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FEASIBILITY STUDY OF RENEWABLE ENERGY
SYSTEMS FOR OFF-GRID ISLANDS: A CASE STUDY
CONCERNING CUTTYHUNK ISLAND

BY

MARVIN ALEXANDER GÖRGEN

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
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IN
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MASTER OF SCIENCE
OF
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2016

ABSTRACT

Renewable energy can be a promising approach to supply energy for remote areas and islands, address price volatility of fuels, hedge against supply insecurities, and reduce CO₂ emissions. Renewable energy has the power to create self-sufficiency in terms of electricity and the ability to be cost-effective and competitive in many areas. However, renewable energies are site specific. It is necessary to assess each case study separately to examine the available resources, environmental constraints, and socio-economic factors. Site assessments include resource characterization, technical practicability, economic feasibility, and market conditions.

The objective of this thesis is to assess the feasibility of renewable energy technologies in Cuttyhunk Island in Massachusetts, USA. Cuttyhunk Island is subjected to the constraints of islands' electricity supply and it therefore can represent a good case study. Renewable resource assessments as well as technical, economic and market analyses have been performed to assess advantages and drawbacks of the site for the transition towards renewable energies.

Based on the analysis, which was carried out using available data and information from local residents, the feasibility of an integrated renewable energy system using wind, solar and wave power has been studied in order to supply electricity demand. The initial assessment showed that wave energy is not competitive compared to wind and solar in terms of cost and technology readiness. An integrated renewable energy system for the island was proposed, which includes a Photovoltaic-Wind-Diesel-Storage (PWDS) system. It was shown that the performance indicators for a renewable system

combined with battery storage and diesel generators are the most competitive solution. The Levelized cost of electricity (LCOE) for the PWDS is estimated at \$0.2587/kWh based on the available data and simplifications which were applied.

The wind turbine used in the system has a capacity of 100 kW and a portion of the electricity generated was 42.96 %. Total production of the wind turbines is 323,339 kWh/yr. The ground mounted solar arrays of the system have a portion of the electricity consumed of 42.9% with a capacity of 234.7 kW. The total energy production of the PV array is 322,867 kWh/yr. The 100 kW diesel generator accounts for 14.14 % of the electricity supplied. The battery storage system consists of lithium-ion batteries and has a capacity of 533 kWh. The storage can establish an autonomy time of 8.20 hours on average and stores 1,599,000 kWh before it has to be substituted at the end of its expected lifetime of 11.84 years. The storage ensures that the system has a renewable fraction of about 79 %.

This research shows that a self-sufficient renewable energy system is also possible for Cuttyhunk Island. The LCOE of a system with 100 % renewable energy fraction are \$0.66/kWh. Subsidies for self-sufficiency however, can change these numbers, as they can contribute a proportion for the development of self-sufficient energy systems, even though a hybrid system has lower net present costs and provides electricity at lower costs.

The work in hand should be understood as a n initial feasibility study that needs to be continued with more detailed data. For instance, wind measurements should be performed on Cuttyhunk Island in order to better estimate the real wind speeds and its available power.

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ABBREVIATIONS

AC	Alternating current
CAPM	Capital Asset Pricing Model
CAPEX	Capital Expenditures
CBA	Cost-benefit analysis
CCC	Committee on climate change
CES	Community energy storage
COE	Cost of energy
CUE	Cost-utility analysis
CSP	Concentrated solar power
dB	Decibel
DC	Direct Current
DCF	Discounted cash flow
DER	Distributed energy resources
DES	Distributed energy storage
DHI	Diffuse Horizontal Irradiance
DIR	Mean wave direction
DNI	Direct Normal Irradiance
DOD	Depth of discharge
EU	European Union
EPR	Energy-to-power ratio
GHI	Global Horizontal Irradiance

GW	Gigawatt
GWh	Gigawatt hours
HOMER	Hybrid Optimization Model for Electric Renewables
HPWS	Hybrid photovoltaic/wind system
HSIGN	Significant wave height
IRR	Internal rate of return
JEEP	Just enough essential parts
kW	Kilowatt
kWh	Kilowatt-hours
LCC	Life-cycle-costs
LCOE	Levelized cost of electricity
LCOS	Levelized cost of storage
LED	Light-emitting diodes
MHK	Marine and hydrokinetic
MSL	Mean sea level
MWh	Megawatt hour
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NDBC	National Data Buoy Center
NOCT	Nominal operating cell temperature
NPC	Net present cost
NPV	Net present value
NREL	National Renewable Energy Laboratory

NSRD	National Solar Radiation Database
OWSC	Oscillating Wave Surge Converter
O&M	Operation & Maintenance
OPEX	Operational Expenditures
PF	Power factor
PI	Profitability index
PPA	Power purchase agreements
PtG	Power-to-Gas
PtL	Power-to-Liquid
PDS	PV-Diesel- Storage
PTO	Power take-off
PV	Photovoltaic
PWD	PV-Wind-Diesel
PWDS	PV-Wind-Diesel-Storage
PWS	PV-Wind-Storage
R&D	Research and Development
RUS	U.S. Rural Utilities Service
SAMP	Rhode Island Ocean Special Area Management Plan
SOWFIA	Streamlining of Ocean Wave Farms Impact Assessment
SOC	State of charge
SWAN	Simulating Waves Nearshore
TM01	Mean absolute wave period
TMY	Typical Meteorological Year

TRA	Theoretical energy
TVM	Time value of money
TWh/yr	Terawatt hours per year
UNFCCC	United Nations Climate Change Conference
US	United States
WACC	Weighted average cost of capital
WEC	Wave energy converter
WIS	Wave Information Studies
WHO	World Health Organization
WD	Wind-Diesel
WDS	Wind-Diesel- Storage

1 INTRODUCTION

Change of energy sources has accompanied the process of energy production in every century. Adapting to changing circumstances and global requirements has resulted in the fact that the energy resource changed from wood to coal in the 18th century, to oil and gas in the 20th century. Growing concerns about uncertainties in the security of supply, price volatility and awareness of responsibility for the planet leads to the need to alter the current system from fossil fuels towards renewable energies. Islands are affected by high energy costs and uncertainties in particular. In terms of security and costs of energy, it is of special interest to islanders to build a reliable and sustainable self-sufficiency that offers the chance to become independent from expensive imports and energy supply.

1.1 Motivation

Reducing carbon emissions from fossil fuels is a major goal in the current century and has been determined lately by all members of the United Nations Framework Convention on Climate Change (UNFCCC) at the United Nations Climate Change Conference in Paris 2015 (United Nations, 2015). The awareness of climate change and increasing greenhouse gases, which heat the atmosphere, led to the agreement to reduce the human carbon footprint. The commonly accepted goal is to limit global warming to 2° Celsius, even though current projections have shown that global temperature decrease is unlikely to fall below. In order to reach this goal, a consequent turn-around in energy generation is necessary. This involves the transformation of the energy sector to reduce carbon emission by 80 % till 2050 (Petersen, et al., 2013; Gates, 2015).

Energy transition as a long-term change of energy systems from fossil fuels to renewable energies is being implemented in many countries in their domestic politics. This big challenge requires changes on both sides, the societal and the technical system. In terms of islands, there are more issues because the entire system needs to change. Additionally, islands have special needs and difficult conditions, because of their particular geography and isolation. The isolation results into a limited range of resources and a fragile eco-system. This lack of resources and infrastructure is a major drawback for islands, because economies of scale do not exist to meet own needs. Economies of scale are proportionate saving in costs that are gained by an increased level of production. Furthermore, structural developments are hampered and energy resources, which can be very price volatile, need to be imported. These imports of fossil fuels are essential for providing consistent electricity supply.

However, oil prices rose constantly in prior years and are subjected to significant variations. Currently, the price dropped from its high in 2011 ‘about \$125/barrel’ to almost \$30/barrel in early 2016 (NASDAQ, 2016; Apergis, Ewing, & Payne, 2016). Geopolitical measures, decreasing demand and advancement in fracking technology have caused this price slump (Willet, 2016). Sharp increasing oil prices to a six-month high of about \$50/barrel show that prices can fluctuate significantly within a short time period. As a conclusion, it can be stated that missing price predictability is a serious hazard and uncertainty for the electricity generation from fossil fuels of remote communities. For coastal island, this uncertainty is in some cases encountered by a connection to the grid through undersea cables. However, small island markets and remoteness

harm this intention in many cases. Therefore, research of reliable and economical electricity supply for islands is a consideration of the work in hand.

Further, growing concerns about uncertainties in the security of supply, price volatility and awareness of environmental responsibility ensure that a shift from fossil fuels towards renewable sources is necessary. Islands are affected in particular by these factors, which is why self-sufficiency is a logical consideration. Self-sufficiency can be defined as self-supply to a degree, where imports are no longer necessary (Auer, 1976). Security of supply can be granted due to the infinite availability in terms of the lifespan of renewable energy devices. As a consequence, this research focusses on the integration of renewable energy systems with the aim to reduce the stake of fossil energy generation to a minimum, or to avoid it in general. Self-sufficiency has the advantage that price volatility does not take place, since renewable energy investments require mostly an initial expense or fixed payments for loans.

In conclusion, renewable energy systems can provide stable energy costs and a safe supply, and hedge against the fluctuations of global energy prices. Another reason for renewable energy systems is its increasing cost competitiveness for solar and wind technology developments that have set new conditions for the energy industry. Ocean technologies are still in an early research and development (R&D) phase, but can play a vital role if current prototypes confirm reliability and come into the market with competitive energy prices. Therefore, islands can become a seedbed for ocean energy technologies in particular due to their usually high energy costs.

1.2 Objectives

As mentioned, it is of special interest to islanders to build reliable, sustainable and self-sufficient systems. This is why this thesis will investigate cost competitiveness and security of supply of any conceivable compositions of energy systems, which will be characterized as integrated renewable energy systems in Cuttyhunk. The transformation from fossil fuel systems towards integrated renewable energy systems in this island, which avoids network failures and ensure absolute reliability, is the primary objective of this thesis. Thereby, different alternatives based on wind, solar and ocean energy sources will be examined by means of the software HOMER in order to identify the most reasonable setup and to elucidate feasibility of the system modification.

The purpose is to create a detailed analysis for the alteration of the energy system with the focus on Cuttyhunk island, as a case study. The case study was considered to make the right financial decisions based on resource availability and technical feasibility. In view of the fact that islands resources are limited, the available resources of waves, wind and solar will be investigated. However, other aspects like environmental and socio-economic effects will be taken into account to provide a big picture, and to judge a project comprehensively. The detailed objectives are listed as follows:

- 1.** Find the most cost-effective energy system with the required reliability for Cuttyhunk Island
- 2.** Determine the most feasible combination of energy sources for self-sufficiency for Cuttyhunk Island
- 3.** Define key parameters for renewable energy systems in the case study

1.3 Synopsis

Figure 1 illustrates the outline of this thesis. Initially, a literature review will be done in Section **Fehler! Verweisquelle konnte nicht gefunden werden.**. This literature review will comprise background information concerning renewable energy resources, supply systems, costs of energy and renewable energy systems. It specifies the framework for the thesis and approaches the subject matter in detail.

Thereafter, Section 3 discusses the methodology. It includes the following parts: The case study and its current energy status will be surveyed. Thereby, comparisons of electricity costs and electricity consumption will be done for federal, state, regional and local level in order to show differences between economic constraints. A general overview to local conditions, the electricity generation process and the demand behavior will be performed. Both will be done qualitatively.

Figure 1 Scope of thesis

Section 4 will encompass a renewable energy resource assessment. This will be carried out using data publicly available. The resource assessments examine the historical data and refer to resources that are locally available. This approach enables to select

appropriate devices to evaluate different variants of systems to be proposed. These alternative solutions represent concepts that need to be analyzed and tested. This testing and evaluation concerning the optimal setup of cost-effective and reliable systems combines the different renewable energies and energy storages and diesel backup systems. The investigation finishes with a trade-off concerning economic viability and technical feasibility. After technical concerns are analyzed and assessed, financial plausibility has to be performed in more detail for the most promising energy setup. Depending on the system, the associated devices and construction techniques, a market assessment will state whether close attention needs to be paid to technical, environmental or socio-economic considerations. This estimation could also result in an iterative process when the impacts are considered to be critical.

Finally, Section 6 derives conclusions for the case study concerning Cuttyhunk Island. Essential findings will be illustrated and linked to general requirements or conditions for an energy transition towards renewable energies under perspectives of economical and reliability aspects. Prospects for other islands and remote areas may originate from this to give advice with the aim to facilitate achieving renewable energy grids with superior cost-benefit ratios.

It should be mentioned that the analyses provided are initial assessments, and further data collection and analysis are required in practical sense, because the used values uncertainties, as they are chosen on a general level.

2 LITERATURE REVIEW

Islands and rural places face challenging conditions for electrification in general. Long distances separate thinly populated areas from national grids and economic pre-conditions do not allow a comprehensive provision due to its small market and high supplying costs. A reliable grid is a basis for economic growth and social stability and supplies lighting, heating, cooling and consumer devices with energy. The demands of rural areas can be separated in electricity and heating demand. Renewables can cover both. Furthermore, they offer an environmental friendly solution at the same time (Woodruff, 2007).

Twidell and Weir define renewable energy, as extractable energy from natural flows of energy, which occurs in the immediate environment (Twidell & Weir, 2015). These flows of energy include solar, wind, hydro, thermal, ocean and biomass resources. Thermal resources can only be used in geothermal active areas. Otherwise deep depths need to be reached, which result in an expensive enterprise. Hydropower is inapplicable, if no existing spring of water is available or minor altitude differences exist. Small islands usually lack these criteria. Examples like Samsø in Sweden show that biomass technology is applicable for islands. However, in terms of smaller islands, biomass usage may be inappropriate due to resource restrictions and incompatibility for land use in terms of agricultural cultivation (Jørgensen, et al., 2007).

This thesis uses three types of energy for the investigation of energy. Those three terms are theoretical, technical and practicable energy (National Research Council, 2013). Theoretical available energy is defined as the amount of energy that exists in a

system/ body in terms of kinetic energy and potential energy, which may be derived into work (Espinosa, E.; Alkorta, I.; Roza, I.; Elguero, J.; Molins, E., 2001). Technical extractable energy is the part of the available energy that is usable for production using an energy converter (Shihon, Straub, & Elimelech, 2014). In contrast, practical energy is the specific proportion of technical energy a system can use due to political restrictions or ecological constraints (DOE, 2012).

Referring to the definition of renewable energies from Twidell & Weir (2015), energies need to be obtained from the occurring immediate environment. Therefore, this thesis confines on solar, wind and ocean resources since they are commonly available and the technologies are most widely approved.

2.1 Wave Energy

Power in ocean waves originates from wind that transfers its energy to oceans. Waves have different frequencies and different directions, but can be characterized by their directional wave spectrum. The theoretical energy in waves is expressed as wave power density, which states how much energy flux waves contain. Therefore, the power per unit length of wave crest needs to be evaluated in terms of its direction and magnitude (National Research Council, 2013).

The total available wave energy along the United States (U.S.) is estimated by Jacobson, Hagerman & Scott (2011) to be 2,640 Terawatt hours per year (TWh/yr). The main areas, where ocean conditions meet the requirements for installations, are Alaska with 1570 TWh/yr, some areas in the West Coast with 590 TWh/yr and some areas in the East Coast with 240 TWh/yr (Jacobson, Hagerman, & Scott, 2011). The available U.S. wave energy represents more than 60 % of the 4,162 TWh total electricity used in

the U.S. in 2014 (EIA, 2014). This amount is therefore considerable. However, theoretical available energy does not represent the electricity that is technically extractable. Wave energy has temporal and spatial fluctuations and is therefore site specific.

The fact that wave energy converter (WEC) extract energy from waves reduces their theoretical available power in the wake of a device. Those devices that are located in the second row are therefore not capable of producing the same electricity, if they are close. This effect is commonly known as the shadowing effect. The shadowing effect implies that there is only one line of WECs deployable at a potential site, which sets WECs apart from for example solar technologies (National Research Council, 2013).

Wave energy industry is stunted in its development and could be compared to the wind industry 40 years ago, when the technology has been in an early stage of development (Van Beek, 2015). Wave energy is not widely deployed as most of the technology is still at an early stage of development. Currently, practical wave resources are insignificant for the global energy production, but can become more important. Wave and tidal energies represent only 0.01% of the worldwide electricity generated at the moment (Ernst & Young, 2015). The amount of the produced US ocean energies per year of about 0.04 MW is solely produced by test sited and nearly negligible. The reason therefore is that wave technologies do not have reached commercialization stage and still involve high costs in R&D. However, if reliable technology can be brought to global markets, penetration potential for wave energy capacity is estimated to be up to 340 GW by 2050 depending on the speed of development (Ernst & Young, 2015).

The emergence of waves, its distribution and variability result mainly from wind, which is strongest in winter on the east coast of the US (Klink, 1999). The average wave

power level is more than three times bigger than in summer months (WIS, 2016a). This coincides with the seasonal energy consumption of typical U.S households due to heating and lightning. (Brook, Bhattacharyya, & McCormick, 2003). The wave power is a proportional interaction of the square of wave amplitude and wave period of the motion (Clément, et al., 2002). WEC however, capture usually a distinct range of wave heights and periods, wherefore the exploitation of wave energy depends highly on device characteristics (Whittaker & Folley, 2012). Currently, there are eight main concepts of WEC that can extract energy from waves (EMEC, 2015):

- Attenuator
- Point absorber
- Oscillating wave surge converter
- Oscillating water column
- Overtopping device
- Submerged pressure differential
- Bulge wave
- Rotating mass

Research and development of these systems started intensively after 1973, since when several WEC have been tested and operated (Walton-Bott, Hailey, & Hunter, 1978; Whittaker, et al., 2007; Durand, et al., 2007; Kofoed, Frigaard, Friis-Madsen, & Sørensen, 2006). Most of these systems are still in an early stage of market entry, because no commercialization stage has been reached yet. Therefore, it cannot be concluded which of the different approaches will emerge as dominant. One of the promising

concepts is the point absorber due to recent prototype development in industrial dimensions that can either be visual on the surface or submerged (Drew, Plummer, & Sahinkaya, 2009).

The PowerBuoy from Ocean Power Technologies (OPT) is a point absorber that can be installed in water depth ranging from 25-1,000 m. With continuous power supply of 40 Kilowatt (kW) and a power capacity of 150 kW for a single unit, these devices have the ability to power communities if connected to arrays. Currently, operational safety is tested, which means that development is progressed. OPT states an efficiency in optimal conditions of 35-40 % and cost of electricity (COE) is estimated to be \$0.15/kW once large scale production is started. An additional advantage is an integrated battery capacity with capacities between 25-250 Kilowatt-hours (kWh). The OPT can be seen in Figure 2 and Figure 3 (OPT, 2016).

Figure 2 Point absorber components
(Subsea World News, 2012)

Figure 3 Point absorber array (OPT,
2012)

However, the load factor with respect to power factor is decisive for any electricity generating device, not the efficiency in optimal conditions (Rusu, 2014). The load factor

is defined as the average generated power divided by the nominal power of the device. As Rusu (2014) has found, the load factor for attenuator (Pelamis) are 15.2-16.9 % and for overtopping device (Wave Dragon) 34.5-37.3 % in the Spanish nearshore. Rusu also found that a heaving point absorber (Aqua Buoy) has a load factor of 8.4-9.5 %.

Grilli *et al.* (2007) developed an original free-floating point absorber consisting of spare buoys that are connected to a short-stroke linear generator (Grilli, Merrill, Grilli, Spaulding, & Cheung, 2007). This system has shown that viscous friction and resonance are the dominant damping mechanism, and that the buoys must be properly streamlined, as it increases damping. A system consisting of three buoys of the same diameter mounted in an equilateral triangle one diameter apart from each other, can reduce the mentioned mechanisms. (Josset, Babarit, & Clément, 2007; Grilli, Grilli, Bastien, Sepe Jr., & Spaulding, 2011).

The point absorber is not only pursued by OPT, but by several ocean energy companies. It converts energy from the heaving movement of a buoy that produces a mechanical motion. Devices like the SEAREV however, can also extract energy from roll motion (Josset, Babarit, & Clément, 2007; Ruellan, et al., 2010) This motion gets converted into electricity by a power take-off (PTO) unit. The PTO functions like a non-constant electromagnetic generator and is illustrated in Figure 4.

Figure 4 Power take-off unit (Mentzer & Schwartz, 2015)

Beside the point absorber, the oscillating wave surge converter (OWSC) is a second promising approach for WECs. In contrast to point absorber, OWSC can be installed in shallow waters between 10-15 m. The device is mounted to the seabed and generates energy from wave surge and its heaving movement. Figure 5 shows that OWSC have three major parts. The buoy (a), the PTO (b) and a low voltage connection (c) to the grid or consumer.

The company Aquamarine Power has modified this technology slightly for its prototype device Oyster. The Oyster does not have a PTO, but two pistons that pump high pressured water to a power plant on the shore. In the power plant, the pressurized water drives a turbine that itself drives a generator. Multiple OWSC can be added to the system. This system is capable of generating 0.8 MW of electricity for each OWSC installed (AP Limited, 2015). Nevertheless, capacity factors or specific information concerning costs of produced electricity or device costs are not available due to its early stage of development.

Figure 5 Oscillating Wave Surge Converter components (Blazej, 2011)

Figure 6 Oscillating Wave Surge Converter array (AP Limited, 2015)

However, WEC are site specific, therefore each WEC has to be selected and adapted to the local wave climate conditions to ensure maximum efficiency. This may require other approaches than the introduced point absorber. Hence, developers need to ascertain the specific requirements to the individual area. This includes assessing the amplitude of waves respectively their significant wave heights, as well as their period.

The simulation of the wave energy is typically done using wave models, satellite altimetry or in situ measurements based on wave buoys. Wave buoys are the most reliable approach to evaluate wave heights and periods. For assessing the wave climate, recorded extreme events like storms and hurricanes are mostly disregarded. The advantage of buoy data is the provision of direct measurements of the actual conditions at a specific site. Nevertheless, they can only submit localized information, therefore interpolations between each measured point have to be made, which includes high uncertainties. Wave models offer both, a cheapest and fastest way to assess the wave energy climate, and an approach to estimate available energy for the area of interest (Arinaga & Cheung, 2012). Altimetry measurements have the advantages that they can cover a

spacious area, are accurate and transfer the measured data immediately. The third approach comprises hindcast data and propagation models (WIS, 2015).

The characterization of wave climate is the first step to define the wave energy potential. The equation of deep wave energy flux can be used for this purpose. In terms of waves, annual variability is the most important information to judge the wave climate, even though there can be inter-annual variability. Likewise, spatial variability is an important aspect that has to be considered, because wave power depends on the local conditions, as for example on the bathymetry (Neill & Hashemi, 2013).

Wave energy is estimated as,

$$P_W = \frac{\rho g^2}{64 \pi} T_e H_s^2 \quad (1)$$

, where P_W is the wave energy flux in watts per meter of crest length determined by the density ($\rho = 1025 \text{ kg/m}^3$) of sea water, the gravitational acceleration ($g = 9.81 \text{ m/s}^2$), the energy period (T_e), and by H_s , which is the significant wave height (Brook, Bhattacharyya, & McCormick, 2003).

Density and gravitational acceleration are relatively constant. As a consequence, the essential factors of wave energy flux are wave height and their associated periods. This implies that waves with high amplitude and long period carry along the most energy. For convenience, wave energy flux per unit of wave crest can be assumed to be significant wave height squared times the wave period divided times 0.5.

2.2 Wind Energy

Along with hydro kinetic energy, wind energy has been the dominant source of mechanical power for centuries. Today, the kinetic power of moving air masses of the atmosphere is converted into electrical power by means of wind turbines. In the U.S.,

the electricity generation from onshore wind is a reliable energy resource and meets about 5 % of the nation's electricity portfolio in 2014 (DOE, 2015). The usage of wind as a power source is becoming more meaningful, since developments and the scale-up of turbine technologies accelerate performance and cost competitiveness. Currently, the largest wind turbines reach heights of 112 m and blade spans of 167 m (Samsung Heavy Industries, 2016).

The general idea of generating electricity by means of wind turbines is that moving air particles transfer their kinetic energy into the blades of the wind turbine, which causes rotation of a generator that itself produces electricity. The theoretical limit of energy extraction of wind turbines can be maximal 59.3 % and is called Betz Law. The Betz Law states that if a turbine extracts all energy from the air, the single molecule would be stationary and be an obstacle for the returning blade. The blade would have to move the molecule and reduce its energy accordingly. Optimized wind turbines can reach approximately 80 % of this restrictive barrier (Ackermann & Söder, 2002).

Modern wind turbines can be either horizontal axis wind turbines (HAWT) or vertical axis wind turbines (VAWT). HAWTs are the dominant technology for harnessing wind. In general, HAWTs have higher energy efficiencies and lower system costs per generated kW due to the amount of produced electricity. However, HAWTs produce more energy only when wind quality is high. This implies that directional variability, turbulences and fluctuations of the wind have to be low. These factors however, do not affect VAWT. VAWT can operate well even though wind quality is not sufficient. For this reason, VAWT are beneficial in areas with low quality wind speeds (Pope, Dincer, & Naterer, 2010).

Cost of electricity of wind turbines decrease steadily, since the dimensions of wind turbine increase and the price for wind turbines decreases (Redlinger, Andersen, & Morthorst, 2016). The average installed prices for wind turbines were about \$850 – 1,250/kW in 2014 and with that significantly cheaper compared to 2008 when the average price increased to more than \$1,500/kW (U.S. Department of Energy, 2015). In 2014 the prices in recent power purchase agreements (PPA) have fallen to an all-time low of about \$22.4/MWh from its high in 2008 of nearly \$70/MWh (U.S. Department of Energy, 2015). Considering that price agreements in PPAs compose of, turbine prices, installation costs, operation & maintenance (O&M) costs, and project financing, it can be concluded that these determinants decreased collectively. These price reductions are linked to technology improvements and increasing reliability, for which reason overall project costs fall. As a consequence, produced electricity becomes cheaper (U.S. Department of Energy, 2015).

Figure 7 Global annual and installed wind capacity 2000-2015 (GWEC, 2016)

In 2014, wind has been the second most electricity producing energy source in the world with a share of 3.1 % after hydropower with a share of 16.6 % (Ren21, 2015).

For the same year, hydropower has a growth rate of 3.6 %, whereas wind has a growth rate of 16 %. Hydropower is the energy generated from water that is captured in dams or reservoirs. The gap between wind and hydropower in electricity production shows that hydro has been a widely used energy source for a long time, but wind energy has higher potential and is therefore a prospering technology, which can be seen in Figure 7 (Ren21, 2015).

In 2014, the global added wind power capacity has been 48 GW of total added capacities of 128 GW. This contributed 37 % to the final sum of renewable energy investments, for which reason wind energy is currently the leading renewable energy source (Ren21, 2015). Investment in wind energy worldwide increased from \$14 billion in 2004 to \$80 billion in 2013. The growth in wind capacity is mostly led by onshore installations with currently 97 % of total energy production (IEA, 2015). Offshore projects have increased as well, but are most prevalent in Europe, where more than 91 % of the world's offshore wind power is installed (GWEC, 2016). Until today, the U.S. do not have offshore wind farms, but will do so when the first project is expected to go on stream at the end of 2016 (Deepwater Wind, 2016).

Figure 8 Land and offshore annual wind speed at 80 m in the United States (NREL, 2010)

There are higher wind speeds and more potential energy in offshore areas compared to onshore. Therefore, wind turbines offshore can produce greater amounts of energy. Figure 8 illustrates that wind speeds on the ocean are higher and shows the resource potential of wind in the US. Nevertheless, wind energy is not as consistent as one would expect by analyzing US annual wind speeds at 80 m.

Wind turbine siting is an important part in wind resource assessments due to its spatial fluctuating nature, which implies that the evaluation of uncertainties in wind resources and their siting is inalienable (Spaulding, Grilli, Damon, & Fugate, 2010; Grilli, Insua, & Spaulding, 2012). In addition to it, the estimation of the wind power resources is best validated by the Weibull distribution, because it represents the most accuracy of the wind speed distribution (Grilli & Spaulding, 2013).

The terminology of wind energy is as inconsistent as marine and hydrokinetic (MHK) energy is defined, because there is no particular definition for the power resource (Da Rosa, 2012; Bailey & Freedman, 2008). In order to provide a consistent base in this thesis, the definition will orientate on the definition of MHK energy (National Research Council, 2013). The theoretical power resource is defined as the wind power density P in W/m^2 . The technical power resource is defined as the maximum power density P_t in W/m^2 once a wind turbine is sited.

There are three factors that limit the technical power resource based on turbine characteristics. These factors are cut-in wind speeds (u_{in}), cut-out wind speeds (u_{out}), and rated speed (u_r). The cut-in wind speed is the minimum wind speed that a turbine needs to start operating. The cut-out wind speed is the maximum wind speed at which the rotation of the turbine blades is stopped in order to avoid damage. The wind speeds in-between cut-in and cut-out wind speed is defined as the available power. The rated wind speed is the wind speed at which a turbine produces its maximum power (Hansen, 2015).

Hennessey (1978) defined the concept of usable power P_u based on the three wind speeds (Hennessey Jr, 1977). This definition is used in addition to Betz law to determine the maximum extractable power for a wind turbine with a 100 % efficiency. Equations (2), (3), and (4) give the three power definitions of available (P_a), usable (P_u), and technical power (P_t): (Grilli & Spaulding, 2013)

$$P_a = \int_{u_{in}}^{u_{out}} P(u)f(u)du \quad (2)$$

$$P_u = \int_{u_{in}}^{u_r} P(u)f(u)du + \int_{u_r}^{u_{out}} P(u_r)f(u)du \quad (3)$$

$$P_t = 0.59P_u \quad (4)$$

, where $f(u)$ is the function of wind speed probability density and $P(u)$ is the theoretical power density (P) that is associated with wind speed at a distinct hub height.

The definition of wind speed is the rate at which air flows at a distinct point in the atmosphere, whereas wind power density is defined as the theoretical power in the air flow. The wind power is a function of energy flux (E_f) which is given for a constant air stream with a constant density wind speed (v), divided by the area of the air stream. This relationship is shown in the following equation: (Manwell, McGowan, & Rogers, Wind energy explained: theory, design and application, 2010)

$$P = \frac{E_f}{A} = \frac{1}{2}\rho v^3 \quad (5)$$

Air density depends on elevation, temperature and weather, but can be assumed constant because it does not fluctuate much. A standard value that comprises elevation, temperature and weather is commonly used as an approximation. This value is 1.225 (kg/m^3) for an average temperature of 59°F (Jamil, Parsa, & Majidi, 1995). Hence Equation (5) can be simplified to:

$$P = 0.6125v^3 \quad (6)$$

The equation shows that theoretical power is mostly influenced by the cube of wind speeds. The wind energy density is decisive in order to give general estimations for wind resources and allows to compare sites for different wind turbines.

Onshore wind turbines are currently more cost-effectiveness compared to offshore wind turbines. Offshore wind turbines may do not represent a viable solution for small islands, because of installation costs and electricity transfer costs for underwater cabling (Breton & Moe, 2009). Furthermore, social refusal is currently a project constraint when it comes to offshore wind energy, which however also effects onshore wind farm projects. A current project that aimed to construct the first offshore wind park in the US in the Nantucket Sound off Cape Cod, Massachusetts has been abandoned after public opinion declined it among other things. The project had been associated with the ruination of the scenic views from both, private properties as well as from public beaches, because the wind farm had been supposed to be 4.8 miles off the coast. This aspect has been a major constraint for the project beside political and financial issues (Dennery, 2015; Brownlee, et al., 2015; Kimmell & Stalenhoef, 2011).

Especially political requirements concerning regulatory and permitting, as well as environmental and socio-economic risks slow down the development of offshore wind farms. The designated area has to be jurisdictive confirmed and should be available for leasing, when the site is located in federal waters. This approval process alone may take as long as 7-10 years. Stakeholder concerns of wind farms affect both environmental and socio-economic effects (Musial & Ram, 2010). The main factors are listed as follows:

- Marine animal populations
- Visual effects
- Property values
- Noise
- Tourism
- Marine safety
- Fisheries

Due to these concerns, US States developed guidelines for ocean areas. One of these guidelines is the Rhode Island Ocean Special Area Management Plan (SAMP) that gives comprehensive regulations including fisheries stocks, transport channels and the siting of offshore wind farms. The requirements for offshore wind farms are considerable, and demand long planning processes (Rhode Island Coastal Resources Management Council, 2010).

In terms of Cuttyhunk Island, offshore wind turbines are not taken into account in this thesis due to the stated reasons of cost-competitiveness, regulation, permitting as well as environmental and socio-economic constraints. However, issues of onshore wind turbines will be assessed to figure out whether wind technology is a potential candidate for energy generation on Cuttyhunk. These issues deal with land use, loudness, visual disturbance and the problem of shadow flicker, which is the flickering effect of rotating wind turbine blades on the ground.

2.3 Solar Energy

Solar energy is the origin of almost any energy used by humanity and is convertible into electricity due to the photoelectric effect. The photoelectric effect was first

found by Heinrich in 1887, but explained in more detail by Einstein in 1905. The photoelectric effect is used in photovoltaic (PV) cells to convert solar radiation into electricity. The amount of electricity that can be produced is based on intensity and wavelength (Kleissel, 2013).

Shielding and passive use of solar energy developed early in human history. Avoiding solar radiation in sunny areas and heating up facilities in cooler regions has been readily used. By means of technology progress, more advanced use of solar energy for electricity generation became possible, and two approaches for converting solar radiation emerged. These approaches are PV systems and concentrated solar power (CSP).

Figure 9 Annual solar radiation for monthly average radiation (NREL, 2014)

The solar technology that is mostly used is PV. Figure 9 shows the annual solar radiation for the US. It shows clearly that the highest concentration of solar energy occurs in the south-west in New Mexico, Arizona, Nevada and California. These areas

have energy densities of 7.5 kWh/m²/day. The states in the US that have the lowest solar radiation are located in the north-east.

PV systems are an increasingly cost-effective technology for the generation of electricity. They can be mounted on roofs, as it can be seen in Figure 10, or installed as standalone systems. The global solar PV capacity has been about 177 GW in 2014. This amount more than quadrupled in four years from 40 GW in 2011 and shows the increasing relevance and competitiveness in terms of costs (Ren21, 2015). Even though PV is an evolving technology, it is still only accountable for 0.9 % of global energy production (Ren21, 2015).

Figure 10 Example of PV-roof -panels
(Great Brook Solar NRG LLC, 2016)

Figure 11 Solar thermal power plant in
Spain (Abengoa Solar, 2015)

CSP uses solar thermal, which can be used for water heating. Unlike PV, warmth production from solar thermal can be based on a centralized method, as it can be seen in Figure 11. This figure shows the concentrated solar power generating plant in Seville, Spain. Nevertheless, this method is still in pilot stage and other than that not viable for islands, where space is limited. For this reason, CSP will not be considered for the purpose of this thesis.

Silicon wafers are the starting product for PV cells. Those wafers can be produced in different methods as monocrystalline, polycrystalline and amorphous cells with differing efficiencies. The cells are assembled into modules and represent one unit. These modules can then be assembled to arrays. Monocrystalline cells can reach high efficiencies in laboratory environments of up to 25.6 %, a high durability and a very low failure proneness. Losses in diffuse light conditions are low and the operating reliability is steady, but production of monocrystalline solar modules is currently most expensive. Polycrystalline units have the same characteristics except lower efficiency of under 21.7 % and also lower costs (Polman, Knight, Garnett, Ehrler, & Sinke, 2016).

Amorphous solar cells are thin-layered cells and can be manufactured flexible on different structures, because they absorb solar radiation directly by the silicon. However, their efficiency is approximately 5-8 % and their durability is substantially lower compared to mono- and polycrystalline modules. All three types of PV have their legitimation for different application areas. A solar resource assessment can reveal the most qualified technology and device for a site (Willeke & Grassi, 2008).

Ground measurements can be performed for solar resource assessments. However, these measurements are contingent on accuracy and instrument performance. Data can contain errors and it is possible that these inconsistencies influence results. Thus, solar irradiance models have been developed. These models use meteorological data to estimate the variability of available solar resources accurately (Wong & Chow, 2001).

For this reason, Typical Meteorological Year (TMY) data is used in most solar resource assessments due to its representativeness of a location's long term climate. TMY consists of Global Horizontal Irradiance (GHI), Diffuse Horizontal Irradiance

(DHI), and Direct Normal Irradiance (DNI). The relationship between GHI, DHI and DNI can be seen in Equation (7). Schnitzer *et al.* state that TMY is most likely to under-predict long-term solar resource compared to other sources. Nevertheless, TMY data is conservative because it does not overestimate solar potential. It can be considered as a reliable source for an economic analysis (Schnitzer, Thuman, & Johnson, 2012).

$$GHI = DHI + DNI(\cos(\Theta)) \quad (7)$$

GHI is the total amount of radiation received by a surface horizontal to the ground. It is of particular interest for PV installations and consists of DHI and DNI, which needs to be corrected for the angle of incidence on the surface (Θ). DNI is the amount of solar radiation received by a surface, which is perpendicular to incoming irradiance of the sun at its current position. DHI is the amount of irradiance that comes from the surrounding or has been scattered in the atmosphere (Schnitzer, Thuman, & Johnson, 2012).

Hierofka and Kanuk (2009) used GHI data in an approach based on a geographical information system (GIS) for the assessment of photovoltaic potential. Thereby, they estimated the electricity production in kWh for a system based on following equation: (Hierofka & Kanuk, 2009)

$$E_{out} = A_e E_e G \quad (8)$$

, where E_{out} is the annual electricity production in kWh, A_e is the total surface area of solar cells in square meters, E_e is the annual mean power conversion efficiency, and G is the annual solar irradiation in Watt-hours per square meter.

2.4 Energy supply systems

Energy supply is defined as the delivery of energy to its destination of demand, which contains conversion, transmission, storage, and distribution of energy. Conversions of renewable energies have been explained in Subsections 2.1, 2.2 and 2.3. In the following Subsection, transmission, storage and distribution will be explained to review energy supply systems for renewable energies.

2.4.1 Energy grids

Studies concerning the electrification of remote areas have shown that distributed energy systems are well suited in terms of renewable energies (Alanne & Saari, 2006). Distributed generation is defined as the obtaining of demanded energy from many sources through small-scaled energy producer. This means that an array of energy plants is able to generate the amount of a conventional centralized power plant. The challenge for implementing renewable energies in an existing grid lays in the variability of energy supply of natural resources. In addition, energy demand is variable too. Therefore, it is likely that energy production and energy use do not meet in time. This risk is a major issue for the implementation of renewable energies. The allocation of energy supply towards different energy sources is a possible mitigation, because different sources have different occurrences and can flatten the energy production as required. This is defined as distributed energy resources (DER), which is essentially the combination of different small-scale energy devices (Jiayi, Chuanwen, & Rong, 2008).

DER can be aggregated towards a smart grid (Tushar, et al., 2015). A smart grid adjusts itself to the actual energy variation and regulates the temporary usage. Overall, an smart grid adapts fluctuating diurnal and seasonal demands. A smart grid uses computer-based automations and can be remote-controlled. Further advantages of smart

grids are improvements in energy efficiency due to individual adjustment and control, and more consumer-interactivity (DOE, 2015).

As a result of the restriction in size, the grid structure of most islands can be described as a micro-grid. A micro-grid is a small-scale energy system that handles the local energy supply in a defined and autonomous area. The system can be composed of either central or DER and forms a unique set-up. Most energy systems are AC/DC-systems that have the ability to operate both, devices on the basis of alternating current (AC) and on the basis of direct current (DC). AC is available for most homes. It transmits electricity without great losses over great distances. Transformers then convert voltage levels into DC that is required by electronic device (Luo & Ye, 2016).

Figure 12 Exemplary renewable energy system setup (U.S. Department of Energy, 2007)

Figure 12 shows an exemplary hybrid photovoltaic/wind system (HPWS) that is based on different sources. The illustrated DER system considers the fact of temporal mismatch of renewable energy production and electrical load by including a battery and

a backup to the system. Design and performance of renewable energy generation requires the accurate knowledge of issues that could arise during a project. These corresponding deliberations include transient overvoltage, harmonic problems, transformer saturation, power factor, reactive power and voltage control, power ramp rates, and response to system disturbances anticipatory (ABB Ltd, 2015)

Micro-grids are standalone operating AC systems with high durability and resilience, and low amounts of electricity failure. Currently, the majority runs on diesel. The categories that micro-grids can be subdivided are structured according to their size: (Microgrid Institute, 2015)

- Nano micro-grids
- Off-grid micro-grids
- Campus micro-grids
- Community micro-grids

Besides its size, the classification of micro-grids is also made concerning eventual connection to the regional grid. Typically, nano micro-grids refer to a single building that can be operated independently. Off-grid micro-grids supply electricity to one or more remote areas or islands. Campus grids and community micro-grids are integrated to the national grid. Community grids can isolate the system for a reasonable amount of time. In comparison, campus-grids can stay independent (Microgrid Institute, 2015).

As described, micro-grids can use either centralized or decentralized sources of power. This means that several power plants can be connected together or that just one major power plant supplies electricity. Renewable energy resources are mostly distributed for which reason this represents an ideal system. The drawbacks are higher maintenance costs and installation needs. In contrast, central systems provide lower costs than

distributed systems. However, this approach has disadvantages too, because it requires additional land usage (Carlisle, Elling, & Penney, 2008).

As mentioned previously, the contribution of energy from renewable sources varies, wherefore the implementation of DER requires energy storages or backup systems. These backups can be both a connection to the regional grid or diesel generator systems.

2.4.2 Energy storages

A common problem with renewable energy is the lack of consistency in the availability of the power source. Solar power is only available when the sun is out, while wave energy is highly dependent on offshore wind activity. If DER are not capable for maintaining a constant frequency in a system, the system setup needs to be modified to account for fluctuation of electricity. Jacobson *et al.* (2015) have shown that both, distribution of energy and storing energy is crucial for integrated renewable energy systems. Establishing a renewable energy system becomes considerably difficult when self-sufficiency is intended. The fluctuating and discontinuous nature of renewable energies can affect the stability and operations of the electrical grid significantly. Storages overcome this problem and allow saving electricity in times when it is not needed, and to use it in times with high demand. Commonly used power storage technologies are (Borden, 2014):

- Batteries
- Redox systems
- Hydro storages
- Power-to-Gas (PtG)
- Power-to-Liquid (PtL)

The technology behind it stores either excess electricity or converts it to a different form of energy. It has been subject of research during recent years, because storage is widely considered the primary solutions for the replacement of fossil fuels by renewables (Borden, 2014). However, the amount of time these systems can provide energy for a community is limited. Batteries and redox systems are short term supply technologies and have an average energy-to-power ratio (EPR) of 6 h. The EPR states how long the system can provide self-sufficiency. Hydro storages are medium term storages with an average EPR of 15 h. In contrast, power-to-technologies are considered as long-term storages with an average EPR of 1200 h or approximately 50 days. However, those numbers represent the average. The time these systems can meet the demand of the grid depend on the sizing of the system and should therefore not be understood as fixed. It has been shown that the duration of possible self-sufficiency can be extended and geared for specific needs (Leuthold, 2014).

Hydro storages, which are the combination of reservoirs and water turbines, need reasonable height differences due to increasing energy potential with increasing heights. Therefore, hydro storages are unqualified for most usages on small islands. However, this energy storage technology has shown that is suitable for larger scaled projects, as it was done on El Hierro, Spain (Plitt, 2015). PtG and PtL are both still in pilot stages. The technology is immature and would need several facilities, which would accompany with large required dimensions. Redox systems and batteries though are the technologies that can be installed in small dimensions. They are most widely proven and do not need special requirements in terms of location (Schmidt, 2015).

A redox-flow battery stores electrical energy in a chemical compound, where the term “red” stands for reduction, and the term “ox” stands for oxidation. This process absorbs and releases electrons in liquids whereby energy can be stored and released. “Flow” implies that the chemical compound is a liquid like vanadium salt and streams through the system. The reactants are dissolved and act as an electrolyte in two separate systems (Schmidt, 2015).

The set-up of a redox-flow battery can be seen in Figure 13. The chemical reaction happens in the cell, when the two substances circulate. In the cell, an ion exchange of the two electrolytes takes place through the membrane. In this manner, electrical energy is either stored or released and the battery is either charged or discharged. Storage of the electrolytes in external tanks outside the cell permits free scalability. However, a disadvantage of this system is its required space (SmartRegion Pellworm, 2015).

Figure 13 Processes within a redox flow system (SmartRegion Pellworm, 2015)

Figure 14 Lithium-ion home battery (Tesla Motors Inc., 2015)

Lithium-ion batteries represent the state-of-the-art technology that are used most widely in electric consumer products or in vehicles. The technology is the fastest growing and most promising battery chemistry that is established for short-term storages.

Lithium-ion batteries have a high energy density, need low maintenance and have a low self-discharge in comparison to other solid battery types like nickel-based or lead-acid batteries. Furthermore, stored energy can be released quickly, but long-term usage is subject to aging. Furthermore, lithium-ion batteries are still expensive for large scale operations like it is needed for self-sufficiency purposes (Wood & Daniel, 2015).

In principal, storage systems can be deployed in a decentralized or centralized manner. Hydro reservoirs for example are large energy storages and can provide a great amount of energy, but disqualify to be built close to a consumers' facility. In terms of a decentralized establishment, the single devices are distributed and can be mounted directly in the near of the demander. The decentralized approach is defined as distributed energy storage (DES). The size of DES units can be scaled for different demands. The affiliation of several DES is called community energy storage, or short CES (Xu, Zhang, Hug, Kar, & Li, 2015).

Currently, the lithium-ion market is on the move due to the development of the car industry concerning electro mobility. One of the biggest driver concerning the scale-up of lithium-ion manufacturing is a factory of Tesla Motors and Panasonic, which promises significant performance and cost improvements. In particular, this project is going to double the current global cell supply within 5 years to an estimated production of 80 GWh/year (Tesla Motors Inc., 2015).

Particular products that have the ability to be installed in DES are home battery systems with distinct energy storage capacities. An exemplifying home battery is illustrated in Figure 14. The capacity can be increased by stringing several batteries together to guarantee autarky. The advantage of the system is that it offers independence from

the grid up to one day, regulates the varying energy supply from renewable sources and functions as an emergency backup system. In addition, it functions automated and can therefore be described as a smart system that establishes a nano-grid in a compact and simple manner (Tesla Motors Inc., 2015).

The current objectives of the market concerning improvements of DES are achieving higher cost-competitiveness, enlarging the capacity, demonstrating reliability and safety (U.S. Department of Energy, 2013). These four criteria are the key factors that ensure a long-term implementing of DES. Cost-competitiveness implies that life-cycle costs and performance need to improve, which is connected to capacity and reliability. Simultaneously, increasing the energy density, improving life span and minimizing the capacity fade results in increasing performance-cost ratios (Jiayi, Chuanwen, & Rong, 2008).

2.5 Investment costs

Resources and technologies for electricity production cause different costs and therefore different economic considerations. This requires a common base to compare their competitiveness. The difficulty in designing an energy system is to find the most reliable and cost-effective sources for a certain planning period. This comparison of different energy sources can be done by comparing the costs of energy (COE). The COE reflect the tradeoff between minimizing costs and maximizing energy production and are important in order to compare the energy production for different variants. Essentially, COE consist of initial investment costs (I_0) at the beginning of a project, project lifetime (t), fuel expenditures (F_t) during the operation of the project, operation and maintenance expenditures (OM_t) and the used generated electricity (E_t) for one year in

kWh. The calculation is straight forward and can be seen in Equation (9), where the units are \$/kWh: (EIA, 2015),

$$COE = \frac{\frac{I_o}{t} + F_t + OM_t}{E_t} \quad (9)$$

COE give a general overview about the value of energy projects, but do not take all economic factors into account. In order to assess a project entirely, the total economic factors should be included. This can be done using cost-benefit analyses (CBA). In CBAs the aim is to identify and measure social, environmental, and technical factors besides the economic analysis. This includes the perspective of both, monetary and non-monetary factors. Non-monetary factors are for example health, safety and societal benefits (Pleil, 1995). A major drawback of this assessment method is that it is subject to individual estimations concerning several factors and the weighting of these factors. This can yield in subjective change of the results (Joskoaw, 2011).

Therefore, projects can only be assessed objectively from a financial perspective in terms of value creation or cost avoidance for the owner or investor. Non-monetary factors should be assessed from an individual point according to its purpose. A value would be created if the project generates more income as a comparable investment over its lifespan. The net present value (NPV) can state whether this is achievable. Costs are avoided if the project has less life-cycle costs as a comparable project. The net present cost (NPC) assess this. Additionally, payback period or discounted payback period, internal rate of return (IRR) and profitability index (PI) represent investment criteria that have to be determined to see the total picture (Ross, Westerfield, & Jordan, 2010).

NPV can be defined as the difference between an investment's market value and its costs. The discounted payback period is a derivative of the payback period and does not only state after which amount of time an investment has recovered its initial costs, but also accounts for the time value of money (TVM). The NPC includes initial expenses as well as replacement, operation and maintenance, fuel cost and interest. It condenses all occurring costs and cash flows within the project lifetime into a single lump sum at the appropriate discounted rate to the present day. The IRR is quite similar to the NPV, as it tries to find a single rate of return that incorporates a project's advantageousness to compare it to a required rate of return. In theory, IRR is the discount rate that sets an investment's NPV to zero. The PI is also called benefit-cost-ratio. It is a dimensionless key figure that is computed by dividing the prospected future cash flows by the initial investment costs. It can be understood as a measure of project performance (Ross, Westerfield, & Jordan, 2010).

The introduced measures need to be considered in their entirety to determine projects' advantageousness and to assist in comparing different project variants.

2.5.1 Levelized costs of electricity

The levelized costs of electricity (LCOE) go one step further compared to COE. LCOE attempt to compare different sources of electricity based on their individual lifespan, and attempt to reflect the TVM. There is a variety of approaches to determine LCOE that differ slightly from each other mainly due to data availability. However, studies show that results stay in a narrow margin and among the range of LCOE models, the approach by Konstantin (2009) is reasonable for limited information (Fraunhofer Institute for Solar Systems, 2013).

This approach computes the LCOE by evaluating the total average costs over the lifetime divided by the total energy output shown in Equation (10) (Konstantin, 2009)

$$LCOE = \frac{I_0 + \sum_{t=1}^n \frac{OM_t + F_t}{(1+r)^t}}{\sum_{t=1}^n \frac{E_t}{(1+r)^t}} \quad (10)$$

, where I_0 are initial investment costs, OM_t are operation and maintenance expenditures, F_t are fuel expenditures, E_t is generated electrical energy, r is the discount rate and n is the expected lifespan.

The time value of money has to be considered, due to decreasing value of future costs and benefits from a time perspective. Consequently, the discount rate weights costs and benefits of a project over time, and can be differentiated into two types. The first type is the individual investing discount rate that is applied to investment-models based on the net present value (NPV) of a project (Steinbach & Staniaszek, 2015). The appropriate discount rate can be assumed to be the weighted average cost of capital (WACC) in terms of investing companies. The formula for the WACC can be seen in Equation (11): (Ross, Westerfield, & Jordan, 2010)

$$WACC = \frac{E}{E+D} C_E + \frac{D}{E+D} C_D (1 - TAX_{corp}) \quad (11)$$

, where E is equity, D is debt, C_E is the associated cost of equity, C_D is the associated cost of debt and TAX_{corp} is the corporate tax. The WACC varies due to opportunity cost, inflation, interest rate and risk. Equation (11) disregards factors like incentives, although those factors can include game-changing effects. Furthermore, it should be considered that different source of information affect financing.

The second type is the social discount rate, which is applied to evaluate total costs and benefits. The difference to the investing discount rate is that market and individual risks are not included. For this reason, the after tax rate of government bonds, which have essentially no market risk, serve as a proxy. Therefore, the social discount rate is considerably smaller compared to the investing discount rate (Steinbach & Staniaszek, 2015).

Example calculations for different LCOE are given in Table 1 from the U.S. Energy Information Administration for general comparison purposes. It should be noted that energy plants have differently sized cost components according to technology and application, but also according to project size. However, key aspects and differences for conventional and renewable energies are derivable.

Table 1 Cost-components of conventional power plants in 2013 (EIA, 2015)

Plant Type	Capacity factor (%)	Investment (\$/MWh)	Fixed O&M (\$/MWh)	Variable O&M (\$/MWh)	Transmission (\$/MWh)	LCOE (\$/MWh)
Coal	85	60.4	4.2	29.4	1.2	95.1
Advanced Coal	85	76.9	6.9	30.7	1.2	115.7
Coal with CCS¹	85	97.3	9.8	36.1	1.2	114.4
Natural gas	87	14.4	1.7	57.8	1.2	75.2
Advanced Natural Gas	87	15.9	2.0	53.6	1.2	72.6
Natural Gas & CCS	87	30.1	4.2	54.7	1.2	100.2
Nuclear	90	70.1	11.8	12.2	1.1	95.2
Average	86.6	52.2	5.8	39.2	1.2	95,5

¹ CCS = Carbone Capture and Storage

The capacity factor of conventional power plants in Table 1 is the ratio of average power generated, divided by the rated peak power. It shows that conventional power plants have a high occupancy rate with an average of about 86 %, which is an indicator that they can be well adjusted to actual electricity needs. In general, adaptable systems have more value to the grid, because loads must be balanced to the demand. It can be seen that variable O&M are about seven times larger in average compared to fixed O&M. In addition, average variable costs are almost as high as investment costs. Transmission costs are low with about \$1.2/MWh and LCOE level out at an average of \$95/MWh respectively \$0.095/kWh.

Table 2 Cost-components of renewable power plants in 2013 (EIA, 2015)

Plant Type	Capacity factor (%)	Investment (\$/MWh)	Fixed O&M (\$/MWh)	Variable O&M (\$/MWh)	Trans-mission (\$/MWh)	LCOE² (\$/MWh)
Onshore wind	36	57.7	12.8	0.0	3.1	73.6
Offshore wind	38	168.6	22.5	0.0	5.8	196.9
Solar PV	25	109.8	11.4	0.0	4.1	125.3
Solar CSP	20	191.6	42.1	0.0	6.0	239.7
Hydro³	54	70.7	3.9	7.0	2.0	83.5
Geothermal	92	34.1	12.3	0.0	1.4	47.8
Biomass	83	47.1	14.5	37.6	1.2	100.5
Average	49.7	97.1	17.1	6.3	3.4	123.9

² Includes subsidies for Geothermal (3.4 \$/MWh), Solar PV (11.0 \$/MWh) and Solar Thermal (19.2 \$/MWh)

³ Energy conversion from dams, reservoirs and rivers

The capacity factor of renewable power plants in Table 2 varies significantly from 20-92 % depending on the technology and the site where a plant is installed. This shows that renewable energy generation fluctuates greatly, which can have adverse effects for the grid. The conclusion is that they are more difficult to integrate in a system due to the uncontrollability of electricity generation. Based on average values, variable O&M are with \$6.3/MWh about a third of fixed O&M, which cost \$17.1/MWh. Together, fixed and variable O&M account for 24 % of the initial investment expenses. Costs for transmission account for less than 3 % of total LCOE, which averages at about \$124/MWh respectively \$0.124/kWh.

By comparing Table 1 and Table 2, it can be seen that renewables have high initial costs. However, lower variable and fixed O&M for renewable energies compensate these additional expenditures. Due to the distributed character of most renewable energy plants, transmission costs are three times as high as they are for conventional power plants. These three components result in higher LCOE for renewable energies. It is clear that if the capacity factor for renewable energy plant can be increased, LCOE can be reduced either due to lower investment cost because the plant has either more generated electricity or could be scaled smaller.

Going into detail, it can be seen that individual LCOE of renewable energies are much higher as some conventional energies. Based on this information, offshore wind and CSP are not competitive at this moment. Their prices of 196.9 and 239.7 \$/MWh are nearly three times as high as the price for natural gas. Likewise, investment costs

are much higher. For example, solar PV costs 109.8 \$/MWh upfront as opposed to 14.4 \$/MWh for natural gas.

Nevertheless, it has to be considered that the given values represent the costs for devices on mainland. Remote areas and islands in particular deal with special circumstances. Depending on the region and area, this can result in price disparity. For example, the electricity price on Block Island, RI changes from \$370/MWh to \$580/MWh during the year, even though electricity is produced by a centralized system (Block Island Power Co, 2015). Compared to the average electricity price of Rhode Island of \$154.1/MWh, costs are at least doubled depending on the season and fuel prices (EIA, 2014).

To avoid dependence on fluctuating fuel prices, Block Island's solution was the development of a wind farm that produces energy for a flat rate of 24.4 cents/kWh with an annual escalating factor of 3.5 %. This PPA has resulted in a halving of cost on average. It is estimated to recoup the project costs of \$300 million in about half of its lifespan of 20 years and to generate additional profits thereafter. The final revenue is estimated to be \$497 million (Van Beek, 2015).

Even though general LCOE for offshore wind are about \$196.9/MWh, it is still less than half the price of Block island's lowest electricity price. Considering that electricity on Block island is based on diesel generators, it can be stated that renewable energies are cost-competitive when it comes to island electrification. Therefore, renewable technologies attach importance for islands, because they can lower costs and establish autonomy from varying variable O&M cost (Lazard, 2015).

Summarizing it can be said that LCOE allow a comparison between several energies and are a general approach for the selection of suitable technology. It is possible to draw conclusions in the early stage of a design process concerning the economic viability concerning a certain alignment of a project (EIA, 2015).

2.5.2 Levelized cost of storage

If the early assessment comes to the conclusion that energy storages are needed in the system, levelized cost of storage (LCOS) can state whether one energy storage system is more favorable than another. The systems can be rated in terms of both instantaneous power capacity and potential energy output. For the purpose of this thesis potential energy output is considered only, because instantaneous power capacity is defined as the maximum output at a time and potential energy output is defined as the maximum amount of energy storable. Due to the limited amount of energy consumer of small communities and somewhat predictable energy-consuming habits the maximum storing capacity is decisive for micro-grids (Lazard, 2015).

The common quoting is given by capital cost divided by potential energy output and is usually evaluated for the different types of energy storages and for several devices within one type of device. If self-sufficiency is aimed without any backup-systems, energy storages need to be sized greater than they would actually be necessary. It is important to guarantee security of supply for which reason greater amounts of energy need to be stored. This oversizing results in significantly higher cost.

2.5.3 Discounted cash flow valuation

Energy projects need to be assessed from an economic point of view. The discounted cash flow (DCF) valuation is a possibility to do so. The basic idea behind the DCF is the NPV of a project. The NPV is the difference between an investment's market value and its cost, which means in the specific case of transforming an energy system that it needs to add value to the community or decrease costs for the residents. The NPV measures this amount of value added or cost decreasing by undertaking a project.

Therefore, financial modeling of future cash flows is an essential part of developing an investment project. The DCF valuation includes receipts and expenditures, and factors like, taxation, subsidies or incentives. It aims to enable decision making concerning the value of a project by discounting multiple cash flows to its present value. This can be done in two ways. The first approach compounds the accumulated balance forward one year at a time. The second approach calculates the present value for each cash flow period and adds them up thereafter (Ross, Westerfield, & Jordan, 2010). The second approach is the most advisable, because the assessment becomes more precise (IRENA, 2015).

In terms of community projects, life-cycle costs (LCC) play a major role and pursue the objective of a sustainable approach from construction to dismantling to renewal. They are made up of initial capital costs, costs for operation and maintenance, replacement and fuels. The objective of using LCC is to maximize the value of investments and to find its present value (ASCE, 2014).

2.6 Renewable energy project development

The development of renewable energy systems is firmly connected with the renewable energy potential at a location. The renewable energy potential of renewable energy systems attempts to estimate the quantity of achievable electricity generation at a certain location. For this thesis, renewable energy potential is defined as the amount of practical potential of the technical available resources that can be extracted from the theoretical resources. In simplified terms, the process of an early feasibility study follows the sequence of resources availability, technical possibility, economic analysis and market constraints. This is illustrated in Figure 15.

Figure 15 Analysis steps for renewable energy feasibility analysis (NREL, 2012)

As it can be seen, assessing the potential of resources for an area of interest is the starting point in a feasibility analysis for renewable energy system developments. Physical constraints need to be described, and the available energy of each resource, that is considered, needs to be determined. Especially the maximum practicably extractable energy also called extractable energy is the most important aspect for a feasibility study.

This can be done by assuming common devices for each resource. This analysis can also assess the general costs for the electricity generation by each source only.

Technical assessment is an additional key factor in a feasibility study. Topography, land-use and system performance need to be weighted and assessed accordingly. These steps need to be done before the economic assessment, because they can have distinct influence on the financial assessment. In the economic assessment, a general overview concerning prospects of success can be given. Projected investment costs and LCOE are the resulting facts from this assessment. This means that different projects become comparable in terms of financial reasonableness.

However, it does not mean that when economic feasibility can be proven, market potential would be ensured. As it can be seen in Figure 15, the economic potential is just an intermediate step. It does not consider market development, policy drivers like incentives, or socio-politic constraints. As Timmons *et al.* stated, energy subsidies are essential project driver and can be crucial aspects for renewable energy projects. Direct payments, favorable loans, tax credits, price support, or purchase quotas can facilitate aggravating circumstances distinctly (Timmons, Harris, & Roach, 2014). It should be noted that developing a project is an iterative procedure that contains the evaluation of all aspects in any stage of process. Finding a viable system setup, contains ecological, technical, economical and socio-political factors.

The World Health Organization (WHO) states that an economic assessment values potential costs and benefits of a project and reveals inherent tradeoffs. Valued environment and health impacts provide adequate consideration and enumerate hidden costs and benefits for environmental and socio-economic aspects. Likewise, synergies may

be entered into the equation. For instance, impacts of air pollution from diesel generator are deleterious compared to renewable technology. Fossil fuel systems affect the health of the community and need to be related to the health costs of associated diseases (WHO, 2016).

The cost-utility analysis (CUA) is such an approach that considers other factors than monetary costs only. It lists each aspect and weights them according to their importance. Thereby, the positive aspect is that several beneficial and counterproductive effects can be taken into account, so that overall impacts over the lifetime of a project can be aggregated, valued and compared. The drawback is that the outcome depends on subjective appraisals (ADB, 2001).

Beside cost-utility analysis, least-cost analysis or cost-effectiveness analysis may be suitable for remote communities. However, small markets make it difficult to quantify and measure benefits. By assuming that utilities are equal for different renewable technologies, comparison based on their NPC is required only. This approach is less subjective than CUAs, because they avoid assumptions concerning benefits associated with each option (Woodruff, 2007).

3 METHODOLOGY

The methodology chosen for this thesis is a feasibility study following the bottom up approach described in Subsection 2.6. This feasibility study will be a case study for an Cuttyhunk Island, which allows to prove feasibility of self-sufficiency in a small scale environment. Moreover, it allows to transfer lessons learned for other remote areas. This process will enable drawing conclusions for transforming energy grids towards renewable energy sources. This bottom up analysis follows a probabilistic empirical process and can be seen in Figure 16. The probabilistic aspect results from economic and market constraints as well as interviews, who's unambiguity cannot be guaranteed with certainty. The empiricism results from collect data that in the process.

Figure 16 Methodology flowchart

The procedure of the feasibility analysis defines the available resources first in the individual resource assessment, determines the extractable energy thereafter and proves initial financial conditions. The resource assessment will be the basis for subsequent technical, environmental and economical deliberations. Technical considerations outline issues and potential project drivers. The next step is the economic assessment. Thereby, different conceivable variants will be developed based on findings from the resource and technical assessment. The final step is the investigation of socio-economic effects and political requirements as well as the monitoring of consumer behavior in the market assessment. Based on the results of these four steps, the most suitable variant can be selected. This selection will consider all previous findings and will discuss advantages and disadvantages of the most suitable system.

The resource assessment enables to estimate the quantities and overall potential of the single source in terms of available energy and extractable energy. The resources wave, wind and solar will be investigated in detail due to their availability at the study area. This represents the basis for the following assessments as it determines the overall potential for each energy source and their potential COE as a solely energy source. The COE are computed to judge whether the technology is cost-competitive in means of available resources

The wave energy resource assessment analyses the wave climate based on hindcast datasets for a period of 32 years. The data used will be buoy data from the Wave Information Studies (WIS) by the U.S. Army Corps of Engineers. The program SWAN will be used to determine the theoretical available energy. SWAN is a third generation wave model that propagates wave parameters from wind bottom and current

conditions including dissipation and wave-wave interactions, based on the wave action balance equation that is illustrated in Equation (7): (Neill & Hashemi, 2013; Rogers, Hwang, & Wang, 2003)

$$\frac{\partial N}{\partial t} + \frac{\partial C_{g,x}N}{\partial x} + \frac{\partial C_{g,y}N}{\partial y} + \frac{\partial C_{g,\sigma}N}{\partial \sigma} + \frac{\partial C_{g,\theta}N}{\partial \theta} = \frac{S}{\sigma} \quad (12)$$

, where N is wave action density, t is time, σ is the frequency, θ is wave direction, S is the total of source/sink terms expressed as wave energy density, C_g is the wave action propagation speed in space for x and y , as well as for frequency (σ) and wave direction (θ).

SWAN can structure a domain in different ways concerning resolution and orientation, and can be either structured or unstructured, as well as nested. Structured grids are rectilinear and uniform or curvilinear and consists of quadrilaterals in a Cartesian or spherical coordinate system. These quadrilaterals connect in internal points in which the number of cells that meet is always four. Unstructured grids however, have usually between four and ten, and arbitrary in general. Therefore, the flexibility of the unstructured grid is higher, which makes it the more precise grid (Booij, Holthuijsen, & Ris, 1996).

Based on the bathymetry of a region, SWAN propagates waves occurrence on the domain for both, wind input as well as wave height and wave periods. The inputs act as a boundary on the domain. The output that will be used is significant wave height (H_{SIGN}), mean absolute wave period (TM01) and mean wave direction (DIR). Additionally, SWAN is used to determine the spatial, monthly, directional inter-annual wave power (TRA) that is theoretical available (Delft University of Technology, 1993).

Theoretical wave power (TRA) is computed for each cell in the domain per meter of wave front by Equation (13), where ρ is the sea water density, g is the acceleration of gravity, S is spectral density in m^2Hz^{-1} , C_g is the group velocity in ms^{-1} , f is wave frequency in Hz, θ is mean wave direction, h is local water depth (Carballo & Iglesias, 2012).

$$P = \rho g \int_0^{2\pi} \int_0^{\infty} S(f, \theta) C_g(f, h) df d\theta \quad (13)$$

Subsequently, the output will be validated by comparing the propagations of SWAN with hindcast data from a WIS station that is located inside the domain. Thereafter, significant wave heights are visualized in Matlab to map the wave climate, because there are spatial fluctuations. Based on the evaluation of this data, areas are defined where significant wave height is highest for each month in order to select conceivable locations for WEC-deployment. For these locations, significant wave heights, wave periods and theoretical power will be compared. For the location with the most theoretical power, technical extractable power will be computed by using the device features of a suitable WEC. The device used for the computation is Oyster 1 from Aquamarine Power Inc.

The wind resource assessment considers measured data from a buoy close to the study area. This data will be retrieved from National Oceanic and Atmospheric Administration's (NOAA) National Data Buoy Center (NDBC). In particular average wind speeds and the wind speed distribution are major aspects in order to estimate available energy and extractable energy, wherefore the wind assessment will focus hereon. The device that is used for computing the extractable energy is the M-21 from XANT NV.

The solar resource assessment will be based on typical meteorological year data for the closest available dataset. GHI data will be assessed as it is the most important radiation for solar panels. The data will be retrieved from the National Solar Radiation Database (NSRD) and analyzed for daily and hourly averages. TMY relies on various meteorological measurements at hourly intervals over a certain amount of years. The unit of TMY data is W/m²/h. For this period, the month that is most comparable to the average radiation of the location is selected, because the average would distort the occurrence of variability. This month is then selected as the TMY data for that month. All selected month are then added together for a full year of hourly samples (Gansler, Klein, & Beckman, 1994).

The computation of extractable energy is based on the following equation for power: (Mackay, 2015)

$$P = E_{av} A C_p h_{day} \quad (14)$$

, where P is the generated power, E_{av} is the available energy, A is the area of the solar cells, C_p is the module efficiency h_{day} are the daylight hours and 24h the hours in one day. In order to compute the monthly energy, the power has to be multiplied times the days in the single month. The device that will be used to assess extractable solar energy is the SPR-X21-255 mono from SunPower Co.

After calculating the initial costs and system size manually, the System Advisor Model (SAM) is used to validate the approach. SAM is a performance and financial model designed by NREL that makes performance predictions and cost of energy estimates for grid-connected power projects. In order to adjust the output process for off-grid purposes, prices for excess electricity that would be generated if the electricity

could be sold to the grid, need to be set to zero. Source codes are not open to public, however, they rely upon definitions and methods described by Short, Packey & Holt (1995) in terms of financial calculations, and upon the performance calculator PVWatts developed by Marion & Anderberg (2000). It facilitates decision making for photovoltaic technologies considerably, as it reduces time required and is more reliable than manual calculation (Short, Packey, & Holt, 1995; Marion & Anderberg, 2000).

After the resource assessment, the technical assessment will be responsible for analyzing the electricity generation for the study area and the environmental considerations each resource has. This part will analyze the electric load in order to select the most suitable energy source with the lowest impacts on the environment. The data necessary in this part will be retrieved from the local utility company.

Subsequently, the modeling of the system aims to find the most reasonable and feasible setup of the system. Both is investigated, integrated renewable energy system, where renewable energies contribute partly, and a self-sufficient renewable energy system with backup generators. To find the optimal sized and suitable system, different variants will be investigated. This will be done for multiple systems with different energy sources and varying contribution in the optimization program HOMER, that determines LCOE and NPC as the two most significant economic factors for the assessment of energy systems. The aim is to determination the system with the minimized LCOE and NPC. This optimization process incorporates the determination of the appropriate sizes of the required system parts in order to assure reliability of supply.

HOMER is a micro-grid optimization model developed by NREL. It models the system's physical interaction and the life-cycle cost by performing the steps simulation,

optimization and sensitivity for a time-series. The simulation models a particular system configuration to determine its technical feasibility and life-cycle cost. The optimization simulates different system setups for each system configuration that meet technical conditions in order to find the lowest life-cycle costs. The sensitivity analysis repeats the optimization process for defined input uncertainties in order to evaluate changing economic components (Lambert, Gilman, & Lilienthal, 2006).

Figure 17 Conceptual relationship between simulation, optimization, and sensitivity analysis of HOMER, (Lambert, Gilman, & Lilienthal, 2006)

The mathematical modeling of hybrid energy system components needs to be explained for the considered resource technologies. Lambert *et al.* (2006) as well as Kumar *et al.* (2011) have explained HOMER and reviewed the model. Therefore, Equations (15) - (31) are obtained from their studies (Lambert, Gilman, & Lilienthal, 2006; Lal, Dash, & Akella, 2011). The considered resources are wave power, wind power and solar power in combination with battery storages and diesel generators. Additionally, AC/DC converter and charge controller need to be explained. The theory behind the simulation and optimization is explained in the equations below for solar PV generators, wind energy generators, diesel generators, converter, charge controller and battery banks. The implementation of wave energy converter is currently not an element of the software.

The mathematical model for solar radiation on tilted surface for hourly energy output is shown in the following equation in which temperature effects on the PV cells are ignored. $G(t)$ is the hourly irradiance in kWh/m², A is the Surface area of the PV modules in m², P is the PV penetration level factor, η_{PV} is the module efficiency.

$$E_{PV} = G(t) A P \eta_{PV} \quad (15)$$

The mathematical model for wind energy generators is shown in Equation (16), where P_{WEG} is the electrical power generated by the wind generator, ρ_{wind} is the density of air in Kg/m³, A is the rotational area of the wind turbine blades, v is the wind speed in m/s, C_P is the performance coefficient for the turbine for the ratio of rotor blade tip speed to wind speed (λ) and for the blade pitch angle in degrees (β), η_t is the wind turbine efficiency, and η_g is the turbine efficiency. The hourly energy generated by the wind turbine $E_{WEG}(t)$ is expressed in Equation (17), where t is the time in hours.

$$P_{WEG} = \frac{1}{2} \rho_{Wind} A v^3 C_p(\lambda, \beta) \eta_t \eta_g \quad (16)$$

$$E_{WEG}(t) = P_{WEG} \eta_{DEG} \quad (17)$$

The mathematical model for diesel generators is shown in Equation (38), where E_{DEG} is the hourly energy generated by the diesel generator, P_{DEG} is the rated power output of the diesel generator, and η_{DEG} is the diesel generator efficiency. HOMER assumes that the performance and efficiency is best between 80 % and 100 % of the rated power of the device, and aims to run it in this range.

$$E_{DEG}(t) = P_{DEG}(t) \eta_{DEG} \quad (18)$$

The mathematical model for converter contains both, rectifier and inverter. Rectifier are converters that change an AC into a DC. Inverter are converters that change a

DC to an AC. Both are needed, because the diesel generator and the wind turbines generated AC electricity and the PV and battery supply DC electricity. The inverter model for PV and battery storage is given in Equation (19) and (20), where $E_{PV-in}(t)$ is the hourly energy output from the inverter in terms of the PV module in kWh, $E_{PV}(t)$ is the hourly energy output of the PV generator, η_{INV} is the efficiency of the inverter, $E_{BAT-INV}(t)$ is the hourly energy output from the inverter in terms of the battery in kWh, $E_{BAT}(t-1)$ is the energy stored in the battery at t-1 in kWh, E_{LOAD} is the hourly energy consumed by the load side in kWh, and η_{DCHG} is the battery discharging efficiency.

$$E_{PV-in}(t) = E_{PV}(t) \eta_{INV} \quad (19)$$

$$E_{BAT-INV}(t) = [(E_{BAT}(t-1) - E_{LOAD})/(\eta_{INV} \eta_{DCHG})] \quad (20)$$

The rectifier model for wind and diesel is given in Equation (21), (22), and (23), where $E_{REC-OUT}(t)$ is the hourly energy output from the rectifier in kWh, $E_{REC-IN}(t)$ is the hourly energy input to the rectifier in kWh, η_{REC} is the efficiency of the rectifier, $E_{SUR-AC}(t)$ is the amount of surplus energy from AC sources in kWh, $E_{PV}(t)$ is the hourly energy generated by the photovoltaic modules in kWh, $E_{WEG}(t)$ is the hourly energy generated by the wind generator in kWh, $E_{DEG}(t)$ is the hourly energy generated by the diesel generator in kWh, and $E_{LOAD}(t)$ is the hourly energy consumed by the load side in kWh.

$$E_{REC-OUT}(t) = E_{REC-IN}(t) \eta_{REC} \quad (21)$$

$$E_{REC-IN}(t) = E_{SUR-AC}(t) \quad (22)$$

$$E_{SUR-AC}(t) = E_{PV}(t) + E_{WEG}(t) + E_{DEG}(t) - E_{LOAD}(t) \quad (23)$$

The battery state of charge is the sum of the daily charging and discharging. The battery capacity at hour t can be described by Equation (24), when total output of all generators exceeds the load demand, where $E_{BAT}(t)$ is the energy stored in the battery at hour t , $E_{BAT}(t-1)$ is the energy stored in the battery at hour $t-1$ in kWh, $E_{CC-OUT}(t)$ is the hourly energy output from the charge controller in kWh, and η_{CHG} is the battery charging efficiency.

$$E_{BAT}(t) = E_{BAT}(t-1) + E_{CC-OUT}(t) \eta_{CHG} \quad (24)$$

The discharging state of the battery, when the load demand is greater than energy output from the generators, is given by Equation (15), where $E_{demand}(t)$ is the hourly energy needed by the load side in kWh due to shortage of energy generation from the generators. The depth of discharge (DOD) is given in Equation (26), where d represents the ratio of the minimum allowable state of charge (SOC) voltage limit to the maximum SOC voltage.

$$E_{BAT}(t) = E_{BAT}(t-1) - E_{demand}(t) \quad (25)$$

$$DOD = (1 - d) 100 \quad (26)$$

HOMER models the total hybrid power generated $P(t)$ by summarizing the power generation of every system component. The equation is shown in the following, where N_M , N_W , N_P and N_D are the unit numbers of wave, wind, solar and diesel generator size.

$$P(t) = \sum_{1}^{N_H} P_{MHK} + \sum_{1}^{N_W} P_{WEG} + \sum_{1}^{N_P} P_{PV} + \sum_{1}^{N_D} P_{DEG} \quad (27)$$

The total capital cost (C_C) and annual operating cost (C_O) are given in Equation (28) and (29), where C_{MHK} , C_{WEG} , C_{PV} , C_{DEG} and C_{BAT} are capital cost of energy generation from wave, wind, PV, diesel and capital costs of the battery system. C_F are the fixed cost of converter and other installation.

$$C_C = \sum_{1}^{N_H} C_{MHK} + \sum_{1}^{N_W} C_{WEG} + \sum_{1}^{N_P} C_{PV} + \sum_{1}^{N_D} C_{DEG} + \sum_{BAT=1}^{N_D} C_{BAT} + C_F \quad (28)$$

$$C_O = \sum_{t=1}^{365} \left\{ \sum_{t=1}^{24} (C_{OMHK}(t) + C_{OWEG}(t) + C_{OPV}(t) + C_{ODEG}(t) + C_{OBAT} + C_{OF}) \right\} \quad (29)$$

Based on total capital cost and operating cost, HOMER computes annul life cycle cost of the system shown in Equation (30), where CRF is the capital recovery factor for the system with expected discount rate (i) and expected lifetime (N). The CRF is given in Equation (31)

$$C_{annual} = C_C CRF + C_O \quad (30)$$

$$CRF(i, N) = \frac{i(1+i)^N}{(1-i)} \quad (31)$$

After assessing the economic feasibility, the market assessment has the function of a closing process where socio-economic effects and political requirements will be assessed. These aspects account for the regularity of the project and state whether authorities support the project or not. Based on the findings, the most promising variant will be chosen and described concerning system architecture, costs structure and amount of renewable energy delivered to the load. This final step will also include the discussion

of impact for the proposed system. Strength and weaknesses of the chosen system will be defined. Furthermore, it will also outline conceivable opportunities and threats.

3.1 Study area

A case study is necessary for this thesis to exemplify feasibility for the energy transition of remote islands, and in order to detect practicable elements for the implementation process. The case study will be done for Cuttyhunk island in Massachusetts. Cuttyhunk island is located 14 miles off the coast of New Bedford at the outer edge of Buzzard's Bay. The island is remote and not connected to the grid on mainland. The electric system of the island is a micro-grid that currently runs on diesel generators. The islands dimensions are 2.4 km in length and 1.2 km in width, representing an area of about 2.3 km². The central point of the study area has a latitude of 41°25'8"N and longitude of 70°56'2"W. Its highest elevation is at 47 m above mean sea level (MSL). It is the southern-most island in a chain of the 13 Elizabeth Islands that are separating Buzzards Bay from Vineyard Sound. Figure 19 shows the location of the island.

Figure 18 Location of Cuttyhunk Island (New York Times, 2012)

Figure 19 Aerial view on Cuttyhunk from 20 miles (HOMER Energy, 2016)

The accessibility of the island is limited due to its solitude. The only connection to mainland is ensured by a ferry connection starting from New Bedford. The island encompasses a large natural harbor in the north of the island, which contains a landing stage for these ferries. Two peninsular arms surround the natural harbor, which represents the juncture to main island. The shore consists of glacial moraine, rocks, clay and sand. Figure 19 shows the island from aerial perspective at a height of 20 km.

The number of residents' changes during the year. In winter, the population is at its lowest at approximately 20 residents. In the shoulder season from April to June, and September to November population reaches about 70. In summer month from June to August, the number of people on the island is estimated to peak to 500 (Garfield, S., 2016). This annual development happens due to the fact that tourists come to the island in the beginning of June until the end of August. It is estimated that 200-225 residents

live on Cuttyhunk in the summer. Therefore, tourists represent a great stake of the people on the island (Garfield, W., 2016).

Approximately half of the island is a privately owned nature preserve and contains a variety of wildlife and nature. This and its peaceful character make it a tourist attraction and of particular interest for recreational holiday and convalescent leaves. Bird watching, hiking and the beaches make the island a destination for short trips, and for people looking for rest and relaxation. Furthermore, the island is a well know destination for salt water anglers. It has a great reputation for abundant stripe bass fishing.

Ambitions to alter the current electricity generation and corresponding actions are backed socially. This ambition has resulted into an approach of the island community to implement a solar array with the potential to generate nearly half of the needs. The plan is to construct a 300 kW system. It is expected to start operations at the end of fall 2016. Currently, there are four residential PV systems used on the island with a total capacity of 12 KW. The PV modules are not allowed to feed power back into the grid due to risk of power surges of the generators. However, in summer, when high loads are reached, they are allowed to feed back into the system because they represent a small portion of the load with negligible risks (Garfield, S., 2016).

Like the town itself, the micro-grid is located in the north of the island. There are currently five distribution lines that distribute electricity to the 33 transformers. 20 of the 33 transformers were renewed recently and supply the 175 customers of the micro-grid. The distribution lines are named according to its delivery area. The names are Broadway, Marina, Town East, Town South and Town West. Most of the transformers

were replaced recently with new models and are supposed to save about 15 % of electricity compared to the old transformers. The distribution map is shown in Figure 20.

The electricity distribution can be assumed to be up to date and is able to fit the prerequisites for the installation of renewable energies. It may be necessary to change the remaining transformers to optimize the system to its fullest potential in order to reduce electric losses.

Figure 20 Electrical map of Cuttyhunk island

The extension of the grid on mainland to the island has not been considered as economical in the past due to its small population. For this reason, the micro-grid on the island is a standalone system, which is solely running on four diesel generators. The generators are operated in a powerhouse by Cuttyhunk Electric Light Department, the local municipal utility company. The total installed capacity amounts for 750 kW and can be feed in by a three-phase 480-volt grid. Two generators have a capacity of 275 kW and two have a capacity of 100 kW. 55,000 gallon of diesel were needed in 2014 to feed in nearly 600,000 kWh. The monthly values can be seen in Table 3.

Table 3 Monthly peak loads in kW and electricity consumption in kWh

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Peak loads	97.41	85.62	85.33	68.56	128.8	120.7	164.4	178.8	163.6	77.93	66.75	63.12	1300.89
Energy consumption	49.61	39.74	39.34	30.65	33.58	56.08	98.22	86.98	50.16	34.97	35.22	39.31	593.86

The diesel fuel has been imported from mainland for approximately \$4.50/gallon. The generators are outdated, cost-intensive and polluting. Therefore, administration intends to alter the existing energy system to one that is economically reasonable, reliable and more sustainable.

The electricity is distributed at 480 Volt in the AC/DC system. The transformers drop the voltage to the secondary level of 120/240 volt for residential needs. As mentioned, recent efforts have been made to replace the existing transformers on the island. This happened due to increasing losses of the system. Overall, the power quality cannot be controlled with anything other than the generator. The load in the winter varies commonly by up to 20%. In the summer, 30% or more variation is not uncommon as there is more diversity of use (Garfield, S., 2016).

An automatic controller for the generators matches electricity generation to actual loads and ensures a constant frequency of power fed in of about 60 Hz. One 100 kW generator ascertains the Islands normal electric supply in winter. In the summer month, two generators are needed. This only happens when the demands are assumed to peak above 225 kW to avoid power outages. The two remaining generators have the function of a backup provision (Garfield, S., 2016).

The annual electric energy consumption on the island has been measured to be nearly 600,000 kWh according to data obtained. These data include the power factor and power supplied. In AC circuits the ratio of used power in kilowatts (P_w) and the apparent power supplied in kilovolt-amps (S_w) is defined as the power factor (PF) and illustrated in Equation (32): (Beaty & Santoso, 2015)

$$PF = \frac{P_w}{S_w} \quad (32)$$

Essentially, the power factor states whether the system is working to capacity or running inefficient. The PF ratio is affected by both reactance in the circuit and provision of electricity for safety buffer. Both aspects represent power that is not used properly or dissipated by the AC circuit. The power factor for 2014 is illustrated in Figure 21.

Figure 21 Daily power factor on Cuttyhunk Island for 2014

The power factor for the year 2014 shows that efficiency declined during the year. Starting from 85-90 % efficiency in January, the system roughly maintained this level until the end of April. Thereafter, efficiency decreased to a range between 85-75 % until the first week of June. Then, the PF dropped to 66 % abruptly and remained at one level fluctuating between 67-75 % until the beginning of August. In August high fluctuations with the lowest efficiency of the system of 59 % are recognizable. At the end of August, the PF bumped up quickly 10 % to values higher than 75 %. From there on, the ratio decreased steadily to the end of the year where it reached a PF of about 65 %.

The explanation for the fluctuation has different reasons. On the one hand, there are a few number of residents and steady loads during winter. On the other hand, an abrupt increase in residents and tourists make an electric reserve necessary, for which reason an additional generator is start up. This is needed to prevent power outages due to high peak loads in the system. The consequence is that the efficiency of the system

decreases and more fuel is used than it is actually necessary. The fact that more electricity is needed in summer can be seen in Figure 22, which shows the load exemplified for 2014 (Elias, 2016).

Figure 22 Average daily electric load profile for 2014

Figure 22 shows the daily average loads of the micro-grid on Cuttyhunk. It can be seen that the electric load fluctuates during the year. The range of the loads varies from January to June approximately from 80 kW to 40 kW and rises sharply to values between 90-120 kW in July to September. From September to October the load falls up to 40 kW and stays at this level until the end of the year. This seasonal variation and the plateau peak loads in the summer month are explicable by considering the fluctuation of population on the island. An explanation for this is that population changes from 20 residents in the winter to 200 residents in the summer, as it was described in the beginning of this Section. Additionally, around 300 tourists stay on the island on average in the summer. The load profile is illustrated for hourly values in Figure 23.

Figure 23 Hourly electric load profile for 2014

The electric load profile in both figures show data for 2014 only. A longer period would be needed in order to evaluate the electric load precisely. However, data for longer periods are not available. Nevertheless, Figure 24 from a report from RERL and the University of Massachusetts at Amherst contains the load profile for the year 2001. It indicates that there is temporal variability in the load in terms of periodically high values in summer. The base loads are comparable with approximately 40-60 kW.

Figure 24 Yearly electric load profile for 2001 (Manwell, McGowan, & Blanco, Potential for wind energy development on New England Islands, 2003)

The energy consumption in 2001 has been 500,000 kWh. The energy consumption in 2014 has been 600,000 kWh. Over 13 years, this difference results in a yearly increase of approximately 0.8 %. By comparing both diagrams, it can be stated that the load profile is periodically recurring. Additionally, it is noticeable that the total energy consumption increased since 2001, and that summer month loads stay now for longer time on absolute high. Beside the total electric load, monthly and daily fluctuations are necessary to assess. Illustrating diagrams are given for averaged hourly values of all month in 2014 in Figure 26, and for exemplary daily loads of July 2014 in Figure 25.

Figure 25 Average electric load profile for July 2014

The monthly electric load profile for July 2014 shows that daily variations occur. These daily variations occur steady. For each week, Friday and Saturday are the dates where electricity is consumed the most. These days are July 04 & 05, 11 & 12, 18 & 19 and 26 & 27. Especially visitors who stay a day or a weekend are responsible for these peaks.

Figure 26 Averaged hourly electric loads for each month in 2014

The daily averages show that June to September are different compared to the remaining month. In general, demand for energy reaches its highest level during daytime and stays low during the night. Compared to the month from January to May and from September to December, average daily electricity loads for June to September stay low during the night and have distinct morning ramps between 7 a.m. and 10 a.m. A morning ramp is the transition from relatively low load to higher loads in the morning, which can potentially stress the system (EIA, 2011). Likewise, do peak demands in the early evening occur.

This is caused by the significant fluctuation in number of people during the seasons. As electric loads peak in summer because of the relatively great number of people, the demand increases and can be described as a bell curve distribution with weakening demand in the winter months.

Summarizing the electric grid, it can be said that, highly fluctuating loads, resulting mechanical transformer problems, low efficiencies and the response to system disturbances lead to power supply hazards in terms of power outages during the year. As it turns out, not only renewable energy systems have to deal with the issue of fluctuating electricity loads. Diesel generator systems face the same problems, but have the advantage that they can be adjusted steadily. Nevertheless, they have to provide capabilities for the micro-grid. These overconsumptions result in low power factors respectively low efficiencies.

This overconsumption in combination with the high price of diesel imports affect the electricity price on Cuttyhunk. The electricity price is illustrated for a time period starting in July 2012 and ending in June 2014 in Figure 27. This figure also includes

average residential electricity prices for the US, New England and Massachusetts (EIA, 2012-2014).

Figure 27 Costs of Electricity

The figure shows that the electricity prices in the US, New England and Massachusetts stayed in a narrow margin for the investigated period. This margin lays between \$0.11-0.20/kW. The electricity price on Cuttyhunk however, fluctuated considerably from \$0.34-0.67/kW. This prices have been computed using COE equation presented in Subsection 2.5. However, investment and maintenance costs have been neglected, because salvage value can be neglected and maintenance costs were not obtainable. Nevertheless, the local utility company charges a flat electricity price of \$0.60/kWh to account for fluctuations and uncertainties. The COE averaged \$0.56/kWh on Cuttyhunk, \$0.12/kWh in the US, \$0.16/kWh in New England and \$0.16/kWh in Massachusetts. The average, minimum and maximum electricity prices are shown in Table 4.

Table 4 Comparison costs of electricity in \$/kWh

	Cuttyhunk	US	New England	Massachusetts
AVG	0.5645	0.1210	0.1654	0.1596
MIN	0.3463	0.1146	0.1526	0.1379
MAX	0.6779	0.1285	0.1835	0.2014

As stated, the total electricity amounts 600,000 kWh in 2014. Considering the changing number of population, an average number of residents can hardly be given. However, a presumptive number can be computed by using the weighted average based on the seasonal population.

$$\text{Weighted average population} = \frac{4}{12}(20) + \frac{6}{12}(70) + \frac{2}{12}(500) = 125 \quad (33)$$

As Equation (33) shows, the weighted average of the population on Cuttyhunk is 125 people for consecutive twelve months, as there are four months where the number of residents is 20, six months of 70 residents and two months of 500 people, a weighted average can be computed. Dividing the total energy consumption by the weighted average of population results in an average electricity consumption per capita of 4,800 kWh. The electricity consumption for Cuttyhunk is illustrated in Figure 28 and compared to US, New England and Massachusetts averages.

Average monthly consumption key figures for the US, New England and Massachusetts are retrievable from the US Energy Administration Information and available for the year 2014 (EIA, 2016). The residential electricity consumption per capita in 2014 has been 10,935 kWh in the US, 7,562 kWh in New England and 7,379 kWh in Massachusetts. Compared to the calculated average electricity consumption per capita on Cuttyhunk, great difference of at least 35 % are noticeable.

In order to clarify differences between electricity consumption and electricity cost of the four regions, both are illustrated for the regions in the comparative analysis diagram in Figure 28.

Figure 28 Comparison of electricity usage per capita of US, New England, Massachusetts and Cuttyhunk in relation to electricity costs in 2014

The comparative analysis diagram shows that at the same time the costs of electricity increases, the usage of electricity decreases. In terms of the US, New England and Massachusetts, the costs per household tend to decrease as the consumption decreases, because the reduction of electricity consumption is more weighted relative to electricity cost. This leads to the conclusion that electricity consumers with reduced electricity costs tend to conserve less energy. The reason is that decreases in terms of energy cost and improvements in terms of energy efficiency encourage greater usage.

However, as the cost of electricity increases substantially, household costs increase significantly on Cuttyhunk, even though consumption decreases considerably. That allows the conclusion that Cuttyhunk residents have a mindful consumer behavior. The general observation that consumption increases, when cost decrease is commonly known as the rebound effect and should be kept in mind for altering the cost structure. Nevertheless, research does not show how isolated communities are affected by this effect (Sorrell, 2007).

In summary, Cuttyhunk island can be described as a little island that is appealing to tourists, who search for privacy and quietness due to its remoteness and low level of noises. The island is a popular destination for vacation trips and a well-known place for its stripe bass fishing grounds. The challenge of the island in terms of the energy transition are of best interest for the island administration, as the current costs are disproportionate in terms of today's technology. The major challenge is to find a suitable renewable energy that is capable of meeting the seasonal specifics of the electric loads. A condensation of the characteristics of Cuttyhunk is made in Table 5.

Table 5 Summary of parameters of Cuttyhunk island

Cuttyhunk island			
General characteristic		Electricity supply	
Economy:	Tourism, fishing,	Electric customers:	175
Dimensions:	2.4 km * 1.2 km	Electricity distribution:	5 lines, 33 transformers
Area:	2.3 km ²	Grid:	3-Phase, 480 Volt, AC/DC, micro-grid
Elevation:	47 m	Generator capacity:	770 kW
Summer population:	500 residents & tourists	Solar PV capacity:	12 kW
Spring/ Fall population:	70 residents	Diesel consumption:	55,000 gal.
Winter population:	20 residents	Diesel price:	\$4.5/gal.
Average Population:	125 residents & tourists	Electricity rate:	\$0.60/kWh
Mainland Connection:	Ferry service, harbor for vessels up to 100 ft	Electricity consumption:	600,000 kWh/year

4 RESULTS

4.1 Resource assessment

As described, the resource assessment provides the basis for any deliberations concerning economic feasibility of renewable energies. The assessment of the theoretical resources is therefore inevitable in order to draw conclusions for the following analyses. This assessment evaluates resources according to their spatial and temporal occurrence. Spatial variability relates to a defined area and how resource varies over a region. Temporal variability refers to occurrence in distinct time periods (Kunz, Hagens, & Balogh, 2014).

Temporal variability may be daily, monthly, seasonal, annual, inter-seasonal and inter-annual periods. As the term suggest, daily variability relates to the changes of data within one day, monthly variability shows the variability within certain month and yearly variability shows the variability of several observed years. Inter-seasonal variability though refers to the differences between selected seasons. Comparing several years with each other shows the inter-annual variability.

The aim of the resource assessment is to assess the theoretical available and the technical extractable power in either of the three resources. As explained in Section **Fehler! Verweisquelle konnte nicht gefunden werden.**, theoretical available power is defined as the amount of wave, wind and solar power that exists in a region in terms of kinetic power and potential power, which may be used to supply energy (Espinosa, E.; Alkorta, I.; Roza, I.; Elguero, J.; Molins, E., 2001). Technical extractable power is the part of the available power that is usable for production using an energy

converter (Shihon, Straub, & Elimelech, 2014). In contrast, practical power is the specific proportion of technical power a system can use due to political restrictions or ecological constraints. (National Research Council, 2013). Therefore, available power is always greater than extractable power, and extractable power is greater than practicable power.

Figure 29 Process of the resource assessment

The process of the resource assessment is shown in Figure 29. This figure shows that the first step of the process is the determination of the theoretical available power. Thereafter, a device needs to be selected, which characteristics are used to determine the technical extractable power. Based on these amounts, initial costs for can be computed. The initial cost analysis states whether the resource is suitable or unsuitable.

4.1.1 Wave resources

The present assessment of wave resources uses hindcast data from the Wave Information Studies (WIS) by the U.S. Army Corps of Engineers from WIS station 63088 for this purpose (WIS, 2016a). The WIS station contains monthly average wave heights, period, maximum height, for a period of 32 years of records. The location of the WIS station is illustrated in Figure 30.

Figure 30 Location of the used WIS stations 63088 and 63074 in the Rhode Island Sound, and location of the real measurement buoy BUZM3 located in Buzzards Bay

It appears that WIS station 63088 is farer away from Cuttyhunk than WIS station 63074 and buoy BUZM3. However, WIS station 63088 is selected, because BUZM3 does not have significant wave height records and WIS station 63074 is used for validation purposes in the later process of the assessment. The coordinates of WIS station 63088 are 41.17°N and 70.92°W and the coordinates of WIS station 63074 are 41.25°N and 71°W .

As it was described in Section 3 SWAN wave model simulates changes of waves height and direction due to wind, white capping, wave breaking, energy transfer between waves, and the local bathymetry (TU Delft, 2016). For resource assessment, initial conditions of wave height, wave direction and wave period need to be specified. First, a computational grid has to be set up. This was done using bathymetry for the region and by choosing the grid dimensions. Bathymetry data for New England was supplied by NOAA. The bathymetry of the area can be seen in Figure 31.

Figure 31 Bathymetry at Cuttyhunk Island and Rhode Island Sound in meters

Referring to Figure 31, it is apparent that the water depth around the Elizabethan Islands is shallower, which is expressed by yellow in the color bar. They are surrounded by deeper water, which has the color turquoise. Deeper water formed as a line can indicate that either the current has a higher velocity, that shipping lanes erode the seabed or that geology has a different topography. Tagg and Uchupi (1967) found that the topography at Buzzards Bay is due to fluvial erosion and has been modified later by glacial erosion and deposition. However, it also built up sediments (Tagg & Uchupi, 1967).

Higher velocity appears in narrow sections. This is known as the fundamental principle of the continuity equation of flow. This principle is derived from the fact that mass is always conserved in fluids. It is defined in Equation (34): (Svendsen, 2006)

$$Q = V_1 A_1 = V_2 A_2 \quad (34)$$

, where Q is the flow in m^3/s , v is the velocity at point 1 and 2 in m/s , and A is the area at that point in m^2 . By rearranging the equation, the velocity becomes dependent on the area of the flow. This means, the narrower the passage, the higher the velocity. As a consequence, higher velocities erode these sections.

Except of the maritime traffic coming from and entering New Bedford harbor, there is no major subsistence of vessels in Buzzards Bay, wherefore the deeper depth is due to natural geological developments and natural erosion processes.

Furthermore, the location of Cuttyhunk at the outer edge of the island array is a significant obstacle. Taken in mind the high velocities of the currents, high wave heights are conceivable. The height of waves is one aspect of the theoretical potential for wave energy generation. However, the swell window for Cuttyhunk Island raises some concerns, as it is north-west of Martha's Vineyard. The swell window is the range in which swell carries out to a point in space. Swells traveling from $\text{S}10^\circ\text{E}$ will experience significant shadowing. Likewise, swells traveling out of the west, from $\text{S}70^\circ\text{W}$ will be blocked by both Block Island and Long Island. This is of particular interest as the swell comes from this direction (WIS, 2016a). Furthermore, referring back to Figure 19, it can be seen that the island itself blocks swell. Therefore, the waters south of Cuttyhunk are of greater interest compared to the waters north of the island.

Further analysis is provided by modeling the wave climate at the Rhode Island Sound and Buzzards Bay. A grid with enough resolution needs to be chosen to avoid inaccurate predictions. The origin of the grid is set to $41^\circ 17'\text{N}$ and $71^\circ 25'\text{W}$ and the length in x- and y-direction is determined to be 0.5° respectively 6 km. The orientation and direction of the computational grid is set to 0° in terms of the Cartesian coordinate

system. The number of meshes in the structured grid in x- and y-direction is defined to be 480, which gives an amount of 230,400 cells and a resolution of 12.5 m x 12.5 m for each cell in the model output. This is a high-resolution grid, as Booij, Ris and Holthuijsen (1999) used a 100 m x 100 m grid in their review of SWAN computations compared to actual measured data (Booij, Ris, & Holthuijsen, 1999).

This resolution is an acceptable combination between computation time and accuracy. As a next step, the spatial grid needs to be defined. This is done for the computational spatial grid on which SWAN performs the computations. The input for the grid are mean wave height, mean wave period and mean wave direction. The data for mean wave height and mean wave period is retrieved from WIS for monthly averages of the 32-year period in order to cover inter-annual variability. They are summarized from the output protocols from WIS in Table 6.

Table 6 Wave direction, mean wave height and wave period recorded by WIS station 63088 and adjustment of wave direction to Cartesian coordinates (WIS, 2016b)

Month	Nautical wave direction	Cartesian wave direction	Mean wave height	Mean period
[-]	[°]	[°]	[m]	[s]
January	202.5	67.50	1.60	8.00
February	180.0	90.00	1.50	8.70
March	157.5	112.50	1.30	9.10
April	157.5	112.50	1.10	8.50
May	180.0	90.00	1.00	7.10
June	180.0	90.00	0.90	6.80
July	157.5	112.50	0.90	6.80
August	157.5	112.50	0.80	8.00
September	135.0	135.00	1.00	9.60
October	135.0	135.00	1.10	9.80
November	135.0	135.00	1.40	10.30
December	225.0	45.00	1.70	7.40

Likewise, main wave direction is obtained from WIS for monthly averages of the average period in order to cover inter-annual variability. For this purpose, the mean wave direction of each month is estimated, which is exemplified in Figure 32.

Figure 32 Wave rose for WIS station 63088 for the average wave heights for the month of June for a 32-year period from 1980 – 2012 (WIS, 2016b)

As it can be seen, the major wave direction is 180° in nautical coordinates. This direction must be converted to Cartesian coordinates due to requirements by SWAN. Both, nautical and Cartesian coordinate are provided in Table 6.

With these input variables, simulations can be performed for each month. The output includes significant wave height and wave direction for each grid cell, as well as theoretical available wave power. In order to avoid software conflicts a constant wind of 1 m/s has been set. The visualization of these data is done in Matlab and can be seen in the following figures. It should be noted that more accurate analysis includes non-stationary mode for several years. For example, computations for a ten-year period would be more accurate. However, in order to give approximate estimates for the feasibility of the deployment of WEC, the stationary approach was performed.

The resulting simulations by SWAN model need to be validated to ascertain the reliability of the results first in order to use it. WIS station data for WIS station 63704 is chosen for this validation, because the station is located inside the model domain. The location of station 63704 is shown in Figure 30. For the coordinates of WIS station 63074, output data has been extracted from SWAN. This output data is contrasted on a monthly base for the 32-year hindcast records of the WIS station. The model validation can be seen in Figure 33.

Figure 33 Comparison of SWAN and WIS Station 63074 for monthly average wave heights

Figure 33 shows that SWAN and the data from WIS station agree in general. However, there is a discrepancy specially in the winter month. The highest variation occurs in December when the difference amounts to 0.3 m. It can be concluded that the approach undertaken to assess the wave climate is correct in general, but is imprecise due to simplified modeling assumptions and data concerning wave direction, wave period and wave height. As mentioned, the more accurate approach would include running

SWAN for all data for a longer period of time (e.g. ten years), where wave height, period and direction are computed hourly in unstationary mode.

The absolute mean error is 0.1325 m as it can be seen in Table 7. This value needs to be considered when available wave power is computed. For more detailed results of computations of significant wave heights, adjustments in the computation process would be needed. However, these results can be accepted for the stage of an early feasibility analysis.

Table 7 Comparison of SWAN results and WIS data at WIS Station 63074

Month	WIS-Hs	SWAN-Hs	Absolute error	Absolute mean error
[-]	[m]	[m]	[m]	[m]
Jan	1.4	1.63	0.2250	0.1325
Feb	1.3	1.52	0.2219	
Mar	1.3	1.38	0.0816	
Apr	1.1	1.16	0.0605	
May	0.9	1.00	0.1048	
Jun	0.8	0.90	0.1031	
Jul	0.8	0.92	0.1222	
Aug	0.8	0.78	0.0227	
Sep	1.0	0.88	0.1234	
Oct	1.1	0.96	0.1364	
Nov	1.3	1.22	0.0823	
Dec	1.4	1.71	0.3061	

After validating the model, average wave heights have been extracted from SWAN for each month. These plots allow to understand the general conditions of the wave climate. Furthermore, the figures allow to evaluate which locations are the best for the installation of WECs. In addition, wave directions are shown by arrows in each figure, which has a scale of 0-3 m in terms of wave heights. These plots are shown in Figure 34 - Figure 39.

Figure 34 Significant wave heights at Rhode Island Sound and Buzzards Bay on a scale from 0 to 3 meters for January and February shown for an area of 36 km²

Figure 35 Significant wave heights at Rhode Island Sound and Buzzards Bay on a scale from 0 to 3 meters for March and April shown for an area of 36 km²

Figure 36 Significant wave heights at Rhode Island Sound and Buzzards Bay on a scale from 0 to 3 meters for May and June shown for an area of 36 km²

Figure 37 Significant wave heights at Rhode Island Sound and Buzzards Bay on a scale from 0 to 3 meters for July and August shown for an area of 36 km²

Figure 38 Significant wave heights at Rhode Island Sound and Buzzards Bay on a scale from 0 to 3 meters for September and October shown for an area of 36 km²

Figure 39 Significant wave heights at Rhode Island Sound and Buzzards Bay on a scale from 0 to 3 meters for November and December shown for an area of 36 km²

It can be seen that the significant wave heights are highest in January, February and December, when average wave heights reach about 2 m offshore and decrease to approximately 1 m when they enter the Vineyard Sound and Buzzards Bay. It can be seen that one area close to Cuttyhunk stands out with high values. This area in the south-west of the island can be observed best in the month January, February and December by its red color. By referring to Figure 31, it can be seen that this area is relatively shallow with an approximate depth of 10-15 m. The region that have been considered for installation of WECs in the near of the island are shown in Figure 40. The results consisted of the monthly mean significant wave height, and mean wave period. Both were analyzed and the corresponding values determined, because available power is proportional to the square of the wave height and wave period. Monthly mean wave data are reported in Table 8 for the significant wave heights and in Table 9 for the wave periods.

Figure 40 Nearshore locations considered for WEC installation at Cuttyhunk Island

Table 8 Significant wave heights for selected WEC locations in Figure 40

Month	Significant Wave Heights (m)									
	Loc 1	Loc 2	Loc 3	Loc 4	Loc 5	Loc 6	Loc 7	Loc 8	Loc 9	Loc 10
Jan	1.23	1.37	1.42	1.87	2.41	1.65	1.65	1.48	1.41	1.33
Feb	1.13	1.15	1.27	1.83	2.27	1.54	1.54	1.29	1.20	1.14
Mar	0.76	0.97	1.15	1.74	2.02	1.14	1.41	1.17	1.03	0.97
Apr	0.64	0.84	0.98	1.44	1.63	1.16	1.16	0.99	0.89	0.83
May	0.67	0.79	0.86	1.13	1.27	0.94	0.94	0.86	0.83	0.80
Jun	0.60	0.72	0.78	1.00	1.11	0.83	0.83	0.78	0.76	0.73
Jul	0.51	0.76	0.80	1.06	1.11	0.89	0.89	0.84	0.78	0.72
Aug	0.44	0.53	0.62	0.87	0.98	0.71	0.71	0.60	0.56	0.54
Sep	0.45	0.52	0.64	0.98	1.17	0.80	0.80	0.59	0.53	0.52
Oct	0.49	0.57	0.70	1.09	1.31	0.89	0.89	0.65	0.58	0.57
Nov	0.63	0.72	0.89	1.42	1.72	1.16	1.16	0.83	0.74	0.72
Dec	1.39	1.53	1.49	1.78	2.42	1.70	1.70	1.57	1.51	1.42

Figure 41 Average monthly significant wave heights for selected WEC locations in the nearshore of Cuttyhunk shown in Figure 40

It is clear, that Location 5 has the highest wave heights compared with other locations. For this point, the maximum significant wave height is predicted in December, January, February and March with values above 2.00 m. The peak wave height is 2.42 m in December. The lowest wave height occurs during summer period from May until October, when average wave heights stay in a range from 0.44-1.27 m. The lowest value of Location 5 is predicted as 0.98 m in August.

Table 9 Wave periods for selected WEC locations in Figure 40

Month	Periods (s)									
	Loc 1	Loc 2	Loc 3	Loc 4	Loc 5	Loc 6	Loc 7	Loc 8	Loc 9	Loc 10
Jan	6.52	6.44	6.46	6.95	7.34	6.88	6.88	6.56	6.47	6.37
Feb	7.16	6.94	7.10	7.66	8.07	7.59	7.58	7.16	7.01	6.92
Mar	7.87	6.98	7.54	8.07	8.39	7.88	7.88	7.39	7.09	7.08
Apr	7.38	6.52	7.05	7.53	7.84	7.31	7.31	6.90	6.62	6.59
May	5.71	5.64	5.79	6.17	6.49	6.02	6.02	5.80	5.75	5.69
Jun	5.45	5.41	5.55	5.89	6.18	5.73	5.73	5.57	5.53	5.47
Jul	6.00	5.32	5.63	5.93	6.16	5.70	5.70	5.53	5.38	5.27
Aug	6.60	6.33	6.59	7.06	7.42	6.93	6.93	6.55	6.45	6.41
Sep	8.19	7.67	8.02	8.59	8.99	8.51	8.51	7.94	7.76	7.78
Oct	8.37	7.84	8.19	8.77	9.17	8.70	8.70	8.12	7.93	7.95
Nov	8.80	8.27	8.62	9.22	9.63	9.16	9.16	8.56	8.34	8.36
Dec	6.04	6.03	5.94	6.32	6.72	6.30	6.30	6.06	6.00	5.92

Figure 42 Average monthly wave periods for selected WEC locations in the nearshore of Cuttyhunk shown in Figure 40

Monthly fluctuations of wave periods can be seen within each location. The time series are quite similar for all locations. Highest period values are trending towards winter months and lower values during summer. The wave periods are highest from September to November. The values for the locations fluctuate during this time period from 7.76 s to 9.63 s. The lowest wave periods can be detected in the period from May to

July. These values stay between 5.27 s and 5.64 s. Wave periods of Location 5 peak in November at 9.63 s and have its lowest value in July at 6.16 s.

Table 10 Available wave power for selected WEC locations in Figure 40

Month	Available Power (kW/m)									
	Loc 1	Loc 2	Loc 3	Loc 4	Loc 5	Loc 6	Loc 7	Loc 8	Loc 9	Loc 10
Jan	5.28	5.95	6.56	10.45	12.14	8.06	8.06	7.38	6.82	6.25
Feb	3.89	4.79	6.08	10.94	10.83	7.68	7.68	6.29	5.48	5.08
Mar	2.20	2.88	4.12	7.58	7.18	5.39	5.39	3.81	3.17	3.01
Apr	1.47	1.96	2.73	4.90	4.58	3.50	3.50	2.54	2.17	2.06
May	1.44	1.83	2.22	3.56	3.40	2.55	2.55	2.24	2.09	1.98
Jun	1.12	1.45	1.73	2.70	2.56	1.95	1.95	1.74	1.64	1.56
Jul	0.78	1.12	1.41	2.29	2.07	1.68	1.68	1.34	1.25	1.19
Aug	0.73	0.99	1.35	2.37	2.20	1.70	1.70	1.27	1.11	1.05
Sep	0.86	1.18	1.81	3.40	3.38	2.57	2.57	1.57	1.25	1.21
Oct	1.06	1.45	2.24	4.25	4.23	3.21	3.21	1.94	1.54	1.49
Nov	1.77	2.44	3.82	7.34	7.32	5.49	5.49	3.27	2.55	2.49
Dec	6.37	6.80	6.25	8.49	12.69	8.22	8.22	7.60	7.25	6.62

Figure 43 Average monthly theoretical available power for selected WEC locations in the nearshore of Cuttyhunk shown in Figure 40

Table 10 and Figure 43 show the available wave power for the selected locations around Cuttyhunk for monthly averages. The graphs show that wave power is maximum during November to February, and December has most wave power. In December, the

available power varies from 6.2-12.7 kW/m. In addition, the month in which no practical wave energy can be produced, are excluded by the color red, because wave heights fall under the threshold of 1 m (Rahuma & Yaakob, 2015).

It can be assumed that wave power is extractable from October to April. The power is too low from May to September and not extractable by the OWSC. The location with the highest available power is Location 5 that can be seen in Figure 40. The available power at Location 5 alternates between 7.3-12.7 kW/m from November to February. From May to September, theoretical power varies between 0.7-3.4 kW/m. The theoretical power varies from March to May and from September to November between 3.4- 7.3 kW/m.

Considering the proximity of the selected locations to the shoreline of about 1 km and their depth of 10-15 m, the heaving point absorber is not selected, because free floating point absorber require depth between 40 – 100 m (Vicente, António, Gato, & Justino, 2009). The oscillating wave surge converter is more conceivable, because it requires depth between 10-15 m in nearshore waters (Whittaker & Folley, 2012). This device was considered for the assessment, even though it is still in an early development stage. As mentioned in Section **Fehler! Verweisquelle konnte nicht gefunden werden.**, Aquamarine Power does not give detailed information for its oscillating wave surge converter device Oyster. Likewise, power curves are not available for different wave heights. Therefore, assumptions need to be made.

Rusu (2014) has analyzed several WEC and found that the capacity factor for a heaving point absorber ranges between 8.4-9.5 % in Spanish nearshore waters (Rusu,

2014). Based on this, a capacity factor of 8.4 % is assumed for the Oyster device. Furthermore, it is assumed that the capacity factor applies to any wave height due to a lack of studies describing performance of nearshore OWSCs (Rahuma & Yaakob, 2015). This is a generalized approach as power curves for any device are not constant, but change with resource availability. However, assuming a constant value allows to assess the extractable power for generalized conditions, and initial stages of studies.

The assessment for technical extractable power is done by multiplying the device length of 26 m in width with the available power at each month for Location 5 times the capacity factor of 0.084 results in the extractable power yield for each month.

Further assumptions need to be made in order to compute COE based on device cost and additional costs, because both prices are unknown. The device cost are not public and additional costs, which are O&M, installation and connection are unknown. IRENA (2014) estimates that the cost for WEC are approximately \$4070/kW for the year 2020 (IRENA, 2014). Based on that, device costs would range between \$ 3.25M. Additional costs can be derived based on the WEC cost breakdown that has been done by the Strategic Initiative for Ocean Energy that is shown in Figure 44. They have computed the percentage cost for structure, PTO, installation, O&M, foundation, and connection (SI Ocean, 2013).

Figure 44 Cost breakdown for wave energy projects (SI Ocean, 2013)

Figure 44 illustrates that O&M account for approximately 17 % of the overall cost for WEC. The PTO and the system structure account for the greater part of costs and sum up to just over the half of the cumulative costs. The PTO accounts for 31 % and the Structure accounts for 22 %. Together, foundation, installation and connection have a portion of costs of 30 %. These numbers are included in the device estimation costs of IRENA (2014). Therefore, O&M costs of 17 % need to be included in the COE computations. The computations result in COE of \$0.29-0.86/kWh for different amounts of energy contribution for a project with a 25-year lifespan. In reference to Figure 43, it is not possible for OWSC to generate electricity in the summer month from May to September. Therefore, these computations are not available out in Table 11.

As it can be seen in Table 11, multiple devices are necessary to meet the demand, which is possible as several units can be connected to an array. Demanded capacity can be established modularly. October is the decisive month for choosing the number of devices, as there is the lowest power available. The available power is 4.23 kW/m. This leads to a usage to energy yield ratio of 2.36. This means that 2.36 devices would be necessary, in theory, to meet the demand of 34.97 MWh. Therefore, approximately 3

Oyster devices are necessary in practice. In other words, a system that relies completely on WEC as its only energy source for the winter month, has capital expenditures (CAPEX) of \$9.77M, and operational expenditures (OPEX) of \$3.13M and COE of \$0.86 /kWh. CAPEX is the money spend for the acquisition of assets. OPEX is the money spend for ongoing processes in the operation of those assets.

Table 11 Extractable wave energy, project outline and energy cost

Wave Resources	Demand		Supply			Project Outline			Cost		
Month	Peak loads (kW)	Energy usage (MWh)	Available energy (kW/m)	Power output (kW)	Energy yield (MWh)	usage-yield ratio	load-output ratio	Required devices	CAPEX (Mio \$)	OPEX (Mio \$)	COE (\$/kWh)
January	97.41	49.61	12.14	94.69	70.45	1.03	0.70	2	6.51	2.09	0.57
February	85.62	39.74	10.83	84.47	62.85	1.01	0.63	2	6.51	2.09	0.57
March	85.33	39.34	7.18	56.00	41.67	1.52	0.94	2	6.51	2.09	0.57
April	68.56	30.65	4.58	35.72	26.58	1.92	1.15	2	6.51	2.09	0.57
May	-	-	-	-	-	-	-	-	-	-	-
June	-	-	-	-	-	-	-	-	-	-	-
July	-	-	-	-	-	-	-	-	-	-	-
August	-	-	-	-	-	-	-	-	-	-	-
September	-	-	-	-	-	-	-	-	-	-	-
October	77.93	34.97	4.23	32.99	24.55	2.36	1.42	3	9.77	3.13	0.86
November	66.75	35.22	7.32	57.10	42.48	1.17	0.83	2	6.51	2.09	0.57
December	63.12	39.31	12.69	98.98	73.64	0.64	0.53	1	3.26	1.04	0.29

In summary, it can be said that the wave climate on Cuttyhunk varies greatly throughout the year. In winter months, swells with mean significant wave heights of around 2.2 meters, and periods between 7-9 seconds are estimated at Location 5, which is about 1 km off the island. The values change significantly as summer approaches, and the monthly averages of significant wave heights decrease to approximately 1.0 to 1.5 meters. The less frequent occurrences of low-pressure storms result in a decrease of mean wave period to values below 6 seconds. These values are not sufficient for the installation of a heaving point absorber like the PowerBuoy. Considering the proximity

and sea depth of the chosen location, a suitable WEC system for Cuttyhunk Island such as an oscillating wave surge converter was considered. Furthermore, the energy generated by WECs for Cuttyhunk Island is not significant, because wave amplitude and period are not sufficient.

Therefore, the possibility of Cuttyhunk being a completely wave-powered island is a remote target given the current WEC technology. A combination of the islands small swell window, and the lack of wave activity during the peak summer months minimize the potential of wave power development. However, winter months are more reliable as far as extractable power is concerned in combination with low demand during winter. COE are relatively high compared to the current electricity price on Cuttyhunk. The COE range between \$0.29-0.86/kWh. Therefore, WEC could theoretically be a solution that could potentially power a portion of the base loads during the winter months, if the technology advances more. Therefore, wave energy generation was not included in the final energy solution of this study.

4.1.2 Wind resources

The potential of wind energy has been measured in 1988 for winds in New England and on Cuttyhunk (Manwell, McGowan, & Blanco, 2003). The data showed that winds were increased in fall/ winter and averaged 7.86 m/s (17.6 mph) at a height of 18.3 m, respectively 60ft. NREL gives average annual wind speed values for heights of 50 m and 80 m. The map for 80 m heights can be seen in Figure 45. For 50 m winds, resource potential at Cuttyhunk can be classified as fair to good conditions. The wind speeds for fair to good conditions are 6.4-7.5 m/s. The wind power density at 50 m is stated to be 300-500 W/m². The US Department of Energy quotes the average annual

wind speed with 9.0 m/s for a height of 80 meters (DOE, 2015). Figure 45 shows the average annual wind speed at 80 m. These values differ reasonably from each other due to different heights. However, they are insufficient for a project development and need to be investigated in more detail. Therefore, a wind resource assessment is inevitable and will be performed in the following.

Figure 45 Average Annual Wind Speed at 80 m in Massachusetts (DOE, 2015)

Data of NOAA's National Data Buoy Center (NDBC) is used for the assessment, because it is the source of information that is closest to Cuttyhunk. Buoy BUZM3 is estimated to be representative for Cuttyhunk Island due to its close distance of approximately 5 miles western from Cuttyhunk, as it can be seen in Figure 30. The coordinates of the buoy are $41^{\circ}23'48''\text{N}$ and $71^{\circ}2'0''\text{W}$. In the case of Cuttyhunk, buoy data is reasonable, because no other data is obtainable and due to its close location to the island.

In view of the fact that offshore wind is less affected by surface roughness and friction, which slows wind speeds down, offshore wind speeds are higher in general

(Charnock, 1955). For this reason, a modification of the data could be performed by means of a scale factor that reduces the wind speeds measured at BUZM3. The proposed scale factor is based on a ratio of two measurements stations, one on Block Island, RI and the other at offshore waters close to the island. The offshore measurement station is located 3.8 miles south of Block Island on a jetty station at a height of 59 m. This station measured the wind speeds from 2009-2011. The data has been extrapolated to 80 m meter to ensure comparability with the onshore measurements. The onshore anemometer is a DOE station that is located at the airport on the island and has measurements at 80 m. The wind speed distributions for both sites are obtained from SAMP, and shown in Figure 46 and Figure 47 (Grilli A. , Spaulding, Crosby, & Sharma, 2010).

Figure 46 Wind speed distribution at the jetty station at Block Island from Oct 2005 to Sep 2009 at 80 m

Figure 47 Wind speed distribution at the DOE station from Oct 2005 to Sep 2009 at 80 m

The distributions show that offshore and onshore wind at Block Island are comparable. The k values for the distributions are 2.38 for onshore and 2.018 for offshore wind. The c values for the distributions are 9.74 for onshore and 10.9 for offshore wind. Both parameters are part of the Weibull distribution that is used for the analysis of wind

speed, as it represents the occurrence of wind speeds best (Stevens & Smulders, 1979). Its mathematical function is expressed in Equation (35), where v is the wind speed in m/s, k is the shape parameter and c is the scale parameter (Weibull, 1951).

$$f(v) = \left(\frac{k}{c}\right) \left(\frac{v}{c}\right)^{k-1} \exp\left(-\left(\frac{v}{c}\right)^k\right) \quad (35)$$

Since the shape factors are comparable for both measurements ($k_{\text{offshore}}=2.018$, $k_{\text{onshore}}=2.38$), the ratio of the scale factors can be taken as a modification factor for the wind measured at BUZM3. The scale factor is 0.8936, as $c_{\text{onshore}}=9.74$ and $c_{\text{offshore}}=10.9$. Nevertheless, looking at the Weibull coefficients, there is in fact very little difference between the Jetty station and the tower. In addition, there is also the problem of the shape coefficient which distorts the distribution. Therefore, the differences are neglected for the computation of theoretical power since further analysis are needed to compare the differences between airport and Jetty measurements. At this point of a global level of assessment, it is assumed that the offshore wind at BUZM3 is representative of the wind field on the island.

BUZM3 consists of 10-minute increment data taken at a height of 24.8 m beginning in 1985 until the present day. The 10-minute increments are shown for 2015, to demonstrate the fluctuation of wind. The wind speed values for the 10-minute increments can be seen by a black trendline in Figure 48.

Figure 48 Annual wind profile at a height of 24.5 m for 2015 and average annual wind speed at a height of 24.5 m from 1985 to 2015

It can be seen that wind speeds are higher in winter as compared to summer. Average wind speeds stay approximately at a margin between 8-10 m/s during winter. In summer, average wind speeds stay approximately between 6-8 m/s. The values can therefore be described as periodically.

Apposed to that, 10-minute increments are fluctuating conceivable. However, the overall occurrence reflects the average wind speeds. In 2015, the Peak wind speed occurred in February and reached 25.45 m/s. Lows at about 0 m/s are reached throughout the year. In general, wind turbines shut down at these high speeds, wherefore the average wind speed gives a better estimation.

Figure 48 shows the tendency of occurrence, but does not give specific values for most frequent winds. Most frequent wind can be a decisive factor for system design. Therefore, they need to be known for evaluation of an appropriate device. A histogram is capable of showing the distribution of wind speed. The histogram is illustrated in Figure 49.

Figure 49 Wind speed distribution at BUZM3 for 1985-2015

The wind speed distribution has a modal value of wind speed of 6.5 m/s with a frequency of 4.25 %. The arithmetic average is 7.5 m/s and the mean value is 14.8 m/s. These numbers show that the distribution is slightly positive skewed. The most probable single wind speed to occur solely is 6.5 m/s and the most probable wind speed in average is 7.5 m/s. The highest wind speed that appeared is 29.6 m/s, which shows that values for one year do not represent a sufficient base to judge a project with sufficient certainty.

To examine the potential of wind energy, not only wind speeds need to be elucidated, but wind power or wind power density respectively. Available energy density is commonly computed for W/m^2 . The great variability effects can be seen in the illustration of available wind power for the wind dataset in Figure 50.

Figure 50 Available wind power

It can be seen that the available power curve for wind is comparable to the available power curve for waves. Both have their highs in winter and their overall lows in summer. The available power in winter is around 600-1,000 W/m² and around 200 W/m² in summer. However, the extractable power from wind turbines are mostly caused by the power curve of the specific device. For this reason, a common device is chosen for the determination of extractable energy. The selected device is XANT's M-21. The M-21 is a mid-sized device with a capacity of 100 kW. It works at low wind speeds starting at 3 m/s and is available for hub heights of either 23, 31.8 or 38 m. With a rotor diameter of 21 m, the swept area of the turbine blades is 55.41 m². The swept area refers to the area of the circle created by the blades as they sweep through the air. The turbine has been selected because it is easily erectable without a crane and likewise easily shippable in a 40-foot container, which simplifies logistics. Furthermore, M-21 follows the just enough essential parts (JEEP) principle, which makes it robust, lowers

operational cost and simplifies maintenance considerably. The installation process can be seen in Figure 51.

Figure 51 Installation process of XANT M-21

On site assembly is an advantage of the technology in addition to erection using a gin pole. Prospected lifetime for the M-21 is 20 years. The turbine is designed for integration in off-grid systems due to its included energy management control system, and a small energy storage that minimizes power ramps and controls dump-loads. The turbine characteristics are summarized in Figure 52 and can be seen in detail in Appendix G.

Device	Xant M-21
Hub Height	23/31.8/38 m
Rotor diameter	21 m
Rated power	100 kW
Operating wind speeds	3-70 m/s
Number of blades	3
Power factor	0.9
Type	Standalone or guyed tower

Figure 52 Device features of a Xant M-21 wind turbine (Xant, 2016)

As mentioned, the power curve is decisive for extracting energy from the system. Hence, once a sufficient wind speed actuates the blades, the increase in power output

for increasing wind speeds is more linearly than curved, because the efficiency of the system reduces the output. The power curve for the XANT M-21 and its annual energy yield are given in following Figure 53.

Figure 53 Power curve and energy production of XANT M-21 (Xant, 2016)

Based on the turbine features and wind speeds at the location, actual electricity output can be computed. The ratio of electricity demand in terms of energy usage and peak loads can be computed by dividing with the monthly power and energy production. In addition to that, device cost and O&M costs need to be estimated. However, both are not available, but can be back calculated based on average cost per kW.

Wiser and Bollinger (2014) analyzed power cost for wind turbines. They computed average onshore wind turbine costs to be 1,657 USD/kW, which accounts for any size of wind energy projects. In terms of a small scale wind turbines with a capacity of 100 kW, this would amount to \$165,700 (Wiser & Bollinger, 2014).. However, the industry is greatly correlated to economics of scale as it was described in Section 2.2. Therefore, small scale wind turbines are more expensive than their bigger sized counterparts. After personal information from XANT has been requested, device costs of

\$275,000 are taken for calculations. Xant states that their installation, supervision and commissioning costs are \$25,000, and that civil works, grid connection and balancing of the plant would costs \$50,000 resulting in a CAPEX of \$350,000 for one wind turbine (Heuverswyn, 2016).

Due to manufacturer's information O&M costs are low for the beginning of the deployment, but increase over its lifetime. This is considered by setting the OPEX to \$3,800. Based on these information, the computations of extractable power, number of required devices and COE can be performed in order to state how much a project outline costs that is solely based on wind turbines. The results are presented in Table 12.

Table 12 Extractable wind power, project outline and energy cost

Wind Resources	Demand		Supply			Project outline			Cost		
Month	Peak loads (kW)	Energy usage (MWh)	Wind speed (m/s)	Power output (kW)	Energy yield (MWh)	usage-yield ratio	load-output ratio	Required devices	CAPEX (Mio \$)	OPEX (Mio \$)	COE (\$/kWh)
January	97.41	49.61	10.0	80.0	39.2	1.27	1.22	2	0.70	0.23	0.08
February	85.62	39.74	9.0	62.5	36.2	1.10	1.37	2	0.70	0.23	0.08
March	85.33	39.34	8.0	45.0	31.9	1.23	1.90	2	0.70	0.23	0.08
April	68.56	30.65	7.0	30.0	26.4	1.16	2.29	3	1.05	0.34	0.12
May	128.80	33.58	6.5	25.0	23.3	1.44	5.15	6	2.10	0.68	0.23
June	120.69	56.08	6.0	20.0	20.0	2.81	6.03	7	2.45	0.79	0.27
July	164.38	98.22	6.0	20.0	20.0	4.92	8.22	9	3.15	1.02	0.35
August	178.75	86.98	6.5	25.0	23.3	3.73	7.15	8	2.80	0.90	0.31
September	163.55	50.16	7.0	30.0	26.4	1.90	5.45	6	2.10	0.68	0.23
October	77.93	34.97	7.5	37.5	29.3	1.19	2.08	3	1.05	0.34	0.12
November	66.75	35.22	8.0	45.0	31.9	1.10	1.48	2	0.70	0.23	0.08
December	63.12	39.31	8.5	55.0	34.2	1.15	1.15	2	0.70	0.23	0.08

As it can be seen, estimations of the necessary number of turbines are done based on the ratio of total monthly energy usage divided by the monthly energy yield of the turbine and based on the ratio of monthly peak loads divided by wind turbine output. These ratios are the highest for the summer month June, July and August. For the demand of 98.22 MWh and an energy yield of 21 MWh for wind speeds of 6 m/s in July,

9 wind turbines would be needed to meet the temporary needs of the grid in July. For the same month, peak loads reach 164.38 kW, which results in 5 required devices in theory. This shows that the peak loads are decisive for the determination of required wind turbines.

The costs for a system with a 25-year lifetime that relies completely on wind energy would be \$2.98M in terms of CAPEX and \$3.19M in terms of OPEX, resulting in COE of \$0.41/kW. However, the number of required devices can be higher, if it is considered that produced electricity and demand do not often meet in time. This is a reason, why it is unrealistic to assume that Cuttyhunk could rely completely on wind energy as its only supplying resource without storing any excess electricity. Therefore, wind power is a suitable resource, and a potential part of the system.

4.1.3 Solar resources

The solar resource assessment is the systematic collection of meteorological data to estimate the solar climate of a site and to evaluate the prospective output of PV modules. Solar irradiance varies with geographic location and time. On this basis, devices can be selected, and system performance and operations can be determined. Solar irradiance is in general more consistent and predictable compared to waves and wind, which means that spatial variability of theoretical available power is not site specific. However, shading can be an important aspect that could reduce technical extractable power. For this reason, location and project size need to be investigated, because the reduction of technical extractable power has the potential to escalate cost due to less energy generation by the panels.

The weather is a determining aspect for the assessment of solar radiation, as it can reduce energy output. Clouds reduce the incoming radiation as well as snowfall, and high temperatures. All three need to be evaluated, because they can either reduce electricity output significantly or interrupt electricity generation in general. NREL gives a general assessment (NREL, 2007). This assessment states that the average annual average daily radiation is approximately between 4.0-4.5 kWh/m²/Day on Cuttyhunk. The graphical illustration can be seen in Figure 54.

Figure 54 Annual average daily total radiation, averaged from hourly estimates of direct normal irradiance from 1998-2005 (NREL, 2007)

Figure 54 shows that annual average daily total radiation does not have any variabilities in the near area, as the yellow coloring expresses that there is only solar irradiance between 4.0-4.5 kWh/m²/Day on average. This number would simplify the computation of extractable energy, but it would not account for seasonal variability, which can be a major advantage of the technology, because it is an off-grid system. Therefore, this number gives just a general overview. In the following, Figure 55, Figure 56 and Figure 57 assess the average weather on Cuttyhunk in terms of cloudiness, snowfall and average temperature.

Figure 55 Cloudy Days at Gosnold, MA (City Data, 2006)

Over the year, cloudy days are most common compared to partly cloudy days and days that are clear of clouds. Cloudy days account for approximately 45 % on average during the year. Partly cloudy days occur approximately at 25 % of days in the year and sunny days have an occurrence probability of 30 %. This aspect indicates a deployment of mono-crystalline solar panels, as they are most suitable for cloudy conditions. Considering the fact, that TMY data is used, cloudiness is already included as TMY is composed of real data (Crawley & Huang, 1997).

Figure 56 Average snowfall heights for Gosnold, MA (City Data, 2006)

Snowfall happens from mid-November to mid-April. The average snowfall heights are highest in between January and February at 11 inches. Overall, the average

snowfall heights are higher than the US average. However, snow fall is just an issue, if the snow is not removed from the panels. This can be encountered by an appropriate maintenance of the panels. Snow also melts on panels with a bit of wind. Therefore, the rate of O&M has to be adjusted accordingly.

Average temperatures on Gosnold stay in the lower range of the US average, as it can be seen in Figure 57. Especially the summer month are important to investigate for the purposes of PV installation due to decreasing efficiency with increasing temperatures. It can be seen that daily highs have a maximum at 80°F respectively 26.67°C, but panels can heat above these temperatures.

Figure 57 Average temperature on Gosnold, MA (City Data, 2006)

Duffie and Beckman (2006) have shown that power output depends highly on device temperature (Duffie & Beckman, 2006). However, as Saad and Masud (2009) state, as long as device temperatures stay below 60°C, the maximum output just reduces by 5 % (Saad & Masud, 2009). However, as it can be seen in Figure 58, if module temperatures increase over 60°C, losses can lower device output over this threshold. Nevertheless, Figure 59 shows that these losses can be reduced by different cooling system.

Figure 58 PV module output power for different cooling systems for radiation of 1000 W/m². (Saad & Masud, 2009)

Figure 59 Maximum delivered energy for different PV cooling in Darwin, Australia (Saad & Masud, 2009)

However, Figure 57 shows that the average temperature on Gosnold reaches approximately 70°F (21°C). Additionally, a heat map based on the weather data exemplifies that losses due to high module temperatures are not likely to occur. The heat map is shown in Figure 60.

Figure 60 Heat map for module temperature of a solar panel in Celsius located on Cuttyhunk Island

It can be seen that module temperatures reach values between 30°-50°C on average during summer days. This implies that device temperatures above 60°C over long

periods during the day are not likely to occur. Therefore, further measures to cool down the PV modules do not need to be considered.

As described in Subsection 2.3, TMY data is most commonly used for solar resource assessments and consists of GHI, DHI, and DNI. It reflects the typical conditions for a specific site and does not consider extreme weather conditions in its hourly solar radiation data. The National Solar Radiation Database (NSRDB) provides a basis for this information due to data open to public (NSRDB, 2016). This data is used in the following for Martha's Vineyard, because it is the closest available location that consists of Class II data. Class II data has the second best data quality after Class I data. Class I data is available for Boston Logan Airport and for Worcester Regional Airport. Both are not considered due to their greater distance and conceivable differences in DHI from the airport surrounding. Figure 61 illustrates average daily DHI, DNI, and GHI for the TMY dataset.

Figure 61 Average daily DHI, DNI and GHI for typical meteorological year data on Martha's Vineyard

GHI and DHI bulge out in the summer, starting in March and flattening at the end of October. DNI is highly fluctuating and inconstant during the year. For all month, it stays in a range of values close to zero to irradiances up to 700 W/m². However, GHI is most important for PV modules, as it reaches its high in July at around 350 W/m² and average lows at approximately 180 W/m². DHI, as it is a base component of GHI, stays below GHI and between 100 W/m² in the winter month and 200 W/m² in the summer month. The monthly averages of daily average solar radiation are shown in Table 13.

Table 13 Daily average solar radiation in W/m² for each month

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average	179.7	155.0	276.6	276.7	314.2	264.5	353.8	373.1	334.0	210.3	193.2	167.9

The bulge described in Figure 61 can also be seen in Figure 62 by comparing the swings for each month. The figure presents averaged hourly total solar radiation on horizontal surface for each month in a year. It shows that the five month January, February, March, November and December are the month with the lowest radiation in a TMY. The monthly irradiance increases, as one regards to the TMY peak in August.

Figure 62 Average hourly total solar radiation on horizontal surface

It can be seen that solar irradiance follows a diurnal cycle because of the changing position of the sun. In addition, monthly averages show that hourly total solar radiation on horizontal surface changes during month. In descending order, the month with the most solar radiation are August, July, May, June. Around 750 W/m² reaches ground in the afternoon peaks from 12am-2pm in August. The month with the lowest solar radiation is December with solar radiation peaks of nearly 250 W/m². The Monthly averages are listed in Table 13 order to estimate the extractable energy.

To determine the extractable energy, a common device needs to be assumed. However, it needs to be determined whether rooftop mounted panels or ground mounted solar arrays are favorable. These two options have their individual advantages and drawbacks. The first aspect to consider is the fixing mechanism. Rooftop panels are fixed mounted in general, wherefore their overall production will be lower than the ground mounted variant, as they can track the sun on both axes in order to ensure a perpendicular incidence of light. In addition to that, performance of the ground mounted panels

will be higher, as the rooftop mounted systems have less cooling by airflows and are close to the hot surface of the roof, which increases losses in terms of the power temperature coefficient.

Maintenance for rooftop mounted panels is more time-consuming and accompanied by higher cost due to greater effort and dangers for maintenance workers. Furthermore, an expansion of the system is usually accompanied by issues for rooftop mounted systems, because the roof is affected negatively by every single penetration. However, there are building-integrated systems that have the function of a roof. Those called solar shingles replace the outer building envelope skin and provide savings in material and labor (Jelle & Breivik, 2012). In addition to that, it might be an incentive for homeowners that solar systems increase the property value of real estates with respect to system cost. PV systems generate a price premium that can outweigh aboriginal cost (Adomatis, et al., 2015; Black, 2004)

Summarized it can be said that if enough space is available, ground mounted solar arrays should be preferred for utility size projects, since their advantages outweigh benefits from rooftop mounted systems. Nevertheless, the distance of ground mounted arrays to the nearest feed-in source has to be considered as wiring cost can affect the project's profitability and reduce electricity output due to transfer losses (Ito, Kato, Komoto, Kichimi, & Kurokawa, 2008). Roof mounted systems however, can contribute to the aim of becoming self-sufficient by means of electricity. Project management and project design should incorporate this aspect in system design, if private roof-mounted

systems are deliberated by homeowners. For example, the ratio of panels to storage systems could tend to prevail towards storage systems, if it is clear that private PV systems will be added to the overall energy system at a later date.

The trade-off between system type has come to the conclusion that ground mounted solar arrays are favorable. For this selection, the best rated module from Principal Solar Institute Rating has been selected. The best rated device is the SPR-X21-255 from SunPower Co. with a nominal power of 255 Watt-peaks (Wp) and an efficiency of 21.1 %. The nominal operating cell temperature (NOCT) is 41.5°C with a power temperature coefficient of -0.3%/°C. The nominal peak power per unit area for this module is 210.6 W/m². The device chosen costs about \$285.00 and confirms that current system cost range at approximately \$1/Wp (Mayer, Simon, Philipps, Schlegl, & Senkpiel, 2015). The module is a commonly used monocrystalline solar panel with an area of 1.6 m² that can be installed roof mounted or ground mounted on racking systems. A monocrystalline solar panel has been chosen because its higher efficiency does not require as much space as a polycrystalline solar panel would need for its area of 1.6 m² (SunPower Co., 2016). Further device features are illustrated in Table 14.

Table 14 Device features of SunPower SPR-X21-255 (SunPower Co., 2016)

Device	SunPower SPR-X21-255
Cell type	Mono cristalline
Cells per module	72
Weight	21.2 kg
Maximum power in standard test conditions	255 Wp
Maximum power at 800 W/m²	210.6 Wp
Normal operating cell temperature (NOCT)	41.5°C
Operating temperature	-40°C to 85°C
Module efficiency	21.10%
performance degression	< 0.7% p.a.

Considering Equation (8) from Subsection 2.3, the power output for one solar panel can be calculated. The necessary parameter for average GHI are taken from Table 13. Equation (8) needs to be modified in view of the fact that GHI is given for daily averages for each month. The modified equation can be seen in Equation (36): (Patel, 2005)

$$P_{out} = A_e E_e G_d S_d / 1000 \quad (36)$$

, where P_{out} is the power output in kW per day, A_e is the total surface area of solar cells in square meters, E_e is the mean power conversion efficiency, G_d is the daily average global horizontal irradiation in Wh per square meter, and S_d is the average amount of daylight hours for each month.

The average monthly daylight hours for Gosnold, MA are obtained from the Astronomical Applications Department of the U.S. Naval Observatory (U.S. Naval Observatory, 2011). The calculation of the energy yield in MWh is simply the power output times the days per month divided by 1000.

Table 15 Extractable solar power, project outline and energy cost

Solar Resources	Demand		Supply				Project outline			Cost		
Month	Peak loads (kW)	Energy usage (MWh)	Daily avg. GHI (Wh/m ²)	Daylight per day	Power output (kW)	Energy yield (MWh)	usage-yield ratio	load-output ratio	Required devices	CAPEX (Mio \$)	OPEX (Mio \$)	COE (\$/kWh)
January	97.41	49.61	179.7	9.6	0.58	0.02	2757	168	3198	1.12	1.25	0.16
February	85.62	39.74	155.0	10.6	0.56	0.02	2305	154	2674	0.93	1.05	0.13
March	85.33	39.34	276.6	12.0	1.12	0.03	1134	76	1316	0.46	0.52	0.07
April	68.56	30.65	276.7	13.4	1.25	0.04	792	55	919	0.32	0.36	0.05
May	128.80	33.58	314.2	14.5	1.54	0.05	703	84	815	0.28	0.32	0.04
June	120.69	56.08	264.5	15.1	1.35	0.04	1341	89	1555	0.54	0.61	0.08
July	164.38	98.22	353.8	14.8	1.77	0.05	1792	93	2079	0.73	0.82	0.10
August	178.75	86.98	373.1	13.8	1.73	0.05	1620	103	1879	0.66	0.74	0.09
September	163.55	50.16	334.0	12.4	1.40	0.04	1155	117	1339	0.47	0.53	0.07
October	77.93	34.97	210.3	11.1	0.78	0.02	1438	99	1668	0.58	0.65	0.08
November	66.75	35.22	193.2	9.9	0.64	0.02	1768	104	2051	0.72	0.80	0.10
December	63.12	39.31	167.9	9.2	0.52	0.02	2424	121	2811	0.98	1.10	0.14

As explained, the extractable power for each month results from multiplying each device area of 1.6 m^2 times its efficiency of 21.1 %, times the daily average GHI in Wh/m^2 , times the average daylight hours for each month. Table 15 shows that the energy usage divided by the energy yield gives higher values than the ratio of peak loads over power output. The reason for this is the temporal fluctuation of solar irradiation during the day. In the afternoon hours, irradiation is the highest, when peak loads occur. However, demand continues during the night, when no radiation is available. Therefore, necessary panels are contingent upon total energy consumption. In order to account for the performance degression of the modules, the ratios of energy consumption need to be multiplied times the accumulated performance degression over its lifetime, because the capacity of the panels is decreasing over time. For a yearly performance degression of 0.7 % over a 25-year lifetime, the accumulated factor is 16.0 %. SunPower gives a warranty of 90% performance for 10 years and 80 % for 25 years (SunPower Co., 2016). Nevertheless, the calculated value of 84 % will be taken for the calculations, as it has been computed. It can be seen that the usage-yield ratio for January is 2757, which amounts to 3198 required panels, if multiplied times the accumulated factor of the performance regression. These 3198 panels have a capacity of 815.5 kW.

Beside device, further components need to be added to the system. Hardware components for commercial projects account for approximately 60 % of overall costs. Hardware costs consist of rack systems, system balancing hardware and inverter. Chunk *et al.* (2015) estimated US average hardware cost for commercial use. It was estimated that hardware costs add up to \$1.25/W. Subtracting module cost of \$1.00/W, rack costs, system balancing hardware and inverter amount \$0.25/W. These additional costs need

to be added to the CAPEX of the system (Chunk, Davidson, Fu, Ardani, & Margolis, 2015).

COE in Table 15 are based on device cost, additional hardware cost and O&M cost divided by projected energy demand of the lifetime of 25 years. It can be seen that January requires the most panels for electricity generation. Therefore, the calculated key figures for January represent the cost for a system that is completely based on renewable energy. This 100 % PV based electricity generation system would have device costs of \$0.91M, as unit costs are \$285 per panel. The Electric Power Research Institute cites the range of O&M cost from 1-5 % in relation to investment cost (EPRI, 2010). Utility scale projects have O&M costs in the upper range in comparison to resident scale projects. In addition, a surcharge from the additional maintenance for removal of snow needs to be considered. Therefore, O&M costs are assumed to be 4.5% of initial investment cost on a yearly base. The resulting COE is \$0.16/kWh for a system that is completely operated by solar PV without storage systems. As the system will be a community based project, performance indicators like ROI respectively IRR are not considered. The NPC in combination with the COE are decisive to assess the performance of the project. The NPC however, corresponds to the NPV of a project with an opposite sign. Nevertheless, it is not possible to determine the ROI for a community based project on the NPC, as the IRR will be zero.

In order to validate the results, the System Advisor Model (SAM) is used. This model can verify the manual computations based on the same type of calculations that have been performed. The model results can be seen in Table 16 and in Figure 63

Table 16 Summary of model validation by SAM

Metric	Value
Annual energy production	953.452 kWh
Capacity factor	13.40%
Energy yield	1,170 kWh/kW
COE	16.66 cents/kWh
NPC	\$1,822.756

Table 16 shows both, performance measures and financial key figures. The COE that SAM computes are 16.66 cents/kWh, which is close to the 16 cents/kWh that were computed manually. Net present costs are \$1.82M. The NPC that consist of CAPEX and OPEX that was computed manually is \$2.37M, which indicates that SAM uses lower O&M values over the lifetime of 25 years, as hardware costs are exactly the same.

The PV system with a capacity of 815.5 kW would produce 953,452 kWh annually, which meets the load requirements for a year, as the total electricity consumed is around 600,000 kWh. Besides of annually demand-output performance, Figure 63 shows that the system meets monthly loads too.

Figure 63 Comparison of electric load and system output in kWh

The validation shows that the system meets the requirements of the electricity generation for every month. However, it can also be seen that differences in the ratio of output and electricity load occurs, which illustrates the oversizing of the system. This could be encountered by adding storage systems to the system. Nevertheless, the validation has shown that the calculations performed manually are trustworthy for the initial assessment of the resource. Based on that, it can be concluded that solar is a suitable resource.

4.1.4 Summary of resource assessments

Even though, it is not possible that temporary demand in terms of daily, hourly and minutely loads can be met by any of the considered technologies, it is possible to generate enough electricity for the monthly respectively annually demand. The single resource assessments have shown that wind and solar have sufficient available power to generate electricity for the monthly energy needs. Waves power has its highest appearance in winter and correlates with winds. Solar however, has the highest power density in summer. The two power sources that are usable for Cuttyhunk are wind and solar, as their available power is sufficient to meet the demand of the island. The assessment of the wave climate has shown that available wave power is not sufficient for the generation of year-round electricity, because there is a sharp decline of wave height and period in summer, which makes year-round electricity generation not feasible.

However, high overcapacities have to be provided in order to ensure reliability, which itself causes high investment and O&M costs. Solar PV has the lowest costs of the considered resources in terms of investment and O&M. Low costs of solar PV are attributable to both, advancements in technology as well as overlapping of available

power and electric load of Cuttyhunk. Occurrence of available power is the more important aspect, because the available power curve of solar is most adaptable to the electricity load curve and does not create inefficiencies due to oversized capacities. Broadly speaking, solar can meet the high demand in summer because solar power is highest during this season. Additionally, wind can meet the high demand in winter because the occurrence of available wind power is highest during this season. Considering this aspect, the combination of solar and wind technology might represent a viable part of the island's system.

Table 17 shows the summary of the computed key figures of the resources, and shows that solar is favorable for each parameter, with the lowest COE of \$0.26/kWh. However, the computed COE do not represent a reliable measure, because they do not consider the fact that electricity supply is not feasible from a practical point of view, and beyond that they do not include the TVM. The computations should be understood as an indicator that gives some evidence of its importance for an integrated renewable energy system. Therefore, it is indicated as simplified.

Table 17 Summary of resource assessments

Resource	Common Device	Nominal power	Device cost	Required Devices	Device cost	O&M cost	Total cost	Simplified COE
Waves	Oyster 1	1 MW	\$4,070,000	11	\$9.77M	\$3.13M	\$12.90M	\$0.86/kWh
Wind	Xant M-21	100 kW	\$350,000	10	\$3.15M	\$1.02M	\$4.17M	\$0.35/kWh
Solar	SW 270	250 Wp	\$285	3198	\$1.12M	\$1.25M	\$2.37M	\$0.16/kWh

In summary, it can be said that it is possible to supply the island with only one resource technology in theory for annual and monthly electricity demand. In practice, this is not feasible, as daily, hourly and minutely demand and generation do not overlap.

It is generally not possible for off-grid system to meet the temporal fluctuation of electric loads if no energy storages or backup systems are considered. This is because of the natural fluctuation of renewable energy sources, which make the electricity production unpredictable in the short-term. Such a system would cause instability in the voltage, and finally result in power outages. Therefore, it is necessary to include a battery storage to the system. This shows that the only conceivable approach to deal with these issues are battery storages and the combination of several resources towards an integrated renewable energy system. Before doing so in the economic analysis, the technical feasibility is the subsequent step that has to be taken in mind.

4.2 Technical and environmental considerations

The technical evaluation of renewable energy technology has the purpose to identify aspects that have an effects on either the technology or on the environment in that they work. Figure 64 illustrates the complexity of technical and environmental aspects. The general idea is to detect issues of the interaction of technology and environment.

Figure 64 Technical and environmental considerations for waves, wind and solar (EMEC, 2009; Overseas Private Investment , 2012; Dai, Bergot, Liang, Xiang, & Huang, 2015)

EMEC (2009), Dai *et al.* (2015) and OPIC (2012) have shown that the considerations for projects based on waves, wind and solar have a broad spectrum of aspects that have to be considered (EMEC, 2009; Overseas Private Investment , 2012; Dai, Bergot, Liang, Xiang, & Huang, 2015). However, it needs to be clarified whether the technology has effects on the environmental or the environment effects the technology.

4.2.1 Wave technology

In order to assess the possible effects, which WECs could have on the local marine environment, research on both the short and long-term effects must be weighed. Any object placed into the ocean is likely to affect the environment in some way or another. Devices that rest on the bottom can damage reefs or could have significant impacts on marine species. This aspect applies at the selected location of the WEC, because the change in bathymetry at Location 5 is caused by towering rocks that have been populated by fish (Garfield, W., 2016). It is likely that a purpose to place a WEC at Location 5 would evoke protests in the community due to its destructive installation process to the site. Therefore, locations in open water with very little shelter respectively no reefs or rocks are more suitable for the installation of the device.

WECs cause noise that may scare away fish or marine mammals (Richardson, W. J.; Green, C. R.; Malme, C. I.; Thomson, D. H., 1998). However, it is not possible to assess how much noise a OWSC emits, because there are no comparative performance figures published by Aquamarine Power. In addition, research does not have an overall answer regarding consequences of loudness from operations of WEC. Although little research has been done on WECs, some studies were done for offshore wind energy that show environmental impacts of wind turbines. An assessment at the Block Island Wind Farm determined that the greatest negative effect on marine species occurs while piles are driven into the seafloor (Gill & Thomsen, 2010). It is relatively certain that construction noises have an effect on marine mammals, but operation and maintenance effects are not investigated precisely (Greaves, et al., 2016).

The majority of marine species at Cuttyhunk Island are small fish and crustaceans. These marine species are likely to disappear during the installation of any system. However, in the long-run foundations and the structure could house algae and plants that small fish will feed from (Dempster, 2005). This “reef effect” is likely to attract more species over time, and could result in a larger population of more diverse species (Gill & Thomsen, 2010).

Ocean energy systems are designed with the purpose of absorbing wave energy, which makes them an obstacle in the water that can alter coastal currents. In terms of the installation of a WEC at a flat beach that normally experiences uniform waves perpendicularly towards the shore, there will be no significant longshore current, and the water pushed ashore must escape through rip currents or an undertow effect (Mangor, et al., 2008). However, if wave energy is absorbed, the area behind the WEC will be shadowed, resulting in varied wave heights along the shore. This decrease in energy can cause tidal currents to alter its course. Hence, wave energy absorption could completely change the currents at the shore, which could result beach erosion. In conclusion, large-scale installations could have an effect on coastal sediment transport (Mendoza, et al., 2014).

Nevertheless, the described effects of WEC occur at flat beaches with perpendicular waves, which Cuttyhunk does not have. Therefore, the impact of the WEC is assumed to be beneficial due to its shielding of incoming waves. The shielding effect results from the extraction of energy near to the coastline, which has the effect that wave heights decrease. The consequence of reduced wave heights in most cases is that erosion

decreases (Frid, et al., 2012). Further research is necessary in terms of erosive effects of OWSC to compare device effects to local conditions of Cuttyhunk.

Depending on type of WEC, there are risks concerning collision, displacement and electromagnetic fields for marine mammals (Greaves, et al., 2016). At this moment, research regarding collision and displacement has a high level of uncertainty. It is not clear whether these risks have an actual effect on marine mammals or whether they are more hypothetical. However, this is scarcely to be expected for OWSC, because the water is shallow. In addition, concerns regarding electromagnetic fields from underwater power cables have been overcome (Bull & Nishimoto, 2016).

The conceivable location for WECs would be south of Buzzards Bay in shallow water areas. This means WECs locations would be in necessary distance to shipping lanes. Figure 65 illustrates that the two shipping lanes outside of Rhode Island waters go either directly north and south from Newport to the Rhode Island Sound, or north of the light that is close to Cuttyhunk into Buzzards Bay. Systems placed south of the light will be out of any shipping lanes in general, and there is very little risk of collision with vessels.

Figure 65 Shipping lanes at the Rhode Island Sound (Malek, LaFrance, Collie, & King, 2010)

In summary it can be said that WECs are conceivable from a technical and environmental point of view. Even though, they have a destructive installation process and affect the site accordingly, they offer positive aspects in the long run. The “reef effect” could attract species and be a habitat for larger populations. There are no concerns regarding electromagnetic fields from underwater power cables and shipping lanes do not cross the location, wherefore no risk of collision with vessels exists.

Nevertheless, it is unclear if the installation of the OWSC results in erosion or whether the system has a positive effect on the shoreline due to shielding. Likewise, operational effects are not investigated precisely. It can be seen that technology in the ocean has to consider several aspects, wherefore current projects like the Streamlining

of Ocean Wave Farms Impact Assessment tries to answer these issues, which will allow to draw conclusions in the near future. The development of these guidance documents for the assessment of environmental impacts will be a standardized base to determine the effects of ocean energy projects (Kempener & Neumann, 2014).

4.2.2 Wind technology

The technical considerations for wind turbines on a macro scale pertain the protection of air traffic control and electromagnetic interference (O'Reilly, 2013). However, the siting of the turbines has to be analyzed on micro scale as well in order to determine effects of the flicker, and noise pollution the access for vehicles during construction. From an environmental point of view, wind technology pertains the effects on birds and bats (Spaulding, et al., 2010b).

A topographic map of Cuttyhunk shown in Figure 66 illustrates the highest elevation in the northern part of Cuttyhunk, where the community water tank is located at an elevation of 47 m above MSL. The location close to the water tank represents the most suitable location for the installation of a wind turbine, because the highest elevation is supposed to undergo the highest unobstructed wind speeds.

A wind turbine at the highest elevation of Cuttyhunk could interfere with airways and also with instrument landing systems (Spaulding, et al., 2010a). Cuttyhunk has a small private air strip for small aircrafts in the north-east of the island. However, flight paths are approaching the island from the east on the peninsular-like part of the island. Additionally, aviation safety requirements must be considered in terms of light signals on top of the turbine, which is possible for the M-21.

Figure 66 Topographic map of Cuttyhunk Island and proposed location of the wind turbine market by a red dot (mytopo, 2016)

The disruption of data transmission from radar and communication systems has been a struggle in the past because the blades can reflect these signals. This must be taken into account for Cuttyhunk. However, the wind turbine site would be located south of the town and would therefore not interrupt radar or communication coming from mainland (Department for Communities and Local Government, 2013).

The aspect of shadow flicker is a recognized issue of wind turbines. The effect occurs when the moving shadow from the blade flicks on and off in nearby properties. However, it can be avoided, when certain specified limits in distance are observed (Arnett, Schirmacher, Huso, & Hayes, 2010). The installation of a wind turbine at this location in the 1970s, which will be explained in more detail in the market analysis in Subsection 4.4.1, suggests that shadow flicker does not occur as it has been a concern during construction (Rose, 1979). A wind turbine at the selected site is not close to the town as it is approximately 250 m away from the first houses. The Rhode Island Land-

Based Wind Siting Guidelines⁴ recommend a setback distance to private property of 1.5 times the total turbine height (OER, 2016). The hub height of the M-21 is 31.8 m with a 21.0 m rotor diameter. The total height is 42.3 m. The setback distance for the M-21 is 63.45 m.

Therefore, shadow flicker is not considered as a limitation for wind turbines on Cuttyhunk. A more detailed analysis would be done by performing the guidelines proposed by the Renewable Energy Siting Partnership (RESP). RESP has contributed to the determination of wind turbine siting on land. However, RESP is not applicable for Massachusetts, wherefore it has to be waited for the release of the wind farm siting guidelines to determine legal requirements (Payne, Grilli, Spaulding, Damon, & O'Reilley, 2012). In general, if the Massachusetts wind siting guidelines orientate at RESP, required siting distance for wind turbines on Cuttyhunk would be established when turbines are placed in the south of the water tank, due to its approximate distance of 150 m from the nearest building.

In years past, people living close to wind energy plants raised complains about loudness and vibration. The source of the sound is the mechanical and aero-dynamical movement of the rotation of the turbine blades. However, current developments considered these design factors and are less noisy than older generations. For example, minimized imperfections and sound absorbing materials reduce emitted noises (Knopper, L.D.; Ollson, C.A., 2011). This aspect has also been considered in choosing the device,

⁴ Rhode Island Guidelines are used to determine setback standards, because there are no wind turbine siting guidelines for Massachusetts yet that incorporate current jurisdiction of the two sister bills HB 2980 and SB 1591, which are supposed to streamline the siting and permitting process for land-based wind projects at state and local level

because the blades of the M-21 have an aero elastically geometry with a swept-back tip that reduces loudness that is in addition more resistant in harsh environments (Xant, 2016). A sound power assessment for the M-21 has been performed in 2014. The loudness for wind speeds from 6-11 m/s can be seen in Figure 67 for different distances from the wind turbine.

XANT M-21		6 m/s	7 m/s	8 m/s	9 m/s	10 m/s	11 m/s
LwA in dB(A)		91,6	93,7	95,7	97,2	97,8	98,1
LpA in dB(A) at a fixed distance based on spherical spreading	30 m	51,0	53,2	55,1	56,6	57,3	57,5
	40 m	48,5	50,7	52,6	54,1	54,8	55,0
	50 m	46,6	48,7	50,7	52,2	52,9	53,1
	60 m	45,0	47,2	49,1	50,6	51,3	51,5
	70 m	43,7	45,8	47,8	49,3	49,9	50,2
	80 m	42,5	44,7	46,6	48,1	48,8	49,0
	90 m	41,5	43,6	45,6	47,1	47,7	48,0
	100 m	40,6	42,7	44,7	46,2	46,8	47,1
	110 m	39,8	41,9	43,8	45,3	46,0	46,3
	120 m	39,0	41,1	43,1	44,6	45,2	45,5
	130 m	38,3	40,4	42,4	43,9	44,6	44,8
	140 m	37,7	39,8	41,8	43,2	43,9	44,2
	150 m	37,1	39,2	41,2	42,6	43,3	43,6
	160 m	36,5	38,6	40,6	42,1	42,7	43,0
	170 m	36,0	38,1	40,1	41,5	42,2	42,5
	180 m	35,5	37,6	39,6	41,1	41,7	42,0
	190 m	35,0	37,1	39,1	40,6	41,3	41,5
	200 m	34,6	36,7	38,7	40,1	40,8	41,1
	210 m	34,1	36,3	38,2	39,7	40,4	40,6
	220 m	33,7	35,9	37,8	39,3	40,0	40,2
	230 m	33,4	35,5	37,4	38,9	39,6	39,8
	240 m	33,0	35,1	37,1	38,6	39,2	39,5
	250 m	32,6	34,8	36,7	38,2	38,9	39,1

Figure 67 Emission noise level calculated from the apparent sound power levels reported for different rotational speeds and wind speeds (De Bondt & De Fonseca, 2014)

The turbine has been measured according to international standards, which shows that noise level stays under 40 dB for a distance of 250 m, even though the turbine is working under full duty at a wind speed of 11 m/s (IEC, 2012). At days with bad prevailing wind directions, a whisper mode can be turned on in order to reduce loudness of the turbine. Referring to Moorhouse *et al.* (2005), the low frequency hearing threshold level is approximately 38 dB depending on the frequency (Moorhouse, Waddington, & Adams, 2005). This suggests that the M-21 wind turbine is almost not audible for the

residents of the closest property. At this global level of assessment, the noise emissions are assumed to be acceptable. Nevertheless, Rogers *et al.* (2006) proposed regulations and siting practices of utility-scale wind turbines within residential areas, which should be investigated in detail in further analysis (Rogers, Manwell, & Wright, 2006).

Wind energy deals also with land use, and wind turbines have an average direct impact area of about 0.3 hectares/MW of power output capacity according to NREL (2009). Depending on the site, this number can increase up to 1.5 hectares/MW of power output capacity. The determining factor is the topography. The higher and hillier the terrain, the less land do the facilities need. The land use would be 300 m² for one wind turbine of 100 kW in capacity (Denholm, Hand, Jackson, & Ong, 2009).

Environmental considerations concern the death of birds and bats in particular. The National Wind Coordinating Committee has found that the death of birds and the existence of wind plants correlate. The reason for this are air pressure differences and the movement of the spinning blades. The magnitude of bird death can be considered small. Even though there are no great populations of bats on Cuttyhunk, they have to be considered. Bat death can be reduced by keeping wind turbines dormant during low wind speeds due to the fact that bats are more active at low wind speeds. (Arnett, Schirmacher, Huso, & Hayes, 2010).

In consequence, the turbine does not produce energy during this time. However, considering the fact that the power generation level decreases conspicuously with low wind, the losses are justifiable. Furthermore, the M-21 from Xant has proven that there are low to approximately non negative effects on birds and bats, as well as no significant negative effects on habitat use (SWECO, 2016).

In summary it can be said that wind turbines are conceivable from a technical and environmental point of view. It is true that air traffic control can be affected by wind turbines and that electromagnetic interferences can disrupt data transmission from radar, but the selected location and the chosen device are not affecting any of these aspects negatively. According to international directives and guidelines, flicker and noise emission can be neglected as the device is certified and located with sufficient distance to the nearest residential property. Land use is considered with approximately 300 m² for one wind turbine. Significant effects on birds and bats are not expected to occur.

4.2.3 Solar technology

Solar arrays need direct sunlight unobstructed by shades from buildings or trees to work reliable. Therefore, a site needs to be chosen in order to measure the impacts of shading. In accordance with local utility company concerning the development purposes of a solar array on the island, the site is selected to be on a steep slope at the south side of Cuttyhunk. Cuttyhunk Electric Light Department, the local municipal utility company, detected this location as a potential site. The location of the proposed site for the solar array is located close to Quahoag Road and illustrated in Figure 69. A panorama view is shown in Figure 69.

Figure 68 Location of the proposed solar array (Lance, 2007)

Figure 69 and panorama view from the top of the proposed solar site (Lance, 2007)

The area of approximately 10,500 m² (2.6 acres) is not visible from the dirt road at the bottom of the hillside and not accessible for public. The dimensions of the site are approximately 570 ft times 160 ft. Figure 69 shows that the site is cleared, which supports the conjecture that shading does not play a big role. Nevertheless, a shading analysis clarifies the amount of radiation losses due to the surrounding. The shading analysis is done by means of a Solar Pathfinder. This device is installed at three chosen spots that spots are located on the middle of the field. The first measurement is done on the

eastern side, the second one is done at the center of the side and the third measurement is done at the western side. The test locations can be seen in Figure 70.

Figure 70 Test locations for the shading analysis of the Solar pathfinder (Elias, 2016)

The functionality of the Solar Pathfinder allows to do only one tracing for the permanent record of solar data. First, the base is set on a tripod in a reasonably leveled position. The instrument section of the unit is then placed on the base. It is then rotated until the magnetic compass is pointing north. The sun path diagram can also be rotated separately to adjust for magnetic declination in order the diagram is facing true south. The bubble level located in the center of the unit is then used to establish a leveled position by balancing the instrument section out on its base. Finally, the reflective dome is placed on the top of the unit (Solar Pathfinder, 2016). The leveled Solar Pathfinder and the installation process can be seen in Figure 71 and Figure 72.

The shading analysis is done by looking at two things at the same time. A panoramic view of the site reflected on the dome and the sun path diagram seen through the dome. Objects reflected on the dome are shown on the sun path arcs on the diagram. Shading occurs at the site during the time and month and time indicated by the diagram.

By tracing an outline of the object reflected on the dome directly on the sun path diagram, a permanent record of the potential radiation can be made by only one measurement. To find the percentage of the radiation for each month, the numbers in the unshaded part of each sun path arc need to be summed up. This number gives the obstruction of the site. It allows to find the optimal location for the solar array (Solar Pathfinder, 2016).

Figure 71 Levelized Solar Pathfinder at Location 2

Figure 72 Solar Pathfinder Installation process at Location 1

The essential part of the Solar Pathfinder is the sun path diagram. The vertical lines on the diagram show the daily time. The concentric arcs show the sun's average path for each month of the year. The numbers between each arc indicate the percentage of solar radiation in half-hour increments. These numbers add up to 100 % for each month. The diagrams are latitude specific and need to be chosen to the site location. This is because the closer the location is to the equator, the more the sun's path is overhead. Therefore, the further away the location is from the equator, the more the sun's path is down on the horizon (Solar Pathfinder, 2016).

The contour of the shading on the diagram states that shadowing reduces the amount of radiation at the site. The contour of the obstacles has been drawn on the single diagrams. Figure 73 shows the measurement for the eastern investigation of location 1.

Figure 73 Sun path at location 1 of the proposed solar site

The other two measurements are shown in Appendix A and Appendix B. Each sun path is evaluated, which is shown in detail in Appendix C. The evaluation showed that shadowing only occurs in the winter month, when the sun is low on the horizon. The reduction of solar radiation occurs from October to March and stays between 1-7 % depending on month. The effects on available energy due to shadowing of the site for the single month is summarized in the following Table 18.

Table 18 Efficiency due to shadowing at the proposed solar site

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Summary
	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
Location 1	93	96	99	100	100	100	100	100	100	98	96	93	97.92
Location 2	93	99	100	100	100	100	100	100	100	98	96	95	98.42
Location 3	95	97	99	100	100	100	100	100	100	98	93	93	97.92
Average	-	-	-	-	-	-	-	-	-	-	-	-	98.08

Keeping in mind that highest solar radiation occurs in summer, the suitability of the site is given. The only shadowing comes from trees in eastern and western periphery. However, the influence is expected to be low, because trees lose their leaves in fall.

Conceivable environmental impacts related to solar are land use and habitat loss in general, as well as water use for the cooling systems of the panels. Land use and habitat loss can be mitigated by choosing a different type of system, because PV systems can also be deployed on roofs, wherefore they would not require any additional land. Large-scale PV systems however need to be mounted on the ground. In terms of the selected device, it is indisputable that land is drawn. In the view of the fact that the species on Cuttyhunk are either birds or rodents, and that these animals are not critically endangered, the usage of land is justifiable. Water use is only a concern in terms of cooling systems. However, it has been determined that no cooling systems are needed. Therefore, no additional water is need for the generation of electricity (Union of Concerned Scientists, 2015).

In summary it can be said that photovoltaic is conceivable from a technical and environmental point of view. As it can be seen there are no major shadowing impacts on the solar arrays. Accessibility is provided due to road access by the dirt road at the south of the hill. Visual and safety requirements are fulfilled because the area is not open to public and not visible from the road or the beach. The aspect of land use is reasonable in view of the fact that no endangered species live on Cuttyhunk. For this reason, habitat losses are no concern. A facility for load management and grid connection can be installed at the site. There are only general aspects in terms of module disposal at the end of their lifetime, fire and shock hazards that need to be considered.

4.3 Economic analysis

The economic analysis is the decisive investigation in the process of a feasibility study, because it determines whether the investigated resources and technologies are actually realizable in a system. Furthermore, the optimal setup of the system is investigated and different variants are compared, which are evaluated thereafter. The process of the economic analysis that is performed, is shown in Figure 74. It should be noted that after the most feasible variant has been selected, a review of the input data has to be done in order to double-check the system's basis.

Figure 74 Procedure of the economic analysis

As seen in the resource assessment wind and wave energies have their peaks occurrence in the winter months. Solar energy however, has its highest radiation in the summer months and is relatively stable during the year. Main electric loads happen in the summer month. Therefore, solar fits this load curve best and could be a fundamental

part of the system. However, it is a resource that is in average just half of the day available and has its weaknesses in power supply in the winter. Therefore, storage systems and a second energy source need to be added for reliability. As resource and technical assessment have shown, waves are currently not a feasible part of an integrated renewable energy system. Therefore, wind is chosen as an additional component.

Consequently, the system components that will be incorporate in the modeling approach in HOMER, are wind and solar combined with a storage system and a backup. The existing generators are not considered as a backup as they would need a comprehensive refurbishment. New generators with better exhaust values will be considered.

HOMER, which stands for Hybrid Optimization Model for Electric Renewables, is one of the most used micro-grid optimization models in the industry. Cost information are essential for the economic analysis of HOMER, but in early stages of feasibility analyses detailed information are usually not available. HOMER provides default values for typical prices that are only used in case there is no information. The program needs the electrical load profile as well as the resource data as an input Thereafter the system can be modeled subsequently by selecting AC and DC components to the consumer load.

These components are generators (Gen100) and wind turbines (M-21) on the AC side, and a PV-system (PV) and battery storage (Li-Ion) on the DC side. The electric load represents the consumer behavior in between both currents. The converter ensures that both currents can be connected. The components can be seen in Figure 75

Figure 75 System components and current stream

Gen100 represents a generic generator with a capacity of 100 kW. CAPEX is assumed to be \$650/kW, OPEX is supposed to cost \$0.035/h, and lifetime in hours is expected to be 15,000 h (VGB, 2011). Converter initial and replacement costs are input with the default of \$300/kW, because converters are not the decisive aspect in the modeling process. The CAPEX for a M-21 is \$350,000, OPEX is \$3,800/year. Replacement costs are estimated to be somewhat lower due to technology advancements. They are assumed to be \$250,000 after 20 years of project lifetime.

The PV array is selected as a generic system that is scalable in size. The panel selected is the SunPower SPR-X21-255 with hardware costs of \$1,117.65/kW, replacement costs of \$800/kW as they will be lower, and O&M of \$10/kW/year (SunPower Co., 2016). The lifetime of the array is 25 years. A derating factor of 0.84 is used for the assessment, as it was derived in Subsection 4.1.3. The derating factor is the result from multiplying factors that account for total efficiency. 5 % Losses from module heating result in 95 % heating efficiency. Inverter efficiency is 95 %, AC and DC wiring has a 97 % efficiency and module production tolerance is 98 % (Enphase Energy, 2014). The shade factor is 98 %, as it has been computed in Table 18. Furthermore, ground

reflectance is considered with up to 30 % and the panels are supposed to have a horizontal tracking system that gets adjusted monthly.

Lithium-ion batteries are chosen for the system due to their advantages for the regulation of peak loads. Lithium-ion batteries are available in 1 kWh-units, which makes the optimization of system size possible in incremental steps of 1 kWh. Costs derivations for battery storages are available for different scaled projects in terms of LCOS. Zakeri & Syri (2015) have given key figures for different technologies (Zakeri & Syri, 2015). The LCOS for this lithium-ion batteries are stated with 463€/kW respectively \$515.25/kW. The average O&M costs are \$10/kWh per year. These values are selected for the analysis. Replacement costs are assumed to be \$350/kW after 15 years of the batteries' expected lifetime.

As it was described in Section 3, the program chooses whether to charge or discharge the batteries and how to operate the single components. As a result, the NPC of all thinkable system variants are computed. The NPC represents the LCC. In addition to LCC, HOMER sorts feasible systems by energy flows, annual costs, LCOE, and performance.

The economic key figures that need to be set are the discount rate, expected inflation, project lifetime, system fixed O&M cost and capacity shortage penalty. The values are applicable for the assessment except for shortage penalties. Capacity shortage penalties are not appropriate because there is no need for a cap on the market clearing price. The clearing price is an equilibrium price at which quantity supplied is equal to quantity demanded.

Due to the mix of energy sources, project lifetime is expected to be 25 years, with and inflation rate of 2.0 % on average. Fixed administration costs and O&M costs are estimated to be \$40,000 respectively \$10,000/year for small scale projects (NREL, 2016).

The committee on climate change (CCC) researched the investment conditions for renewable energy projects in 2011 (CCC, 2011). The CCC found that different renewable energy sources have different discount rates due to their risk perception ranging. In 2011, they stated solar PV had low risks and a required discount rate of 7-9 %. Onshore wind energy and fixed wave technologies had medium risk perception and a required discount rate between 10-14 %. Since the investing environment has changed during 2011 and there is currently a low-yield environment, the discount rate is assumed to be 7 % for the project in terms of a private investment.

However, an article published by McKinsey suggested that high discount rates are used generally to encounter uncertain outcomes (McKinsey&Company, 2016). However, as the technology becomes more mature, risk premium decreases. Therefore, the discount rate needs to be determined accurately. This is done by modifying Equation (11) from Section 2.5 based on the Green X model developed by Cleijne and Ruijgrok (2004). The modification needs to be done, because the cost structure of Cuttyhunk Electric Light Department is not known. The equation looks as follows: (Cleijne & Ruijgrok, 2002)

$$WACC = a ROE + (1 - a) (1 - T) r \quad (37)$$

, where $WACC$ stands for the discount rate, a stands for the equity stake of the investment, ROE stands for the required return on equity, r is the interest rate, and T is the relevant tax rate.

The required return can be computed using the Capital Asset Pricing Model (CAPM). The ROE of the CAPM is explained in the following equation: (Ross, Westerfield, & Jordan, 2010)

$$ROE = r_f + \beta_a (r_m - r_f) \quad (38)$$

, where r_f is the risk free rate, r_m is the market return and β_a is the Beta of the security respectively the risk measure.

As Bollinger and Wiser (20) state, market risk for renewable energy projects is 5.0 %. Therefore, risk premium has to be 3.1 %, as the risk free rate for bonds with 20-30 years to maturity levels currently at 1.9 % (U.S. Department of the Treasury, 2016). The industry average Beta is 1.62 (NYU, 2016). Plugged into the equation, this results in a required ROE of 6.922 %.

The interest rate of 2.2 % is chosen as the World Bank states this percentage for the US for 2015 (World Bank Group, 2015). A tax rate of 34 % is selected as Cuttyhunk Electric Light Department does not have taxable income above \$10M. Assuming a percentage of equity of 50 % as a base case, the discount rate results in 4.187 %. The results of the system optimization computations can be seen in Table 19.

Table 19 Economic and performance parameters for investigated systems

Architecture				Cost				System
PV (kW)	M-21	Gen100 (kW)	Li-Ion	COE (\$)	NPC (\$)	Operating cost (\$)	Initial capital (\$)	Ren Frac (%)
235	1	100	533	\$0.259	\$2.54M	\$79,203	\$1.02M	79
	2	200	660	\$0.318	\$3.13M	\$99,101	\$1.23M	74
413		100	1,018	\$0.327	\$3.22M	\$109,189	\$1.12M	68
357	2	200		\$0.509	\$5.01M	\$193,132	\$1.30M	50
572		200		\$0.558	\$5.49M	\$241,677	\$849,980	30
	3	200		\$0.569	\$5.59M	\$228,386	\$1.21M	40
		200	208	\$0.601	\$5.92M	\$292,020	\$310,922	0.0
1,681			3,892	\$0.662	\$6.51M	\$131,912	\$3.98M	100
		200		\$0.689	\$6.78M	\$344,680	\$160,000	0.0
1,652	1		3,849	\$0.703	\$6.92M	\$137,943	\$4.27M	100
	13		3,459	\$1.07	\$10.5M	\$205,627	\$6.55M	100

The results show that the implementation of renewable energies are favorable for six different system setups compared to a new diesel generator system. The systems that are theoretically conceivable are:

1. PV-Wind-Diesel-Storage (PWDS)
2. Wind-Diesel-Storage (WDS)
3. PV-Diesel-Storage (PDS)
4. PV-Wind-Diesel (PWD)
5. PV-Diesel (PD)
6. Wind-Diesel (WD)

The electricity price for a new diesel generator system would be \$0.601/kW. The LCOE of most economical variant is \$0.259/kWh. The most economical variant consists of 235kW PV, one 100 kW wind turbine, one 100 kW generator and a 533 kWh capacity of lithium-ion batteries, with a total generating capacity of 435 kW and a renewable fraction of 79 %. The system and NPC of \$2.54M and \$79,203/year operating costs. Included in operating costs are fuel consumption of about 29,986 liters. For a price of

\$1.09/liter the operating costs add up to \$32,684, which accounts for 37 % of total operating costs, while it has a contribution of 14.14 % to the overall electricity generation.

The cost summary is visualized in Figure 76 and summarized in

Figure 76 Costs type summary for net present cost for the optimal economic variant

Component	Capital (\$)	Replacement (\$)	O&M (\$)	Fuel (\$)	Salvage (\$)	Total (\$)
100kW Genset	\$60,000.00	\$44,809.00	\$73,239.00	\$628,889.00	(\$6,472.00)	\$800,465.00
Converter	\$37,269.00	\$27,111.00	\$0.00	\$0.00	(\$7,310.00)	\$57,070.00
Generic 1kWh Li-Ion	\$274,628.00	\$442,238.00	\$102,319.00	\$0.00	(\$167,286.00)	\$651,899.00
Generic flat plate PV	\$262,313.00	\$0.00	\$45,055.00	\$0.00	\$0.00	\$307,368.00
Other	\$40,000.00	\$0.00	\$191,971.00	\$0.00	\$0.00	\$231,971.00
XANT M-21	\$350,000.00	\$0.00	\$145,900.00	\$0.00	\$0.00	\$495,900.00
System	\$1,024,210.00	\$514,158.00	\$558,484.00	\$628,889.00	(\$181,068.00)	\$2,544,673.00

Figure 77 Summary of costs for each component of the optimal economic variant

It shows that initial capital expenses are the major part of the overall costs and account for \$1.02M. O&M accounts for \$0.51M. Taken in mind that fuel costs account for \$0.63M and that they are a part of O&M, the OPEX is the highest stake of overall cost of NPC of \$2.54M. Salvage value of \$0.18M contributes to replacement costs of \$0.51. From an economic perspective, the PWDS is the most suitable variant.

The system evaluation of those systems will be done after the last assessments has been performed. The selection of the adequate system for Cuttyhunk will clarify which of these five systems is most suitable from several perspectives.

4.4 Market considerations

Political forces can potentially dash any project, and is interlinked with socio-economic factors, because political authorities represent the communities' interests. Thus, deliberations concerning the political and socio-economic conditions have to identify threads for successful project implementation. Both factors are driven by public acceptance (Müller, Brown, & Ölz, 2011).

Figure 78 illustrates that the mentioned factors interact with each other for which reason market considerations have to be understood as a total.

Figure 78 Interaction of market factors concerning renewable energy projects

4.4.1 Political influence

In Figure 27 it could be seen that LCOE on Cuttyhunk is a multiple of the average prices in the US, in New England and in Massachusetts. This resulted in a request for federal financial assistance concerning the construction of a renewable energy system by the town. The request has been addressed to the U.S. Rural Utilities Service (RUS), since this agency is in charge for granting financial aid for remote communities. RUS

provides grants for communities that exceed average US energy costs by 275 %. That being the case, a subsidy over \$2.0M. has been granted since the electricity prices on Cuttyhunk exceeds average US electricity costs by 395 % (Garfield, S., 2016; Elias, 2016; EIA, 2015).

A grant can contribute significantly to reduce costs. It led to a positive attitude towards renewable energies in general. This spirit of optimism has been noticeable when the site investigation in the process of this thesis has been conducted. An interview with the major of the island has confirmed this and made clear that politics do not see a different alternative than switching to renewable energies (Blout, 2016). This way of seeing the current challenges by political authorities is a distinct project driver for renewable energy projects. Political influence is especially illustrated by the history of renewable energies on Cuttyhunk. In the 1970s, a project aimed to establish a wind turbine on the island, which is illustrated in Figure 79. This wind turbine had a height of 80 ft and a capacity of 200 kW.

Figure 79 Wind turbine on Cuttyhunk by WTG Energy Systems (Milt Price, 2016)

However, the turbine had been erected before boundary conditions were determined and terms of supply were agreed on. There were no treaties for PPAs or any other economic coverage for the project. Due to this undefined financial terms, a lack of security forced the initiators to dismantle the wind turbine shortly thereafter. This shows strikingly how political intervention can affect renewable energy projects.

4.4.2 Socio-economic considerations

In general, electricity generation from wave, wind and solar has low environmental impact in terms of emission of hazardous substances. This represents a societal benefit over fossil energy generation. At the same time, the fact that renewable energies do not need delivered fuels to operate, deteriorates the business situation for supplying logistics companies. This illustrates that the socio-economic consideration is a tradeoff between both social benefits and drawbacks, as well as economic advantages and disadvantages. Economic disadvantages in terms of diminishing businesses can be turned into opportunities, if employees are retrained for administration respectively O&M. Employments during installation and construction are an additional advantage (IFRI, 2012).

The OWSC considered for Cuttyhunk is designed to rest mainly underwater and should cause just minor visual impacts to the residents. The location of the device could affect local fisheries around Cuttyhunk, as it can be seen in Figure 80. The figure shows local shellfish habitats. The habitats in combination with the location of the device may become an issue, because WEC are obstacles for private and commercial vessels. It is likely that there would be a strict “no fishing” perimeter around the devices, similar to rules enforced during and after the construction of the Block Island wind farm due to safety issues (NOAA, 2016). This would protect both, the devices from sustaining any

damage from fishing equipment and fisherman and their boats from being damaged by the device (Gill & Thomsen, 2010). However, the business of the fisherman may be affected.

Figure 80 Shellfish population in Buzzards bay (Buzzards Bay National Estuary Program, 2008)

The hazardous aspect of WEC for tourism is also important to consider. The coastline is frequented by beach goers in summer, which would be a potential hazard for swimmers and in reverse a threat for tourism industry. However, the location of a WEC device would be one kilometer off the coast of Cuttyhunk. It is doubtful that tourists reach this point.

There is also an ever-present fear that renewable energy devices discourage visitors and tourists from coming. This aspect has been surveyed by the Center for Carbon-free Power Integration at the University of Delaware (Lilley, Firestone, & Kempton, 2010). The study revealed that there are some beachgoers that would avoid beaches with visible devices. However, the opposed effect of people that are attracted to boat tours to

the renewable energy site and of people that want to see beaches with the devices are substantially. Therefore, neither WECs nor wind turbines and solar arrays would disrupt the tourism industry.

However, visual impacts do not only affect tourism. A recent report of the University of Copenhagen has surveyed this case and concluded that wind turbines can drop property values (Jensen, Panduro, Panduro, & Hedemark, 2014). Therefore, wind turbines need to be located out of sight to avoid decreasing real estate values. However, this is not possible for land-based wind turbines for islands. The advantages from wind turbines prevail the drawbacks from possible price drops of closely located real estates, because long-term electricity savings are faced as more important.

Even though there is a lack of research on the socioeconomic impacts of utility-scale solar, it can be said that it has most of its socio-economic impacts in the short term specially during construction. Construction and assembly generate jobs in the starting phase. But there are also O&M and administrative opportunities in the long-run. If local residents are hired, positive effects occur for the local economy. In general, effects of large-scale solar PV are not considered as decisive for microeconomics of a community and public impacts can be considered as minimal (Fernandes, et al., 2010).

Overall, both the social and political impacts should not raise special concerns. The impacts are small in relation to other renewable energy projects. A system such as the PWDS would be mainly out of sight, and would not change the appearance of the landscape in particular manner.

4.4.3 Public acceptance

The assessment of the market also affects the public acceptance of the system.

Conversations and interviews with residents have demonstrated that the curiosity and willingness to contribute are distinctively high among residents. Any system that changes the character of Cuttyhunk to a sustainable role model for the region is greatly appreciated. It is unlikely that residents would disapprove any system or measure for improving the implementation of renewable energies. Such a measure would be a reduction in total demand, because lower demand means smaller sizes of system components and therefore less complexity and less investment cost. It would facilitate implementation of renewable energies. For this reason, consumer behavior in terms of electricity efficiency is important to know.

For this purpose, simplified surveys in the style of energy audits are conducted for two exemplary households. In general, energy audits bring out potential for energy efficiency. It assesses the current energy usage and values improvement measures that could enhance energy efficiency, and normally contain an investigation of several aspects of the house. Those parts are insulation, location of air leakages, heating & cooling system, lighting and appliances & electronics. However, energy needs are in particular caused by appliances & electronics, lighting and an eventual cooling systems. Due to missing cooling systems and no accessibility to appliances in the two surveyed households, electronics and lighting are investigated only. This simplifies the energy audit and does not allow to draw conclusions for overall efficiency measures. However, it characterizes the electric demand and gives indications for optimization.

To cover a broad range, it is aimed to evaluate households with different energy usage behaviors. Two households, named A and B in the following, were available for the survey. Household A had energy usage of 3094 kWh for 2015 and Household B had

energy usage of 777 kWh for 2015. Both consumptions are lower than the computed average, but make sense when considering that the houses are inhabited approximately half of the year. Therefore, consumer A's consumption is above average and consumer B's consumption is below average. House A is an advanced home with a square footage of approximately 1,600 sf. House B is kept basic in its equipment and has an approximate square footage of 1,300 sf.

House A is equipped with 15 electronic devices in the living room and kitchen. In summation, they draw 51.5 W standby power. These phantom loads consume electricity even though the devices are turned off but still plugged in. The 51.5 W account for 451.14 kWh/year respectively \$270/year at an electricity price of \$0.60/kWh. The biggest consumer is the media system. In terms of lighting, almost all lightbulbs have been replaced with light-emitting diodes (LED).

In House B, the fridge has been measured over time to account for its system cycles. For 10 hours, the device has been measured to consume 980 kWh/year respectively \$580/year, which accounts for 63 % of the houses' electricity consumption for the period of 6 months. Alike house A, house B's lightbulbs were replaced with efficient LED's or with halogen lamps. The energy-saving measures that can be implemented effortlessly are interposing power switches and replacing lightbulbs with efficient LEDs.

The comparison of both houses shows that facility equipment has great impacts on the electricity bill. Even though most of the devices are not used for the majority of time, energy is wasted in terms of phantom loads. An energy-conscious use of these devices can reduce phantom loads and would impact the grid because it reduces base-loads. Therefore, dimensions of renewable energy devices could be smaller, which

would lower LCOE. Apparently, 20 out of 85 houses have replaced their lightbulbs with LEDs (Garfield, W., 2016). Furthermore, a number of houses that cannot be quantified accurately, replaced inefficient electronic devices with the newest technology.

This short survey has shown that the efficient usage of electricity is apparent. At the same time, this implies that efficient technology is desirable, wherefore it can be concluded that renewable energy technology does not encounter backlashes in the community. This means in effect that public acceptance is given in general.

4.5 System selection

As shown in Subsection 4.3, the six systems that are suitable from an economic point of view are PWDS, WDS, PDS, PWD, PD and WD. The modeling process has shown how much the LCOE depend on the structure and dimensions of the system. However, the individual system components have advantages and disadvantages, wherefore an evaluation is needed.

As described, the PWDS system is the most cost-effective variant, but also the most complex one, because it contains the most components. The second best cost-effective variant is the WDS system. Compared to the PWDS, its LCOE is \$0.06 higher due to a surplus of operating costs of \$20,000/year and higher investment costs of \$210,000. Its renewable fraction however is 74 % and therefore lower compared to the 79 % of the PWDS. The load management of the WDS is simpler because it does not incorporate solar resources, but fuel imports are higher, as it needs approximately 8,500 liters more than the PWDS. This is a major disadvantage, as the aim is to reduce dependence on fossil fuel imports.

The third best variant from an economic perspective is the PDS, because it has LCOE of \$0.327/kWh and NPC of \$3.22M. Even though it is more expensive on average and in total, it has a simplified system structure like the WDS. The PDS has a 413 kW PV capacity, a 100 kW generator, and a 1,018 kWh battery capacity. However, the system has a lower renewable fraction of about 68 %. Furthermore, the PDS strains the battery more than the PWDS or the WDS, as the energy generation peaks during the day. A steady load is more favorable compared to peaking energy generation (Sharma & Wagemaker, 2015). The straining of the battery in the PDS system can be seen in Figure 81 in comparison to the consistent state of charge of the battery in the WDS system illustrated in Figure 82.

Figure 81 Battery state of charge for PDS system for one year

Figure 82 Battery state of charge for WDS system for one year

Both figures show the state of charge of the battery for one year for every day in percent. It shows how much power is stored at any time of the year. By comparing both

figures it can be seen that the bigger battery capacity of the PDS system discharges almost completely during each day, and is more frequent. The lowest discharging periods occur during winter nights in January and February but also during summer nights from July to August. In comparison, the battery in the WDS system does not experience this intense load cycles. It can be assumed that the battery in the WDS system has a longer life compared to the PDS due to lower discharging cycles and less fluctuations (Yoshida, Sato, Amano, & Koichi, 2015). For this reason and due to its lower LCOE and NPC, the WDS is preferable against the PDS.

The other eligible variants are the PWD, the PD, and the WD system, with renewable fractions of 50 %, 30 % and 40 %. These lower numbers result from the missing energy storage. Therefore, they are of less relevance for the aim of energy self-sufficiency due to the mentioned reasons of reliability and load management.

Nevertheless, the six described variants do not establish self-sufficiency. The system that does so is either a photovoltaic-storage system. This system can meet the electricity demand completely and therefore establishes self-sufficiency. The PV has a size of 1,681 kW and the battery has a size of 3,892 kW. This system requires \$3.98M of investment cost, has a NPC of \$6.51M, and has LCOE of \$0.662\$/kW. Therefore, self-sufficiency is not cost-competitive and economic feasible to the current date.

The investigation of the variants has shown that a mix of the considered resources solar and wind in combination with a diesel backup system and an energy storage is the most reasonable variant as it combines a high stake of renewable energy with most cost-competitive financial key figures. Even though, the load management might be a chal-

lenge, the system is selected as the most feasible variant, because the allocation of electricity producers is a reliability coverage for the island. This aspect is crucial for small dimensioned systems. The electricity contribution of the individual components of the PWDS is shown in Figure 83.

Figure 83 Monthly average electricity production for the optimal economic variant

The graph of the monthly average electricity production shows that PV and Wind energy are the main contributors of the system. There is only a high contribution by diesel generator in July and August, when peak loads on the island are reached. However, a variation regarding the average electricity load curve in Figure 22 is noticeable. The number of kilowatts is higher in the winter as actually necessary. This is mainly due to the electricity production of the wind turbine that produces its maximum electricity in this season. However, electricity is not always stored in the storage system, for which reason the wind turbine does not run effective during this season. Simultaneously, loads during the night need to be regulated by the generator, which is why it needs to run at some days in the winter too. The generator stabilizes the system by supplying a base load, while the battery storage controls maximum peak loads.

5 DISCUSSION

This thesis has shown that the structure of micro-grids in combination with storage systems can establish a safe and reliable energy supply for communities so that applicability of renewable energies can be attested. Currently the most promising technologies for islands are wind and solar technologies. The use of different energy sources in one system enables better adapting to the fluctuating load profile of communities compared to a single resource. The reason for that is the difference in temporal variability, wherefore they generate electricity at different times. Storage systems make renewables reliable, because load can be met at any time. Furthermore, it was shown that a reasonable distribution can reduce the size of the storage system, because the temporal occurrence of available energy can be adapted to the loads. Especially smart-micro-grids have the ability to adapt local requirements and conduce to further energy savings.

However, without storages, renewable energy plants have to exceed the electric demand of islands multiple times to ensure a stable power frequency, because only the base loads of renewable energies are reliable. Storages can be avoided though, if a connection to mainland can be established. On the one hand, electricity could then be sold to mainland and generate new sources of income; on the other hand, transmission needs high investment costs. Especially home batteries seem to be a counteractive approach to utility scale battery storages. The assembly of DER and DES has the potential to keep dimensions small, but the system cost-effective. Furthermore, system reliability and safety increases, because risks are allocated.

The current levelized costs of electricity show that onshore wind and photovoltaics are cost-competitive. The fact that fuel supply for island is more expensive than on mainland makes the transformation even more attractive. The biggest advantage for renewables is that they hedge against risks in fuel price fluctuations, because they have low operation and maintenance costs. Even though renewables have higher initial costs than conventional energy plants, they are increasingly cost-competitive. They become even more competitive, when lifespan can be extended and initial costs lowered. The combination of financing and power purchase agreements offers worthwhile prospects for both islander and financier, and make a project calculable.

If a connection to the mainland grid could be established, the system could be scaled smaller. This would furthermore avoid the cost-pushing effect of the battery storage. Instead, an additional source of revenue could contribute to the economic viability of the system, because excess electricity could be sold. Self-sufficiency would technically be reached, if net energy flow towards mainland would be positive at the end of the year.

The economic assessment, has shown that there are five possible structures that are conceivable from an economic point of view. These systems are:

1. PV-Wind-Diesel-Storage
2. Wind-Diesel-Storage
3. PV-Diesel-Storage
4. PV-Wind-Diesel
5. Wind-Diesel

By comparing these systems, it could be demonstrated that the PWDS is currently the most reasonable and most cost-effective variant. It has been shown that the technologies are competitive in terms of cost of energy and durability.

Beside storing excess electricity, the comparison of PV-Wind-Diesel-Storage and PV-Wind-Diesel has shown that storage systems are favorable, because they can reduce the size of renewable energy devices. In addition, backup systems like diesel generators are an effective measure to establish reliability, because their initial costs are just a fraction of the capital cost necessary for renewable energies. Therefore, they reduce LCOE and maintain security of supply at the same time. For these reasons, the modeled PV-Wind-Diesel-Storage system is the most cost-effective energy system with the highest reliability that can be implemented on Cuttyhunk.

The availability of resources is the general requirement and thus needs to be assessed first. The resource assessment is the fundamental work where the theoretical basis is determined concerning available potential in deference of natural constraints. The technical potential assesses the installation of renewable technologies concerning local environmental constraints and topographic conditions. In this part it may turn out that some resources are not achievable. Both, environmental and topographic conditions have to harmonize with installation requirements to ensure system performance.

It has also been demonstrated that wave energy converters are currently not a mature technique due to its early stage in development. This is a major issue for adding the system to a project as it is a hazard for the project success. This lack of reliability and the current high costs of electricity of the device are key factors that need to be ensured before it can be considered. However, it was also shown that waves are a predictable source of energy with high potential of power production. They potentially play a key role for sustainable development of offshore islands in the future.

The process of the thesis has shown that integrated renewable energy projects are feasible from an economic point of view. The economic assessment of projected costs aims to analyze a financial base frame for system design. Different financial assumptions need to be done to compare key figures that state whether a project is profitable or has a worthwhile risk/return ratio. In terms of communities, this may be determined by computing the LCOE and NPC. In terms of investing companies, NPV or IRR may be the means of the choice.

Even though that this process has been done with due care, it appears that not all input variables are available. Therefore, well-founded assumptions have been made. Assuming values have the advantage that initial hypotheses can be validated. They are inevitable for the assessment of feasibility. By its very nature, feasibility analyses rely on evidence-based presumptions, because they represent the early stage of the finding process. However, they need to be replaced in the later process of project management.

The market analysis assesses rules of competition and prospects of success for project execution. Thereby, political perspectives and regulatory requirements play a major part for investors and communities respectively. In addition to that, social factors play a major role. Campaigns or countermovements can harm the project and apply pressure on project decision-makers and policymakers. It can be avoided by involving residents in the project. This analysis reflects the investment situation and is the last decisive insight to confirm chances of success. This expresses the need to involve all stakeholders to find suitable compromises.

It was also shown that the initial reduction of energy demand can contribute to cost-effective system design. In particular energy audits can visualize the importance.

Induction of internal drive and personal incentives make it easier to achieve additional energy savings. The result of this would be an appropriate design of energy generation and energy storage systems. Furthermore, the system needs to be easy to maintain and to operate

Collaboration of stakeholders and developers is essential at the beginning. Especially, home design and orientation can reduce energy needs even before energy efficiency questions arise. The basic elements that can contribute to less energy needs are energy efficient construction and passive solar design (Carlisle, Elling, & Penney, 2008). These factors can be recognized in a certification program. One program is the Leadership in Energy and Environmental Design (LEED) by U.S. Green Buildings Council. It clarifies the ecofriendly alignment of a project and ensures necessary upgrades for achieving sustainability. To meet the LEED requirements, eco-conscious homes like zero energy buildings need to incorporate renewable energy technologies. (U.S. GBC, 2016).

Beside financial feasibility, economic viability is the decisive factor and basis of decision-making. Apart from this, least-cost analysis or cost-effectiveness analysis may also be suitable for remote communities, because islands' small markets make it difficult to quantify and measure benefits and to generate scalable advantages from the standpoint of local authorities. The impacts of renewable energies for islands are technical, socio-economic and environmental. The technical considerations like overvoltage, harmonic problems or response are related to system disturbances and need to be considered for all renewables. In detail, wind turbines affect the protection of air traffic control and electromagnetic interference. Solar plants need unobstructed direct sunlight.

In respect of socio-economic impacts, former accusations concerning loudness and vibration of wind plants can be disregarded, because current models made great improvements by finding aerodynamic-optimal structures and using sound absorbing materials. However, a fundamental aspect is that visibility of wind plants is seen as visual pollution, which affects the value of real estates. The disadvantage of wave energy conversion technology is that devices may become obstacles for vessels, be a hazard for swimmers and disturb the character the coastline.

In terms of environmental impacts, there are more positive than negative impacts, although not all are investigated in detail. If one assumes that solar technology is installed as PV systems on roofs, land-use and habitat loss can be neglected. They need to be considered only, when the devices are stand-alone appliances. The main environmental impact of wind turbines refers to the death of birds and bats. The magnitude of bird death can be considered small though and decreases for islands.

Not all of the mentioned aspects apply to Cuttyhunk, but they are essential insights that need to be taken into account for other projects. The adaptation to local conditions and use of beneficial location factors is one of the most obvious aspect, because inherent locational advantages improve feasibility in a simple manner. Then, exploitation of these locational factors like high wind velocities need appropriate dimensions of energy and storage systems. If possible, politics must be incorporated to receive support and assistance like subsidies. In addition, incentives to achieve additional energy savings need to be created to enhance the already existing internal drive

The thesis did not consider biofuels as a potential contributor of energy for an integrated renewable energy system. The justification for leaving out this technology is its requirement in space for agricultural cultivation on the one hand, and the aim to reduce imports from mainland on the other hand. However, there are recent advancement in the technology concerning large scale development of algal biofuels (Pandey, Lee, Christi, & Soccol, 2014). In front of the fact that this technology is still in an early research phase, it is too immature to take into consideration. Therefore, it has not been included in the scope of this thesis.

It should be noted that buoy data is not the best suited source of data for the assessment of land based wind turbines. The assumption that its proximity relativizes the use of this data is fairly precise (Anderson, 2013). Nevertheless, other consistent data was not available. Taking into account that this thesis addresses the early stage of a project, it gives a good first impression of the availability of wind energy. It would have had been better, if site measurements could be done over a certain period to compared the buoy data in order to draw conclusions about its representativeness.

6 CONCLUSION & FUTURE RESEARCH

The main objective of this thesis was to find the most cost-effective energy system to supply electricity with the highest reliability using renewable and non-renewable resources on Cuttyhunk Island. The proposed system includes a solar-wind system in combination with a diesel backup and an energy storage (PWDS). The PWDS seems to be the most feasible variant as it combines a renewable energy with the most cost-competitive system, and a reliable supply due to the diesel backup. The estimated COE are \$0.2587/kWh, which represents less than half of the current COE of \$0.60/kWh. The performance indicators of the PWDS can be seen in Figure 84.

Figure 84 Summary of system components for the PWDS system

The PWDS has a renewable fraction of 79 % and NPC of \$2.54M. The most vulnerable point of the system is the reliability of supply, even though it has several energy contributing components. Figure 85 shows the state of charge of the battery and illustrates that there are several days, when the battery is almost discharged. This could affect reliability when the diesel generator works at full capacity and renewables do not contribute.

Figure 85 Battery state of charge in percentage for the PWDS system for each day of one year

In terms of electricity self-sufficiency, there are three systems that could power the island. The system setups are Photovoltaic-Storage (PS), Photovoltaic-Wind-Storage (PWS), and Wind-Storage (WS). The most cost-competitive system that could demonstrate its capability to provide electricity reliable all-seasonal is the PS. However, the PS has total NPC of \$6.51M and LCOE of \$0.66, which is not cost-effective in comparison to the PWDS system.

There are four key steps that are decisive in the process renewable energy projects. These steps include resources, technical & environmental requirements, economic conditions and market situation, which can be seen in Figure 86.

Figure 86 Key elements of renewable energy projects for each step of feasibility, based on NREL (2012)

The figure illustrates both, potential and uncertainty of renewable energy projects for the four general steps and their key elements. It shows that the potential of projects decreases with progress and that uncertainty concerning feasibility reduces at the same time, as long as the key elements can be answered. Even if it was scientifically desirable to balance the key elements, it cannot be carried out since every key element is an important prerequisite that has to be assessed. Therefore, the proposed system has several sources of uncertainty which should be taken into account in future studies.

There were clearly many challenges in obtaining accurate data in this thesis concerning resources and economic analysis. Therefore, the work in hand should be understood as an initial feasibility study that needs to be continued with more data. For instance, the wave climate can be investigated in more detail using a nested grid for a

longer period of 10 years or more, as average quantities have been considered in this study. Wind measurements should be performed on Cuttyhunk in order to better estimate the real wind speeds and its available power. With regard to energy devices, the thesis has only considered one specific device based on an initial assessment. However, multiple devices should be simulated in the analysis to detect the most feasible device.

It would be desirable, if the performance of the economic analysis is reviewed using different analyzing methods of evolutionary algorithm. For example, a generic algorithm could be used to model the optimization of the system with the aim to reduce its cost and increase its reliability. Additionally, sensitivity analysis need to be performed in order to estimate the potential effects of changes in diesel prices or interest rates.

Future work should also include the consideration of emission reduction by the investigated systems, as another parameter. This could be done by using a life-cycle-analysis. Furthermore, it is of great interest to find a system setup for a predefined renewable fraction of electricity. Those scenarios could be performed in increments of percentage, e.g. 5 %-increments, because it might be of interest for political authorities to establish a certain rate of renewable electricity generation. For instance, the renewable percentage could be set to 50 % and the optimum solution could be determined for all system setups.

APPENDIX

A: Diagram of location 2

B: Diagram of location 3

C: Evaluation of the locations of the proposed solar site

location 1	time																								Total
	6:00 AM	6:30 AM	7:00 AM	7:30 AM	8:00 AM	8:30 AM	9:00 AM	9:30 AM	10:00 AM	10:30 AM	11:00 AM	11:30 AM	12:00 PM	12:30 PM	1:00 PM	1:30 PM	2:00 PM	2:30 PM	3:00 PM	3:30 PM	4:00 PM	4:30 PM	5:00 PM	5:30 PM	(%)
January				0	3	4	5	6	7	7	8	8	8	8	7	7	6	5	4	0	0	0			93
February					2	3	4	5	6	7	7	8	8	8	7	7	6	5	4	3	0	0			96
March				2	3	4	5	6	6	7	7	7	7	7	7	6	5	4	3	2	2	0			99
April				2	3	4	5	6	6	7	7	7	7	7	7	6	5	4	3	2	2	1			100
May				2	3	4	5	6	6	7	7	7	7	7	7	6	5	4	3	2	2	2	1		100
June				2	3	4	5	5	6	6	7	7	7	7	6	5	4	3	3	3	2	2	1	1	100
July				2	3	4	5	6	6	7	7	7	7	7	7	6	5	4	3	2	2	2	1		100
August				2	3	4	5	6	6	7	7	7	7	7	7	6	5	4	3	2	2	2	1		100
September				2	3	4	5	6	6	7	7	7	7	7	7	6	5	4	3	2	2	2	1		100
October				2	3	4	5	6	6	7	7	8	8	8	7	7	6	5	4	3	2	0	0		98
November				2	3	4	5	6	7	7	7	8	8	8	7	7	6	5	4	3	0	0			96
December				0	3	4	5	6	7	7	8	8	8	8	7	7	6	5	4	0	0	0			93
location 2	time																								Total
	6:00 AM	6:30 AM	7:00 AM	7:30 AM	8:00 AM	8:30 AM	9:00 AM	9:30 AM	10:00 AM	10:30 AM	11:00 AM	11:30 AM	12:00 PM	12:30 PM	1:00 PM	1:30 PM	2:00 PM	2:30 PM	3:00 PM	3:30 PM	4:00 PM	4:30 PM	5:00 PM	5:30 PM	(%)
January					3	4	5	6	7	7	8	8	8	8	7	7	6	5	4	0	0				93
February					2	3	4	5	6	7	7	8	8	8	7	7	6	5	4	3	2	0			99
March					2	3	4	5	6	6	7	7	7	7	7	6	5	4	3	2	2	1			100
April					2	3	4	5	6	6	7	7	7	7	7	6	5	4	3	2	2	2	1		100
May					2	3	4	5	6	6	7	7	7	7	7	6	5	4	3	2	2	2	1		100
June					2	3	4	5	6	6	7	7	7	7	6	5	4	3	3	3	2	2	1	1	100
July					2	3	4	5	6	6	7	7	7	7	7	6	5	4	3	2	2	2	1		100
August					2	3	4	5	6	6	7	7	7	7	7	6	5	4	3	2	2	2	1		100
September					2	3	4	5	6	6	7	7	7	7	7	6	5	4	3	2	2	2	1		100
October					2	3	4	5	6	6	7	8	8	8	7	7	6	5	4	3	2	0	0		98
November					2	3	4	5	6	7	7	8	8	8	7	7	6	5	4	3	0	0			96
December					2	3	4	5	6	7	8	8	8	8	7	7	6	5	4	0	0	0			95
location 3	time																								Total
	6:00 AM	6:30 AM	7:00 AM	7:30 AM	8:00 AM	8:30 AM	9:00 AM	9:30 AM	10:00 AM	10:30 AM	11:00 AM	11:30 AM	12:00 PM	12:30 PM	1:00 PM	1:30 PM	2:00 PM	2:30 PM	3:00 PM	3:30 PM	4:00 PM	4:30 PM	5:00 PM	5:30 PM	(%)
January					2	3	4	5	6	7	7	8	8	8	7	7	6	5	4	0	0				95
February					2	3	4	5	6	7	7	8	8	8	7	7	6	5	4	3	0	0			97
March					2	3	4	5	6	6	7	7	7	7	7	6	5	4	3	2	2	0			99
April					2	3	4	5	6	6	7	7	7	7	7	6	5	4	3	2	2	2	1		100
May					2	3	4	5	6	6	7	7	7	7	7	6	5	4	3	2	2	2	1		100
June					2	3	4	5	5	6	6	7	7	7	6	5	4	3	3	3	2	2	1	1	100
July					2	3	4	5	6	6	7	7	7	7	7	6	5	4	3	2	2	2	1		100
August					2	3	4	5	6	6	7	7	7	7	7	6	5	4	3	2	2	2	1		100
September					2	3	4	5	6	6	7	7	7	7	7	6	5	4	3	2	2	2	1		100
October					2	3	4	5	6	6	7	8	8	8	7	7	6	5	4	3	2	0	0		98
November					2	3	4	5	6	7	7	8	8	8	7	7	6	5	4	0	0	0			93
December					0	3	4	5	6	7	8	8	8	8	7	7	6	5	4	0	0	0			93

D: Wind turbine XANT

XANT M-21 (100 kW) - Class I^A

XANT N.V. | Vaartstraat 63 - 65, 1000 Brussels, BELGIUM
Tel. + 32 56 707 055 | info@xant.com | www.xant.com

WIND TURBINE RATING

Rated electrical power	100 kW
Power factor	0.9 inductive - 0.9 capacitive
Cut-in wind speed	3 m/s
Survival wind speed	70 m/s
Electrical output	400 VAC, 50 - 60 Hz

GENERAL CONFIGURATION

Rotation axis	Horizontal
Rotor Orientation	Downwind
Rotor Diameter	21 m
Number of blades	3
Drive train	Direct-drive permanent-magnet generator
Converter	Full-power electronic converter

SAFETY & CONTROL SYSTEMS

Power regulation	Variable speed, stall with aeroelastically-tailored blades
Braking systems	Electrical brake and electromechanical brake
Monitoring system	Webbased HMI
Controller	Industrial PLC

PRODUCT MASS & FOOTPRINT

Tower top mass	7.5 tons
Total mass	14 tons (stand-alone tower)
Footprint	+/- 15 m ² (stand-alone tower)
Concrete volume	50 m ³

CERTIFICATIONS

Turbine Class	IEC 61400-1 Class I ^A
Certification	Design compliance by DNV-GL

TOWER

Type	Tubular stand-alone or tubular guyed tower
Hub height	23 / 31.8 / 38 m *

TRANSPORT AND INSTALLATION

Transport	standard 40ft OT container
Erection	Gin pole with reeving systems or crane

POWER CURVE

Average Wind Speed (m/s)	Annual Energy Yield (MWh)
4.0	90.5
4.5	126.3
5.0	166.4
5.5	209.0
6.0	252.2
6.5	294.3
7.0	334.1
7.5	370.7
8.0	403.6
8.5	432.5
9.0	457.4
9.5	478.3
10.0	495.3

* other heights available upon request

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