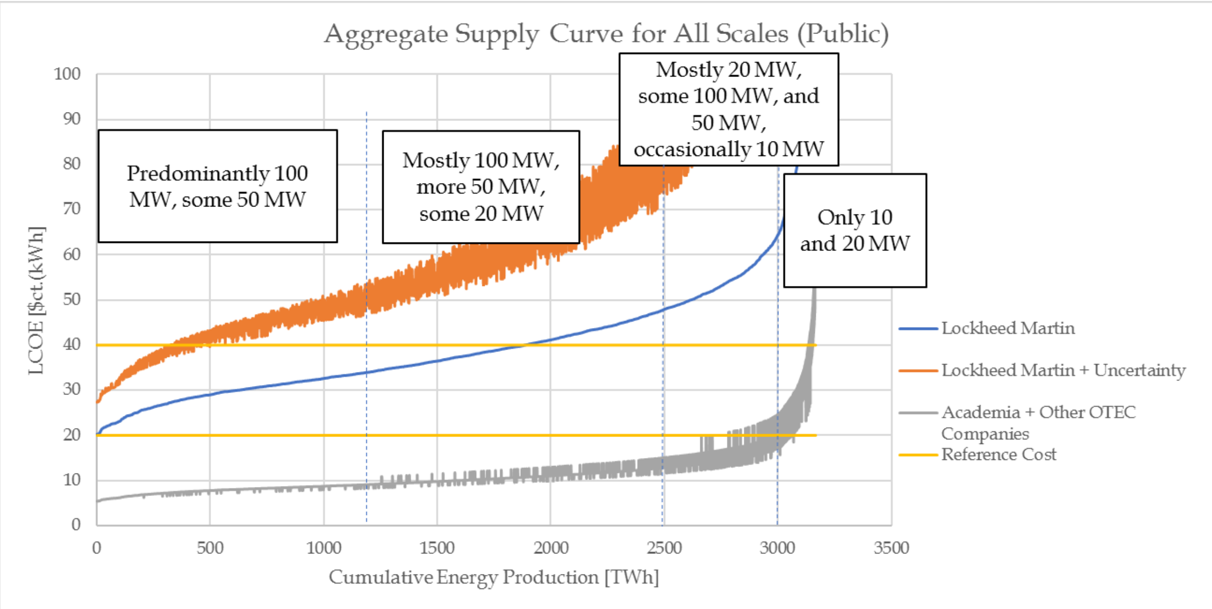

Figure 4.5 Aggregate Supply Curve for All Scales of OTEC Orange Plot Cut Off at LCOE = 100 $ct./kWh to Maintain Clarity of Graph. Final Value of Orange Graph is LCOE = 321 $ct./kWh at 2.861 TWh of Energy Production (Own Illustration).

Again, Figure 4.5 shows all too well that the economic potential of OTEC lingers somewhere between all or nothing. Interestingly, now the grey curve also starts to oscillate, which is explained by the blend of different scales in one plot. Despite the effects of economies of scale, there can be extraordinary locations where a smaller OTEC plant can have a lower LCOE vis-à-vis larger systems. Figure 4.5 also implies at which ranges to expect certain scales of power output.

The results above should be a warning, both for the representatives of low- and high-cost OTEC. On the one hand, the former need to prove that it is in fact possible to build a commercial plant at the low costs proclaimed in their feasibility reports and academic papers. On the other hand, should the dystopian cost estimates by Lockheed Martin hold true, further increases in cost must be avoided by any chance and future cost reductions via learning are a *sine qua non*.

Even though the choice of discount rate does not affect the economic potential of OTEC considerably in the best case, it does matter a whole lot for the worst- and base case. Depending on how the discount rate is defined, the blue and oranges curves in the supply curve can either be tight to the reference lines or rather peripheral. Therefore, to understand the gravity of changes in discount rate on the shape of the supply curves, it is pivotal to perform a sensitivity analysis.

4.3. Sensitivity Analysis

As of now, only the supply curves of publicly funded projects are shown in the main text, with the results of private projects being thoroughly shifted to the appendix. This is vindicated by the fact that the only difference between private and public OTEC in this thesis is the discount rate, which is assumed as 18 % for the former and 10 % for the latter. Therefore, to maintain consistency and to avoid redundancy, the placement of private supply curves to the appendix is defended.

Figures 4.6 and 4.7 below illustrate the results of the sensitivity analysis for 2.5 and 100 MW plants for varying discount rates between 3 and 18 %. The costs refer to the base case with estimates by Lockheed Martin without uncertainties. Nevertheless, the results for different scales and costs can be found in Appendix I.

Even if the deliverables of this thesis are merely ranges of conceivable economic potentials, it can be agreed upon that the most desirable objective of the OTEC niche is to make even high-cost OTEC plants profitable. In other words, if the supply curves based on the Lockheed Martin reports could undercut a wholesale price of 20 $ct./kWh, it would be an uplifting insight and a strong impetus to further develop the technology.

Then again, Figure 4.6 somewhat dampens any uprising euphoria. Even at a generous discount rate of 3 %, only some individual 2.5 MW plants undercut a wholesale price of 40 $ct./kWh. From a commercial perspective, such plants generally do not seem like a reasonable venture. Instead, they should be implemented as pilot projects to gather technical and economic data and to propel the commercialisation of larger OTEC systems.

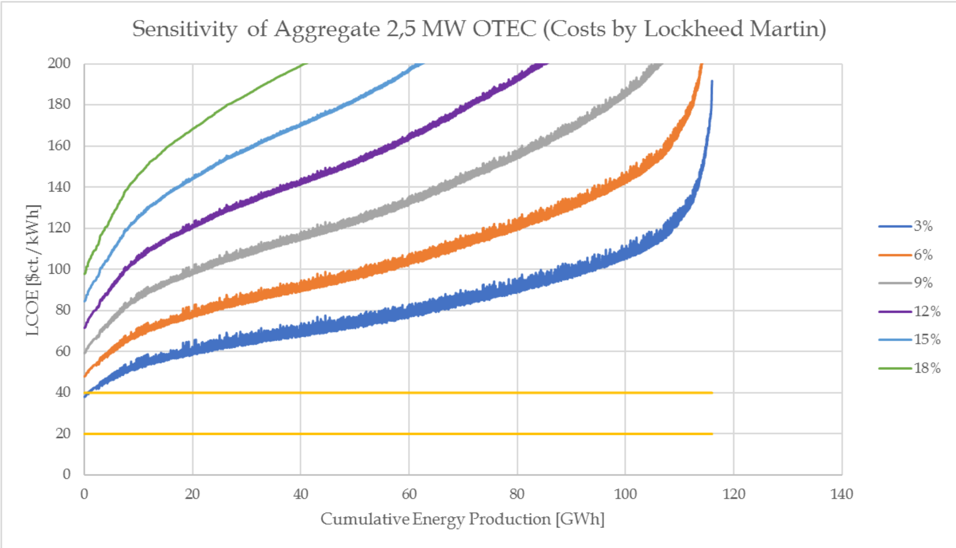

Figure 4.6 Sensitivity Analysis of Public 2.5 MW OTEC. No Uncertainties Included, Y-Axis Cut Off at LCOE = 200 $ct./kWh to Maintain Clarity (Own Illustration).

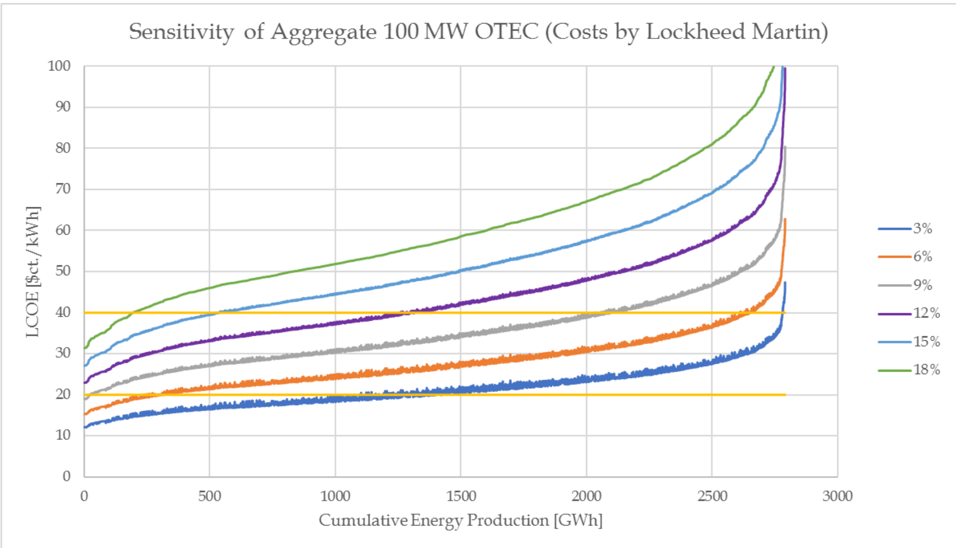

Figure 4.7 Sensitivity Analysis of Public 100 MW OTEC. No Uncertainties Included, Y-Axis Cut Off at LCOE = 100 $ct./kWh to Maintain Clarity (Own Illustration).

Turning to 100 MW, the results of the sensitivity analysis are slightly better, albeit dubious. At a discount rate of 9 %, the supply curve starts to undercut a wholesale price of 20 $ct./kWh and gradually descends for lower discount rates. At a rate of 3 %, almost half of the cumulative electricity supply is economically sound. This sounds great at first, but then one needs to question the likelihood of such a scenario. What is required to justify a discount rate of 3 %? For most islands analysed here, which are recommended to use a discount rate of 10 – 12 % depending on their state of development, such a rate seems rather notional. From all 29 islands, merely Hawaii would be suitable for such a low discount rate but only because it belongs to the USA. Therefore, such projections as shown in Figure 4.7 must be taken lightly and contrasted to the context of the analysed country.

Generally, the main message of the sensitivity analysis is that the choice of discount rate has a tremendous impact on the outcome of the economic analysis performed here. Only a slight change can turn a country economically unfit for OTEC deployment or enhance its potential at otherwise mediocre locations. The results also indicate how the reduction of the discount rate could increase OTEC's economic potential over time. This makes sense as with further experience and lower risks associated with OTEC, the discount rate could decrease to the levels shown above. The choice of two discount rates in this thesis is corroborated as it enables the comparison of private and public projects. It becomes clear that OTEC's success is far more likely if the technology is implemented with public support, since this would allow the use of a lower discount rate. Furthermore, interdisciplinary stakeholders, both private and public ones, must collaborate closely to render OTEC sustainably prosperous. A solo run from either side might end at an insurmountable brick wall of unforgiving business conditions.

4.4. Extrapolation of the Results to a Global Scope

Although this study might imply otherwise, the potential of OTEC is not limited to the 29 islands discussed in this work. In fact, many champions of OTEC are neglected as of now, for example Japan, Malaysia or China. Leaving the analysis as it is, it would only address a small part of the global OTEC niche. Therefore, the insights gained so far are elevated to a global level to ameliorate their relevance. In this section, the supply curves shown above and in the appendix are extrapolated to represent projections of the economic potential of OTEC on a worldwide level.

4.4.1. Analysis of the Remaining Countries Suitable for OTEC

As already mentioned before, Chalkiadakis mapped the practicable potential of OTEC for over 90 countries and territories which unfold to a global host of 15.295 offshore and 599 onshore cells. Out of these, 8.049 offshore and 405 onshore units belong to the 29 islands analysed in this thesis. Thus, to extrapolate the aggregate supply curves to a global level, the remaining 7.246 offshore and 194 onshore cells need to be included as well. Besides some islands which did not meet the requirements of this study earlier, like Antigua & Barbuda or the Bahamas, most of the remaining 52 countries are situated at the mainland of South America, Africa or East Asia. A detailed list is shown in Appendix J.

Before the extrapolation commences, several questions need to be asked. Who are those countries? What is their electricity demand? Do the observations made so far also apply on a global scope? Concerning the last question, the most important insights are that the economic potential of *publicly* funded OTEC at tropical islands only covers 15.4 % of the practicable potential proclaimed by

Chalkiadakis. Furthermore, the aggregated, economically viable output of OTEC at these islands would cover their final electricity consumption in 2015 by over an eightfold.

If only 15.4 % of the practicable potential are economically feasible, that would mean that merely 676 GW of the 4.4 TW determined by Chalkiadakis are of any relevance. From that, the 29 tropical islands discussed in this thesis already occupy around 390 GW, which leaves the remaining 52 countries with only 286 GW. However, such a value seems reasonable, since the most promising locations for OTEC deployment like Indonesia and Papua New Guinea have already been analysed. In contrast, most of the 52 countries only comprise little space for OTEC, especially in Africa (Chalkiadakis, 2017). Later in this section, it is shown to which extent this assumption holds true.

On the other hand, such correlations are not feasible for the global electricity demand. Considering vast countries like China, India, Mexico being among the remaining 52 countries, it would be absurd to argue that 286 GW of OTEC could cover their electricity demand over eight times. In fact, this capacity could only cover around 15 % of their electricity demand based on 2015 values (United Nations, 2015). This is plausible since most of these continental countries surpass the examined tropical islands in both size and population. Then again, such a logic implies that OTEC ought to cover the electricity demand of whole China or whole India, for example. This would most likely not be the case and merely coastal areas would benefit from the supply of OTEC power instead. Then, the supply of OTEC power would need to be contrasted to the electricity demand of coastal regions only. Such considerations, however, surpass the scope of this study by far and are therefore discarded.

The discrepancy of electricity demand also reverberates in the choice of suitable OTEC systems. As of now, 38 % of the 29 islands are suitable for 100 MW OTEC, 14 % for 50 MW, 31 % for 20 MW and 17 % for 10 MW, respectively. Recalling the selection process preceding the analysis, one criterion is that an island must be suitable for at least 10 MW to be examined any further. To obtain a whole picture of the global supply curve at *each* scale, this criterion is now abolished. Countries like Antigua & Barbuda, which are only suitable for 2.5 MW and therefore previously excluded from the analysis, are welcomed again.

It is not possible to apply the proportions of capacities enumerated above to a global case. Since the countries included now encompass a far greater electricity demand, there are concomitantly far more opportunities for large-scale 50 and 100 MW OTEC deployment. To determine the suitable scale of OTEC for each country, the same procedure as in chapter 3.2.1.2 is exercised. A country is eligible for a certain power output if one system does not cover more than 30 % of the country's electricity demand. If one 2.5 MW plant already trespasses this threshold, it is excluded from the global curve. This was the case for a total of 16 countries. As a result, 42.3 % of the remaining 52 countries are suitable for 100 MW, 7.7 % for 50 MW, 1.9 % for 20 MW, 5.8 % for 10 MW and 11.5 % for 2.5 MW. 30.8 % of these cells refer to countries which are generally not suitable for OTEC, such as Kiribati or Micronesia. One important note is that the number of cells suitable for each scale are computed cumulatively. For example, if a country is eligible for 100 MW, it is automatically suitable for 50 MW as well. Thus, the cells regarding to 100 MW need to be supplemented by the 7.7 % of countries suitable for 50 MW to obtain the total number of global 50 MW OTEC cells. This procedure is analogously carried on for each scale of power output.

Furthermore, some cells might be further than 370 km away from a demand centre. For this criterion, it is assumed that the trends observed for the 29 analysed islands also hold for a global scope. In the case of offshore OTEC, around 64 % of the cells are within the proclaimed boundary. For onshore cells, the proportion is only 44 %. Table 4.2 illustrates the insights gained so far.

Scale	Proportions Among Countries	∑ of Cells	Total Offshore Cells within Spatial Boundary	Total Suitable Onshore Cells within Spatial Boundary
0 MW	30,8%	2289	-	-
2,5 MW	11,5%	5151	3211	59
10 MW	5,8%	4262	2675	49
20 MW	1,9%	3863	2408	44
50 MW	7,7%	3720	2319	43
100 MW	42,3%	3149	1962	36

Table 4.2 Allocation of Grid Cells to Each Scale of Power Output. To Determine Cells within Spatial Boundaries, a Fixed Proportion 66% for Offshore and 44% for Onshore Cells was Used Based on the Insights of the Economic Analysis Previously Performed (Own Illustration).

4.4.2. Modelling of Global OTEC Supply Curves

Although the total number of suitable OTEC cells and their allocation among various sizes of power output are now determined, this is not enough to model global supply curves. Therefore, one also needs to know how their real energy output and LCOEs are distributed. The ranges of possible values can be depicted in the form of histograms as shown in Figure 4.8 and 4.9. The graphs refer to 2.5 MW systems, which comprise the largest number of OTEC cells and are therefore the most representative. Interestingly, the general shapes of the histograms for both energy output and LCOE roughly stay the same independent of scale, discount rate and range of uncertainty. The remaining histograms for both private and public projects and the other scales of power output can be found in Appendix K and L..

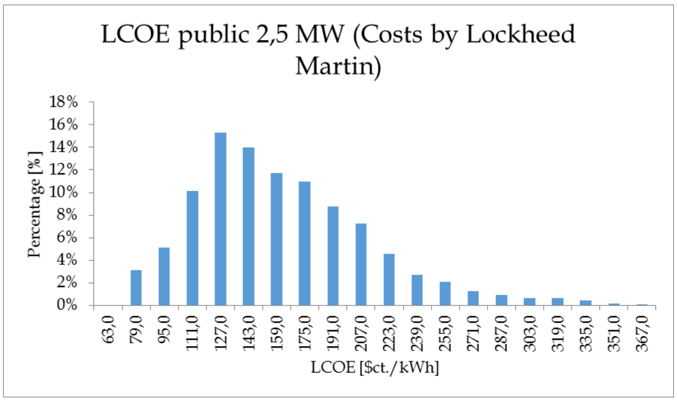

Figure 4.8 Histogram of LCOE for Public 2.5 MW OTEC. Cost Estimates Based on Lockheed Martin (Own Illustration).

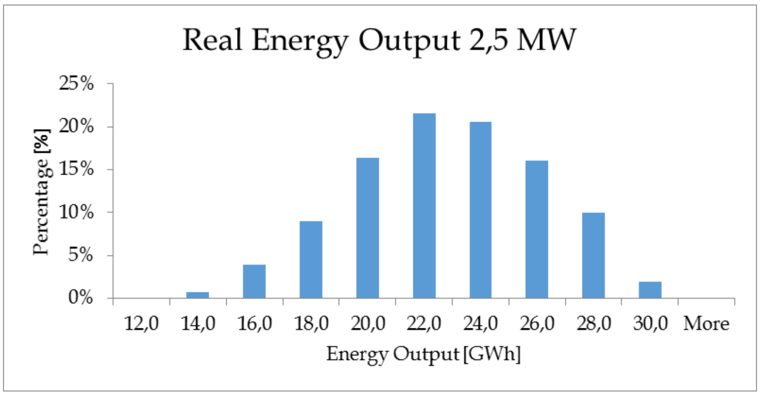

Figure 4.9 Histogram of Real Energy Output for 2.5 MW OTEC(Own Illustration).

Based on these Figures, it is possible to tell the likelihood of a certain energy output and LCOE for each OTEC cell. For example, a cell regarding to a country suitable for 2.5 MW has a chance of 20 % to generate an energy output of around 22 GWh. Hence, the remaining cells are attributed with a certain real energy output and LCOE and added to the dataset of the 29 tropical islands. Again, the most valuable insights can be gained from a supply curve which integrates all possible scales into one plot, as shown in Figure 4.10. Nevertheless, the remaining global supply curves for individual scales and different discount rates are listed in Appendix M.

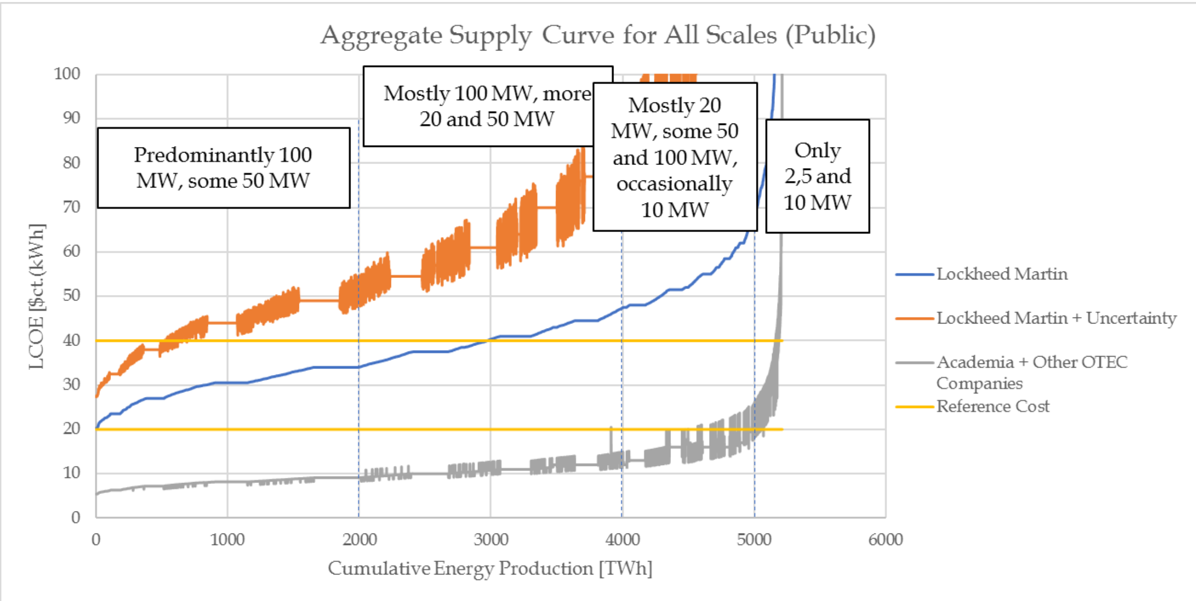

Figure 4.10 Global Supply Curve for All Scales of OTEC. Orange Plot Cut Off at LCOE = 100 $ct./kWh to Maintain Clarity of Graph. Final Value of Orange Graph is LCOE = 532 $ct./kWh at 5.212 TWh of Energy Production (Own Illustration).

Figure 4.10 adheres to the results obtained from the national and international supply curves. In the worst and base case, none of the OTEC units worldwide can undercut a wholesale price of 20 $ct./kWh according to the orange and blue lines. However, the grey curve in Figure 4.10 would engender an economically sound deployment of almost all OTEC cells, promising an auspicious future for OTEC if such low costs could actually be maintained.

Although it cannot be seen in Figures 4.5 and 4.10, there are great differences between their maximum LCOEs at the end of their supply curves. While the highest LCOE associated to the supply curve in Figure 4.5 is "only" around 321 $ct./kWh, the respective zenith is reached at around 530 $ct./kWh in the plot regarding Figure 4.10. The histograms of a scale of OTEC foot on cells of *all* countries suitable for such a capacity. So, if a histogram is designed for 2.5 MW, it also includes countries which are eligible for any other, larger scales. As it turns out, a LCOE of 530 $ct./kWh can be found in Madagascar and Seychelles, among others, which are both located in the Indian Ocean close to East Africa. However, these LCOEs cannot be spotted in Figure 4.5, because Seychelles can regard to 10 MW, while Madagascar is also suitable for 20 MW. For these power outputs, the LCOEs are somewhat smaller and consequently, the supply curve does not end at such horrendous costs. Notwithstanding, some of the remaining global countries at the East African coast, such as Tanzania or Comoros, could not resort to such high scales. This thesis argues for the chance of such large LCOEs to occur, based on the location and the electricity demand of the remaining countries.

With the method deployed here, it is not possible to reproduce the oscillations observed from the previous analysis. Instead, the extrapolated cells are shown as straight, horizontal lines. Nevertheless, these lines are averages of the amplitudes, from which the oscillations at these regions can be deduced. The impact of these straight lines could be somewhat curbed by choosing a smaller bin width for the histograms. For example, the range of likely LCOEs is distributed over 20 bins for each scale. The more bins are used, the smaller the steps between conceivable values and the more precise the extrapolation becomes. But since a higher precision leads to a higher workload, a compromise between simplicity and accuracy is made.

Based on Figure 4.10, a **global potential of 0 – 5.200 TWh (or 0 – 645 GW) for a discount rate of 10 %** is determined.[16] This comes fairly close to 5.448 TWh, which is 15.4 % of the practicable potential calculated by Chalkiadakis. The small deviation can be explained by a higher proportion of generally unsuitable cells. Considering that every of the 29 analysed has at least some economic potential for OTEC, there are some countries among the remaining 52 countries not eligible to OTEC at all, i.e. Kiribati, Solomon Islands and Micronesia. The exclusion of these three countries has far-reaching effects as they comprise a considerable practicable potential for OTEC according to

[16] For private projects with a discount rate of 18%, a global potential of 0 – 5100 TWh is estimated. This shows that if the cost estimations by academia and other OTEC companies hold true, OTEC might be a promising technology regardless of the discount rate chosen.

Chalkiadakis. Thus, the actual proportion of practicable potential being economically sound must be somewhat lower than 15.4 %.

Curiously, OTEC's economic potential is still distributed strongly heterogeneously as the triumvirate of Indonesia, Papua New Guinea and the Philippines still comprises 36.4 % of the total collective. However, this is only around half of the proportion observed in the previous chapter. Now, much of the global economic potential is administered to continental countries like Brazil, Mexico and Colombia in South America and China, India and Japan in Asia. Nevertheless, the emergence of distinct hotspots seems likely if the technology should lift off in the future, with some regions more heavily involved in the deployment of OTEC than others.

4.5. Conclusion of the Economic Analysis of OTEC

The economic potential of OTEC at 29 tropical islands is computed and aggregated to a total range of 0 – 390.1 GW for a discount rate of 10 % and 0 – 381.7 GW for 18 %, respectively. The lower boundary is determined by the worst-case costs and the lower reference cost of 20 $ct./kWh. The upper range foots on the best-case costs and a reference cost of 40 $ct./kWh. The small difference in maximally possible potential shows that the choice of discount rate loses gravity the less stringent the circumstances are. However, a sensitivity analysis elucidated the considerable impact of the discount rate on the shape of supply curves. Hence, while the discount rate might not matter for best-case costs, it does matter a whole lot for any cost estimations based on Lockheed Martin. The wide range of possible supply curves and reference costs are responsible for the ambivalence of the results. Based on the perspective, either all practicable OTEC locations or none could be economically attractive, which is perceived not only on the national, but also international and global level. Another striking peculiarity is the starkly heterogenous distribution of the economic potential across the 29 islands. Indonesia, Papua New Guinea and the Philippines already comprise around 61.5 % of the aggregate potential, while it is merely 9.8 % for the second-best hotspot consisting of Cuba and the Dominican Republic.

Almost 8.500 OTEC cells have been analysed to model the economic potential of OTEC for 29 tropical islands. The observed trends in LCOE and real energy output are used to extrapolate the supply curves to a global level. After the remaining global countries suitable for OTEC are analysed for their electricity demand and practicable potential for OTEC, their respective OTEC cells are attributed with values for LCOE and real energy output based on phenomena observed in histograms. For a discount rate of 10 %, a global potential of 0 – 645 GW is computed, which reduces to 0 – 633 GW for a discount rate of 18 %. The heterogeneity of OTEC's economic potential persists on a global level, albeit to an curbed extent compared to the conglomerate of island countries.

5. Implementation Scenarios and Global Experience Curves for OTEC

Chapter 4 showed that the economic analysis of OTEC is a complicated undertaking. Alas, as insightful as the understanding forged there might be, it is yet of limited aid. In fact, it might even be scorned as deceptive and might provide the fodder for dissecting objections. What is it supposed to mean if the economic potential of OTEC might be all or nothing? If the discount rate is so crucial, how could the upper limit of profitable capacity be so similar for both 10 and 18 %? What do these supply curves mean for the implementation of OTEC? Are the shapes of these supply curves rigid or will they change over time?

How the results presented in chapter 4 are evaluated depends on the eye of the beholder. Supporters of OTEC might pat each other's shoulders in agreement that there is hope. After all, the grey curve promises over 600 GW of economically viable OTEC; somebody just needs to grasp it! On the other hand, investors interested in the technology will most likely notice the blue and orange curves first. They might be puzzled by the wide gap of possible costs and repelled by the absence of any profitability in the worst case. Under this light, it would be speculative to take the upper range of economic potential at face value and discouraging for any investor to put a single dime into OTEC.

It is pivotal to understand under which circumstances the supply curves of OTEC could be pushed below the lower reference cost for *any* cost estimation. Only then could the technology's profitability be assessed from an unbiased point of view. The problem of the supply curves is that they barely reveal anything about these circumstances. They merely provide a snapshot of what it would look like if all OTEC cells would be deployed overnight, without elaborating the preconditions, developments and implications of such a case. While the effects of economies of scale could already be observed, learning effects have been thoroughly ignored until now. Thus, these supply curves only tell one part of the story and give an incomplete picture of OTEC's economic constitution.

This chapter strives to add the missing pieces by conceiving implementation scenarios for OTEC. Based on the developments in the offshore wind niche, these scenarios provide insights about the feasibility of the supply curves in chapter 4, the impact of learning and a roadmap for implementation. Thereby, the thesis shifts from a static to a dynamic perspective and embraces future trends and developments as well.

The chapter is structured as followed. First, the scenarios are explained and contrasted to each other in terms of chosen OTEC growth rate, learning rate and the continuity of learning. Then, the results of the scenarios are presented in the form of global experience curves. These are then integrated into the static global supply curves of chapter 4, which ultimately deliver dynamic illustrations which include cost reductions by learning. Based on these plots, it is possible to tell under which circumstances the supply curves can be sustainably pushed below a wholesale price of 20 $ct./kWh. Finally, this chapter elaborates the different implementation phases and where to find them on the global supply curves.

5.1. Results and Discussion of the Implementation Scenarios

5.1.1. Results Unrelated to Learning

Table 5.1 summarises the results of this chapter. It makes a tremendous difference at which rate OTEC installation grows. Merely 1.46 GW of real OTEC capacity are implemented in the *Modest Growth* scenario. It surprises little that OTEC's contribution to the global energy supply are marginal with a real electricity demand coverage of only 0.06 %. With rising growth rate, more and larger OTEC systems are implemented which explains a higher installed capacity and coverage for the *Fast Growth* and *Rapid Growth* cases. In Appendix N, the schedules of every scenario are shown, revealing which and how many OTEC plants are deployed throughout time.

When compared to offshore wind power, OTEC could deploy a larger real power output within the same period due to the favourable impact of higher seawater temperature differences. While offshore wind power reached a cumulative capacity of roughly 14.5 GW within the last 24 years (Takami & Lidington, 2017), OTEC could surpass this value by almost 60 % with 23.1 GW at a constant growth rate of 40 % per annum. However, offshore wind's expansion oscillated between 25 and 40 % in recent years, so the comparison to a constant rate of 40 %/year as in the *Rapid Growth* scenario is somewhat flawed. Then again, the real capacity at the end of the *Fast Growth* scenario, being 6.77 GW, is already 53 % lower than the cumulative capacity of offshore wind power. Thus, OTEC would need a growth rate of something between 30 – 40 %/year to imitate offshore wind's development.

Notwithstanding an ambitious growth rate of 40 %/year, OTEC would still not make a great impression on global energy systems. After 24 years, the technology would only cover 0.91 % of global electricity demand and would merely harness 3.58 % of the economic potential promised by the supply curves in chapter 4. This proves how previous results should be taken lightly and that only a minuscule fraction of the previously determined economic potential can be implemented in the short- to mid-run.

	Implementation Scenarios									
Scenarios	OTEC Growth Rate	Duration	Installed Capacity (nominal/real)	Coverage of Global Electricity Demand (nom./real)	Coverage of Global Economic OTEC Potential	Learning Rate	<20 $ct./kWh for Blue Curve?		<20 $ct./kWh for Orange Curve?	
							Public	Private	Public	Private
Modest Growth	20 %/year	24 years	1,03/ 1,46 GW	0,04/ 0,06 %	0,23 %	6 %	Yes	No	No	No
						12 %	Yes	Yes	Yes	Yes
						18 %	Yes	Yes	Yes	Yes
Fast Growth	30 %/year	24 years	4,85/ 6,77 GW	0,19/ 0,27 %	1,03 %	6 %	Yes	Yes	Yes	No
						12 %	Yes	Yes	Yes	Yes
						18 %	Yes	Yes	Yes	Yes
Rapid Growth	40 %/year	24 years	16,6/ 23,1 GW	0,65/ 0,91 %	3,58 %	6 %	Yes	Yes	Yes	No
						12 %	Yes	Yes	Yes	Yes
						18 %	Yes	Yes	Yes	Yes
Superaggressive Expansion	40 %/year	35 years	585,4/ 644,6 GW	20,4/ 22,5 %	99,9 %	6 %	Yes	No	No	No
						12 %	Yes	Yes	Yes	Yes
						18 %	Yes	Yes	Yes	Yes

Table 5.1 Results of Implementation Scenarios. (Own Illustration).

In the case of the *Superaggressive Expansion* scenario, things look slightly more optimistic. If all the economic potential of OTEC is utilised, it would cover over 20 % of global electricity demand. However, such a scenario is far from realistic, since it would imply thousands of plants being installed *per year*. This scenario is not supposed to give practical insights on how the technology could be implemented, but in lieu serves as an extreme, purely hypothetical case revealing what could be maximally possible.

The magic of economies of scale was already discussed in earlier chapters. But interestingly, its impact declines the more OTEC plants are implemented as illustrated by Figure 5.1. The curves regard to the base costs by Lockheed Martin.

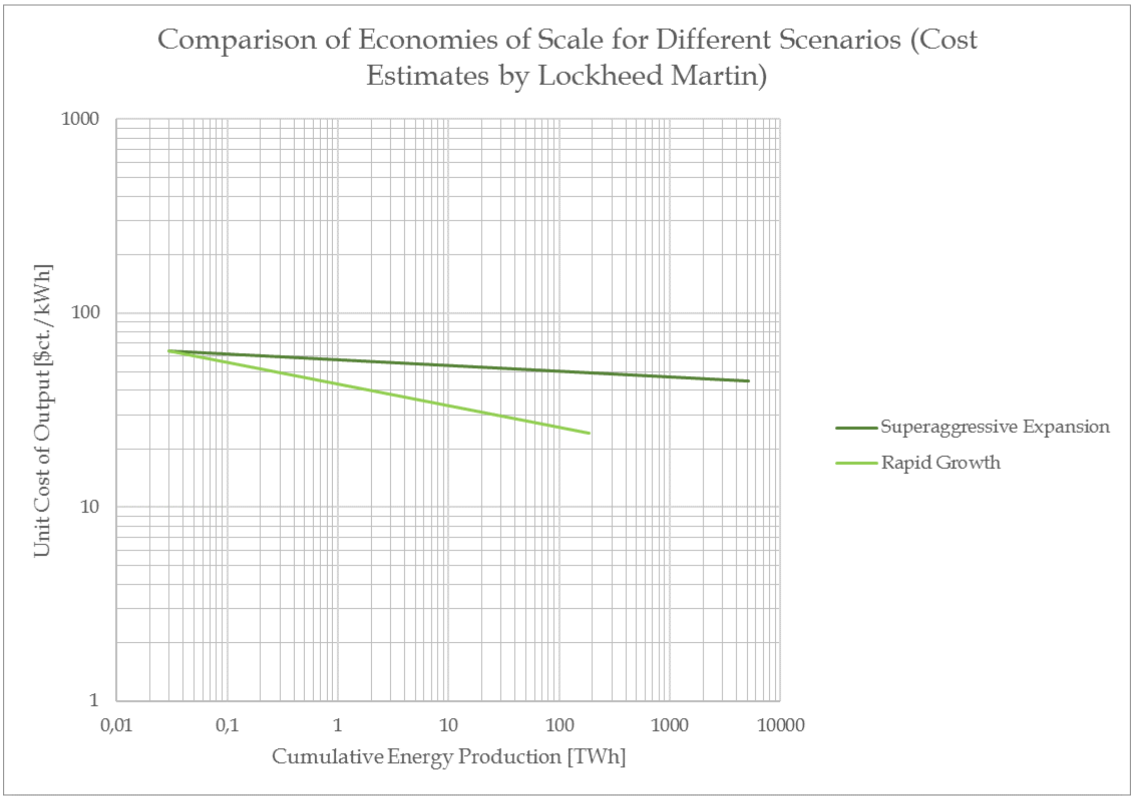

Figure 5.1 Comparison of Economies of Scale for Different Scenarios. Discount Rate 10%, Learning Rate 0% (Own Illustration).

In Figure 5.1, the scenarios of *Rapid Growth* and *Superaggressive Expansion* are compared due to their identical OTEC growth rate and learning effects are yet excluded to isolate the effects of economies of scale. A remarkable minutia of the plot is the deterioration of cost reduction, since the dark green line regarding to *Superaggressive Expansion* proceeds almost horizontally while the light green graph representing *Rapid Growth* shows a steeper decline. The reason for this lies in the availability of high-quality locations for OTEC deployment. Since the *Modest, Fast* and *Rapid Growth* scenarios only consider a marginal proportion of available OTEC cells, they only draw on the best cells with close distances from plant to demand centre and high seawater temperature differences. Subsequently, the quality of the cells decreases with progressing implementation which counteracts the effects of economies of scale. Hence, there is a trade-off between maximum installed capacity (186 vs 5.195 TWh) and intensity of cost reduction.

But how are the lines in Figure 5.1 obtained in the first place? Technically, the graphs above are experience curves, albeit without learning effects, and resemble a trendline of all the OTEC units implemented during a scenario. Figure 5.2 visualises this process.

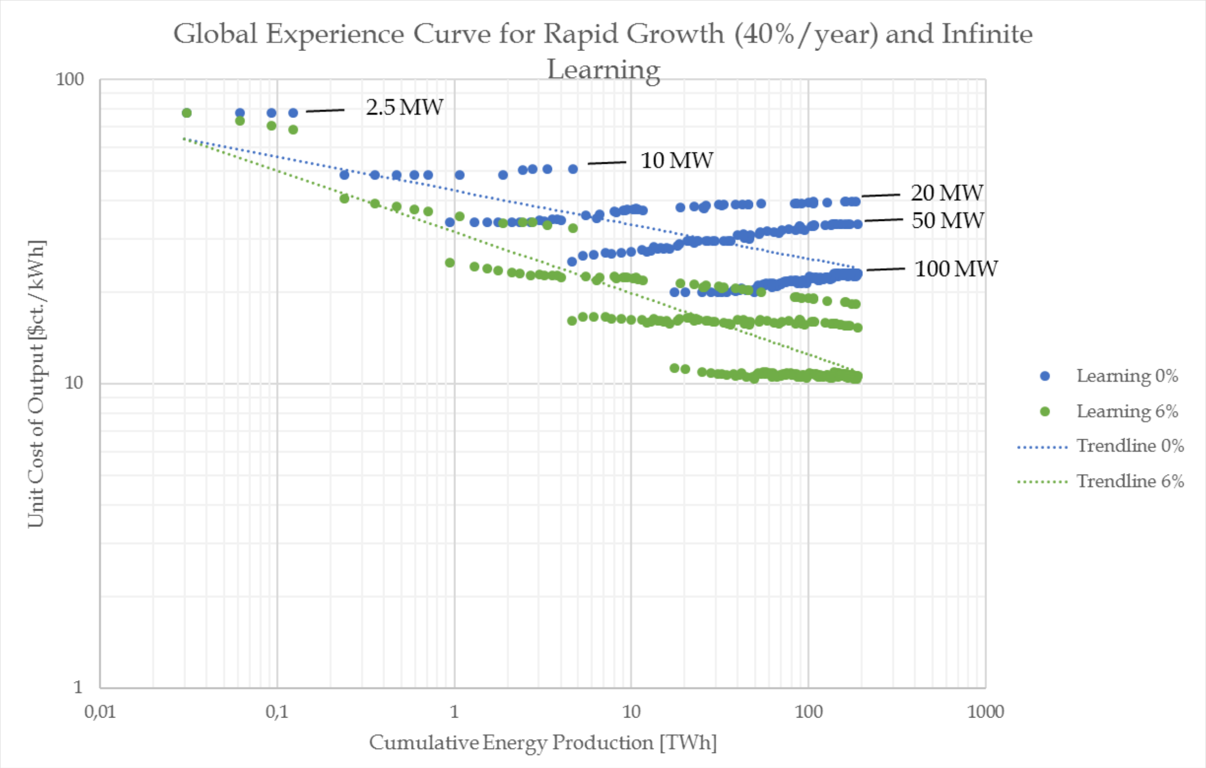

Figure 5.2 Global Experience Curve for Rapid Growth and Infinite Learning. Blue Dots and Lines Represent Absence of Learning, Green Dots and Lines Represent Learning Rate of 6%. Discount Rate 10% (Own Illustration).

For now, the reader is asked to solely focus on the blue illustrations in Figure 5.2 and to leave the green ones unnoticed. The trendline consists of several dots which resemble every OTEC cell implemented throughout a scenario over time. A distinguishable feature of the plot above is that these dots form a total of five lines which are located at descending cost levels. These curves display the five different scales analysed in this thesis and their cost plateaus decline due to economies of scale. Interestingly, the lines themselves eventually rise with increasing installed capacity and underline once again the scramble for high-quality OTEC locations and how their deterioration affect the costs of the systems. These findings, namely the initial decline in LCOE followed by an eventual rise with progressing implementation, strike an accord with the results of TU Delft master graduate Dean Marcus

Gioutsos, who analysed cost-optimal electricity systems with increasing shares of renewable energy (Gioutsos et al., 2018).

The reader might rightfully wonder how representative the trendlines are, given the peripheral position of some dots. Indeed, this is a clear shortcoming of the methodology employed here and can be explained by the discontinuity of analysed OTEC systems. In practice, the upscaling of capacity is a continuous and gradual process. Contrarily, the power output leapfrogs from one scale to another in this study, in the most extreme case from 50 MW directly to 100 MW, which is a rather unlikely event. However, the workload would have soared to infeasibility if continuous scales would have been analysed. Then, the dots would oscillate closely around the trendline and therefore enhance its representative quality. This drawback is acknowledged and should be addressed in future research.

To maintain clarity within the main text, not every trendline for every scenario can be shown here. But in Appendix N, a comprehensive elaboration on the scenario designs and trendlines are shown for each scenario and discount rate. The mathematical expressions of all experience curves can be found there as well. In the following sections, the impact of learning is thoroughly discussed.

5.1.2. Impact of Learning on Scenarios

Now, the focus is finally set on cost reductions via learning. Every scenario uses learning rates of 6, 12 and 18 % and their respective trendlines are plotted analogously to the process described above. When the green illustrations in Figure 5.2 are perceived, even a low learning rate of 6 % suffices to neutralise the cost increases due to the decline in cell quality. Instead of rising with cumulative energy output, the five green lines hover horizontally or even descend as in the case for 2.5, 10 and 20 MW systems. However, the more OTEC cells are implemented, the stronger the decline in quality and therefore the stronger the increase in costs. While a learning rate of 6 % is sufficient for *Modest*, *Fast* and *Rapid Growth* to offset the hikes in cost, higher learning rates are required for the *Superaggressive Expansion* scenario. Furthermore, even a learning rate of 18 % is not enough to prevent an exponential climb in LCOE at the very end of the scenario. It seems that some locations are so disagreeable in distance to shore and seawater temperature difference that is would be fair to just leave them unoccupied.

Notwithstanding, it is proven that learning effects are not only a supplement, but a compliment urgently needed to push the costs of OTEC further down. The following graphs only regard to the scenario of *Superaggressive Expansion*, but again, the reader is warmly invited to consult Appendix N for the remaining illustrations. Figure 5.3 shows the global experience curve of publicly funded OTEC for different learning rates, with infinite and finite learning. The cost estimates of these graphs are taken from Lockheed Martin excluding uncertainties.

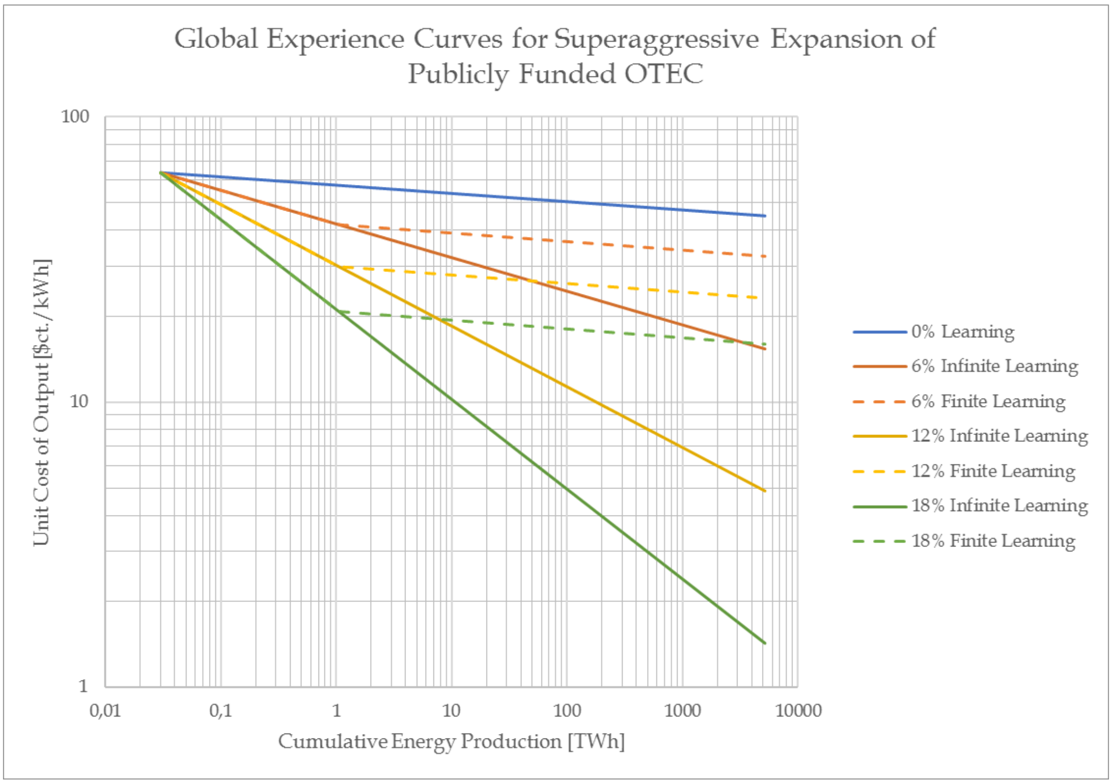

Figure 5.3 Global Experience Curves for Superaggressive Expansion Scenario. Solid and Dashed Lines Show Infinite and Finite Learning, Respectively. Cost Estimates are Taken from Lockheed Martin Without Uncertainties. Discount Rate 10% (Own Illustration).

Remarkable peculiarities can be extracted from Figure 5.3. Even at a low rate of only 6 %, the solid line falls below a wholesale price of 20 $ct./kWh, which is generally good news. Moreover, a strong learning rate of 18 % could reduce the LCOE to a level of around 2 $ct./kWh which would offer strong incentives to pursue the development of OTEC and to appease sceptics[17]. More interesting however are the dashed lines in Figure 5.3 which illustrate global experience curves for finite learning. In the beginning, the dashed lines follow their solid counterpart. However, after the 4th to 5th doubling, the two lines separate from each other as the slope of the dashed line becomes flatter than the solid one. This shows that the costs of the dashed lines are not reduced by learning, but merely by economies of scale. Perceiving the dashed lines as they are, they produce more questions than answers. First, it was not possible to validate the kinked shape with learning curves of any other technology in literature. Second, they are counterintuitive, especially in the case of strong learning. If learning is so effective, why would it suddenly stop? Even more intriguing, finite learning with a rate of 18 % would generate the same cost reductions as weak, infinite learning. Before these predicaments wrinkle the foreheads of both author

[17] Again, it is emphasised that these results refer to the cost reductions excluding the upper layer of uncertainty. These uncertainties, incorporated in the orange graphs throughout this thesis, will be discussed in the ensuing sections.

and reader further, this thesis argues strongly against finite learning and supports learning as an infinite process in accordance to other scholars (Junginger et al., 2005; Weiss, 2009).

But if learning is infinite, how did OTEC literature justify its evanescence? Lockheed Martin states that over time, costs for 100 MW plants would converge to an asymptote which inhibits any further reductions. However, there are two problems with this train of thought. First, a segregated analysis of 100 MW plants implies that such systems are the alpha and omega of OTEC. But what about learning effects of other, smaller systems? If learning is supposed to start and end at 100 MW as according to Lockheed Martin, this would mean that the doubling of output would refer to 100 MW, which is far more stringent than if it would commence with small-scale OTEC. For example, it is way easier to double the power output from 2.5 to 5 MW than from 100 to 200 MW. Such an assumption also conceals the progress made to reach a scale of 100 MW in the first place. Organisational learning, spill over effects, automatization and many other mechanisms which affect the costs of any system regardless its capacity are thoroughly excluded from their analysis. Hence, this thesis argues that cost reductions will not start at 100 MW and instead unfold in a continuous process, commencing at small-scale pilot plants and progressing to commercial, large-scale systems.

Second, their learning curves plot the unit costs of output against time, not against the cumulative energy output. This implies that learning is curbed by time which is a highly questionable statement. Take the combustion engine invented over one century ago. Although its basic functionality did not change, technological progress never stopped, and its costs and performance are still optimised today. Yes, it is reasonable to assume that the implementation of OTEC might slow down over time. But a deceleration of installation does not necessarily entail a slowdown in learning. Learning is an everlasting process related not to time, but to cumulative production. This assertion is backed by scholars like Junginger, who discussed the very same conflict (Junginger et al., 2005). Based on this argumentation, finite learning will not be treated for the remainder of this work anymore.

In the beginning of this chapter, it is stated that all supply curves shown in chapter 4 should be able to undercut a wholesale price of 20 $ct./kWh, not just the grey ones. Whether or whether not this is possible can be depicted for every scenario as shown in Figure 5.4.

Figure 5.4 reveals that only the grey and blue line penetrate a threshold of 20 $st./kWh in the *Superaggressive Expansion* scenario. Then again, the orange curve fails to undercut such a cost level even at high cumulative capacities. It is shown later that the global supply curves only sustainably persist below the reference costs if their respective experience curves sooner or later penetrate the yellow line in Figure 5.4. If this does not happen, the global supply curves might temporarily dip below the threshold, just to rise above it eventually (see Figure 5.6 later). In such a case, the impetus to develop OTEC might be severely hampered its profitability could not be sustained in the long-term.

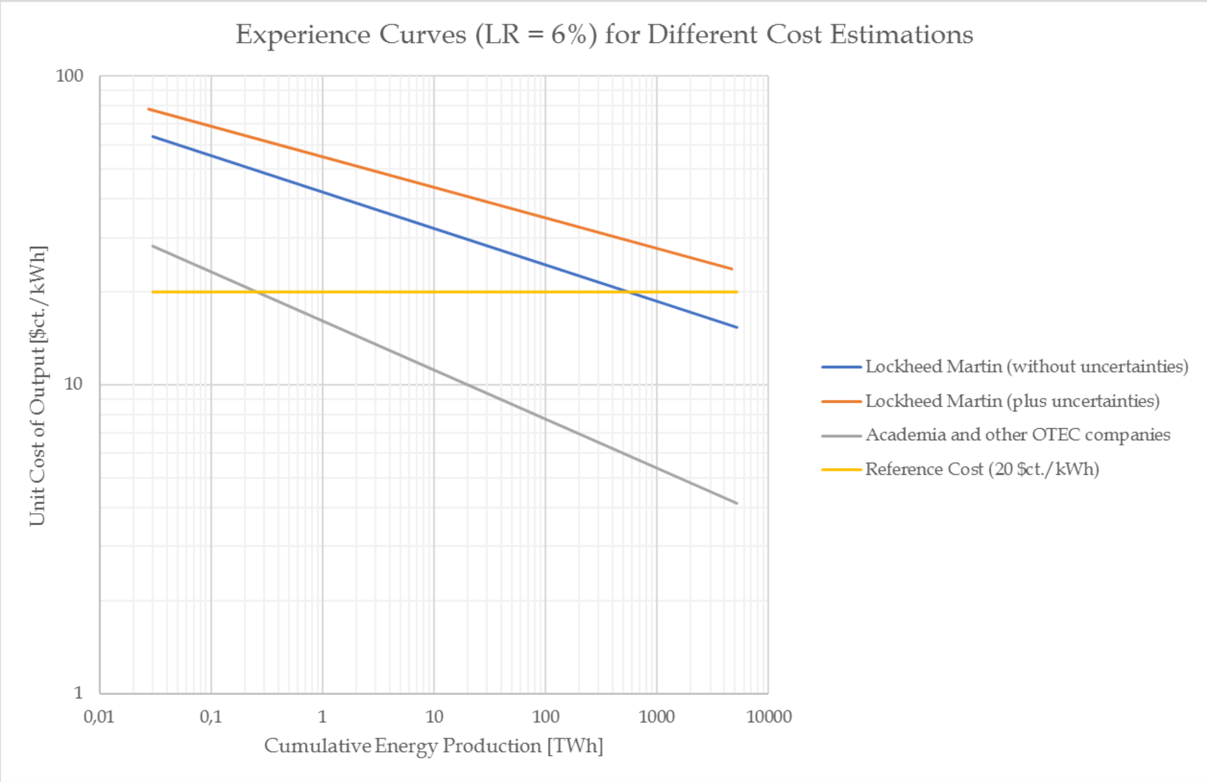

Figure 5.4 Experience Curves for Different Cost Estimations. Superaggressive Expansion Scenario, Learning Rate 6%, Discount Rate 10% (Own Illustration).

The columns on the right-hand side of Table 5.1 on page 69 summarise whether the blue and orange curves can breach the lower reference cost. The grey curves are excluded since their long-term profitability is already proven in chapter 4. One of the points of criticism at the beginning of this chapter is small impact of the discount rate in the best case (5.200 versus 5.100 TWh, respectively). This raised the objection whether the discount rate is really as crucial as argued in this thesis. After perceiving Table 5.1, such doubts do not hold anymore. Now, it is obvious that there is a vast difference between the two rates. For a learning rate of 6 %, *none* of the orange curves adhering to a discount rate of 18 % can penetrate a wholesale price of 20 $ct./kWh, consequently demanding for stronger learning to do so. For the *Modest Growth* and *Superaggressive Expansion* scenarios, even the blue curves remain above the threshold. For the former, this can be explained by the slow capacity growth rate. OTEC installations proceed too slowly to implement enough large-scale systems and the resulting experience curves are adversely affected by the less profitable small- to medium-scale systems. For the latter, the impact of low-quality OTEC locations is responsible. Although plenty of large-scale plants are installed, the cost increases due to longer cables and lower power output push the experience curves above the threshold.

Publicly funded OTEC shows noticeably better outcomes. Merely the orange curves for a learning rate of 6 % fail to penetrate the reference costs in the cases of *Modest Growth* and *Superaggressive Expansion*, for the same reasons as elaborated above. But other than that, all other experience curves undercut a wholesale price of 20 $ct./kWh eventually. This is the ultimate proof that OTEC needs to be implemented in collaboration with public authorities. Given that a learning rate of around 6 % seems most probable, the risks of solely private OTEC ventures seem to be insurmountable to ensure the sound development of the technology. Conversely, if OTEC is implemented privately, a learning rate markedly higher than 6 % is required. How this is going to be accomplished cannot be foreseen at this point and such uncertainty does not necessarily speak for OTEC.

Furthermore, the scenarios revealed that OTEC capacity needs to grow at a rate of at least 30 % per annum to ascertain a sustainable shift to profitability for any cost estimation. In the case of *Modest Growth*, too many experience curves failed to descend to an appreciable level, since its growth rate does not sufficiently justify the wide-spread implementation of profitable large-scale system. In contrast, scenarios of *Fast* and *Rapid Growth* engender the deployment of considerably more of these plants and therefore allow other mechanisms like economies of scale to unfold their effects more thoroughly.

5.1.3. Integration of Experience Curves into Supply Curves

Figures 5.5 to 5.6 illustrate the supply curves for different learning and discount rates in the case of *Superaggressive Expansion*. Both plots are based on the orange curves previously shown in chapter 4. Dynamic global supply curves for other scenarios and for the other relevant cost estimations can be found in Appendix N. The reader is strongly advised to consult section 3.4.3 before continuing with the paragraphs below to get accustomed to the differences between experience and supply curves and how the integration of the results presented in this chapter into dynamic supply curves proceeds.

For a discount rate of 18 % and a learning rate of 6 %, the supply curve in Figure 5.5 comes just shy to the reference cost and subsequently rises far above it. For a discount rate of 10 % and the same learning rate, the supply curve in Figure 5.6 shows only slightly better results. There, the curve surpasses 20 $ct./kWh at a cumulative energy output of 2.100 TWh. This means that OTEC's long-term profitability cannot be ascertained for the worst case. In contrast, all other supply curves with a learning rate higher than 6 % predominantly comprise LCOEs lower than the reference cost. For a rate of 12 %, the threshold is only breached at around 4.400 TWh and 4.600 TWh in Figures 5.5 and 5.6, respectively. In such cases, exuberantly high costs could be seen as a temporary inconvenience which would subside in the near future.

What is the impact of learning on the range of economic potential of OTEC? For both a discount rate of 10 and 18 %, the economic potential is now depending on the learning rate and can vary from **0 – 5.200 TWh** for a learning rate of 0 % to **4.700 – 5.200 TWh** for a learning rate of 18 %. This is not very telling, but more insights can be gained from looking at learning rates in between the boundary values. For a learning rate of 6 % for example, which is perceived as the most likely, the differences are vast. While the supply curve for a discount rate of 18 % still only ranges between **0 – 5.200 TWh**, the range is **2.100 – 5.200 TWh** for a discount rate of 10 %. This proves the necessity of public participation in OTEC deployment and the gravity of learning on the technology's profitability.

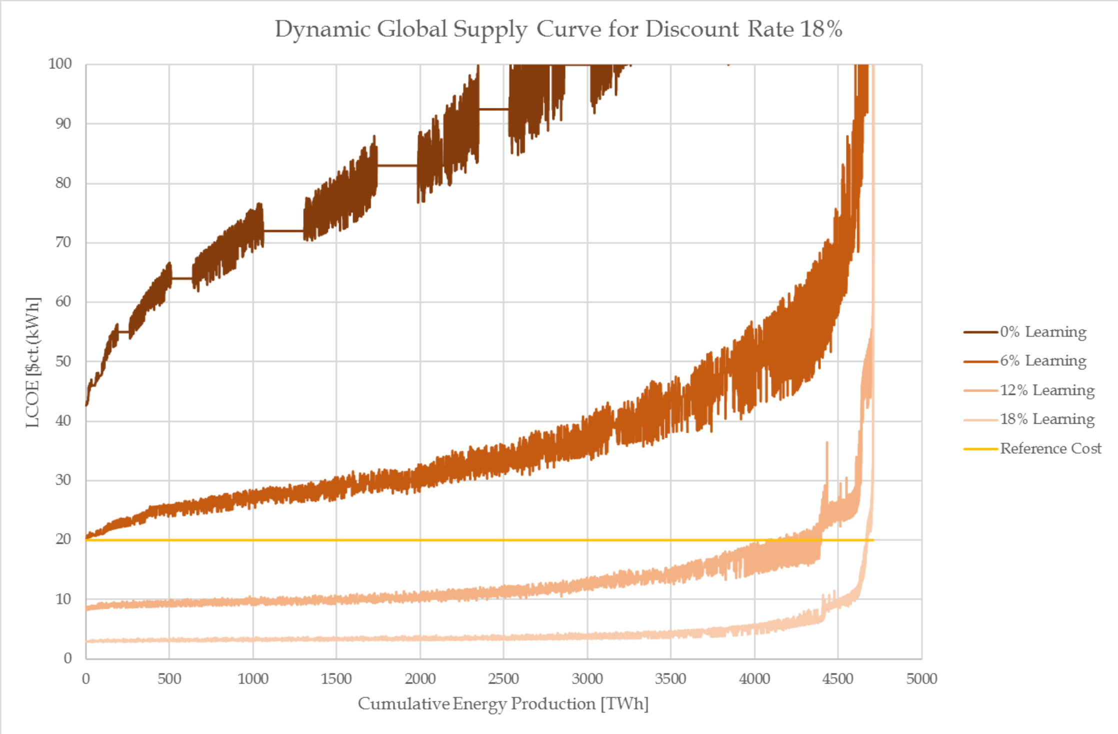

Figure 5.5 Dynamic Global Supply Curve for Privately Funded OTEC. Cost Estimations Based on Lockheed Martin plus Uncertainties. (Own Illustration).

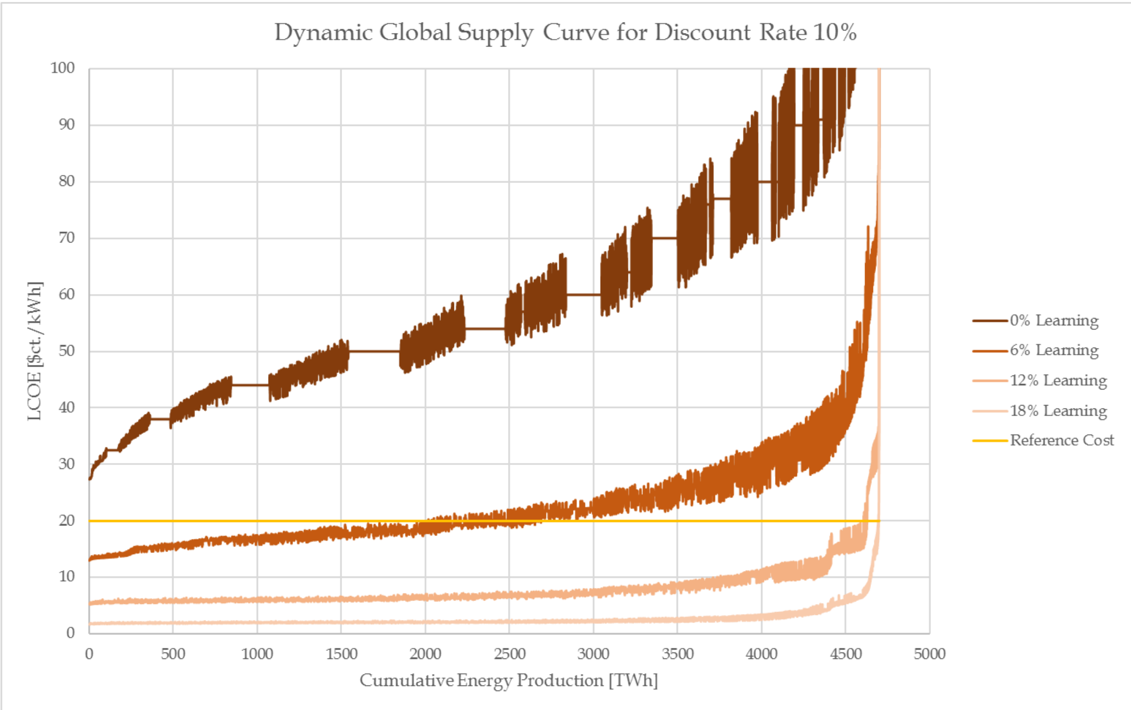

Figure 5.6 Dynamic Global Supply Curve for Publicly Funded OTEC. Cost Estimations Based on Lockheed Martin plus Uncertainties. Y-Axis Cut Off at 100 $ct./kWh for Clarity (Own Illustration).

5.2. Implementation Phases and Roadmap of OTEC

Above it was explained that the supply curves presented here do not incorporate the time of implementation of OTEC plants. However, when the LCOEs of an implementation scenario are ordered from smallest to largest – forming a supply curve – it is possible to observe the implementation stages of the scenarios in these graphs. To wrap up this chapter, it will be explained how the dynamic global supply curves above can be interpreted as roadmaps for implementation based on the observed patterns. Figure 5.7 displays a qualitative supply curve with indications of different implementation phases.

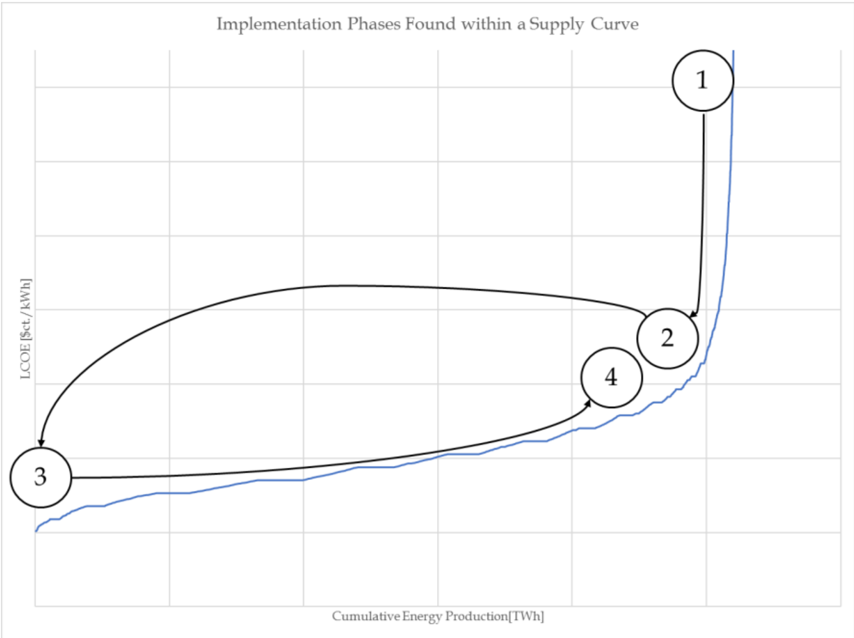

Figure 5.7 Implementation Phases Within a Supply Curve. Qualitative Illustration (Own Illustration).

Phase (1) is the *pilot phase*. For each scenario, the pilot phase encompasses a frame of eight years, which is comparable to the trajectories within the offshore wind power niche. There, only 2.5 and 10 MW OTEC systems are installed and the main objective is the accumulation of operational data, the proof of commercial feasibility and the gathering of experience. Learning progresses rapidly and so do cost reductions, which explain the steep fall of costs as the implementation moves from the right to the left on the supply curve. It might sound counterintuitive that phase (1) starts at the very right. After all, should it not be on the very left at the top? For experience curves, that would indeed be the case, but since in the supply curves the cells are ordered from lowest to highest LCOE, they are situated at the very right. Due to their small scale of only 2.5 and 10 MW, the LCOEs of these plants is considerably higher compared to the upscaled plants in later implementation phases.

Phase (2) proclaims the beginning of *commercialisation*. Small-scale 2.5 MW plants are not implemented anymore due to their high costs and obsolescence. Instead, installed capacities are slowly upscaled, moving slowly from 10 to 20 MW. Cost reductions are not as rapid as in phase (1) anymore, but still exert noticeable effects. The duration of this phase depends on the scenario but does not exceed fifteen years. At the end of this period, capacity starts to reach medium- to large-scale and besides 50 MW, 100 MW plants are eventually inaugurated.

Phase (3) deals with the *drive to maturity*. Both economies of scale and learning effects reduce the LCOE of OTEC plants starkly enough to jump to the very left side of the supply curve. At that point, the LCOE reaches its absolute minimum. Large-scale 100 MW plants take off and medium-scale 50 MW systems are well-established. Cost reductions via learning are now relatively sluggish, since the cumulative output has been doubled multiple times already. As the quality of OTEC locations continuously declines, cost reductions are not possible anymore and the LCOE starts to rise with each additional unit installed, gradually moving to the right of the supply curve due to the arrangement of LCOEs in ascending order.

Eventually, the effects of economies of scale are fully utilised, only low-quality locations are available and OTEC finally reaches the fourth and last phase of (4) *maturity*. The LCOE steadily moves to the right and eventually meets with the spot where the niche leapfrogged from phase (2) to (3).

Figure 5.7 explains why it is so important for all experience curves to go below 20 $ct./kWh. Economies of scale and learning cannot reduce the LCOE forever and as soon as the quality of OTEC locations declines, the supply curves start to hike again. Thus, if the experience curves of one scenario do not undercut a wholesale price of 20 $ct./kWh, its respective supply curve will eventually surpass the reference cost again somewhere between phase (3) and (4), if it even undercuts the threshold in the first place.

This roadmap also underlines the importance of high learning rates. Here, the transition from phase (3) to (4) is described as a gradual rise in LCOE due to quality deterioration of OTEC locations. But this must not necessarily happen. If the learning rate is high enough, say between 12 and 18%, the shift from (3) to (4) resembles more a horizontal line. In such a case, learning effects would be strong enough to offset most of the location-related cost increases.

5.3. Conclusion of Implementation Scenarios and Experience Curves

The supply curves of chapter 4 do not tell much about OTEC's implementation and the cost reductions engendered by it. A total of four scenarios are created which differ in growth rate of installed capacity and time frame. The former is based on observations made from the offshore wind niche, which shares plenty of similarities with OTEC. These scenarios are contrasted to different learning rates of 6, 12 and 18 % based on contemporary literature. The resulting global experience curves are integrated into the global supply curves to form dynamic plots which consider the effects of both economies of scale and learning.

In the near to medium future, OTEC's impact on global electricity system is going to be marginal with a proportion of just 0.91 % at an annual installation growth rate of 40 % after 24 years. In such a scenario, merely 3.58 % of the previously determined economic potential would be harnessed. To employ 99.9 %, it would take 35 years at the same growth rate. Considering an increase of global electricity demand of 1.15 % per annum, OTEC could theoretically cover over 20 % of global electricity consumption. With progressing implementation of OTEC, the effects of economies of scale are offset by the deterioration of the quality of possible deployment locations. However, even a low learning rate of 6 %, combined with economies of scale, can neutralise the cost increases due to low-quality locations. Only for extremely disagreeable OTEC cells it is not possible to counteract their surge in costs, even for large learning rates. Finite learning as proposed by OTEC literature is analysed and disagreed upon.

To sustainably push the dynamic global supply curves below a reference cost of 20 $ct./kWh, several conditions need to be fulfilled. First, the growth rate of installed capacity must be higher than 20 %/year to obtain sensible cost reductions by economies of scale. Second, the learning rate needs to be higher than 6 % to shift the worst-case supply curve below the threshold. Third, a discount rate of 10 % is required, which underlines the necessity of public involvement during OTEC implementation.

6. Discussion

The remaining chapters reflect upon the work that has been done in the previous months and that has formed this thesis as it is today, starting with a discussion. To avoid redundancy, the economic results of the study are not elaborated here since they already have been in earlier sections and since they are elaborated in the concluding chapter as well. Instead, this chapter discusses the thesis as a whole, addressing overarching achievements, shortcomings and limitations.

6.1. Achievements and Validation of Results

This thesis detected four knowledge gaps in contemporary literature and directly addressed three of them. First, no publication was found which assesses the national and global economic potential of OTEC. Instead, evaluations merely encompass the economics of individual, notional projects. As a response, this study delivered an unprecedented projection of the national, international and global economic potential of OTEC for different cost estimations, both with and without the consideration of learning effects. Second, the choice of discount rate in literature foots on oversimplification and does not reflect the aggravated business conditions a high-risk technology like OTEC faces. Here, the discount rate is carefully assessed and discussed for both private and public projects, with impacts of its variation elucidated by a sensitivity analysis. Third, there are no projections on global experience curves of OTEC and current economic analyses on the technology do not take into account cost reductions via learning. As a first-of-its-kind study, OTEC experience curves have been modelled and integrated into dynamic supply curves which reflect the profitability of OTEC under the light of implementation scenarios and different learning rates. The results presented here contribute considerably to the body of research revolving around OTEC and can serve as the cornerstone of more detailed investigations. However, the fourth knowledge gap in contemporary literature, namely the negligence of advanced financial and fiscal data, is not tackled in this study either and needs to be addressed in future research.

If contrasted to literature, the results generated here might differ depending on the underlying assumptions of the studies. For example, if the base LCOEs in this thesis for a 100 MW plant are compared with the LCOEs obtained by Lockheed Martin, one encounters slight deviations. While a LCOE of 29.4 $ct./kWh is computed here for a plant at the Hawaiian coast, Lockheed Martin finds a LCOE of 19.5 $ct./kWh (2018 value). This is mainly due to the considerable difference in discount rate, which is 4 % for the latter and 10 % for the former. If the discount rate in the model used here is altered to 4 %, one obtains a LCOE of 19.0 $ct./kWh which comes fairly close to Lockheed Martin’s result. Deviations in discount rate are not the only reason why the results presented here can slightly differ from values found in literature. Since the scale curves used in this work are merely trendlines, they do not precisely reflect the cost estimations on which they are based. For example, the grey scale curve in Figure 2.3 at page 19 proclaims noticeably lower capital costs compared to the estimations by Bluerise (2014). This results in a LCOE for a 10 MW system of 22.8 $ct./kWh (still at Hawaii) in this thesis vis-à-vis 27.2 $ct./kWh[18] from the OTEC company, despite their use of a lower discount rate of 8 % versus 10 % deployed here. Contrarily, the scale curve in Figure 2.3 at 50 MW is slightly above the cost estimate by Straatman & van Sark (2008), which in combination with a lower discount rate of only 8 % leads to a discrepancy in LCOE of 8.8 $ct./kWh here versus 6.9 $ct./kWh[18] in their study. Therefore, it is pivotal to assess the underlying assumptions of each study before their results are compared. When the differences between them are comprehended, it is fair to say that the figures presented here are in line with literature.

Unfortunately, it is not possible to validate the experience curves designed in chapter 5. Elaborations on learning effects on OTEC in literature are scarce and the only more detailed analysis performed by Lockheed Martin is argued against in this thesis due to their debatable assumptions. In fact, as long as OTEC does not make the jump from blueprints and desktops into the ocean and onto the electricity grid, nothing tangible can be said about the practical application of the theoretical curves presented here. As already discussed before, not only the technology, but also the market influences the shape of experience curves, so only time can tell to which extent the results presented here hold true.

6.2. Methodology and Data

Notwithstanding the congruency of the results with contemporary literature, no methodology is impeccable and the one employed here poses no exemption. In the following, methodological shortcomings and limitations in data from different domains like economics, geography, engineering and social sciences are elucidated. All of them affected the course of the study and the results it generated to a varying extent. These deficiencies are subsequently addressed in the ensuing chapter, providing recommendations to tackle them.

Based on the methodology employed here, it is possible to obtain the average cost of electricity required to reach parity with all expenses over a projects lifetime. However, nothing can be said about the financial soundness of the proposed projects. Important aspects like the *Net Present Value* (NPV) or *Internal Rate of Return* (IRR) based on the reference costs used here are yet to be determined for the

[18] Values converted from 2013 € (Bluerise) and 2008 € (Straatman & van Sark) to 2018 $ values.

OTEC units analysed here. Thus, as valuable as the insights presented here are, they are only the tip of the iceberg and require further attention in terms of project finance.

Due to the differences in system design among academic and industrial studies on OTEC, it was not possible to analyse the economics of the technology on a micro level. Notwithstanding, this is a shortcoming of the methodology used here since it would have been interesting to see how the costs of individual components change based on upscaling and learning effects. Instead, the results here only refer to a macro level and do not discuss the cost components in particular.

If there is a term which perfectly summarises the predicaments encountered in this thesis, then it is *uncertainty*. However, one limitation of the methodology is the neglection of a deep analysis of the uncertainties involved in the economics of OTEC. This thesis does not provide insight on the standard deviation of power outputs or costs at a specific island, among others, or whether the histograms shown in chapter 4 are normally distributed or not. Hence, from a mathematical point of view, the results presented here are not validated or proven.

Whenever the scope of a study shifts to an international or global level, it comes at the cost of precision and detail. Although this thesis succeeded to sketch a worldwide picture of the economic potential of OTEC and its implementation – with and without learning – a lot of peculiarities got lost in transition. Deep financial and fiscal data like income tax could not be included since every country comprises a particular financial environment and thus provides little room for generalisation. Social costs in the form of positive and negative externalities could not be included as well as no one knows what explicit impact OTEC would have on local and global marine ecosystems (Hammar et al., 2017). And even if it was known, it is impossible to differentiate the distinct environmental conditions at each analysed country. The negligence of these and other cash flows inevitably distort the results of the analyses and might lead to an overvaluation of the economic potential of OTEC.

Another shortcoming due to generalisation is the choice of wholesale electricity prices. Due to the absence of tangible data for *any* analysed country, a range of 20 – 40 $/kWh was chosen as a general proxy. While such an assumption might have been reasonable for small tropical island states, it is strongly debatable for larger islands and continental countries like China, India and many more. These countries probably comprise considerably lower prices which affect the results of this study markedly.

Regarding environmental limitations, many natural phenomena had to be abandoned due to complexity. The power output of an OTEC plant strongly depends on the availability of cold deep-seawater. It would require highly sophisticated soft- and hardware to measure or to even model the global sea currents from which the cold water availability is deduced. The same goes for the bathymetry of sea grounds. Although this thesis tried to capture the impacts of varying sea floor depths in the form of a higher percentage of mooring costs, this is not a final solution. Then again, mankind knows so little about the oceans and it is hard to imagine that this will change in the near future. Thus, there is a disparity between the necessity of more detailed physical information on deep-sea currents and marine geography and the feasibility to obtain it.

Easier to obtain but certainly not easier to implement are variations in seawater temperature difference. In the course of the year, the temperature of the seawater at the surface is exposed to the caprices of the seasons. These alterations directly affect the performance of an OTEC plant, either beneficially or adversely. In this thesis, the seawater temperature was averaged over a time span of ten years which provided a decent foundation to analyse OTEC for mid- to long-term implementation. But it was not possible to consider yearly and seasonal fluctuation which is a shortcoming of the methodology employed here.

6.3. Technical, Economic and Social Scope of Analysis

Being too general is one limitation but being too specific can be as problematic. Merely one type of OTEC has been analysed, namely moored, closed-cycle systems. They have been chosen due to the relatively broad availability of literature. However, there are also open- and hybrid cycles, land-based and grazing OTEC, producing other products besides electricity, like freshwater or hydrogen. Unfortunately, these systems are barely acknowledged in literature and an objective, unbiased and relevant analysis of them was not possible. Furthermore, power transmission is limited to AC cables in this study although DC cables are gaining more and more momentum recently (Martel et al., 2012). The latter are more efficient for long-distance transmission and their inclusion could have ameliorated the economic performance of peripheral OTEC locations.

There are also shortcomings regarding societal factors. The limitation of what is a demand centre and what not was already discussed in earlier chapters, but when it comes to tropical islands, especially small island developing states, there is more to address than what meets the eye. The electricity consumptions recorded in the energy balances used in this study do not necessarily reflect the true demand of the islands' populations. Energy poverty – the inaccessibility of electricity – poses a grave problem for some island countries and bereaves local residents of basic amenities like lighting and refrigeration (Dornan & Shah, 2016; Urmee, Harries, & Schlapfer, 2009). It explains why Haiti is merely suitable for 10 MW OTEC, although their population is virtually the same size as the population of the Dominican Republic, which could deploy 100 MW systems economically. Yes, one could argue that energy poverty might be tackled in the implementation scenarios, which include the exponential, annual growth of global electricity demand. But this line of reasoning is flawed. What proportion of demand growth serves for the electrification of rural villages? No one knows. Most likely, most of the 1.15 % of global demand growth per year flow into industrialised and emerging countries like China and India due to growing economies and populations. Therefore, it must be assumed that the scenarios presented in this thesis would only have a marginal impact on energy poverty and that the deployed OTEC plants would predominantly cover the demand of already electrified communities.

In the introduction of this thesis, it is mentioned that the practicable potential of OTEC by Chalkiadakis would not reflect the true potential of the technology under practical conditions. Now that the range of economic potential of OTEC is projected here, is this problem finally resolved? Unfortunately, not even closely! To do so, one would have to consider other energy technologies as well, both conventional and renewable. This is what separates the *economic potential* from the *market potential*, which also includes the interaction between competitors in the market (Blok & Nieuwlaar, 2016). As of now, the supply and experience curves only reflect the profitability of OTEC under current market conditions as an external, passive outsider. But in reality, it will be part of the market, influencing and being influenced by it. Only if OTEC is contrasted to other technologies and their costs, it is possible to make relevant and tangible statements about near-, medium- and long-term prospects. It is conceded that this thesis does not provide explicit insights about the market potential of OTEC, but it never stated to do so. Instead, this study continued what Chalkiadakis and other scholars begun and conversely, it paves the way for future research to carry on the journey towards the market potential of OTEC.

7. Recommendations

The previous chapter discussed the shortcomings of this thesis. Here, recommendations are provided to tackle them and to contribute to OTEC's further development. Every now and then, remarks on future research have been made throughout this study. These remarks are now gathered and expanded by further aspects to provide an agenda for future work on OTEC.

7.1. Possible Objects of Future Research

To address the shortcomings due to generalisation, the economic potential of OTEC needs to be assessed on a solely national and regional level. This would resolve many problems encountered in this thesis simultaneously. First, the economic analysis could be expanded to a national discounted cash flow analysis as elaborated in Appendix C, with country-specific data like national tax and interest rates being included. In this regard, other values than the LCOE could be calculated like the NPV or IRR providing more comprehensive understanding about the financial soundness of individual OTEC locations. Although the discount rates used in this thesis foot on careful considerations, a rate specifically designed for the underlying country or region would considerably improve the future studies. Then, multidisciplinary factors from economics, politics, institutions, society and culture would coalesce to a discount rate which adequately represents the conditions prevailing in the analysed country. The economic potential resulting from a more regional analysis would also be more relevant since the supply curves would be contrasted to the national and regional wholesale prices and not to a notional proxy as done here. Furthermore, a more local focus would simplify the incorporation of fluctuations in seawater temperature difference to produce more detailed forecasts on the profitability of OTEC throughout the year. It would also engender a more profound determination of demand centres, especially if the scholars conducting the study originate from these locations.

To tackle the methodological flaws of this thesis, more understanding must be forged about the scaling effects of individual components of OTEC, with more consistency in system design within and beyond academia and industry. With the lack of comparability as of now, the economic analysis of OTEC is limited to a macro level. Furthermore, it would prove beneficial to perform comprehensive statistical analyses like a Monte-Carlo simulation to gain more insights about the uncertainty inherent in OTEC, not only in terms of costs, but also power output, external influences and operation.

Regarding the technology itself, more research is needed on other types of OTEC besides moored, closed systems. If more state-of-the-art cost estimations and feasibility studies would be available on other OTEC configurations, it would enable an unbiased, broad and considerate assessment of the economic potential of the whole niche, not just of one option. Moreover, the effects of other sources of revenue like freshwater and hydrogen on the overall profitability of OTEC could be investigated as well. Under the light of its gargantuan capital costs, OTEC might struggle to convince decision makers of its benefits compared to other, cheaper technologies like solar and wind power. If multifunctional OTEC plants get more attention by academia and industry, it would provide more arguments for its implementation. Another recommendation is to scrutinise how the results presented here would change under the consideration of cold water availability and sea floor levels. A model on global deep-sea water currents and a thorough bathymetry of worldwide oceans would not only benefit the OTEC niche, but also other offshore technologies and even other research fields related to environmental sciences.

Another object of future research could be OTEC's impact on energy poverty. Most of the technology's possible customer base comprises tropical islands in varying stages of development. Its deployment could be further motivated if it was known whether and to which extent rural communities without access to electricity would benefit from OTEC. If energy poverty can be tackled, the economic potential of OTEC would be considerably higher than projected in this study because the electricity demand of a country would not only be determined by its electrified communities, but by its entire population. Therefore, OTEC could promote equality and serve as a step stone for rural villages to improve their living conditions.

As already discussed in the previous chapter, the economic potentials estimated in this thesis do not include the competition imposed by other energy technologies on national and global markets. Future research must address OTEC's potential under the light of real market conditions, with OTEC affecting the market and vice versa. Possible questions could be "How does the aggressive implementation of OTEC affect its potential based on changes in electricity supply and demand?" or "How does the widespread deployment of other energy technologies affect the economic potential of OTEC?". Furthermore, it is important to study what and where OTEC's markets are. Many of the locations analysed here might be interfering with shipping routes, touristic centres or other offshore technologies like oil rigs or offshore wind farms. Such and many other aspects need to be considered to draw a convincing picture of OTEC's chances to finally lift off.

7.2. Recommendations on Organisation and Implementation

However, it is argued that the most important recommendation is not related to research at all. What OTEC desperately needs, above more academic papers, more feasibility studies, more models and more scenarios, are pilot plants. OTEC finally needs to put rubber on the road! Future investigations need to be based not on further hypothetical estimations or projections, but on hard, empirical data gained from continuous operation. The concept of OTEC already exists for over one century and research has been conducted on it ever since. Over one hundred years of research did not produce a single commercial OTEC plant as of today in summer 2018, so it is about time to change the strategy. Yes, there are already pilot plants out there, but their capacity is way too small to represent a commercial OTEC system. Only a symbiosis of academic research and industrial execution can make a genuine impact on OTEC's development, with estimations being refined and projections turning into prognoses. Only pilot plants can turn the question marks of decision makers, both public and private, into exclamations marks and spark its broad development.

To make this bold undertaking reality, cooperation is the key. As many actors and institutions as possible need to be involved, both up- and downstream, to end the odyssey of cancelled, delayed and failed projects and to get OTEC on the right track. Producers must understand who their customer base is, what they need and how consumers can benefit from OTEC compared to the competition. Public authorities on all levels need to steer the development of the technology into the right direction by providing favourable policies, such as subsidies, funds, tax advantages and more streamlined administration. The process of obtaining the required permits to operate the plants need to be optimised and regulated better. To tackle OTEC's most severe problem, its monumental capital expenses, an international cooperation in form of an OTEC fund would contribute considerably to its further development. Organisations like the *International Renewable Energy Association* (IRENA) already cooperate with small island countries, represented by the *Alliance of Small Island States* (AOSIS). With their Lighthouse Projects, the former mobilised several hundred millions of dollars which is used among others to provide renewable energies to small island states (Gordon-Harper, 2017). If such funds would put more attention to OTEC, or if there would even be a fund specifically designed for it, there is genuine hope for the technology to eventually lift off to a commercial scale at which it does not require external support anymore.

8. Conclusion

The final chapter concludes this thesis and provides answers to the main and sub research questions. Explicit results are discussed for each sub question, while the main research question is answered on a meta-level at the end. This avoids redundancy and allows the study to end with some final, overall remarks on the prospects of OTEC.

1. *How is the economic potential of renewable energy technologies determined in current literature and which methodology is suitable for the evaluation of OTEC and its economics?*

Based on contemporary literature, the construction of supply curves is the methodology of choice to determine the economic potential of renewable energies. There, suitable locations for deployment are analysed for cost-affecting parameters. The locations and their properties are often provided by geographical information systems. The deliverable of this step is a catalogue of low-, medium- and high-quality locations differing in costs. If these costs are ordered from smallest to largest, one obtains a supply curve which can be contrasted to local reference costs, i.e. wholesale electricity prices. The output of every location underneath the reference line is considered as profitable and accumulate to an economic potential. Since the physical properties of practicable OTEC locations were already mapped on a global level by TU Delft graduate Charalampos Chalkiadakis in his master thesis, the framework mentioned above is perceived as the most suitable methodology.

The literature review on the economics of OTEC revealed a stark discrepancy in cost estimations. On the one side, there is U.S. company Lockheed Martin, who proclaims rather conservative but also reasonably argued for capital expenses of several million and up to billion dollars. On the other side are cost estimations by academia and other OTEC companies who suggest significantly more optimistic values for CAPEX. In any case, capital expenses pose a monumental hurdle for OTEC's economic potential, especially in comparison to other energy technologies. For this thesis, the profitability of OTEC is analysed based on three different cost levels, namely (1) Lockheed Martin, (2) Lockheed Martin plus additional uncertainties and (3) academia and other OTEC companies. The uncertainties in case (2) foot on possible cost increases due to higher cable and mooring costs, larger transmission losses from the plant to the grid and shorter operation due to unscheduled maintenance. The objects of investigation are five different scales of moored, closed-cycle OTEC systems with a nominal capacity of 2.5, 10, 20, 50 and 100 MW. The economic potential is computed in the form of Levelized Costs of Electricity (LCOE), based on two discount rates perceived suitable for OTEC with 10% for public and 18% for private projects, respectively. The supply curves are then contrasted to a range of reference costs between 20 and 40 $ct./kWh.

2. *Which tropical islands are the most suitable for OTEC deployment in terms of geography, demography and electricity demand?*

In his thesis, Chalkiadakis mapped the practicable potential for over 90 sovereignties worldwide. To comply to the context of this study, the set of analysed countries is further refined based on five selection criteria, videlicet (1) geography, (2) climate, (3) fossil fuel import dependency, (4) final electricity consumption and (5) electricity demand distribution. As a result, 29 tropical islands are considered suitable for the ensuing analyses. They are spread all over the world and comprise islands in different stages of development, from underdeveloped countries like Papua New Guinea and Haiti over emerging countries like Indonesia to industrialised islands like Hawaii and Aruba. Out of these 29 islands, five of them are suitable for 2.5 and 10 MW, nine for 20 MW, four for 50 MW and eleven islands for 100 MW. The economic potential of OTEC on each individual island is based on the maximally deployable capacity.

3. *What is the range of economic potential of OTEC for the selected host of tropical islands and how can the economic potentials be translated from a national to a global level?*

The economic potential for each of the 29 tropical islands is computed and aggregated to a total range of 0 – 390.1 GW for a discount rate of 10 % and 0 – 381.7 GW for 18 %, respectively. The lower boundary is determined by the worst-case costs and the lower reference cost of 20 $ct./kWh. The upper range foots on the lowest cost estimates and a reference cost of 40 $ct./kWh. The small difference in maximally possible potential shows that the choice of discount rate loses gravity the less stringent the circumstances are. However, a sensitivity analysis elucidated the considerable impact of the discount rate on the shape of supply curves. Hence, while the discount rate might not matter for best-case costs, it does matter a whole lot for any cost estimations based on Lockheed Martin. The wide range of possible supply curves and reference costs are responsible for the ambivalence of the results. Based on the perspective, either all practicable OTEC locations or none could be economically attractive, which is perceived not only on the national, but also international and global level. Another striking peculiarity is the starkly heterogenous distribution of the economic potential across the 29 islands. Indonesia, Papua New Guinea and the Philippines already comprise around 61.5 % of the aggregate potential, while it is merely 9.8 % for the second-best hotspot consisting of Cuba and the Dominican Republic.

Almost 8.500 OTEC cells have been analysed to model the economic potential of OTEC for 29 tropical islands. The observed trends in LCOE and real energy output are used to extrapolate the supply curves to a global level. After the remaining global countries suitable for OTEC are analysed for their electricity demand and practicable potential for OTEC, their respective OTEC cells are attributed with values for LCOE and real energy output based on phenomena observed in histograms. For a discount rate of 10 %, a global potential of 0 – 645 GW is computed, which reduces to 0 – 633 GW for a discount rate of 18 %. This shows that OTEC’s economic potential could be enormous under the right terms. But it also underlines once more that OTEC’s largest hurdle, its monumental CAPEX, could thoroughly obliterate its profitability and competitiveness.

4. *What are conceivable global implementation scenarios for OTEC and how do they affect its future economic potential based on global experience curves?*

The supply curves mentioned above do not tell much about its implementation and the cost reductions enabled by it. A total of four scenarios are created which differ in growth rate of installed capacity and time frame. The former is based on observations made from the offshore wind niche, which shares plenty of similarities with OTEC. These scenarios are contrasted to different learning rates of 6, 12 and 18% based on contemporary literature. The resulting global experience curves are integrated into the global supply curves to form dynamic plots which consider the effects of both economies of scale and learning.

In the near to medium future, OTEC’s impact on global electricity system is going to be marginal with a proportion of just 0.91 % at an annual installation growth rate of 40 % after 24 years. In such a scenario, merely 3.58 % of the previously determined economic potential would be harnessed. To employ 99.9 %, it would take 35 years at the same growth rate. Considering an increase of global electricity demand of 1.15 % per annum, OTEC could theoretically cover over 20 % of global electricity consumption. With progressing implementation of OTEC, the effects of economies of scale are offset by the deterioration of the quality of possible deployment locations. However, even a low learning rate of 6 %, combined with economies of scale, can neutralise the cost increases due to low-quality locations. Only for extremely disagreeable OTEC cells it is not possible to counteract their surge in costs, even for large learning rates.

To sustainably push the dynamic global supply curves below a reference cost of 20 $ct./kWh, several conditions need to be fulfilled. First, the growth rate of installed capacity must be higher than 20 %/year to obtain sensible cost reductions by economies of scale. Second, the learning rate needs to be higher than 6 % to shift the worst-case supply curve below the threshold. Third, a discount rate of 10 % is required, which underlines the necessity of public involvement during OTEC implementation.

What is the national and global economic potential of OTEC and what are conceivable trajectories of global OTEC implementation under consideration of learning effects?

From the very beginning of this thesis, it became clear that there is no single answer to the main research question. At almost any conjecture, there were discrepancies, debates, compromises, simplifications and even contradictions which made it extremely challenging to perceive OTEC from an unbiased and objective stance. This study strived to include as many perspectives as possible and to serve in a diplomatic fashion. It is pivotal to comprehend the line of reasoning of all sides, of both the yay- and nay-sayers, to assess the credibility and reliability of their assertions. Thus, what this thesis produced are not explicit facts and prognoses, because that is impossible, but pathways OTEC could take if certain preconditions are met.

These conditions are that the cost estimations made by academia and other OTEC companies hold true, that private and public stakeholders cooperate closely, that its implementation proceeds quickly with strong learning effects and that wholesale electricity prices are high. Then, OTEC's economic potential would be enormous.

On paper, such statements sound great, but how likely are these events to happen individually and simultaneously? This study showed what OTEC might be capable of if learning effects are strong, but putting it into perspective, what is the value of such claims if OTEC's actual prospects are considerably less optimistic? If it follows the footsteps of comparable energy technologies like offshore wind which comprises a rather low learning rate, all these projections turn to dust. The same goes for public involvement. Bluntly asked, why would anyone go for a multibillion technology with no commercial experience if there are alternatives which are significantly cheaper and better known? And how likely is a growth rate of 30 or 40 %/year if not even highflyers like solar photovoltaic and onshore wind can consistently maintain such expansion rates?

There is no beating around the bush, the odds are against OTEC. It comprises monumental costs and its learning rate might be low. Its centralised constitution does not conform to the trend of decentralisation as proclaimed by other technologies like photovoltaic and wind power. Their customer base is heterogeneously spread across the world and consists predominantly of developing and emerging states with lacking finance, infrastructure and education. Also, no one knows what the environmental impacts are on marine ecosystems in case of large-scale deployment. However, who would have predicted offshore wind's radical and explosive development? People tend to discard what they do not know and reject future benefits based on contemporary risks. The past repeatedly showed how sombre prospects can turn into bright realities. Considering the shift of mindset within society, away from negligence and into the arms of environmental consciousness, today is the best time to pursue change. But OTEC must deliver. It must awake up from its slumber and prove that it can write the next success story. It must act swiftly. It must act determinedly. But most importantly, it must act now.

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