Assessment of Economic Potential of Ocean Thermal Energy Conversion in Indonesia: A Spatial Approach

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Assessment of Economic Potential of Ocean Thermal Energy Conversion in Indonesia: A Spatial Approach

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Aida Astuti Cahyaningwidi Rahayu Sutopo

Executive Summary

The Republic of Indonesia as a nation faces the 'energy trilemma', i.e. the problem of providing energy security, tackling energy poverty, and mitigating climate change at the same time. With this problem in mind, increasing the renewable energy share in the total primary energy supply of the country is crucial. Taking the archipelagic geographical condition of Indonesia into account, ocean energy technologies sounds like a good option. Among the various ocean energy technologies available, ocean thermal energy conversion (OTEC) comes out as the technology with the highest potential in Indonesia. There are two very recent publications that include Indonesia as a part of global scale assessments of technical and economic potentials of OTEC. However, research specifically directed to assess the economic potential of OTEC in Indonesia has not existed. It leads to a knowledge gap fitting for the thesis under the Sustainable Energy Technology MSc programme at Delft University of Technology. The main research question of the thesis is:

What are the national and provincial economic potentials of ocean thermal energy conversion in relation to the provincial electricity demand fulfilment in Indonesia?

The literature study in Chapter 2 reveals that there are already many studies in Indonesia about renewable energy from the ocean. Yet, only a few of them discuss the potential of OTEC in Indonesia. Up until today, there are no commercial OTEC plants available yet. This causes the costs values quoted in literature to vary considerably. The last part of the literature study shows that the combination of the GIS and the techno-economic analysis methods is proven to be useful in determining the potential of various renewable energy types.

The methodology in Chapter 3 is designed to be reproducible easily for analysing the economic potential of OTEC in different locations. The methodology consists of 5 main stages. The first stage is the problem definition, where the location and the type of renewable energy resource to be analysed are chosen. The second stage is gathering and pre-processing the data. The third stage is the potential areas determination, which is done by assigning the economic parameters, computing the levelized cost of electricity (LCOE) of each station, and calculating the economic potential. In this thesis, a station's nominal size is 100 MW and it is said to have an economic potential if it has an LCOE of less than 0.20 €/kWh. The economic potential is calculated both on national and provincial levels. The fourth stage is building the electrification scenarios by selecting the stations and enumerating the economic potential of the selected stations. There are three scenarios present in this study, i.e. electrification with resources within the province boundaries ("in-stations"), with scaled-down plants ("scaled-down"), and with resources beyond the province boundaries ("out-stations"). The fifth stage is presenting the results and the sixth stage is establishing the conclusions.

The results of the economic potential calculation are presented in Chapter 4.. Initially, the distance used to calculate the LCOE is the closest distance between the stations and any closest shore. With the original distance, the economic potential of OTEC on the national level in Indonesia ranges between 330-473 MW or equivalent to 2607-3691 TWh/year, depending on the cost assumption being used. Then, the distance is adjusted to the demand centres and all results following the adjustment are calculated based on the adjusted distance. The economic potential on the national level with the adjusted distance range between 50-192 MW or 318-1431 TWh/year, considerably lower than the economic potential with the original distance. The total economic potential on the provincial level ranges between 253-904 TWh. It is slightly lower than the national potential as some of the stations are located outside the boundaries of the provinces.

The results of the electrification scenarios are presented in Chapter 5. The result shows that it is relatively easy to cover 100% of the demand only with the production of OTEC plants if the LCOE limit is ignored. Once the limit is considered, many provinces lost any potential, even under the lower cost assumption of Vega (2012). The economic potential for the in-stations ranges from 15.52-29.79 TWh/year depending on the cost assumption. For the scaled-down stations, the economic potential is 2.7 TWh/year under the Vega (2012) cost assumption and nothing under the Lockheed Martin cost assumption. Similarly, for the out-stations, the stations only hold the economic potential of 113 TWh/year under Vega (2012) cost assumption and nothing at all under the Lockheed Martin cost assumption.

Discussions on the thesis at it is and the recommendation to foster OTEC implementation can be found in Chapter 6. The discussion part includes the validation of the results, the reflections and refinements of the methodology, the limitations of the research, and the added value and broader relevance of the study. In addition, it discusses the selection of the ocean energy technology type. The recommendations are directed towards different actors of OTEC. First, for the academia in form of research topics ideas. The other recommendations are for the energy industry and for the government of Indonesia.

Lastly, the answers to the research questions are offered in Chapter 7. It can be concluded that on the national level, the economic potentials of both cost assumptions are more than enough to fulfil the total electricity demand of the country. However, a big part of the potential lies outside the provincial boundaries, far away from demand centres, rendering them not economically feasible to be used. Hence, it is not possible to fully supply the electricity demand on the provincial level in Indonesia solely by OTEC electricity production of the selected stations.

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1. Introduction

1.1 Background

As the fourth biggest population in the world, Indonesia has an extremely high demand of energy (Sekretariat Jenderal DEN, 2015). In fact, it has the largest energy consumption in Southeast Asia (IRENA, 2015). Yet, the amount of energy consumption does not reflect the 'energy trilemma' that Indonesia faces. This problem needs to be solved by providing energy security, tackling energy poverty, and mitigating climate change all at the same time (Gunningham, 2013). Fossil fuels such as coal, oil, and natural gas still hold their position as the most prominent energy sources up until today. Albeit being an oil producer and exporter, Indonesia is a net importer of oil (IEA, 2017; Schaffartzik, Brad, & Pichler, 2017), implying the country's dependence to other countries support on energy sufficiency. Adding complexity to the problem Indonesia has, its archipelagic geographical condition makes it hard to distribute energy evenly across the nation (IEA, 2017). People living in rural areas or islands far from the capital suffer from lack of grid access and sky-rocketed fuel prices (Blum, Sryantoro Wakeling, & Schmidt, 2013). Besides, with most of the people in Indonesia live along its coastlines, the country is susceptible to the effects of climate change. Impacts such as more intense storms, extreme droughts, and sea level rise (UNFCC, 2005) are already happening throughout the country.

With this problem in mind, increasing the renewable energy share within total primary energy supply (TPES) of the country is crucial. It can help by securing the energy supply, enabling decentralised electricity generation, and leaving less carbon footprint compared to fossil fuels plants. Nevertheless, integrating renewable energy technologies into the electricity market is not without challenges. The first question one might ask is what kind of renewables is more suitable for electricity generation in Indonesia. Taking the archipelagic geographical condition of Indonesia into account, ocean energy technologies such as tidal energy, wave energy, and ocean thermal energy conversion (OTEC) sounds like a good option. Based on a report issued by the Indonesian Ocean Energy Association (INOSEAN), the theoretical potential of ocean energy technology resources reached 727 GW (Quirapas et al., 2015). Interestingly, this number seems to be an extreme underestimation, as a study by Chalkiadakis (2017) shows that in Indonesia the practicable potential of OTEC alone accounts for 600 GW. In light of the vast potential, OTEC strikes as the best technology to be assessed further.

OTEC uses the temperature difference between warm surface water and the colder water at depth to generate electricity. The concept is similar to any other Rankine cycle, in which a working fluid is vaporised to turn a turbine connected to a generator. This technology is very potential to be deployed in tropical countries along the equator, due to the high temperature of the surface water (Vega, 2012). The working principle of OTEC is not newly discovered. In fact, it has been around for more than one century. It started when Jules Verne published an idea of using the thermal difference to generate electricity in 1870. Then in 1881, Jacques D'Arsonval proposed the closed-cycle system, followed by Georges Claude in 1931 who suggested the open-cycle using the sea water as the working fluid (ibid.). Their system proved to be working, but until today, there are no commercial OTEC plants in the world. Here come the next questions, why is this the case and what exactly does *potential* mean?

As mentioned before, there are different types of potential namely theoretical, technical, practicable, economic, profitable, market, and policy-enhanced market potential. The theoretical potential accounts for the energy that can be generated by a resource if only physical limits are exercised. The technical potential is obtained by considering the technical constraints of the technology, for example, a minimum temperature difference of 20°C for an OTEC plant. The practicable potential is the amount of energy available if aspects such as distance from the shore and population density at demand centres are considered. The economic potential is the part of the practicable potential that is economically feasible to access (Blok & Nieuwlaar, 2017). The profitable potential, market potential, and policy-enhanced potential are well beyond the scope of this thesis and will not be addressed further.

1.2 Problem Statement and Research Questions

This thesis is meant to continue the work of former students, Chalkiadakis (2017) and Langer (2018). In his thesis, Chalkiadakis calculated the technical potential of OTEC throughout the whole world and highlighted the most suitable countries for OTEC application. Langer continued by constructing supply curves in each suitable country and by projecting the result to the global level to obtain the global economic potential. In Langer's study, the economic potential of OTEC in Indonesia has been studied as a part of a worldwide scale study. However, there is no assessment explicitly directed to fulfil the real demand of Indonesia. This leaves a knowledge gap for a master's thesis under the Sustainable Energy Technology (SET) programme at Delft University of Technology on the assessment of the economic potential of OTEC in Indonesia. Based on the knowledge gaps detected in the literature review, the main research question and sub-questions are formulated as follows:

What are the national and provincial economic potentials of ocean thermal energy conversion in relation to the provincial electricity demand fulfilment in Indonesia?

1. What is the most suitable methodology to assess the economic potential of OTEC?
2. What are the economic potentials of OTEC on national and provincial levels in Indonesia?

3. What are the possible electrification scenarios to fulfil provincial electricity demands solely from OTEC production and what are the economic potentials?
4. What are the recommendations to foster OTEC implementation?

1.3 Research Objective

The research aims to serve as support to the government's efforts in embedding the use of ocean energy within Indonesia's energy mix. It is in line with one of SET's goals, to help integrate new energy technologies into existing networks through energy market restructure. Through gained knowledge on its economic potential, OTEC could be one of the important aspects in rising electrification ratio and renewables mix within the energy landscape in Indonesia.

1.4 Thesis Outline

This thesis comprises 7 chapter and is structured as follows:

Chapter 2 gives a review of existing studies on ocean energy in Indonesia, the techno-economic of OTEC, and the use of geographic information system as a tool for renewable techno-economic analysis

Chapter 3 discloses the methodology of the determination of areas with OTEC economic potential, the procedure of the sensitivity analysis, and design of the electrification scenarios.

Chapter 4 presents the results of the determination of areas with OTEC economic potential, both on national and provincial level, and the outcome of the sensitivity analysis.

Chapter 5 displays the results of the three electrification scenarios, i.e. electrification with resources within the province boundaries, with scaled-down plants, and with resources beyond the province boundaries.

Chapter 6 exposes the discussion on the research at it is and the recommendations to foster OTEC implementation in the future.

Chapter 7 reveals the answers to research questions.

2. Literature Review

2.1 Renewable Energy from The Ocean in Indonesia

As of 2015, the total installed capacity of renewable energy power plants only accounts for around 7 GW, or 6% of TPES (Purwanto et al., 2015) with mainly hydropower installed (Mappangara & Warokka, 2015). Renewable energy suits Indonesia's geographical condition best as it allows for distributed power generation with decentralised power grids (PwC Indonesia, 2017; Schaffartzik et al., 2017). Several matters hinder the realisation of renewable energy, the most important ones being the lack of financial and fiscal incentives, decentralised governance power, and complicated power division between energy sector stakeholders (Gunningham, 2013; Mappangara & Warokka, 2015).

Regardless of the hindrance, efforts and measures are being taken. The government has introduced feed-in tariffs (FIT) for renewable energy resources (Kumar, 2016), targeted renewable energy to account for 23% of TPES in 2025 in Presidential Decree No. 5 2006, and applied tax concessions for renewable energy projects in Ministry of Finance Regulation No. 24/PMK.011/2010, Indonesia has potential to utilise hydropower, geothermal, solar energy, biomass, wind, (Dutu, 2016; Hasan, Mahlia, & Nur, 2012; Mappangara & Warokka, 2015; Purwanto et al., 2015; Tasri & Susilawati, 2014) and MET (Mujiyanto & Tiess, 2013). Plans and scenarios for this transition are constructed to analyse the most appropriate renewable energy to be implemented (Mujiyanto & Tiess, 2013; Sugiyono et al., 2016; Tasri & Susilawati, 2014), but these omit ocean energy in the design. This omission is unfortunate as the application of ocean energy technologies would aid coastal communities, especially in remote islands, who have limited or even no access to other energy services (Siswandi, 2017).

In Indonesia, various kinds of ocean energy, such as the tidal stream, sea wave, tidal, OTEC, and offshore wind, account for 727 GW of theoretical potential (Quirapas et al., 2015). Despite the fact that MET is yet to be employed in Indonesia, its potential is highly recognised by the government and scientific community. It is apparent in the number of publications concerning the matter both internationally and nationally, as registered in Table 2.1.

Table 2.1. Existing Research on Ocean Energy in Indonesia

Author	*Energy Source*				*Research Type*		
	Tidal Stream	Wave	OTEC	Tidal Barrage	*Theoretical Potential*	Practicable Potential	Energy Converter
Rachmayani et al. (2006)	▪				▪		
Nugraha & Rijanto (2010)	▪						▪
Wijaya (2010)		▪			▪		▪
Aiki et al. (2011)		▪			▪		
Yuningsih (2011)	▪				▪		
Yuningsih & Masduki (2011)	▪				▪		
Prabowo (2012)	▪	▪	▪		▪	▪	
Maulani et al. (2012)				▪	▪		
Blunden et al. (2013)	▪				▪		
Darmawi (2014)	▪						▪
Aryono et al. (2014)	▪				▪		
Irhas & Suryaningsih (2014)		▪			▪		
Yosi (2014)	▪	▪	▪		▪	▪	
Sandro et al. (2014)	▪	▪			▪		
Purba et al. (2014)	▪				▪		
Handoyo et al. (2015)				▪	▪		
Muhammad et al. (2015)			▪				▪
Riyanto (2015)			▪		▪		
Ihsan et al. (2015)	▪				▪		
Orhan et al. (2015)	▪				▪	▪	
Purba et al. (2015)	▪	▪		▪	▪		
Quirapas et al. (2015)	▪	▪	▪		▪		
Syamsuddin et al. (2015)			▪		▪		
Sutopo (2015)	▪				▪		
Orhan et al. (2016)	▪				▪		
Alifdini et al. (2016)		▪			▪		
Mustain & Suroso (2016)	▪						▪
Rahmawati et al. (2016)	▪				▪		
Alifdini et al. (2017)		▪			▪		
Sugianto et al. (2017)		▪			▪		
Ajiwibowo et al. (2017)	▪				▪		
Rompas et al. (2017a)	▪				▪		
Ribat et al. (2017)	▪				▪		
Wijaya et al. (2017)		▪					▪
Chalkiadakis (2017)			▪		▪	▪	
Rompas et al. (2017b)	▪				▪		

The literature shows that ocean energy is still at an early development stage, with the studies predominantly being limited to preliminary assessments of specific sites without considering practicability or economic aspects. For example, Blunden *et al.* (2013) assessed the initial estimation of tidal current only in Alas Strait while Irhas & Suryaningsih (2014) considered wave energy conversion at the south coast of Yogyakarta. Several studies were conducted on the national level, using mapping methods, for instance by Yosi (2014), Quirapas *et al.* (2015), and Purba *et al.* (2015). However, almost all research regards to the theoretical potential, with the exception of Prabowo (2012), Yosi (2014), Orhan *et al.* (2015), and Chalkiadakis (2017), all of whom mentioned the practicable potential estimation. Unfortunately, in Prabowo (2012) and Yosi (2014), it is unclear what they meant with 'technical' and 'practical' potentials, rendering the information rather dubious.

From the vast array of studies conducted on ocean energy in Indonesia, only a handful of them discusses OTEC in Indonesia. Prabowo (2012) and Quirapas et al. (2014) mentioned the total theoretical, technical, and practical potentials of OTEC throughout the country. Both publications cite the values issued by INOSEAN. Yosi (2014) listed the potential areas for OTEC alongside the potentials. Nonetheless, as stated before, there is no clear indication of what is meant by technical and practical potential in those publications nor a pronounced method or formula to get the values. Syamsuddin et al. (2015) researched the OTEC potential of many locations in Indonesia. Yet, the final result is only the Carnot efficiency of those locations instead of the possible power or energy produced. Similarly, Riyanto (2015) also calculates the efficiency but on a smaller local level. Muhammad et al. (2015) focus on the power generator operation efficiency. In sum, none of these studies really gives reliable information on the potential of OTEC in Indonesia. Fortunately, there are two very recent works that actually computes and analyses the technical and economic potential of OTEC in Indonesia, albeit as a part of a global scale. The theses of Chalkiadakis (2017) and Langer (2018) are the direct predecessors of this thesis. Chalkiadakis analysed the technical potential and the most suitable countries for OTEC worldwide while Langer continued by computing the economic potential for those suitable countries.

2.2 Techno-Economics of OTEC

2.2.1 Basic Overview of OTEC

OTEC is a way to harness the thermal solar energy in the sea by using the temperature difference of the warm surface water and the cold deep water of the sea. OTEC works best in the equatorial zone where the temperature gradient of at least 20°C can be achieved throughout the year. The working mechanism of OTEC is very similar to that of a geothermal energy plant, i.e. using a steam turbine to generate electricity. The warm surface water, which has the temperature of around 27°C, vapourises a working fluid with a low boiling point. The working fluid used is usually ammonia, although the use of propylene and other refrigerants are also considered. The vapour expands and spins the turbine that is coupled to a generator, producing electricity. The vapour is then cooled by cold deep-sea water from the depth of 1000 m, with the temperature as low as 4°C. That way, the working fluid condenses back into a liquid and can be reused again, resulting in a continuous electricity generation cycle (Bluerise, 2014; Kempener & Neumann, 2014; Nihous, 2007; Vega, 2012). The working principle of closed-cycle OTEC is presented in Figure 2.1.

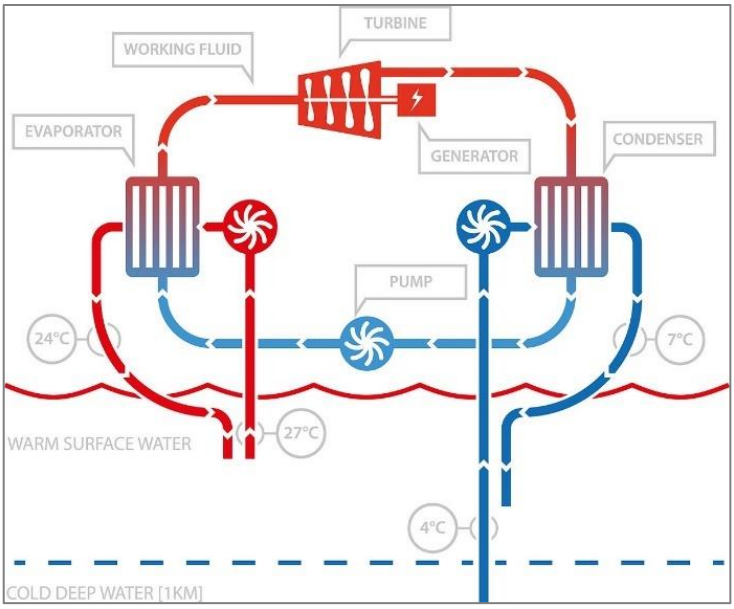


Figure 2.1. Closed-cycle OTEC Working Principle (Bluerise, 2014)

Aside from closed-cycle OTEC, there are also open-cycle versions, in which the seawater itself is used as the working fluid. Warm water from the surface is pumped into a low-pressure compartment. The low pressure allows the water to boil at a lower temperature, giving way to flash evaporation that turns a part of the sea water into steam. The steam expands through a generator, generating electricity. The steam is then condensed by using the cold sea water. There are two ways to condense the working fluid.

The first one is called direct contact condensation (DCC). In this system, the vapour is condensed by spraying cold sea-water (Masutani & Takahashi, 2001; Vega, 2012). DCC system is relatively cheap and enables good heat transfer, but as the sea-water is added directly to the vapour, this system does not allow the plant to produce desalinated water (Masutani & Takahashi, 2001). The second way uses surface condensation, where the cold sea-water is not sprayed directly to the vapour. This system, albeit more expensive, allows for a desalinated water by-product (Masutani & Takahashi, 2001; Vega, 2012).

As an electricity producer, OTEC possesses many advantages. First, with its ability to continuously produce electricity, it can serve as a base-load provider. In this matter, OTEC is far superior compared to the intermittency of wind and solar energy (Dessne, 2015). Second, except for the reusable working fluid, OTEC does not need any external fuel to be operating. This removes the fuel price volatility from the equation and reduces carbon emission from burning fossil fuel starkly (Banerjee, Duckers, & Blanchard, 2015). Third, by varying the configuration of the plant, an OTEC plant can provide more than just electricity. For example, by employing an open-cycle OTEC with surface desalination, freshwater can be produced. The production of freshwater might be especially vital in islands which face water scarcity. The cold water from the depth can also be circulated as a chiller fluid for cold storage or air conditioning. In addition, as the water from the depth is rich with nutrition, mariculture farming can be engendered by OTEC (Banerjee et al., 2015; Kempener & Neumann, 2014; Osorio et al., 2016; Vega, 2012).

The last advantages might provoke a question in mind of how close the plant is to the shore as the plants need to be close enough to a population centre to allow the distribution of the freshwater and the cold water for cooling. Obviously, these could only apply for onshore OTEC platform. Nevertheless, there are other configurations e.g. shelf-mounted plant and offshore (or floating) plant (Chalkiadakis, 2017). Each type of instalment has its own drawbacks and benefits that is explained in the next section.

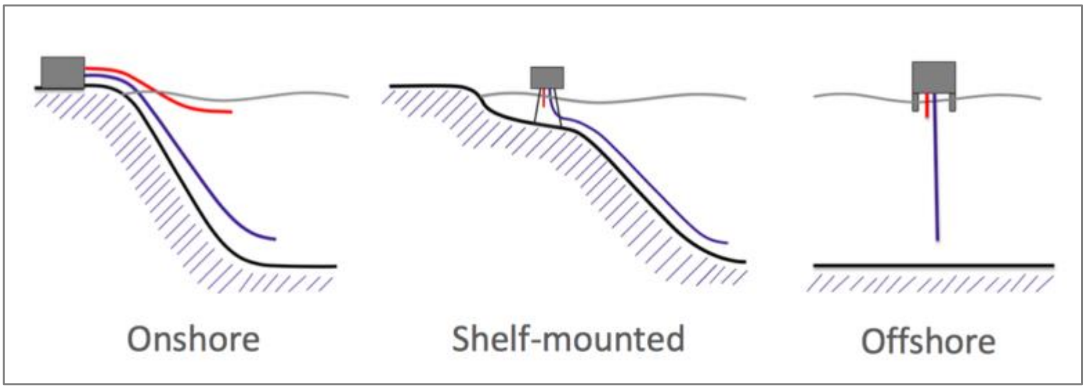


Figure 2.2. Different OTEC Platform Configurations
red line: warm water pipe and blue line: cold water pipe (Chalkiadakis, 2017)

2.2.2 Siting Criteria and Spacing Concerns

Although the sea covers two-thirds of the world, it does not mean that OTEC plant can be located just anywhere. Certain siting criteria need to be fulfilled before one can consider building an OTEC plant in a particular spot. An OTEC plant needs to be located at a favourable location in order to extract most of the useful ocean thermal energy. The first thing to be considered is the temperature difference between the surface and the deep water. It is because OTEC in general is working solely based on the water temperature. The higher the difference between the surface water and the deep water, the higher the potential of ocean thermal energy. The typical rule of thumb is that a difference of 20°C is needed to make the energy extraction possible. This temperature difference usually occurs in deep seas along the equator, where the surface water temperature can reach 26-28°C and the temperature of water at 1000 m depth is relatively constant at 4°C (Kempener & Neumann, 2014; Masutani & Takahashi, 2001; Vega, 2010). The potential areas in the world can be seen in Figure 2.3.

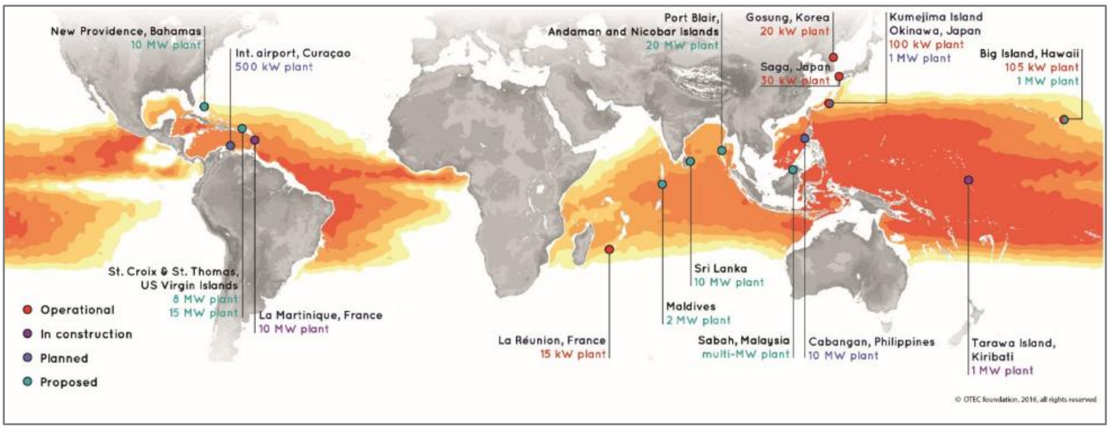


Figure 2.3. Potential Areas and OTEC Projects Around the World

The siting of OTEC plants must also take into account the market demand. It has to be within reach to a population centre with the electricity demand matching the size of the plant (Vega, 2010). Chalkiadakis (2017) and Langer (2018) use the population density and population number to define whether a population centre is suitable for OTEC. In addition, the vast volume of water involved in the operation might leave unwanted effect on the surrounding area. The discharged water's temperature is lower than the surface temperature and may cause a reduction in ocean surface temperature. The change in water temperature may have local weather effect and may degrade the performance of nearby OTEC plants. This issue can be avoided by regulating the cold water flow rate (w_{cw}) and the spacing between plants. The cold water flow rate, expressed in m/year is the rate of water in the sea moving upwards towards the surface. Chalkiadakis (2017) argues that it is relatively safe to use the w_{cw} of 175 m/year with the spacing of 20 km.

2.2.3 Costs Factors

In order to determine the economic potential of OTEC, one must have the knowledge of the economics of state-of-the-art OTEC. Within the literature review, the system in discussion is only offshore, closed-cycle OTEC, while the other configurations are not being presented due to lack of data. As mentioned in the previous section, onshore plants show multiple advantages as they are located very close to the population. It is also very convenient to distribute the electricity and freshwater to the market from onshore plants. However, there are some significant drawbacks of onshore plants. The first is that an onshore plant needs a longer cold water pipe (CWP) than an offshore plant. An offshore plant only needs a pipe with the length of 1000 m directly to the deep sea. On the other hand, to cater to an onshore plant's need, the pipe needs to travel first to the point where the sea is deep enough. This will result in extremely high costs. Additionally, the length of the pipe creates pressure losses and reduces efficiency. The second is that an onshore plant poses a more substantial disturbance to the environment, by risking thermal degradation of the sea water. The solution to avoid these effects is by discharging the warm water above the thermocline and the cold water below the thermocline (a region where the seawater temperature drops sharply) so that the impact of the discharge water on the seawater is minimised. This again results in long pipes, rendering the project economically and technically infeasible (Upshaw, 2012).

When one looks at the available literature regarding the costs of an OTEC plant, they will find that there is a wide range of cost available even on the same plant scale. It is evident, though, that the economies of scale have a significant impact on reducing the costs: they decrease with the increase of plant size. It has to be noted that most of the authors do not elaborate on the cost components. One of the few reports laying bare all the cost components is a report by Lockheed Martin (Lockheed Martin Mission Systems & Sensors, 2012a). Interestingly, compared to other studies, for instance by Vega (2010) and other scholars, the costs from Lockheed Martin are far higher. Langer (2018) creates scale curves comprising the cost estimations by Lockheed Martin (2012a), Vega (2010), and academia, presented in Figure 2.4. It's interesting how all the curves look similar. However, among the three curves, it is apparent that the costs vary quite remarkably, with the uncertainty up to 70 %. It is quite acceptable to say that the true OTEC costs lie between the grey and blue curves.

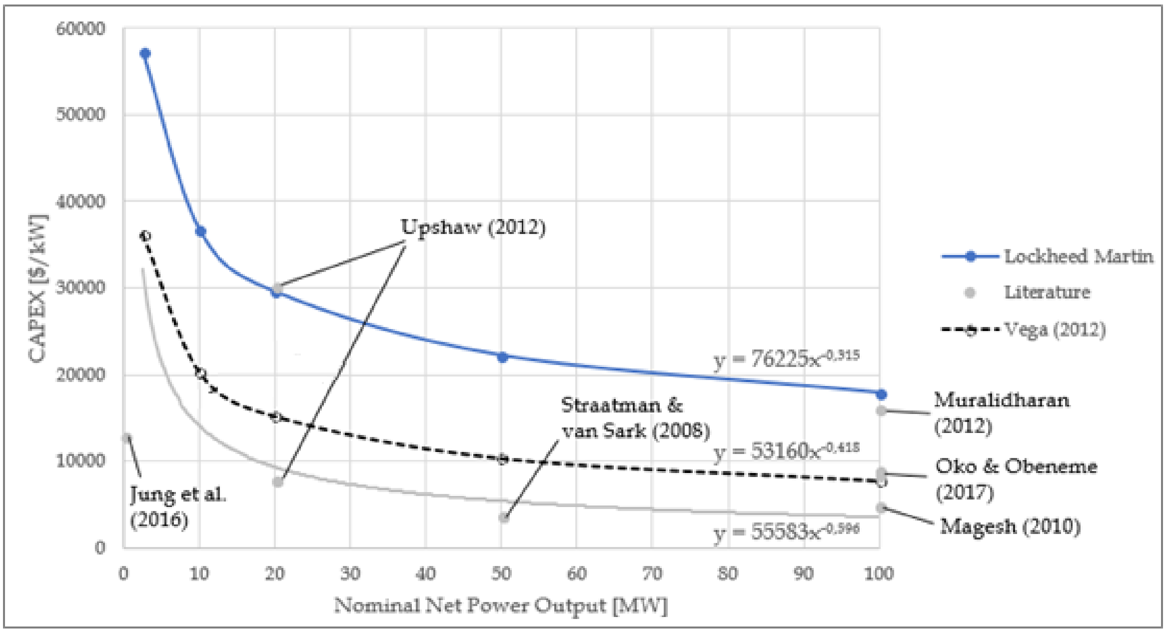


Figure 2.4. Scale Curve for Nominal OTEC Plants (Langer, 2018)

Similar to the capital costs, estimations of lifetime operation and maintenance (O&M) vary widely. Interested readers are invited to read the thesis by Langer (2018). There it is discussed at length the discrepancies of costs in the literature, where an agreement of a range of costs seems to be non-existent. Most publications present OPEX as a percentage of CAPEX, thus, it is understandable that the values vary following the value of the CAPEX. As a fraction of the CAPEX, the annual OPEX ranges from 1 % to 5 % (Banerjee et al., 2015; Bluerise, 2014; Lockheed Martin Mission Systems & Sensors, 2012a; Magesh, 2010; Muralidharan, 2012; Oko & Obeneme, 2017; Straatman & van Sark, 2008; Upshaw, 2012; Vega, 2010). The summary of OTEC costs in literature can be found in Table 2.2.

Table 2.2. OTEC Economics Summary

Author	CAPEX (million €)	OPEX (% CAPEX)	Plant Size (MW)	Assumptions
Upshaw (2012)	144 – 533.4	5	20	DR = 10%; CF = 70-90% Lifetime = 20 years
Straatman & van Sark (2008)	110	1.4	50	DR = 8-10%; CF = 90% Lifetime = 30 years
Plocek, Laboy, & Marti (2009)	600	n.a.	75	No aditional information supplied
Vega (2012)	780	5	100	DR = 8%; CF = 92.3% Lifetime = 20 years
Oko & Obeneme (2017)	795	2	100	DR = 13% Lifetime = 25 years
Magesh (2010)	420	1	100	DR = 10% Lifetime = 30 years
Muralidharan (2012)	1400	3.2	100	DR = 7.4%; CF = 95-97% Lifetime = 30 years
Banerjee, Duckers, & Blanchard (2015)	145	1.5	100	DR = 8%; CF = 80% Lifetime = 30 years
Lockheed Martin (2012a)	1400	3	100	DR = 4%; CF = 92% Lifetime = 30 years

DR = discount rate, CF = capacity factor

2.3 Geographic Information System for Techno-Economic Analysis of Renewable Energy

As mentioned in Chapter 1, a modelling approach is chosen to answer the research questions as gaining data from field measurements is not possible. In the scope of this research, the model serves the purpose of prediction, i.e. predicting the value of a system variable in a particular period based on known variables in the same period. (Kelly et al., 2013). Modelling allows the predictions of MET potential locations and the magnitude of economic potential based on the base data. From the perspective of space and time, grid-based spatial modelling and transient modelling will be exercised. A station-based spatial model means that the research area will be divided into uniform grids where each station on the corner of the grids has its own variable value. A transient or discrete temporal model denotes that the output of the model will have relation with time, but only covering a single time period rather than a time series.

A geographic information system (GIS) is defined as "a computer hardware and software system designed to capture, edit, manage, house, manipulate, analyse, and display georeferenced data" (Griffith & Chun, 2018, p. 1). The use of GIS enables integrating an array of environmental features, technical criteria, and economic criteria (Sliz-Szkliniarz & Vogt, 2012) by setting the data in a spatial-based (Artz & Baumann, 2009). In the recent years, the GIS approach has been used for assessment of both technical and economic potential of renewable energy (Sliz-Szkliniarz & Vogt, 2012) from local to regional analyses (Mentis et al., 2016a). The utilisation of GIS in this subject has increased quite considerably as its adequacy of energy analysis functions has been proven (Li, 2018). This method will be exercised to answer sub-question 3, which focuses mainly on maps as the sub-deliverables.

According to Artz and Baumann (2009), there are five steps in the geographic method. The five steps are *Ask*, *Acquire*, *Examine*, *Analyse*, and *Act*. The explanation of each step as follows:

1. *Ask* : defining the problem that will be tackled with the geographic approach
2. *Acquire* : determining the data needed for the analysis, which includes in the process defining the scope of the analysis and finding or generating the data
3. *Examine* : examining the data in hand to ensure it is appropriate for the analysis, including checking whether the data is well organised and matched to other datasets, as well as monitoring the background of the data
4. *Analyse* : processing and analysing the data with the help of GIS tools, this research uses ArcGIS
5. *Act* : presenting the result of the analysis in the form of maps and reports

These steps are followed carefully throughout the study. However, the presentation of each step is not strictly divided as it is used in combination with the steps of techno-economic analysis of renewable energy resources.

In order to get the economic potential of OTEC, a techno-economic analysis of renewable energy resources is exercised. A techno-economic analysis of renewable energy concentrates on energy system characterised by the availability of renewable energy sources and the energy conversion processes within the energy markets (Mentis et al., 2016a). According to Blok and Nieuwlaar (2017), the process consisting of three steps:

1. Analysis of resource availability areas
2. Characterisation of sites by identifying the physical constraints and economic parameters
3. Calculation of potentials

These steps are embedded within the spatial domain with the help of the GIS tool. The first step will be done by constructing a map of technical potential of MET in Indonesia. Afterwards, boundaries and parameters are defined to define the economic potentials. Included in this step is the calculation of the levelized cost of electricity (LCOE) of MET. In the third step, results from the previous step are applied and the economic potential is then calculated. This analysis will be embedded in the spatial domain by using the GIS method.

A very similar approach of combining the two methods has been used successfully before for different types of renewable energy resources. The most common energy to be analyzed with this method is wind energy. Cavazzi and Dutton (2016) and Nagababu et al. (2017) did the analysis for offshore wind energy in the United Kingdom and India respectively. Hoogwijk et al. (2004) assessed the potential of onshore wind energy worldwide and Mentis et al. (2016b) did the investigation in India. Besides the wind energy, Vazquez and Iglesias published articles on the LCOE mapping and the selection of energy hotspots for tidal energy in the Bristol Channel, United Kingdom (Vazquez & Iglesias, 2015, 2016). The methodology can also be used for multiple energy resources at once, as done by Blechinger et al. (2016) who analyzed the techno-economic potential of renewable energy hybrid systems on small island worldwide.

2.4 Conclusion of The Literature Review

There are already many studies in Indonesia about renewable energy from the ocean yet, only a few of them discuss the potential of OTEC in Indonesia. This study is a continuation of two studies done in the last two years by former TU Delft students. In those studies, the practicable and economic potentials of OTEC in Indonesia are analysed as a part of global level studies. Up until today, there are no commercial OTEC plants available yet. This causes the costs values quoted in literature to vary considerably. As a further outcome, three different scale curves of CAPEX/kWh against nominal net power output are available. It is reasonable to claim that the real OTEC costs will fall between the highest and lowest curves. With the high uncertainties, the two top curves are used as the base cost values in this thesis. The combination of the GIS and the techno-economic analysis methods is proven to be useful in determining the potential of various renewable energy types. Hence, this research employs the same methodology.

3. Methodology

As concluded in the previous chapter, the combination of the GIS and techno-economic analysis methods can be useful to determine the economic potential of OTEC. In this chapter, the methodology is elaborated further, along with the parameters used in the calculations. The chapter starts with an overview of the methodology, followed by the data gathering and pre-processing description. Then, the methods of calculating LCOE and the economic potential as well as the parameters used are described. Next, the procedure of the sensitivity analysis is explained. The chapter closes with the setup for the three electrification scenarios.

The methodology of this thesis is designed to be reproducible easily for analysing the economic potential of OTEC, or even other types of renewables with slight modifications, in different locations. It follows the steps of the GIS method while incorporating the steps of the techno-economic analysis at the same time. The stages taken in this thesis are as follow:

1. Defining the problem
    a. Choosing the location to be analysed
    b. Choosing the type of renewable energy resource
2. Gathering and pre-processing the data
3. Determining the potential areas
    a. Assigning the economic parameters
    b. Computing the LCOE
    c. Calculating the economic potential
4. Building the electrification scenarios
    a. Selecting the stations to be used
    b. Enumerating the economic potential of the selected stations
5. Presenting the results through maps, tables, and graphs
6. Establishing the conclusions of the research

Each of these stages is correlated to the steps of the GIS and techno-economic methods discussed in Chapter 2. These stages also dictate the content of this thesis. An overview of how everything is related is presented in the research flow diagram (Figure 3.1). In the diagram, the steps of techno-economic methods are not included as they are all correlated to the *Analyse* part of the GIS method.

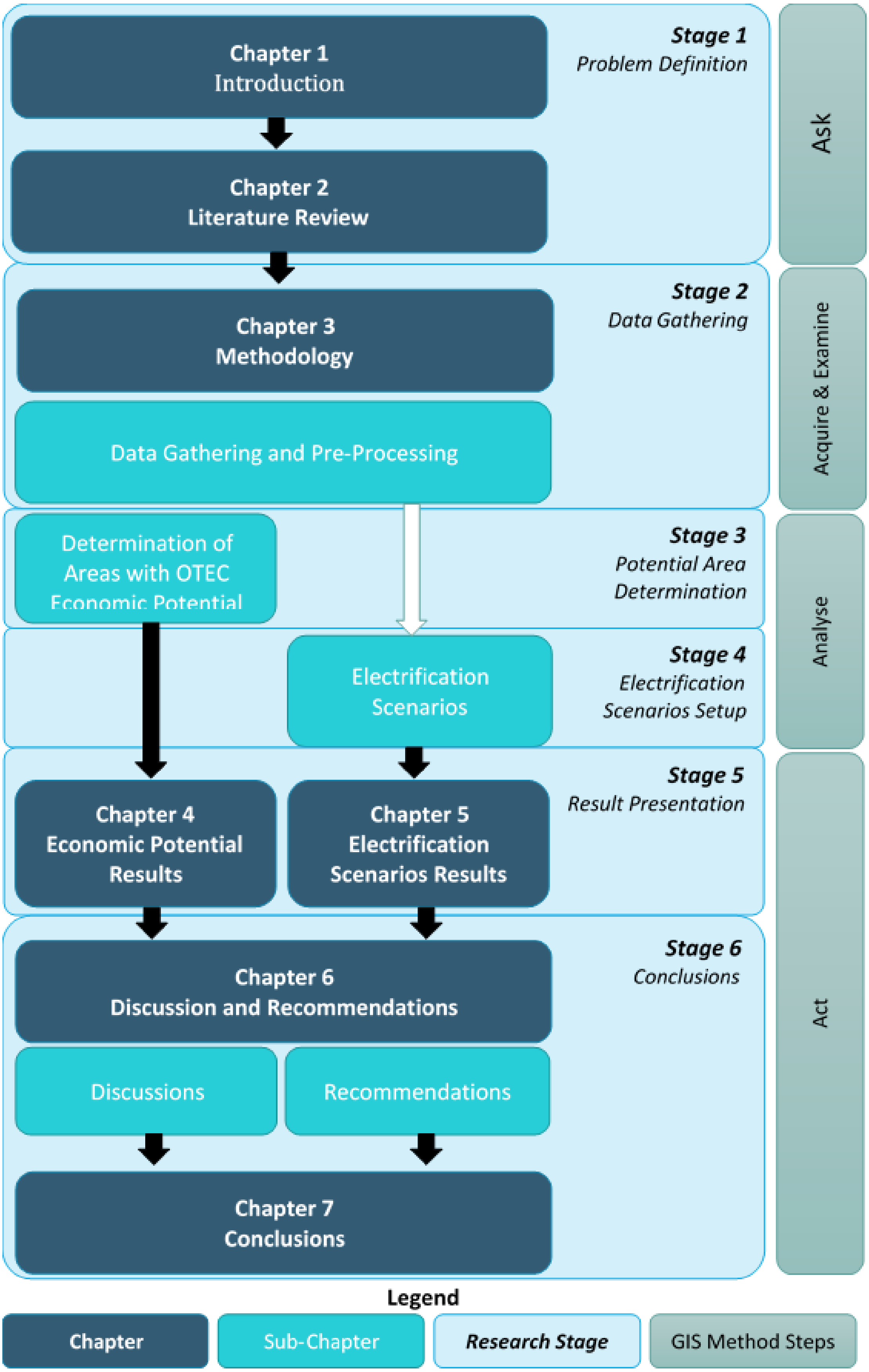


Figure 3.1 Research Flow Diagram

3.1 Data Gathering and Pre-Processing

There are three groups of data used in this research, i.e. geographical data, ocean characteristic data, and socio-economic data. The geographic data mainly comprises the boundaries of Indonesia, both the frontier line of the exclusive economic zone (EEZ) and borderlines of provinces inside the country. The EEZ map is needed as all OTEC plants are designed to be deployed within the area. The map was made with the help of ArcGIS and a map of Indonesia published by the government through the geospatial agency (BIG, 2017). The provinces boundary map consists of both the land and sea boundaries, downloaded from the OpenStreetMap website (OpenStreetMap, 2018). These boundaries are used for the regional implementation scenario. In addition to these maps, a map of marine protected areas (MPA) is also used to rule out those areas from the potential areas. The map of MPA was made with ArcGIS from the map published by the Ministry of Fisheries and Marine Affairs (Direktorat Konservasi Kawasan dan Jenis Ikan, 2013).

As it is impossible to do a field examination to measure the values of ocean characteristic in the whole country, another source of ocean characteristic data was used in this research, i.e. data from Hybrid Coordinate Ocean Model (HYCOM). HYCOM is a consortium supported by the National Ocean Partnership Program (NOPP), a part of the U.S. Global Ocean Data Assimilation Experiment (GODAE). HYCOM provides access to the output of near real-time global HYCOM- and NCODA-based ocean forecast system (HYCOM, n.d.). Favourably, an ocean general circulation model should

1. keep its water mass characteristics for centuries (an aspect of isopycnic coordinates),
2. have a high vertical resolution in the surface mixed layer (a feature of z-level coordinates) for proper representation of thermodynamic and biochemical processes,
3. maintain sufficient vertical resolution in unstratified or weakly-stratified regions of the ocean,
4. have a high vertical resolution in the coastal regions (a characteristic of terrain-following coordinates).

By using the hybrid coordinates, HYCOM strives to achieve all these through combining the superiority of various types of coordinates to simulate coastal and open-ocean circulation in the best way (Halliwell, 2002). The temperature data is downloaded with the setup as in Table 3.1.

Table 3.1. HYCOM Download Setup

Element		Value
Dataset		HYCOM + NCODA Global 1/12 Degree Analysis/GLBa0.08/expt_91.2/2017 Data: Jan-01-2017 to Dec-31-2017/Data at 00Z (temp)
Coordinates	West	92°
	East	142°
	North	7.5°
	South	-14°
Horizontal Stride		3
Time Range	Start	01-01-2017
	End	31-12-2017
Vertical Level	Surface	Single level 0 m
	Deep	Single level 1000 m

The 'Horizontal Stride' setup determines the distance of each station point, i.e. 0.24° or around 27.5 km from each other. It is assumed that each station will only be occupied by one single OTEC plant. It means that the distance between each OTEC plant will be slightly closer than 32 km recommended by Chalkiadakis (2017). This distance was calculated by taking into account the cold-water intake flow from the ocean depth, as to not disrupt the temperature of the whole ocean. However, this is still debatable as there is yet no way to measure the area from which an OTEC plant takes the cold water. Hence, for the sake of simplicity and with the difference of only 4.5 km, the assumed distance of 27.5 km stands.

The downloaded data is extracted by using *Ocean Data View* (ODV) software and brought to ArcGIS to remove the stations lie beyond Indonesia's exclusive economic zone (EEZ). By using MATLAB, first, the daily data is turned into monthly averages. Then, the temperature difference of each station is computed and stations with a temperature difference of less than 20 °C are omitted from further calculations. The socio-economic data consist of the costs needed to build an OTEC plant, population density data, current electricity demand and production data. The costs data is taken from previous publications from both academic and industrial sides, i.e. from Vega (2012) and Lockheed Martin (2012a) respectively. The demand centres are determined by choosing cities with a high population. The population data is obtained from Statistics Indonesia (Badan Pusat Statistik, 2017). Lastly, the data on demand and production of electricity are gathered from the national electricity statistics (Dirjen Ketenagalistrikan, 2017).

3.2 Determination of Areas with OTEC Economic Potential

3.2.1 LCOE Calculations

The economic potential of a renewable energy is assessed by calculating the levelized cost of electricity (LCOE). LCOE is a widely used parameter for this purpose, including for ocean energy technologies (OES IEA, 2015). The formula for LCOE calculation is taken from Lockheed Martin (2012a) as follows. A station is said to be economically potential for OTEC if the LCOE is below 0.20 €/kWh.

$$LCOE = \frac{CRF\ (CAPEX + \sum_t^T (1+r)^{-t}\ OPEX_t)}{AEP}$$

where

CRF = capital recovery factor= $\frac{r}{1-(1+r)^{-T}}$

r = discount rate (%)

T = lifespan over which LCOE is being calculated (years)

CAPEX= capital expenditures, consists of fixed costs (system, fabrication, installation, environmental, and decommissioning costs) and variable cost (cable cost)

$OPEX_t$ = operation and maintenance expenditures at year t since deployment

AEP = annual energy production

There are different nominal sizes of plants being used in the analysis, i.e. the 100 MW standard sized plant and the 25 and 50 MW scaled-down plants. Each of these scales have different CAPEX, OPEX, cable costs values, and real power output. Hence, the description of the cost factors and the real power output come after the general parameter such as the discount rate, lifetime, annual energy production (AEP), distance determination, and cable efficiency.

This study assumes that the lifetime of the OTEC plants reaches 30 years. The value is chosen based on the literature in Table 2.2, The capacity factor of the plants is assumed to be 92 %. In the literature, the discount rate used to calculate the LCOE of OTEC plants ranges from 4 to 13 %. This thesis employs the discount rate of 10%, in accordance to the suggested values by the World Bank and the Asian Development Bank (Langer, 2018). The annual energy production is computed with the following formula:

$$AEP = P_{output} \cdot n \cdot L_{cable} \cdot cf$$

where

P_{output} = net power output

n = number of hours in a year

L_{cable} = cable efficiency (%)

cf = capacity factor (%)

The cable efficiency can be computed with the following function of 132 kV cable efficiency versus distance to shore (Langer, 2018; Lockheed Martin Mission Systems & Sensors, 2012a) with the corresponding graph shown in Figure 3.2.

$$L_{cable} = (-0.0002\ D^2 - 0.0199D + 99.971)$$

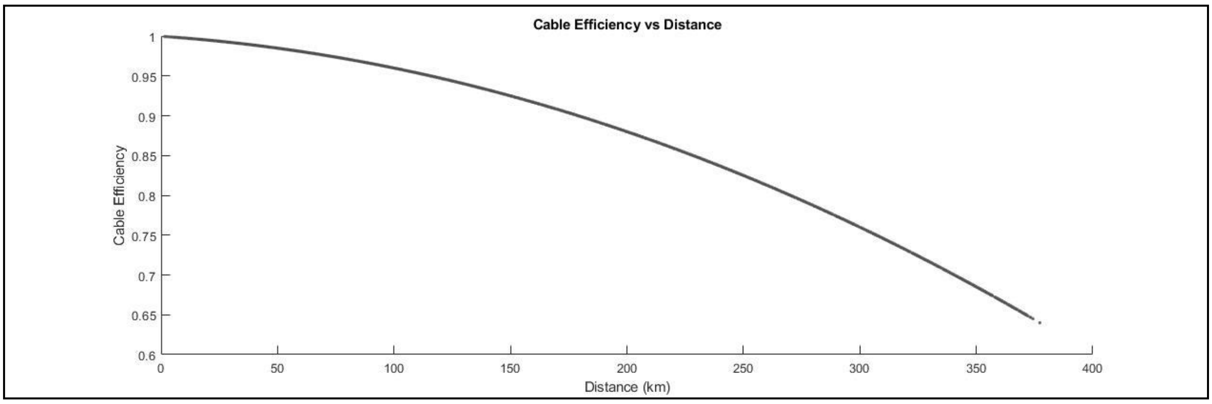


Figure 3.2. Correlation between Cable Efficiency and Distance for 132kV Cable (based on an extrapolated function by Langer (2018))

The letter D in the cable efficiency equation stands for distance in km. From the figure it is apparent that with the increasing distance, the cable efficiency drops considerably, leading to less power being delivered to the shore. Aside from affecting the cable efficiency and the energy production, the distance is also an important parameter in determining the cable cost. As all these in the end influence the LCOE, the determination of distance become very crucial and the increase of the distance is undesirable.

Now, how to decide the definition of distance? Is it the closest distance to *any* shoreline or is it the distance to a demand centre? In this thesis, both are employed by the help of ArcGIS tool. The first one is calculated by taking the shortest distance from the station to any shoreline. This method is very simple, and it can serve as a display of the best case where all shores are inhabited. The drawback of this method is that it does not adhere very well to the real-life situation. The second way is by measuring the distance from the station to a demand centre. This method is employed as it is ought to represent the real condition better. It has to be noted that this method disregards any on-land connection. In other word, the cable cost assumptions for the underwater and on-land portions of the distance are the same. It is kept this way to reduce complication in the cost calculation. Figure 3.3 shows the comparison of the different distances for two stations. For both stations, the distance increases considerably when it is adjusted to the demand centre instead of to the closest shore.

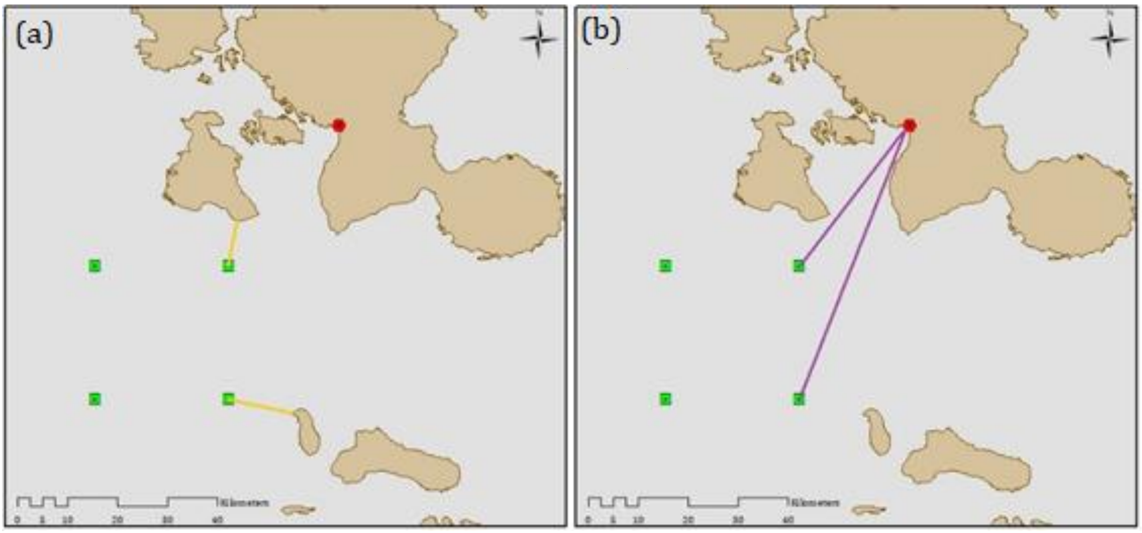


Figure 3.3. Distance Determination Comparison
(a) Closest distance to shore (b) Distance to demand centre

Calculations for 100 MW Nominal Plant

The standard size of the OTEC plants used in this thesis is 100 MW. It is chosen in accordance to the study by Langer (2018), which deemed Indonesia suitable for such large plant. The calculation of net power output is based on the report by Lockheed Martin (2012b), all the formulas below are in MW.

$$P_{gross} = 13.89\ \Delta T - 149.71$$
$$L_{fixed} = 42.7$$
$$L_{var} = 0.0038d + 4.488d\ (5.234 \cdot 10^{-10} d^3 - 1.378 \cdot 10^{-6} d^2 + 1.313 \cdot 10^{-3} d - 0.6541) \left(\frac{-0.00599 T_{surface}^2 + 0.031\ T_{surface} + 1025}{-0.00599\ T_{1000m}^2 + 0.031\ T_{1000m} + 1025} - 1 \right)$$
$$P_{output,100MW} = P_{gross} - L_{fixed} - L_{var}$$

where P is power, L is loss, T is temperature, and d is depth. Fixed loss factors include cold water intake power losses, condenser and distribution pumping losses, evaporator and distribution pumping losses, and ammonia pumping losses. Variable loss factors consist of cold water head loss due to pumping, cold water pipe friction loss, and static head loss. Interested readers are invited to consult the report for further explanation.

In this thesis, two nominals of both OPEX and CAPEX are being used. One comes from Lockheed Martin (2012a), representing the side of corporations, while the other one from Vega (2012) as the representative of academia. These costs of 100 MW nominal plant are presented in Table 3.2. All numbers are in 2018 Euro value, as a result of conversion from 2012 US dollar value.

Table 3.2. CAPEX and OPEX for 100 MW plant (in million Euros)

	Lockheed Martin (2012a)	Vega (2012)
CAPEX without cable	1144.3	780
OPEX per year	40.105	33.978

The CAPEX consists of fixed capital costs and a variable cost for the cable. The cost of cable (in million Euros) is a function of distance, as follows (Lockheed Martin, 2012a).

$$C_{cable} = 26 + 4.25\,D$$

Calculations for Scaled-Down Plants

Aside from the 100 MW nominal plants, other smaller-sized plants are also employed. However, the cost assumption for the scaled-down plants are not readily available. Hence, scale curves are used. Same as in the previous calculation, assumptions by Lockheed Martin (2012a) and Vega (2012) are used for the capital expenses. Lockheed Martin, however, does not provide any scale curve. The cost curve is constructed by Langer (2018) from the costs for different OTEC plant scales (2.5 MW, 100 MW, 200 MW, and 400 MW). The equations are as follow.

Lockheed Martin (by Langer,2018) $\quad y = 76225 \cdot x^{-0.315} \cdot z$

Vega $\quad y = 53160 \cdot x^{-0.418} \cdot z$

where

y = CAPEX ($\$_{2012}$/kWh)

x = nominal net power output (MW)

z = the conversion factor from 2012 US Dollar value to 2018 Euro value

The real power output for the scaled-down plants is calculated in a more straightforward manner than the real power output of the standard size plant. From the base temperature of 21.6°C, a change of 1°C incurs a change of power output by 15%. For example, for the 50 MW nominal plant, if the temperature drops to 20.6°C, then the real power output would be 42.5 MW.

The annual OPEX used for the calculation is 3% of the CAPEX. The cable cost is calculated by using the following formula (Langer, 2018), in million Euros. The distance is subtracted by 20 km as the CAPEX from the scale curves already includes the cost of 20 km of cables.

$$C_{cable} = 21.12 + 3.45\,(D - 20)$$

3.2.2 Presentation of Economic Potential Calculation Results

After the LCOE is obtained for every available station throughout the exclusive economic zone of the Republic of Indonesia, the results must be presented in certain ways. The presentation of the results in this thesis mainly takes three forms, i.e. maps, graphs, and tables.

The maps are made with the help of ArcGIS software. It is constructed by plotting the LCOE values into the spatial domain. By employing maps, it is effortless to analyse the distribution of areas which hold the economic potential. Even further, the LCOEs is coloured differently according to several ranges, starting from less than 0.10 €/kWh to more than 0.20 €/kWh with 0.025 € intervals. This way, the areas with very low LCOEs can be easily detected, and the areas with very high LCOEs can be instantly eliminated from further consideration.

However, presentation with maps does not help in determining the actual number of economic potential present in the areas. Hence, a supply curve for each cost estimation is built. According to Langer (2018), a supply curve is commonly used by contemporary scholars. To construct the supply curve, the LCOEs of every station are ordered from smallest to largest. Then, the cumulative annual energy production is calculated. Lastly, they are plotted against one another. From the supply curve, it is possible to estimate the energy production potential values of a certain LCOE. The tables are made to summarise the results. Within a table, the exact value of the results from different provinces can be presented together.

3.3 Sensitivity Analysis

As seen in the previous sections, the changes in certain parameters affect the LCOE with varying impact. A way to determine which factor has the greatest influence is through a sensitivity analysis. The sensitivity analysis is conducted by changing the value of each parameter by $\pm 20\%$, based on the lower boundary of the uncertainty of OTEC costs found in literature. The sensitivity analysis is carried out in isolation for each parameter. It means that when one parameter is altered, the others stay the same. The effect of change of multiple parameters at once is not examined in this thesis. The factors and the base values used for the sensitivity analysis can be found in Table 3.3. The base values of resource quality and distance are chosen based on the average from the data used.

Table 3.3 Parameters and Base Values for Sensitivity Analysis

Parameter	Base Value	Unit
Resource quality (temperature difference)	23.73	°C
Distance to shore	128	km
Cable costs (for 128 km)	0.48	Million €
OPEX/year	0.04	Million €
CAPEX (without cable costs)	1.14	Million €
Discount rate	10	%
Lifetime	30	Year

3.4 Electrification Scenarios

The electrification scenarios are assembled with the target of fulfilling the whole electricity demand of a province only with the production of OTEC plants. Naturally, each province has different demand and hence, different configuration needed to fulfil the demand. There are three different scenarios available, each of which is applied to cater the need of a particular province. Each of the scenarios starts with selecting the stations until the 100% electrification target is fulfilled, disregarding the maximum LCOE limit. Nevertheless, it is unrealistic to assume that all stations are possessing economic potential. Ergo, the economic potentials of the selected stations are calculated. The result will confirm how much of the available resource is economically feasible to be used.

3.4.1 Electrification with Resource Within Province Boundary

For this scenario, a province only uses the stations located within their own boundaries with a standard size OTEC plant (100 MW nominal plant). One province might only need one station, but the others might need multiple stations. The selection of the stations is based on the shortest distance from the stations to the demand centre of the particular province. The selected stations are not supposed to be located within a marine protected area.

3.4.2 Electrification with Scaled-Down Plants

Similar with the previous scenario, in this scenario, a province also only utilise the stations located within their region. The difference is that at least one station is scaled-down to either 25 or 50 MW nominal plant. With the different electricity demand, it is not impossible that the standard size plants are too big for some stations. The stations are selected based on the shortest distance to the demand centre and are not allowed to be located within a marine protected area as well.

3.4.3 Electrification with Resource Beyond Province Boundary

This scenario is an ambitious scenario, in which a province exploits the resource beyond their area in addition to the stations within the boundary. This scenario is meant for the provinces which own low available resources but comprise high electricity demand. In this scenario, only 100 MW nominal plants are used. The method of selecting stations is identical with the other two stations.

3.5 Conclusion of Methodology

The methodology used for this thesis is following the steps of the geographic method while incorporating the steps of the techno-economic analysis at the same time, resulting in six main stages in this thesis. The economic potential is defined by summing up the annual energy production of stations with LCOE lower than 0.20 €/kWh, both on national and provincial levels. The geographical characteristics considered in calculating the LCOE are temperature difference of surface- and deep-water and the distance between the station and the shore or the demand centre. Aside from the 100 MW nominal plants, scaled-down plants of 25 and 50 MW are also used, with the cost function based on the scale curves. The results of the LCOE calculations are presented in multiple ways, i.e. distribution maps, graphs, and tables. The sensitivity analysis is conducted by varying input parameters by $\pm$ 20%. There are three electrification scenarios to fulfil the whole electricity demand only with electricity produced by OTEC plants, i.e. electrification with resource within province boundary, electrification with scaled down plants, and electrification with resource beyond province boundary. Lastly, the economic potential of the selected stations is calculated to check the feasibility of the scenarios.

4. Economic Potential Results

In this chapter, the results of the economic potential calculations are presented. The first section presents the potential areas based on the temperature difference, the real power output, and the annual energy production. The second section exhibit the national economic potentials of OTEC under different distance measurements and cost assumptions. The third section displays the result of the sensitivity analysis. The last section gives the economic potential of OTEC on the provincial level.

4.1 Determination of Potential Areas

The first and foremost thing before one can think of building an OTEC plant is the availability of a high temperature difference between the surface water and the deep water of the sea. Ideally, the difference should be at least 20 °C. Being located along the equator, Indonesia has the advantage of having warm surface water. Hence, virtually all stations have the gradient of more than 20 °C. The distribution of the temperature difference throughout the country is presented in Figure 4.1.

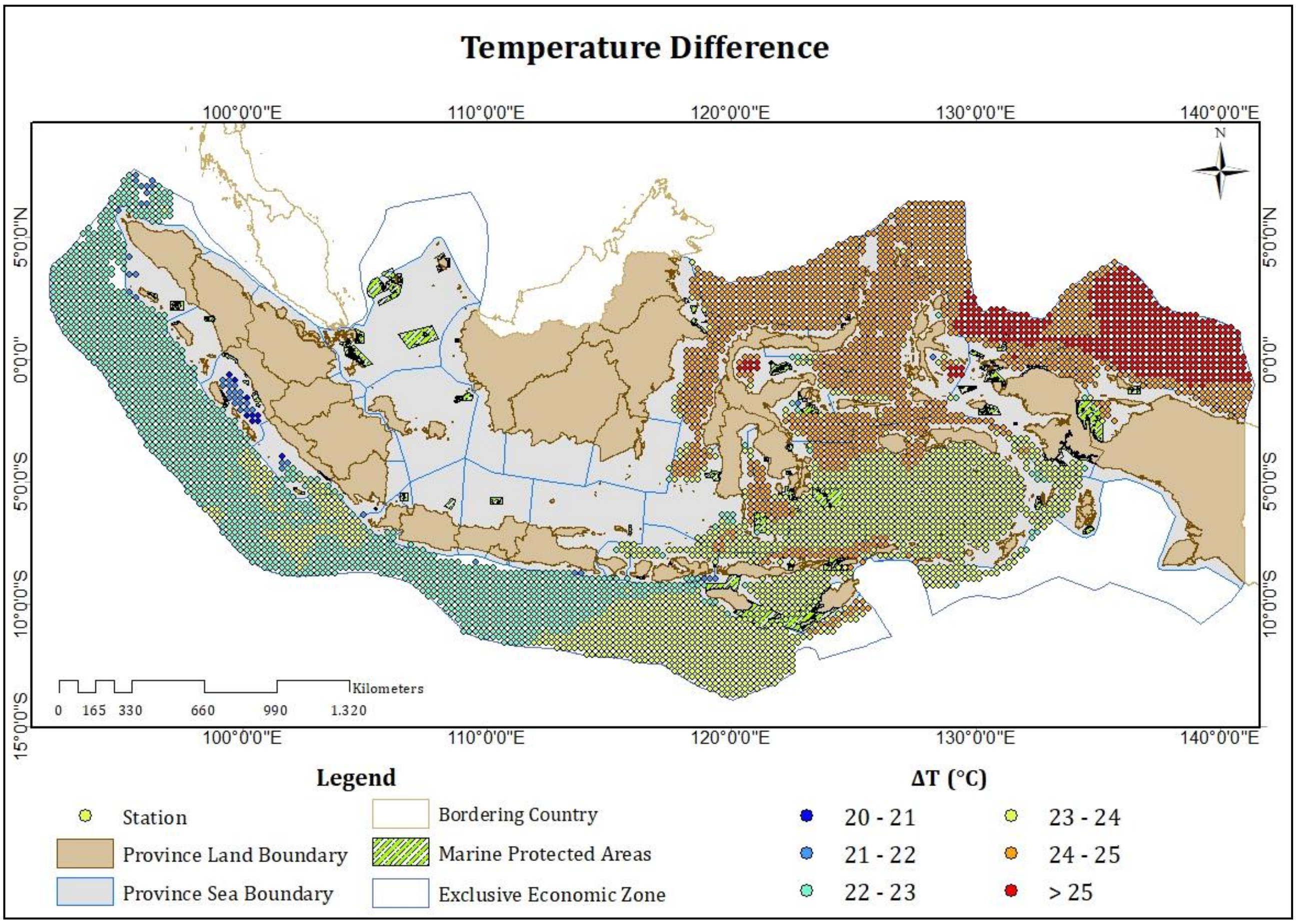


Figure 4.1 Temperature Difference Distribution within Indonesia EEZ

The temperature difference directly influences the real power output of an OTEC plant. Lockheed Martin (2012a) states that for a 100 MW nominal plant, the power output change by 13.6 MW with a deviation of 1°C. Figure 4.1 shows that only a small proportion of the country has 'low' differences of 20 to 21 °C. In fact, more than half the of the stations have a high gradient of more than 23 °C (yellow, orange, and red dots). This shows that theoretically, Indonesia is indeed an excellent location for OTEC with high power output. The resulting distribution of real power output, displayed in Figure 4.2, is very similar to the distribution of the temperature difference.

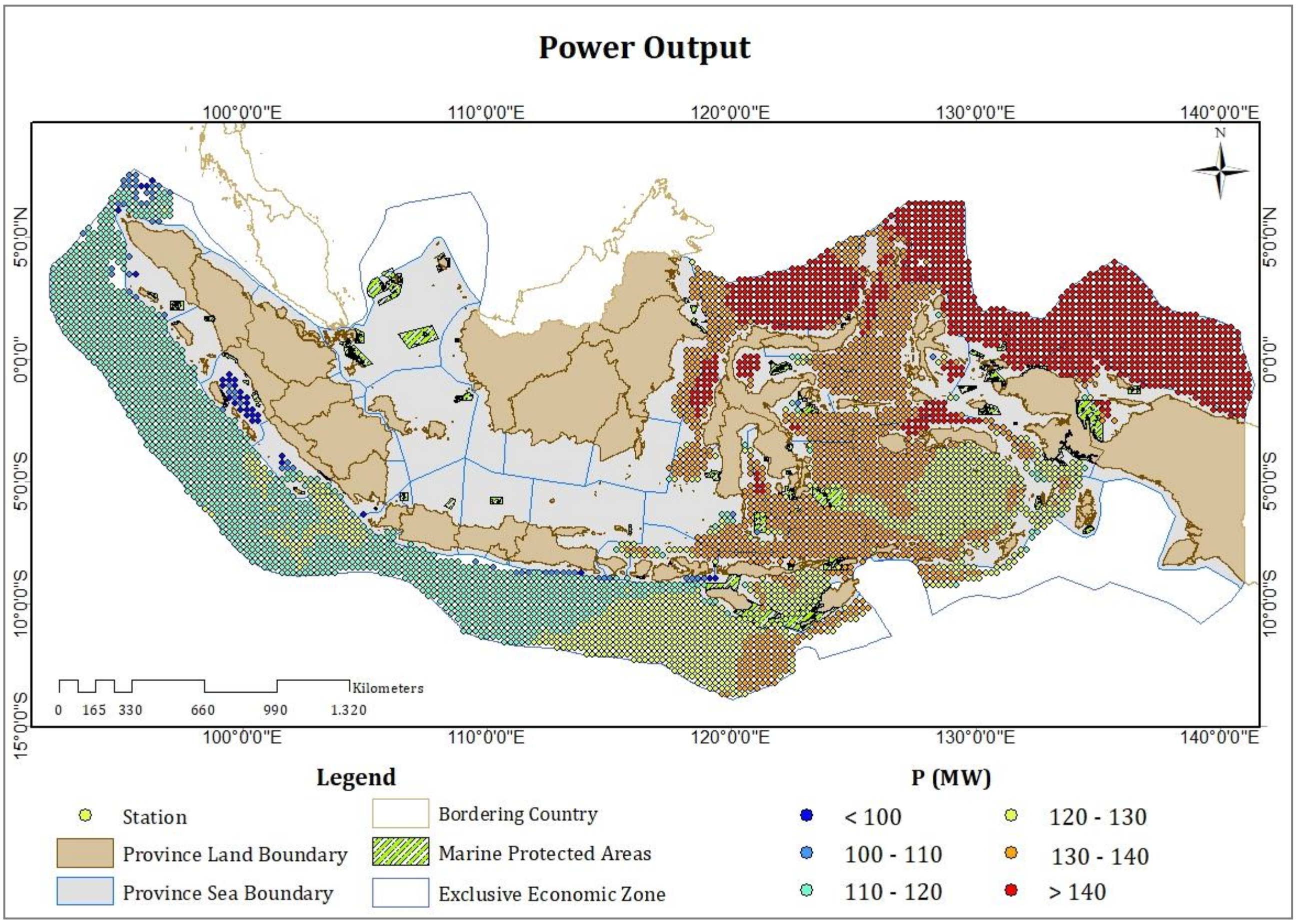


Figure 4.2. Real Power Output Distribution within Indonesia EEZ

As mentioned in Chapter 3. the distance between the plant and the shore has a massive impact on the energy production. Simply put the further away from the shore, the smaller the energy production. However, the annual energy production is not only getting influence from the cable losses, but also from real power output. This makes the annual energy production of different stations varies not only by distance. Hence, the resulting distribution looks quite interesting. In the western part of Indonesia, even the plants very close to the shore produces only around 800-1000 GWh of energy per year. On the contrary, in the eastern part of Indonesia, plants further away from the shore can already produce the same amount of energy per year due to better resource quality. The distribution map can be found in Figure 4.3.

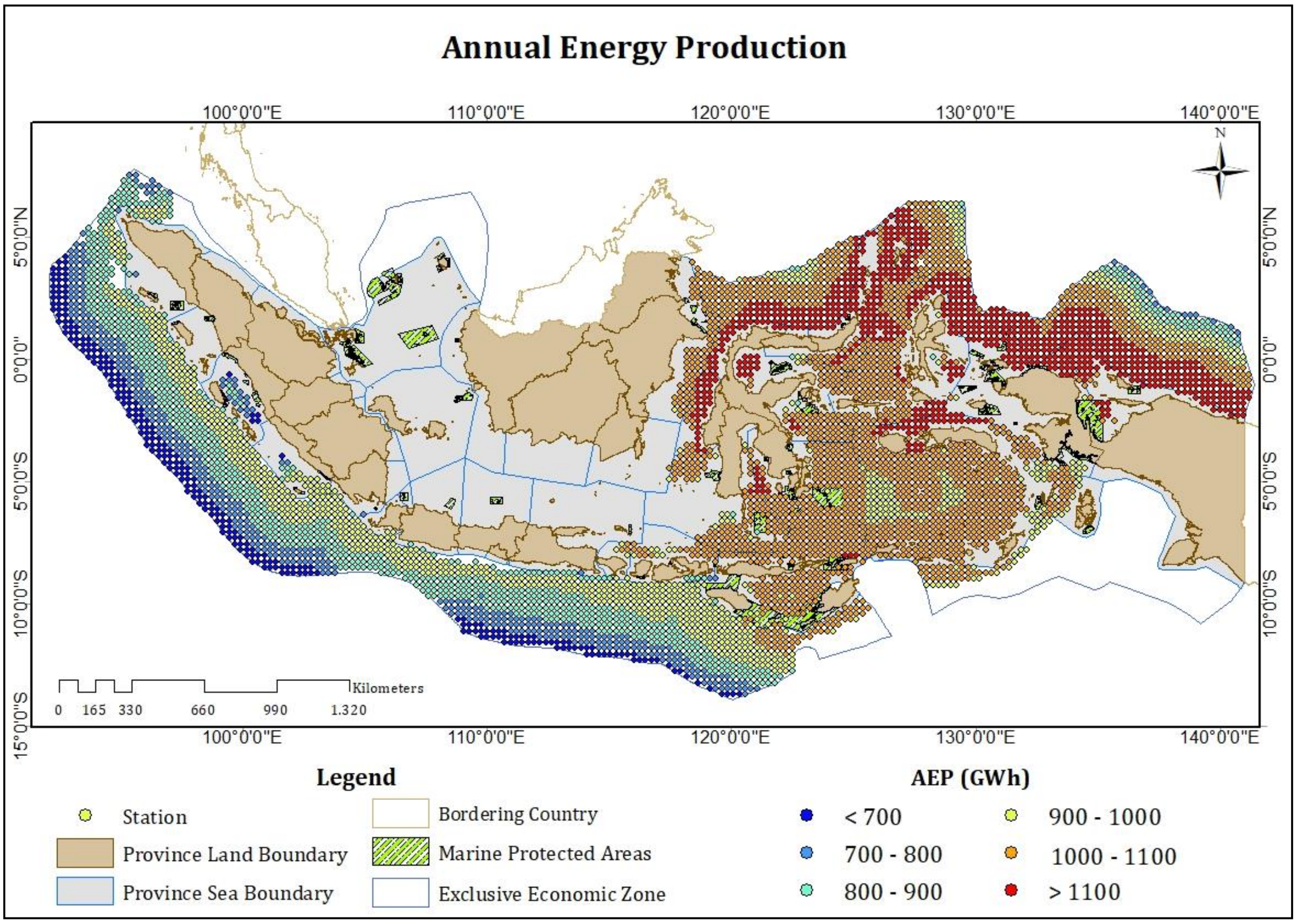


Figure 4.3. Distribution of Annual Energy Production in Indonesia

4.2 National Economic Potential

4.2.1 Closest-to-Shore Distance

In this section, the results for the LCOE calculations and the subsequent economic potential are presented for the calculation with the closest distance to any shore. The correlation between distance and annual energy production has been revealed in the previous section. This, in turn, affects the LCOE as well. There is a strong correlation between distance and LCOE: the further away from shore, the higher the LCOE. It is caused by the increasing loss of annual energy production as well as the increase in cable costs. From Figure 4.4 it can be concluded that stations located at a distance up to 150 km from the shore (with Lockheed Martin (2012a) costs assumption) and around 230 km from the shore (with Vega (2012) costs assumptions) can still have LCOE under 0.20 €/kWh.

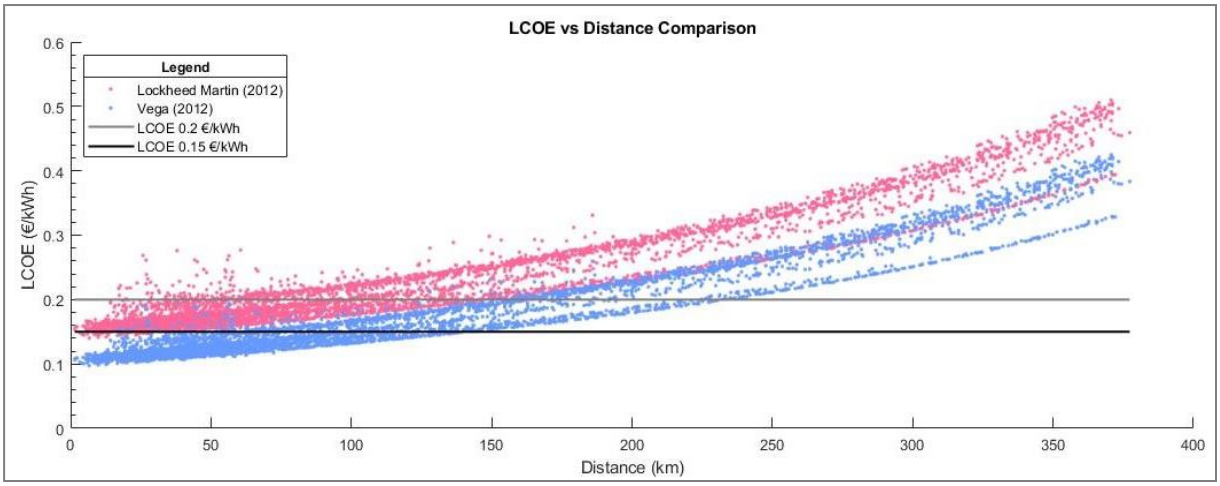
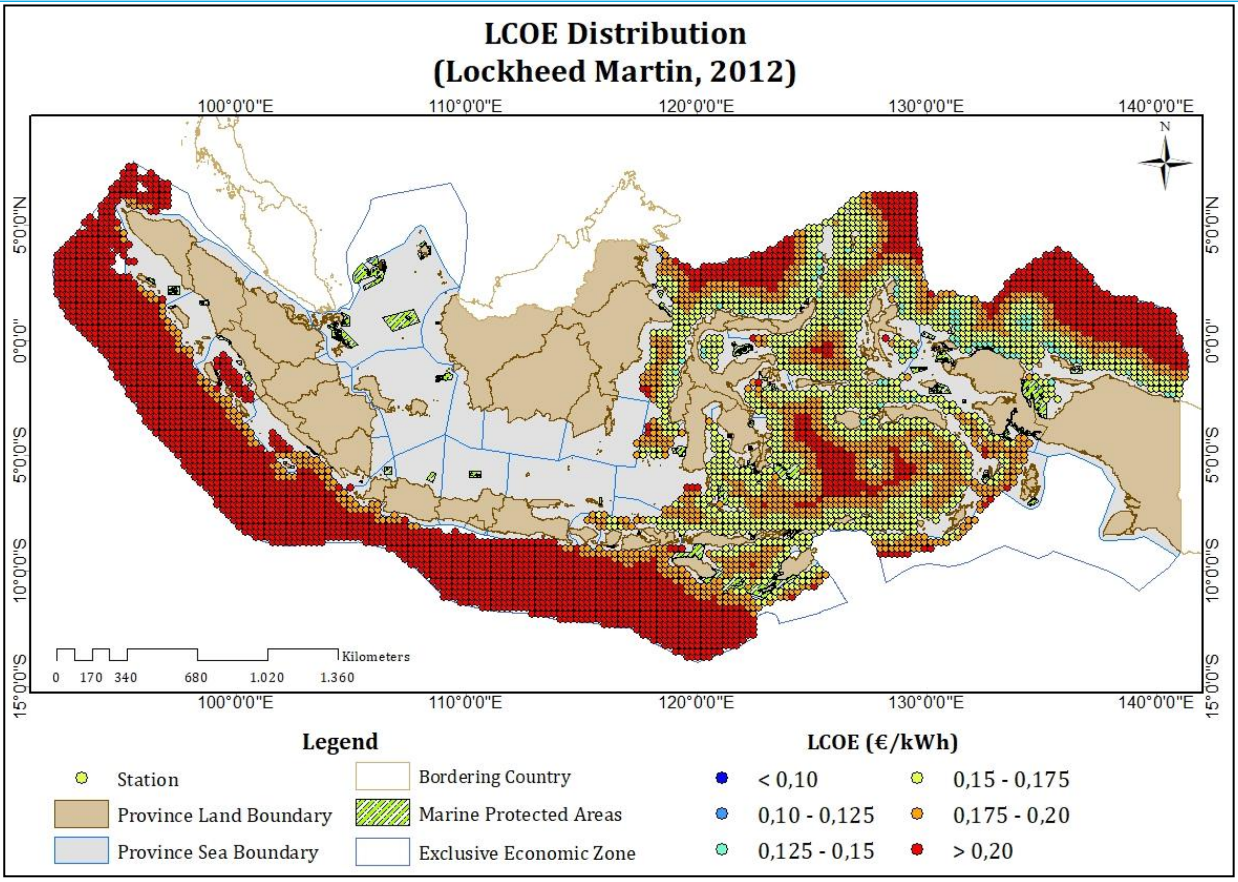
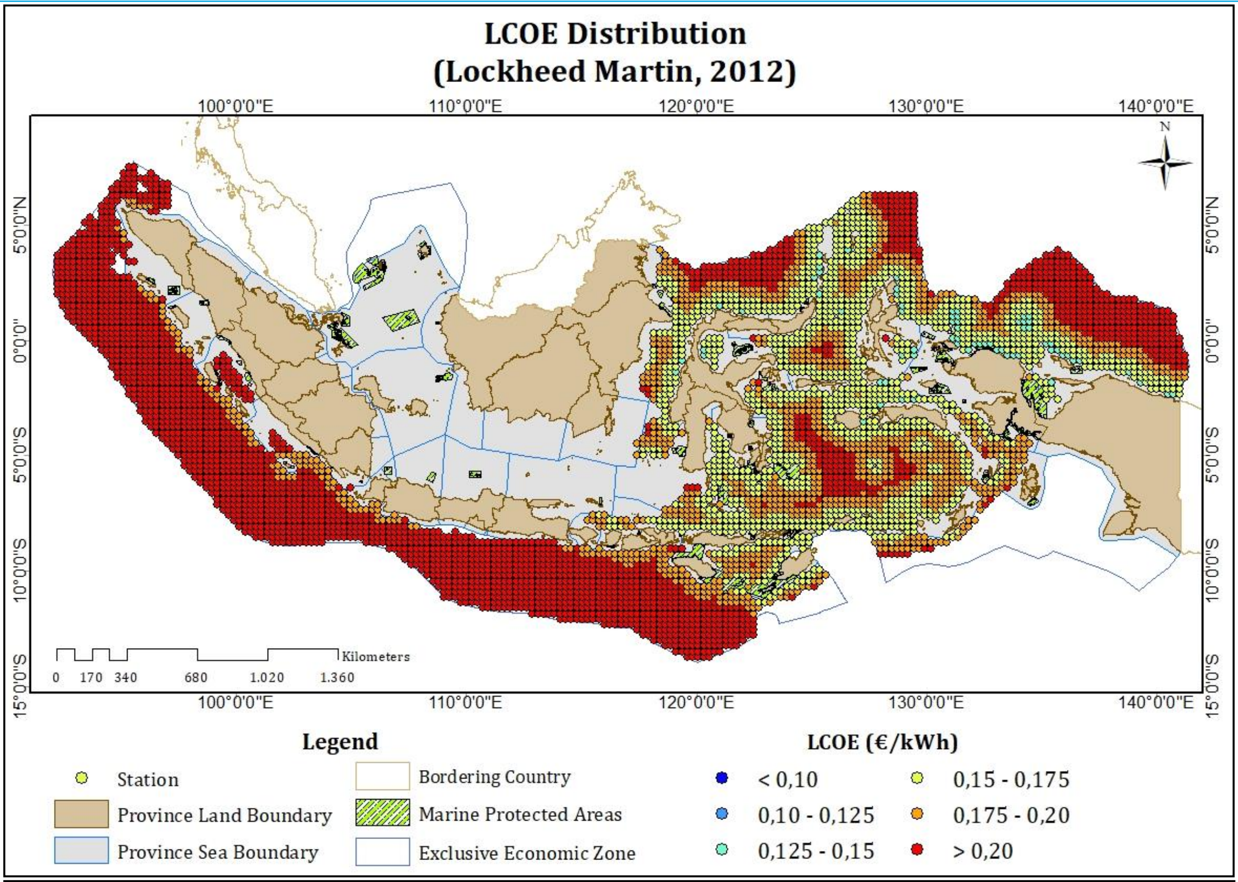


Figure 4.4. Correlation between LCOE and Distance for The Closest-to-Distance Case

But how do these results look when they are embedded into the spatial domain? Figure 4.5 provides the answer. In the top picture, the prospect of economic OTEC potential looks very sombre. Most of the stations are coloured red, which means that the LCOE is more than 0.20 €/kWh. This looks especially bad in the west part of the country. In the east part of the country where the resource quality is better, the situation is better as well. Nevertheless, there are only a handful of stations having LCOE as low as 0.15 €/kWh.

Fortunately, the situation looks better when the other cost estimations by Vega (2012) is employed. Throughout the whole country, there are plenty of stations with LCOE of less than 0.15 €/kWh. Even in the east part, still many stations have the LCOE of less than 0.125 €/kWh. This is good as the feed-in tariff for renewables in Indonesia lies at a number around 0.12 €/kWh. The comparison between the two maps shows that costs estimation is very important when it comes to determination of economic potential, as one cost assumption can make it while the other can break it.


LCOE Distribution
(Lockheed Martin, 2012)
100°0'0"E
110°0'0"E
120°0'0"E
130°0'0"E
140°0'0"E
5°0'0"N
0°0'0"
5°0'0"S
10°0'0"S
15°0'0"S
N
Kilometers
0 170 340 680 1.020 1.360
Legend
Station
Province Land Boundary
Province Sea Boundary
Bordering Country
Marine Protected Areas
Exclusive Economic Zone
LCOE (€/kWh)
< 0,10
0,10 - 0,125
0,125 - 0,15
0,15 - 0,175
0,175 - 0,20
> 0,20



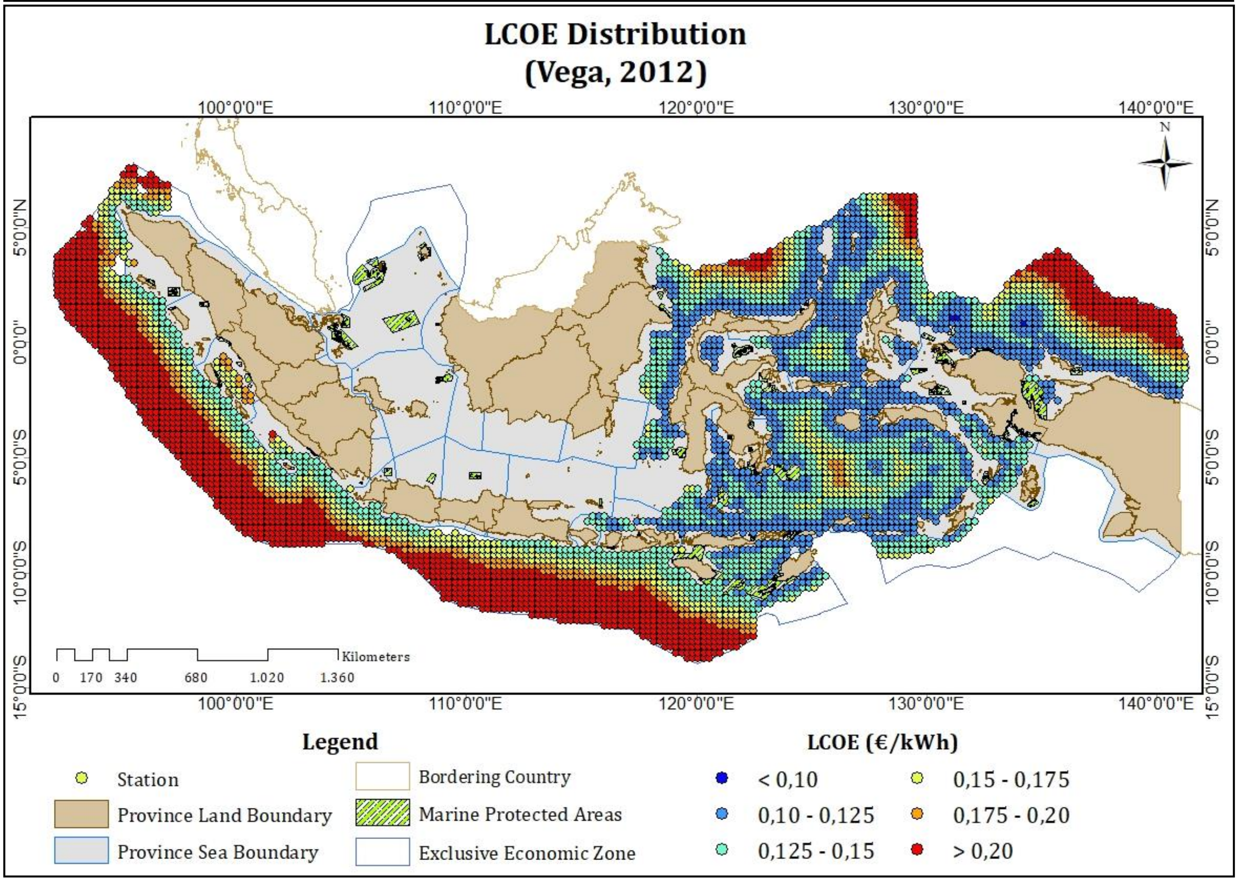


Figure 4.5. Distribution of LCOE in Indonesia with Closest-to-Shore Distance
Top: Lockheed Martin (2012a) cost; Bottom: Vega (2012) cost

Looking at the results in the spatial domain gives a demonstration of how the LCOEs are distributed in the country and how the situation looks like at a glance. It does not, nevertheless, deliver the exact values of the economic potential scale. Hence, a supply curve for each cost estimation is built (Figure 4.6). From the supply curve, it is visible that for both costs estimations the amount of potential is quite high. The curves also show the contrast between the two costs estimations. In the Lockheed Martin estimation, around the 2600 TWh of energy can be produced per year if the LCOE limit is up to 0.20 €/kWh. However, with the Vega estimation, the same amount of energy production can be achieved even if the LCOE limit is lowered to 0.15 €/kWh. This shows once again how crucial the cost estimations are. The complete values of potential below a certain LCOE limit are presented in Table 4.1.

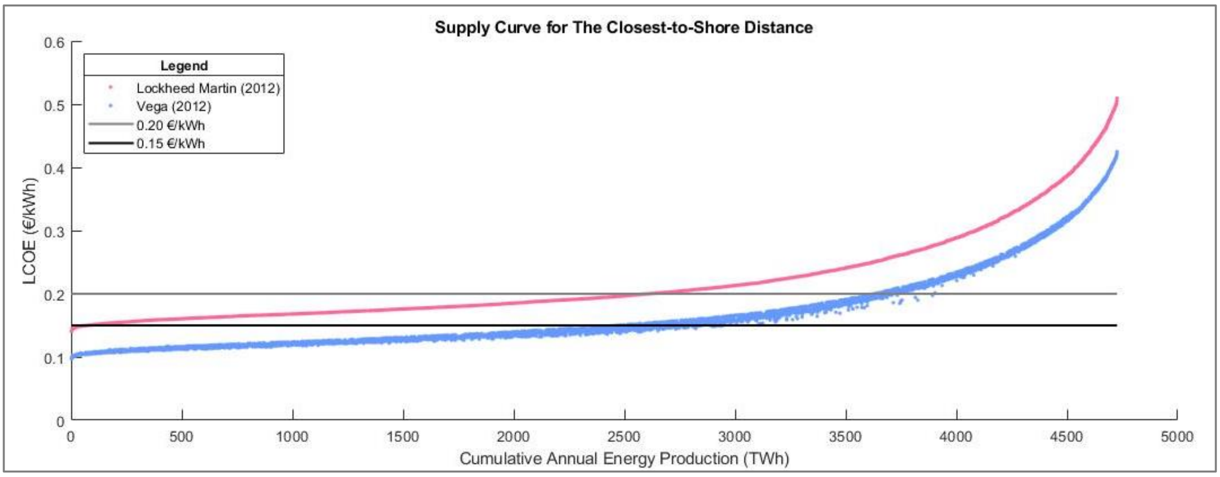


Figure 4.6 Supply Curve of OTEC Stations with Closest-To-Shore Distance

4.2.2 Adjusted-to-Demand Centre Distance

In the previous section, the economic potential of OTEC in Indonesia has been determined with the condition that the plants can be connected to any closest shore. In real life, this is not exactly realistic. There are demand centres to where the plants are connected. This rearrangement causes many changes, from the distance measurement, the annual energy production, the LCOE, and ultimately, the economic potential.

The annual energy production distribution is displayed in Figure 4.7. The effect of the change in distance measurement is indisputable here. Instead of having gradients adjacent to the shoreline, the gradients are shaped in circular areas around the demand centres. It is also apparent that the new distance measurement lowered the annual energy production considerably. In Figure 4.3, most of the stations in the eastern part of the country have an annual energy production of more than 1000 GWh per year, however in Figure 4.7 that is not the case. It can be concluded that the methodology of distance measurement is very important as well in determining economic potentials.

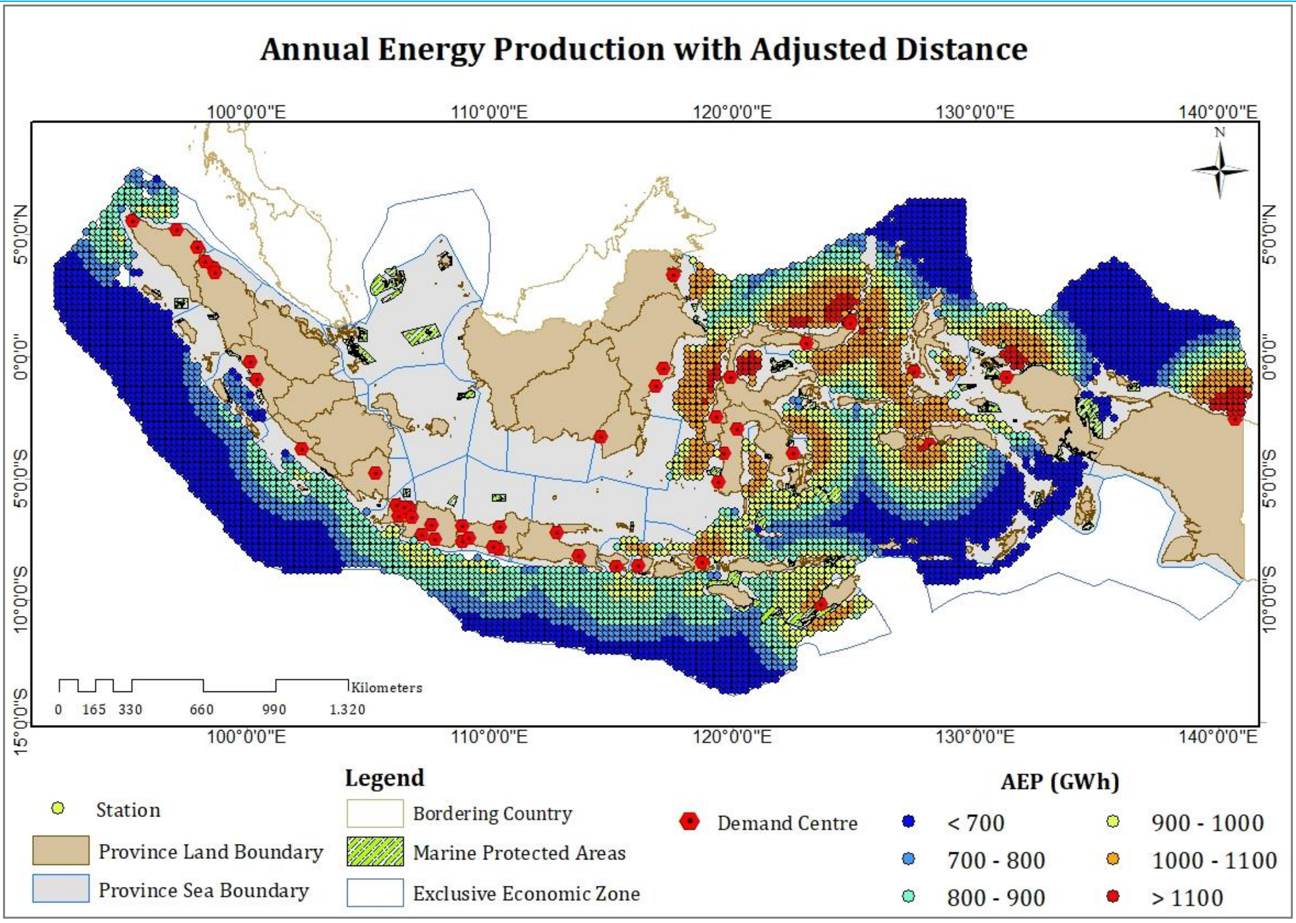


Figure 4.7 Annual Energy Production in Indonesia with Adjusted Distance

With the modification of distance, not only annual energy production is affected, but also the cable costs. These alterations, in turn, influence the LCOE. Same with the previous section, the LCOEs are plotted against the distance. This time, not all available stations are visible in the graph because many stations are now located very far from the demand centres. Only the stations with the distance of less than 400 km are presented. Then, based on the provincial demands, stations around the demand centres are selected. The selected stations are marked with green circles in the graph. The different colours of the green show the selected stations on the different cost assumption used, and do not mean doubling of the stations.

When the results are brought into the spatial domain, as can be found in Figure 4.10, the situation looks sombre. For both Lockheed Martin and Vega cost estimations, most of the stations have LCOE higher than 0.20 €/kWh. Nevertheless, not all stations will be employed to fulfil the demand of the demand centres. Looking at the maps closely, it can be said that there are still hopes for 'usable' stations around some of the demand centres. Whether these stations can actually answer the demand is answered in Chapter 5.

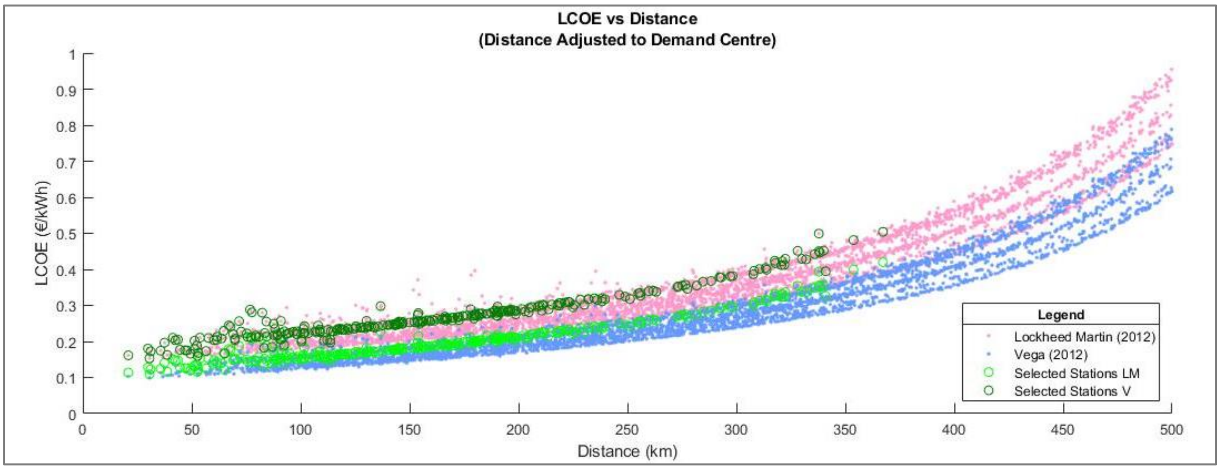


Figure 4.8 Correlation between LCOE and Distance for The Adjusted Distance Case

Supply curves are also constructed for this case of newly adjusted distance (Figure 4.9). The curves have to be limited for the stations with the LCOE of less than 1 €/kWh to maintain the readability of the graph. From the curves, it is apparent that amount of the cumulative annual energy production under the LCOE upper limits drops considerably compared to the original distance. It is also visible that starting from around 3500 TWh, the LCOEs rises indefinitely while the cumulative annual energy production does not increase. It occurs mainly because with the increase of distance, the cable efficiency decreases. It means that there is less and less energy being transported to the demand centre if the stations are located further away. After some distance, it is even possible that all the energy is lost in the transmission.

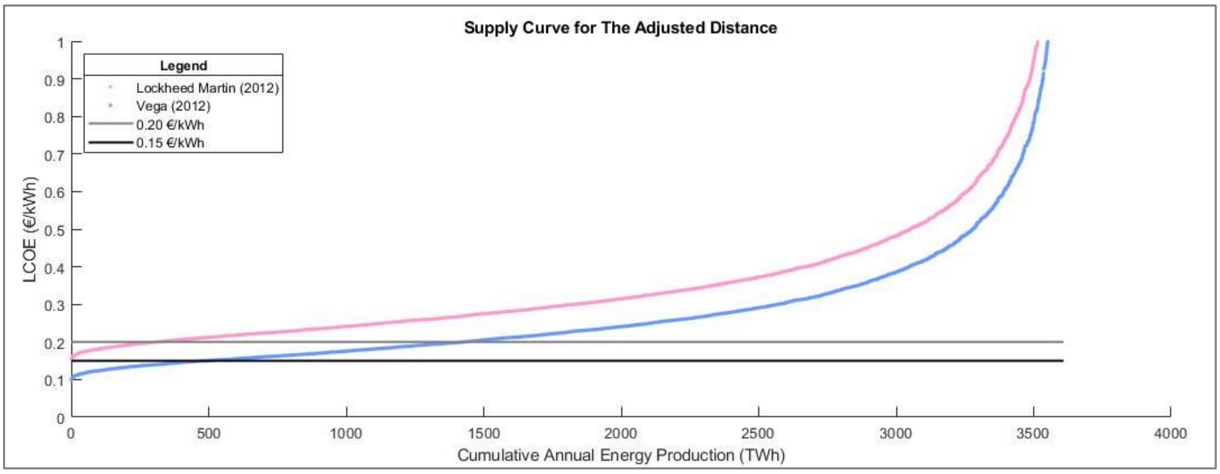


Figure 4.9. Supply Curves OTEC Stations with Adjusted Distance

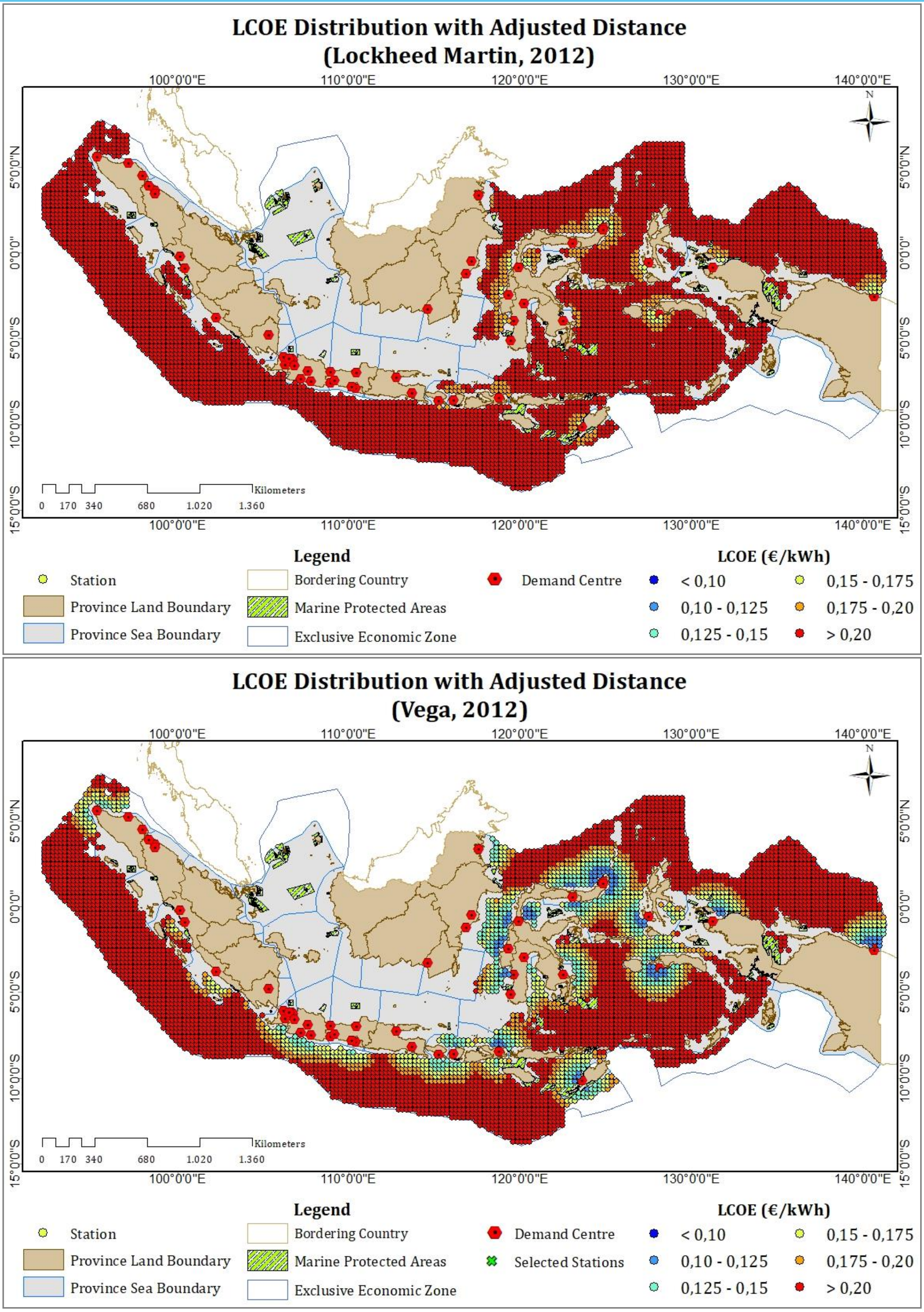


Figure 4.10. Distribution of LCOE in Indonesia with Adjusted Distance
Top: Lockheed Martin (2012a) cost; Bottom: Vega (2012) cost

4.2.3 Result Comparison

The comparison of the economic potentials of OTEC in Indonesia with original and adjusted distance is presented in Table 4.1. As already expected, the amount of the potential with adjusted distance drops considerably. With Lockheed Martin (2012a) cost estimations, there are no stations with LCOE less than 0.15 €/kWh. Meanwhile, the power production potential with LCOE less than 0.20 €/kWh only amounts for 41 GW. It means that out of 4888 available stations, only around 400 stations are economically feasible. On the brighter side, if we are to use Vega (2012) cost estimations, there are even stations with LCOE less than 0.10 €/kWh, leading to higher total power production potential of almost five times compared to the Lockheed Martin.

Table 4.1. Economic Potential of OTEC in Indonesia

LCOE Upper Limit (€/kWh)	Original Distance		Adjusted Distance	
	Power Potential (GW)	Energy Potential (TWh/year)	Power Potential (GW)	Energy Potential (TWh/year)
Lockheed Martin (2012a) Costs				
0.10	0	0	0	0
0.15	9.69	77.67	0	0
0.20	330.08	2607	40.97	317.79
Vega (2012) Costs				
0.10	0.44	3.56	0.14	1.15
0.15	337.63	2669	63.69	491.59
0.20	473.54	3691	192.32	1431

4.3 Sensitivity Analysis

The result of the sensitivity analysis is as follows. The discount rate has the highest impact on the LCOE, followed by CAPEX without cable costs, with more than 10% change in the LCOE. Changes in distance to the shore, cable costs, and OPEX/year only change the LCOE by less than 10%. Interestingly, while the other parameters' effects are quite symmetrical, the effects of increasing and decreasing the lifetime are very different. Shortening the lifetime of the plant increases the LCOE by more than 5% while prolonging the lifetime of the plant only reduces it by around 2%.

The impact of temperature difference to LCOE is not true to scale in the graph to maintain the readability of the graph, as the values are way more extensive than the others. Increasing the temperature of 20% yields an LCOE reduction of 33.09 % while reducing the difference of 20% results in an LCOE increase of 98.85 %! It has to be noted nevertheless, that varying the base value temperature difference by ±20% means that the lower bound is 18.89°C and the upper bound is 28.47°C. In reality, the temperature difference found in the data does not reach these bounds.

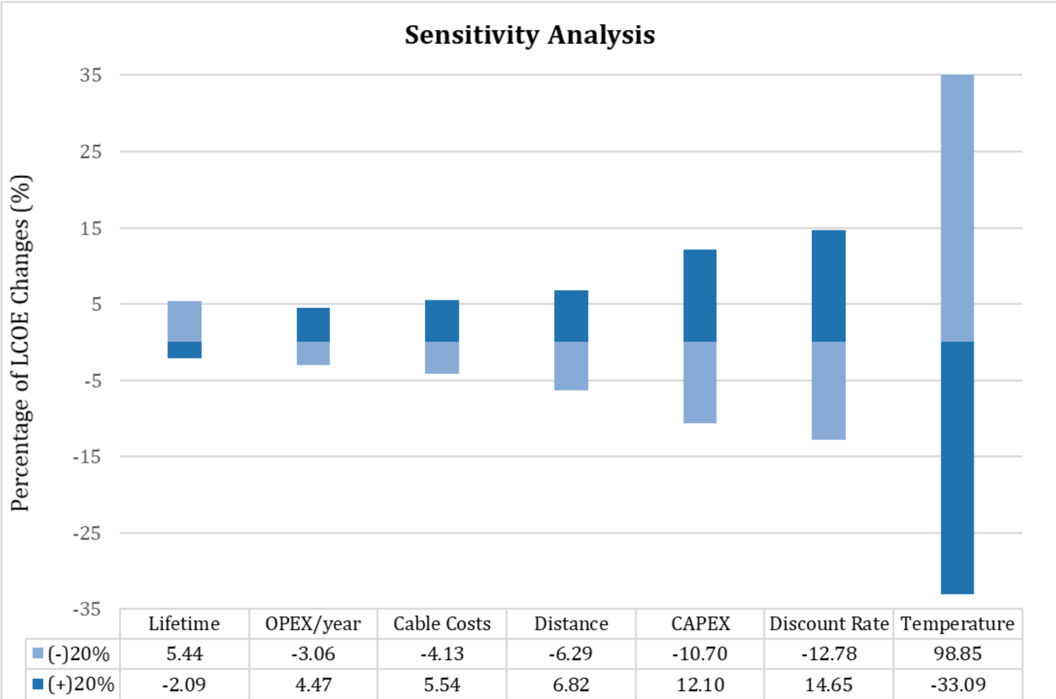


Figure 4.11. Sensitivity Analysis for Deviation of 20% from Each Factor
(the bar for effect of reducing 'Temperature' is cut short to maintain readability of the figure)

4.4 Provincial Economic Potential

There are 34 provinces in Indonesia, 24 of which possess the potential of OTEC resources. Spread across 5000 km from west to east and 2000 km from north to south, each province has their own characteristic that varies widely from one province to another. Geographically speaking, one province might consist mostly of land, but another province might have more body of water. The ten provinces which do not have potential are all located on the shallow sea of Sunda Plate. Figure 4.12 gives an overview of the provinces locations within the country to help readers have a clearer understanding.

Aside from the geographical features, other characteristics also vary wildly from one province from another. The electricity demand, for instance, ranges from around 20 GWh to almost 50 TWh per year. The provinces on Java Island, where the capital city is located, have a much higher demand compared to the rest of the country combined. This high demand, however, is not accompanied by high availability of OTEC resources. As an example, the province of Jawa Barat has the demand of 46 TWh/year, but only 2.67 TWh of annual OTEC energy production available. Even when all the resources are used, the electricity production barely makes a dent to the demand. On the contrary, there are provinces with very low demand but very high amount of available resources. Maluku's demand is only 0.48 TWh/year, but it boasts an enormous available resource of almost 416 TWh/year!

The magnitude of the available resource depends mainly on two things, namely the area of the sea a province owns within its boundary and the temperature difference between the surface- and deep-water of the sea. The western part of Indonesia has been at a disadvantage for both parameters. The provinces on the western part which have access to deep water, only possess a small area of the sea. The eastern part of Indonesia, on the other hand, is fortunate enough to have both. The eastern part mainly consists of small islands surrounded by fast sea. Remembering the result from the previous chapter, it is also known that the temperature difference is quite high. The combination of these two results in an abundance of resource for the eastern part.

Figure 4.12. Indonesia Provincial Borders

As nice as it might sound to use OTEC for electricity production, there is a price to pay. Literally. Not all of these stations are economically feasible to be built. As in the previous chapter, the economic potential is determined by setting a cut-out LCOE and summing up the annual energy production. The difference is that within this chapter, only the upper limit of 0.20 €/kWh is employed. Table 4.2 contains the provincial electricity demand, available technical potential resources, and the economic potential as the percentage of resources for both Vega and Lockheed Martin cost assumptions. The economic potential is presented in percentage to enable a straightforward interpretation. The total available annual energy production for all provinces is 1640 TWh. The economic potential with Vega and Lockheed Martin costs assumptions are 904 TWh and 253 TWh respectively, which amounts to around 70% of the available resources. The complete table with the amount of economic potential in TWh can be seen in Table B.1 in the appendix.

In all but three provinces, the economic potential of OTEC with Vega costs assumptions is bigger than the one with Lockheed Martin costs assumptions. The three exceptions are Lampung, Kalimantan Selatan, and Sumatra Utara. These provinces do not have economic potential at all, be it with Vega or Lockheed Martin costs. This is caused by both the high distances from the stations to the demand centres and the relatively low temperature difference at the location of the stations. Aside from those three, there are six more provinces which do not have any economic potential under the Lockheed Martin costs assumption, namely Aceh, Banten, Jawa Barat, and Jawa Timur. Interestingly, with Vega costs assumption, all the available resources of Jawa Barat and Jawa Timur are economically potential. The case in which a province's resource is fully economically potential with Vega costs also happen in five more provinces, namely Bali, Kalimantan Utara, Gorontalo, Nusa Tenggara Barat, and Sulawesi Barat. In all these provinces, the economic potentials with Lockheed Martin cost are pretty high in percentage. In these provinces, the annual energy productions are relatively hefty with the moderate distance of no more than 160 km. In the remaining provinces, the economic potentials with both Vega and Lockheed Martin cost assumptions are unable to completely supply the electricity demand.

It is worth mentioning that there is only a little relevance between the quantity of the available resources and the extent of economic potential in per cent for both cost assumptions. The volume of the available resources reflects the number of the stations within the province boundary which are distributed evenly throughout the whole area. In other words, the stations have varying distances to the demand centres. As seen in Figure 4.10, the stations with the cheapest LCOE are distributed in a sort of circular shape around the demand centre, followed by the stations with higher LCOE in a similar pattern. This pattern is evident on the demand centres in the eastern part of the country. Each demand centre is surrounded by a seemingly similar number of stations, which means that the magnitude of the real economic potential values should not differ that much. However, when this is turned into a percentage of available potential, these numbers become very different based on the total resource throughout the whole area.

Table 4.2. Provincial Demand, Available Resource, and Economic Potential

Province	Demand (TWh)	Available Resource (TWh)	Economic Potential as Percentage of Resource	
			Vega (2012)	Lockheed Martin (2012a)
Kalimantan Selatan	2.32	0.9	0	0
Lampung	3.82	1.71	0	0
Sumatra Utara	9.24	3.6	0	0
Aceh	2.33	7.5	35	0
Sumatra Barat	3.15	21.11	43	0
Banten[1]	51.66	3.47	79	0
Bengkulu	0.82	20.48	79	0
Jawa Timur	32.93	2.45	100	0
Jawa Barat	46.14	2.67	100	0
Sulawesi Tenggara	0.8	141.1	45	4
Nusa Tenggara Timur	0.83	175.76	43	8
Kalimantan Timur	3.2	49.97	86	8
Papua Barat	0.5	45.76	17	10
Maluku	0.48	415.62	32	10
Sulawesi Selatan	4.94	108.89	72	10
Maluku Utara	0.34	213.8	69	12
Papua	0.83	74.46	55	20
Sulawesi Tengah	1.04	117.12	82	26
Sulawesi Utara	1.4	130.61	61	30
Bali	5.1	6.6	100	44
Nusa Tenggara Barat	1.59	37.72	100	57
Sulawesi Barat	0.29	47.91	100	68
Gorontalo	0.44	5.97	100	70
Kalimantan Utara	0.22	4.17	100	75
Total AEP (TWh)	**174.43**	**1639.35**	**904.21**	**253.06**

[1] Banten demand includes the demand of DKI Jakarta

4.5 Conclusion of Economic Potential

The temperature difference between the surface mainly determines potential locations of OTEC plants- and deep-water. The economic potential on the national level varies between 318 – 3691 TWh, depending on the distance and the cost assumption used. This shows that determining the correct distance and cost assumptions are very crucial to the resulting LCOE. This finding is consistent with the result of the sensitivity analysis, where it is found that the temperature difference has the highest effect on LCOE, followed by CAPEX and distance. The total economic potential from the province range between 253 – 904 TWh, depends on the cost assumptions used. The value of provincial economic potential is lower than the national as there are plenty of stations located beyond the province boundaries.

5. Electrification Scenarios Results

This chapter endeavours to take a closer look at the provincial level. There are three different electrification scenarios i.e. using only stations within the province boundary, replacing some of the selected stations with smaller-scale plants, and utilising stations beyond the province boundary to fulfil the demand. Each scenario starts with the premise of selecting the number of OTEC plants needed to fulfil the electricity demand regardless of the LCOE. Later on, the actual economic potentials of the selected stations in each province are computed based on a cut-out LCOE value of 0.20 €/kWh.

5.1 Electrification with Resource from Within Province Boundary

This scenario is the most basic of all the three applied scenarios. Within this scenario, the demand of a province is fulfilled only by utilising the stations in that particular province's area. These stations inside the boundary are further called the "in-stations". Figure 5.1 depicts the distribution of the entire selected in-stations throughout the country.

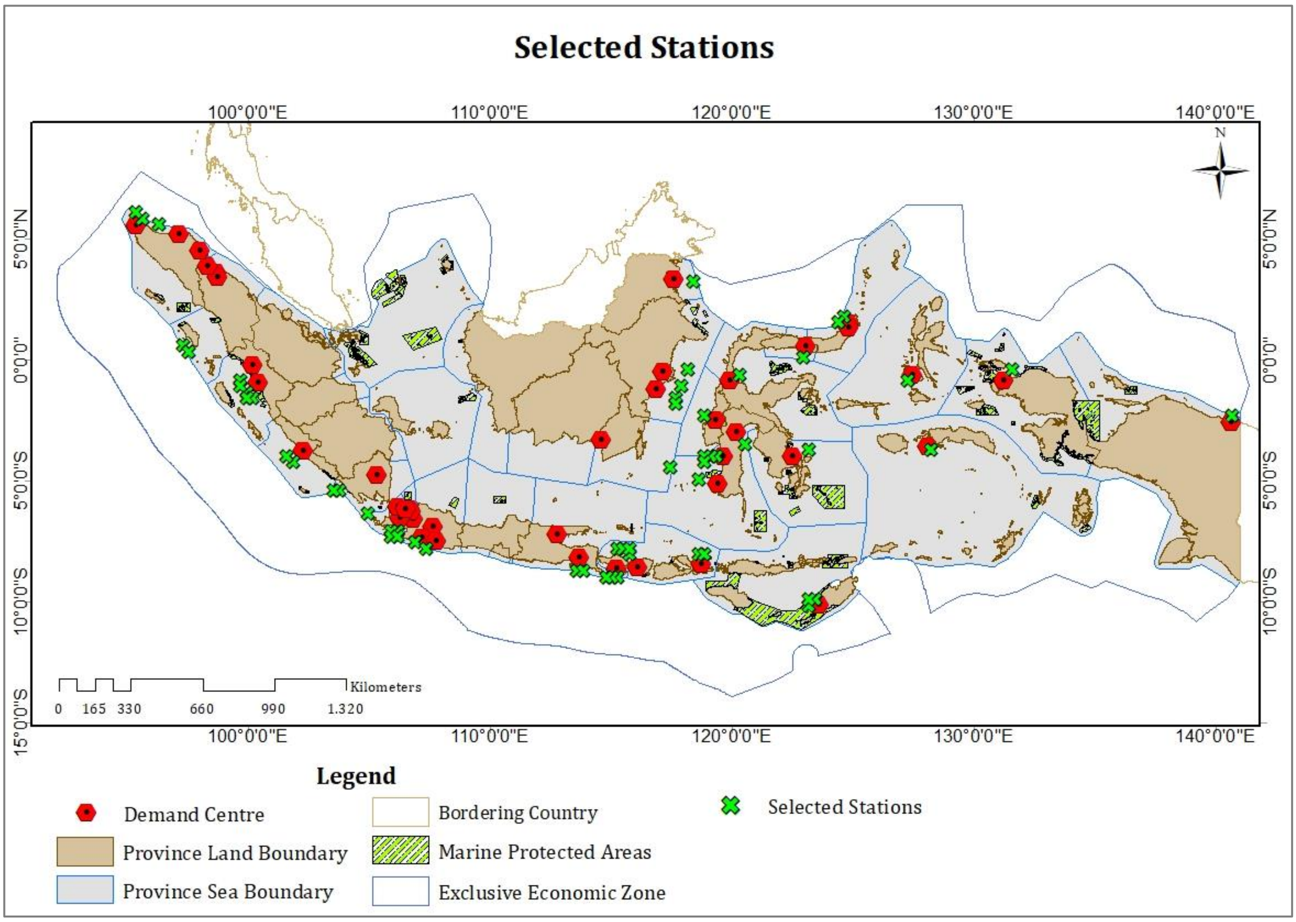


Figure 5.1. Selected In-Stations in Indonesia

Figure 5.1shows all the selected in-stations in Indonesia as not only this scenario is using the in-stations. The scaled-down plants in the second scenario are based on the in-stations, while in the third scenario, all in-stations are used before more stations from outside the boundaries are added.

The annual energy production of the selected in-stations must at least cover 100% of the province's electricity demand. In some cases, a single station would be more than enough to provide for the demand. In other cases, multiple stations are needed to reach the target. In almost all cases, the supply is higher than the actual demand as the plant's size are not changed from the nominal 100 MW. The list of the provinces in this scenario is presented in Table 5.1.

Table 5.1. Number of Selected In-Stations and Demand Coverage

Province	Number of In-Stations	Demand Coverage (%)
Aceh	3	112
Bali	6	110
Kalimantan Selatan	1	32
Kalimantan Timur	4	128
Nusa Tenggara Barat	2	130
Nusa Tenggara Timur	1	123
Papua	1	138
Sulawesi Selatan	6	123
Sulawesi Tengah	1	111
Sulawesi Tenggara	1	115
Sumatra Barat	5	117

From the table, there is an odd one out in this scenario, namely Kalimantan Selatan. The province only owns one station within its area and it only produces energy as much as 32% of the demand. This case should go to the last scenario of using resources beyond the province boundary; however, it is not possible. As the selection of the stations is not done arbitrarily, but by using shortest-distance measurement in the ArcGIS modelling, it is established that aside from the one station, there are no other stations considering Kalimantan Selatan as the closest demand centre. For that reason, it stays in this scenario.

Figure 5.2 below represents the examples of a single-station and a multi-station case respectively. In the maps of Papua, it is very evident that the further away from the demand centre, the higher the LCOE of a station is. Fortunately, Papua only needs one station to fulfil its electricity demand completely and the station is located very close to the demand centre. With both Vega and Lockheed Martin costs, the LCOEs of the selected stations are lower than the upper limit.

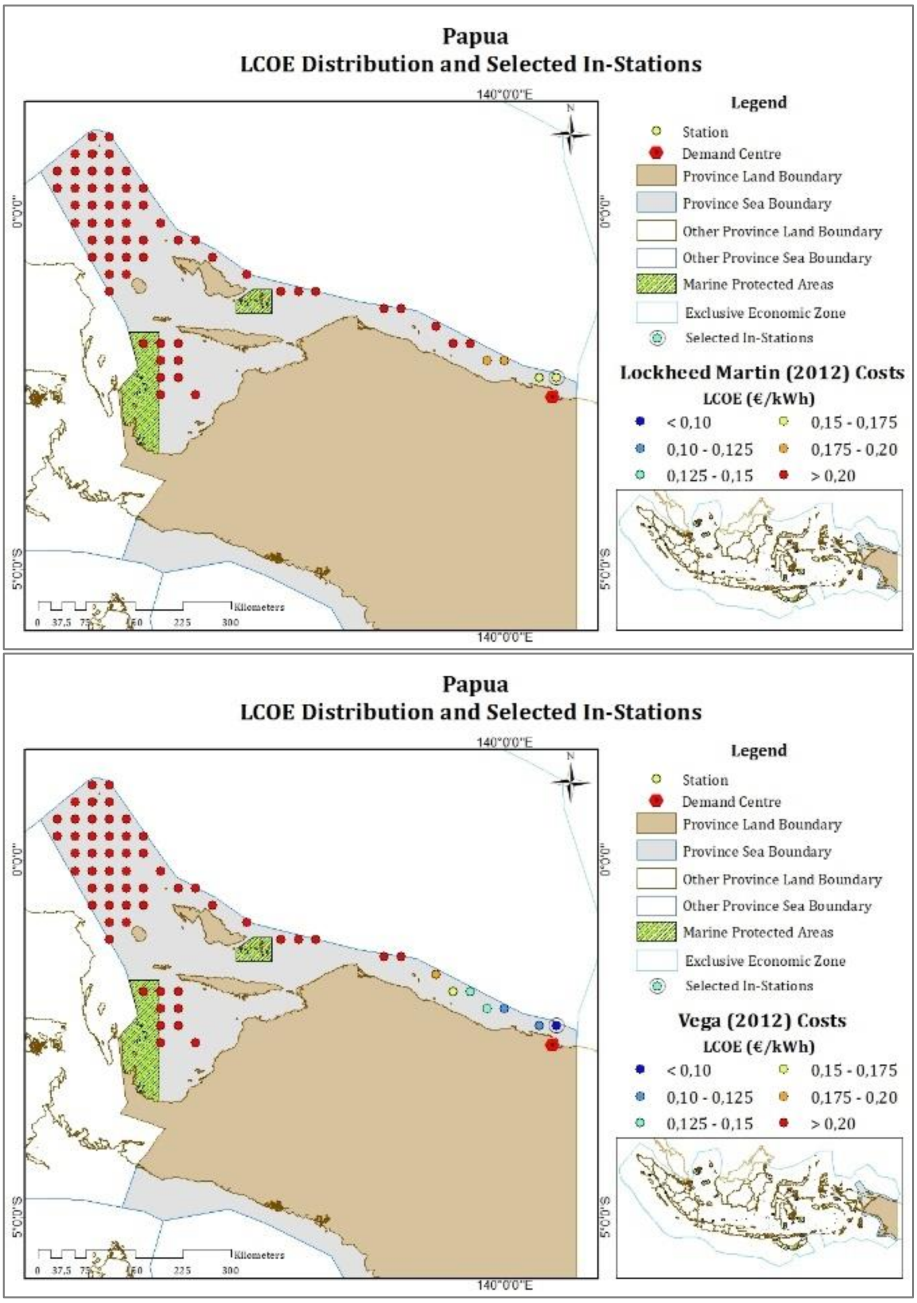


Figure 5.2. LCOE Distribution and Selected In-Stations for Papua
top: Lockheed Martin (2012a) Costs; bottom: Vega (2012) Costs

In the case of Bali, presented in Figure 5.3, apparently, one station is far from enough. The province needs 6 out of 7 available stations to supply the electricity. Clearly, with more than one station, there will be different LCOEs for different stations. With Vega cost, all the selected stations are economically viable. Unfortunately, with Lockheed Martin's costs, three stations have a higher LCOE than 0.20 €/kWh, rendering them unsuitable.

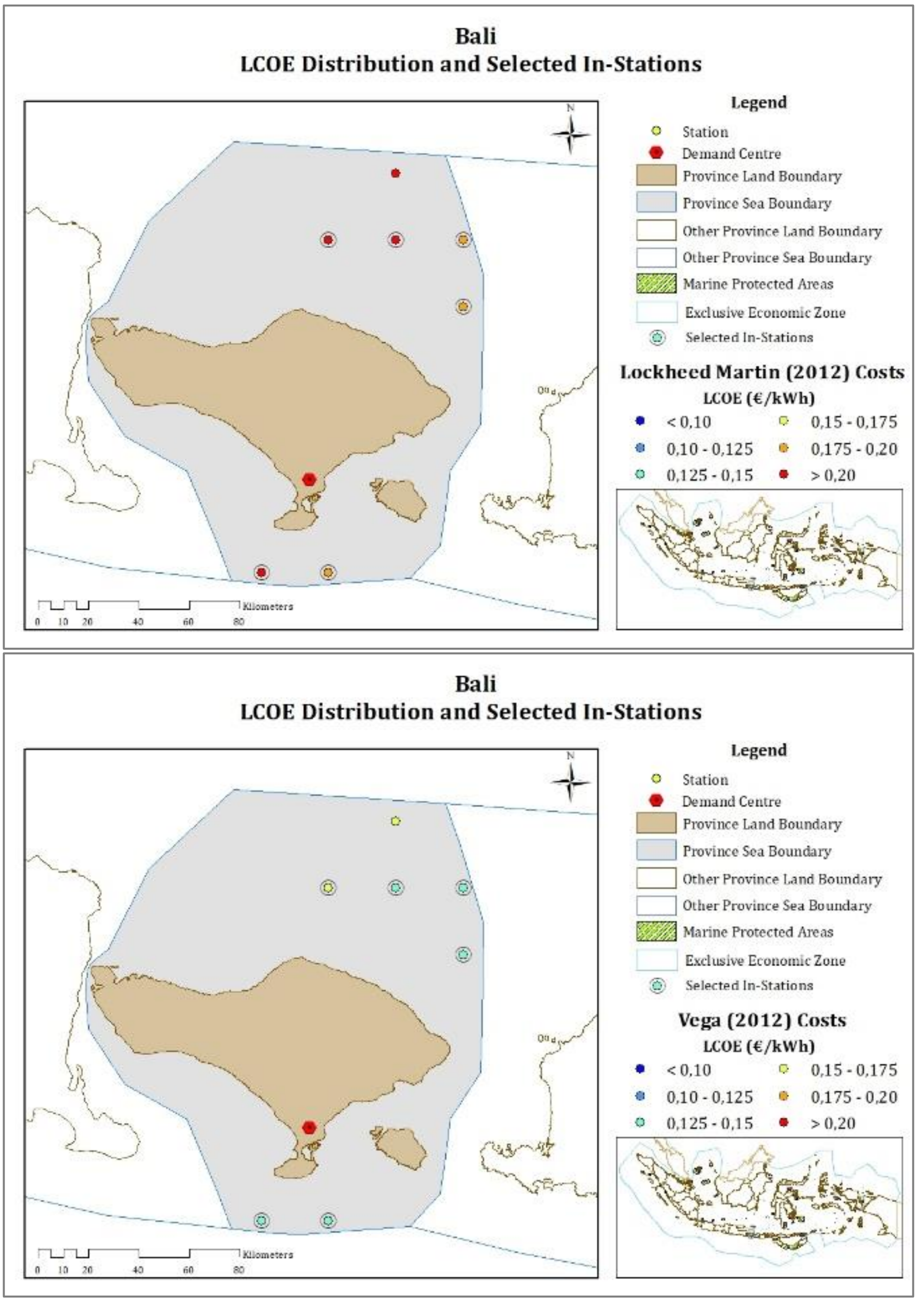


Figure 5.3. LCOE Distribution and Selected In-Stations for Bali
Top: Lockheed Martin (2012a) Costs; bottom: Vega (2012) Costs

It is fascinating to look at all the maps of the provinces one-by-one, but considering the length of the thesis, it would be impossible. In all cases, similar situations arise. Aside from Kalimantan Selatan, all the provinces of this scenario have more available resources than the demand, so that the selected stations are only a fraction of the total number of stations available. The maps for all the provinces can be found in Appendix A.

Although the maps help to quickly notice which stations are usable and which are not, it does not say how much of the potential from the selected stations are economically feasible. Table 5.2 shows that the economic potential for the in-stations ranges from 15.5-27 TWh/year depending on the cost assumption used. Compared to the demand of 26.13

TWh/year, it does not fare too poorly. It has to be noted, nevertheless, that some of the provinces do not have any economic potential at all under the Lockheed Martin cost. It is revealed that the preliminary premise of fulfilling 100% demand can be thwarted.

Table 5.2 Economic Potential of the In-Stations Scenario

Province	Demand (TWh)	Economic Potential					
		Vega (2012)			Lockheed Martin (2012a)		
		TWh	n	%	TWh	n	%
Aceh	2.33	2.6	3	112	0	0	0
Bali	5.10	5.62	6	110	0.91	1	18
Kalimantan Selatan	2.32	0	0	0	0	0	0
Kalimantan Timur	3.20	4.1	4	128	4.1	4	128
Nusa Tenggara Barat	1.59	2.07	2	130	2.07	1	130
Nusa Tenggara Timur	0.83	1.02	1	123	1.02	1	123
Papua	0.83	1.15	1	138	1.15	1	138
Sulawesi Selatan	4.94	6.08	6	123	5.12	5	104
Sulawesi Tengah	1.04	1.15	1	111	1.15	1	111
Sulawesi Tenggara	0.80	0.92	1	115	0	0	0
Sumatra Barat	3.15	2.29	3	73	0	0	0
TOTAL	**26.13**	**27**	**28**		**15.52**	**14**	

n = number of stations with economic potential,
% = the percentage of the economic potential compared to the demand

5.2 Electrification with Scaled-Down Plants

In this scenario, some of the 100 MW nominal plants are replaced with smaller plants. It is done as some provinces have extremely minute demand, that a 100 MW plant would produce way too much electricity. In two cases, Bengkulu and Sulawesi Utara, scaled-down plants are put forth to replace one 100 MW plant for the same reason. Similar to the previous scenario, the objective is to cover the whole demand for electricity production. In order to achieve that, each province is provided with plants of different nominal power capacities. The scaled-down plant sizes used are 25 and 50 MW, depending on the need of a province. Table 5.3 provides the sizing of the plants and the demand coverage.

Again, the same with the previous scenario, there is a strange case here. Sulawesi Barat is equipped with a 25 MW nominal plant and can only produce 96% of its electricity demand. It would be possible to increase the power capacity to 50 MW; however, the demand coverage percentage would reach around 190% and that is an enormous oversupply. Instead of going for the unnecessary oversupply, it is decided that slight undersupply is preferable.

Table 5.3. Number or Scaled-Down Plants and Demand Coverage

Province	Number of Stations	Size of Plants	Demand Coverage (%)
Bengkulu	2	100 + 50 MW	129
Gorontalo	1	50 MW	112
Kalimantan Utara	1	25 MW	122
Maluku	1	50 MW	112
Maluku Utara	1	50 MW	152
Papua Barat	1	50 MW	116
Sulawesi Barat	1	25 MW	96
Sulawesi Utara	2	100 + 50 MW	119

In this scenario, the LCOE for scaled-down plants is only recalculated for the selected stations. Hence, it is deemed unnecessary to provide LCOE distribution maps as it would be irrelevant. For the two provinces which need one regular plant in addition to the scaled-down plant, the LCOE is recalculated for the station with the shortest distance to the demand centre. The result of the LCOE recalculation is exhibited in Figure 5.4.

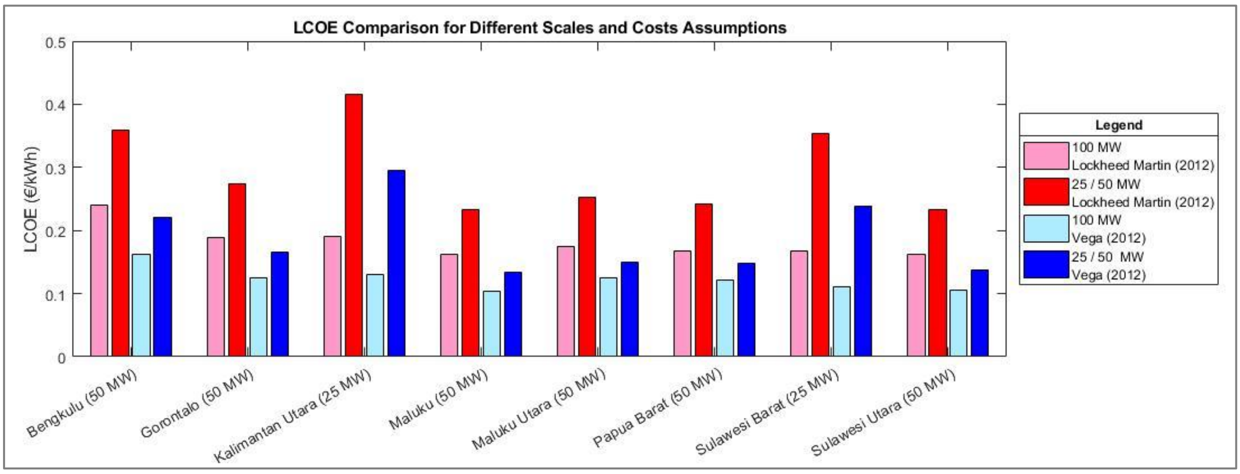


Figure 5.4. LCOE Comparison for Different Scales and Costs Assumptions

At first glance, it is visible that all scaled-down plants have higher LCOEs vis-à-vis the nominal 100 MW plants, both with Vega's and Lockheed Martin's costs. It can also be deduced that no scaled-down plant is economically feasible under Lockheed Martin costs. 25 MW plants have much higher LCOEs than the 50 MW, that even with low cost from Vega all 25 MW plants have the LCOEs of more than 0.20 €/kWh. This finding is in accordance with the scale curve showed earlier in the literature review (Figure 2.4). On the bright side, with Vega costs, only one 50 MW plant in Bengkulu is not economically feasible. This is reasonable as the resource quality of this particular station is not the best. With the temperature difference of only 21.5°, the real power output is less than 50 MW, affecting the annual energy production and LCOE negatively. The other 50 MW plant stations with Vega cost prove that OTEC plant with smaller scale can also add to the economic potential.

The maps of this scenario's results are not presented in the main text but can be found in Appendix A as they do not directly contribute to the analysis. Table 5.4 presents the values of the economic potential of the scaled-down plants. Within this scenario, an all-or-nothing situation occurs. None of the provinces has economic potential under the Lockheed Martin cost. Three of the provinces have economic potential even under the lower cost from Vega. However, under the Vega cost, three of the provinces possess enough economic potential to cover all the demand. Only Sulawesi Utara is not able to cover 100% of the demand.

Table 5.4 Economic Potential of the Scaled-Down Plants Scenario

Province	Demand (TWh)	Economic Potential					
		Vega (2012)			Lockheed Martin (2012a)		
		TWh	n	%	TWh	n	%
Bengkulu	0.82	0	0	0	0	0	0
Gorontalo	0.44	0.50	1	112	0	0	0
Kalimantan Utara	0.22	0	0	0	0	0	0
Maluku	0.48	0.54	1	112	0	0	0
Maluku Utara	0.34	0.52	1	151	0	0	0
Papua Barat	0.50	0.58	1	116	0	0	0
Sulawesi Barat	0.29	0	0	0	0	0	0
Sulawesi Utara	1.40	0.56	1	40	0	0	0
TOTAL	**4.49**	**2.7**	**5**		**0**	**0**	

n = number of stations with economic potential,
% = the percentage of the economic potential compared to the demand

5.3 Electrification with Resource from Beyond Province Boundary

The last scenario is the ambitious one. It aims to fulfil the electricity demand at any stake, even by exploiting resources outside of the province boundary in addition to the in-stations. These resources beyond the boundary from now on are called "out-stations". The out-stations are selected by the closest stations first, until the annual energy production of both in- and out-stations equals or slightly exceeds the demand. The number of in- and out-stations for each province in this scenario is showed in Table 5.5.

Table 5.5. Number of In- and Out-Stations and Demand Coverage

Province	Number of In-Stations	Number of Out-Stations	Demand Coverage (%)
Banten[1]	4	70	117
DI Yogyakarta	-	4	128
Jawa Barat	3	64	123
Jawa Tengah	-	30	112
Jawa Timur	3	40	106
Lampung	2	3	113
Sumatra Utara	2	12	101

[1] Demand for Banten includes demand for DKI Jakarta

It might not be surprising that most of the provinces needing the out-stations are located on the Java Island. The island has a vast population density, hence the gargantuan electricity demand. This, coupled with the narrow area of sea and relatively low temperature difference, leads to an inability to provide enough electricity supply only from the in-stations. In fact, two of the provinces listed in Table 5.5. DI Yogyakarta and Jawa Tengah, do not possess any available resource. Nevertheless, with the closeness to the out-stations, it was possible to include these provinces in this scenario. Aside from the provinces in Java Island, there are two provinces from Sumatra Island that also need the out-stations, namely Lampung and Sumatra Utara. Lampung has a quite high population, as it was a destination of transmigration from Java Island in the past. In Sumatra Utara, there are some of the biggest cities of the island, including the metropole of Medan.

Banten has the highest number of out-stations because of the inclusion of DKI Jakarta. DKI Jakarta as the capital city of Indonesia relies on the support of surrounding provinces, including Banten, to fulfil its electricity demand. Thus, it is decided to include the demand to be fulfilled by electricity from OTEC plants. Looking at Figure 5.5, the out-stations spread over the area bigger than the whole province, almost all the way to the exclusive economic zone border. With Lockheed Martin costs assumption, all selected stations are not economically feasible. Time and time again, Vega costs show a somewhat brighter result, with some of the out-stations having LCOE below the limit.

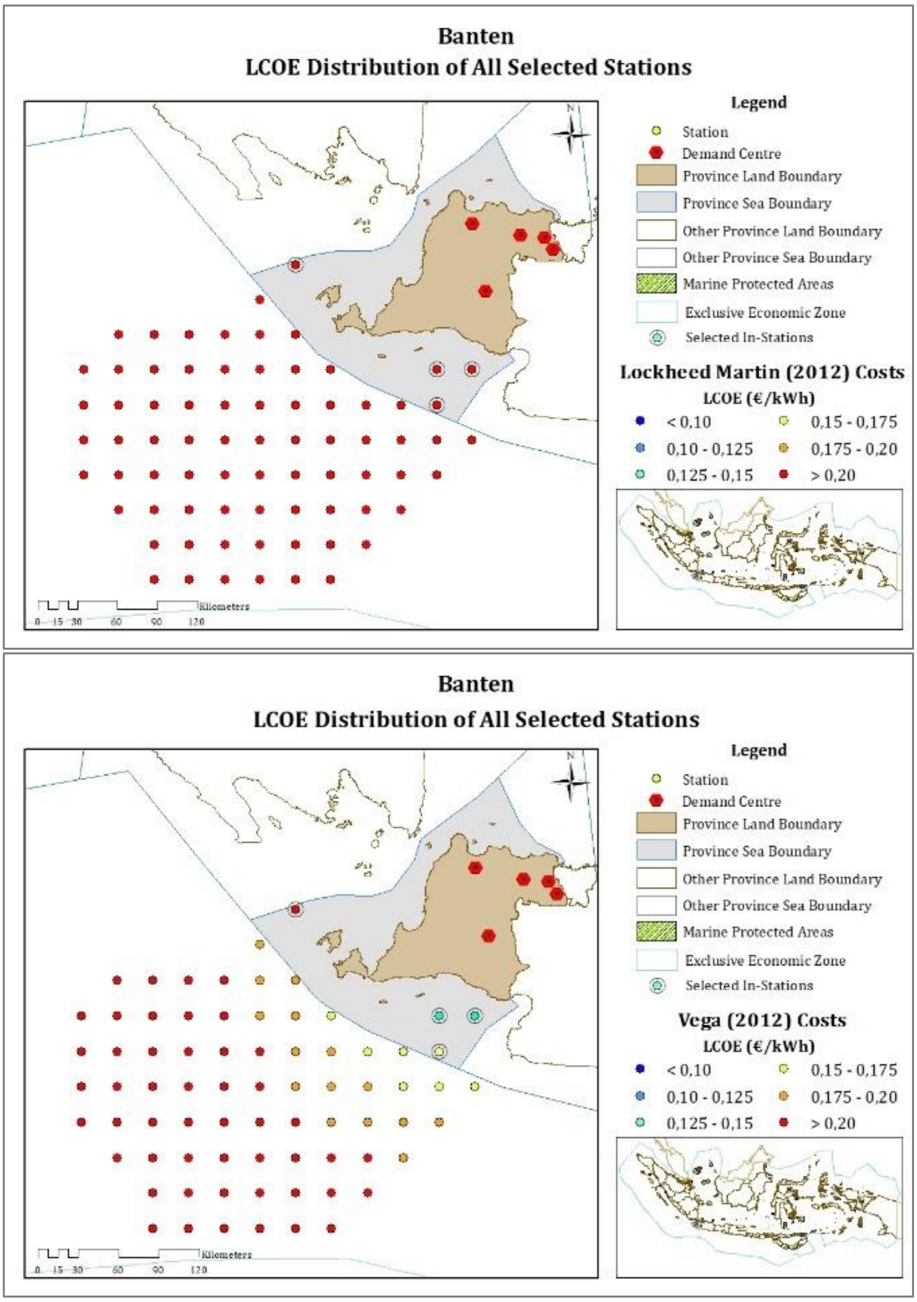


Figure 5.5. LCOE Distribution of All Selected Stations for Banten
top: Lockheed Martin (2012a) Costs; bottom: Vega (2012) Costs

DI Yogyakarta is one of the two provinces which do not possess any in-stations but assigned out-stations. This decision is prompted by the GIS model that attributed some of the stations to the demand centres in this province. This province shows once again the stark difference of Vega and Lockheed Martin costs assumptions. With the Vega costs assumption, all out-stations possess economic potential, while with the Lockheed Martin costs assumption, all out-stations have too high LCOEs. The LCOE distribution for DI Yogyakarta can be seen in Figure 5.6.

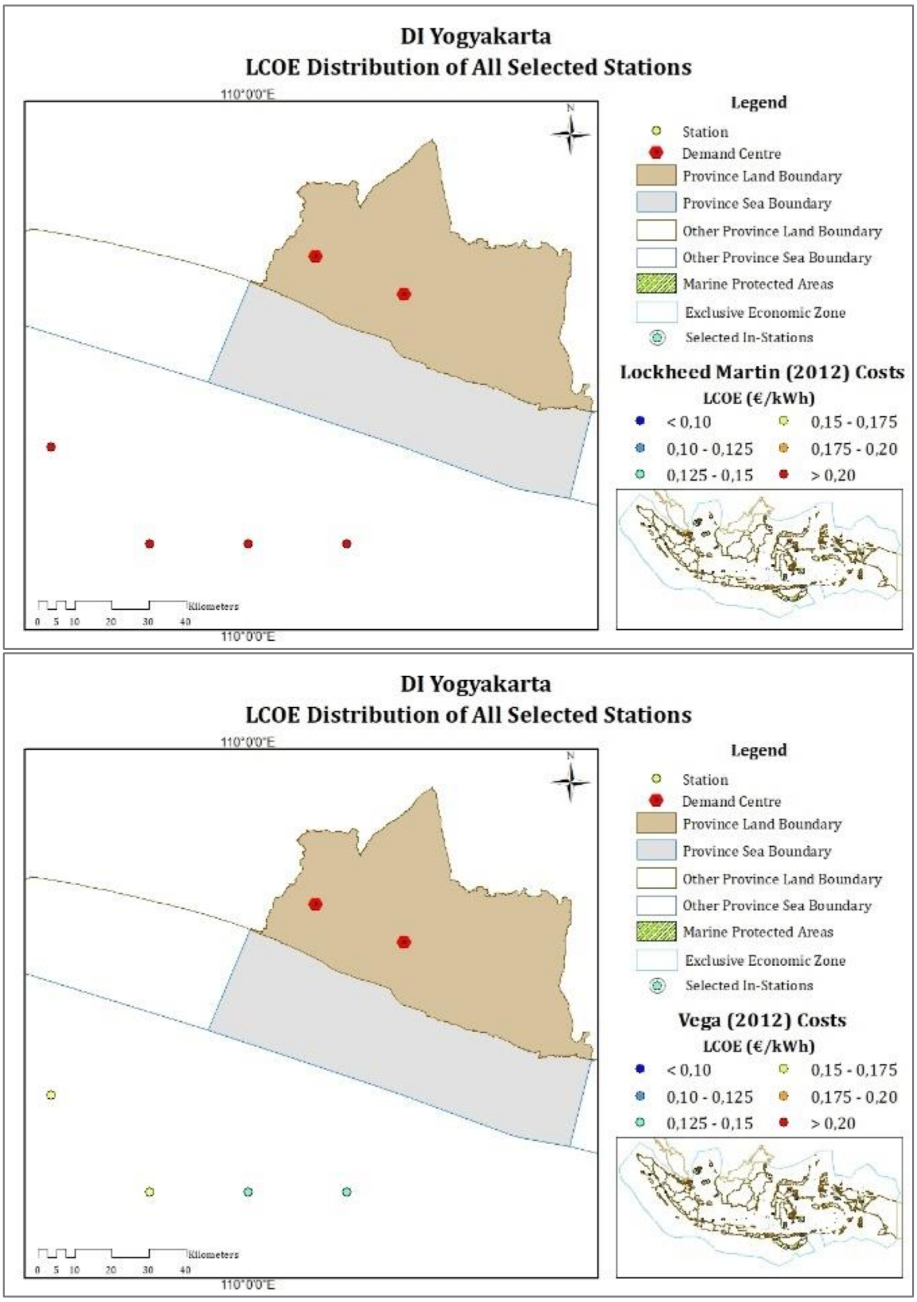


Figure 5.6. LCOE Distribution of Selected Out-Stations for DI Yogyakarta
top: Lockheed Martin (2012a) Costs; bottom: Vega (2012) Costs

Up to this point, it is known that with Lockheed Martin cost assumptions, all of the out-stations have more than 0.20 €/kWh. Unfortunately, the situation does not only happen to these two but to all the provinces in this scenario, as visible in Table 5.6. Luckily, there are still some hopes for economic potentials when Vega cost assumption is used. Only Sumatra Utara does not have any economic potential under both cost assumptions. The LCOE distribution maps of all provinces are provided in Appendix A.

Table 5.6 Economic Potential of the Out-Stations Scenario

Province	Demand	Economic Potential					
		Vega (2012)			Lockheed Martin (2012a)		
		TWh	n	%	TWh	n	%
Banten	51.66	21.27	25	41	0	0	0
DI Yogyakarta[1]	4	3.46	4	128	0	0	0
Jawa Barat	46.14	42.86	46	93	0	0	0
Jawa Tengah[1]	30	15.94	18	74	0	0	0
Jawa Timur	32.93	27.58	32	84	0	0	0
Lampung	3.82	1.73	2	45	0	0	0
Sumatra Utara	9.24	0	0	0	0	0	0
TOTAL	**225**	**112.84**	**127**		**0**	**0**	

n = number of stations with economic potential,
% = the percentage of the economic potential compared to the demand
[1] DI Yogyakarta and Jawa Tengah do not have any in-stations

Figure 5.7 illustrates the distribution of all selected stations in the country. It can be seen that the out-stations come as a farm while the in-stations are more of a standalone nature.

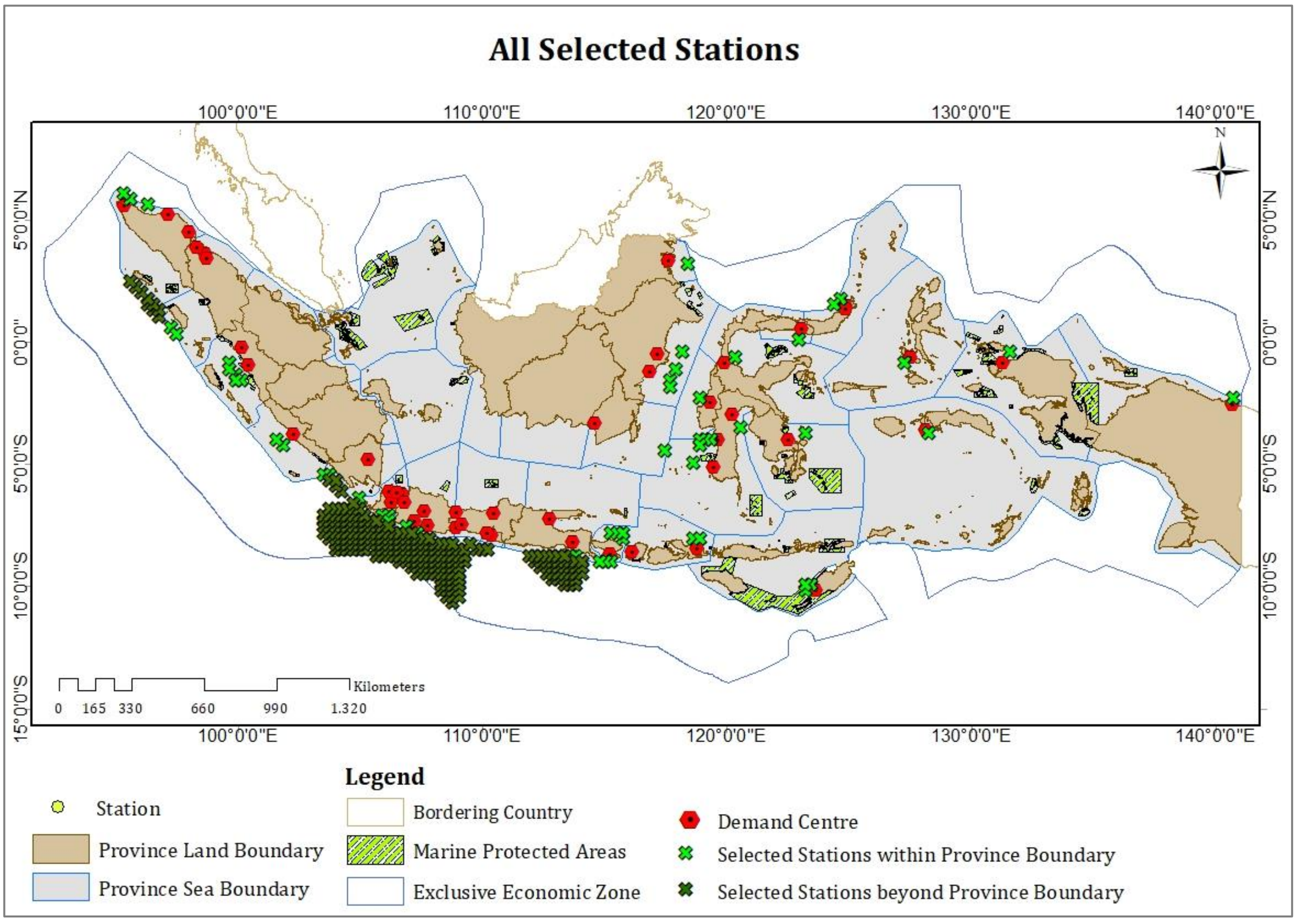


Figure 5.7. Selected In- and Out-Stations

5.4 Conclusion of Electrification Scenarios

With the exception of one province, it is possible to fulfil the entire demand of each province only by using electricity produced by OTEC plants, as long as the LCOE limit is ignored. The total available annual energy production in this case is 228 TWh, slightly higher than the total demand of 199 TWh. However, when the LCOE limit is employed, the result is very different. The total available annual energy production, now also the economic potential, ranges between 15.52 – 142.54 depending on the cost assumption being used.

6. Discussion and Recommendations

6.1 Discussion

6.1.1 Validation of The Results

Although this thesis is a continuation of work by Chalkiadakis (2017) and Langer (2018), the approach used here is very different from the approach of the other authors. Chalkiadakis focused very much on the analysis of the geographical characteristics of the locations in determining the potential. In contrast, Langer delved deeply into the economic analysis and not paying more attention than necessary to the geographical aspects. This thesis is quite in between the two by first looking into the available stations based on geographical aspects before then calculating the economic potential. The difference in the approach leads to the difference in results. Compared to Langer who also did economic potential analysis, it seems that this thesis has lower LCOE and thus, higher economic potential. Langer states that the economic potential ranges between 0 – 913 TWh, depending on the cost assumption and LCOE limit used. For this thesis, the national calculation yields the economic potential of OTEC is 2607 – 3691 TWh/year with original distance to closest shore and 317 – 1431 TWh/year with adjusted distance to demand centres. To make an apple-to-apple comparison, the potential of annual energy production with Lockheed Martin cost assumption under the LCOE of 0.40 $/kWh (0.35 €/kWh) is computed for both studies. In Langer's study the potential amounts to around 500 TWh, while in this thesis the potential reaches 2446 TWh, almost 5 times bigger. This stark difference might come from the initially available stations. While Langer uses 1028 stations only throughout the country, this thesis possesses 4888 suitable stations in the beginning. Looking at the ratio of initial stations, the earlier comparison of the results is very much in line.

6.1.2 Limitations in Methodology

In this thesis, a new methodology is built by combining the steps of GIS and techno-economic analysis methods. This methodology has been proven by literature and again proven to be sufficient to conduct this research. However, the way the stages were conducted is not without flaw. The most important thing to be addressed is the data. The temperature data were obtained from an online modelling source. Although this data is deemed to be reliable to be used in various studies, it is still important to conduct a field measurement to verify the data.

Along the research, it is realised how big the effect of a methodology is to the result. The comparison of results with Langer described above is one example. Another example lies in this thesis when the distance is adjusted from to-nearest-shore to to-demand-centre in an effort to adhering more to reality. However, the new distance measurement also comes with a shortcoming that is not addressed in the thesis. If one tries to connect a station to a demand centre, then they must lay cable in the sea and on land. These cables might have different characteristics and thus, different cost. Unfortunately, to maintain simplicity, the cable costs assumption stays the same in both sea and land part.

Aside from that, the calculation of cable cost still holds other drawbacks. In this thesis, there is only one cable cost function being used. Initially, another cable cost function was to be brought about in the calculation, based on the offshore wind farm. However, it was discovered that the cable used in the literature was too big for a single 100 MW OTEC plant, as it was for a farm with the power output of GW, instead of MW (Xiang, Merlin, & Green, 2016). This cable cost function could have been used if the selected stations are configured as a farm and connected to the shore with a single cable instead of multiple cables for multiple stations. It is yet another weakness of the thesis. In this thesis, the cable length is simply the shortest distance from the station to the shore or the demand centre. In reality, the cable length might be considerably longer if it is to be laid down on the seabed.

From the results, it is apparent that there are “jumps” in the economic potential values from the lower Vega (2012) cost to Lockheed Martin (2012a) cost. The results would be better if there are more cost estimation values being used at smaller intervals between each other. It might be beneficial as one can pinpoint from which cost the OTEC plant is entirely infeasible.

The scenarios of this thesis are not realistic. It was meant only to give an idea of the capability of OTEC as an electricity producer. OTEC indeed is capable of providing baseload compare to the intermittent renewables such as wind or solar energy but employing OTEC as a single source of energy is not realistic and adding a problem to the energy security. The scenarios also did not consider the implementation timeframe. It was assumed that all OTEC plants are ready to be built overnight. This is not the case. To improve the result, a timeline of implementation is important to be employed, along with the learning effect. As shown by Langer (2018), this is beneficial for reducing the cost considerably.

6.1.3 Added Value, Novelty, and Broader Relevance

This thesis proposes a new methodological stage sequence. True, it is based on the methodologies already exist before, however, no one has presented the stage sequence explicitly as it is. This stage sequence can be easily applied to assess the economic potential of OTEC in other locations. With slight modification, it can even be applied for other types of renewable energy resources. Another good thing about the methodology is that it can be applied to almost any scale, from very local to global.

The results of the research give an idea of how feasible the application of OTEC plants as an electricity producer in Indonesia is. In fact, it is not that feasible. In relation to the market, this thesis is pretty much secluded. For one, it does not consider the competition with other electricity producers when it aims to fulfil the whole electricity demand with electricity from OTEC. It means that the scale of plants employed in real life might actually be considerably smaller than the ones being discussed in this thesis. As already found out, smaller plants have higher LCOE. The second problem is, the base LCOE limit employed here (0.20 €/kWh is actually too high for OTEC to be actually economically feasible. As a comparison, the PLN can buy electricity from coal plant in Java island with the price as low as 4 $ct./kWh. The good news is an appendix of the Ministerial Decree of Ministry of Energy and Mineral Resources No. 16 Year 2016 states that the feed-in tariff for energy from solar PV in Indonesia ranges from 14.5 to 23 $ct./kWh (around 0.13 to 0.20 €/kWh). If the feed-in tariff can be applied to OTEC as well, that would pave the way towards implementation.

6.2 Recommendations

Up until today, there are no commercial OTEC plants being in operation as of yet. The main hurdle is the gigantic capital cost needed to build an OTEC plant. With the availability of other cheaper renewable energy resources, it is quite understandable that there is a reluctance towards this particular technology. However, there are still some hopes that OTEC will someday take off and become a prominent part of the electricity production landscape. There are some recommendations for fostering OTEC implementations.

6.2.1 Recommendations for Further Research

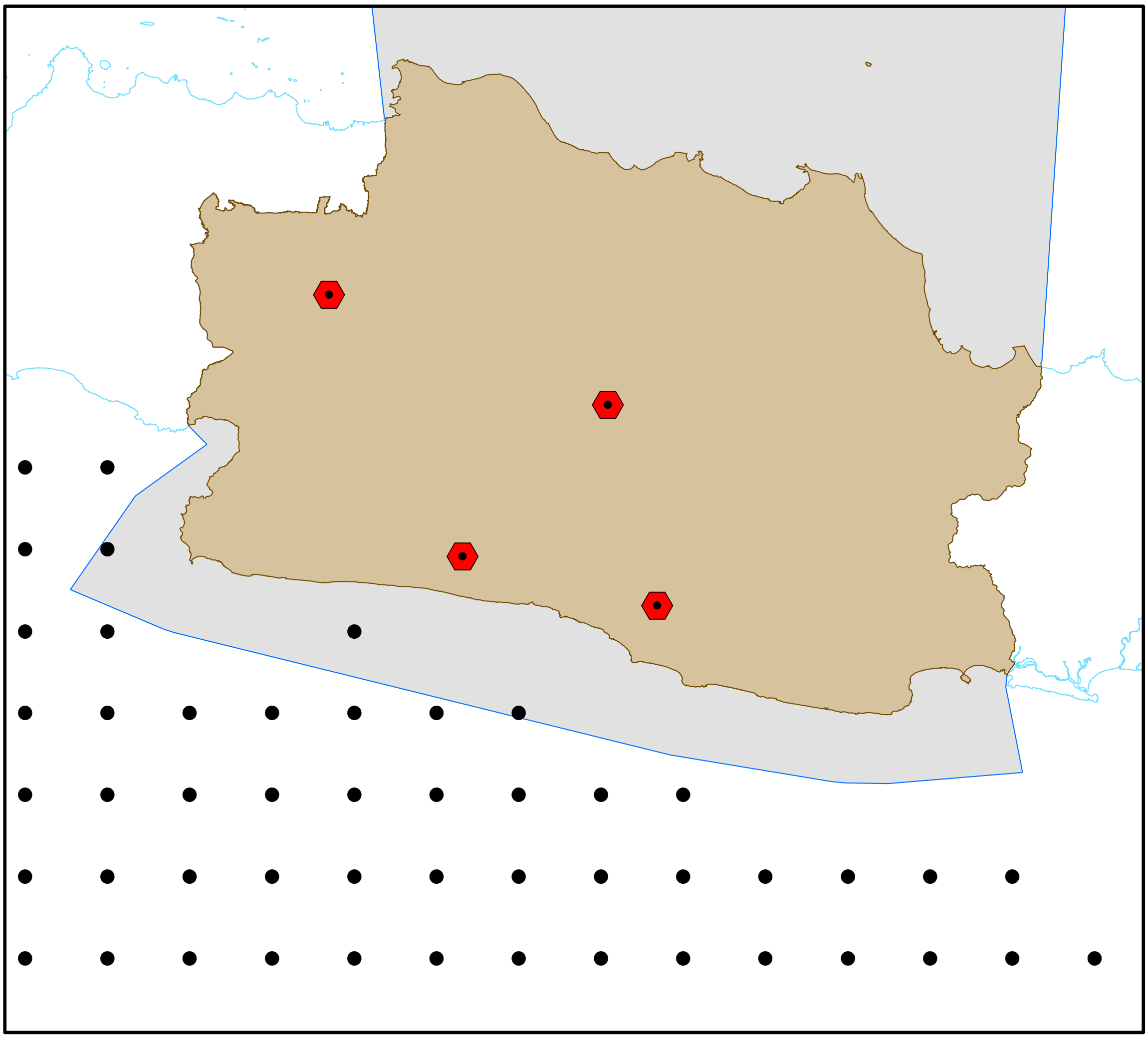
The first set of recommendations is directed towards academia. Many different parts of an OTEC plant are not new technology. For instance, the structure, the machinery, the cables. However, aside from the report from Lockheed Martin, there is scarcely any literature discussing about OTEC parts in detail. It is recommended to conduct a study on different OTEC parts and compare the parts with state-of-the-art technologies from other fields, e.g. offshore wind farm and offshore oil rig. Further analysis about the potential of OTEC, such as the profitable potential, market potential, and policy-enhanced potential can also be helpful, especially to see how OTEC stands against other technologies. Surely there are already comparisons of the LCOEs from multiple technologies, but an optimisation study to find the best configuration of OTEC coupled with other technologies is not present yet. Related with the market, it is needed to study the policies related to OTEC implementation, e.g. with what renewables are OTEC comparable to and how to deal with the environmental impact of OTEC.

6.2.2 Recommendations for Energy Industry

Aside from the academia, the industry needs to step up the game. Engineering companies such as Lockheed Martin and Bluerise should start building OTEC plants of any scale. On the other hand, utility companies should also start to think about investing in new electricity production technologies. This should start first in the more developed countries with enough monetary resources. Of course, the massive capital cost will be a hurdle, but in cooperation with the government, academic institutions, and international organisations it is possible to overcome this problem. To allow for this massive international cooperation, companies need to share their shortcomings and achievements transparently. This way, the companies can learn from each other instead of having to start everything from scratch.

6.2.3 Recommendations for the Government of Indonesia

The next recommendations are directed towards the government of Indonesia, further called as 'the government'. The government should be more open towards new renewable energy technologies by making the policies more fluid, e.g. by not limiting the type of technology in the feed-in tariff scheme and by not putting a cap of renewable energy quota allowed in a region. Limiting the type of technology allowed in the feed tariff scheme is putting the less mature technology at a further disadvantage. Surely a cap in feed-in tariff or other subsidies is needed but limiting the amount of renewables production allowed in a region can seriously hamper the implementation of renewables. The government can also help by simplifying the procedures of getting a permit for building renewables. In Indonesia, the procedure for getting a permit can be a long and exhausting road. Tidal Bridge BV, a Dutch company planning to build a bridge with tidal turbines underneath in Nusa Tenggara Timur, needed 2 years before the government finally agreed to the proposal. The last recommendation for the government is to provide funding schemes in cooperation with industry and international organisations.



7. Conclusions

This chapter is the final chapter of this thesis. In this chapter, the sub-questions asked in the beginning of the thesis are answered one by one. This chapter is concluded by the answer of the main research question.

1. What is the most suitable methodology to assess the economic potential of OTEC?

Similar to the studies found in literature, it follows the steps of the GIS method while incorporating the steps of the techno-economic analysis at the same time. The combined methodology consists of 5 main stages that are designed to be reproducible easily for analysing the economic potential of OTEC in different locations. The first stage is the problem definition, where the location and the type of renewable energy resource to be analysed are chosen. The second stage is gathering and pre-processing the data. The third stage is the potential areas determination, which is done by assigning the economic parameters, computing the levelized cost of electricity (LCOE) of each station, and calculating the economic potential. In this thesis, a station's nominal size is 100 MW and it is said to have an economic potential if it has an LCOE of less than 0.20 €/kWh. The economic potential is calculated both on national and provincial levels. The fourth stage is building the electrification scenarios by selecting the stations and enumerating the economic potential of the selected stations. The fifth stage is presenting the results and the sixth stage is establishing the conclusions.

2. What are the economic potentials of OTEC on national and provincial levels in Indonesia?

The potential areas of OTEC plants are mainly determined by the temperature difference between the surface- and deep-water. Based on the temperature difference data, the real power output of each station is calculated. The result shows that in Indonesia, the real power output of an OTEC plant at any given station is almost always larger than the nominal power. The distribution of the annual energy production (AEP) shows that the further away a plant is located, the less annual energy it produces. Initially, the distance used to calculate the LCOE is the closest distance between the stations and any closest shore. With the original distance, the economic potential of OTEC on the national level in Indonesia ranges between 330-473 MW or equivalent to 2607-3691 TWh/year, depending on the cost assumption being used. However, this is not realistic. Hence, the distance is adjusted to the demand centres. All results that follow the adjustment are calculated based on the adjusted distance. The economic potential on the national level with the adjusted distance range between 50-192 MW or 318-1431 TWh/year, considerably lower than the economic potential with the original distance. On the provincial level, it is discovered that high availability of resource does not directly translate to high economic potential. The total economic potential on the provincial level ranges between 253-904 TWh. It is slightly lower than the national potential as some of the stations are located outside the boundaries of the provinces. In any case, the amount of economic potential in Indonesia can cover its total electricity demand of 175 TWh/year.

3. What are the possible electrification scenarios to fulfil provincial electricity demands solely from OTEC production and what are the economic potentials?

There are three scenarios present in this study, i.e. electrification with resources within the province boundaries ("in-stations"), with scaled-down plants ("scaled-down"), and with resources beyond the province boundaries ("out-stations"). The result shows that it is relatively easy to cover 100% of the demand only with the production of OTEC plants if the LCOE limit is ignored. Once the limit is considered, many provinces lost any potential, even under the lower cost assumption of Vega (2012). The economic potential for the in-stations ranges from 15.52-29.79 TWh/year depending on the cost assumption. For the scaled-down stations, the economic potential is 2.7 TWh/year under the Vega (2012) cost assumption and nothing under the Lockheed Martin cost assumption. Similarly, for the out-stations, the stations only hold the economic potential of 113 TWh/year under Vega (2012) cost assumption and nothing at all under the Lockheed Martin cost assumption. In total, 164 of the 273 selected stations hold economic potential with Vega (2012) cost assumption and only 14 stations with Lockheed Martin (2012a) cost assumption. The total economic potentials of these usable stations are 145 TWh/year and 15.52 TWh/year respectively.

4. What are the recommendations to foster OTEC implementation?

The recommendations are directed towards three different actor groups, i.e. the academia, the industry, and the government of Indonesia. The recommendation for the academia consists of the interesting topics to be researched in the future, ranging from research on OTEC parts to the analysis of OTEC in the market. The recommendations for the energy industry are directed towards both the engineering companies and utility companies. There should be a cooperation between these companies, academic institutions, and international organisations to enable the construction of new OTEC plants. The last recommendations are directed towards the government of Indonesia. The government should be more open towards new renewable energy technologies, should simplify the procedures of getting a permit for building renewables, and should provide funding scheme in cooperation with industry and international organisations.

What are the national and provincial economic potentials of ocean thermal energy conversion in relation to the provincial electricity demand fulfilment in Indonesia?

When we are talking about the economic potential of OTEC in Indonesia, we are talking about potential as a result of different possible configurations. On the national level, the economic potentials of both cost assumptions are more than enough to fulfil the total electricity demand of the country. However, Indonesia seizes an immensely broad area of land and sea. A big part of the potential lies outside the provincial boundaries, far away from demand centres. Still, when only the provincial potentials are considered, the total economic potential is higher than the demand. This does not necessarily mean that the available resource is accessible by the demand centres, though. The available resources of OTEC are not distributed evenly throughout the country. Some areas are blessed with remarkably good resources in abundance while the other areas are not so lucky with the resources. Hence, the stations are selected based on the proximity to the demand centres. It turns out that based on the results of the thesis, it is not possible to fully supply the electricity demand on the provincial level in Indonesia solely by OTEC electricity production of the selected stations. It is indeed possible for some areas to do that, but in other areas, there is no economic potential at all. However, it is not likely that a single resource will ever be used to cover 100% of supply. In this sense, there is a huge opportunity for OTEC to enter the energy landscape and become the provider of baseload electricity.

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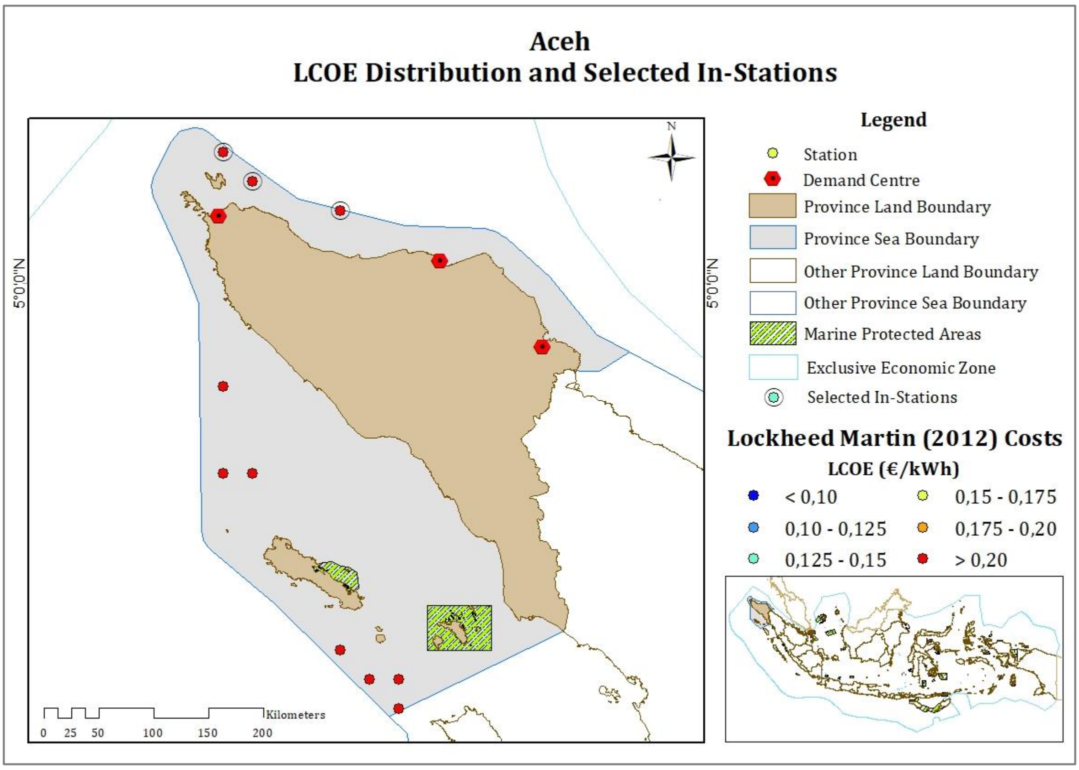
Appendix

A. LCOE Distribution Maps

1. Aceh



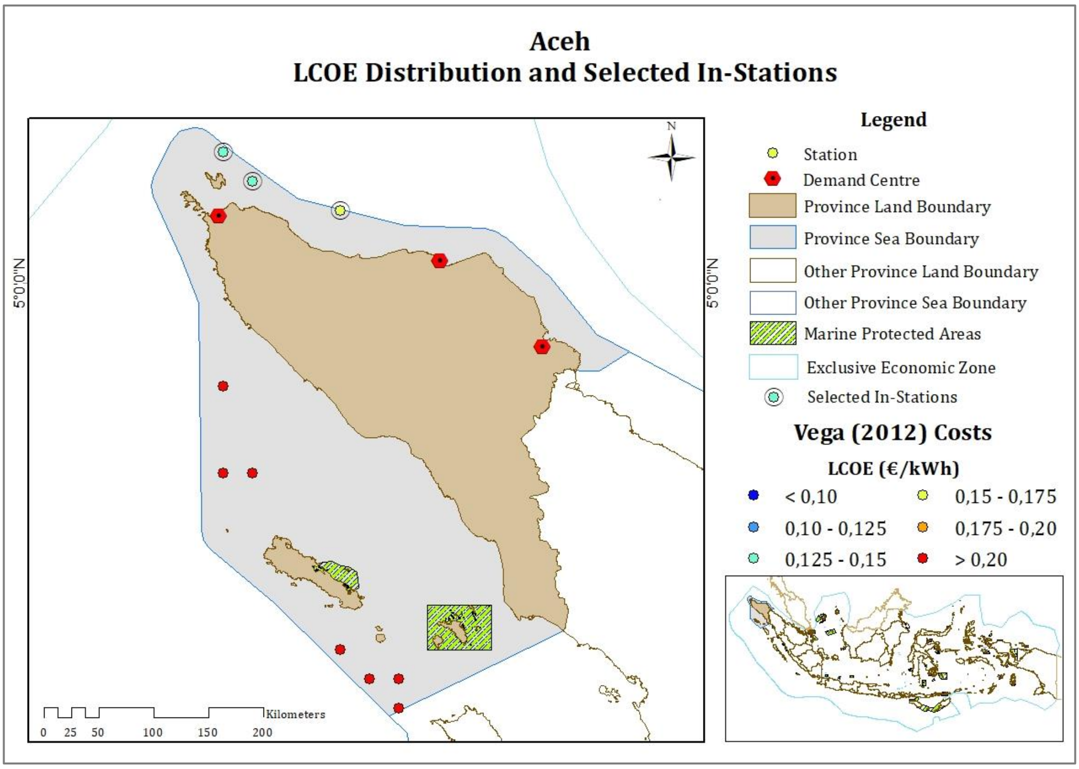
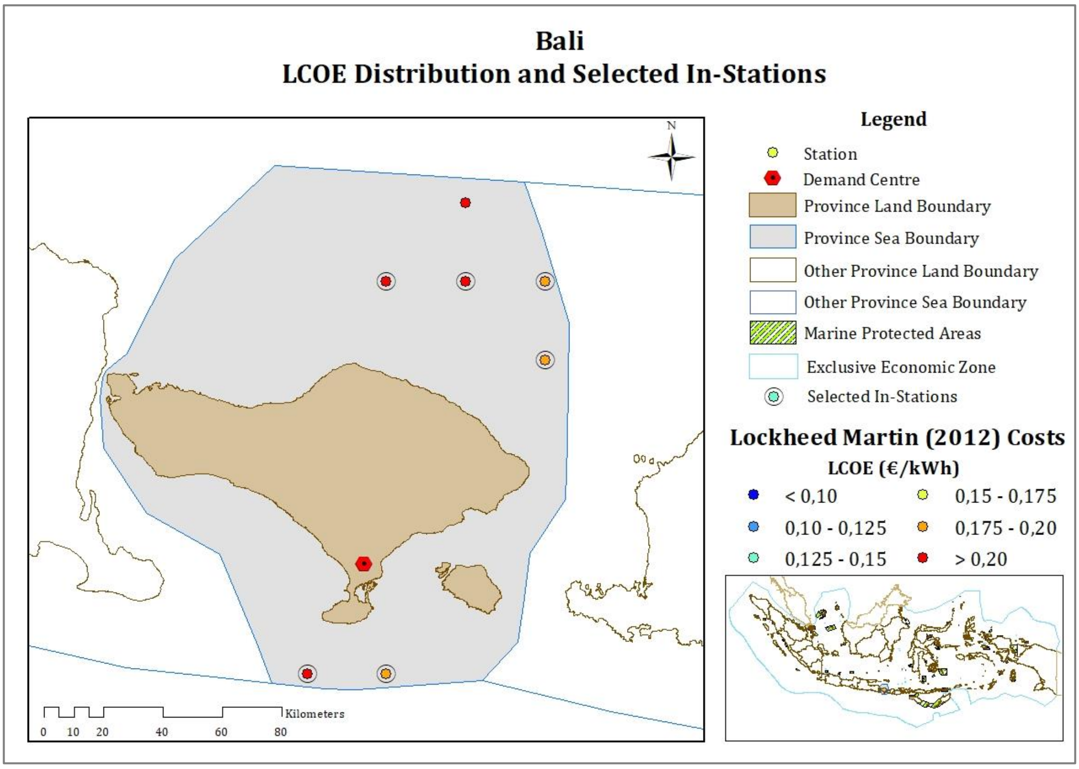


Figure A.1 LCOE Distribution of In-Stations for Aceh
Top: Lockheed Martin (2012a) costs, Bottom: Vega (2012) Costs

2. Bali



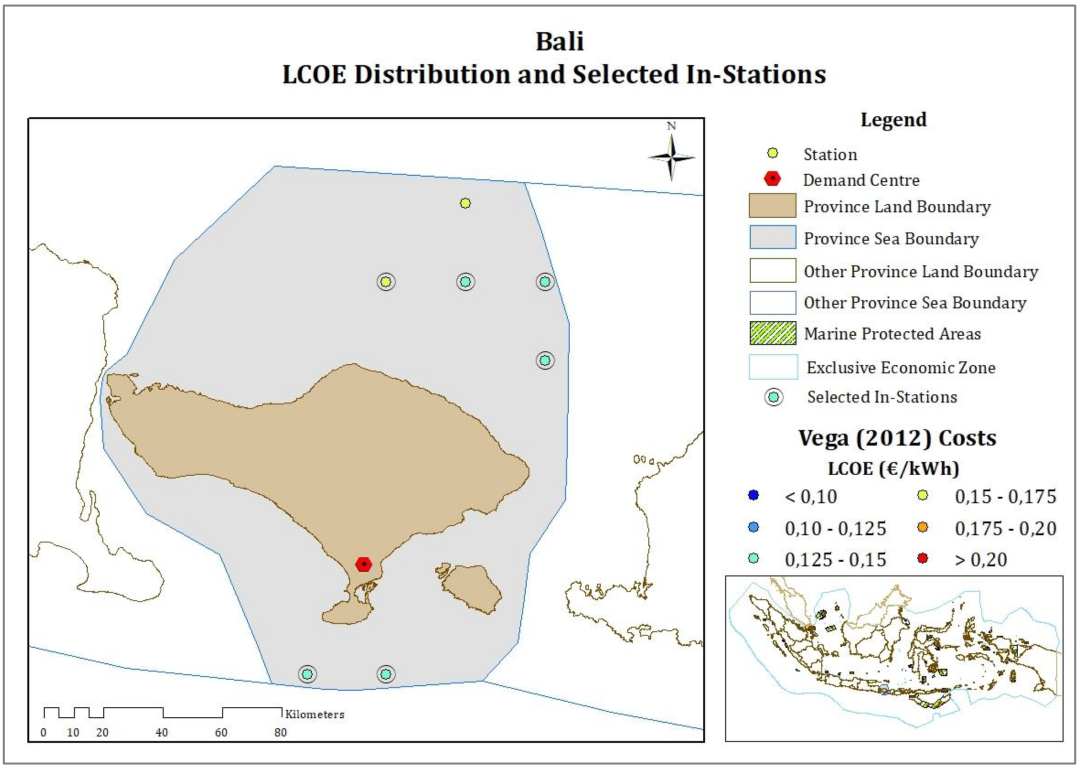
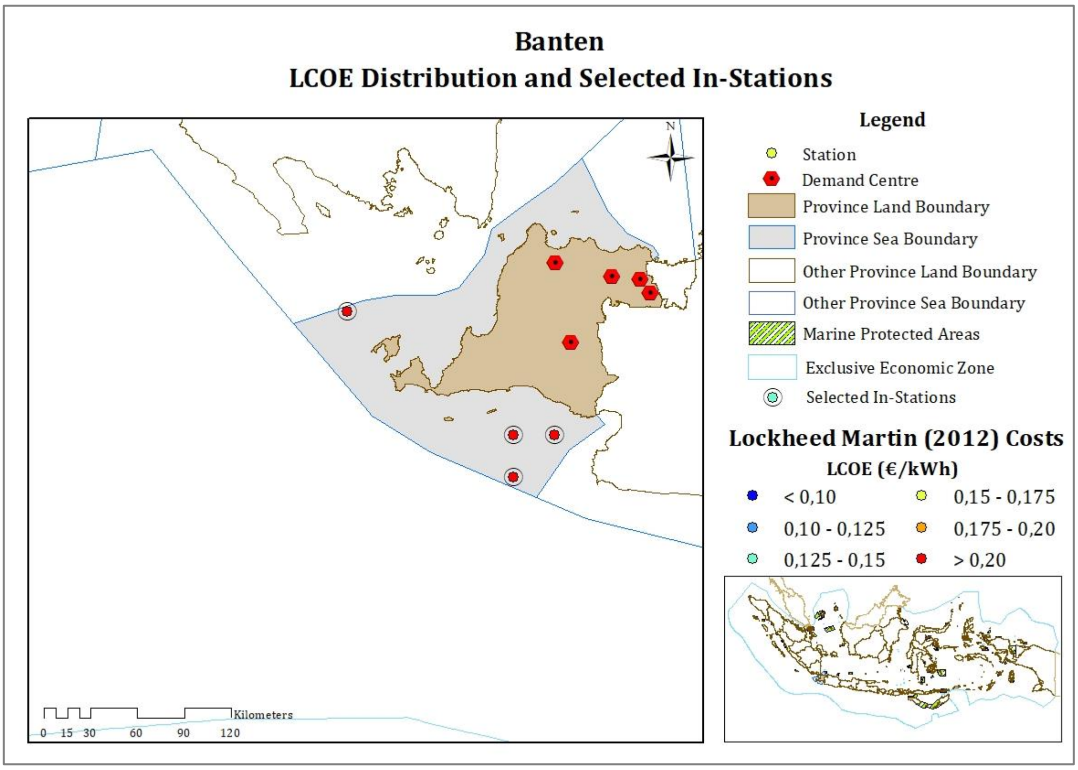


Figure A.2 LCOE Distribution of In-Stations for Bali
Top: Lockheed Martin (2012a) costs, Bottom: Vega (2012) costs

3. Banten



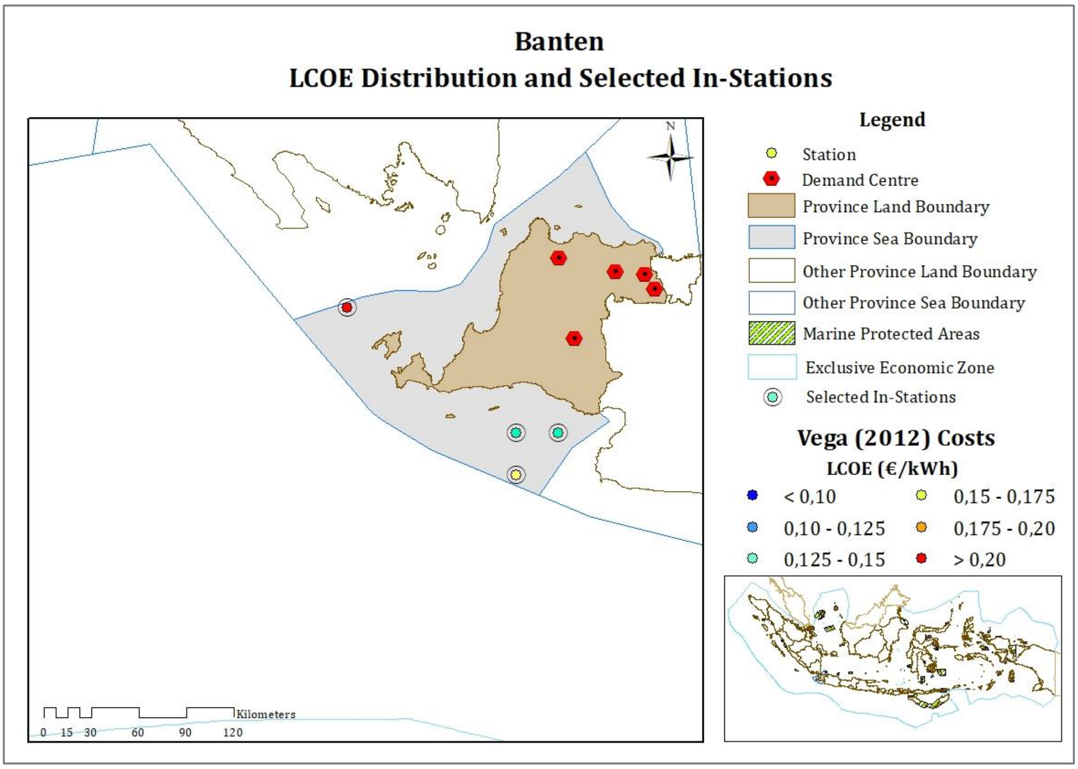
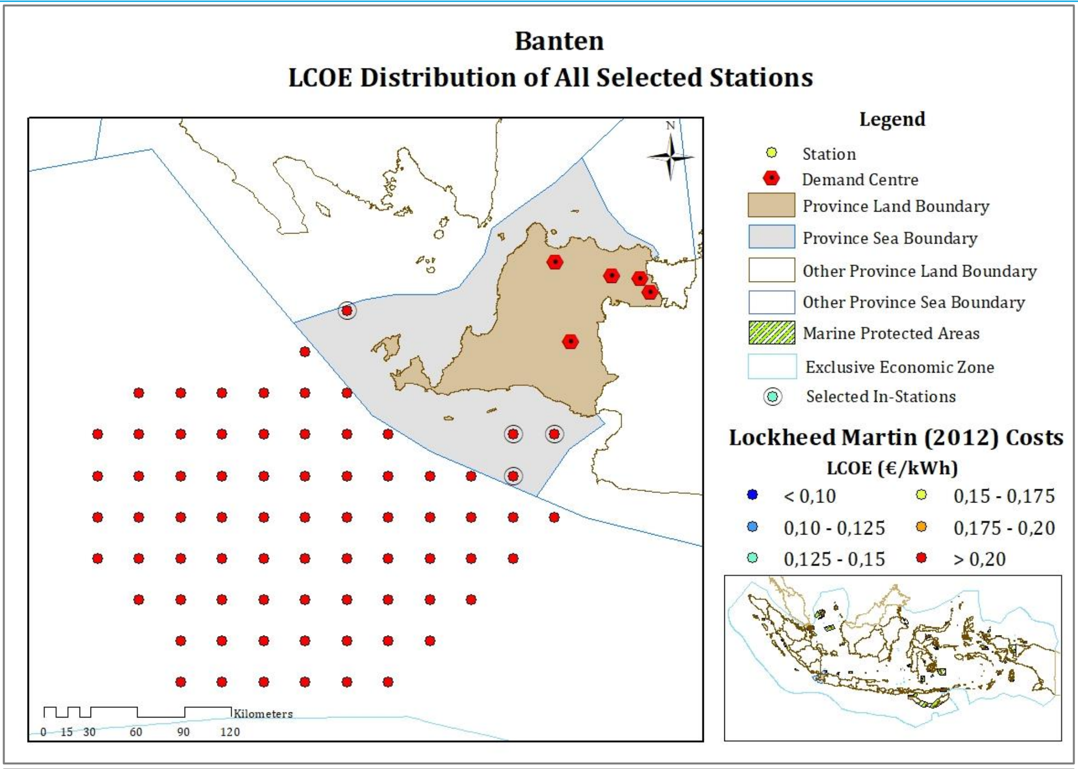


Figure A.3. LCOE Distribution of In-Stations for Banten
Top: Lockheed Martin (2012a) costs, Bottom: Vega (2012) Costs



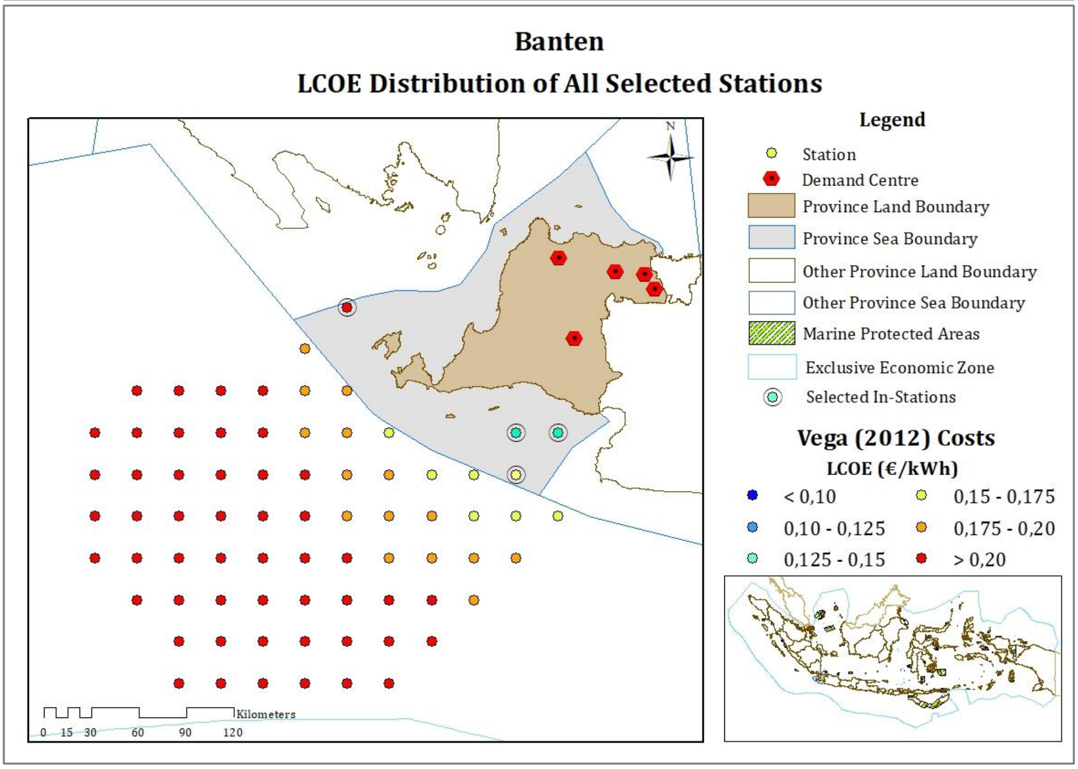
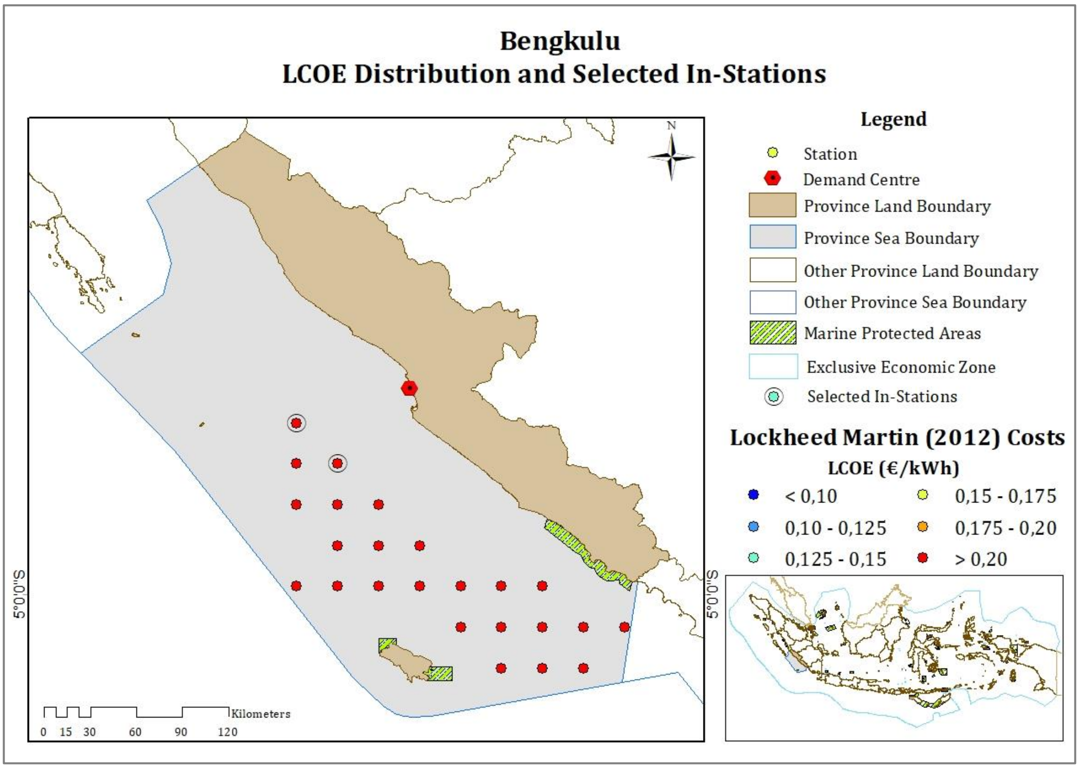


Figure A.4. LCOE Distribution of All Selected Stations for Banten
Top: Lockheed Martin (2012a) costs, Bottom: Vega (2012) Costs

4. Bengkulu



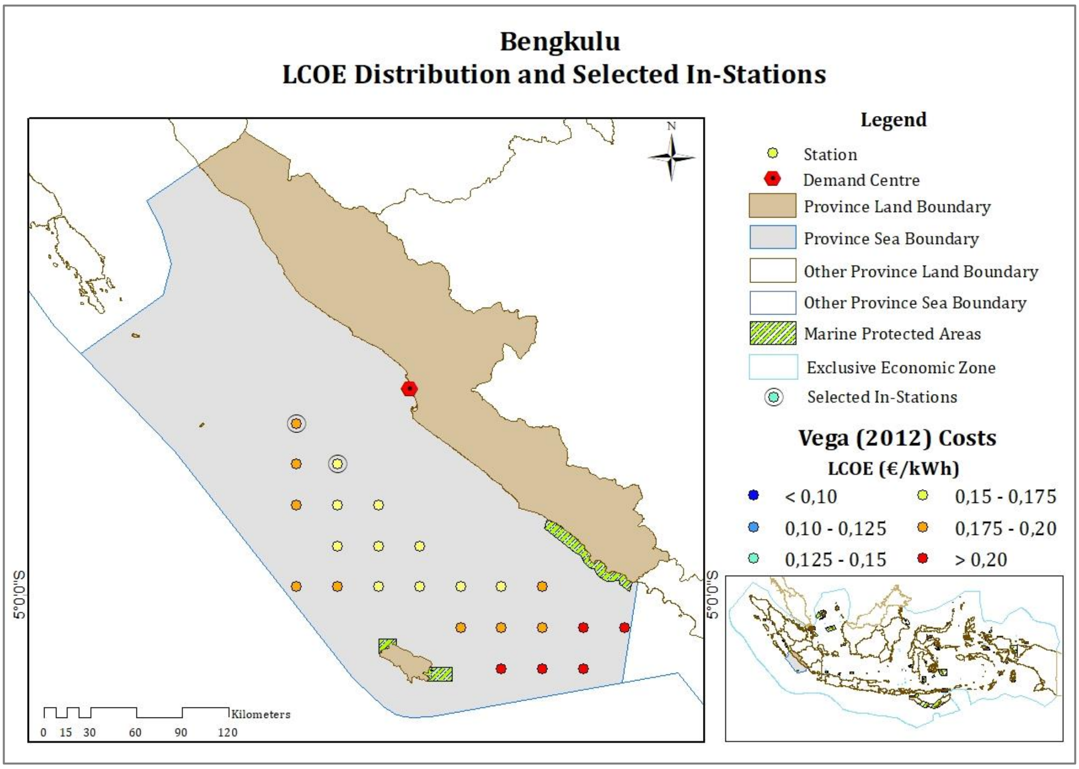


Figure A.5 LCOE Distribution of In-Stations for Bengkulu
Top: Lockheed Martin (2012a) costs, Bottom: Vega (2012) Costs

5. DI Yogyakarta

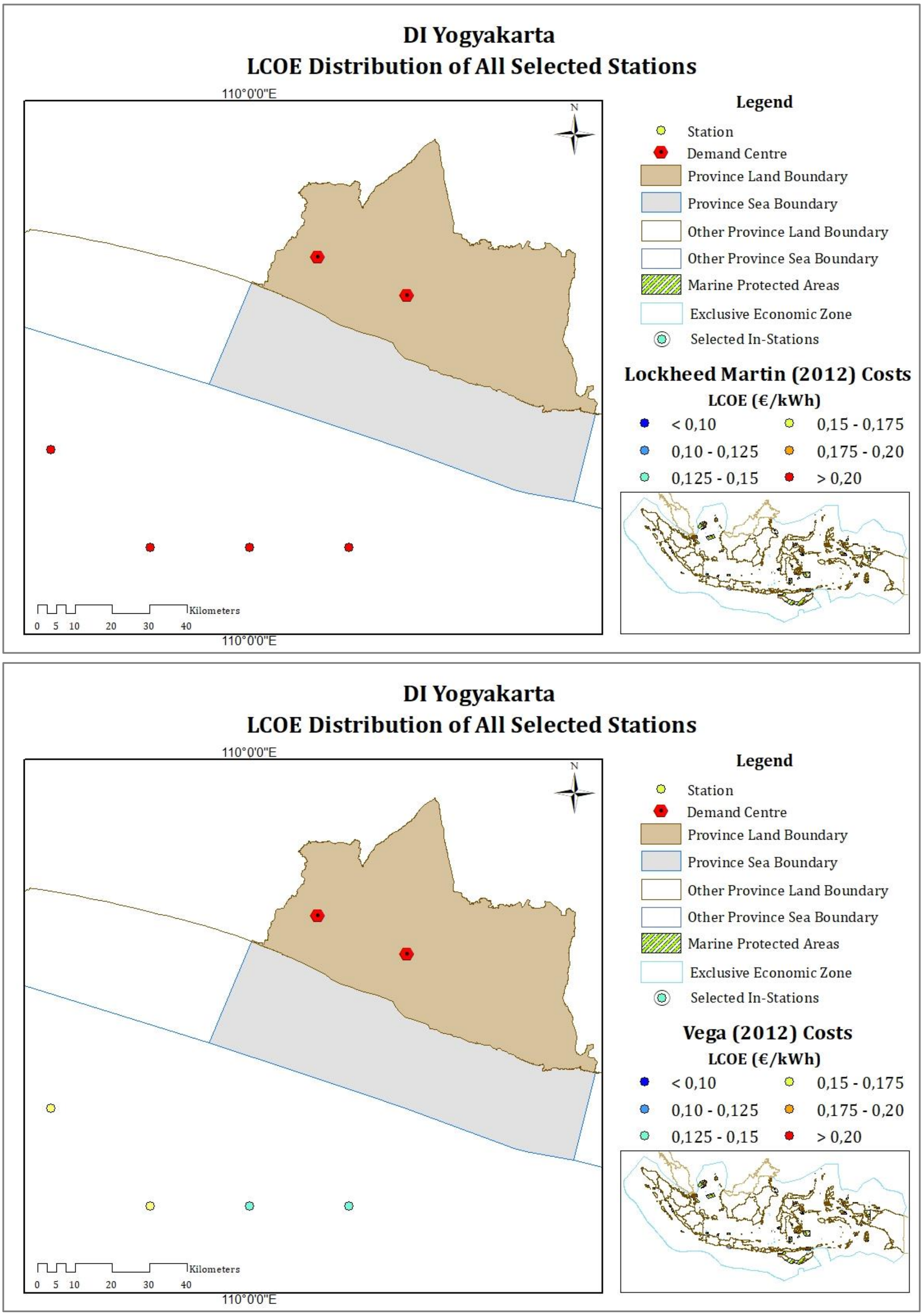
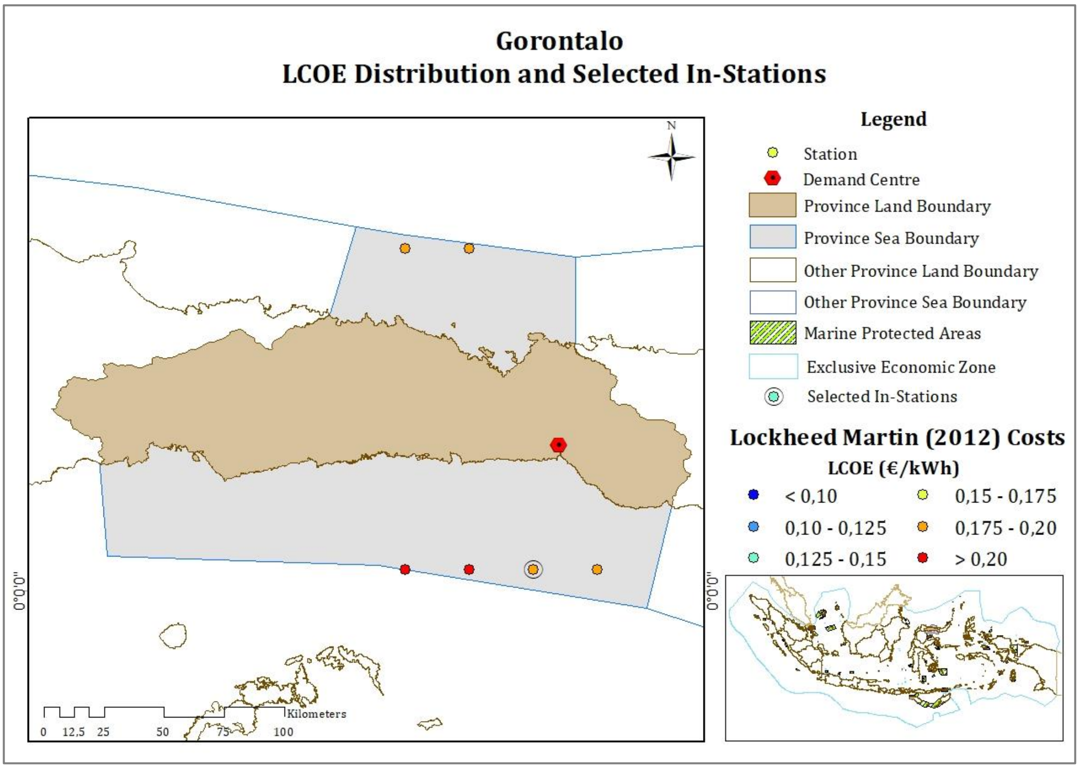


Figure A.6 LCOE Distribution of All Selected Stations for DI Yogyakarta
Top: Lockheed Martin (2012a) costs, Bottom: Vega (2012) Costs

6. Gorontalo



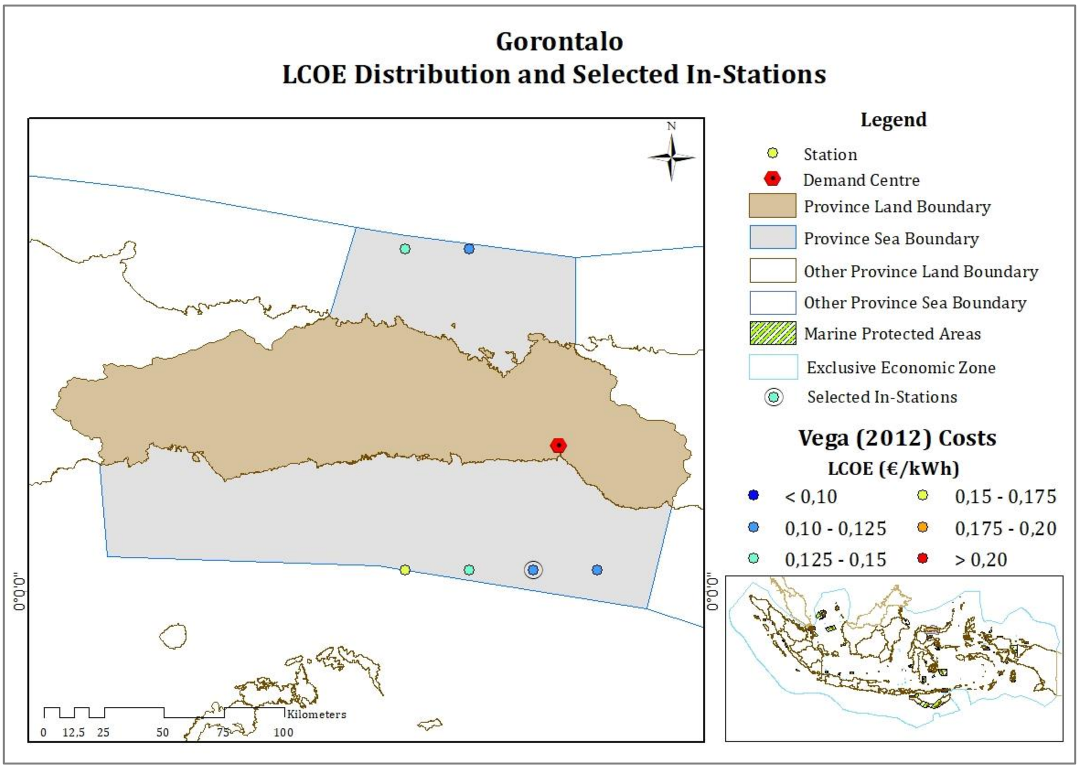
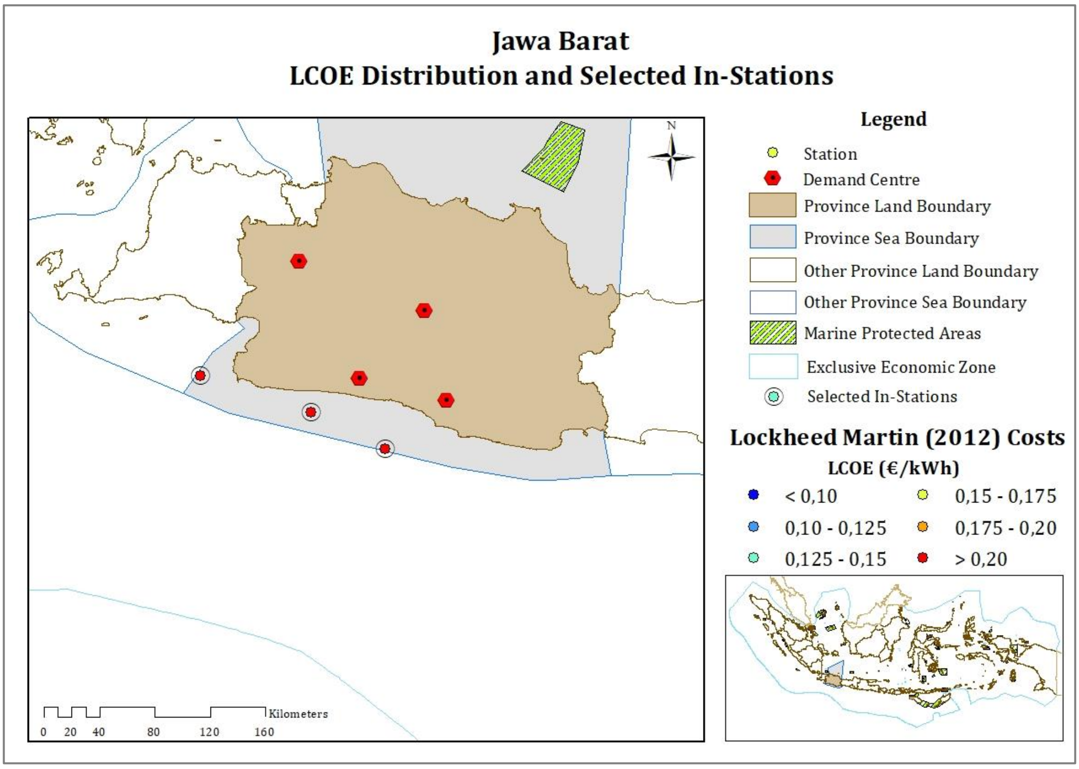


Figure A.7 LCOE Distribution of In-Stations for Gorontalo
Top: Lockheed Martin (2012a) costs, Bottom: Vega (2012) Costs

7. Jawa Barat



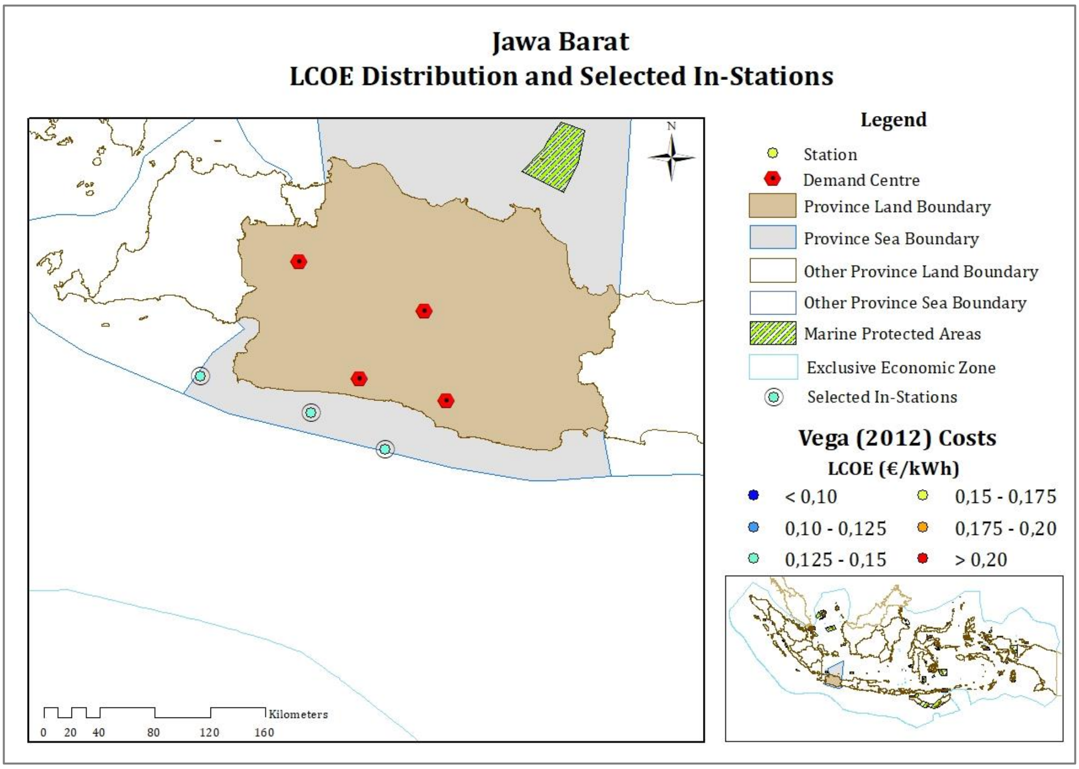
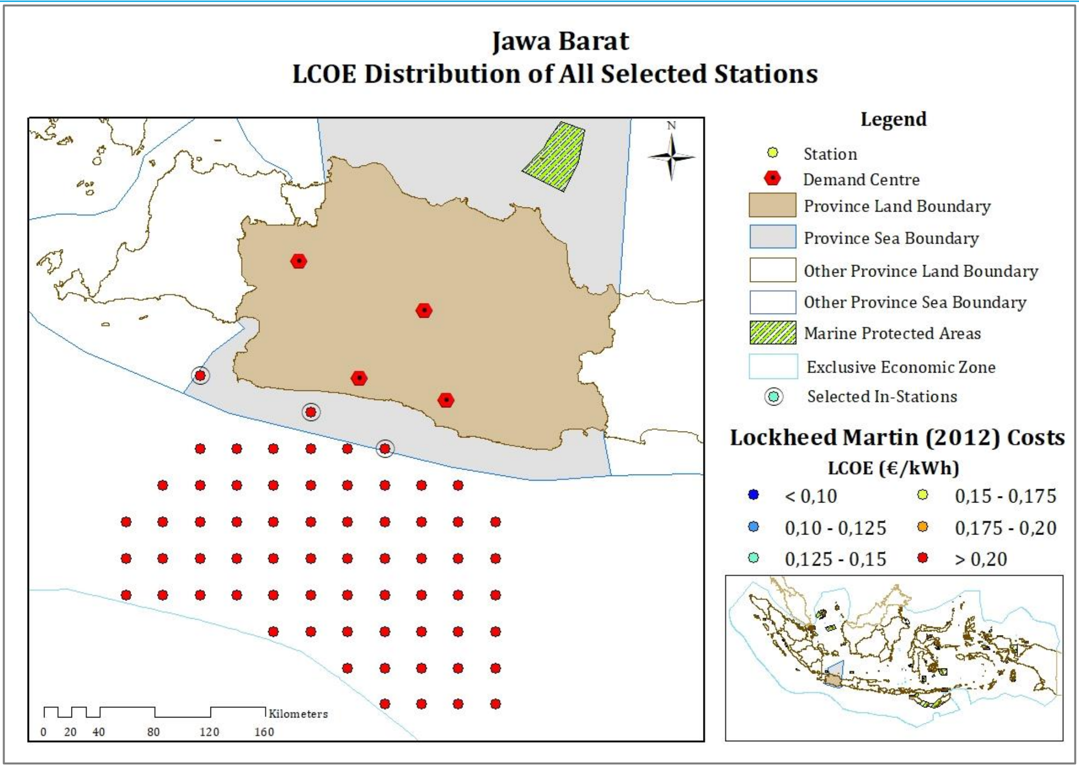


Figure A.8 LCOE Distribution of In-Stations for Jawa Barat
Top: Lockheed Martin (2012a) costs, Bottom: Vega (2012) Costs



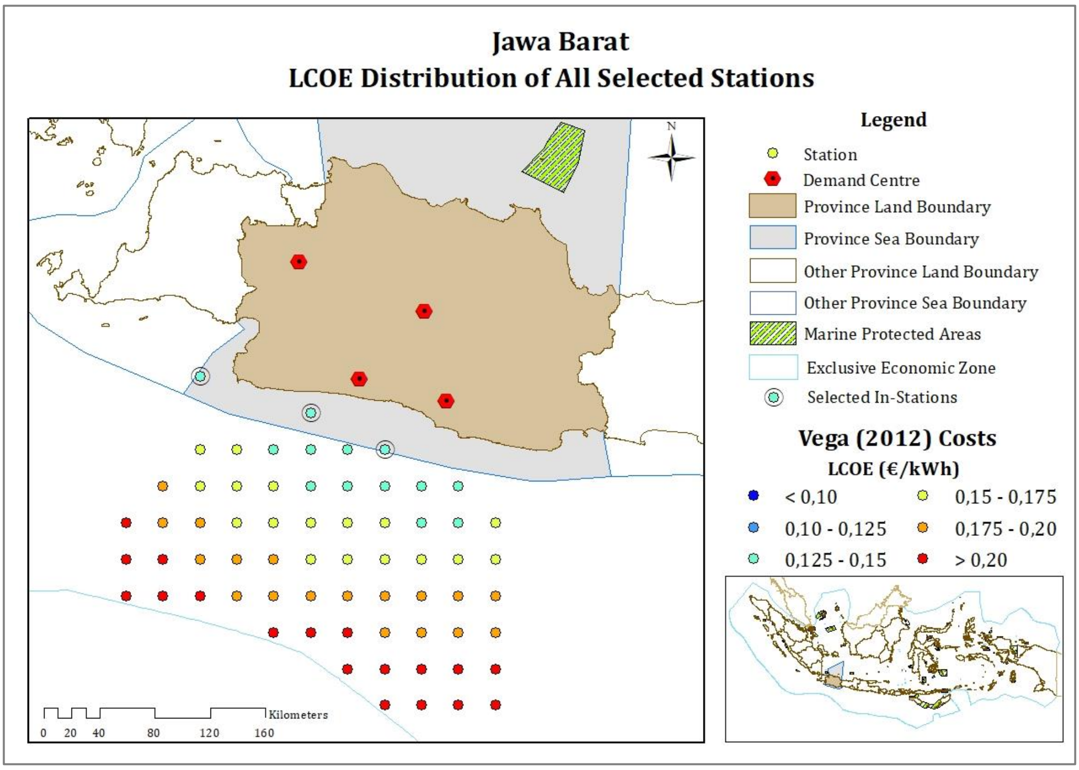
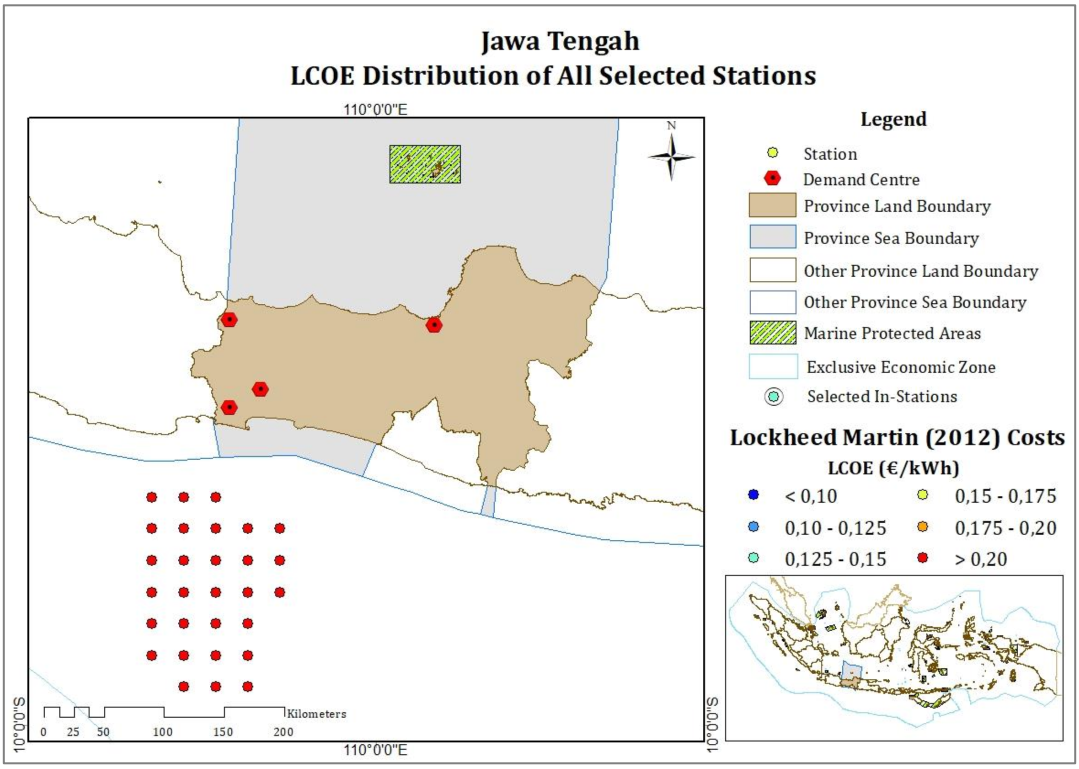


Figure A.9 LCOE Distribution of All Selected Stations for Jawa Barat
Top: Lockheed Martin (2012a) costs, Bottom: Vega (2012) Costs

8. Jawa Tengah



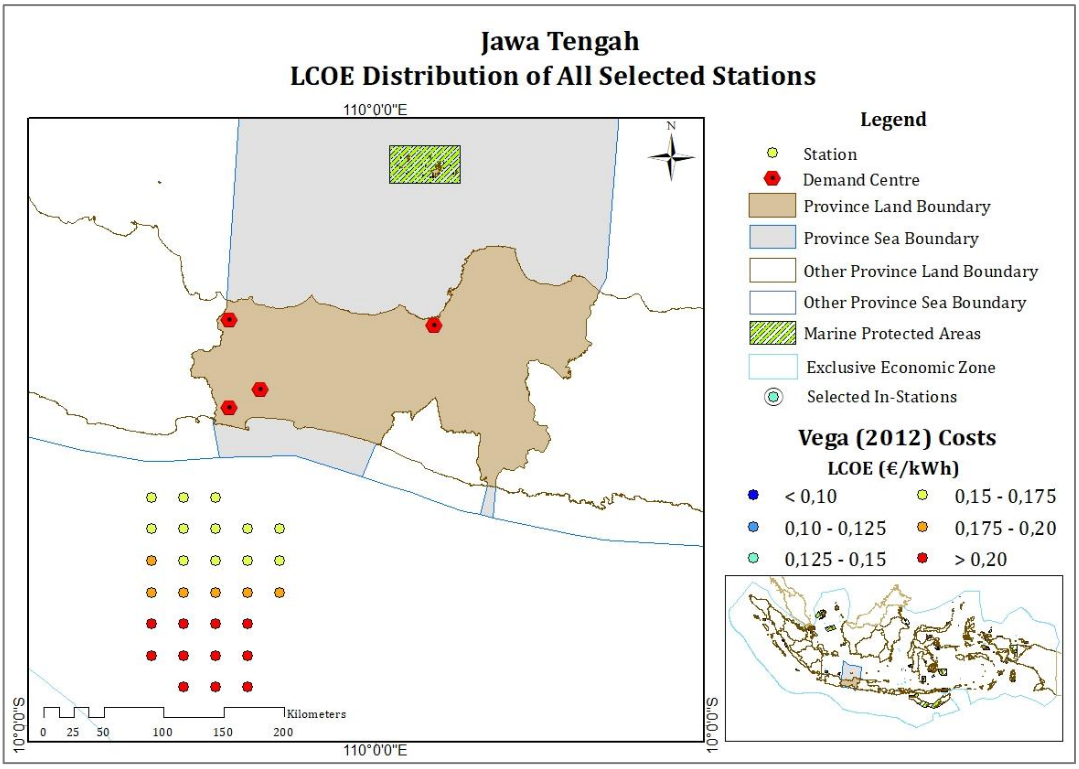
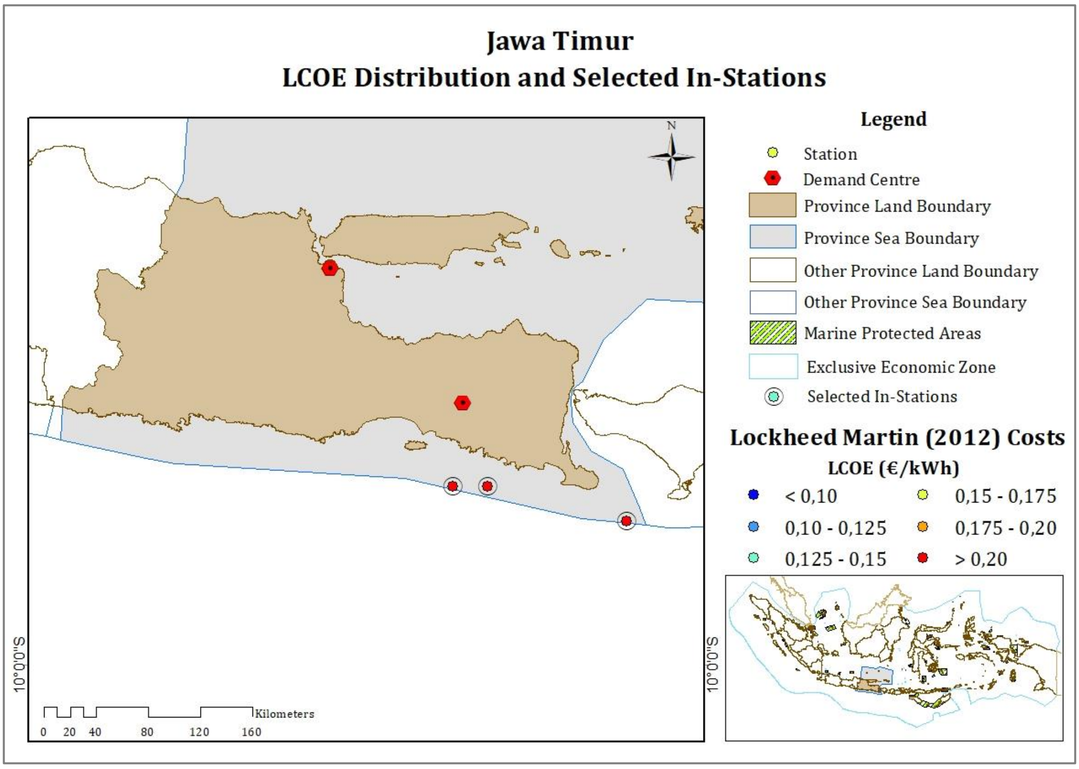


Figure A.10 LCOE Distribution of All Selected Stations for Jawa Tengah
Top: Lockheed Martin (2012a) costs, Bottom: Vega (2012) Costs

9. Jawa Timur



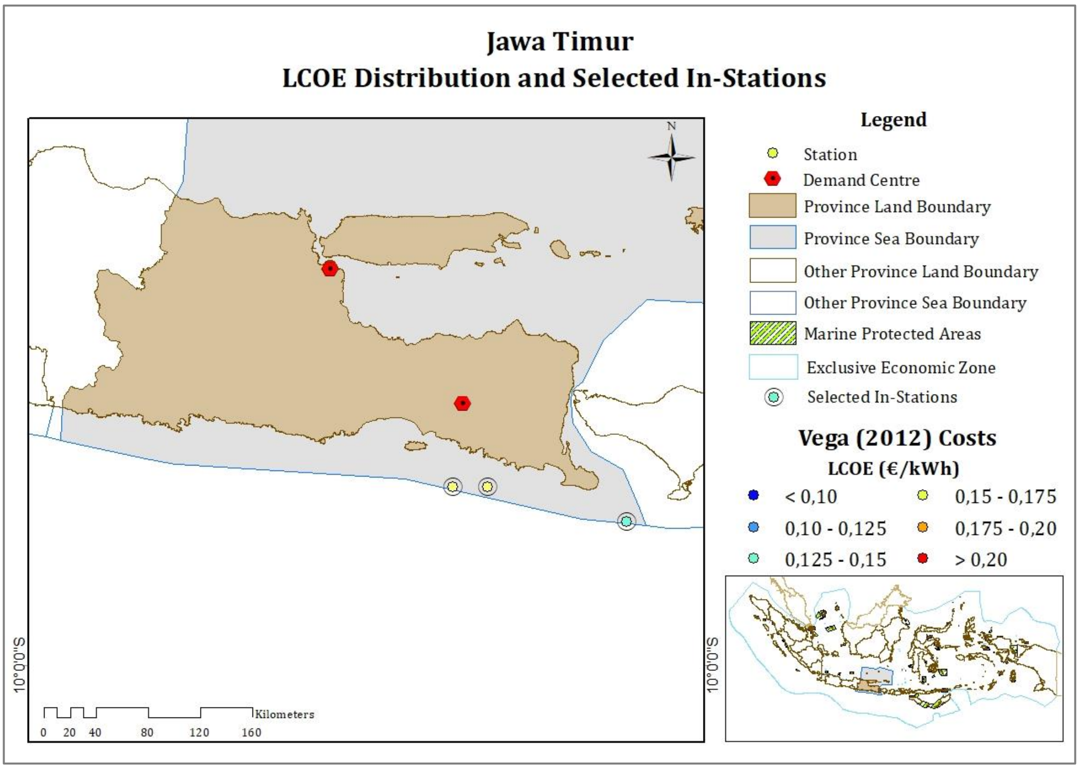
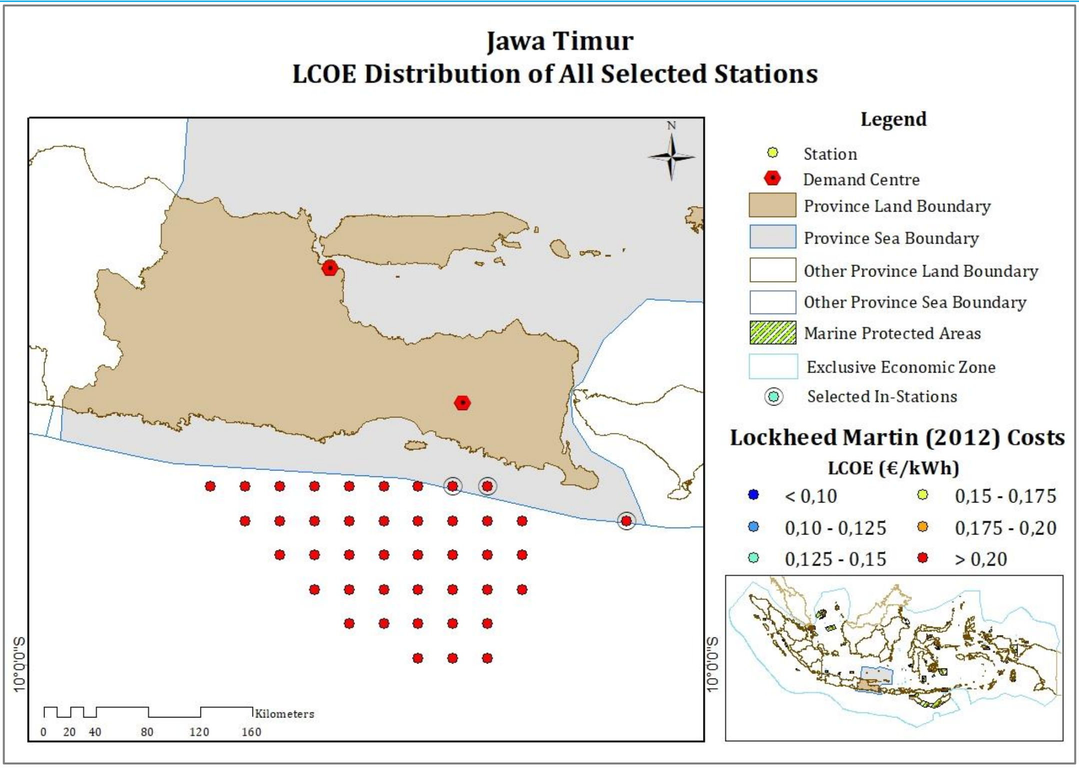


Figure A.11 LCOE Distribution of In-Stations for Jawa Timur
Top: Lockheed Martin (2012a) costs, Bottom: Vega (2012) Costs



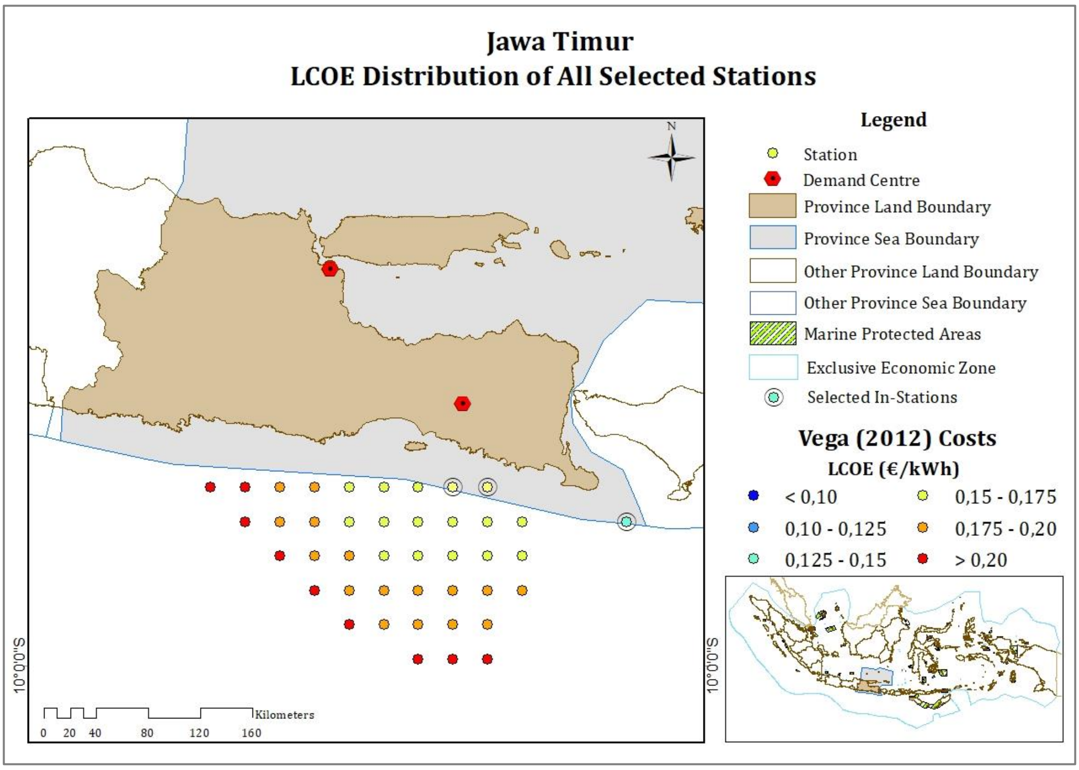
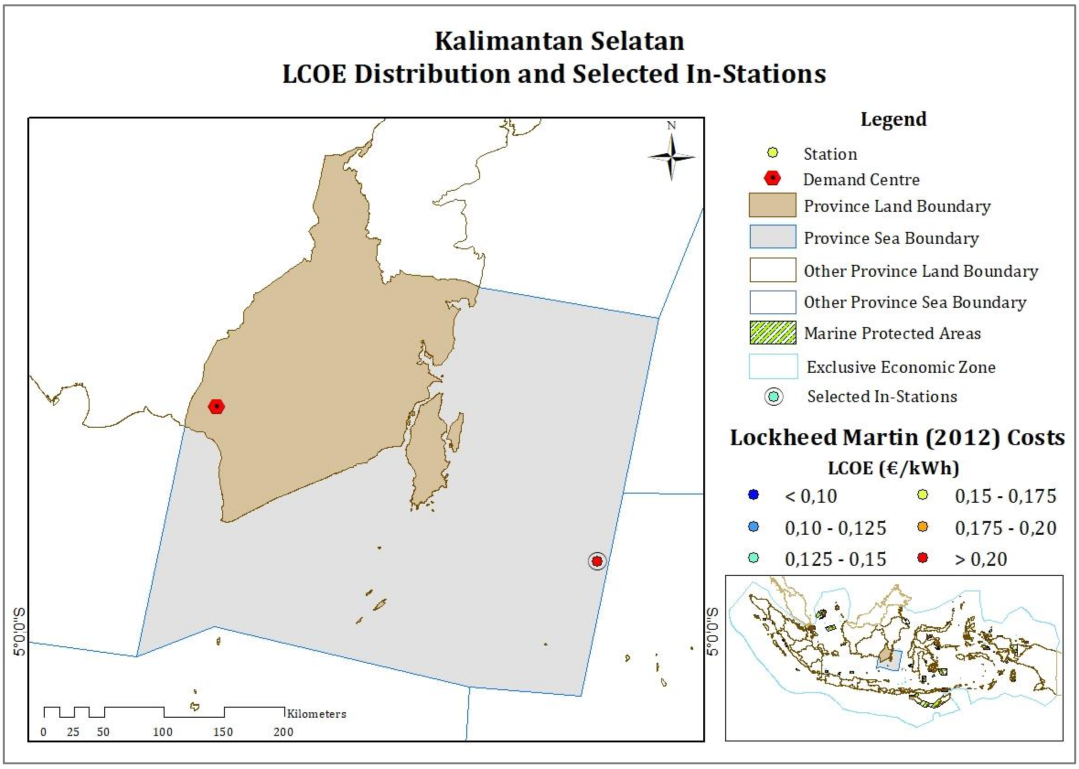


Figure A.12 LCOE Distribution of All Selected Stations for Jawa Timur
Top: Lockheed Martin (2012a) costs, Bottom: Vega (2012) Costs

10. Kalimantan Selatan



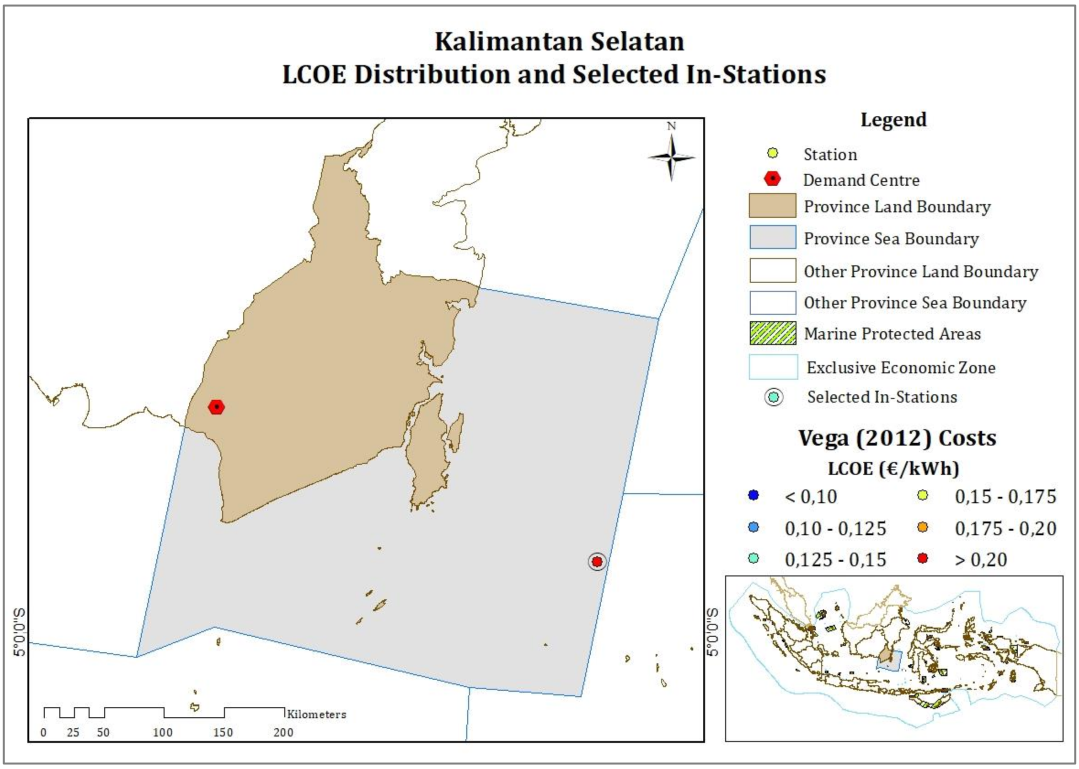
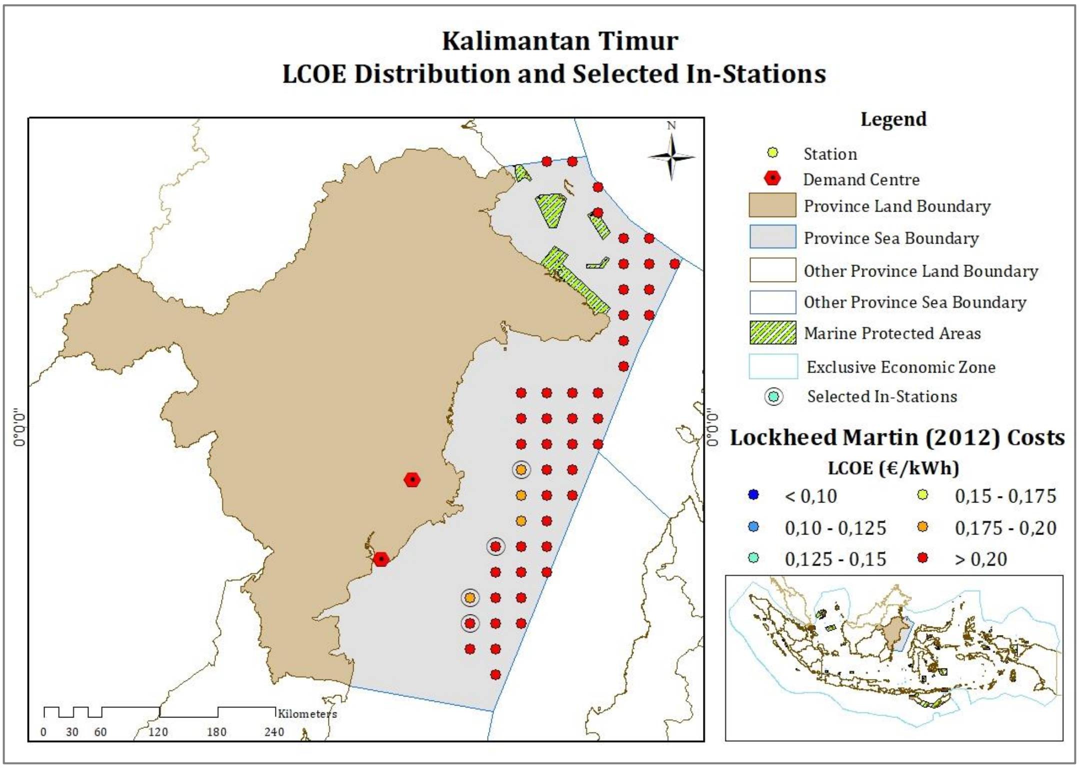


Figure A.13 LCOE Distribution of In-Stations for Kalimantan Selatan
Top: Lockheed Martin (2012a) costs, Bottom: Vega (2012) Costs

11. Kalimantan Timur



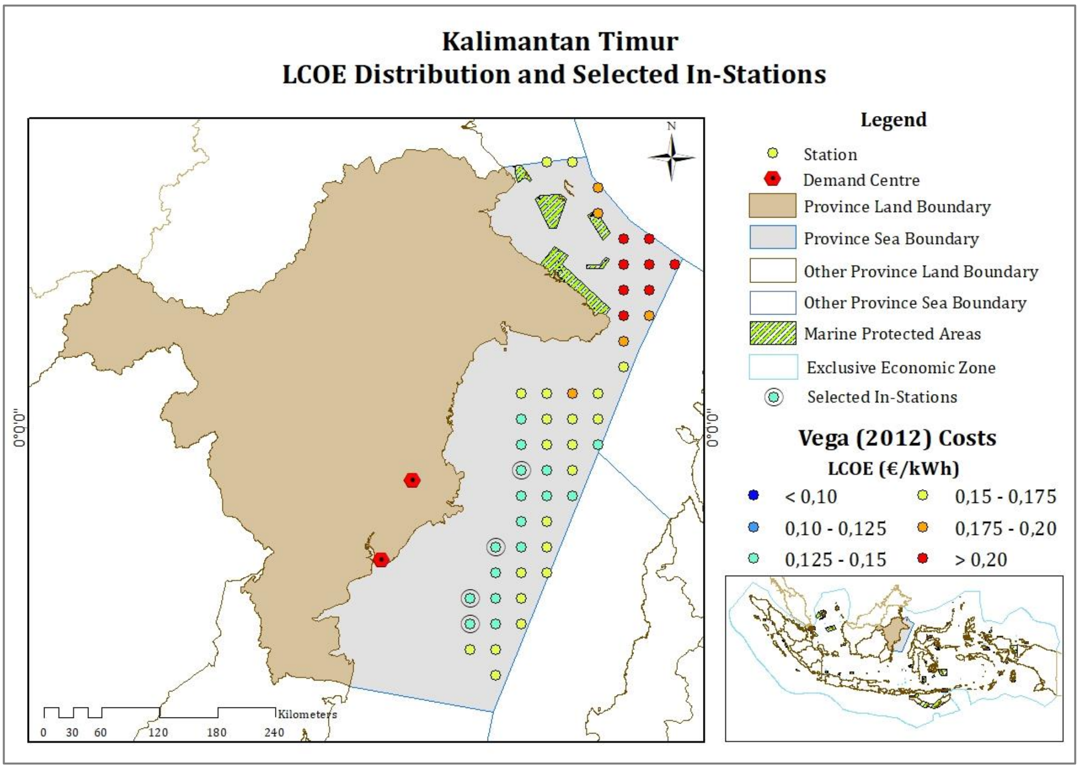
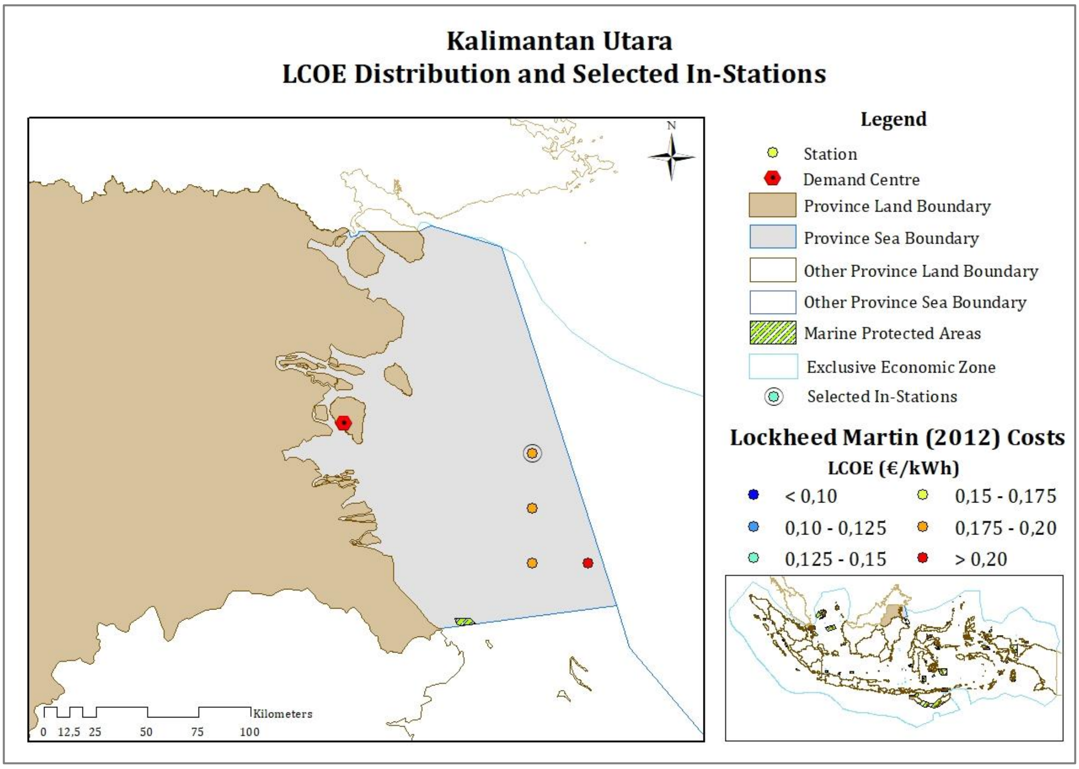


Figure A.14 LCOE Distribution of In-Stations for Kalimantan Timur
Top: Lockheed Martin (2012a) costs, Bottom: Vega (2012) Costs

12. Kalimantan Utara



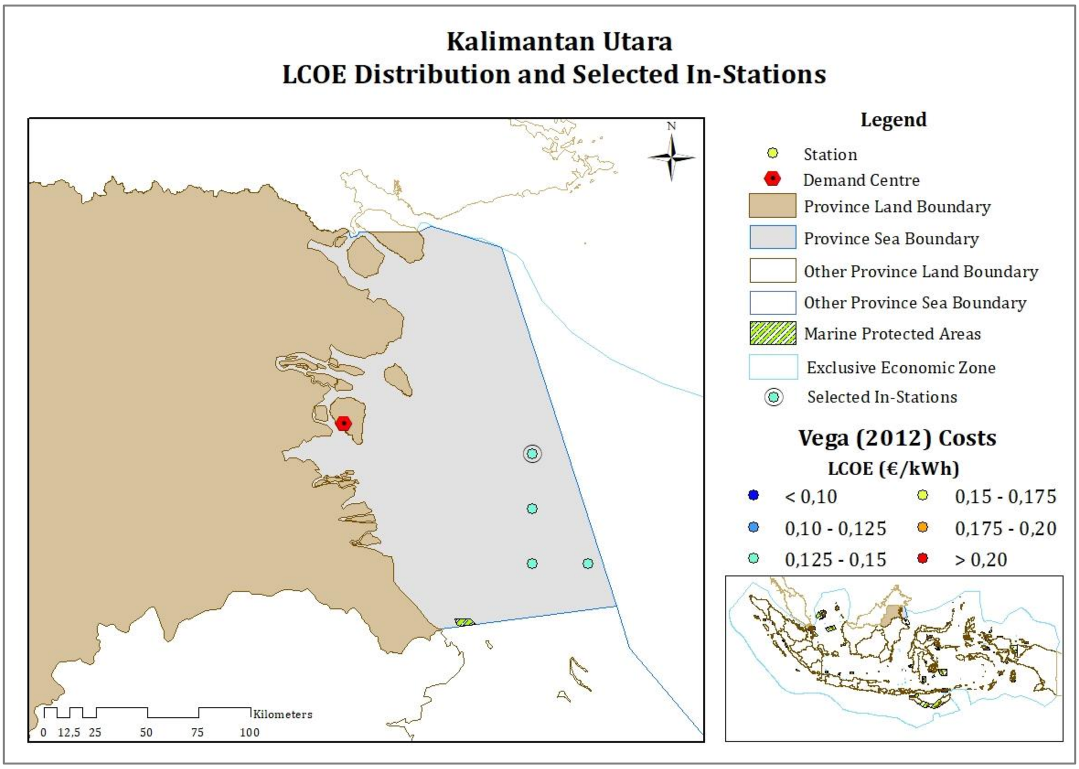
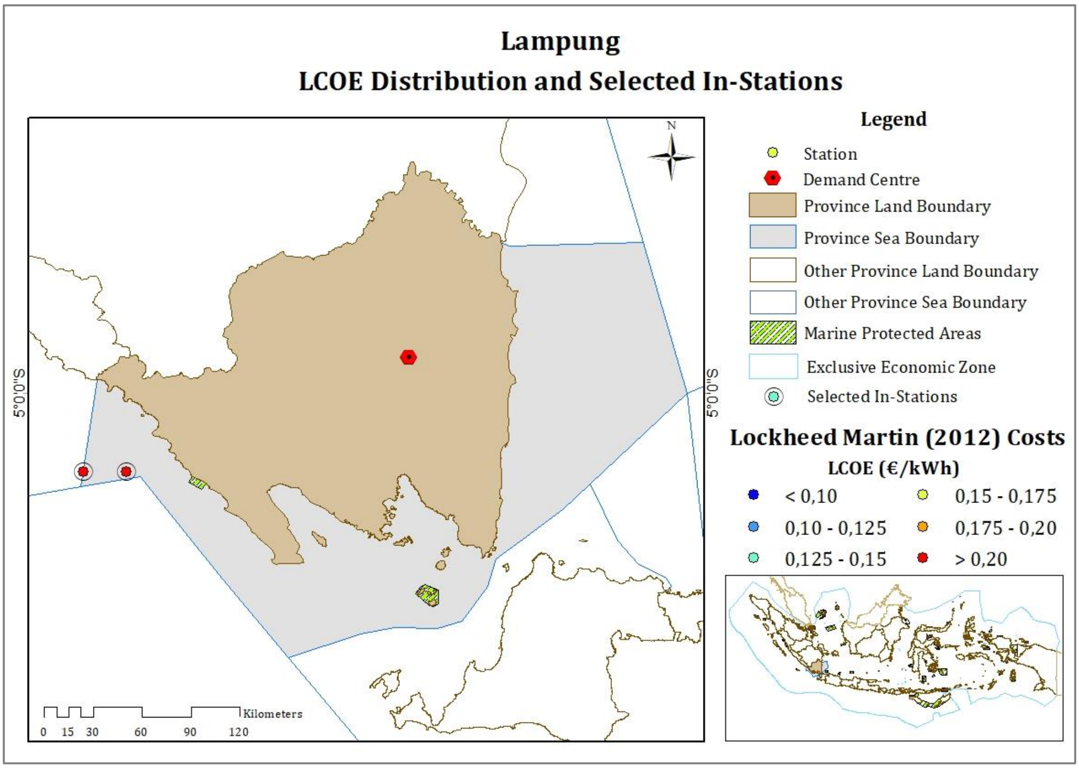


Figure A.15 LCOE Distribution of In-Stations for Kalimantan Utara
Top: Lockheed Martin (2012a) costs, Bottom: Vega (2012) Costs

13. Lampung



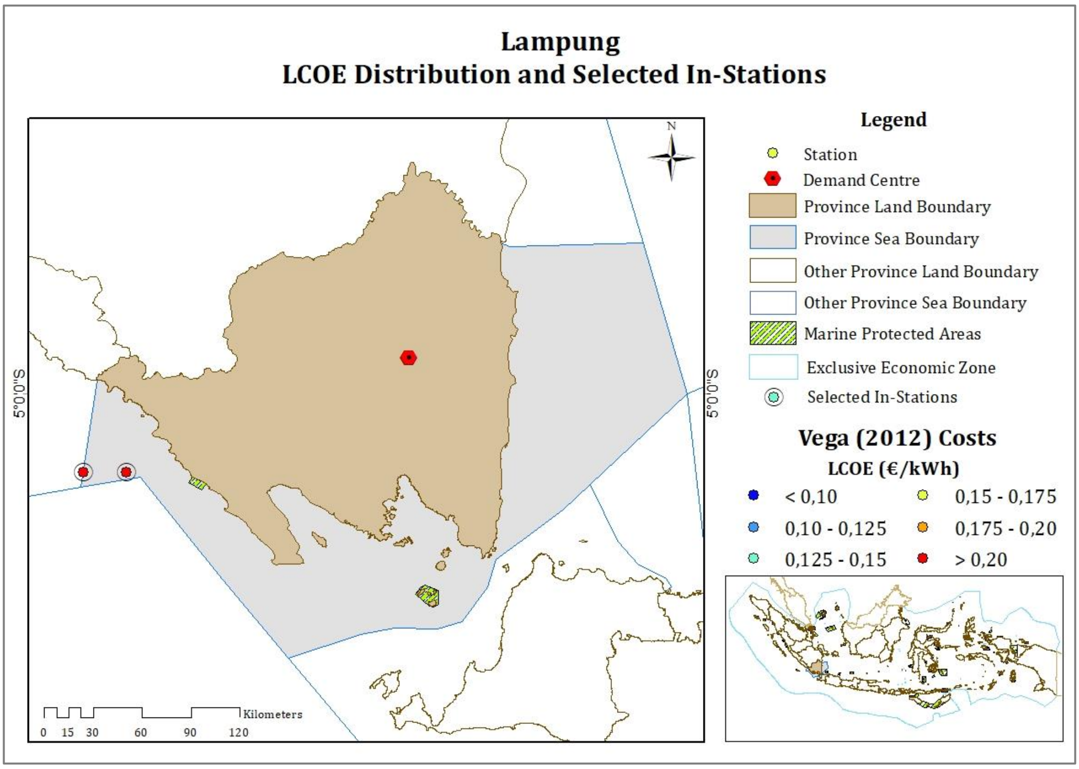
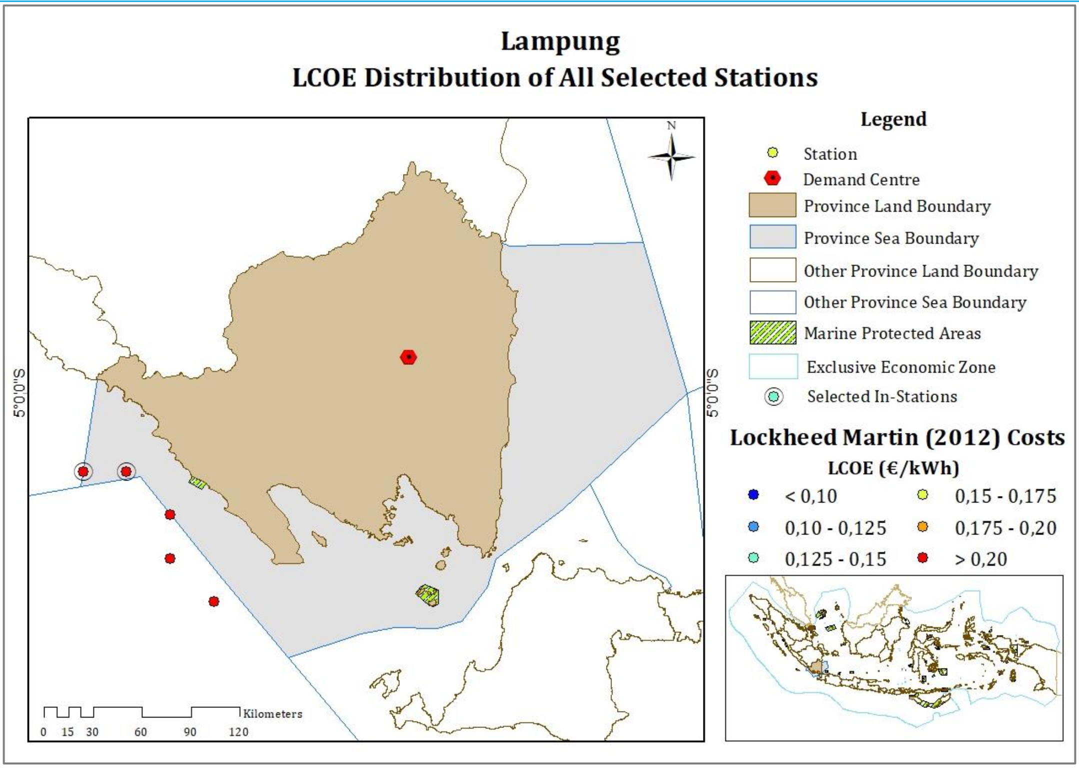


Figure A.16 LCOE Distribution of In-Stations for Lampung
Top: Lockheed Martin (2012a) costs, Bottom: Vega (2012) Costs



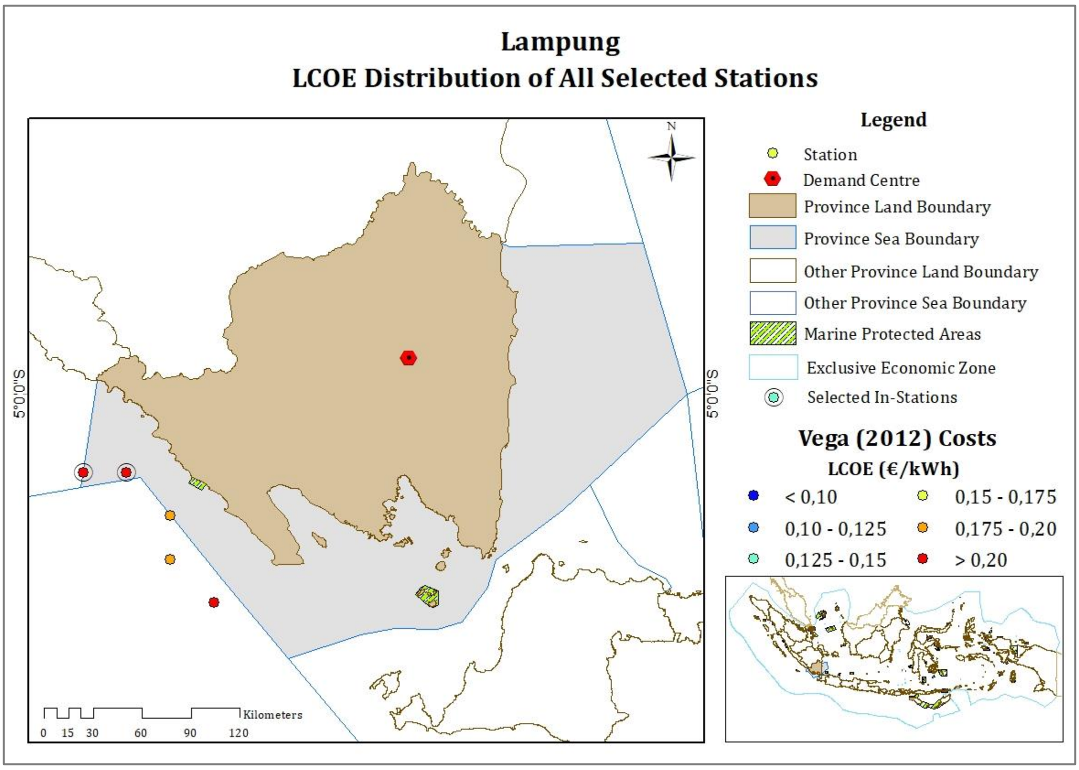
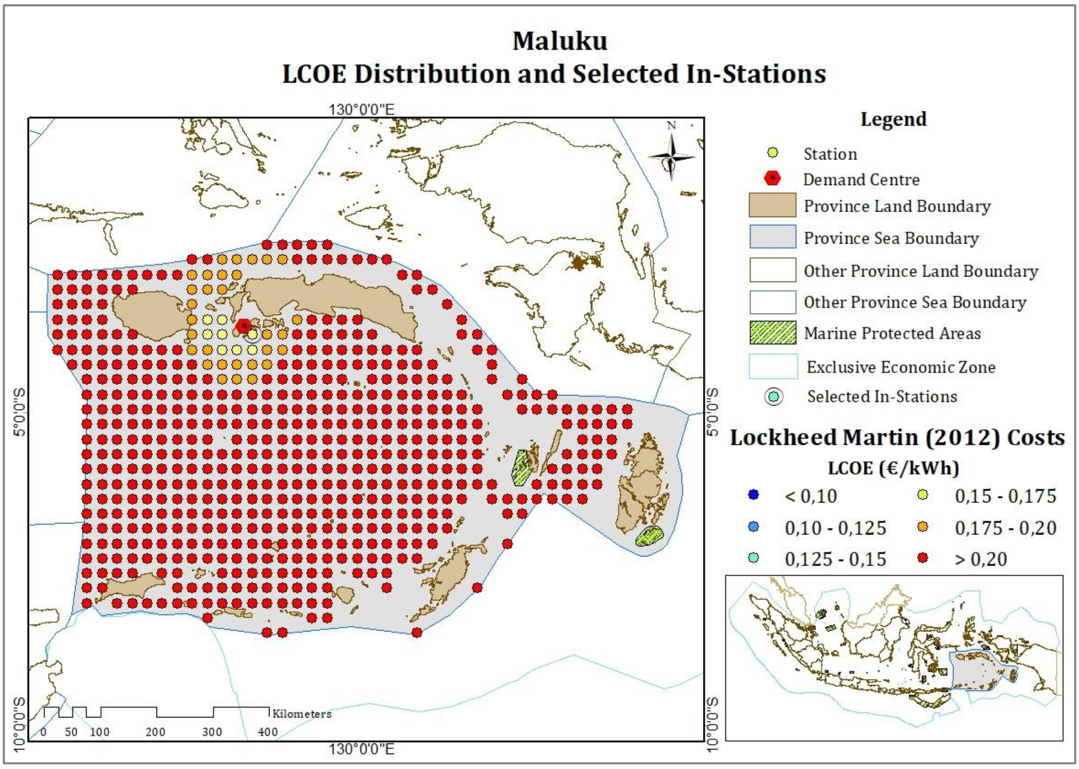


Figure A.17 LCOE Distribution of All Selected Stations for Lampung
Top: Lockheed Martin (2012a) costs, Bottom: Vega (2012) Costs

14. Maluku



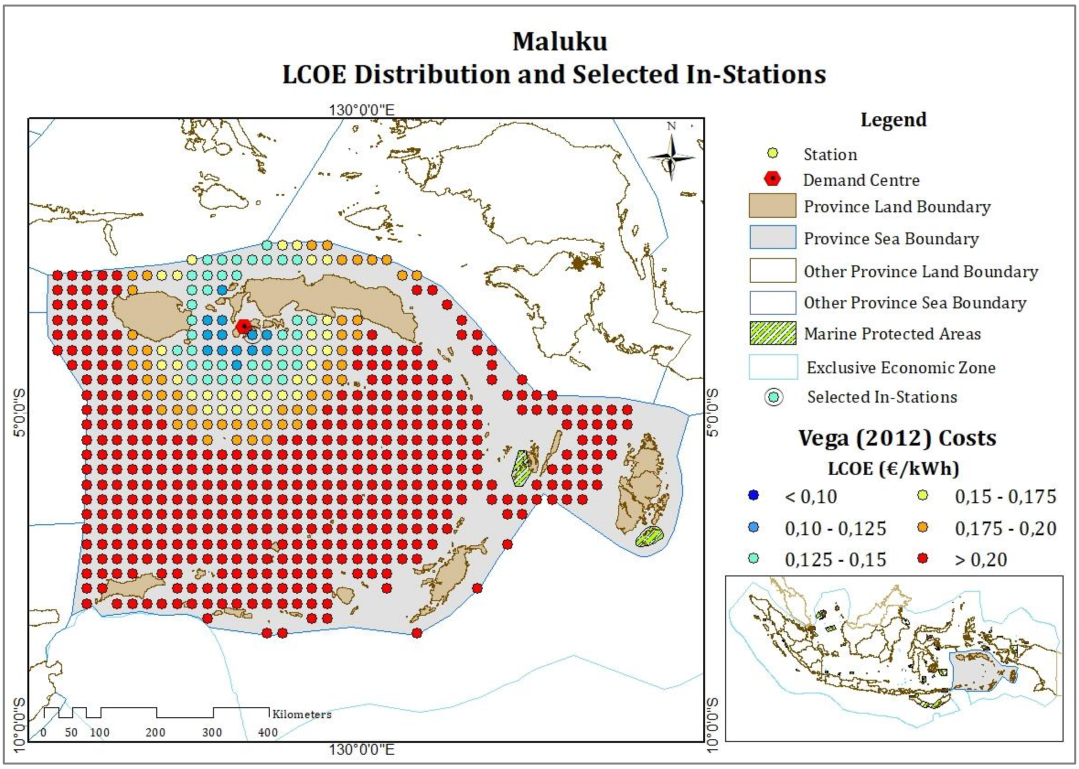
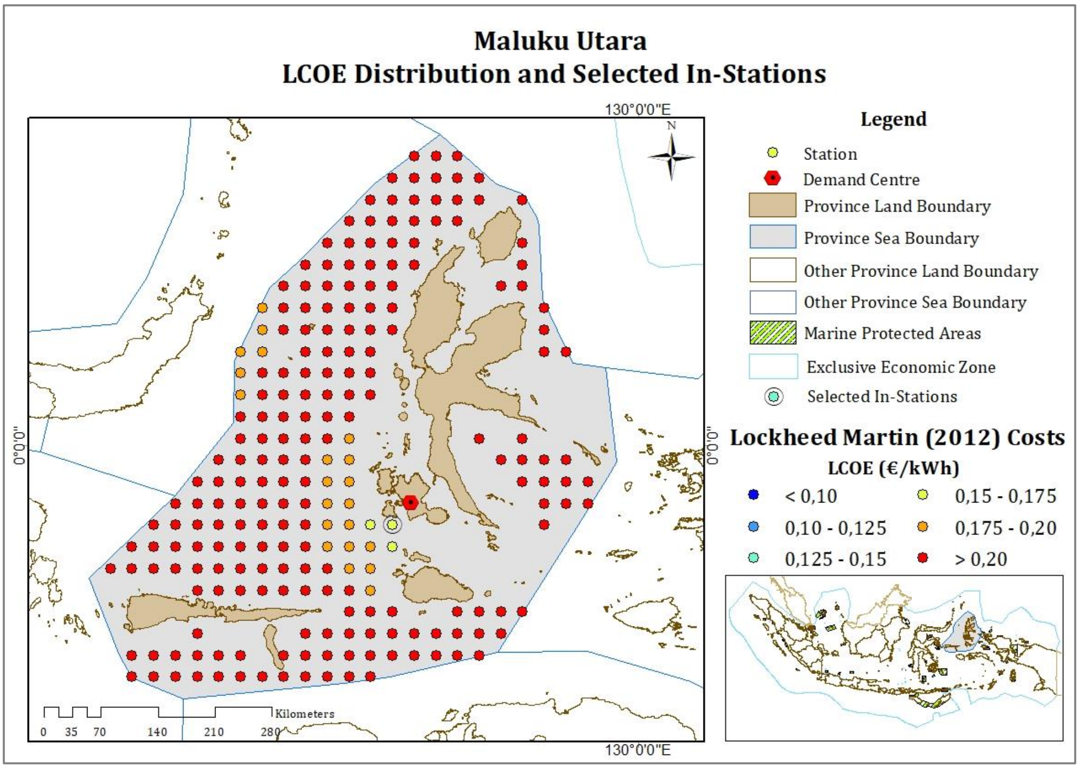


Figure A.18 LCOE Distribution of In-Stations for Maluku
Top: Lockheed Martin (2012a) costs, Bottom: Vega (2012) Costs

15. Maluku Utara



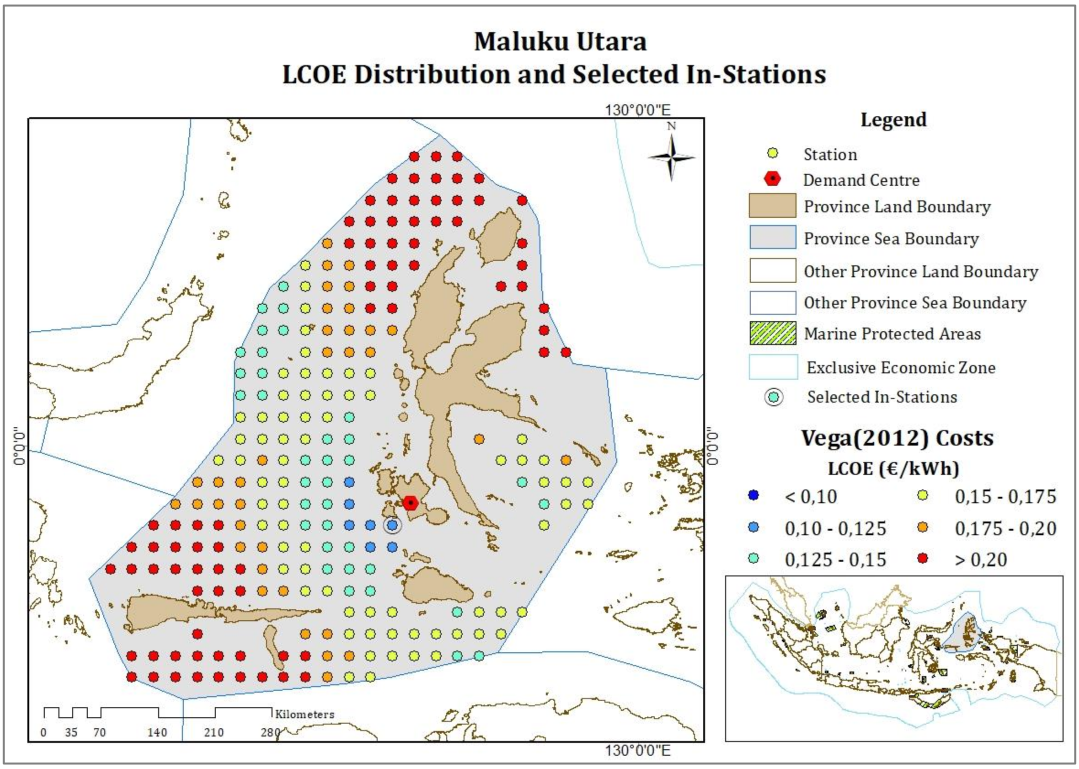
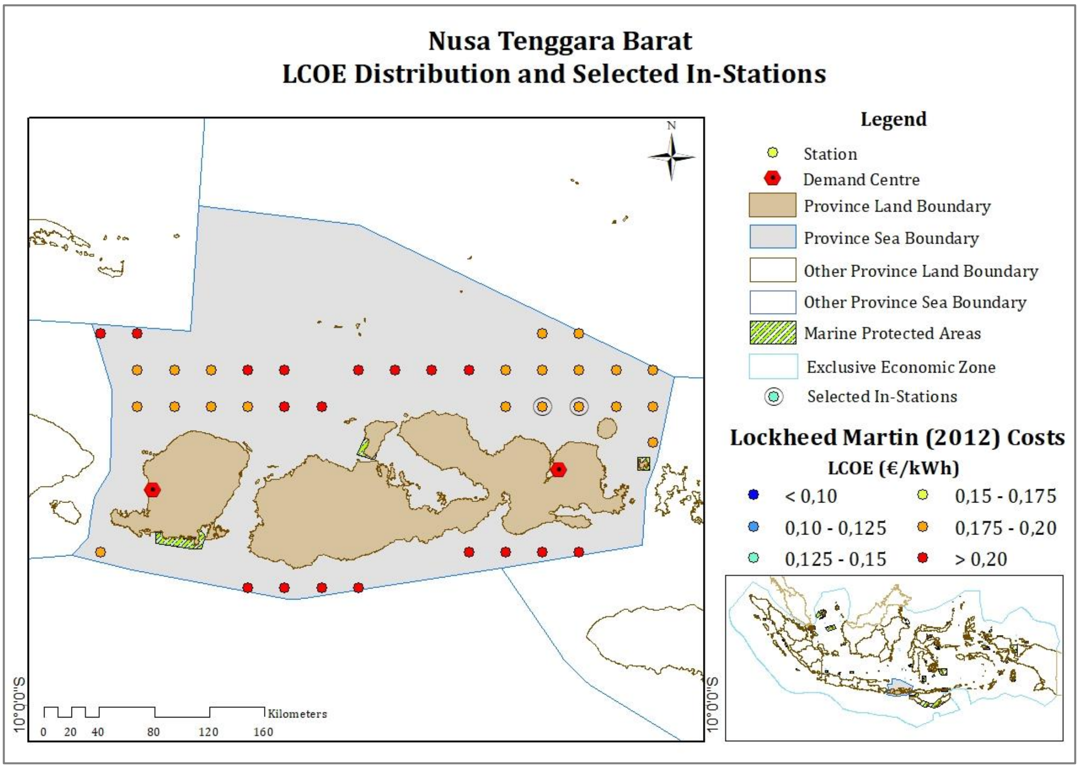


Figure A.19 LCOE Distribution of In-Stations for Maluku Utara
Top: Lockheed Martin (2012a) costs, Bottom: Vega (2012) Costs

16. Nusa Tenggara Barat



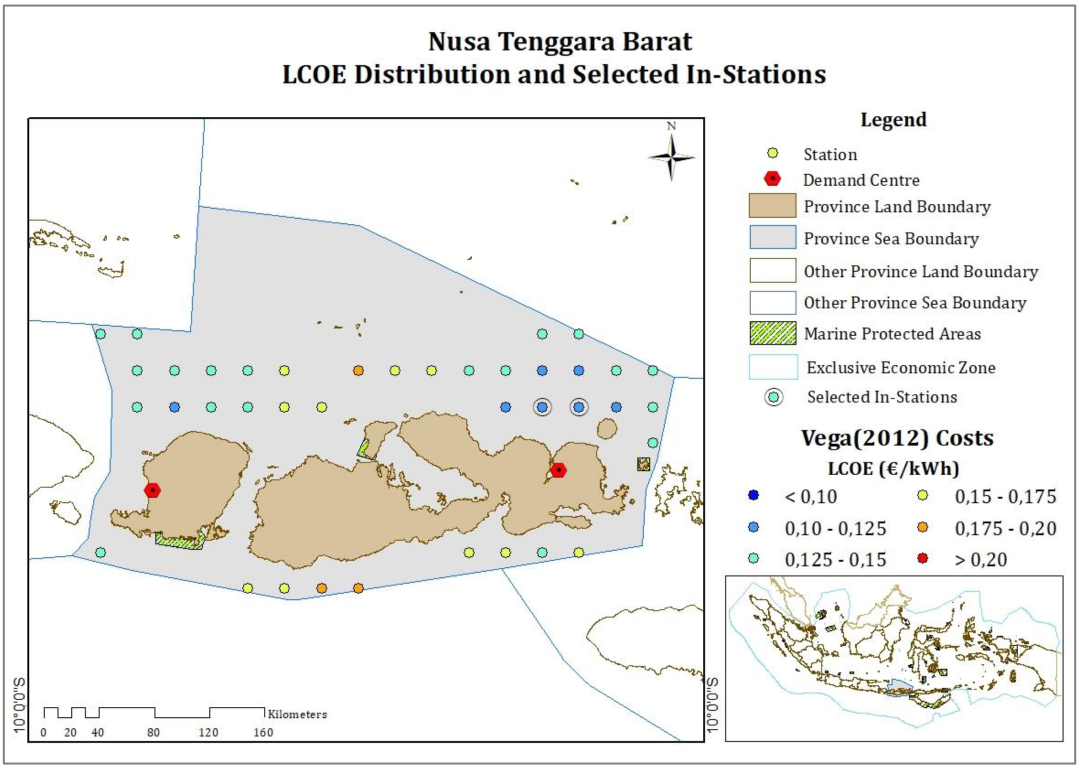
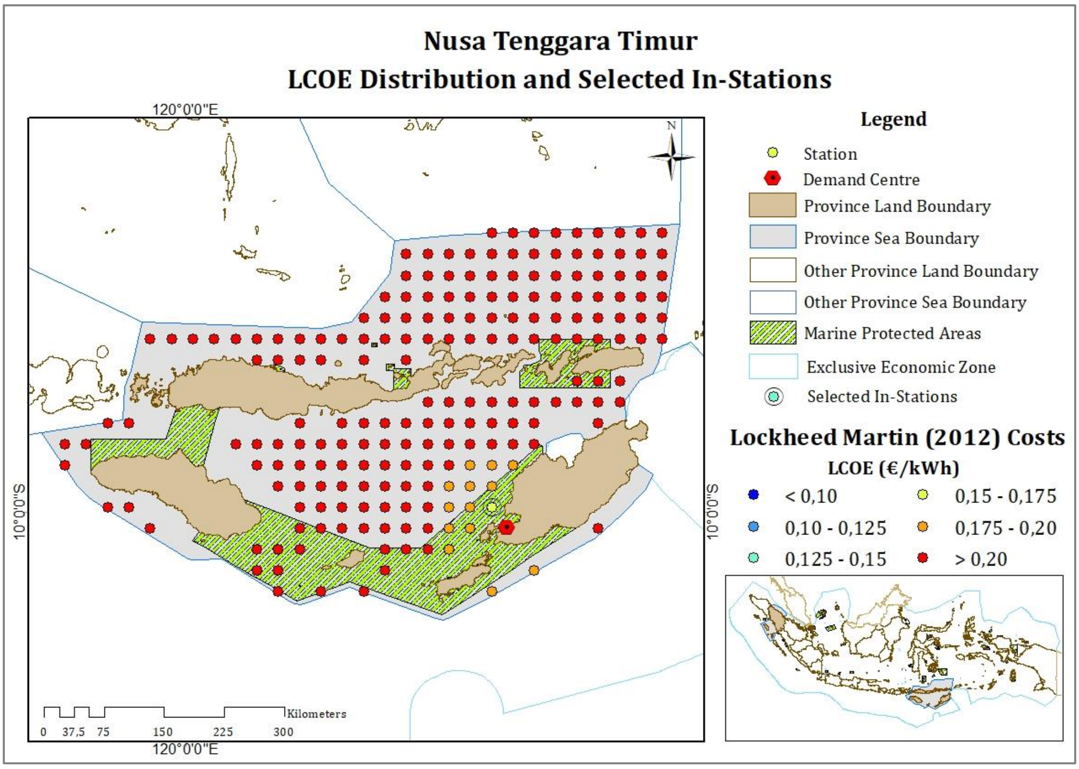


Figure A.20 LCOE Distribution of In-Stations for Nusa Tenggara Barat
Top: Lockheed Martin (2012a) costs, Bottom: Vega (2012) Costs

17. Nusa Tenggara Timur



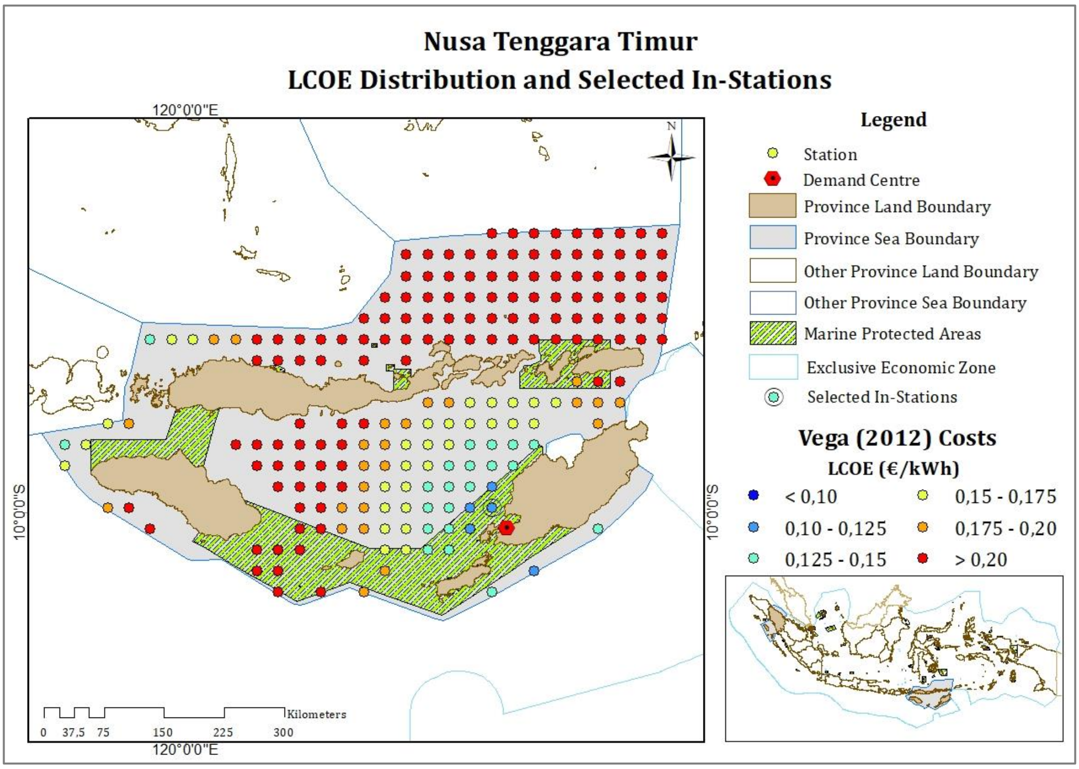
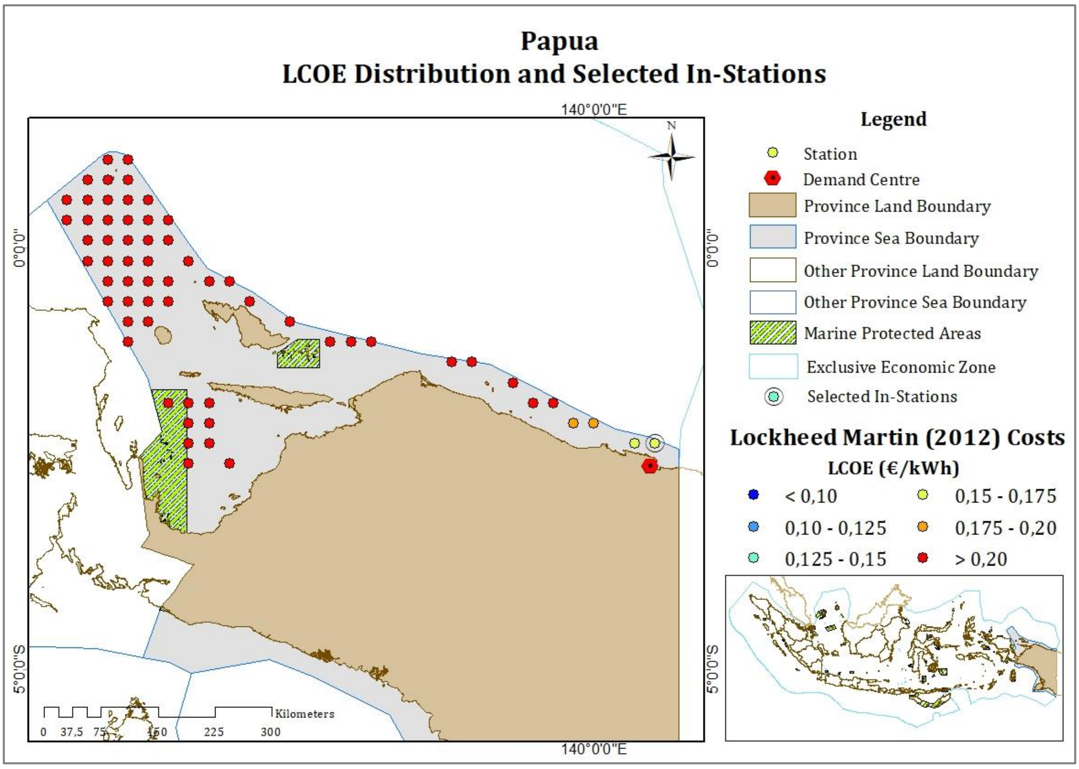


Figure A.21 LCOE Distribution of In-Stations for Nusa Tenggara Timur
Top: Lockheed Martin (2012a) costs, Bottom: Vega (2012) Costs

18. Papua



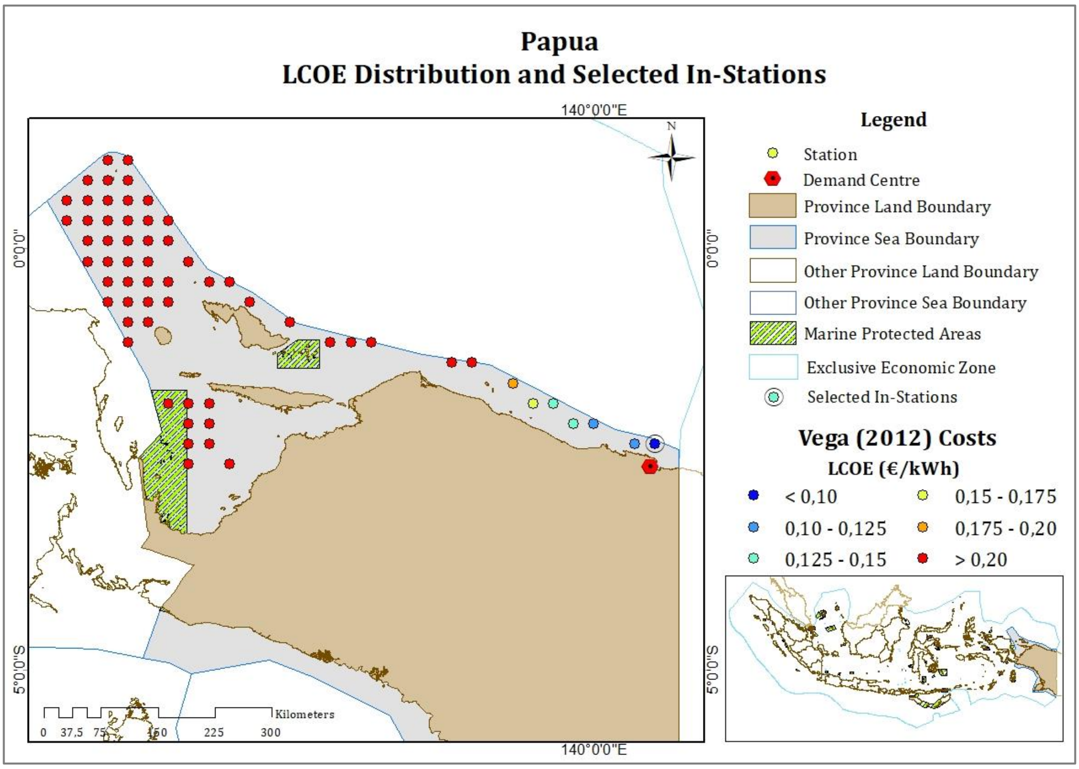
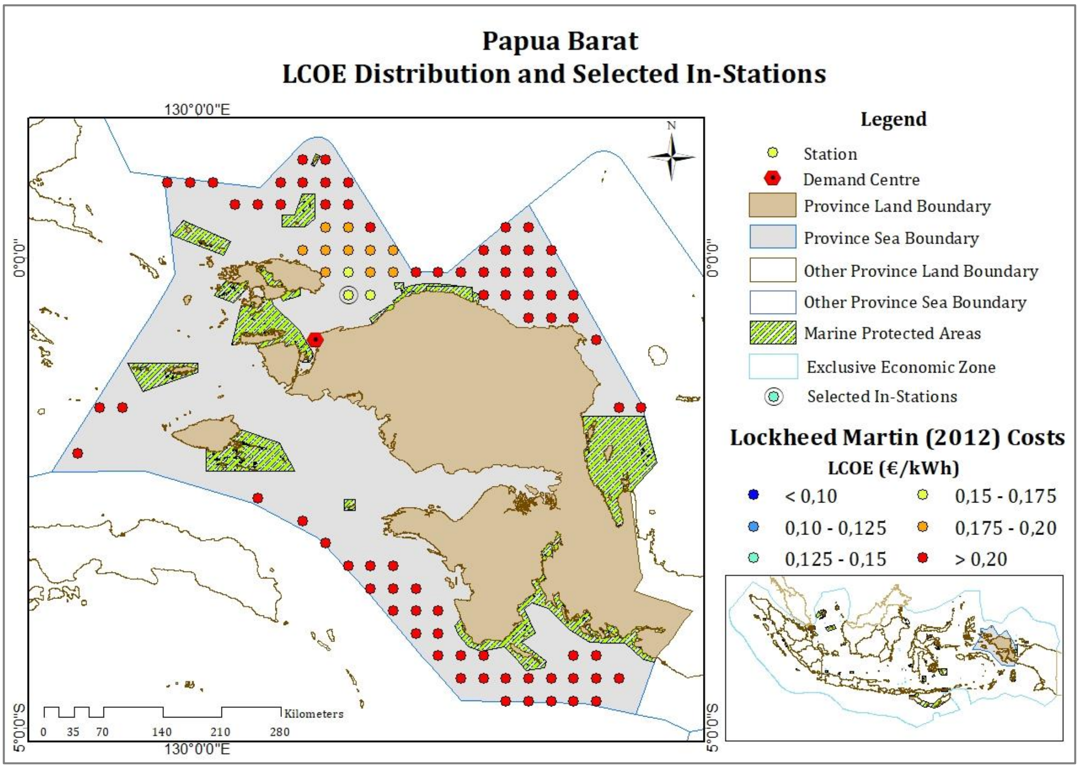


Figure A.22 LCOE Distribution of In-Stations for Papua
Top: Lockheed Martin (2012a) costs, Bottom: Vega (2012) Costs

19. Papua Barat



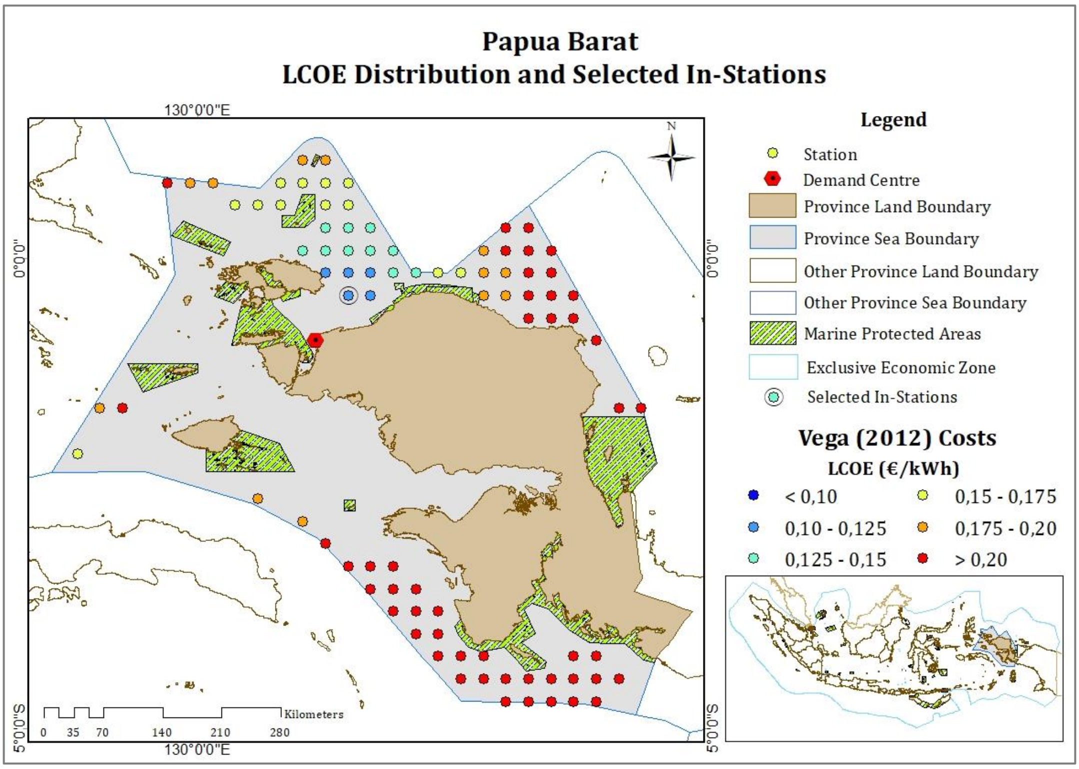
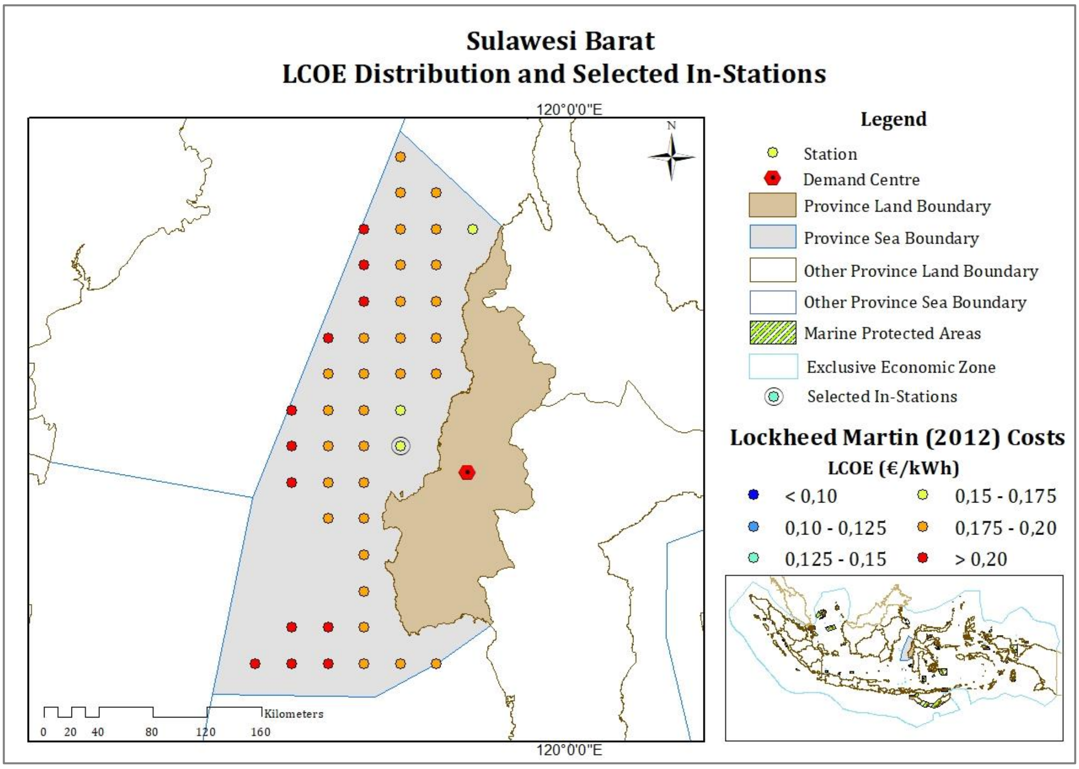


Figure A.23 LCOE Distribution of In-Stations for Papua Barat
Top: Lockheed Martin (2012a) costs, Bottom: Vega (2012) Costs

20. Sulawesi Barat



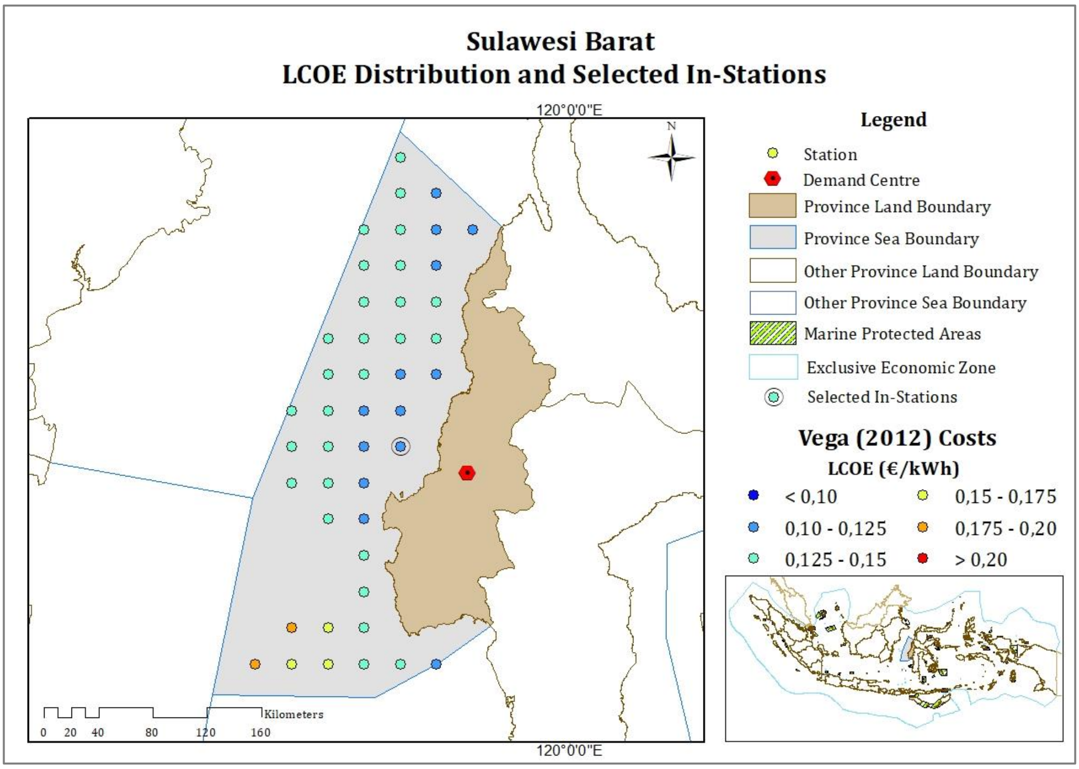
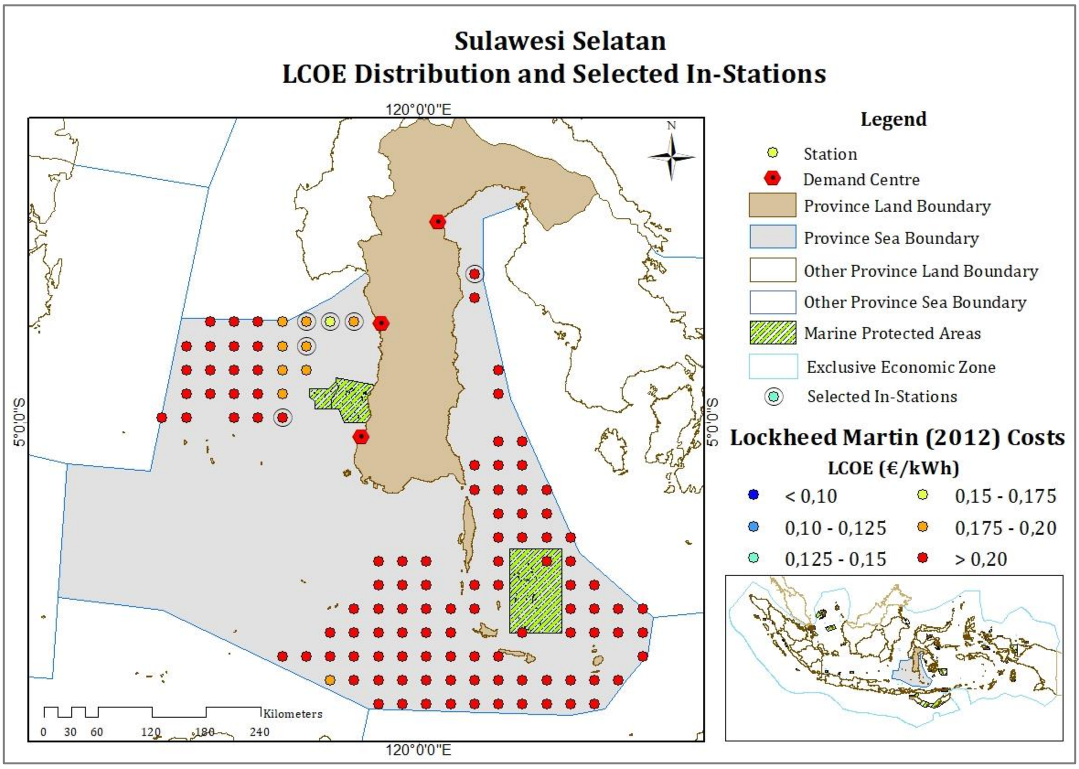


Figure A.24 LCOE Distribution of In-Stations for Sulawesi Barat
Top: Lockheed Martin (2012a) costs, Bottom: Vega (2012) Costs

21. Sulawesi Selatan



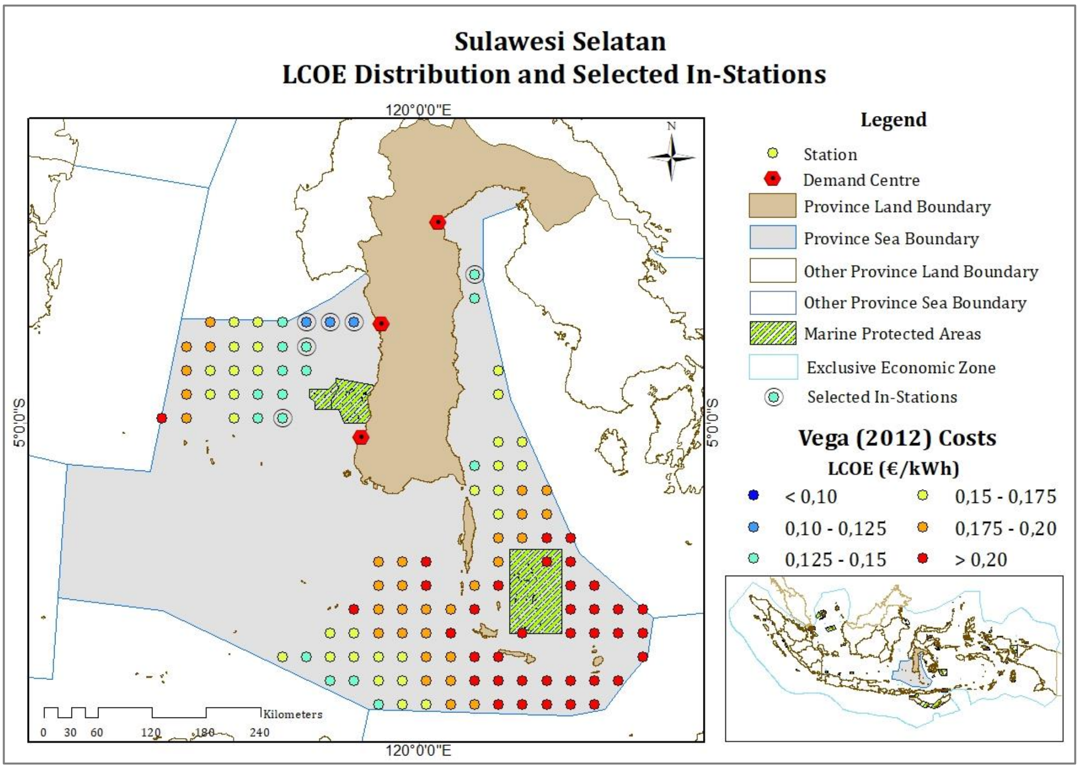
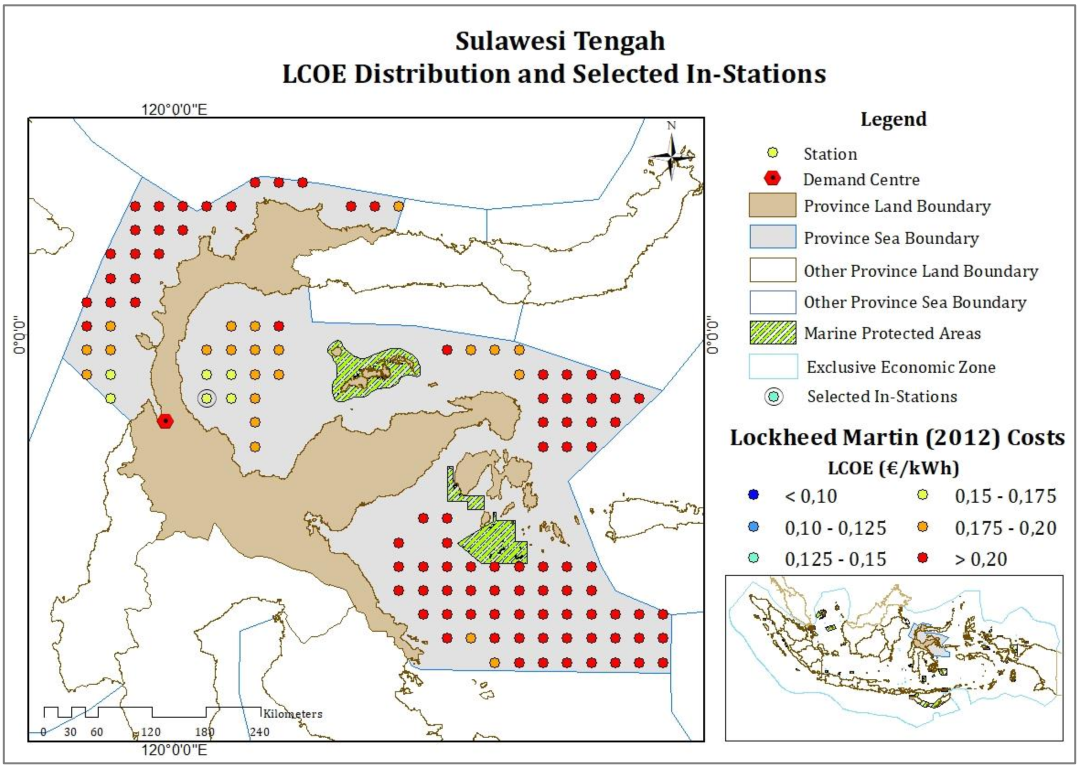


Figure A.25 LCOE Distribution of In-Stations for Sulawesi Selatan
Top: Lockheed Martin (2012a) costs, Bottom: Vega (2012) Costs

22. Sulawesi Tengah



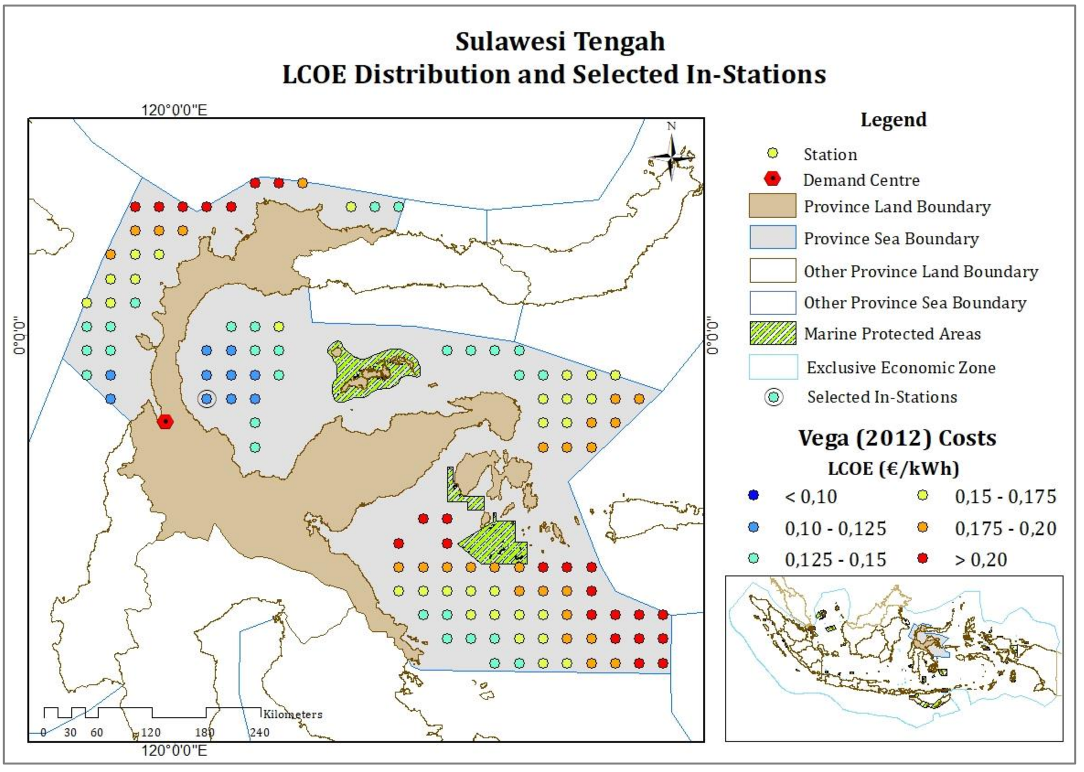
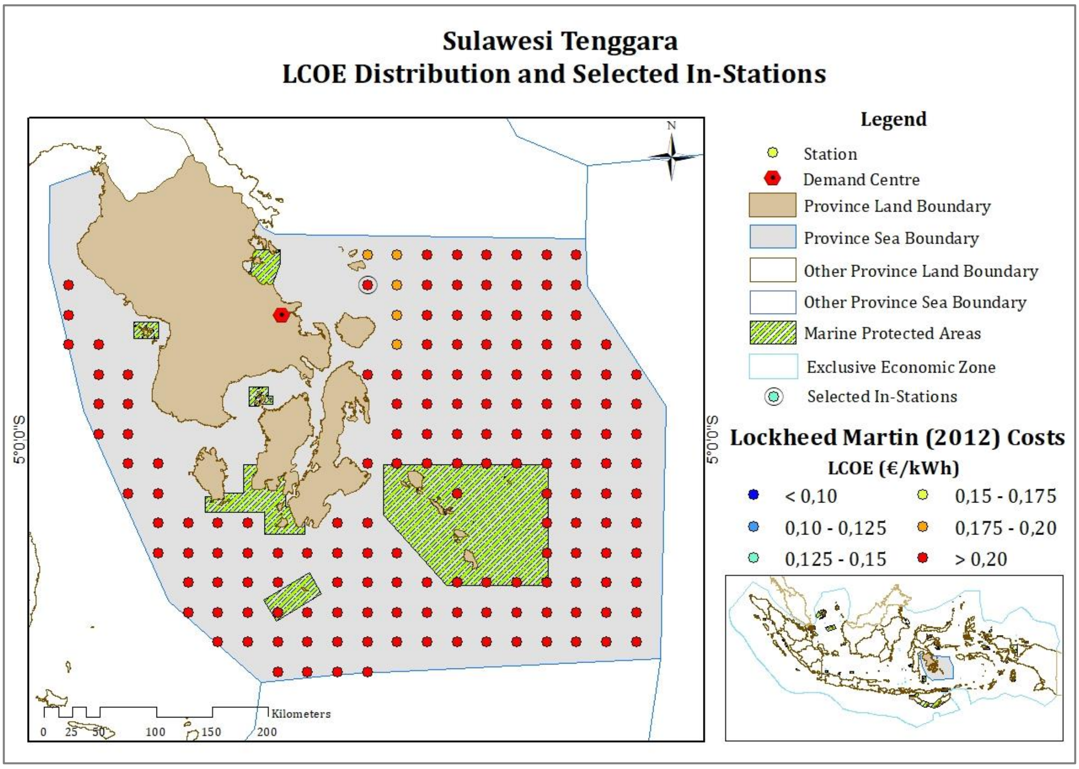


Figure A.26 LCOE Distribution of In-Stations for Sulawesi Tengah
Top: Lockheed Martin (2012a) costs, Bottom: Vega (2012) Costs

23. Sulawesi Tenggara



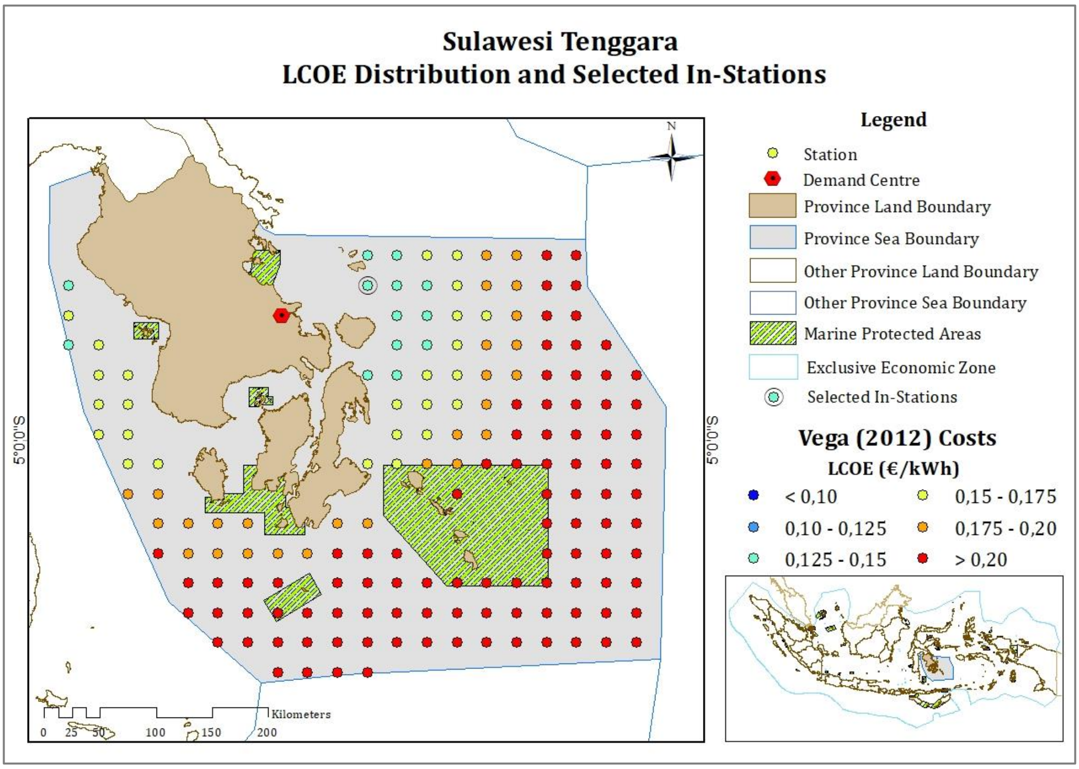
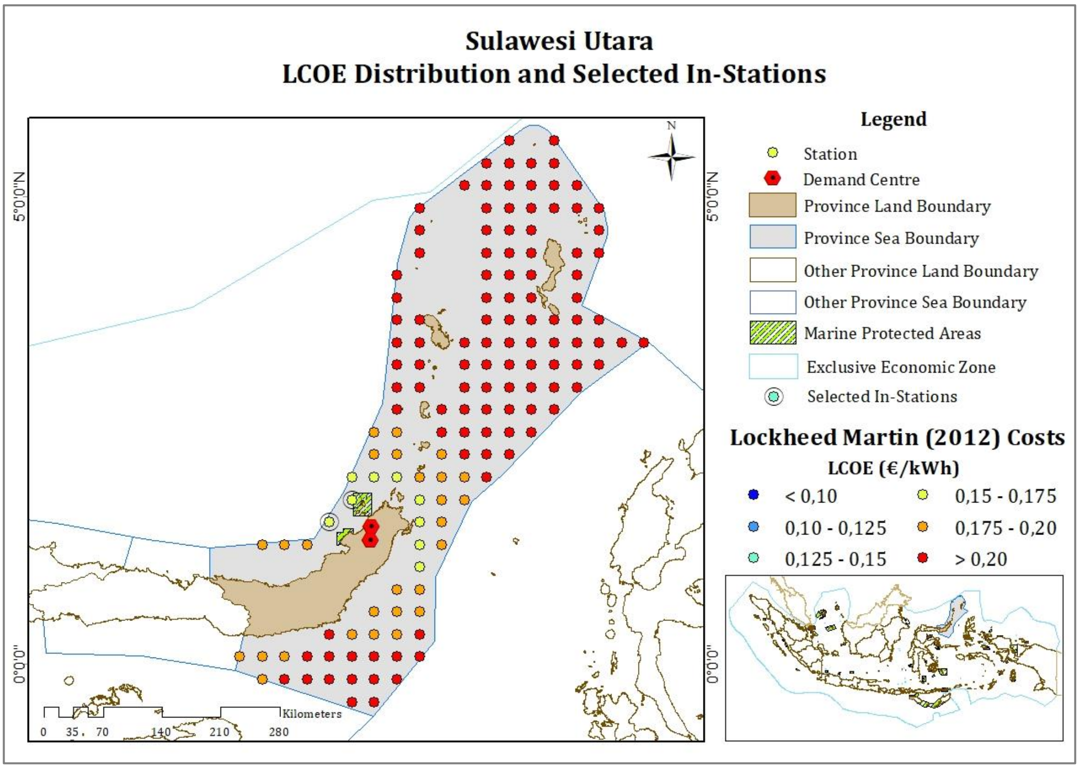


Figure A.27 LCOE Distribution of In-Stations for Sulawesi Tenggara
Top: Lockheed Martin (2012a) costs, Bottom: Vega (2012) Costs

24. Sulawesi Utara



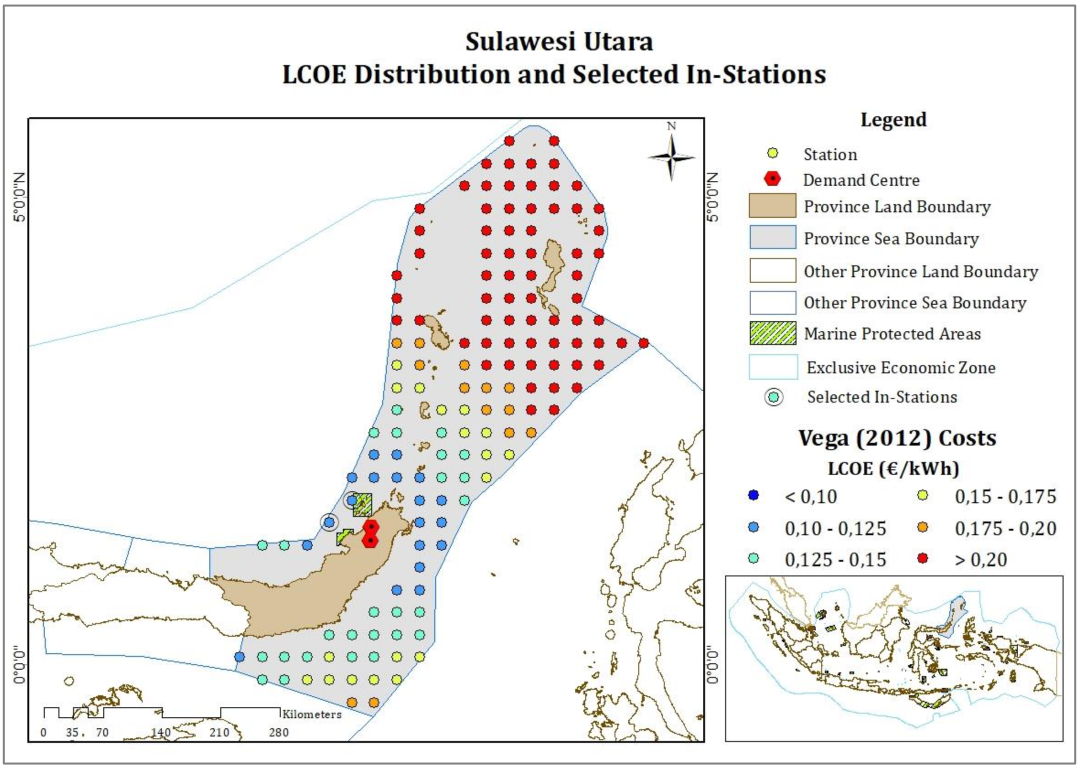
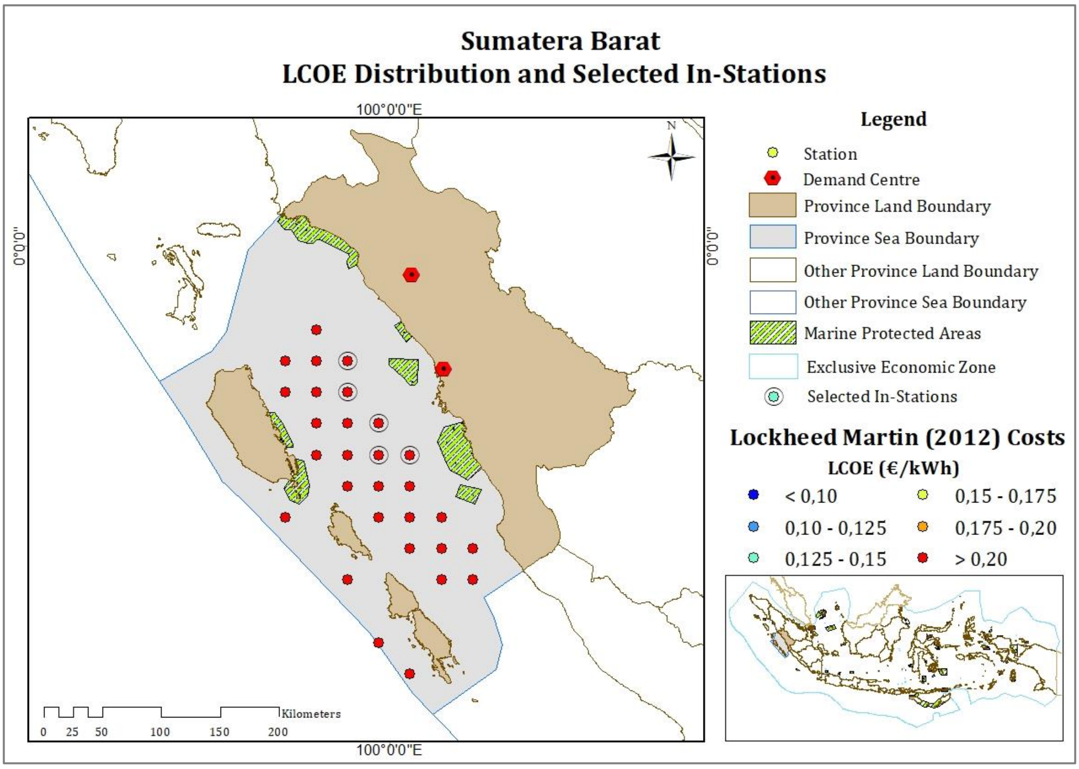


Figure A.28 LCOE Distribution of In-Stations for Sulawesi Utara
Top: Lockheed Martin (2012a) costs, Bottom: Vega (2012) Costs

25. Sumatra Barat



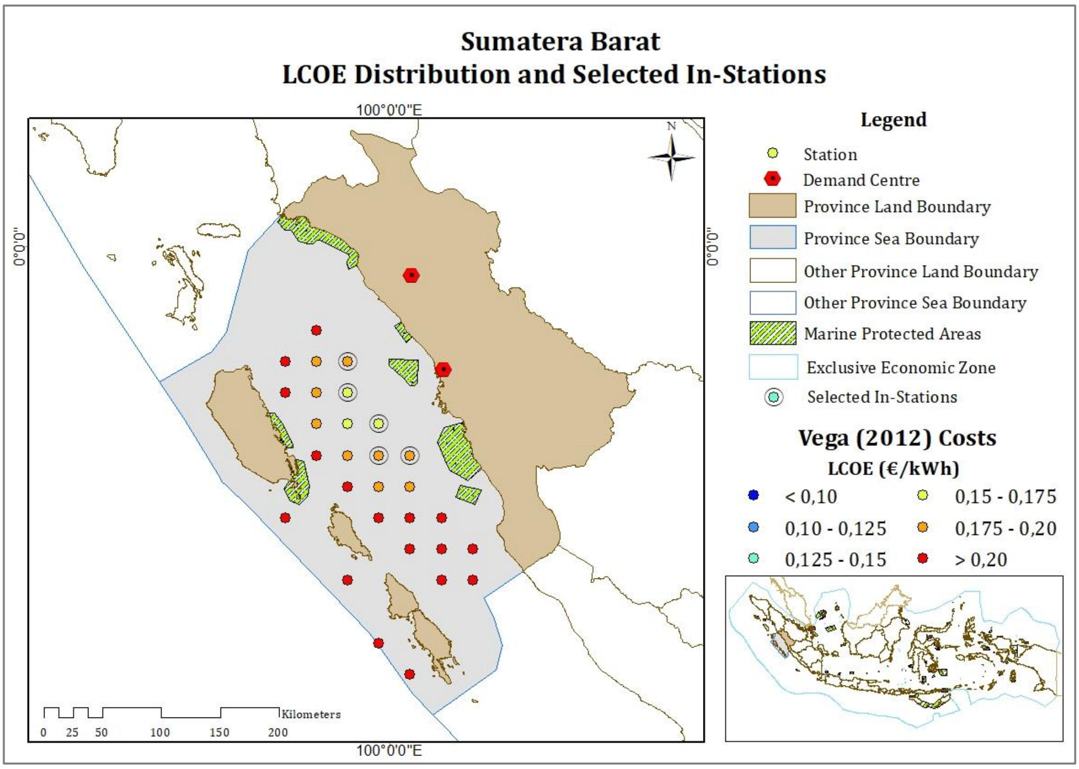
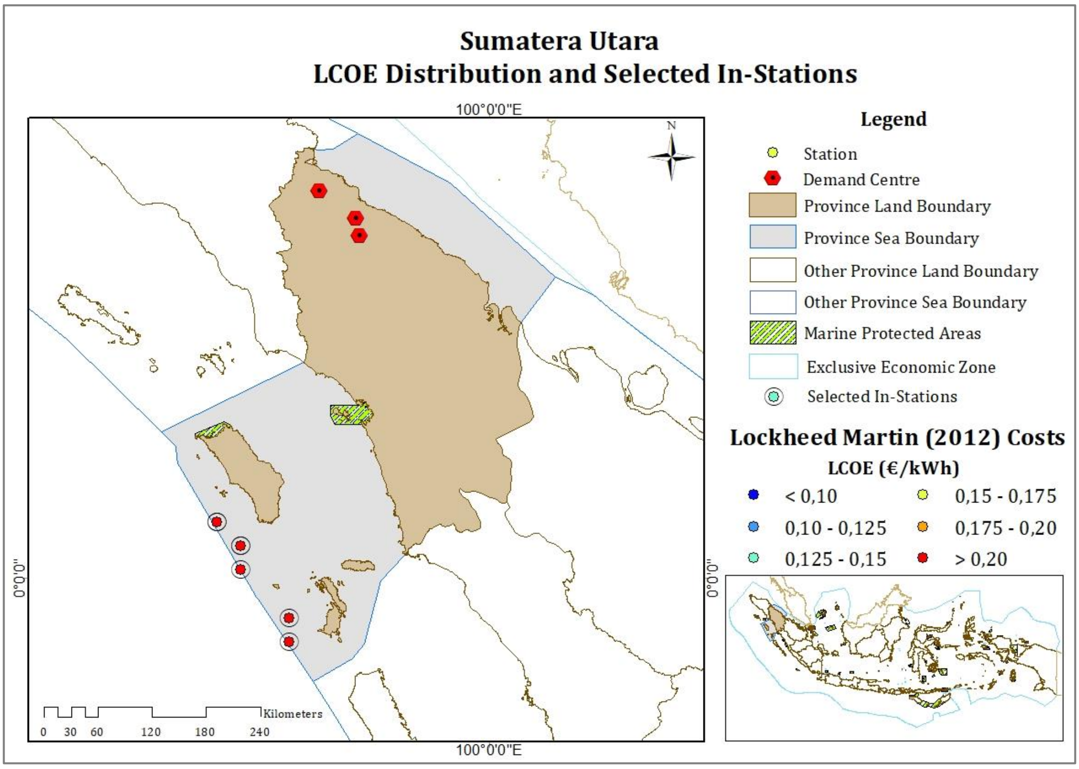


Figure A.29 LCOE Distribution of In-Stations for Sumatera Barat
Top: Lockheed Martin (2012a) costs, Bottom: Vega (2012) Costs

26. Sumatra Utara



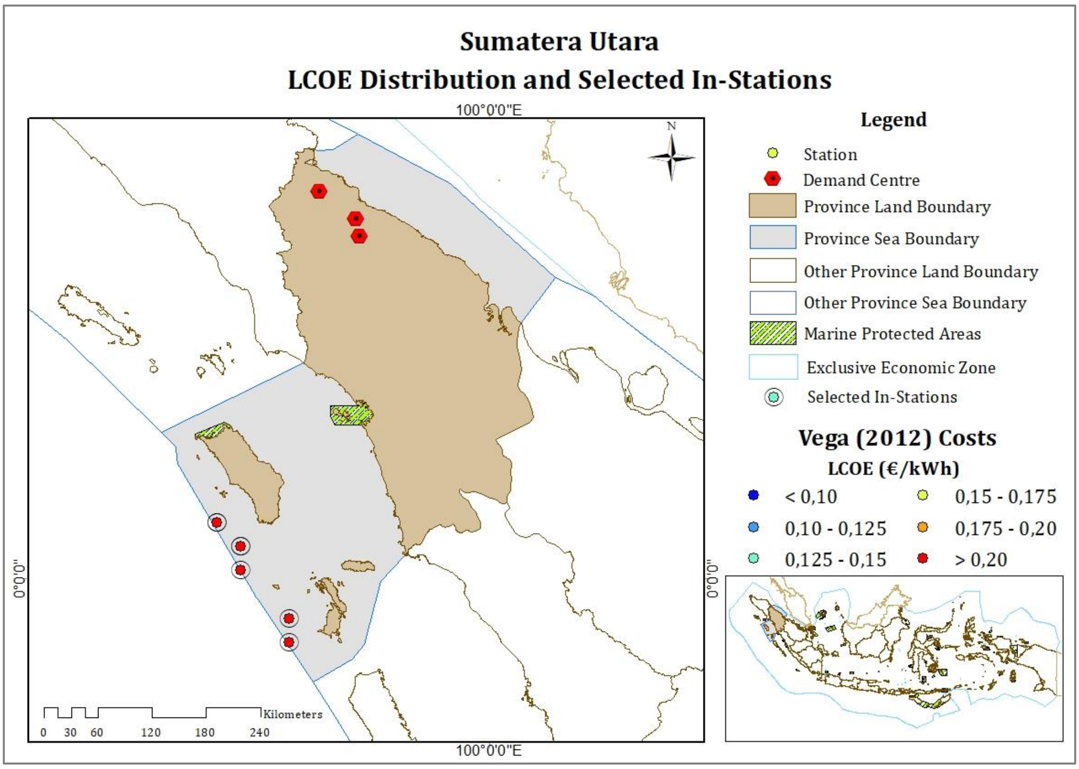
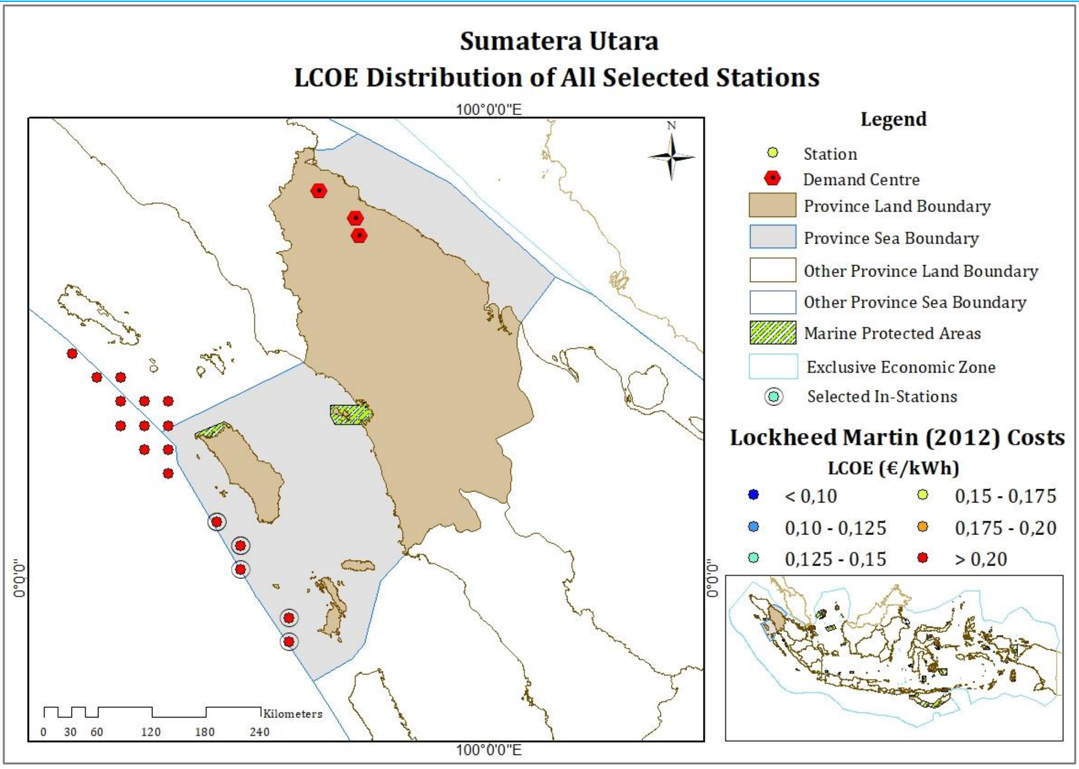


Figure A.30 LCOE Distribution of In-Stations for Sumatera Utara
Top: Lockheed Martin (2012a) costs, Bottom: Vega (2012) Costs



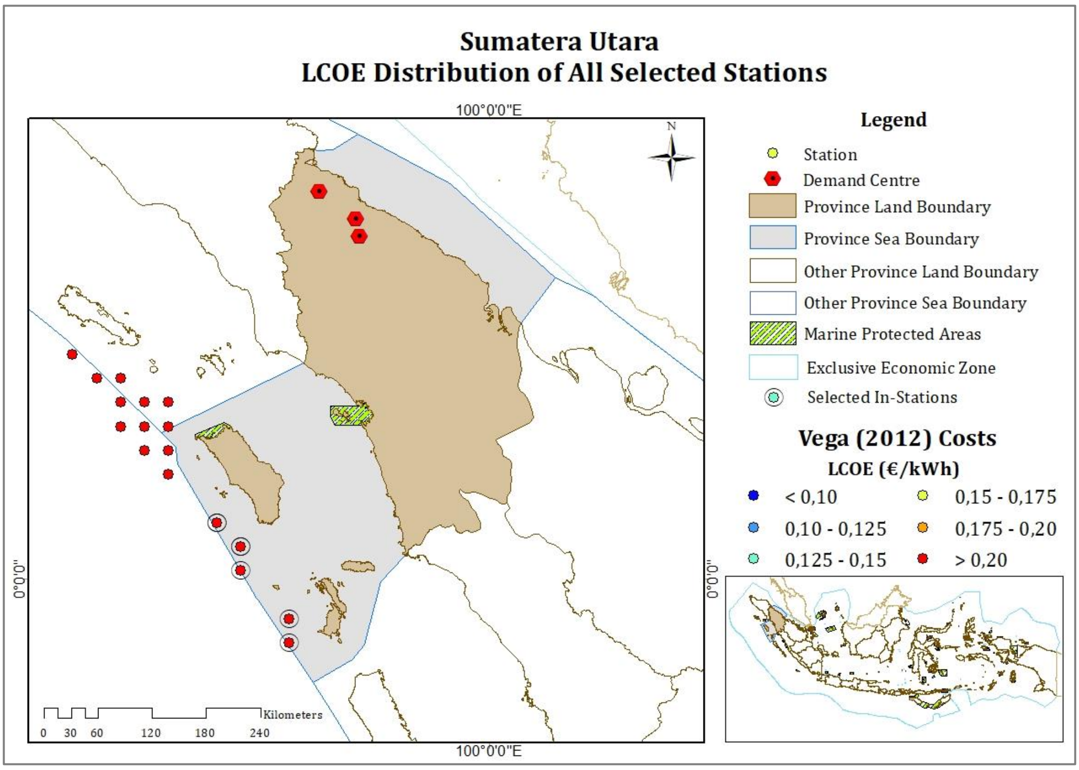


Figure A.31 LCOE Distribution of All Selected Stations for Sumatera Utara
Top: Lockheed Martin (2012a) costs, Bottom: Vega (2012) Costs

B. Table

Table B.1. Province Demand, Available Resource, and Economic Potential

Province	Demand (TWh)	Available Resource (TWh)	Vega (2012)		Lockheed Martin (2012a)	
			Economic Potential (TWh)	% Resource	Economic Potential (TWh)	% Resource
Aceh	2.33	7.5	2.6	35	0	0
Bali	5.10	6.6	6.6	100	2.91	44
Banten	51.66	3.47	2.75	79	0	0
Bengkulu	0.82	20.48	16.2	79	0	0
Gorontalo	0.44	5.97	5.97	100	4.19	70
Jawa Barat	46.14	2.67	2.67	100	0	0
Jawa Timur	32.93	2.45	2.45	100	0	0
Kalimantan Selatan	2.32	0.9	0	0	0	0
Kalimantan Timur	3.20	49.97	42.8	86	4.18	8
Kalimantan Utara	0.22	4.17	4.17	100	3.14	75
Lampung	3.82	1.71	0	0	0	0
Maluku	0.48	415.62	134.05	32	40.14	10
Maluku Utara	0.34	213.8	147.41	69	25.58	12
Nusa Tenggara Barat	1.59	37.72	37.72	100	21.46	57
Nusa Tenggara Timur	0.83	175.76	75.17	43	14.19	8
Papua	0.83	74.46	41.25	55	14.56	20
Papua Barat	0.50	45.76	7.63	17	4.5	10
Sulawesi Barat	0.29	47.91	47.91	100	32.74	68
Sulawesi Selatan	4.94	108.89	78.59	72	10.44	10
Sulawesi Tengah	1.04	117.12	95.77	82	30.84	26
Sulawesi Tenggara	0.80	141.1	63.74	45	5.17	4
Sulawesi Utara	1.40	130.61	79.66	61	39.02	30
Sumatra Barat	3.15	21.11	9.1	43	0	0
Sumatra Utara	9.24	3.6	0	0	0	0
TOTAL	**174.43**	**1639.35**	**904.21**		**253.06**	

Table B.2. Scaled-Down Calculations Results and Comparison to Reference LCOE

Province	$P_{nominal}$ (MW)	P_{output} (MW)	AEP (GWh)	LCOE Lockheed Martin (2012a)		LCOE Vega (2012)	
				Small	100MW	Small	100MW
Bengkulu	50	48.81	398.24	0.36	0.24	0.22	0.16
Gorontalo	50	62.44	495.05	0.27	0.19	0.17	0.13
Kalimantan Utara	25	34.42	267.47	0.42	0.19	0.29	0.13
Maluku	50	67.41	540.39	0.23	0.16	0.13	0.10
Maluku Utara	50	64.75	516.66	0.25	0.17	0.15	0.12
Papua Barat	50	73.46	579.15	0.24	0.17	0.15	0.12
Sulawesi Barat	25	35.27	279.58	0.36	0.17	0.24	0.11
Sulawesi Utara	50	70.75	563.93	0.23	0.16	0.14	0.11

Table B.3 Complete Results of The Electrification Scenarios

Province	N	Demand (TWh)	AEP of Selected Stations (TWh)	Coverage (%)	Economic Potential					
					Vega (2012)			Lockheed Martin (2012a)		
					TWh	n	%	TWh	n	%
In-Stations Only										
Aceh	3	2.33	2.6	112	2.6	3	112	0	0	0
Bali	6	5.1	5.62	110	5.62	6	110	0.91	1	18
Kalimantan Selatan	1	2.32	0.75	32	0	0	0	0	0	0
Kalimantan Timur	4	3.2	4.1	128	4.1	4	128	4.1	4	128
Nusa Tenggara Barat	2	1.59	2.07	130	2.07	2	130	2.07	1	130
Nusa Tenggara Timur	1	0.83	1.02	123	1.02	1	123	1.02	1	123
Papua	1	0.83	1.15	138	1.15	1	138	1.15	1	138
Sulawesi Selatan	6	4.94	6.08	123	6.08	6	123	5.12	5	104
Sulawesi Tengah	1	1.04	1.15	111	1.15	1	111	1.15	1	111
Sulawesi Tenggara	1	0.8	0.92	115	0.92	1	115	0	0	0
Sumatra Barat	5	3.15	3.68	117	2.29	3	73	0	0	0
Sub-Total	39	30.99	34.77		29.79	32		15.52	14	
Scaled-Down										
Bengkulu	2	0.82	1.06	129	0	0	0	0	0	0
Gorontalo	1	0.44	0.5	121	0.5	1	112	0	0	0
Kalimantan Utara	1	0.22	0.27	122	0	0	0	0	0	0
Maluku	1	0.48	0.54	112	0.54	1	112	0	0	0
Maluku Utara	1	0.34	0.52	152	0.52	1	151	0	0	0
Papua Barat	1	0.5	0.58	116	0.58	1	116	0	0	0
Sulawesi Barat	1	0.29	0.28	96	0	0	0	0	0	0
Sulawesi Utara	2	1.4	1.66	119	0.56	1	40	0	0	0
Sub-Total	9	4.27	5.14		2.7	5		0	0	
In- and Out-Stations										
Banten1	74	51.66	60.28	117	21.27	25	41	0	0	0
DI Yogyakarta2	4	2.7	3.46	128	3.46	4	128	0	0	0
Jawa Barat	67	46.14	56.91	123	42.86	46	93	0	0	0
Jawa Tengah2	30	21.67	24.19	112	15.94	18	74	0	0	0
Jawa Timur	43	32.93	35.06	106	27.58	32	84	0	0	0
Lampung	5	3.82	4.3	113	1.73	2	45	0	0	0
Sumatra Utara	2	9.24	9.33	101	0	0	0	0	0	0
Sub-Total	225	168.16	193.53		112.84	127		0	0	
TOTAL	**273**	**203.42**	**233.4**	**4**	**145.33**	**164**		**15.52**	**14**	

N = total number of stations selected for each province, n = the number of stations with economic potential
% economic potential = percentage of economic potential compared to the demand of a particular province