MSc Program
Environmental Technology & International Affairs

Energy Transformation of Cape Verde - Establishing a 100% renewable energy mix for 2020 and 2030

A Master's Thesis submitted for the degree of
"Master of Science"

supervised by
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Vienna, 17.06.2015

Affidavit

I, **KONSTANTIN EROL**, hereby declare

1. that I am the sole author of the present Master's Thesis, "ENERGY TRANSFORMATION OF CAPE VERDE - ESTABLISHING A 100% RENWABLE ENERGY MIX FOR 2020 AND 2030", 130 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master's Thesis as an examination paper in any form in Austria or abroad.

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Signature

Abstract

This thesis concludes that a 100% renwable energy system throughout the nine populated islands of Cape Verde is technically feasible. 2012 was chosen as the base year due to availability of consistent data. Values of 2012 and projections from the Ministry of Energy were taken to predict the size of the energy sector by 2020 and 2030. In consequence, the results are presented for these two years. Besides, the thesis is built upon a thorough literature review which provided the integral equations and processes for the assessment of potential. Furthermore, this study has been supported by the expertise of ECREEE staff as well as other experts in the field.

In a first step the theoretical overall technical possibility of deploying 100% RE has been established by computing the required land area for solar PV respectively the number of wind turbines to supply the annual energy demand. It was found that Cape Verde can accommodate sufficient facilities either relying on 100% wind or solar PV.

In a second step, an individual energy mix for each of the nine islands has been derived. The approach was based on a numerical analysis of hourly values for loads and the wind and solar resource. Additionally, two different energy storage schemes were applied, without which no 100% renewable electricity system can succesfully work. For this study, energy storage was designed to sustain a 1,5 day respectively a 1 week period without newly produced energy. Moreover, four distinct ways of storing excess energy were considered. All islands proved to be able to accommodate power-to-gas energy storage while only individual islands have been selected for battery, thermal energy and pumped hydro storage. The outcome indicates that solar PV is the most reliable resource in two thirds of all scenarios while wind only plays a vital role for two of the nine islands. The excess energy produced by both scenarios (1,5DS and 1WS) is extensive, however, especially for the shorter storage scheme.

Finally, all scenarios have been put in a financial context. It has been deduced that costs will be vast and might prove to be an obstacle in achieving 100% RE penetration. Among all storage scenarios assessed power-to-gas storage is the most attractive one in terms of costs. Furthermore, larger sized energy storage schemes turned out to be the least cost option.

Table of Contents

List of abbreviations

A – Ampere

Ah – Ampere Hour

CSP – Concentrating Solar Power

DG – Director General

DNI – Direct Normal Irradiation

ECOWAS – Economic Community of West African States

ECREEE – ECOWAS Center for Renewable Energy and Energy Efficiency

EWEA – European Wind Energy Association

IRENA – International Renewable Energy Agency

KE – Konstantin Erol

kW – Kilowatt

kWh – Kilowatt Hour

MDP – Movimento para a Democracia

P2G – Power-to-Gas

PAICV – Partido Africano da Independencia de Cabo Verde

PHS – Pumped Hydro Storage

PV – Photovoltaics

REN21 – Renewable Energy Policy Network for the 21st Century

SM – Solar Multiple

TES – Thermal Energy Storage

UNIDO – United Nations Industrial Development Organisation

WTG – Wind Turbine Generator

Acknowledgments

I would like to take this opportunity to express my gratitude to certain people that have been accompanying me and supporting me throughout various phases of my life and the process of writing this thesis.

My deepest gratitude and respect to my supervisor Ph.D MSc. Mario Ortner who encouraged me to write about this topic and set favourable conditions for its success. Also, I would like to thank Mr Lugmayr from UNIDO who made it possible that I could spend two incredibly interesting and challenging months in Cape Verde with ECREEE. I was able to get into contact with experts in the field such as Jansenio Delgado or Heleno Sanches. Additionally, I want to thank Djeneba, Karin, Youba, Mohamed, Siré, Lucius, Dani, Phil and Faron for making my stay here so enjoyable and fun.

Most importantly, I want to honour my parents and my sister for always being there for me. I could not have come to this point in life without your presence. The continuous support and unquestioned love you showed let me develop into the person I am today. I consider myself lucky to be born into such a beautiful and peaceful surrounding.

I also want to emphasize the impact by my grandparents who never spared any trouble when it came down to helping their grand-children. Your involvement in our drive to success has been integral and it is imperative to acknowledge it.

A big “Thank you” to the four people who share with me the privilege of calling themselves “NC”: Alex, Clemens, Philip and Rainer. We proved that fun and success can easily go hand in hand. Also, I want to thank the “RB”, my second family. Someone of you is always around me making sure life isn’t boring.

Finally, the last two years at the Diplomatic Academy of Vienna and the University of Technology have been highly interesting and allowed myself to pursuit personal interests on an academic basis. I have to mention Pili and Koko who accompanied me in this endeavour.

“People only start to become concerned about energy when it is in short supply. Without energy, however, our daily life would be very different as the factories would grind to a halt, aeroplanes could not take off, cars could not start, and we would have no heating, hot water, electricity or computers. When we flick the switch on entering an unlit room, when we switch on the heating in our homes when the air starts to get chilly, we hardly spare a thought for the power stations which generate electricity, the electricity networks, and the oil and gas pipelines.”

(European Comission, 2002: p.2).

1 Introduction

1.1 Motivation

Our world is in constant transformation in manifold ways. Some of them we haven't even started exploring. Others, such as climate change, we have been researching for a long time now. It seems that the collective efforts have finally paid off. Renewable energy technologies have been deployed during the last 5 years in a scope never witnessed before. Concomitant, prices for the deployment of RE technologies drop constantly, making it increasingly competitive. Denmark's market even experiences RE as its most cost competitive participant (IRENA, 2014b).

At the same time, climate change is becoming an increasingly important and dangerous issue. For some nations of the world –countries with a low elevation over the sea surface – this is even more true than for others. Switching to renewable energy can not only decrease long term effects such as climate change but can also benefit short term economic and social development. Small island developing states, therefore, are the most suitable place to engage in an energy transformation towards 100% renewables. Some islands (Tokelau, El Hierro/Spain, Bonaire/Venezuela and Samso/Denmark) are currently demonstrating that the abolishment of fossil fuels is not just some green advocate's fantasy but very well feasible.

Cape Verde has proven once before its motivation to being sovereign when it succeeded in becoming independent from Portugal in 1975. Nowadays, the government of Cape Verde attempts a novel revolution – the energy revolution. In 2008 the Energy Policy "Building a secure and sustainable energy future" was established by the MECC (Ministry of Economy). It set the objective of 50% of renewable penetration in the energy sector by 2020. At that time, Cape Verde still relied only on diesel and heavy fuel generators to power its islands. However, since then, the energy sector has undergone huge transformation. Cabeolica is one famous example operating 25,5MW of wind turbines and outputting roughly 20% of total electricity production. This year the government will set even more ambitious goals which aim at 100% renewable electricity penetration by 2020.

In the light of all these developments of the last years this thesis aims to make a contribution towards a more sustainable energy sector of Cape Verde.

1.2 Objective, Research Question and Hypothesis

It is the objective of this thesis to find an efficient energy mix in terms of energy efficiency (as little excess energy as possible) for each of the nine populated islands (Maio, Brava, Fogo, Sal, Boavista, Sao Vicente, Sao Nicolau, Santo Antão and Santiago) of the Cape Verde archipelago for 2020 and 2030. Moreover, the different scenarios will undergo a financial evaluation to determine which is the most cost effective. The objective will be achieved based on the assessment of hourly load and natural resource (wind, solar irradiation, DNI) data. This will allow for the description of the energy sector in a reasonable accurate resolution. The outcome of the thesis will be presented for each island individually by providing two to four different scenarios for each of the years and islands in focus.

The first research question of this study puts the necessity of an energy transformation in question, however, without doubting the need. The requirement for action in the light of climate change is acknowledged as a fundamental principle. Nevertheless, there are more short-term needs such as energy security and economic development that need exploration. Furthermore and most essential, this thesis will explore the possibility of a 100% renewable electricity production on each of the nine populated islands pillowed on the collaboration of RE technologies with long term storage schemes (1 day and 1 week).

The author hypothesizes that a 100% RE penetration on each of the islands is feasible, however, only with the help of huge investments into the energy sector of Cape Verde making this endeavour a protracted and cost intensive one.

1.3 Methodology

Each topic within this thesis will be supported by a thorough literature review of current articles, books, reports and websites. This approach ensures that the newest findings of national, regional and international authors and organisations will be incorporated in the subsequent chapters. Additionally, a research project in the form of an internship with ECREEE (ECOWAS Center for Renewable Energy and Energy Efficiency) will be conducted. These two months in Praia on Santiago Island will allow the author to get into connection with experts affiliated with Cape Verde and renewable energy issues. Furthermore, this internship will give the opportunity to get local data and information. In the scope of the internship interviews with key experts will be held. Finally, a numerical evaluation - based on the knowledge gained from the literature - of hourly load and resource data will result in residual loads which can be used to establish an energy mix.

The data used in this paper was not collected by the author, but is extracted from statistics and reports of national ministries and companies as well as from conference reports and publications. Additionally, personal communications and interviews were used to gain more expertise in the field.

2 Theory

2.1 Country Profile

The analysis of the energy sector of Cape Verde and its possible transformation needs to be based on some basic understanding of the country itself and its origins. Furthermore, a certain overview of the main country specific data such as GDP, population size and synthesis of the economy build the frame for the analysis in chapter 3. Hence, I want to introduce Cape Verde in the subsequent two chapters starting with the history and ending with crucial data.

2.1.1 History

The 10 uninhabited islands and several islets were discovered by the Portuguese colonialists in the 15th century (BBC News, 2014). Situated on the route from African colonies to Europe Cape Verde soon became an important intermediate resting and trading point for Portugal’s military and trading fleet (Central Intelligency Agency, 2014). It was only in 1975 when the archipelago became independent from Portugal and set up its own government. Until 1990 the islands were governed under a one-party system which was then transformed into a multi-party system (Lobban, 2014). Cape Verde struggled to create economic growth during the 1990s and 2000s. These economic difficulties caused mass emigration resulting in an expatriate population which exceeds Cape Verde’s domestic one (Central Intelligency Agency, 2014). However, since 2010 the government of Cape Verde enhances economic and political relationships with global partners to increase general wealth and living standards (Lobban, 2014). Nowadays the island state belongs to the wealthiest African states with one of the most stable democratic governments (Berié et al., 2013). Furthermore, Cape Verde is member of ECOWAS – Economic Community of West African States – which was established in 1975. Especially, the ECOWAS initiative on renewable energy and energy efficiency was beneficial for Cape Verde as the secretariat was set up in its capital Praia on Santiago Island in 2010. Since then, ECREEE – ECOWAS Center for Renewable Energy and Energy Efficiency - is one of the main regional focal points when it comes to energy topics.

2.1.2 Country data

Cape Verde (official name: República de Cabo Verde) is an island state situated in the Atlantic Ocean approximately 500km off the west coast of Senegal, Africa. Its total area is

4036km² (coast line: of 965km) which makes it one of the smallest countries in the world (Central Intelligency Agency, 2014). The 10 islands and 13 closely situated islets (UNIDO; ECREEE, n.d.) are populated by 512.096 people with most of them (274,044 people) living on the biggest island Santiago (ECOWAS, 2015). Also, Praia, the capital and biggest city, is located on this island (Berié et al., 2013). Here, the governmental centre with its parliament can be found. President of the republic is Jorge Carlos Fonseca (MDP) and head of government is José Maria Pereira Neves (PAICV) (Berié et al., 2013).

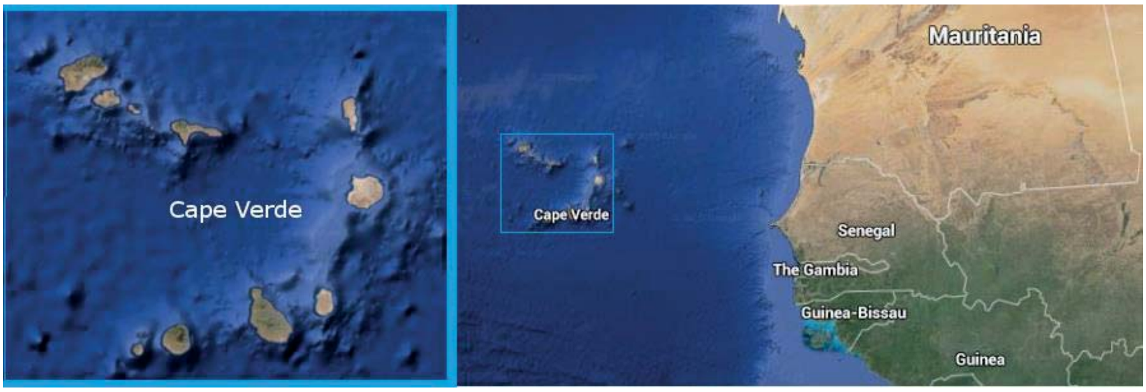

Figure 1 – Location of Cape Verde off the west coast of Senegal (adopted from Google Maps, 2015)

The island state of Cape Verde generated a GDP of 1.897bn US-$ in 2012 which equals an average income of 3810 US-$ per capita. The largest share of the GDP stems from the service sector which makes up 72%. The rest of the GDP comes from industry (18%) and agriculture (10%). Remittances sum up to a relatively large amount (9.3% of the GDP) which can be explained by the extraordinarily big expatriate population (approximately 700,000). Cape Verde imports goods and services in the value of 947 million US-$ (mostly food) while exporting goods and services of only 73 million US-$ value (mostly fish and clothes) (Berié et al., 2013).

The climatic conditions in Cape Verde are moderate with a warm and dry summer and generally very little and erratic precipitation (5-10 days of the year witness rain). The terrain of the islands is rocky and volcanic with the highest elevation of 2829m on the volcano Mt. Fogo. The arable land makes up 11.66% with permanent crops growing only on 0.74% of total surface area. Total renewable water resources amounted to 0.3 cu km in 2011 (Central Intelligency Agency, 2014).

2.2 Energy Security

This chapter stands as a proxy for reasons to engage in an energy transformation. Therefore, the term energy security should be understood as synonym for independence (financial, economic), for acknowledging the fact of climate change and for the understanding that our world has limited resources which we need to treat carefully.

2.2.1 What is energy security?

The notion of energy security is acknowledged throughout the world, yet there is no consensus on its exact meaning (Kruyt et al., 2009: p.2167). Kruyt et al. (2009) name the elusive and context-based nature of energy security as reason for that. The IEA in its World Energy Outlook of 2007 define energy security as the following: "*Energy security (…) means adequate, affordable and reliable supplies of energy*." (IEA, 2007: p.160). According to Kruyt et al. (2009: p.2167) energy security traditionally was based on the availability and access to crude oil supplies. Nowadays, the evaluation of the oil sector (supply and stocks of oil) alone is not sufficient enough anymore (Jewel, 2011: p.7). Concepts of security of energy supply expanded their focus to other impact factors such as the price of energy, supply chain security, political stability in supplier states, energy intensity and carbon intensity (Kruyt et al., 2009), (Jansen and Seebregts, 2010), (IEA, 2007). Finally, these concepts started to include other fuel sources into their portfolio (Jewel, 2011: p.8).

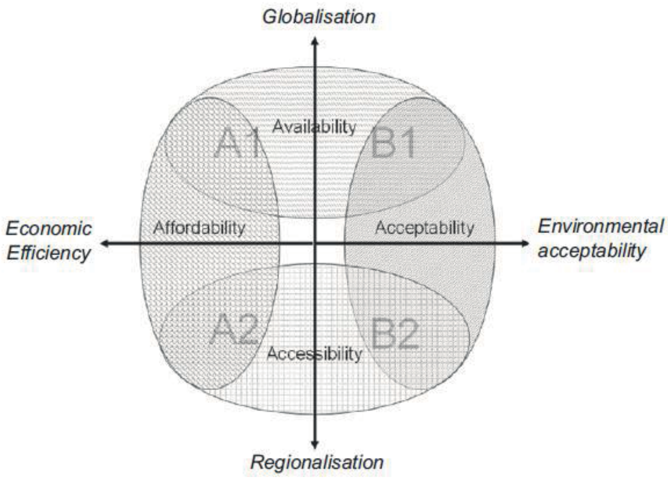

Figure 2 - Energy security spectrum; four dimensions of energy security and their relation to global orientations (Kruyt et al., 2009: p.2168)

In most studies ((Asia Pacific Energy Research Centre (APERC), 2007), (European Comission, 2002) and (Kruyt et al., 2009)) four elements which are strongly attributable to be characterizing and shaping energy security can be found. The IEA ((IEA, 2007) (Jewel, 2011)) indicates only the first three of them as mainly influential (see also Figure 3), also due to the fact that rather a short-term energy security is analysed.

- Availability
- Accessibility
- Affordability
- Acceptability

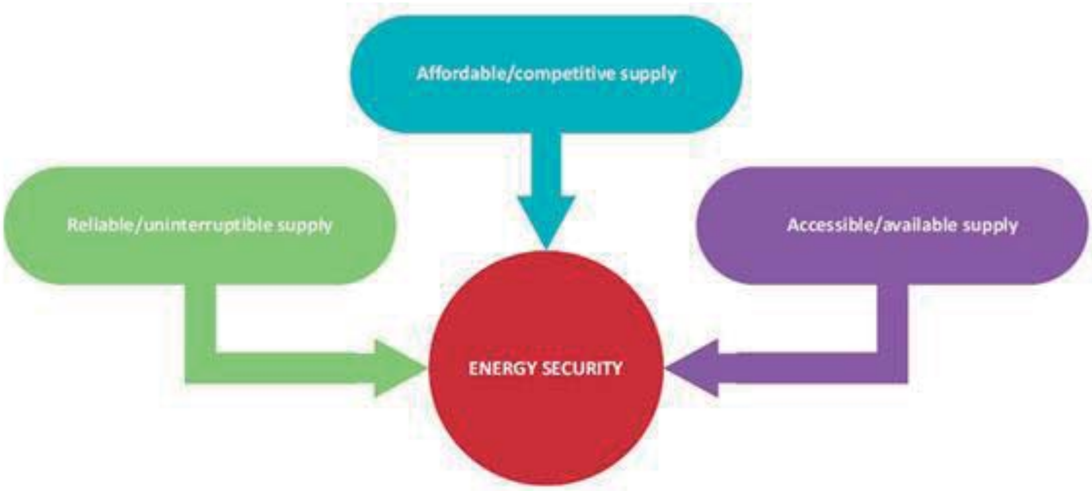

Figure 3 - Three dimension of energy security (OECD/IEA, 2014)

2.2.2 Energy Security's link to renewable energy

The reason energy security is discussed on a broad scale according to the European Commission is very basic: "*(…) energy is essential in our daily life.*" (2002: p.4). A more sophisticated explanation is given by Kruyt et al. (2009). Their study comes to the conclusion that the increasing interest in the concept of energy security is based on the fundamental necessity of an uninterrupted supply of energy for the functioning of our economies. Additionally, energy security plays such an integral role due to the fact that "*our enormous dependence on fossil fuels (oil, gas and coal) is becoming ever more marked*" (European Comission, 2002: p.4). Another reason for the growing importance of energy security is our interconnected global market. In such an environment market participants are inevitably affected by another participant's behaviour and condition (IEA, 2007: p.160). The power of a few suppliers creating market disturbances, as witnessed from time to time, is just one example. Its effects can be even stronger when considering that many power plants built decades ago come to the end of their life-span. However, the European Commission (2002) find in their study that all of these developments can only have upsides, namely an improved management of global natural resources as well as efficiency enhancements. In conclusion, energy security demands our attention for various urgent dangers and risks which, however, may help global systems to improve in consequence. Many island states have already adapted to this new situation. Caribbean and Pacific islands are aggressively following a path towards energy independence. Authorities have understood that small islands face imminent danger from climate change (REN21, 2014: p.24).

2.3 Power systems

Power systems spread out over the world are like circulatory systems in the human body supplying electricity instead of oxygen and sugar to areas in demand. They are also equally complex and need close studying for them to be effective. In the following pages an overview of main characteristics and properties of power grids will be given. It is essential to gain knowledge about the energy system which is in need of transformation in order to meet the loads the future.

2.3.1 General

A classical power grid comprises of three parts which are interconnected. These are supplier, distribution system and consumer (Ter-Gazarian, 2011: p.27). Basically, the supplier or producer provides electricity which is transported via transmission lines of different length and voltage to the consumer (Keyhani, 2011: p.24). The way of electricity production is chosen by the producer based on reserves and economic considerations. Power generation facilities are manifold – some of them are described within this thesis – and their output varies significantly in size, frequency and voltage. A typical composition of such a power grid can be taken from Figure 4.

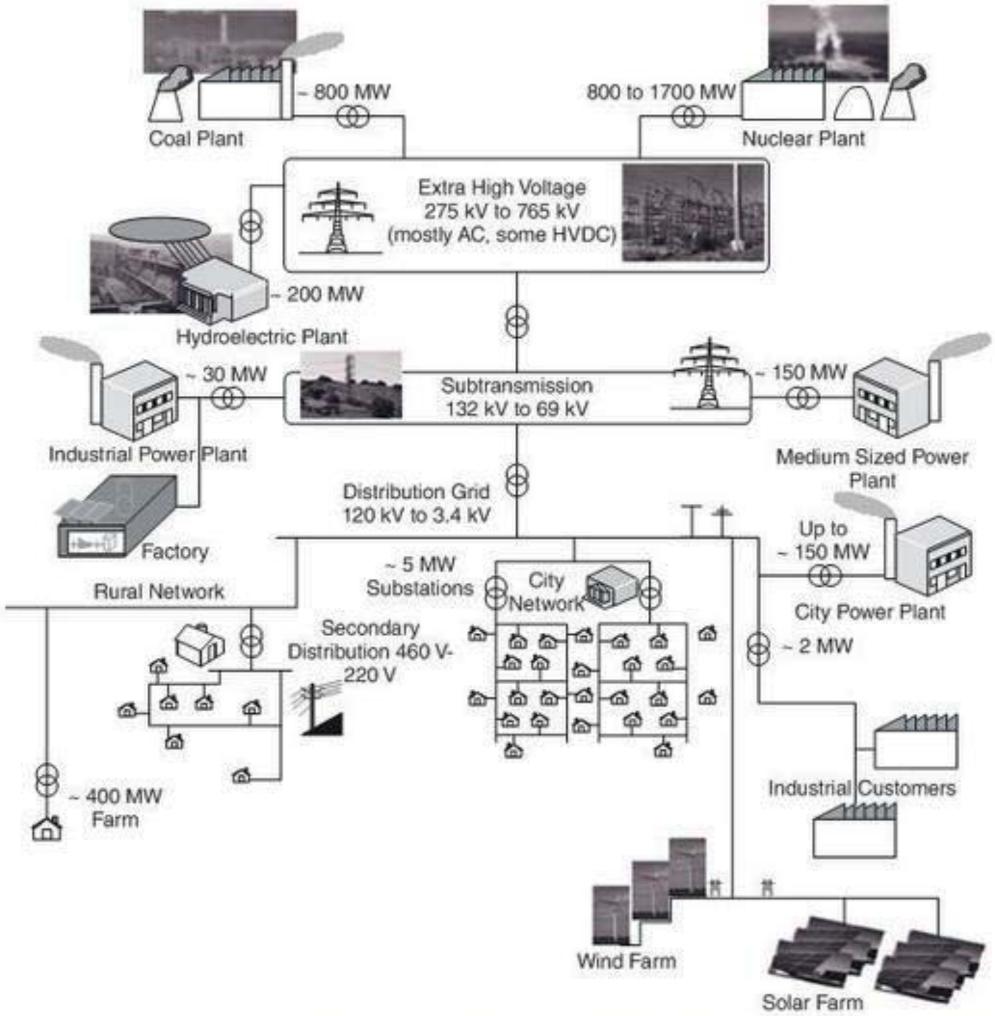

Figure 4 – Composition of a Power Grid (Keyhani, 2011)

A rather new development in the field of power grids is the smart grid. A smart grid consists of many small micro-grids which can be operated independently or in connection with the main power grid. The most common example for such a micro grid is the PV residential system. Larger in size would be the independent wind energy system of a community. (Keyhani, 2011: p.175). These semi-independent parts can even supply electricity to the main grid if excess energy is produced. Of course, smart grids need a lot of supervision and automation which is of complex nature. Furthermore, grids (classic or smart grids) are of dynamic properties. These dynamic characteristics stem from the intermittent nature of the load as well as the exchange and addition of power plants (Ter-Gazarian, 2011: p.27). In consequence, modern grids – relying on large amount of intermittent production such as renewables – need support from storage facilities to compensate fluctuations in energy supply (Keyhani, 2011: p.217).

2.3.2 Meeting the load

The main objective of any power grid is to supply the load demanded by the consumers at any point in time during a year respectively the lifetime of the grid (Keyhani, 2011: p.176). The main issue planning the capacity necessary to meet demand is the long time between planning phase and deployment. Ter-Gazarian (2011: p.27-28) indicates time frames of around five to six years until a plant goes into operation. Hence, it is imperative to derive a long-term forecast for energy production and consumption as well as transmission capacities. However, besides the absolute figures of supply, distribution, and demand there are a number of other categories to be considered such as technical (e.g. type of power plant, etc.), financial (e.g. capital vs. operating costs, etc.), environmental (e.g. emissions, land change, etc.) and social issues (e.g. creation of employment, social acceptance of nuclear power, etc.) (Ter-Gazarian, 2011: p.27-28). The following section will mainly focus on technical issues.

As already stated, the main objective of a power system is to deliver electricity to the consumer. However, delivered electricity has to be of decent quality (at acceptable voltage and frequency), secure (back up schemes if individual plants or transmission lines fail to deliver energy) and reliable (reasonable volatility in demand poses no difficulty to the power system) (Keyhani, 2011: p.176). The main problem of these requirements is that demand is not constant in nature but volatile and irrational. Still, loads are cyclic, in principle, when examined over daily, weekly, monthly or yearly periods. In each period an individual peak can be identified. These peaks have to be assessed and managed carefully because installed capacity is based on these peak loads while average loads are mostly much lower (Keyhani, 2011: p.177). A proper management of future loads can be facilitated with the help of recorded operations accounting data (Keyhani, 2011: p.178). The top priorities managing power systems are to schedule the right resources and facilities on different time scales (as mentioned above - these are daily, weekly, monthly and yearly).

In order to understand the behaviour of power systems better it is advisable to distinguish base load (does not vary over time), intermediate load (varies twice daily maximum) and peak load (rest of the load). Furthermore, it helps to define certain key indicators based on which power systems can be evaluated quickly. ((Ter-Gazarian, 2011: p.14-15) and

(Keyhani, 2011: p.204-205)). This following collection of indicators and their formulas is based on the books by Ter-Gazarian (2011), Keyhani (2011) and Krzikalla et al. (2013) and does not raise the claim to be complete. On the contrary, there is much more to consider when setting up a power system[1]. However, the purpose of this chapter is identifying certain key indicators with the help of which it will be possible to answer the research questions of this thesis.

2.3.3 Key indicators

A first good indicator describing the homogeneity of demand is the load factor.

$$load\ factor = \beta = \frac{L_{average}}{L_{max}}$$

Equation 1 – load factor of power systems

Load factors close to one are desirable as peak load and average load are similar. Values significantly lower than one can be seen in power systems which have a big difference between peak loads and average loads (often commercial electricity consumers show this behaviour). Furthermore, low load factors imply that installed capacities are big while their average use is low. Hence, the efficiency of the system is rather low - depending on the power generation.

Secondly, the power variation should be examined. This value when assessed on a day to day basis gives an indication of their volatility. Thus, days with increased management requirement are identified.

$$\delta L = L_{max} - L_{min}$$

Equation 2 – power variation of the load

Additionally, the load gradient (load rise or fall rate) is valuable. This value shows how fast loads change within a power system. It can be used to dimension storage or back up facilities and their start up times. Usually, loads are changing rather continuously while certain events can have different characteristics. One example on the supply side would

[1] Two references that give a detailed insight into the world of power systems and their specific characteristics is Ter-Gazarian's book called Energy Storage for Power Systems and especially Keyhani's book named Smart power Grid Renewable Energy Systems.

be a cloud front intermitting the production of a PV plant. On the demand side, the start of a certain TV program can increase loads significantly over a very short period.

$$L_v = \frac{dL}{dt}$$

Equation 3 – load gradient of demand and supply

A factor of importance in power systems which incorporate renewable energy sources is the residual load deriving from changes in the RE production. In principle, this value is valid for all types of power generation facilities. However, traditional plants usually have a very continuous production.

$$L_{residual,t} = L_{total,t} - L_{RE,t}$$

Equation 4 – residual load at a certain point in time due to renewable energy production

The residual load, as the difference between total energy production and renewable energy production which can be either positive or negative, gives a hint of the necessity for storage facilities. In case of a high and negative residual load, renewable energy production is responsible for an excess production which is lost without suitable storage devices (Krzikalla et al., 2013: p.15-26).

For the purpose of this study it also makes sense to calculate the hours and frequency of residual loads of either negative and positive sign. With this information it will be possible to dimension storage apparatuses such as batteries, pumped hydro, etc. The formula for this endeavour is somewhat empiric and was transformed from diagrams in Krzikalla et al.'s study (Krzikalla et al., 2013: p.19)

$$T_{residual} = t_{2,Lresidual<0} - t_{1,Lresidual<0}$$

$$T_{residual} = t_{2,Lresidual>0} - t_{1,Lresidual>0}$$

Equation 5, Equation 6 – time of constant negative/positive residual loads

For all the indicators listed above it is clear that their figure can vary tremendously depending on the time they were measured based on numerous influences such as weather, holidays, economic events, etc. (Ter-Gazarian, 2011: p.15).

2.4 Renewable Energy Technologies

Technologies harvesting energy out of renewable resources such as wind and solar irradiation are the heart of this thesis. Therefore, I will introduce the main issues regarding these technologies in the course of this chapter based on selected literature. Each section will start off by giving information on the current state of maturity on a global scale, the so called global outlook. In the next part, technical issues will be presented. Finally, there will be a section on the assessment of the potential. These parts are essentially important as the empirical part relies mainly on the presented calculations. At the end of chapter 2.4 there will be a cost comparison of solar PV, wind energy and CSP – these technologies are considered in the actual study. Nevertheless, other renewable technologies such as ocean energy systems or geothermal energy have to be introduced to understand the explanation for their rejection in the case of Cape Verde.

2.4.1 Wind Energy

2.4.1.1 Global outlook

Wind energy is nowadays still a small contributor to world energy with an installed generating capacity of approximately 318GW in the end of 2013 (REN21, 2014: p.15). This accounts for only a 1,2% of world electricity production (IRENA, 2012b: p.13). However, the last decades have seen a steady increase of wind energy's share. Looking at absolute numbers reaffirms this trend: from close to zero in the 1980s to 7,5TWh in 1995 and finally to roughly 534TWh in 2012 (Observ'ER, 2013). During the past five years wind power has increased its capacity the most among all other renewable energy sources (average growth rate of 21,4% since 2008) (REN21, 2014: p.56).

The European Union is still the strongest contributor of wind power to the world's energy mix with 37% of the total. This comes as no surprise as Denmark and Spain supply large shares of their domestic electricity demand via this technology (33.2% and 20.9% respectively). Spain even produced more electricity from wind power than from any other source and several German states could show off 50% shares supplied by wind energy. The EU as largest supplier for electricity harvested from wind is closely followed by Asia with 36% of the total capacity (REN21, 2014: p.56).

All in all, years of explosive growth in this specific renewable sector has brought about considerable environmental benefits. In many areas of the world wind energy has replaced large amounts of fossil fuelled power production. It could be shown that carbon emissions from wind power plants are 40 times less than from usual natural gas power plants (REN21, 2014: p.57).

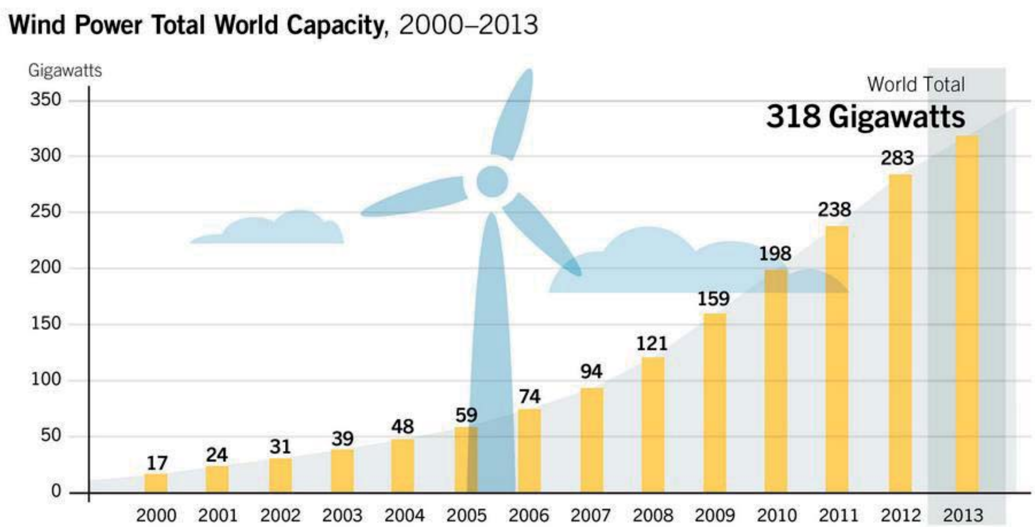

Figure 5 – Evolution of Wind Energy Capacity (REN21, 2014: p.59)

2.4.1.2 Technology

The basic idea and concept of using a rotor to harvest wind energy is ancient and has been used for centuries all over the world (EWEA, 2009: p.63). In general, wind energy technologies transform kinetic energy of moving air into useful mechanical power via a generator in the wind turbine (IRENA, 2012b: p.4). This method of generating useful energy is emission-free and available without additional costs in many areas. A supplemental advantage of wind energy over some other renewable energy sources is its permanent production possibility. In principal, wind energy plants can harvest energy 24 hours a day which allows them to produce power at competitive costs ((Wizelius, 2007) and (Demirbas, 2005: p.178-179)). The ultimate power generated by a wind turbine depends among other factors on the capacity of the turbine (kW or MW), wind speeds, height of the turbine and finally the lengths of the blades (respectively the diameter of the turbine) (IRENA, 2012b: p.4).

Wind energy can be sub-classified into several categories namely location, size and aggregation. The first classification which wind turbines are divided in is their location onshore or offshore. There are two reasons that can explain accepting risks and difficulties from building offshore wind turbines. Firstly, there is a huge potential for offshore wind (EWEA, 2009: p.70-73) and secondly it can be hard to find sufficient space on land – this phenomenon can be observed in the case of Denmark and Germany (Wizelius, 2007). Next, wind turbines are commonly differentiated by their size. On the one hand we have small wind turbines which produce up to 100kW and on the other we designate big wind turbines producing more than 100kW of electricity. This classification of size is not necessarily important. However, small wind turbines are in the majority of cases used to supply local demand, satisfy social benefits or achieve rural electrification (especially in developing countries) (IRENA, 2012b: p.9). Size also matters in regards of deployment in a wind park or an individual turbine. As already mentioned, smaller wind turbines are most often used to supply local demand and therefore are stand-alone turbines. While, big turbines (up to 8MW (Wind Power Monthly, 2014)) are also deployed as individual plants they are very often accumulated to form wind parks (up to 240 turbines and 1200MW (Tweed, 2014)) and thus increase power generation. In conclusion, depending on the prospective use the design of the generator can be selected.

2.4.1.3 Assessment of Potential

With a good understanding of what kind of wind turbine technologies and locations are commonly used it is necessary to assess the local potential. Basically, one accumulates data needed (economic, environmental, social, etc.) and gives recommendations. Based on these recommendations further planning can be continued or cancelled. In the case of wind power the most influential factor is the wind itself. However, many other factors can decrease chances of success drastically (Wizelius, 2007: p.221). These will be discussed briefly in the following section.

First and foremost, some knowledge of the size of the wind resource across the area of interest has to be collected (EWEA, 2009). Usually, power of wind energy is expressed as wind speeds or energy density. Consequently, there will be a limit value that has to be exceeded or its power will be insufficient for an economic feasible project (EWEA, 2009). The simplest way to get a feeling for the wind resource is to use wind resource maps which are put together from data of meteorological stations (Wizelius, 2007: p.222). A more sophisticated way of analysing the wind's behaviour is to study wind atlases[2] or similar computer programs (EWEA, 2009).

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[2] WAsP, WindScout, etc.

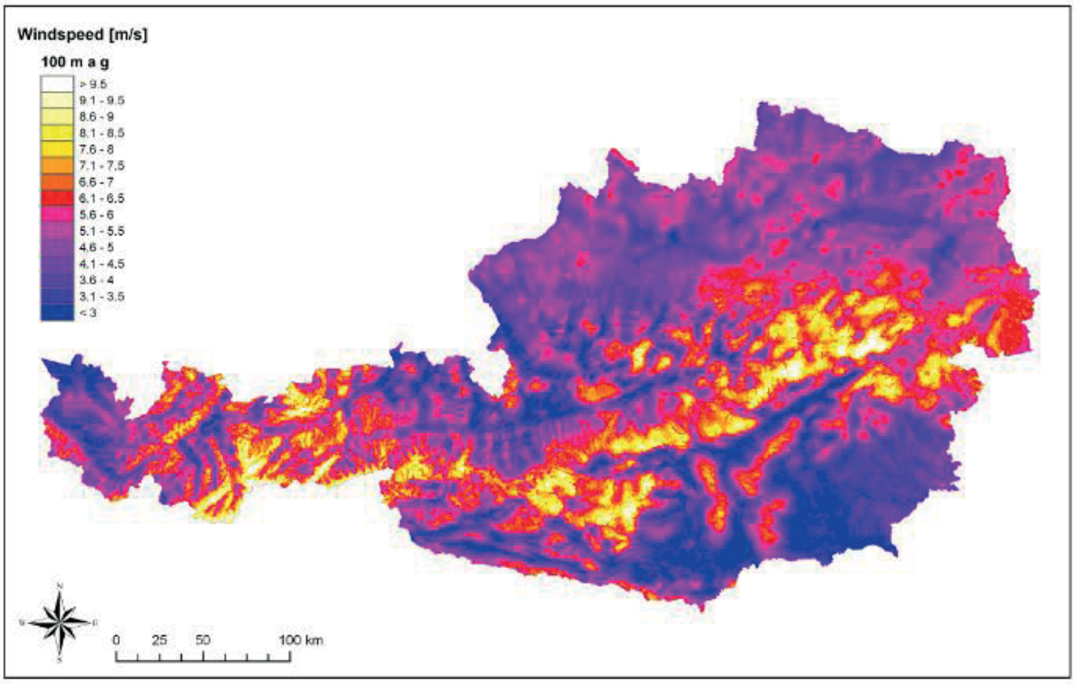

Figure 6 – Wind Atlas for Austria (Krenn et al., 2010)

Both methods are rather used to facilitate the first selection of sites than to predict exact values. The most accurate results can be derived through on-site measurements with anemometer and wind vane. The only downsides to this are the immense costs and the time consumption (EWEA, 2009: p.32). Analysing the wind resource intensively is vital to come up with a sound economic calculation in the end. In EWEA's study (2009) it is shown that long term effects of an increased wind speed by 67% can result in an increasing production by 134%. Once, the wind resource is studied extensively enough for one's purposes it is crucial to predict the possible power output.

The last technical step therefore is the estimation of power production. In this process all previously mentioned factors are accumulated and evaluated according to their results. The power estimation is usually calculated based on the following equations.

$$A = \pi * r^2$$

Equation 7 – Rotor area (Wizelius, 2007: p.225)

Here A stands for the rotor area and R indicates the radius of the wind turbine.

$$P = T_w * A * C_e$$

Equation 8 – Power production of a WTG (Wizelius, 2007: p.225)

To calculate P (Estimated power production) one has to consider T_w (estimated power of the wind resource per m² and year) and (C_e – factor indicating how much energy can be harvested by a specific turbine (normally 0.25)).

2.4.2 Solar PV

2.4.2.1 Global Outlook

Energy production from photovoltaic (PV) panels accounts for roughly 0,85% of global electricity demand, according to IEA (2014a: p.5). PV is predicted to increase its share to 1% in 2014. The present fraction of 0.85% equals 139GW installed capacity worldwide ((REN21, 2014: p.105), (IEA, 2014a: p.5)).

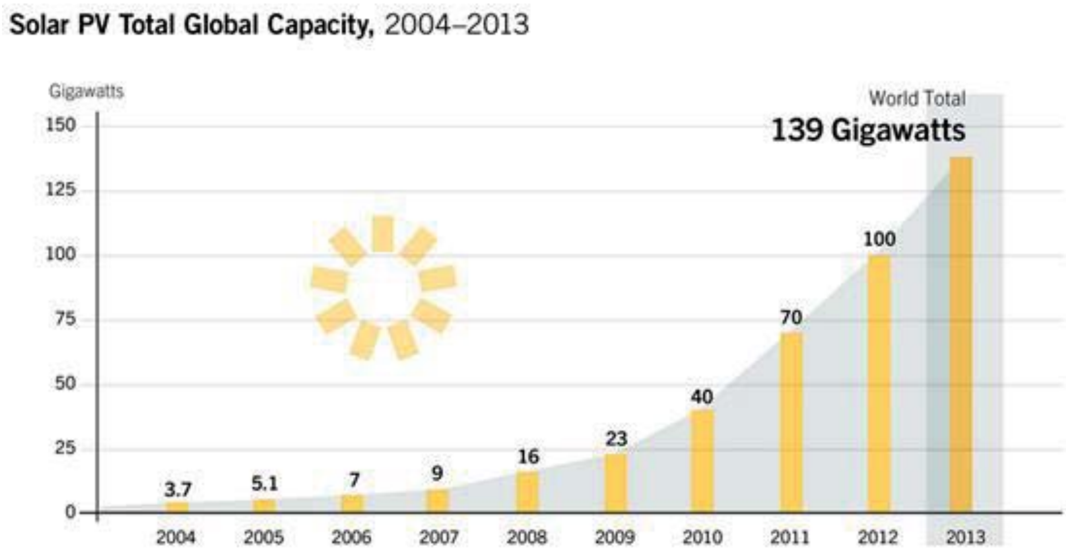

Figure 7 – Evolution of Solar PV Capacity (REN21, 2014)

The five strongest countries in terms of PV are China, Japan, USA, Germany and Italy. All together they amount to more than 75% of all installations ((IEA, 2014a: p.5), (REN21, 2014: p.111)). On average, Germany produces 6.2% and Italy 7.8% of their annual electricity demand from PVs. Many other countries have even higher peak rates on a daily basis. Some African countries have been identified to serve as promising markets in the future.

The strong growth during the last years comes as no surprise. IRENA (2014b), REN21 (2014) and the IEA (2014a) all point towards the increased efficiencies, decreased costs and simple deployment as beneficial factors. Besides onshore-wind turbines solar PV reached new levels of cost competitiveness. Thus, prices declined by 65-70%. The levelised costs of electricity (LCOE) from PV panels are estimated to be as low as USD 0,11/kWh – 0,35/kWh (IRENA, 2014b: p.36). However, this depends strongly on the market and the deployment site. REN21 (2014) states that rooftop solar panels fell under the price of retail electricity prices or fossil fuel options and hence strengthened the case for the competitiveness of solar PV. Like wind power markets, PV markets have seen rapid growth and costs have fallen dramatically (Demirbas, 2005: p.178). This development has been witnessed in multiple nations – also developing states and/or island states in which the grid is not reliable or spread out (IRENA, 2014b: p.36).

2.4.2.2 Technology

The solar energy penetrating Earth every year is massive. An estimated amount of 885 million TWh of radiation hits our planet annually[3] (IRENA, 2012a: p.8). Consequently, it was only a matter of time until this unlimited source was tapped. First experiences with solar radiation transforming into electricity go back over 150 years during the construction of transatlantic telecommunication cables[4]. Its first real application came in aerospace powering satellites (Wagner, 2010: p.3). Nowadays, PV is an experienced and mature technology that has proven its feasibility and durability for decades. Furthermore, it taps a sustainable energy source which makes it unsusceptible to fuel price volatility (IRENA, 2012a: p.15). In order to understand the applicability of PV it seems advisable to explore the complex nature of PV.

Photovoltaic panels or solar cells convert sunlight (solar radiation) directly into electricity ((Demirbas, 2005: p.178), (Wesselak and Voswinckel, 2012: p.1), (IRENA, 2012a: p.4) and (Wagner, 2010: p.34)). The technology is based on the characteristics of semi-

[3] This number can only be grasped when compared to global energy demand which was 0.155 Million TWh in 2012 and is expected to rise to 0.233 Million TWh by 2040 in the Current Policy Scenario in the World Energy Outlook 2014 (IEA, 2014b). Current global energy demand therefore is by a factor of 5729 smaller than annual solar radiation.

[4] Engineers of that time used a testing apparatus made out of selenium and reported that measuring worked fine during night-time but found deviations when working in sunlight. In consequence, experiments were conducted finding that the electric resistance of selenium changes due to the abundance of light.

conductors[5]. To scale up production solar cells are grouped to form PV modules (IRENA, 2012a: p.4). Although, additional components are needed PV systems do not have moving parts and thus need little maintenance (Wesselak and Voswinckel, 2012: p.1). There is a wide range of photovoltaic technologies on the market. Usually, they are characterized into three categories according to their maturity and material ((U.S. Department of Energy, 2012) and (IRENA, 2012a: p.9-11)).

First generation solar cells or crystalline solar cells are the dominant and most mature form of PV panels on the market. The second generation of photovoltaic panels are the thin-film solar cells. According to (Wesselak and Voswinckel, 2012) they are becoming a real economic alternative. The main difference to first generation PV is the thickness of the material used. In the last category of PV or third generation solar cells one can mainly find future developments in the PV markets. These technologies are not yet ready for commercial deployment but experience permanent evolution and high efficiencies.

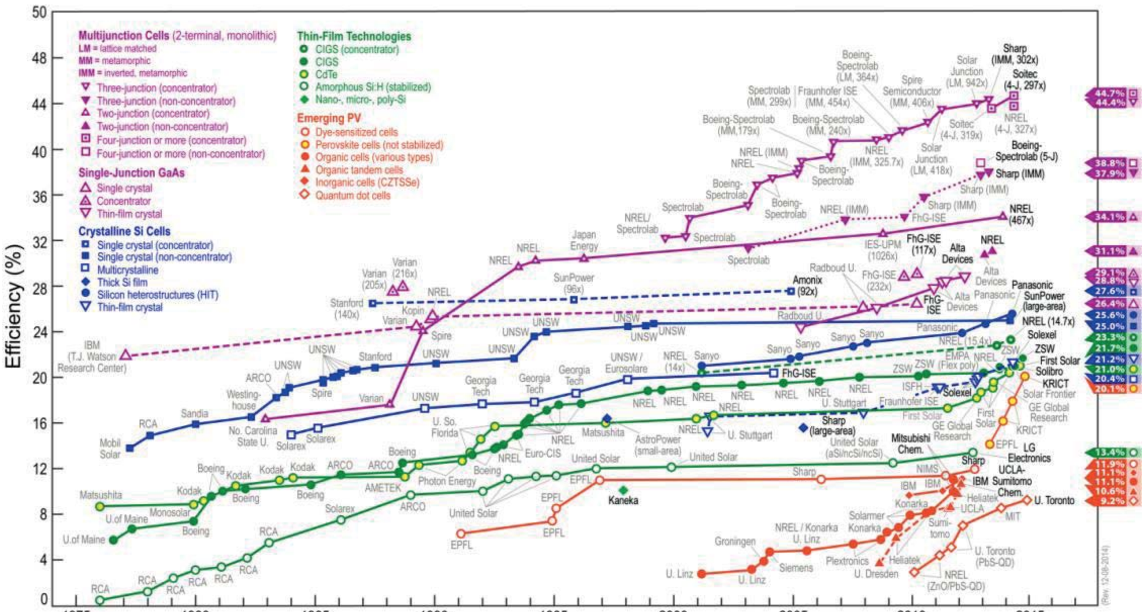

Figure 8 – PV Technologies and their efficiency rates (NREL, 2015)

[5] Semi-conductors when exposed to sunlight absorb photons. This process provides enough energy to make electrons move between the two materials (one direction is favoured). Consequently, negative and positive charges are created. Thus, voltage and a DC current are generated which is readily available for usage ((Wesselak and Voswinckel, 2012), (Wagner, 2010) and (IRENA, 2012a)).

2.4.2.3 Energy Production of a photovoltaic cell

As already mentioned, the energy production of photovoltaic cells is directly dependent on the solar radiation a solar panel is exposed to. This irradiance can be direct or diffuse based on momentary circumstances at the site of deployment. For the aforementioned reasons it is crucial to select a site in which the mean annual value (kWh/m²/year) is comparatively high (IRENA, 2012a: p.8). This mainly builds upon the geographical location as radiation is stronger closer to the sun (closer to the equator) and closer to a perpendicular angle between surface and solar ray (Wesselak and Voswinckel, 2012: p.22). Wagner (2010: p.4) seconds this opinion and adds the quality of auxiliary components as second most important factor in the production of energy from photovoltaic cells. Especially, the availability of the system during the year has an influence on the gross production. Therefore, it can be concluded that long-term mean values of radiation and weather have to be collected to make a sophisticated prediction of prospective production data. These values are readily available in radiation atlases (very similar to wind atlases) (Wagner, 2010: p.23).

Subsequently, I will present the calculations which derive the predictable power output of a solar panel based on the elaborations by (Wagner, 2010: p.6) in a short form of his.

First we need to introduce the solar constant E which was defined by World Meteorological Organisation.

$$E = 1367\ \frac{W}{m^2}$$

Equation 9 – Definition of the solar constant

Now that we have introduced this constant we can define the power output as P_{el} which is

$$P_{el} = \eta * E * A * cos\Theta$$

Equation 10 – Power output of a solar cell

Here, η stands for the efficiency, A for the area which is penetrated by solar radiation and cosΘ is the angle in which the radiation reaches the area. In principal, cosΘ is affected by many more factors like geographical location, azimuth and season. However, we will skip this part for the sake of comprehensibility and simplicity.

Consequently, we have to calculate the mean value of solar radiation penetrating a specific area.

$$G = \int_{SR}^{SS} E(t)dt$$

Equation 11 – Mean value of solar radiation between sunrise and sunset (Wagner, 2010)

Table 1 – Mean values of solar irradiation for the island of Santiago (Cape Verde) in January (data taken from (European Union, 2015))

Mean value of solar irradiation					
Time	G	Time	G	Time	G
06:52	96	10:22	740	13:52	713
07:07	148	10:37	764	14:07	681
07:22	203	10:52	784	14:22	646
07:37	258	11:07	801	14:37	607
07:52	314	11:22	813	14:52	565
08:07	368	11:37	821	15:07	520
08:22	421	11:52	825	15:22	472
08:37	472	12:07	825	15:37	421
08:52	520	12:22	821	15:52	368
09:07	565	12:37	813	16:07	314
09:22	607	12:52	801	16:22	258
09:37	646	13:07	784	16:37	203
09:52	681	13:22	764	16:52	148
10:07	713	13:37	740	17:07	96

The previous formula describes the mean value of one day from sunrise (SR) to sunset (SS) as an integral of the solar constant. With this value G we can then calculate the mean annual value as follows.

$$\bar{G} = \frac{1}{n} * \sum_{i=1}^{n} G_i$$

Equation 12 – Radiation energy received and summed up to daily, weekly or monthly values (Wagner, 2010)

$\bar{G}$ is the value that can usually be found in solar atlases as daily, monthly or annual value depending on the amount (n) of days used. An example of such a table is Table 2. The values shown could easily be improved by up to 35% by a tilted mounting position or a tracking device which moves the panel according to the altitude of the sun (IRENA, 2012a:

p.7). Again, I will not discuss this issue in detail for the sake of comprehensiveness and simplicity.

Table 2 – Daily, Monthly and Annual Values for solar irradiation collected by PV panels (data taken from (European Union, 2015) and adapted by (KE, 2015))

Irradiation Energy received per day, month, year		
Month	**$\bar{G}$ daily average**	**$\bar{G}$ monthly**
January	4.300 Wh/m²	133.000 Wh/m²
February	4.820 Wh/m²	135.000 Wh/m²
March	5.710 Wh/m²	177.000 Wh/m²
April	5.350 Wh/m²	161.000 Wh/m²
May	5.280 Wh/m²	164.000 Wh/m²
June	4.790 Wh/m²	144.000 Wh/m²
July	4.410 Wh/m²	137.000 Wh/m²
August	4.280 Wh/m²	133.000 Wh/m²
September	4.480 Wh/m²	134.000 Wh/m²
October	4.650 Wh/m²	144.000 Wh/m²
November	4.360 Wh/m²	131.000 Wh/m²
December	4.190 Wh/m²	130.000 Wh/m²
Total/Average	4.718 Wh/m²	1.723.000 Wh/m²

With the daily, monthly or annual mean value it is possible to compute the gross energy output by the solar panel. Following formula is used in which the index m indicates a monthly mean value as shown in the following formula.

$$W_m = G_m * \eta$$

Equation 13 – Monthly electricity production of a solar panel (Wagner, 2010)

In this equation η represents the overall efficiency of the system and G_m is the monthly value calculated with Equation 12. Finally, we can calculate the total annual electricity output of the PV panel.

$$W_a = 12 * W_m$$

Equation 14 – Annual electricity production of a solar panel (Wagner, 2010)

2.4.3 CSP

2.4.3.1 Global Outlook

Concentrated Solar Power as a renewable energy sources on an industrial scale had its beginning in the 80s and 90s (Py et al., 2012: p.308). The first plants (parabolic trough technology) were installed in the Mohave Desert in California and are still operating today (IRENA, 2012d: p.11). Basically, these unconventional plants used existing thermal power plants and applied concentrated solar rays as the heat source (Py et al., 2012: p.308). Despite the success of these plants, interest in deploying CSP power plants came to a halt after 1991 which persisted until 2006 (Ummadisingu and Soni, 2011: p.5170). Since then, concentrated solar power is again used to produce electricity with Spain and the US as the main contributors (70% and 24% of all installed capacity respectively) (Klein, 2013: p.13925). At the end of 2012, 1.9GW was installed worldwide (dominated by parabolic trough technology) (IRENA, 2012d: 11). Moreover, numerous new plants are in the developing phase or under construction at the moment. Projections promise between 30-150 GW installed capacity by 2020 (Py et al., 2012: p.309-311). The possibility to install CSP plants depends on the abundant solar resource. According to Larraín and Escobar (2012: p.124) the minimum solar irradiation for the deployment of such technologies is around 4.5kWh/m²/day or 2000kWh/m²/year (Ummadisingu and Soni, 2011: p.5170). Many sites around the world, however, offer values of direct normal irradiation[6] (DNI) which are substantially higher[7]. Additionally, CSP can work in a hybrid technology with traditional thermal power plants or in cooperation with energy storage devices (most effectively thermal energy storage) to increase operating hours and thus efficiency (Klein, 2013: p.13925).

2.4.3.2 Technology

CSP or solar thermal technologies use the possibility of concentrating solar radiation for the purpose of increasing temperature and apply it to a conventional steam turbine process (Clifton and Boruff, 2010: p.5272). In principle, power plants fuelled by concentrated solar power are nothing more than thermal power plants in which the boiler has been replaced by large surfaces of optical devices able to transform solar radiation into high temperatures (Py et al., 2012: p.306-307). These high temperatures are applied

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[6] DNI is defined as the energy measured on a surface that is perpendicular to the ray and tracks the sun’s movement (IEA, 2010: p.9)

[7] California has typical values of 5.8kWh/m²/day or Northern Chile with values around 8kWh/m²/day.

to different kinds of fluids which exchange their energy with water and thus power a steam cycle. The power output of such a power plant relies mainly on the direct normal irradiation at the level of the reflectors and therefore does not produce any electricity during cloudy conditions or at night time. However, many new installations use thermal energy storage to bridge these hours and increase their capacity factor (Larraín and Escobar, 2012: p.124).

The CSP technologies are commonly divided into two groups. The first group uses reflectors to concentrate incoming rays at one specific point (solar tower and parabolic dish) while the second group concentrates sun radiation at a focal line (parabolic trough and linear Fresnel reflector) (IRENA, 2012d: p.4). Another differentiation between these two groups of technologies can be made according to their tracking devices which have two or one axis respectively. The following paragraph will shortly introduce all four technologies starting with the one mostly used.

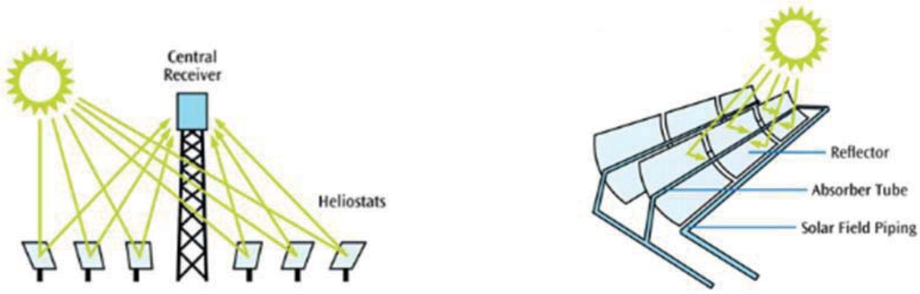

Figure 9 – Central Collector Technology (e.g. Solar Tower) and Parabolic Trough Technology (Clifton and Boruff, 2010: p.5273)

Parabolic troughs are the most mature CSP technology for the production of electricity. Here, direct normal irradiation is reflected by curved mirrors onto an absorber tube (see Figure 9). Through these absorber tubes a heat transfer liquid is pumped constantly heating up as it moves across the various troughs. After a certain length the liquid is hot enough to drive a steam cycle (Klein, 2013: p.13925). The second most advanced technology is the solar tower. This technique uses numerous tracked heliostats distributed over large areas of land to reflect all incident radiation onto a receiver surface mounted on a tower (Ummadisingu and Soni, 2011: p.5171). This technology generates the highest temperatures (temperatures of more than 1500°C possible) of all CSP methods but has an extensive land use (IRENA, 2012d: p.4). The linear Fresnel reflector is based on almost the same technique as the parabolic trough but uses several mirrors for one absorber tube. Lastly, there is the parabolic dish technology. This method of generating electricity is the most modular of all above mentioned. In principle, each dish can be used as a stand-alone system. The problem with this technology is that it cannot be connected to any kind of efficient power storage (Clifton and Boruff, 2010: p.5272).

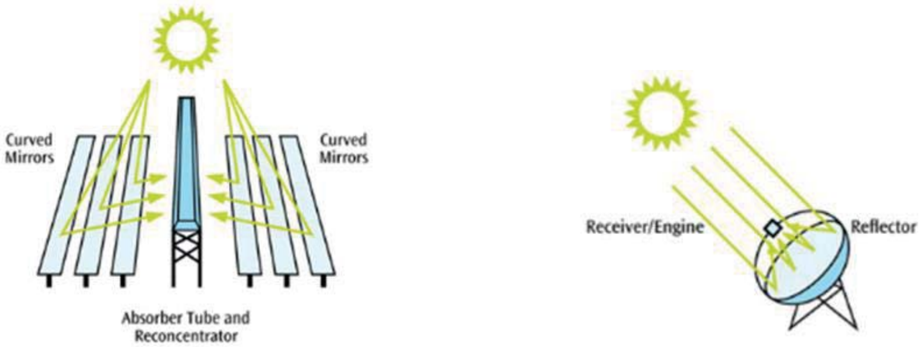

Figure 10 – Linear Fresnel Technology and Parabolic Dish Technology (Clifton and Boruff, 2010: p.5273)

The main difference between CSP and PV is that CSP relies on incoming DNI while PV can be fuelled by diffuse radiation - occurring on cloudy days or shortly after sunset (IRENA, 2012d: p.5170). The main advantage of CSP is its ability to apply energy storage or hybrid systems (Ummadisingu and Soni, 2011). Since, hybrid systems use fossil fuel powered generators to bridge periods of low solar irradiation I will not further elaborate on this approach. However, thermal energy storage is a very good alternative. For this purpose, it is necessary to over-dimension the solar field and produce excess energy during sunny conditions. This excess energy is then stored in the form of hot molten salt or oil which is only pumped through the heat exchanger when needed (Py et al., 2012: p.307). Thereby, CSP power plants can produce electricity outside of sunlight hours (generally demand peaks after sunset) (Ummadisingu and Soni, 2011: p.5170). One operating CSP plant in Spain (Gemasolar) uses a thermal energy storage which is capable of providing nominal electricity output for up to 15 hours (Burgaleta et al., n.d.). By using a thermal energy storage device it is possible to supply a constant base load capacity. For longer hours without sufficient solar irradiation a hybrid system would have to be installed. Additionally, CSP power plants can substitute spinning reserve capacities of conventional thermal power plants (Trieb et al., 2009b: p.54-56). Thus, concentrating solar power is an important benefactor to grid stability in an electricity system fully relying on RE.

2.4.3.3 Assessment of Potential

In the successive paragraphs the process of deriving output of a CSP power plant will be introduced. In order to get a comprehensive overview of CSP potential this elaboration will stick to the basic idea and not touch upon detailed parameters (individual efficiency values, etc.). Additionally, Fresnel and parabolic dish systems will not be taken into further consideration as the experience with these systems has not yet reached a mature level (see above).

The first step of the assessment focuses on the solar resource. A CSP power plant is mainly influenced by the solar irradiation at the selected site. In specific, this means it is dependent on the direct normal irradiance (DNI) (Larraín and Escobar, 2012: p.124). As mentioned above the minimum values are identified to be above 2000kWh/m²/year. Based on the fact that electricity output depends on the amount of solar energy reaching the reflectors it can be said that larger land area respectively reflector surfaces mean higher installed capacities. The average values given by experts in the field ((Clifton and Boruff, 2010), (Burgaleta et al., n.d.), (Ummadisingu and Soni, 2011), (Trieb et al., 2009a), (Trieb et al., 2009b) and (IEA, 2010)) are found between 20.000 and 30.000m² of land per MW installed, 6-12m² land per MWh and year, or 6.000-15.000m² of reflector surface per MW. All these values indicate that the overall efficiency is rather limited. However, it is comparable to PV systems which have efficiency rates between 10-20%. Trieb (2009a), IEA (2010) and IRENA (2012d) give efficiency rates of 10-20% for trough and solar tower systems (applied value will be 14% as the average value).

The overall formula used to calculate the electric output is the following and was formed based on the information and data collected in the above mentioned literature.

$$P_{el} = DNI * reflector\ surface * hours\ of\ irradiation * \eta$$

Equation 15 – Formula for the calculation of the power output by a CSP plant

In the equation above P_{el} stands for the total electricity output by the power plant. Furthermore, DNI indicates the incoming direct normal irradiance at the location under observation. DNI has to be multiplied by the available reflector surface and the time of irradiation (sunlight hours per day, month, year, etc.). Additionally, an efficiency parameter has to be added. It was already mentioned above that this overall efficiency takes values around 15%. Equation 15 can be used to calculate hourly, daily, monthly or yearly values depending on the timescale needed. After a simple transformation, Equation 15 can also be used to calculate the reflector surface needed in order to supply a certain given amount of electricity.

The following paragraph will elaborate on the computation in case thermal energy storage is applied and is based on the models Trieb et al. (2009b). Adding energy storage to the CSP plant increases usability in terms of full load hours and usability (base load, intermediate load, peak load). In order to simulate this, the computation has to take additional factors into consideration. For this purpose we will introduce the concept of solar multiples (SM). A CSP power station with SM1 has a solar field that provides just enough energy for the nominal output. For larger SM values more energy is collected than can actually be fed to the turbine. Plants with SM values above 1 are either designed to minimize risk (balance electricity output during hours of lower irradiation values with added collectors) or to supply thermal energy storage (SM2-4).

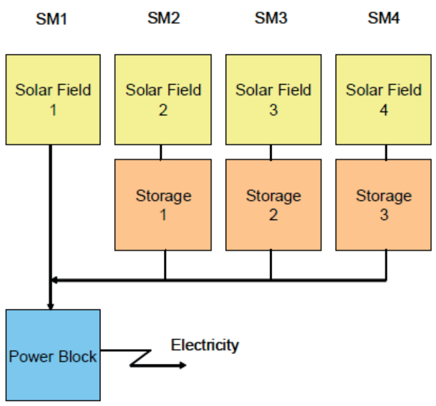

Figure 11 – Concept of a CSP plant with SM4 (Trieb et al., 2009b)

In the beginning, we will again calculate the overall needed reflector surface for the nominal energy needed (total electricity demand). For this purpose we go back to Equation 15 and transform it into Equation 16. Nominal output (P_{el} in Watt hours), DNI, solar-to-electricity efficiency (round-trip efficiency of TES is at roughly 98% according to Sioshansi and Denholm (2010)) and time of irradiation are set as fixed values leaving only the reflector surface as the unknown.

$$reflector\ surface = \frac{P_{el}}{DNI * hours\ of\ irradiation * \eta}$$

Equation 16 – Calculating the required reflector surface

Due to the fact that CSP plants with energy storage are able to supply electricity consistently at the same level it is reasonable to use it as a contributor to base load. Consequently, all energy that exceeds the base load value has to be taken up by storage reservoirs. For this reason, it is required to compare load curve with production curve.

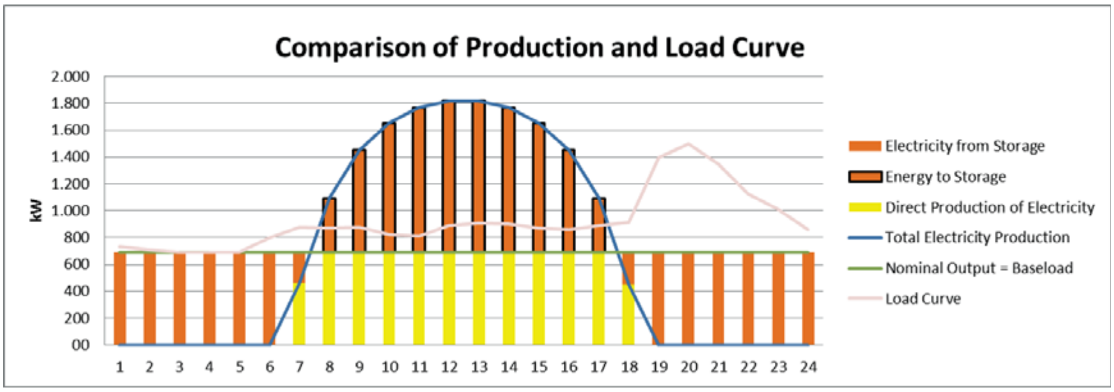

Figure 12 – Production and storage curve for a CSP plant (Adjusted curves based on (IEA, 2010: p.16))

Figure 12 shows such a production curve for a CSP plant which is split into direct use and storage. Furthermore, it illustrates that the excess energy is stored temporarily until DNI is too little to fuel the generator. This is the point in time at which thermal storage releases its energy and maintains power production for as long as enough energy is abundant. In Figure 12 energy storage provides energy until direct production sets in again (high SM value).

Dimensioning of the storage reservoir requires the calculation of electricity which can directly be fed into the grid as well as the excess energy. In Figure 12 the yellow bars represent the direct use while the orange bars with blue border represent excess energy. The amount of excess energy will determine the energy storage capacity. Finally, we can determine the solar multiple. The value of the solar multiple is the result of the division of total collector area over collector area required to sustain nominal output under average conditions (average DNI).

$$SM = \frac{total\ collector\ surface\ installed}{collector\ surface\ to\ sustain\ nominal\ output}$$

Equation 17 – Calculating the solar multiple (adapted from (Trieb et al., 2009b: p.80))

2.4.4 Biomass

Biomass as source for electricity is not available on Cape Verde due to the natural conditions. In my interviews with Mr Sanches and Mr Delgado, both experts in the field of renewable energy and specialised on Cape Verde, reiterated this standpoint. For this reason, I will not consider electricity production based on biomass in my empiric study (see chapter 3) but I will nonetheless give a short overview of the underlying technology.

2.4.4.1 Global Outlook

Global Biomass use in 2013 amounted to roughly 15 722 TWh and is believed to increase on a worldwide scale. Biofuels and electricity production from biomass both made up only approximately 10% of this value (REN21, 2014: p.32). Consequently, most biomass use is traditional use (especially in developing countries) for cooking and heating based on wood, crop residues and animal dung ((Tomaselli, 2007: p.v), (Demirbas, 2005: p.174) and (REN21, 2014: p.31)). According to Tomaselli 70 per cent of total biomass energy takes place in developing countries (2007: p.v).

Modern bioenergy is commonly used to produce three different manufactures, namely electricity, biofuel and heat (World Bioenergy Association, 2014: p.4). Moreover, the electricity production from biomass relies mainly on crop residues, wood pellets, wood chips, biodiesel, ethanol, organic municipal waste (REN21, 2014: p.33).

2.4.4.2 Definition

Biomass is identified as a crucial renewable and sustainable alternative to fossil fuels and one of the most omnifarious resources on Earth (Ackom et al., 2013: p.101). In more detail, biomass is solar energy chemically stored within organic matter (plants, algae and animal manure). Therefore, it is contained in all of Earth’s living matter. It only excludes biological material embedded in geological formations or fossils ((Tomaselli, 2007: p.1), (Gupta et al., 2014: p.3) and (Demirbas, 2005: 174)). The energy recovered via various methods is called bioenergy. The chemical formula of the energy storing process is called photosynthesis (Equation 18).

$$6CO_2 + 6H_2O \xrightarrow{Light} C_6H_{12}O_6 + 6O_2$$

Equation 18 – Photosynthesis (Process of storing energy within organic matter) (Gröbl, 2012: p.6)

2.4.4.3 Technology

Due to its complex nature biomass has to be analysed based on three components, namely feedstock, conversion and power generation (IRENA, 2012c: p.4). The basis for the generation of bioenergy from biomass is the feedstock which is the holder of the energy. For individual applications it makes sense to use specific fuels in order to gain the highest energy yield. In general, the differentiation between first and second generation fuels is appropriate (Gupta et al., 2014: p.ix). The difference is that first generation fuels are also an integral part of the food production industry and consequently more expensive or not accessible for various reasons (Ackom et al., 2013: p.104).

One appliance of biomass is electricity production. Here, almost any kind of organic material can be used but in most cases solid biofuels are combusted (Kaltschmitt and Hartmann, 2001: p.57-72). The major source is wood and its residues (Ortner, 2014). Additionally, grass, straw, dried manure, solid waste or sugar cane can be applied (Gupta et al., 2014: p.35). Therefore, the largest amount for the generation of power comes from non-traded sources which are consumed locally (IRENA, 2012c: p.25). Once, the right fuel for the production of energy is found it has to be converted into usable energy. This is mainly done via thermo-chemical (combustion, gasification, and pyrolysis) or bio-chemical processes (anaerobic digestion) ((World Bioenergy Association, 2014: p.4), (Demirbas, 2005: p.174) and (IRENA, 2012c: p.5)). For more sophisticated information on these processes I suggest to look at chapter 2 of IRENA's cost analysis series (IRENA, 2012c) or chapter 8, 9 and 10 of Kaltschmitt and Hartmann (2001).

2.4.5 Geothermal Energy

The deployment of geothermal energy in Cape Verde seems to be promising based on its location close to the seismic belt. Still, GESTO (2011) in its study on renewable energy of Cape Verde found that no significant amount of electricity can be harvested based on this technology. This evaluation, the limited resources to conduct a feasibility study on my behalf and the complexity of geothermal power production led me to the conclusion to reject geothermal energy from energy mixes for the various islands. In the following, I will give a summary of the main facts about geothermal energy production for the sake of a holistic approach to the topic of renewable energy.

2.4.5.1 Global Outlook

Geothermal energy production is still a very little contributor to global energy supply. According to REN21 (2014) the power capacity was 12GW in 2013 which equals roughly 1% of the power production from hydropower plants. Still, many geothermal power plants are in the developing stage and the potential is huge (Matek, 2013: p.5). Electricity production was about 76TWh and heating amounted to 91TWh in 2013 (REN21, 2014: p.39). Some of the deployed power plants produce both, heat and electricity. The development of the geothermal energy sector is encouraging with more than 500MW of capacity additions for electricity production in 2013. The largest producers were the United States followed by the Philippines, Indonesia, Mexico and Italy (Matek, 2013: p.12). Power plants converting geothermal heat into electricity have sizes of up to 20MW installed capacity. Majority of these plants tap high enthalpy sources (Stober and Bucher, 2014: p.33). In the heat sector the largest producers are China, Turkey and Iceland. These countries have the perfect conditions to apply direct-use power plants as geothermal availability and heat demand coincide (REN21, 2014: p.40). Here, sizes of the power plants of up to 70MW are feasible. In general, Kenya is one of the fastest growing markets in the geothermal energy sector making a promising case for the deployment of this energy source in an increasing amount of developing countries (REN21, 2014: p.39).

2.4.5.2 Definition

Geothermal energy is the heat stored in Earth's crust (Kolditz et al., 2013: p.12). In fact, 99% of the Earth's mass exceeds a temperature level of 1000°C whereas, the average temperature on its surface is 14° (Kosinowski and Ranke, 2012: p.12). The calculated power this geothermal energy incorporates is roughly 40 million MW ((Stober and Bucher, 2014: p.8) and (Gupta et al., 2007: p.20)[8]). However, the extractable energy from this source depends strongly on the location, depth of the resource, the abundance of groundwater and the rock chemistry (Gupta et al., 2007: p.11). Also, geothermal energy reservoirs can be exploited leading to regeneration cycles of the duration of centuries or more (Kosinowski and Ranke, 2012: p.12). To use geothermal energy most efficiently it is advisable to explore encouraging sites. These anomalies of the temperature gradient which can be observed around volcanoes or geysers are promising locations for the

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[8] Kosinowksi and Ranke (2012) speak of $12*10^{24}$ MJ energy stored

economic harvest of energy. Consequently, all geothermal fields are located close to plate boundaries (Gupta et al., 2007: p.29).

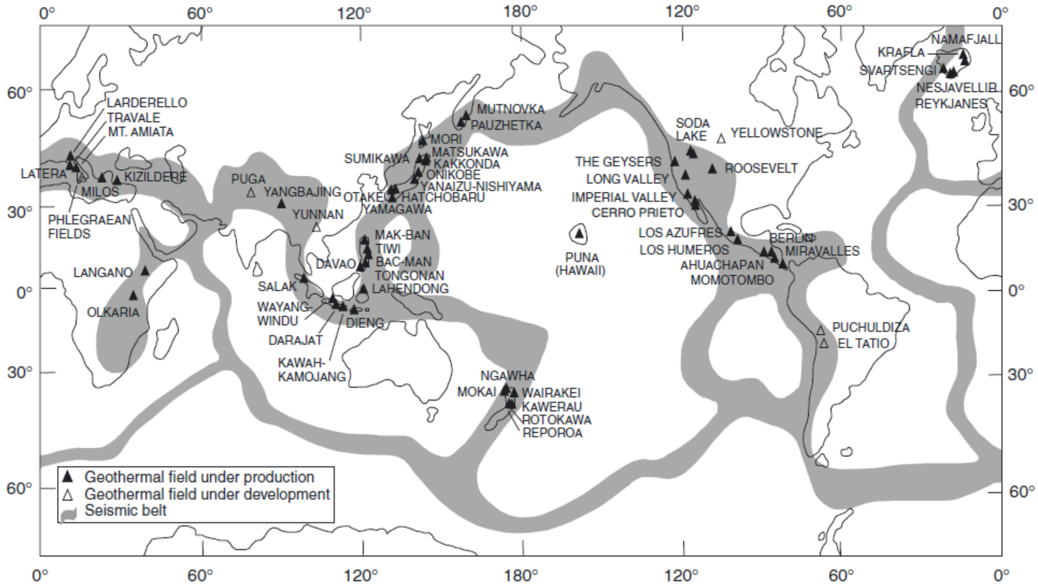

Figure 13- Deployed geothermal power plants worldwide (Gupta et al., 2007: p.29)

2.4.5.3 Technology

For the purpose of understanding how geothermal energy can be used it is necessary to distinguish certain categories. First of all, the transport of geothermal energy can be conductive (on rocks) or convective (on fluids) (Stober and Bucher, 2014: p.9). The next characteristic is the depth in which the source is tapped. Shallow systems are commonly referred to if depths of 400 meters are not exceeded while deep systems can go as deep as technological standards allow for ((Stober and Bucher, 2014: p.35), (Kolditz et al., 2013) and (Gupta et al., 2007: p.11-12)). The main rationale behind this differentiation is the temperature found in varying depths. Shallow systems usually provide temperatures of 25-50°C while deep systems can experience temperatures of up to 250°C or more (Kosinowski and Ranke, 2012: p.14-15). The commercial way of using geothermal energy is the deep geothermal systems.

In all cases, the efficiency of geothermal systems are dependent on the Carnot efficiency ((Stober and Bucher, 2014: p.56) and (Ortner, 2014)) which describes a ratio between incoming temperature (T_i) and outgoing temperature (T_o).

$$\eta = 1 - \frac{T_o}{T_i}$$

Equation 19 – Carnot Efficiency

2.4.5.4 Assessment of Potential

The assessment of the potential energy production from geothermal heat is complex and protracted. Schilliger (2011: p.90) indicates that three quarters of all drillings for measuring purposes predict no energy production. Furthermore, it needs the cooperation of experts from various scientific fields. Consequently, it is not possible to explore the prospective energy production based on basic tools or methods like it would be possible with solar energy.

2.4.6 Ocean Energy Systems

The Earth's oceans incorporate a massive amount of energy. Estimations say between 100-400% of the world's electricity demand could be generated from ocean energy (IRENA, 2014c: p.1). However, the technologies available to harvest this energy are not yet ready to be deployed commercially and on a large scale. For this reason, this chapter will only give a short introduction and an overview over various technologies that could power the future world. Ocean energy should be seen as especially important when talking about island states. Their location is a favourable one for the usage of ocean energy systems. With increasing technological readiness of available methods islands could prospectively satisfy their energy demand completely from ocean energy. Until then other renewable energy sources will have to serve as the alternative to fossil fuels.

2.4.6.1 Global Outlook

The incredible amount of energy stored in oceans, as previously mentioned, accumulates to around 2.5TW tidal dissipation, on continental shelves only (Bahaj and Sayigh, 2012: p.1). IRENA indicates numbers of 20.000-80.000TWh of electricity production would be theoretically possible to harvest (IRENA, 2014c: p.1). The overall global leader in the research of ocean energy is the UK. Here, infrastructure zones have been designated in which developers can test their prototypes. While the UK is leader in research France and Korea have the only two operating tidal energy plants installed (making up 493 of 530MW global capacity installed) (IRENA, 2014c: p.9). In other technologies such as wave or current energy conversion not a single commercially operated plant is deployed on a worldwide scale (Bahaj and Sayigh, 2012: p.4). The IEA in its World Energy Outlook 2014 estimates the production from ocean energy in 2040 – in their most promising scenario – to be at around 120TWh annually which would not even provide 1% of renewable energy production (IEA, 2014b). Still, there are some promising trends, especially in Scotland, the US, Canada and Sweden. These developments could eventually lead to certain regions (e.g. island states) gaining substantial amounts of their energy demand from ocean energy (Bahaj and Sayigh, 2012: p.4-5).

2.4.6.2 Technologies

In ocean energy various different methods are currently in development ((IRENA, 2014c: p.2-9), (Bahaj and Sayigh, 2012: p.1), (Kaltschmitt et al., 2013: p.873-891) and (Bahaj and Sayigh, 2012: p.1)). The most promising among them are tidal and wave energy conversion. While, tides are already commercially used in France and Korea the wave energy sector has not yet demonstrated technical maturity. Other methods of converting energy stored within the oceans are ocean current, ocean thermal, salinity gradient and evaporation technologies. All of these are still in a very early developing stage. In all cases, the success will highly depend on a proper assessment of the location and its resources (Bahaj and Sayigh, 2012: p.4). In conclusion, none of the listed ocean energy technologies is currently on a level attractive to commercial application (Bahaj and Sayigh, 2012: p.164) and will therefore not be further assessed within this thesis.

2.5 Energy Storage

In this chapter I will again provide only an overview of the most common and most promising technologies. The focus on technologies which might become commercially available within the next 5-10 years does not make sense. Furthermore, only longer term energy storage is considered as this thesis does not deal with short term (up to 1 hour) fluctuations and respective balancing methods.

2.5.1 General

Energy storage has the potential to become the main issue determining the functionality of electricity networks in the near future (Krzikalla et al., 2013: p.59). Although this statement is expected to become reality it is legitimate to question it in the first instance. Most electricity grids have developed without any sign of energy storage in almost any area of the world. Thus, do we really need to focus on the field of storage systems? (Menictas et al., 2015: p.590)

The question to this answer is as straight forward as the question itself. Yes, there is imminent need for ways of storing energy. Krzikalla et al. (2013: p.59) argue that with the evolution of renewable energy schemes the need for storage possibilities grew proportionally. This is also in line with IRENA’s (2012e: p.7) observation that storing energy nowadays is feasible not only on a large-scale basis but also for small-scale appliances - due to recent advances in the storage technologies. The result of rising renewable energy capacities is an increasingly volatile electricity supply which has poor efficiency rates (Menictas et al., 2015: p.590). For the aforementioned issues and as a more detailed response to the question posed before – energy storage can be seen as the missing link, the major technical challenge and the most important element of future power systems (Menictas et al., 2015: p.563 + 588).

The ways storage can support electricity grids are manifold. Some technologies provide regulation of supply, others take up excess energy and supply it back to the grid during low production rates and finally, others can help to increase the operating efficiencies of diesel generators ((Menictas et al., 2015: p.593), (Wagner, 2010), (Ter-Gazarian, 2011: p.ix + xii), (Huggins, 2010: p.367-368) and (IRENA, 2012e: p.5)).

2.5.1.1 Types of storage

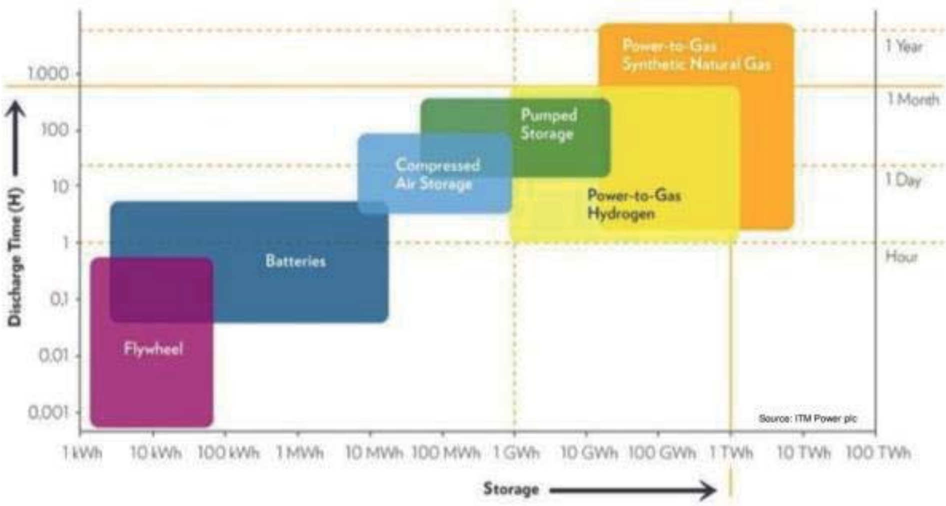

Figure 14 – Ragone plot evaluating different storage mechanisms (IfaS; BELIA, 2013: p.3)

The storage of energy is, in principal, not a very complicated matter and can be achieved in various ways. However, reaching commercial viability is still quite a big challenge. In the following section, the most mature and promising technologies will be introduced.

As it was already pointed out, there are multiple storage devices. Thus, it makes sense to look at their differences to find advantages and detriments. The main differentiation between storage mechanisms is the way energy is kept in the system. This can be done thermally (sensible or latent heat), mechanically (gravitational, kinetic or elastic forms of energy), chemically, biologically or electrically (electromagnetic or electrostatic energy) ((Ter-Gazarian, 2011: p.32), (IRENA, 2012e: p.8) and (Menictas et al., 2015: p.563)). Figure 15 gives an overview according to these categories.

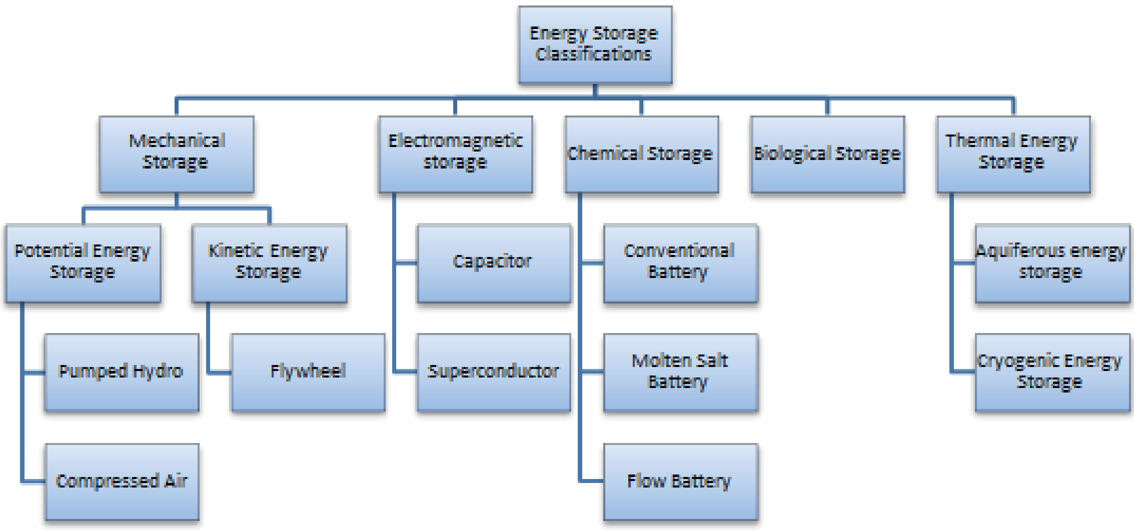

Figure 15 – Classification of storage methods according to their characteristics (adopted from (Menictas et al., 2015: p.563))

Not all technologies in Figure 15 are to be taken into consideration when planning on installing energy storage for power systems. The most common and mature type of storing energy is pumped hydro storage. It is also the largest utility energy storage method in the world ((Menictas et al., 2015: p.564) and (Ter-Gazarian, 2011: p.xi). Behind hydro storage, batteries are next in line when looking at maturity and deployment rates. Multiple types of batteries have been in use for roughly 100 years and during this period reached commercial maturity (Ter-Gazarian, 2011: p.32-33). Besides these two methods also Compressed Air Energy Storage (CAES), power-to-gas (P2G), thermal energy storage and flywheels can be found around the globe in different applications (IRENA, 2012e: p.5).

Further distinction between storage technologies is made upon their intrinsic characteristics. For example, pumped hydro storage can provide energy over a long period. However, the start-up time takes some minutes. On the contrary, energy stored in flywheels is readily available but only for short periods of up to minutes. The following list will give an indication of the most important properties storage devices can carry ((Krzikalla et al., 2013: p.59), (Ter-Gazarian, 2011: p.34), (Menictas et al., 2015: p.564) and (IRENA, 2012e: p.8)[9]). Usually, there is a trade-off between certain categories. The specific features of storage technologies will be assessed in the individual sections.

- Energy storage capacity [kWh or Ah]
- Charge and discharge rates [kW or A]
- Lifetime [cycles, years, kWh_{life}]
- Energy density [kWh/m³ or kW/kg]
- Efficiency [%]
- Capital costs [$/kW and $/kWh]
- Operating costs [$/MWh or $/kW*y]
- Environmental Impact

2.5.1.2 Application

The use of energy storage mechanisms is manifold. These are commonly subdivided into small-scale (up to 10MW) and large-scale (lager than 10MW) appliances (IRENA, 2012e: p.11). While these categories do not claim their individual technologies, there are certain methods that are rather applied on a large-scale than on a small-scale. Another factor influencing the size of an energy storage device is costs. Large-scale applications mostly do not focus so much on initial capital costs contrary to their small counterparts. Small-scale applications require a long life-time of the system. In any case, defining the intended use is the first step in choosing the right technology (Huggins, 2010: p.367).

The main reason for the deployment of storage facilities (in the scope of this thesis) is its balancing function when implementing renewable energies to the grid ((Huggins, 2010: p.367) and (IRENA, 2012e: p.5)). Batteries, flywheels, pumped-hydro or other technologies are able to take up excess energy when it is produced and give it back to the grid when demand is higher than energy production (e.g. wind free periods, low solar

[9] For detailed information on these properties please check (IRENA, 2012e: p.8) (Krzikalla et al., 2013: p.59) (Ter-Gazarian, 2011: p.34)

irradiation, etc.) (Menictas et al., 2015: p.593). The second reason why energy storage is needed is financial constraints. Menictas et al. (2015: p.563) argue that costs of extending the grid (e.g. rural electrification) over longer distances is immensely expensive. Thus, it is necessary to find other solutions such as decentralized energy storage in combination with local power generation. Moreover, energy storage can help to create economic growth. In some instances it is the only possibility to secure the energy supply for tourist, telecommunication or health facilities (e.g. back-up power or night-time power). Additionally, energy storage can increase efficiencies of currently employed power production units, namely diesel generators (Menictas et al., 2015: p.590). In many regions of the world diesel generators are used to balance power supply. Very often, these generators run at a low load level which diminishes efficiency rates to an absolute minimum. With the installation of energy storage capacity it is possible to shut-down diesel generators completely. Instead, the necessary power comes from the energy storage device[10]. Diesel generators could then be used for emergency cases only.

2.5.1.3 Batteries

A battery is an apparatus that allows transforming chemical energy into electrical energy (Menictas et al., 2015: p.3). This device consists of two electrodes and one electrolyte which are exchanging ions and consequently produces electrical energy (Ter-Gazarian, 2011: p.135). Usually, batteries are thought to be rechargeable – energy can be stored inside them. However, primary batteries can supply its intrinsic amount of energy only once ((Menictas et al., 2015: p.3) and (Ter-Gazarian, 2011: p.135)). All batteries this section will assess are secondary batteries and thus can be recharged.

Batteries have been deployed for many years throughout the world and hence reached commercial maturity. The main factors making batteries so attractive is its modularity, efficiency, flexibility, life-time and low costs (Menictas et al., 2015: p.595). Even after deployment, a battery can be enlarged due to its modularity (IRENA, 2012e: p.11). Each battery bank added increases capacity and charge/discharge rate in consequence. The scope of the aforementioned characteristics depends on the individual battery type. The strongest representatives are lead-acid, lithium-ion, sodium-sulphur and flow batteries.

[10] A comparison between a 100MW gas turbine and a storage system to provide an equivalent response was undertaken. Their findings were that a 30 to 50MW storage device was as effective as or more effective than a 100MW open cycle gas turbine. (Menictas et al., 2015: p.590)

Each of them has a characteristic composition of advantages and detriments which will be assessed in the following paragraphs.

2.5.1.3.1 Lead-Acid

The main advantages of this type of battery are its rapid kinetics, costs and high maturity. Their advanced level of development stems from a long lasting history of deployment in energy systems in different size scales worldwide. However, lead-acid batteries are also known for their high need of maintenance, long charge time and low energy density (limited importance in power grids). Additionally, lead-acid batteries should never fall below 20-50% of their full capacity in order to secure long battery life ((Huggins, 2010: p.369), (Ter-Gazarian, 2011: p.137), (Menictas et al., 2015: p.67) and (IRENA, 2012e: p.12-14)). Nevertheless, lead-acid types of batteries make a good fit for many applications. The most common way of using this type is in connection with wind or solar power generation systems ((Huggins, 2010: p.369) and (Menictas et al., 2015: p.67)).

2.5.1.3.2 Lithium-Ion

Lithium-Ion batteries are mostly known from mobile applications such as mobile phones or laptops. Therefore, central advantage of this type of battery is its high energy density, long life-time, small weight and size, and little discharge losses. Furthermore, lithium-ion accumulators can be charged quickly and are not strongly affected by low charging situation. However, lithium-ion batteries are not yet fully developed for the use in energy systems although they are expected to be commercially feasible in the next few years. Also, the costs upfront are relatively higher compared to lead-acid systems ((Menictas et al., 2015: p.17) and (IRENA, 2012e: p.14)).

2.5.1.3.3 Sodium-Sulphur

This type of battery works somehow different than usual types. Sodium-sulphur batteries have a working temperature of 300-350°C which means that the electrodes are liquid. Therefore, it is imperative to keep the systems in a safe environment. The possible application for this kind of battery is rather on the large-scale. Sodium-sulphur devices are already installed in Japan and the US with sizes up to 6MW. In consequence, this type of battery can be used to stabilize and support the grid (bridge outages) or to balance intermittent production (wind and solar power generation) in large grids ((Huggins, 2010: p.370) and (IRENA, 2012e: p.15)).

2.5.1.3.4 Flow Batteries

Flow batteries get their name from the flowing electrodes that penetrate the electrolyte. Therefore, the capacity is not fixed but is rather determined by the storage tanks. These can be changed in size whenever needed. Thus, very large capacities are possible. The main flow battery is the vanadium redox battery – in some cases also the zinc-bromine battery is deployed. Main advantages of the flow battery is its very long lifetime of up to 100 years and the scalable characteristic as well as the possibility to completely discharge the battery without losing lifetime. On the other hand, flow batteries have a low energy density which requires very large tanks and pipes to pump the electrode through the system. Additionally, the initial costs can be relatively high. Due to its characteristics, flow batteries can be applied in almost any kind of energy system ((IRENA, 2012e: p.15), (Huggins, 2010: p.370-372) and (Menictas et al., 2015: p.19)).

2.5.1.4 Pumped hydro storage

The hydraulic generation of electricity is a technology commonly used throughout the world. This form of electricity production started to evolve over 100 years ago. The experience gained over more than a century makes it one of the most mature (Ter-Gazarian, 2011: p.85). Shortly after using water to produce electricity, mankind developed the pumped hydro-storage. Nowadays, this way of storing energy is the most widely deployed way of storing energy (Huggins, 2010: p.368). Globally, the capacity of pumped hydro-storage exceeds 120GW (Menictas et al., 2015: p.587). Furthermore, this way of storing energy will be of essence in future power systems - in order to balance renewable energy supply – because it is quickly adjustable (Hentschel, 2010: p.55).

Pumped hydro-storage usually comprises two reservoirs (upper and lower reservoir) between which the turbine and a generator are located (see Figure 16) (Menictas et al., 2015: p.564). The technology behind storing energy in water reservoirs and generating electricity from tapping these reservoirs is very basic. In principle, the water kept in the upper pool is released as a water jet and directed onto a wheel which is put in motion. The rotating wheel then powers a generator which consequently produces electricity (Hentschel, 2010: p.54). Depending on the velocity of this water jet different turbines are deployed[11]. To maintain a sufficient amount of energy in the upper pool water is pumped

[11] Kaplan turbine (slow water speeds), Francis turbine (medium flow speeds) and Pelton turbine (high velocity applications) (Hentschel, 2010: p.54).

up in times of excess or cheap energy (Ter-Gazarian, 2011: p.85). Typical turnaround efficiency of such a storage power plant is 70-90% ((Huggins, 2010: p.61) and (Ter-Gazarian, 2011: p.87)).

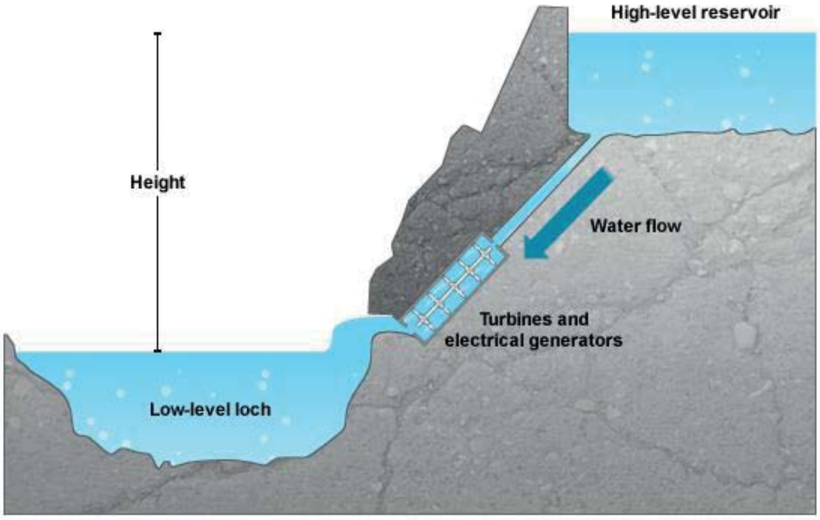

Figure 16 – simplified but typical arrangement of a pumped-hydro storage plant (Huggins, 2010: p.61)

The potential energy production of a pumped hydro-power plant can be calculated with Equation 20. The obtained figure from this formula has to be scaled by the overall efficiency of the plant.

$$E_g = \rho g h V$$

Equation 20 – potential energy production from a pumped hydro-power plant ((Ter-Gazarian, 2011: p.86) and (Busch, 2013: p.18))

Simply calculating the potential of height difference, however, is not enough to find a possible location. Pumped hydro-storage plants are essentially dependent on topographical and geological characteristics. Furthermore, this type of power plant are often constrained by environmental concerns ((Ter-Gazarian, 2011: p.92), (Menictas et al., 2015: p.564) and (Huggins, 2010: p.368)). Usually, lakes, dams, rivers are used for the purpose of the lower reservoir. Therefore, the availability of these formations is necessary. Lack of such reservoirs can be offset by building artificial ones. However, this endeavour is very cost intensive and environmentally doubtful. In recent years, alternative versions have been deployed. One of these alternatives is to use the sea as lower reservoir and locate the upper reservoir at higher coastal areas (Ter-Gazarian, 2011: p.92). While this option can help (island) states with little abundance of freshwater to gain access to hydropower the costs of such a facility have to be considered. Using seawater for a pumped hydro-power plant is cost intensive due to corrosion protection and prevention of leakage to surrounding land (Ter-Gazarian, 2011: p.92). However, once the installation of such a storage facility is completed production costs are low. Moreover, the adjustable electricity production can be used for peak-shaving and load levelling (Huggins, 2010: p.61).

2.5.1.5 Power to Gas

Power-to-Gas is another way of chemically storing energy. This is done in two major steps, namely hydrogen production (electrolysis of water) and conversion of hydrogen and carbon dioxide into methane (methanation) ((Davis and Martín, 2014: p.253) and (Fuchs et al., 2012)). The energy to drive these steps can come from any type of power generator. In combination with RE technologies it can act as a storage device to balance seasonal fluctuations in natural resources like wind and solar irradiation (Jentsch et al., 2013: p.255). Moreover, power-to-gas, also called synthetic methane or renewable power methane, is a substitute for natural gas and thus can rely on the already existing value-chain (Pleßmann et al., 2013: p.23). Once, electricity is needed the synthetic methane can be fed to standard gas turbines operating all over the world. Schneider and Kötter (2015) state that power-to-gas might become a cornerstone of future energy systems. The only drawback according to the literature available is the low round-trip efficiency (electricity – gas – electricity) of around 35% ((Jentsch et al., 2013: p.255), (Schneider and Kötter, 2015: p.1)). Power-to-gas can also be used for heating and cooling processes or as an alternative fuel in vehicles.

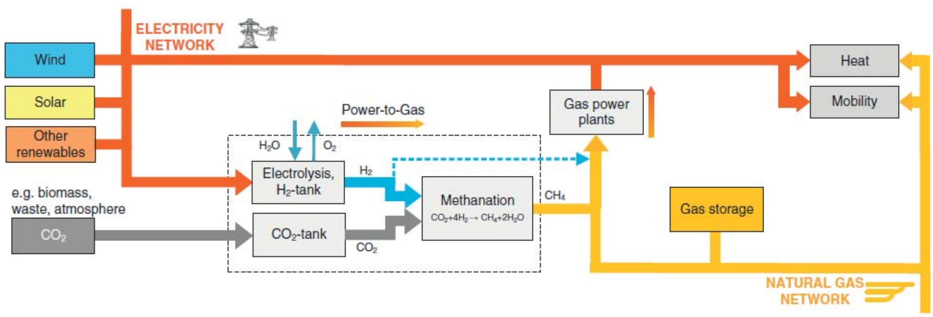

Figure 17 – Processes involved in the P2G storage of electricity (Jentsch et al., 2013: p.255)

2.5.1.6 Summary

	Batteries	Pumped Hydro	Power to Gas
Applicable grid size	Lead Acid + Li-Ion + Flow Batteries: <10MW	any but mostly larger scale	any
Lifetime	<15 years	>25	>25
Cycles	<40.000	>50.000	>50.000
Efficiency	70-95%	75-85%	30-40%
Capital Cost per kWh	120-100$/kWh	10-250$/kWh	0,5-1$/kWh
Capital Cost per kW	120-2000$/kW	600-4000$/kW	750-2000$/kW

Table 3 – Comparison of the applied storage technologies ((Fuchs et al., 2012), (Huggins, 2010), (IRENA, 2013), (IfaS; BELIA, 2013), (Kaltschmitt et al., 2013), (Krzikalla et al., 2013))

3 Empirical Part

3.1 Overview of the Energy Sector

Cape Verde’s electricity sector is dispersed into nine separate systems (Ilha de Santiago, Santo Antão, Sao Nicolau, Sao Vicente, Boavista, Sal, Maio, Fogo and Santiago). Some of these have their own subsystems which consist of one to five production sites[12]. The various islands are not electrically interconnected which means that each of them has to generate its own electricity. However, there are only two companies which are responsible for the electricity production in Cape Verde. Electra is the national electricity and water company (85% held by Cape Verde Government and 15% by Cape Verde Municipalities) serving all islands except Boavista. The electricity production on Boavista is operated under a sub concession by an independent company called AEB (Águas e Energias de Boavista).

The electricity production in Cape Verde is mainly based on the combustion of fossil fuels (Diesel, Fuel Oil 180 and Fuel 380). Some islands (Santiago, Santo Antão, Sao Vicente, Sal and Boavista) also incorporate renewable energy sources (wind and solar energy) into their energy mix. In 2012, the penetration of RE electricity was 21% of Cape Verde’s total electricity generation. Although, the share of renewables in the energy mix is relatively high in comparison with other ECOWAS countries the production costs per kWh are still at a high €0,19 (2013) (Fonseca, 2014). The high prices derive from a still inefficient production of electricity with old diesel generators. Additionally, generators often do not run at full load in order to balance demand variations.

Electra’s electricity is sold to approximately 138.000 clients on all islands of which more than 95% consume low voltage electricity. The biggest single customer in 2012 was the state of Cape Verde. Other big consumers are industrial and commercial customers mainly located on Santiago Island. The largest category of customers is made up of the households of Cape Verde consuming almost 50% of all electricity produced. Electra’s customers had to pay €0,284 per kWh consumed in 2012 in case of less than 600kWh annual consumption (Agência de Regulação Económica, 2015).

[12] By 2015, islands reduced to one system per island.

Table 4 – Population and Electricity Consumption (Electra, 2013)

Electricity per person				
Island	Population (2010)	Electricity per person (2012)	Population (2012)	Electricity per person (2012)
Santo Antão	43.915,00	285,5 kWh/p/y	46.405,94	294,4 kWh/p/y
Sao Vicente	76.107,00	854,4 kWh/p/y	80.423,93	821,8 kWh/p/y
Sao Nicolau	12.817,00	366,5 kWh/p/y	13.544,00	407,8 kWh/p/y
Sal	25.765,00	1417,1 kWh/p/y	27.226,44	1471,2 kWh/p/y
Maio	6.952,00	401,9 kWh/p/y	7.346,33	372,1 kWh/p/y
Santiago	283.443,00	626,7 kWh/p/y	299.520,40	625,5 kWh/p/y
Fogo	27.527,00	377,4 kWh/p/y	29.088,38	415,5 kWh/p/y
Brava	5.995,00	384,7 kWh/p/y	6.335,05	427,0 kWh/p/y
Boavista	9.162,00	709,9 kWh/p/y	9.681,69	1230,0 kWh/p/y
All Islands	**491.683,00**	**602,7 kWh/p/y**	**519.572,15**	**673,9 kWh/p/y**

Table 4 shows that only four islands (Sao Vicente, Sal, Santiago and Boavista) exceed the annual per capita consumption threshold – in regards to electricity prices. The reason for this relatively (in comparison to the other islands) high consumption can be found in increased commercial (Santiago) and touristic activity (Sal and Boavista). All in all, the amount of energy consumed per person and year is very low averaging at roughly 600kWh per capita and could be even lower in case of reduced losses. This notion of low energy demand will be observable throughout the next sections.

3.1.1 Installed Capacity

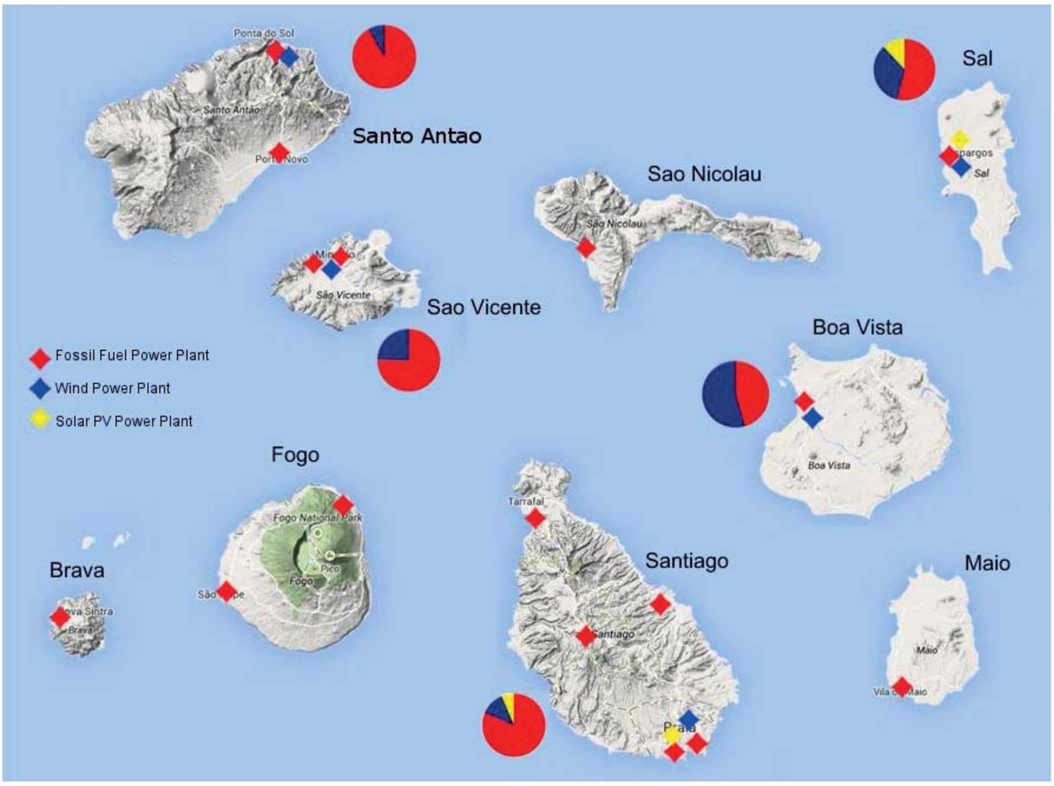

Figure 18 – Location of electricity production centres and shares of capacity of selected islands (information taken from (Gesto Energia S.A., 2011) and put together by (KE, 2015)).

Cape Verde has many different electricity production centres. One reason for this distribution of production centres is the lack of interconnectivity between the islands. Figure 18 presents an overview of the various sites. Furthermore, Table 5 shows a detailed summary of the installed capacities on the various islands based on fossil fuels, wind and solar PV.

Table 5 – List of all production sites and their respective installed capacity ((UNIDO; ECREEE, 2010) and (Electra, 2013))

Installed Capacity							
Island	Power System	2012					
		Thermal	Wind	Solar PV	Total	% of Cape Verde	% RE
Santo Antão	Porto Novo	1,8 MW					
	Ribeira Grande	3,8 MW	0,5 MW				
	Total	5,6 MW	0,5 MW		6,1 MW	4%	8%
Sao Vicente	Matiota	10,9 MW	5,9 MW				
	Lazareto	7,4 MW					
	Total	18,3 MW	5,9 MW		24,2 MW	17%	24%
Sao Nicolau	Tarrafal	2,2 MW					
	Total	2,2 MW			2,2 MW	2%	0%
Sal	Palmeira	11,4 MW	7,2 MW	2,5 MW			
	Total	11,4 MW	7,2 MW	2,5 MW	21,1 MW	15%	46%
Maio	Porto Inglês	1,4 MW					
	Total	1,4 MW			1,4 MW	1%	0%
Santiago	Praia	7,4 MW	9,35 MW				
	Palmarejo	48,0 MW		5,0 MW			
	Assomada (Sta Catarina)	3,9 MW					
	Tarrafal ST	1,4 MW					
	S. Cruz	2,2 MW					
	Total	62,9 MW	9,4 MW	5,0 MW	77,2 MW	54%	19%
Fogo	S.Filipe	3,0 MW					
	Mosteiros	0,8 MW					
	Total	3,8 MW			3,8 MW	3%	0%
Brava	Favetal	1,1 MW					
	Total	1,1 MW			1,1 MW	1%	0%
Boavista	Sal-Rei	2,1 MW	2,55 MW				
	Total	2,1 MW	2,55 MW		4,7 MW	3%	54%
All Islands	**Total**	**108,7 MW**	**25,5 MW**	**7,5 MW**	**141,7 MW**	**100%**	**23%**

Table 5 indicates that more than 50% of the installed capacity is located on the main island Santiago with 77,2MW. Almost 20% of Santiago's installed capacity is based on some form of renewable energy (9,4MW wind and 5MW solar PV). Furthermore, we can see that only three of the nine islands (Sao Nicolau, Fogo and Santiago) do not incorporate any kind of RE technology in their electricity production. On the other hand, Sal and Boavista have a share of renewable technologies of roughly 50% which is a very high value. The overall installed capacity is 141,7MW which is a rather low value. Looking at the values of Luxembourg (Installed Capacity of 1.789MW at a GDP of USD63.481 in 2015) and of Suriname (Installed capacity of 412MW at a GDP of USD6.225) which have both similar population sizes we can see that they are significantly higher ((IMF, n.d.) and (United

Nations Statistics Division, 2015)). However, the RE penetration rate of 23% is a relatively high value (Luxembourg produces only around 5% of its electricity based on RE (European Commission, 2013)).

3.1.2 Electricity Production

In order to get a holistic view on the electricity sector of Cape Verde it is necessary to compare installed capacity with the electricity produced. High numbers of installed wind energy capacity do not necessarily mean a high share in the overall electricity production if the yield of the turbines is deficient due to technical problems.

From Table 6 we can take that the overall share of RE in Cape Verde's electricity production lies at around 22% which is 2 percentage points below the share of RE technologies of installed capacity in the same year. This discrepancy can be explained by the operating hours of the respective technology. While thermal power plants averaged almost 2600 full load hours, wind turbines were only operating during 2500 hours and solar PV plants were operating for poor 910 hours on average. A certain shortfall in terms of full load hours is inherent to some RE technologies due to their dependence on the abundance of wind or solar irradiation respectively. Nevertheless, on the island of Sal where only 656 full load hours were used to produce electricity an average amount of 3286 hours of solar irradiation is recorded annually (values from (European Union, 2015) and processed by (KE, 2015)). Furthermore, we can see that none of the thermal power plants were fired at all times. Therefore, we can conclude that many start-up and shut-down phases had to take place which decreases efficiency and increases fuel consumption considerably. Another important takeaway from Table 6 is that Sao Vicente, Sal and Boavista generated 30% and more of their annual electricity production from wind and solar. The percentage shares of renewables could be substantially higher if losses were reduced. The amount of electricity lost due to technical reasons or theft reached "*worrying levels*" (Electra, 2013: p.24). The absolute and relative figures can be found in Table 7.

Table 6 – Electricity Production in MWh for the individual islands and in total ((UNIDO; ECREEE, 2010), (Electra, 2013) and calculations by (KE, 2015)).

Electricity Production										
Island	Power Plant	2012								
		Thermal	Hours	Wind	Hours	Solar PV	Hours	Total	% of total	% RE
Santo Antão	Porto Novo	5.219 MWh	2.899 h					5.219 MWh		
	Ribeira Grande	7.052 MWh	1.856 h	1.390 MWh	2.780 h			8.442 MWh		
	Total	12.271 MWh	2.191 h	1.390 MWh	2.780 h			13.661 MWh	4%	10%
Sao Vicente	Matiota	11.502 MWh	1.054 h	20.682 MWh	3.505 h			32.184 MWh		
	Lazareto	33.906 MWh	4.557 h					33.906 MWh		
	Total	45.407 MWh	2.475 h	20.682 MWh	3.505 h			66.089 MWh	19%	31%
Sao Nicolau	Tarrafal	5.523 MWh	2.510 h					5.523 MWh		
	Total	5.523 MWh	2.510 h					5.523 MWh	2%	0%
Sal	Palmeira	27.456 MWh	2.418 h	10.960 MWh	1.522 h	1.640 MWh	0.656 h	40.056 MWh		
	Total	27.456 MWh	2.418 h	10.960 MWh	1.522 h	1.640 MWh	0.656 h	40.056 MWh	12%	31%
Maio	Porto Inglês	2.733 MWh	1.987 h					2.733 MWh		
	Total	2.733 MWh	1.987 h					2.733 MWh	1%	0%
Santiago	Praia	3.399 MWh	0.458 h	28.366 MWh	3.034 h			31.765 MWh		
	Palmarejo	141.118 MWh	2.937 h			5.823 MWh	1.165 h	146.941 MWh		
	Assomada (Sta Catarina)	6.515 MWh	1.692 h					6.515 MWh		
	Tarrafal ST	0.816 MWh	0.600 h					0.816 MWh		
	S. Cruz	1.307 MWh	0.601 h					1.307 MWh		
	Total	153.154 MWh	2.437 h	28.366 MWh	3.034 h	5.823 MWh	1.165 h	187.344 MWh	55%	18%
Fogo	S.Filipe	10.596 MWh	3.532 h					10.596 MWh		
	Mosteiros	1.489 MWh	1.861 h					1.489 MWh		
	Total	12.085 MWh	3.180 h					12.085 MWh	4%	0%
Brava	Favetal	2.705 MWh	2.562 h					2.705 MWh		
	Total	2.705 MWh	2.562 h					2.705 MWh	1%	0%
Boavista	Sal-Rei	7.611 MWh	3.556 h	4.298 MWh	1.685 h			11.909 MWh		
	Total	7.611 MWh	3.556 h	4.298 MWh	1.685 h			11.909 MWh	3%	36%
All Islands	**Total**	**268.945 MWh**	**2.591 MWh**	**65.697 MWh**	**2.505 MWh**	**7.464 MWh**	**0.910 MWh**	**342.106 MWh**	**100%**	**21,39%**

Table 7 – Electricity Production, Demand and Losses ((UNIDO; ECREEE, 2010), (Electra, 2013))

Electricity Production, Demand and Losses									
Island	Power Plant	2012							
		Total Production	Self Demand	Desalination	Electricity to grid	Electricity to grid [% of total production]	Losses	Electricity sold	Losses [% of total production]
Santo Antão	Porto Novo	5.218,79 MWh	8,09 MWh		5.210,70 MWh	100%	1.261,72 MWh	3.948,98 MWh	
	Ribeira Grande	8.442,26 MWh	7,57 MWh		8.434,70 MWh	100%	1.956,26 MWh	6.478,44 MWh	
	Total	13.661,05 MWh	15,66 MWh		13.645,40 MWh	100%	3.217,98 MWh	10.427,42 MWh	23,6%
Sao Vicente	Matiota	32.183,92 MWh	817,54 MWh	5.733,47 MWh	25.154,18 MWh	78%	n.a.		
	Lazareto	33.905,55 MWh	1.779,500 MWh		32.126,05 MWh	95%	n.a.		
	Total	66.089,47 MWh	2.597,040 MWh	5.733,47 MWh	57.280,23 MWh	87%	13.676,40 MWh	43.603,83 MWh	20,7%
Sao Nicolau	Tarrafal	5.522,60 MWh	11,95 MWh		5.510,65 MWh	100%	0.925,97 MWh	4.584,68 MWh	
	Total	5.522,60 MWh	11,95 MWh		5.510,65 MWh	100%	0.925,97 MWh	4.584,68 MWh	16,8%
Sal	Palmeira	40.056,23 MWh	2.406,265 MWh	3.940,31 MWh	33.428,08 MWh	83%	2.978,67 MWh	30.449,41 MWh	
	Total	40.056,23 MWh	2.406,265 MWh	3.940,31 MWh	33.428,08 MWh	83%	2.978,67 MWh	30.449,41 MWh	7,4%
Maio	Porto Inglês	2.733,45 MWh	10,81 MWh		2.722,64 MWh	100%	0.720,15 MWh	2.002,49 MWh	
	Total	2.733,45 MWh	10,81 MWh		2.722,64 MWh	100%	0.720,15 MWh	2.002,49 MWh	26,3%
Santiago	Praia	31.765,01 MWh	431,22 MWh		37.157,29 MWh	117%	n.a.		
	Palmarejo	146.941,19 MWh	5.524,545 MWh	7.638,85 MWh	127.193,91 MWh	87%	n.a.		
	Assomada (Sta Catarina)	6.515,23 MWh	14,44 MWh		n.a.		n.a.		
	Tarrafal ST	815,53 MWh	8,28 MWh		n.a.		n.a.		
	S. Cruz	1.306,79 MWh	12,86 MWh		n.a.		n.a.		
	Total	187.343,76 MWh	5.991,346 MWh	7.638,85 MWh	172.953,16 MWh	92%	69.250,10 MWh	103.703,07 MWh	37,0%
Fogo	S.Filipe	10.596,17 MWh	23,00 MWh		10.573,17 MWh	100%	3.155,35 MWh	7.417,83 MWh	
	Mosteiros	1.489,17 MWh	6,73 MWh		1.482,44 MWh	100%	0.215,90 MWh	1.266,55 MWh	
	Total	12.085,35 MWh	29,73 MWh		12.055,62 MWh	100%	3.371,25 MWh	8.684,37 MWh	27,9%
Brava	Favetal	2.705,05 MWh	17,20 MWh		2.687,85 MWh	99%	0.753,06 MWh	1.934,79 MWh	
	Total	2.705,05 MWh	17,20 MWh		2.687,85 MWh	99%	0.753,06 MWh	1.934,79 MWh	27,8%
All Islands	**Total**	**342.105,65 MWh**	**11.079,994 MWh**	**17.312,63 MWh**	**300.283,63 MWh**	**88%**	**94.893,58 MWh**	**205.390,05 MWh**	**27,7%**

3.1.3 Losses

The amount of electricity lost in the grid and thus also not billed to consumers is indeed worrisome. 37% of the total electricity produced is lost on Santiago Island which marks a new high in recent years (see Table 8). Moreover, the amount of electricity not paid for by customers on Santiago for various reasons is 70% of all electricity put into the grid. The loss rates on the other eight islands are not as troubling but still considerable. All islands except Sao Nicolau and Sal lose more than 20% of their electricity fed to the grid. The only one island which is able to sell more than 90% of the electricity fed into the grid is Sal which witnesses loss rates of around 5% during the last six years with only 2012 exceeding this value (7,4%). Table 7 also shows the amounts of energy needed for the desalination of water and the self-demand of Electra. Quite significant amounts of the total output are used for the desalination of seawater (Matiota/Sao Vicente 22%, Palmeira/Sal 17%, and Palmarejo/Santiago 13%) which can be explained by the little indigenous sources of fresh water on the individual islands and the lack of rain. Nevertheless, the desalination accounts for less electricity than the losses – by a factor of 5,5 -. Therefore, it does not seem surprising that electricity tariffs are at levels around €0.3 per kWh.

Table 8 – Electricity Losses on Cape Verde in total and on Santiago and Sal ((Electra, 2009), (Electra, 2010), (Electra, 2011), (Electra, 2012), (Electra, 2013))

Losses			
Year	Overall Losses	Santiago	Sal
2007	25,2%	34,4%	4,4%
2008	26,8%	36,5%	4,1%
2009	26,1%	35,7%	2,8%
2010	26,1%	34,2%	4,9%
2011	27,1%	35,6%	4,2%
2012	28,7%	37,0%	7,4%

3.1.4 Electricity Costs and Tariffs

It is not unusual that island states experience high electricity prices. The fact that these nations are located in isolated areas of the world results in high transportation costs of fossil fuels. Furthermore, most island countries do not have significant natural resources which allow for easy conversion into electricity. In the case of Cape Verde, electricity prices had been at a high level already before 2008 but kept increasing. Only this year (2015) a decrease of prices per kWh could be observed due to the major drop in oil prices in the second half of 2014 (Delgado, 2015).

Table 9 – Electricity Tariffs 2008-2012 ((Electra, 2009), (Electra, 2010), (Electra, 2011), (Electra, 2012), (Electra, 2013), (Agência de Regulação Económica, 2012), (Agência de Regulação Económica, 2013), (Agência de Regulação Económica, 2015))

Electricity Tariffs		
Year	Tariff (<600kWh/month	Tariff (>600kWh/month
2008	0,220 €/kWh	n.a.
2009	0,240 €/kWh	n.a.
2010	0,240 €/kWh	n.a.
2011	0,269 €/kWh	n.a.
2012	0,284 €/kWh	0,350 €/kWh
2013	0,314 €/kWh	0,386 €/kWh
2014	0,314 €/kWh	0,386 €/kWh
2015	0,267 €/kWh	0,339 €/kWh

Table 9 gives an overview of the electricity tariffs throughout the last years starting in 2008. Electricity prices have been constantly increasing (except 2015) although fuel use declined as can be seen in Table 10.

Table 10 – Fossil fuel use 2008-2012 of Cape Verde ((Electra, 2009), (Electra, 2010), (Electra, 2011), (Electra, 2012), (Electra, 2013))

Fuel Use 2008-2012					
Year	2008	2009	2010	2011	2012
Fuel Used	69.765.771 l	71.475.159 l	74.450.797 l	73.613.843 l	63.482.405 l

The installation of the several wind parks in 2011 on various islands of Cape Verde is responsible for the significant drop in fossil fuel use. Nevertheless, costs for the production of electricity are vast and will continue to rise during the next years due to population growth. Also, we can see what impact the installation of renewable power sources can have in terms of fossil fuel use and consequently costs of production. Costs of electricity production and underlying costs of fossil fuel procurement are shown in Table 11 for the year of 2012.

Table 11 – Fuel Costs and Production Costs for 2012 (values adapted from (Electra, 2013) and (Fonseca, 2014))

Fuel Costs and Production Costs							
Island	Power Plant	Production from Fossil Fuels	Gasoleo [litres]	Fuel Oil 180 [litres]	Fuel Oil 380 [litres]	Costs of Fuel	Costs of Production
Santo Antão	Porto Novo	5.219 MWh	1.440.570 l			1.184.805 €	991.570,29 €
	Ribeira Grande	7.052 MWh	1.935.165 l			1.591.588 €	1.604.029,59 €
	Total	12.271 MWh	3.375.735 l			2.776.394 €	2.595.599,88 €
Sao Vicente	Matiota	11.502 MWh	1.070.717 l	1.933.436 l		2.118.017 €	6.114.944,99 €
	Lazareto	33.906 MWh	74.939 l		7.955.014 l	5.073.293 €	6.442.055,07 €
	Total	45.407 MWh	1.145.656 l	1.933.436 l	7.955.014 l	7.191.310 €	12.557.000,06 €
Sao Nicolau	Tarrafal	5.523 MWh	1.590.588 l			1.308.189 €	1.049.293,24 €
	Total	5.523 MWh	1.590.588 l			1.308.189 €	1.049.293,24 €
Sal	Palmeira	27.456 MWh	86.708 l	6.847.742 l		4.453.868 €	7.610.683,89 €
	Total	27.456 MWh	86.708 l	6.847.742 l		4.453.868 €	7.610.683,89 €
Maio	Porto Inglês	2.733 MWh	758.181 l			623.571 €	519.356,07 €
	Total	2.733 MWh	758.181 l			623.571 €	519.356,07 €
Santiago	Praia	3.399 MWh	863.388 l			710.099 €	6.035.351,90 €
	Palmarejo	141.118 MWh	1.058.102 l	31.381.140 l		20.954.172 €	27.918.826,29 €
	Assomada	6.515 MWh	1.807.131 l			1.486.286 €	1.237.894,46 €
	Tarrafal ST	0.816 MWh	256.051 l			210.591 €	154.950,70 €
	S. Cruz	1.307 MWh	371.341 l			305.412 €	248.290,10 €
	Total	153.154 MWh	4.356.013 l	31.381.140 l		23.666.559 €	35.595.313,45 €
Fogo	S.Filipe	10.596 MWh	2.919.557 l			2.401.207 €	2.013.272,68 €
	Mosteiros	1.489 MWh	441.362 l			363.001 €	282.942,87 €
	Total	12.085 MWh	3.360.919 l			2.764.208 €	2.296.215,55 €
Brava	Favetal	2.705 MWh	691.274 l			568.542 €	513.959,31 €
	Total	2.705 MWh	691.274 l			568.542 €	513.959,31 €
Boavista	Total	25.452 MWh	3.285.600 l	3.233.000 l		4.771.382 €	5.652.478,37 €
All Islands	**Total**	**261.334 MWh**	**15.365.074 l**	**40.162.318 l**	**7.955.014 l**	**43.352.640 €**	**62.737.421,45 €**

3.2 The RE potential of Cape Verde

In the following chapter I assess the potential of meeting the annual load of the different islands of Cape Verde by deploying only one single RE technology (wind and PV). I will not assess the eventuality of CSP as only Santiago provides the suitable conditions. However, CSP will be part of the next chapter and of the energy mix of Santiago. Furthermore, the following tables and values are not intended to propose possible energy mixes but to show that deployment of RE is possible based on land area and number of WTGs. The specific shares of wind, PV and CSP for a realistic energy mix will be presented in chapter 3.3.

Both technologies, solar PV and wind turbines, will be evaluated separately. In each part I will first introduce the methodology, then analyse the calculation process and subsequently present the results.

3.2.1 Solar PV

In this section I will evaluate the possibility of deploying solar PV to an extent large enough to produce sufficient energy for the needs of Cape Verde by 2015, 2020 and 2030. The process of calculating this can be split into three steps namely collecting solar irradiation data, calculating the yearly energy received and simulating the transformation of incoming energy into electricity.

3.2.1.1 Methodology

As already mentioned in the theoretical part of this thesis, data on solar irradiation can be collected by measurement devices at the specific site or approximated by remote sensing and accessed at online platforms. I chose the second way by relying on the European Commission's Joint Research Center's dataset (accessible through following link: http://re.jrc.ec.europa.eu/pvgis/imaps/index.htm). Here, it is possible to find data on global average irradiation, direct normal irradiation and many more types of information regarding the solar resource. For the purpose of calculating the power output of a solar panel I chose the global average irradiance (respectively for each island at one of the production centres) as this kind of irradiation is responsible for the energy production of a PV panel. Moreover, data was adapted to optimal azimuth and slope angles in order to make a realistic approach. I chose not to optimize regarding a tracking system due to the reason of technical complexity and higher costs. Additionally, at low latitudes because of relatively low variation of the sun's path (locations like Cape Verde), the marginal increase of yield is low compared to additional costs.

3.2.1.2 Solar Resource

The following tables give an overview of the values for the different islands. I have picked Santiago as the one representative island to show the logic of calculation. For the other islands only the average and total values are presented.

Table 12 – Overview of characteristic irradiation values for Santiago Island ((European Union, 2015) and own calculations)

Hours of irradiation				Irradiation Values		
Month	per day	per month		Month	Daily value	Monthly value
Jan	11,00 h	341,00 h		Jan	5927 Wh/m²	183,7 kWh/m²
Feb	11,50 h	322,00 h		Feb	6654 Wh/m²	186,3 kWh/m²
Mar	12,00 h	372,00 h		Mar	7907 Wh/m²	245,1 kWh/m²
Apr	12,50 h	375,00 h		Apr	7427 Wh/m²	222,8 kWh/m²
May	12,50 h	387,50 h		May	7274 Wh/m²	225,5 kWh/m²
Jun	13,00 h	390,00 h		Jun	6704 Wh/m²	201,1 kWh/m²
Jul	13,00 h	403,00 h		Jul	6231 Wh/m²	193,2 kWh/m²
Aug	12,50 h	387,50 h		Aug	5995 Wh/m²	185,9 kWh/m²
Sep	12,00 h	360,00 h		Sep	6310 Wh/m²	189,3 kWh/m²
Oct	11,50 h	356,50 h		Oct	6540 Wh/m²	202,7 kWh/m²
Nov	11,50 h	345,00 h		Nov	6080 Wh/m²	182,4 kWh/m²
Dec	11,00 h	341,00 h		Dec	5783 Wh/m²	179,3 kWh/m²
Average/ Total	12,00 h	4380,50 h		Average/ Total	6569,4 W/m²	2397,3 kWh/m²

In order to compute the annual value it is necessary to first take a look at more detailed values. The Joint Research Center provides data for every 15 minutes during sunshine hours. I calculated the daily value which is 5927Wh/m² on an average day in January in the case of Santiago Island with Equation 11 (sunrise at 06:52 and sunset at 17:22). I did not use values for each individual day of the year but rather for one average day per month. Consequently, the mean monthly value is the same as the daily value indicated above. From this point, we can start to calculate virtual monthly and annual electricity production rates. For this purpose, it is necessary to multiply the mean monthly value by the respective amount of days (31 in case of January, 28 for February, etc.). The monthly energy received in Santiago in January is 183,7kWh/m² (see Table 12 and Equation 12). Once this process yielded values for each month, it is possible to derive the yearly value which amounts to 2397kWh/m² (variation of Equation 12). This is the theoretical amount of energy transformable into electricity. Due to efficiency rates the actual electricity output of a solar panel is at around 10-20% of this value. The annual energy received by one square meter for the different islands – the energy that can be transformed - can be taken from Table 13 and was calculated with Equation 14.

Table 13 – Characteristic Irradiation Data for each island of Cape Verde

Characteristic Irradiation Data					
Islands	**Santo Antao**	**Sao Vicente**	**Sao Nicolau**	**Sal**	**Maio**
Load Hours (per day)	12,00 h	12,00 h	12,00 h	12,00 h	12,00 h
Load Hours (per year)	4381,00 h	4381,00 h	4381,00 h	4381,00 h	4380,50 h
Daily irradiation energy	571 W/m²	527 W/m²	570 W/m²	514 W/m²	502 W/m²
Annual irradiation energy	2499 kWh/m²	2309 kWh/m²	2491 kWh/m²	2249 kWh/m²	2200 kWh/m²
Islands	**Santiago**	**Fogo**	**Brava**	**Boavista**	
Load Hours (per day)	12,00 h	12,00 h	12,00 h	12,04 h	
Load Hours (per year)	4380,50 h	4380,50 h	4380,50 h	4396,00 h	
Daily irradiation energy	548 W/m²	542 W/m²	513 W/m²	510 W/m²	
Annual irradiation energy	2397 kWh/m²	2363 kWh/m²	2236 kWh/m²	2241 kWh/m²	

All the islands present quite similar conditions for the installation of PV regarding hours of operation and daily irradiation. Still, the annual output varies up to 12% and thus is substantial. The top location in terms of annual solar irradiation is Santo Antão with 2499kWh/m². This is also globally a very good value (2.4.2 Solar PV). Furthermore, Cape Verde's archipelago experiences 12 hours of daily sunshine all year long. Thus, a long production period per day can be upheld. The typical daily load curve representative for the individual islands can be taken from Figure 19. Apart from the peak power output around noon the curves look very similar due to the geographic proximity. Despite the fact that Cape Verde experiences very long hours of sunshine all over the year, Figure 19 also clearly shows the zero output phase from 18:37 to 05:22.

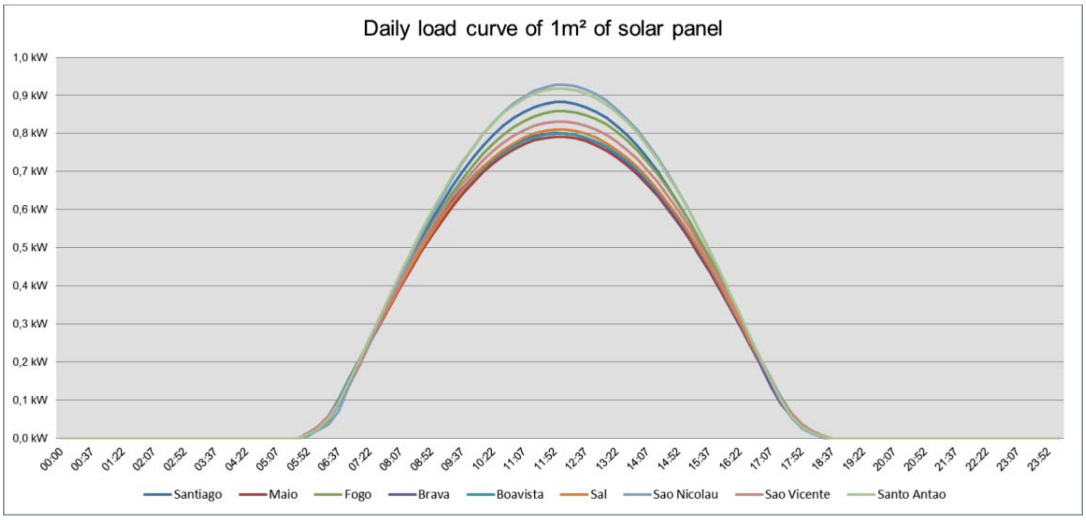

Figure 19 – Average daily load curve due to received solar irradiation of a PV panel on Cape Verde's islands – not subject to system losses (Adaptation and modification of values by (European Union, 2015))

Apart from the daily variation in output also the monthly variation has to be considered. It can be seen, in Figure 20, that solar irradiation is penetrating the islands on a constant level. Only in January, values deviate strongly from the mean value.

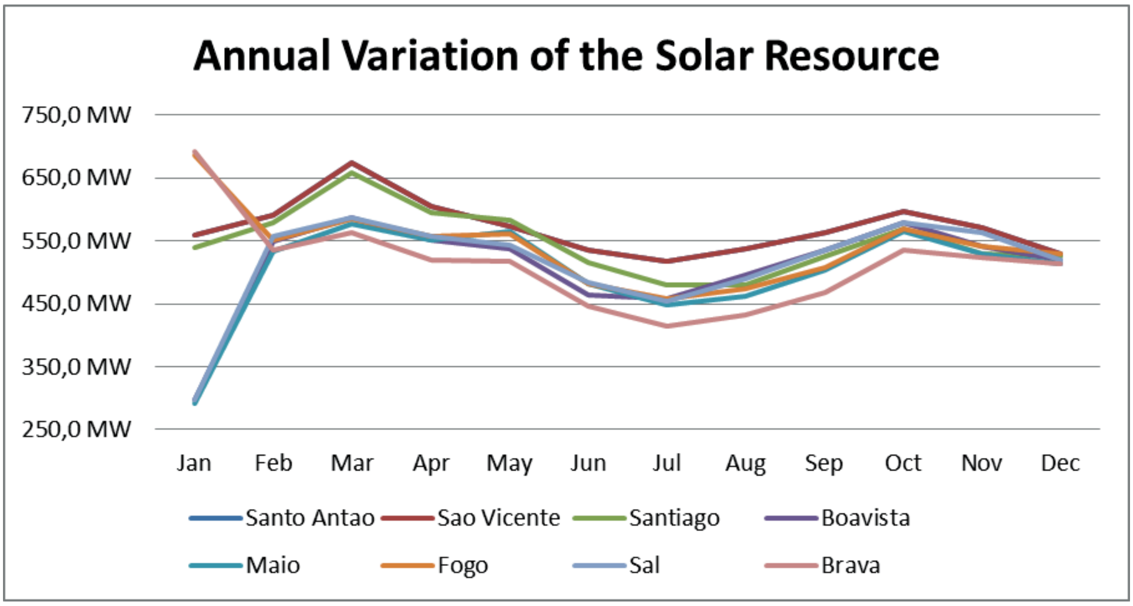

Figure 20 – Annual Variation of the solar resource (values taken from (European Union, 2015) and put together by (KE, 2015)).

3.2.1.3 Required land and installed capacity

For the last step of evaluating the potential of the solar resource for the deployment of PV it is necessary to apply a certain efficiency rate. As was already mentioned above, the efficiency of PV systems lies at around 10-20% which decreases further when taking into account the use of land[13]. For this reason and the strong dust precipitation which reduces energy yield on all Cape Verdean islands I chose to calculate with an overall efficiency (solar irradiation to electricity) of 10% and an efficiency of 5% for the calculation of land area required. The results also go along with the information I got by Mr Sanches (Sanches, 2015).

For the purpose of understandability I will explain the process with the help of Table 14. This table shows the land area needed in order to produce sufficient energy for the individual electricity centres based on the production values by Electra for 2012 (Electra, 2013). This will give an idea of the feasibility of 100% solar PV. Nevertheless, 100% solar

[13] The area of land needed to construct a PV power plant is far larger than the total PV panel surface area. This derives from the space needed between panels in order to prevent from shading.

PV will not be advisable for Cape Verde or any other country. Secondly, the table shows the needed installed capacity to sustain this production. However, this value is based on the total amount of hours solar radiation is available ("Installed Capacity"="Total"/"hours of sunshine"). Using this value of total amount of hours will result in low capacities. Actual capacities would be at least four times the value indicated in Table 14 (Sanches, 2015).

The resulting figures in column "Area" have been calculated in the way outlined in the following. I used the total electricity production of 2012 (5.219MWh in the case of Porto Novo/Santo Antão (see Table 6)) and divided it by the corresponding value in column "Annual Irradiation Energy" (adjusted for unit discrepancies) and the 5% efficiency value. For Porto Novo these calculations give a value of 41.767m². For entire Cape Verde the number adds up to 2,9km² (not even 0,07% of total land area) with Santiago clearly requiring the largest area of land (1.562.940m²).

Table 14 – 2012 Electricity Production Based on 100% Solar Photovoltaics and the consequent land use (KE, 2015)

Electricity Production Based on 100% Solar PV					
		2012			
Island	Power Plant	Area	Annual Irradiation Energy	Installed Capacity	Total
Santo Antão	Porto Novo	41.767 m²	2499,01 kWh/m²	1,19 MW	5.219 MWh
	Ribeira Grande	67.565 m²	2499,01 kWh/m²	1,93 MW	8.442 MWh
	Total	109.332 m²	2499,01 kWh/m²	3,12 MW	13.661 MWh
Sao Vicente	Matiota	278.715 m²	2309,45 kWh/m²	7,35 MW	32.184 MWh
	Lazareto	293.624 m²	2309,45 kWh/m²	7,74 MW	33.906 MWh
	Total	572.339 m²	2309,45 kWh/m²	15,09 MW	66.089 MWh
Sao Nicolau	Tarrafal	44.342 m²	2490,93 kWh/m²	1,26 MW	5.523 MWh
	Total	44.342 m²	2490,93 kWh/m²	1,26 MW	5.523 MWh
Sal	Palmeira	356.181 m²	2249,20 kWh/m²	9,14 MW	40.056 MWh
	Total	356.181 m²	2249,20 kWh/m²	9,14 MW	40.056 MWh
Maio	Porto Inglês	24.848 m²	2200,12 kWh/m²	0,62 MW	2.733 MWh
	Total	24.848 m²	2200,12 kWh/m²	0,62 MW	2.733 MWh
Santiago	Praia	265.004 m²	2397,33 kWh/m²	7,25 MW	31.765 MWh
	Palmarejo	1.225.876 m²	2397,33 kWh/m²	33,54 MW	146.941 MWh
	Assomada (Sta Catarina)	54.354 m²	2397,33 kWh/m²	1,49 MW	6.515 MWh
	Tarrafal ST	6.804 m²	2397,33 kWh/m²	0,19 MW	0.816 MWh
	S. Cruz	10.902 m²	2397,33 kWh/m²	0,30 MW	1.307 MWh
	Total	1.562.940 m²	2397,33 kWh/m²	42,77 MW	187.344 MWh
Fogo	S.Filipe	89.671 m²	2363,33 kWh/m²	2,42 MW	10.596 MWh
	Mosteiros	12.602 m²	2363,33 kWh/m²	0,34 MW	1.489 MWh
	Total	102.274 m²	2363,33 kWh/m²	2,76 MW	12.085 MWh
Brava	Favetal	24.197 m²	2235,86 kWh/m²	0,62 MW	2.705 MWh
	Total	24.197 m²	2235,86 kWh/m²	0,62 MW	2.705 MWh
Boavista	Sal-Rei	106.304 m²	2240,50 kWh/m²	2,71 MW	11.909 MWh
	Total	106.304 m²	2240,50 kWh/m²	2,71 MW	11.909 MWh
All Islands	Total	2.902.756 m²	2331,75 kWh/m²	78,08 MW	342.106 MWh
	Total required land area	2,9 km²			

3.2.1.4 Future Scenarios

The electricity demand of the nine Cape Verdean islands is predicted to increase at a rate of roughly 6% per year reaching a total value of 863.556 MWh by 2030. In order to supply this amount to the customers, electricity production centre's capacities will have to grow considerably. In case of a 100% PV scenario the following tables give an insight in the amount of land and installed capacity required. The irradiation values do not change significantly within 15 years and for that reason have been kept at the same level.

Table 15 – 2020 and 2030 Electricity Production Based on 100% Solar Photovoltaics and the consequent land use (KE, 2015)

Electricity Production Based on 100% Solar Energy						
Island	**Power Plant**	**Annual Irradiation Energy**	2020		2030	
			Area	Installed Capacity	Area	Installed Capacity
Santo Antão	Porto Novo	2499,01 kWh/m²	66.149 m²	5,03 MW	118.113 m²	8,99 MW
	Ribeira Grande	2499,01 kWh/m²	102.359 m²	7,79 MW	175.425 m²	13,35 MW
	Total	2499,01 kWh/m²	168.507 m²	12,82 MW	293.538 m²	22,33 MW
Sao Vicente	Matiota	2309,45 kWh/m²	366.586 m²	25,77 MW	536.313 m²	37,70 MW
	Lazareto	2309,45 kWh/m²	465.031 m²	32,69 MW	830.347 m²	58,38 MW
	Total	2309,45 kWh/m²	831.617 m²	58,47 MW	1.366.660 m²	96,08 MW
Sao Nicolau	Tarrafal	2490,93 kWh/m²	70.226 m²	5,33 MW	125.395 m²	9,51 MW
	Total	2490,93 kWh/m²	70.226 m²	5,33 MW	125.395 m²	9,51 MW
Sal	Palmeira	2249,20 kWh/m²	515.725 m²	35,31 MW	847.715 m²	58,04 MW
	Total	2249,20 kWh/m²	515.725 m²	35,31 MW	847.715 m²	58,04 MW
Maio	Porto Inglês	2200,12 kWh/m²	39.354 m²	2,64 MW	70.269 m²	4,71 MW
	Total	2200,12 kWh/m²	39.354 m²	2,64 MW	70.269 m²	4,71 MW
Santiago	Praia	2397,33 kWh/m²	320.831 m²	23,41 MW	416.625 m²	30,40 MW
	Palmarejo	2397,33 kWh/m²	1.915.972 m²	139,82 MW	3.391.779 m²	247,53 MW
	Assomada	2397,33 kWh/m²	86.084 m²	6,28 MW	153.709 m²	11,22 MW
	Tarrafal ST	2397,33 kWh/m²	10.775 m²	0,79 MW	19.240 m²	1,40 MW
	S. Cruz	2397,33 kWh/m²	17.266 m²	1,26 MW	30.830 m²	2,25 MW
	Total	2397,33 kWh/m²	2.350.928 m²	171,57 MW	4.012.184 m²	292,80 MW
Fogo	S.Filipe	2363,33 kWh/m²	142.018 m²	10,22 MW	253.584 m²	18,24 MW
	Mosteiros	2363,33 kWh/m²	19.959 m²	1,44 MW	35.638 m²	2,56 MW
	Total	2363,33 kWh/m²	161.977 m²	11,65 MW	289.222 m²	20,81 MW
Brava	Favetal	2235,86 kWh/m²	38.322 m²	2,61 MW	68.427 m²	4,66 MW
	Total	2235,86 kWh/m²	38.322 m²	2,61 MW	68.427 m²	4,66 MW
Boavista	Sal-Rei	2240,50 kWh/m²	152.331 m²	10,39 MW	246.667 m²	16,82 MW
	Total	2240,50 kWh/m²	152.331 m²	10,39 MW	246.667 m²	16,82 MW
All Islands	**Total**	**2331,75 kWh/m²**	**4.328.988 m²**	**310,77 MW**	**7.320.076 m²**	**525,76 MW**
			4,3 km²		**7,3 km²**	

Following the increase in electricity demand also installed capacity and needed land area will increase. By 2030 the overall land use for solar PV installations will be at 7,3km² which makes up almost 1,8% of total land area. Additionally, installed capacity will have grown to 525,76MW of which 292,8MW will be installed on Santiago island (more than the current total installed capacity of Cape Verde).

Summarizing Table 14 and Table 15, it can be said that a rather small share of Cape Verde's land area (0,07% in 2012 to 1,8% in 2030) could be used to saturate its overall electricity demand. This, however, is only a theoretical possibility due to the fact that PV panels produce electricity during the day only. In case of a 100% PV scenario a huge amount of storage capacity had to be installed to sustain the constant production of useable energy. We will see some scenarios relying only on solar PV further down.

3.2.2 Wind

In this chapter I will present the possibility of supplying Cape Verdean electricity by 100% wind energy for the years 2020 and 2030. First, I will give an overview of the methodology and secondly, I will explain the process of calculating the electricity output as well as the number of turbines needed.

3.2.2.1 Methodology

The assessment of the energy yield of a specific wind turbine generator (WTG) is mostly influenced by the wind speed, its variation at the turbine's location, the hub height and the type of WTG deployed. In this assessment I will base my calculation solely on the Vestas V52 850kW WTG with a hub height of 55m as this is the turbine currently operated by Cabeolica in all running wind parks of Cape Verde (see Table 16).

Table 16 – Characteristics of Vestas V52 850kW

Vestas V52 850kW WTG				
Hub Height	Installed Capacity	Efficiency	Rotor diameter	Swept Area
55,0 m	850,0 kW	41,10%	52,0 m	2123,7 m²

For the wind speeds, I rely on the data collected by Risø DTU National Laboratory for Sustainable Energy, an institute of the Technical University of Denmark which did a study (Mortensen et al., 2002) for Electra and Programa Energia, Água e Saneamento (PEAS) in 2002. In this project three islands stood in the focus of attention namely Santiago, Sao

Vicente and Sal. For specific locations on each of these islands accurate average wind speeds have been collected and calculated with the help of WAsP[14]. For the assessment of the six other islands I used the WindScout program. This program computes wind speeds for individual WTGs based on various data such as geographical location, height and terrain roughness. However, I compared the wind speeds of the specific sites selected in the Risø study with data from WindScout and found that WindScout's data is usually around 14% lower than Risø's values. Consequently, I scaled up the wind speeds from WindScout by this error fraction – for the islands of Santo Antão, Sao Nicolau, Boavista, Fogo, Santiago and Maio. The values can be taken from Table 17. The highlighted cells indicate that the value was scaled to the Risø format. In the following chapters I will use the indicated average wind speed for the respective island as a whole without differentiating between intra-island locations.

3.2.2.2 Wind Resource

Table 17 – Average Wind Speeds

Average Wind Speeds		
Island	Wind	
	Annual Average Wind Speed Riso-Report	Annual Average Wind Speed WindFinder
Santo Antao	8,71 m/s	7,40 m/s
Sao Vicente	10,25 m/s	8,30 m/s
Sao Nicolau	9,30 m/s	7,90 m/s
Sal	8,20 m/s	7,50 m/s
Maio	8,24 m/s	7,00 m/s
Santiago	8,50 m/s	7,00 m/s
Fogo	8,01 m/s	6,80 m/s
Brava	8,60 m/s	7,30 m/s
Boavista	8,83 m/s	7,50 m/s
All Islands	**8,74 m/s**	**7,41 m/s**

As indicated above Table 17 shows the average wind speeds over a year. For the purpose of assessing the renewable energy potential as set out in the hypothesis this is an acceptable approximation. However, a more detailed analysis is possible with the help of

[14] WAsP is wind energy assessment software that is based on industry standard calculations (WAsP, 2015).

an hourly distribution (see chapter 3.3). Figure 21 shows the production curve for the various islands. The data is taken from Cabeolica. For the islands of Sal, Santo Antão, Santiago and Boavista values from the actual energy production were used. For the residual five islands values from neighbouring islands were adjusted to the respective size of electricity production (Santo Antão and Sao Nicolau based on Sao Vicente; Fogo, Santiago and Maio based on Santiago). The trend of all islands is almost the same showing a drop of available wind resource in August and a peak in December respectively May. The variation between these two months is rather significant. The biggest variance can be observed on Santiago Island. Wind energy production in August amounts to 20% only of the peak value which is reported for May.

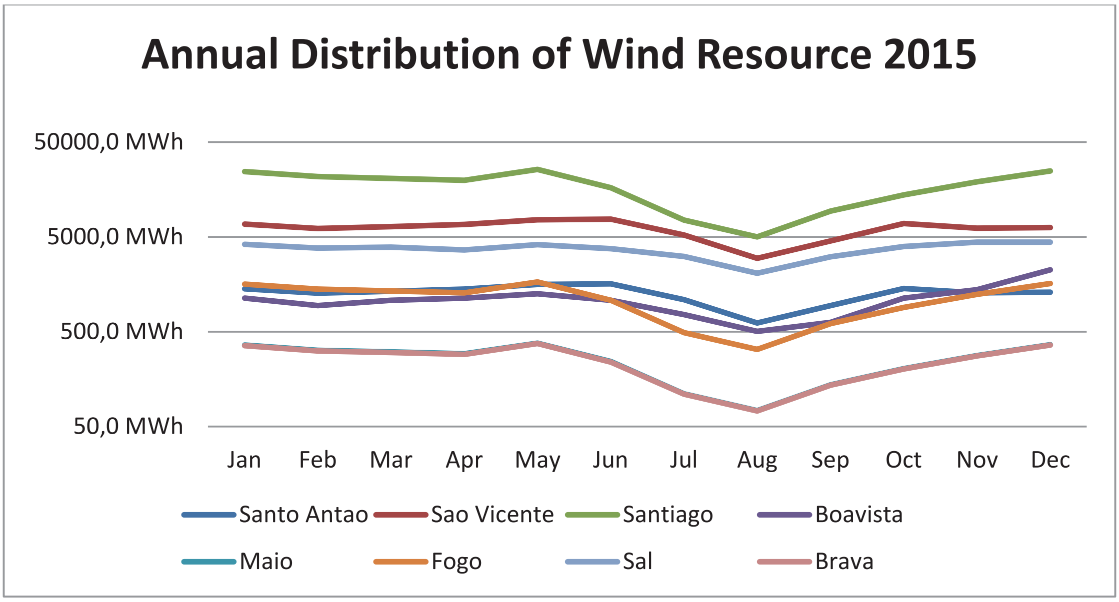

Figure 21 – Annual Distribution of Wind Resource based on power production with a logarithmic y-axis (values taken from (Cabeolica, 2014), (Fonseca, 2014) and (Electra, 2013) and adjusted by (KE, 2015).

3.2.2.3 Required amount of turbines and installed capacity

In order to calculate the annual electricity generation, the power curve of the Vestas turbine (Vestas Wind Systems, 2011) was used to determine power output at certain wind speeds (see Figure 22). In the following, the power output was multiplied by the amount of hours per year (8760 hours per year) which results in the annual electricity production. I have not considered maintenance times but this could easily be done in a follow up study. Actually, the availability of the wind turbines was at around 99% according to Cabeolica (Cabeolica, 2014).

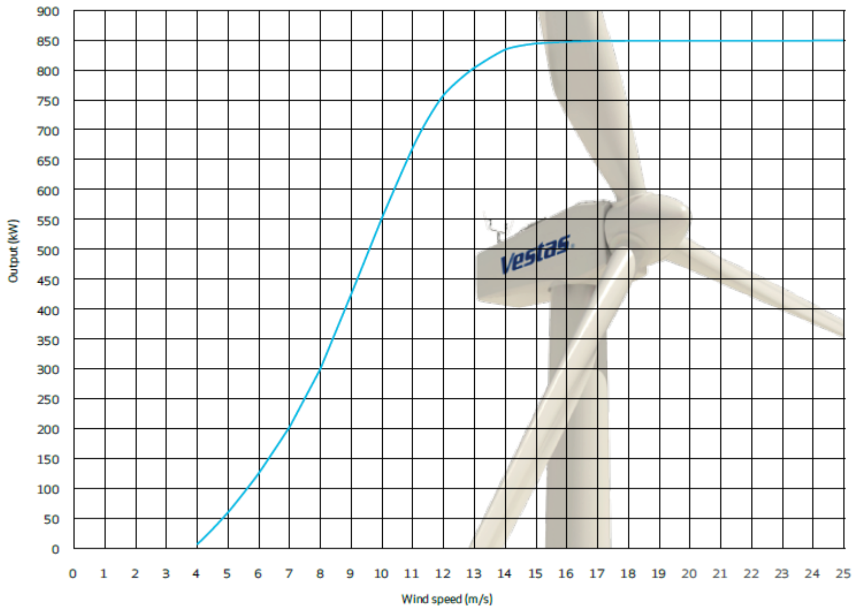

Figure 22 – Power curve of Vestas' V52 850kW wind turbine generator (Vestas Wind Systems, 2011)

Similarly to the chapter on the assessment of solar PV potential, I will try to find the number of turbines that have to be installed and thus the capacity needed. For this purpose, I multiplied the value derived from the power curve with the hours of a year (8760 hours) which gives the power produced by one single WTG. Then, I divided the annual demand of the respective location by the result of the multiplication.

$$\frac{Total\ Demand\ 2012}{Energy\ produced\ by\ one\ WTG} = Number\ of\ WTGs$$

Equation 21 – Calculating the number of wind turbines needed to sustain the electricity demand (KE, 2015)

For most locations this equation will not give an even number of wind turbines. Thus, the value needs to be rounded up to the next bigger even number. Consequently, the number of WTGs for Porto Novo is not 1,53 but 2. In the following, I multiplied the rounded number in the column "Number of WTGs" with the energy output per wind turbine which gives the total annual electricity production. Logically this value will exceed the actually demanded electricity in most cases (31% excess energy in Porto Novo and 10% on average). Furthermore, Table 18 shows that 111 wind turbines alone could have fully saturated electricity consumption of Cape Verde in 2012. Of course, this calculation does not yet take into consideration monthly or daily variations of the wind resource. As we will see in subsequent sections installed capacity will increase as hourly variations of the load are taken into consideration.

Table 18 – 2012 Electricity Production based on 100% Wind Energy (KE, 2015)

Electricity Production Based on 100% Wind Energy							
Island	Power Plant	2012					
		Number of WTGs	Capacity of Turbines	Energy Produced by one WTG	Energy Produced by WTGs	Excess Production [%]	Excess Production [MWh]
Santo Antão	Porto Novo	2	1,70 MW	3.408,7 MWh	6.817,4 MWh	31%	1.598,7 MWh
	Ribeira Grande	3	2,55 MW	3.408,7 MWh	10.226,2 MWh	21%	1.783,9 MWh
	Total	5	4,25 MW	3.408,7 MWh	17.044 MWh	25%	3.382,6 MWh
Sao Vicente	Matiota	7	5,95 MW	5.091,8 MWh	35.642,3 MWh	11%	3.458,3 MWh
	Lazareto	7	5,95 MW	5.091,8 MWh	35.642,3 MWh	5%	1.736,7 MWh
	Total	14	11,90 MW	5.091,8 MWh	71.285 MWh	8%	5.195,0 MWh
Sao Nicolau	Tarrafal	2	1,70 MW	4.053,4 MWh	8.106,7 MWh	47%	2.584,1 MWh
	Total	2	1,70 MW	4.053,4 MWh	8.106,7 MWh	47%	2.584,1 MWh
Sal	Palmeira	15	12,75 MW	2.847,0 MWh	42.705,0 MWh	7%	2.648,8 MWh
	Total	15	12,75 MW	2.847,0 MWh	42.705 MWh	7%	2.648,8 MWh
Maio	Porto Inglês	1	0,85 MW	2.893,0 MWh	2.893,0 MWh	6%	0.159,6 MWh
	Total	1	0,85 MW	2.893,0 MWh	2.893,0 MWh	6%	0.159,6 MWh
Santiago	Praia	11	9,35 MW	3.175,5 MWh	34.930,5 MWh	10%	3.165,5 MWh
	Palmarejo	47	39,95 MW	3.175,5 MWh	149.248,5 MWh	2%	2.307,3 MWh
	Assomada (Sta Catarina)	3	2,55 MW	3.175,5 MWh	9.526,5 MWh	46%	3.011,3 MWh
	Tarrafal ST	1	0,85 MW	3.175,5 MWh	3.175,5 MWh	289%	2.360,0 MWh
	S. Cruz	1	0,85 MW	3.175,5 MWh	3.175,5 MWh	143%	1.868,7 MWh
	Total	63	53,55 MW	3.175,5 MWh	200.057 MWh	7%	12.712,7 MWh
Fogo	S.Filipe	5	4,25 MW	2.635,2 MWh	13.175,8 MWh	24%	2.579,6 MWh
	Mosteiros	1	0,85 MW	2.635,2 MWh	2.635,2 MWh	77%	1.146,0 MWh
	Total	6	5,10 MW	2.635,2 MWh	15.810,9 MWh	31%	3.725,6 MWh
Brava	Favetal	1	0,85 MW	3.279,8 MWh	3.279,8 MWh	21%	0.574,7 MWh
	Total	1	0,85 MW	3.279,8 MWh	3.279,8 MWh	21%	0.574,7 MWh
Boavista	Sal-Rei	4	3,40 MW	3.537,7 MWh	14.150,6 MWh	19%	2.241,9 MWh
	Total	4	3,40 MW	3.537,7 MWh	14.150,6 MWh	19%	2.241,9 MWh
All Islands	**Total**	**111,00**	**94,35 MW**	**3.435,8 kWh**	**375.330,7 kWh**	**10%**	33.225,0 MWh

3.2.2.4 Future Scenarios

As indicated in chapter 3.1, electricity consumption is predicted to grow considerably within the next 15 years. Therefore, the calculations above have to be adjusted accordingly. The following section is based on the same equations and logic set out in the preceding paragraphs. Thus, only the results will be presented here. Additionally, values for total demand, corresponding energy yield and energy produced by one single WTG will not be presented in each table but can be taken from Table 19 or preceding chapters as the values do not change over time.

Table 19 – 2015 Electricity Production Based on 100% Wind Energy (KE, 2015)

Electricity Production Based on 100% Wind Energy											
Island	Power Plant	Vestas V52		2020				2030			
		Corresponding energy yield	Energy Produced by one WTG	Number of WTGs	Capacity of Turbines	Energy Produced by WTGs	Excess Production [%]	Number of WTGs	Capacity of Turbines	Energy Produced by WTGs	Excess Production [%]
Santo Antão	Porto Novo	389,1 kW	3.408,7 MWh	3	2,55 MW	10.226,2 MWh	24%	5	4,25 MW	17.043,6 MWh	15%
	Ribeira Grande	389,1 kW	3.408,7 MWh	4	3,40 MW	13.634,9 MWh	7%	7	5,95 MW	23.861,1 MWh	9%
	Total	389,1 kW	3.408,7 MWh	7	5,95 MW	23.861 MWh	13%	12	10,20 MW	40.905 MWh	12%
Sao Vicente	Matiota	581,3 kW	5.091,8 MWh	9	7,65 MW	45.825,8 MWh	8%	13	11,05 MW	66.192,8 MWh	7%
	Lazareto	581,3 kW	5.091,8 MWh	11	9,35 MW	56.009,3 MWh	4%	19	16,15 MW	96.743,3 MWh	1%
	Total	581,3 kW	5.091,8 MWh	20	17,00 MW	101.835 MWh	6%	32	27,20 MW	162.936 MWh	3%
Sao Nicolau	Tarrafal	462,7 kW	4.053,4 MWh	3	2,55 MW	12.160,1 MWh	39%	4	3,40 MW	16.213,5 MWh	4%
	Total	462,7 kW	4.053,4 MWh	3	2,55 MW	12.160,1 MWh	39%	4	3,40 MW	16.213,5 MWh	4%
Sal	Palmeira	325,0 kW	2.847,0 MWh	21	17,85 MW	59.787,0 MWh	3%	34	28,90 MW	96.798,0 MWh	2%
	Total	325,0 kW	2.847,0 MWh	21	17,85 MW	59.787 MWh	3%	34	28,90 MW	96.798 MWh	2%
Maio	Porto Inglês	330,3 kW	2.893,0 MWh	2	1,70 MW	5.786,0 MWh	34%	3	2,55 MW	8.679,0 MWh	12%
	Total	330,3 kW	2.893,0 MWh	2	1,70 MW	5.786,0 MWh	34%	3	2,55 MW	8.679,0 MWh	12%
Santiago	Praia	362,5 kW	3.175,5 MWh	13	11,05 MW	41.281,5 MWh	7%	16	13,60 MW	50.808,0 MWh	2%
	Palmarejo	362,5 kW	3.175,5 MWh	73	62,05 MW	231.811,5 MWh	1%	129	109,65 MW	409.639,5 MWh	1%
	Assomada (Sta Catarina)	362,5 kW	3.175,5 MWh	4	3,40 MW	12.702,0 MWh	23%	6	5,10 MW	19.053,0 MWh	3%
	Tarrafal ST	362,5 kW	3.175,5 MWh	1	0,85 MW	3.175,5 MWh	146%	1	0,85 MW	3.175,5 MWh	38%
	S. Cruz	362,5 kW	3.175,5 MWh	1	0,85 MW	3.175,5 MWh	53%	2	1,70 MW	6.351,0 MWh	72%
	Total	362,5 kW	3.175,5 MWh	92	78,20 MW	292.146 MWh	4%	154	130,90 MW	489.027 MWh	2%
Fogo	S.Filipe	300,8 kW	2.635,2 MWh	7	5,95 MW	18.446,1 MWh	10%	12	10,20 MW	31.621,8 MWh	6%
	Mosteiros	300,8 kW	2.635,2 MWh	1	0,85 MW	2.635,2 MWh	12%	2	1,70 MW	5.270,3 MWh	25%
	Total	300,8 kW	2.635,2 MWh	8	6,80 MW	21.081,2 MWh	10%	14	11,90 MW	36.892,1 MWh	8%
Brava	Favetal	374,4 kW	3.279,8 MWh	2	1,70 MW	6.559,6 MWh	53%	3	2,55 MW	9.839,4 MWh	29%
	Total	374,4 kW	3.279,8 MWh	2	1,70 MW	6.559,6 MWh	53%	3	2,55 MW	9.839,4 MWh	29%
Boavista	Sal-Rei	403,8 kW	3.537,7 MWh	5	4,25 MW	17.688,3 MWh	4%	8	6,80 MW	28.301,2 MWh	2%
	Total	403,8 kW	3.537,7 MWh	5	4,25 MW	17.688,3 MWh	4%	8	6,80 MW	28.301,2 MWh	2%
All Islands	**Total**	**392,2 kW**	**3.435,8 MWh**	**160,00**	**136,00 MW**	**540.904,3 kWh**	**6%**	**264,00**	**224,40 MW**	**889.590,9 kWh**	**3%**

In Table 19 the values for the years 2020 and 2030 are presented. We can see that excess production drops to 3%. Also, the high values of Tarrafal ST, S.Cruz and Porto Ingles normalized to roughly 38%, 72% and 12% respectively. In Lazareto, production of the wind turbines almost exactly meets the load, exceeding it only by 0,5%. In total, 160 and 264 wind turbines of the size of 850kW would be needed to sustain the energy demand by 2020 and 2030 respectively. Again, the majority of the required capacity would have to be installed on Santiago Island (154 turbines meaning an equivalent of 130,9MW installed capacity).

In conclusion, it can be said that the powerful wind resource makes it possible to meet the prospective annual load by only 264 WTGs distributed all over the nine populated islands of Cape Verde. This number could even be smaller in case of the installation of larger sized turbines. The deployment of 2MW turbines would cut the number of turbines down to approximately 112 units. The decrease in the number of installed turbines would also lower the amount of land area and sites needed. Another aspect worth considering is the monthly volatility of the wind resource which is quite significant. Based on the calculations above an average wind speed and thus an average electricity production are assumed. However, output varies between 20% and 100% on some islands. For these locations, two solutions can be found. One, the deployment of long-term energy storage is required (see chapter 2.5). Two, installed capacity is fitted to the month of peak demand or lowest abundance of wind which consequently results in large amounts of excess capacity available at other times. We will see excess rates exceeding 100% of total power demand in the next chapter. Therefore, the deployment of wind turbines large enough to meet the annual load is not recommendable due to mentioned disadvantages. A mix of solar PV and wind could prove reasonable.

3.3 Finding the energy mix

In the previous chapter we assumed a theoretical deployment of only one technology (wind and solar PV) based on average annual values for solar and wind resource. I was able to derive certain values for land use and WTGs deployed. Furthermore, I presented very low excess energy rates and capacities installed for some islands. I used chapter 3.2 as a basis for the following section. Hence, the subsequent chapter will elaborate in detail on the islands individually and propose an energy mix for each of them according to the prospective *hourly* loads in 2020 and 2030. I will show that the more detailed the analysis the more complex the issue gets. Moreover, installed capacities will more than double in certain scenarios as load variability is great (see Santo Antão in chapter 3.3.2.8).

In principle, I will assess two different scenarios based on storage capacity. The first scenario (1DS) applies a storage scheme that can maintain electricity supply for 24 hours at any time during the year. The second scenario (1WS) applies storage to an extent which can supply seven days of electricity demand for the respective island. Within these scenarios different storage schemes can find application based on the island's situation. These schemes can range from 100% PHS to 100% battery or a mix of all four storage technologies (PHS, P2G, Battery Storage, and CSP-TES). First, I will introduce the methodology, then I will discuss the specific islands and in the end, I will give a conclusion of the results I derived at.

3.3.1 Methodology

The methodology part of this chapter will review the sources, deficiencies, adjustments and characteristics of the data and calculations used in this chapter. 2012 was the base year chosen for all values due to the fact that this was the year with the latest data available. Therefore, values had to be scaled up to 2020 and 2030 levels which we will discuss later. Furthermore, for some days, weeks, months on some of the islands and in some of the categories that will be described, no data was available. In these cases, values were adopted from neighbouring islands or comparable times (e.g. one week earlier).

3.3.1.1 Load Curve

The load curve was received on an hourly basis meaning 8760 values in a year. All data was provided by the DG of Energy of Cape Verde Mr Anildo Costa (Costa, 2015b). For the individual islands different limitations were faced which are summarized in Table 20. Results of this chapter are only marginally affected by the deficiencies in accuracy due to the fact that the usual load curve does not deviate from certain behaviour in general. However, the limitations are noted and will limit the accuracy of the results to some extent.

Table 20 – Limitations to load data (KE, 2015)

	Limitations and Solutions
Boavista	no data available; hourly values taken from the Island of Sal and adjusted according to the total energy production in 2012
Brava	values for December were not available and therefore calculated as a mean of the same hours in January and November
Fogo	values of 2011 were used and adjusted according to the total energy production in 2012; all weekdays, all Saturdays and all Sundays within a month have same values
Maio	values for December were not available; December values were taken from 2011 and adjusted to 2012 levels
Sal	values for February, August and October were not available for 2012 and thus adjusted from values taken from 2011
Santiago	values for December were not available and therefore calculated as a mean of the same hours in January and November; values were only available for the substation of Palmarejo (biggest one on Santiago Island) and thus had to be scaled up to levels of entire Santiago
Santo Antao	only one weekday, one Saturday and one Sunday per month were available; all weekdays, Saturdays and Sundays within a month have same values
Sao Nicolau	values for November and December were only available for 2011 and thus adjusted for a 2012 level
Sao Vicente	values for August, October, November and December were not available for 2012; August values were taken from 2011; the other three months were adjusted from values for 2013

Furthermore, values within data which was absurdly high or low were rejected and thus replaced by values from a week before or after depending on availability of these values. In Figure 23 such an adjustment can be seen. There are three obvious outliers which can be observed immediately. Additionally, hours without values and values of "0" were rejected and also replaced according to the procedure explained above. A load of zero kW could mean that a blackout was happening during this hour. However, I decided to reject these nonetheless as otherwise overall electricity demand would be lower than it actually is.

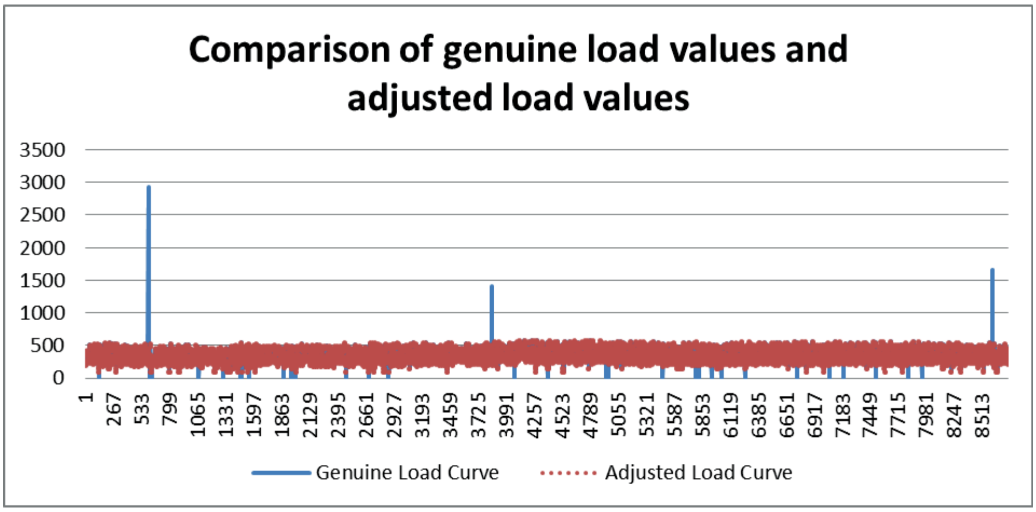

Figure 23 – Comparison of received data with outliers and adjusted load curve for Santiago Island (KE, 2015)

Afterwards, 2012 values were adjusted for 2020 and 2030 values according to the predictions made in Mr Costa's baseline report (Costa, 2015a). These ratios have already been applied in the previous chapter on 100% RE penetration based on one single technology. However, they haven't been stated as such and in numbers. Table 21 indicates that 2020 and 2030 electricity demand will increase by 42% and 139% respectively. The absolute values for 2020 and 2030 can be taken from (Table 6).

Table 21 – Electricity Growth Rates according to (Costa, 2015a)

Electricity Growth Rate
2012-2020
1,42
2012-2030
2,39

3.3.1.2 Solar PV

Irradiation values used for the calculation of a possible energy mix were taken from the European Commission's Joint Research Center's dataset. The methodology behind this dataset was already explained in a previous chapter. For the purpose of this chapter I had to accumulate the 15 minute values into hourly values. Also, the dataset used does only give one average day for each month. Therefore, each single day of a month uses the same values. The accuracy of results is, thus, limited. Nevertheless, Cape Verde's climate is almost perfectly constant experiencing only a few exceptional days with some cloud cover or rain over the course of a full year. Ergo, the average value for each month poses a reasonable alternative to more accurate datasets. Based on my interview with Mr Delgado (2015) I decided to implement seven days without any production from solar PV and CSP during the summer months of August and September. In these months, usually 5-10 days of rain are expected which come along with dense cloud cover and thus no solar irradiation.

In contrast to chapter 3.2.1 in which I used solar irradiance values to calculate a land area to determine a theoretical 100% penetration of solar PV I use irradiance values multiplied by collector surface area and efficiency rates in order to determine annual energy output, in this chapter. The values observed in the following will deviate from values above due to the different percentage of solar PV penetration applied (not 100%).

Figure 24 gives an indication of the values used in the calculations showing an average irradiation value for one day for each of the 12 months. These curves and their underlying values were used for the calculation of the power production based on solar PV. The result was 8760 values for each hour of the year.

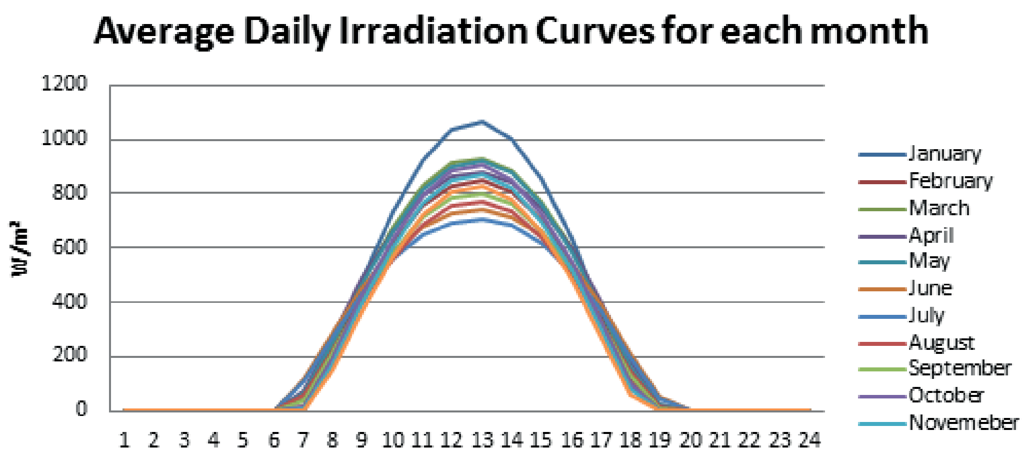

Figure 24 – Monthly Irradiation Curves on an hourly basis for Fogo Island (values taken from (European Union, 2015) and adjusted by (KE, 2015)).

3.3.1.3 Wind

The wind profile for this chapter was based on more detailed data than was used in the previous chapter. Companies operating wind parks on the archipelago of Cape Verde would have very accurate data as wind speeds are constantly measured on the nacelle of the WTGs. However, wind profiles are one of the major assets for these companies which consequently do not share them as stated by Mrs Monteiro working for Cabeolica as

Project Manager (Monteiro, 2015). Hence, the data I used was provided by the DG of Energy Mr Costa and are meteorological data for two of the nine islands (Sao Vicente and Sal). Both datasets give values for every hour in 2012. In order to evaluate the islands without specific data I had to adjust the values from the abundant two wind profiles to their island. Therefore, I used a comparison (ratio) of the average wind speeds used in the previous chapter (see chapter 3.2.2.1) and scaled it up or down respectively. The values can be taken from Table 22. The reasons for the allocation according to Table 22 were made on geographical characteristics. Only Sal and Boavista are almost completely flat without any noteworthy elevation and have a full sand cover. On the other hand, Sao Vicente has significant elevations and fauna typical for all islands (except Boavista and Sal). The constraints which are experienced due to this allocation and the abundance of two wind profiles only can be significant and this issue should be solved in prospective studies. Nevertheless, I want to reference chapter 2.4.1.3 and the difficulties in assessing a wind profile for a specific site. As a conclusion, it can be said that this procedure will still give a reasonable overview of a possible energy mix for islands without an accurate wind profile.

Table 22 – Underlying wind profiles and their respective scaling factor (KE, 2015)

	Wind profile	Scaling Factor
Boavista	Sal	1,08
Brava	Sao Vicente	0,84
Fogo	Sao Vicente	0,78
Maio	Sao Vicente	0,93
Sal	Sal	1
Santiago	Sao Vicente	0,83
Santo Antao	Sao Vicente	0,85
Sao Nicolau	Sao Vicente	0,91
Sao Vicente	Sao Vicente	1

An hourly wind profile allows for the computation of very accurate values of the power output. Based on the wind profiles described above I was able to determine approximate numbers with the help of the power curve of the Vestas V52 turbine. For each of the 8760 wind speeds I was able to determine the power output. This new dataset was then multiplied by the respective amount of WTGs needed to sustain the desired amount of energy per year. Similar to the load curve, outliers were observed which had to be eliminated. This was done by the Vestas power curve itself because values below 4 and above 25m/s do not generate any electricity (see Figure 22).

3.3.1.4 CSP

The methodology behind the calculation of output by CSP is similar to the one used for the PV part. Again, data (values of DNI) was taken from European Commission's Joint Research Center's dataset and accumulated to hourly instead of 15 minute values. Also, this dataset provides only one average day per month which was used consequently for each day of the respective month. Figure 25 shows all 12 curves used for a year for the island of Santo Antão. In the PV section of the methodology chapter I already mentioned that seven days without any solar irradiation were implemented. Of course, absolutely zero irradiation is almost non-existent, however, this approach also allows for the simulation of maintenance periods or other incidents which cause shut down.

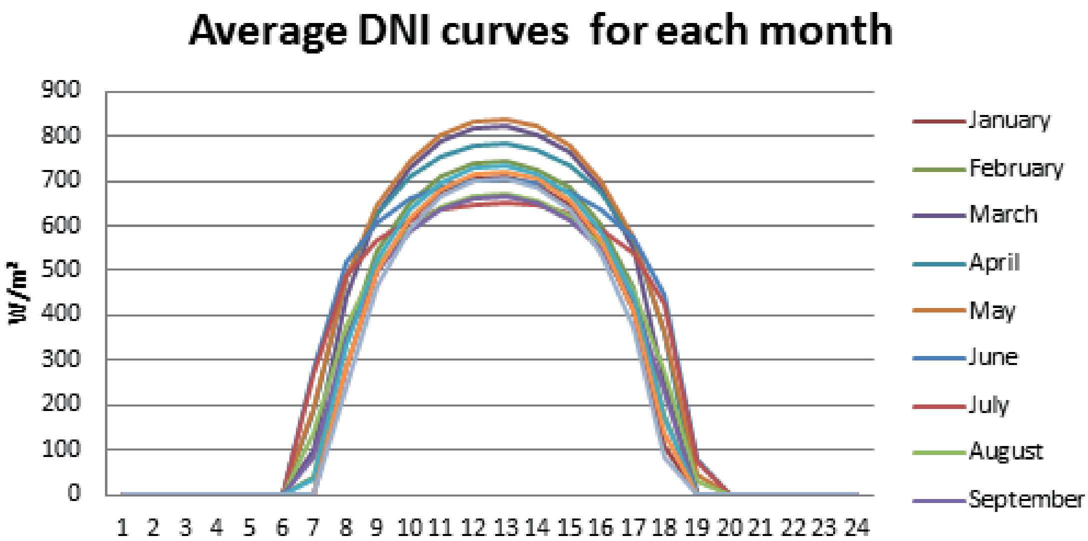

Figure 25 – Average DNI curves for the 12 months on Santo Antão Island

Not all islands account for sufficient high DNI values and thus were not considered for the deployment of CSP consequently[15]. In fact, only three islands qualified for the use of CSP in its energy mix (Santo Antão, Santiago and Sao Vicente) of which only Santiago is large enough to accommodate a CSP plant (Trieb et al., 2009b: p.76). Fogo Island comes very close to the threshold value with 1950kWh/m²/year but will still be rejected from CSP deployment. With the knowledge about the hourly DNI values it is possible to derive the

[15] The threshold value is 2000kWh/m²/year and was introduced in chapter 2.4.3.

hourly electricity production per m² of collector surface and thus per total collector surface deployed.

In Santiago's case I studied the loads and found that more than 8600 hours per year have a load larger than 15MW in 2020 and 20MW in 2030. In order to reduce complexity, I therefore chose to design CSP to have a nominal output sustaining this base load (15MW and 20MW). This naturally means that solar irradiation collected during sunlight hours is in excess. This "excess" energy goes straight into thermal energy storage and will be used during periods of no solar irradiance.

Table 23 – DNI values for the individual islands and respective electricity production ((KE, 2015) and (European Union, 2015))

CSP Characteristic Data		
Island	Annual direct normal irradiance received	Electricity Production per m² collector per year
Santiago	2.149 kWh/m²/year	215 kWh/m²/year
Maio	1.696 kWh/m²/year	170 kWh/m²/year
Fogo	1.950 kWh/m²/year	195 kWh/m²/year
Brava	1.686 kWh/m²/year	169 kWh/m²/year
Boavista	1.676 kWh/m²/year	168 kWh/m²/year
Sal	1.667 kWh/m²/year	167 kWh/m²/year
Sao Nicolau	2.343 kWh/m²/year	234 kWh/m²/year
Sao Vicente	1.856 kWh/m²/year	186 kWh/m²/year
Santo Antao	2.358 kWh/m²/year	236 kWh/m²/year

3.3.1.5 Residual Load

The objective of analysing various RE technologies and the load curves was to get values of the residual load (see chapter 11 and Equation 4). According to Equation 4 residual load is negative when RE production is larger than the load itself which means there is excess energy, either stored or lost. On the contrary, a positive residual load means deficient energy production. Hence, storage steps in and supplies the discrepancy. Figure 26 gives a first look at such a graph with the three main factors (load, RE production and residual load). This specific graph is for the Island of Maio and 1WS. Figure 27 gives a similar graph with values for 1,5DS. The curves follow the same pattern, only the amplitudes are different (larger for the 1,5DS). The reason for that is the smaller amount of storage capacity which means that more excess energy has to be produced.

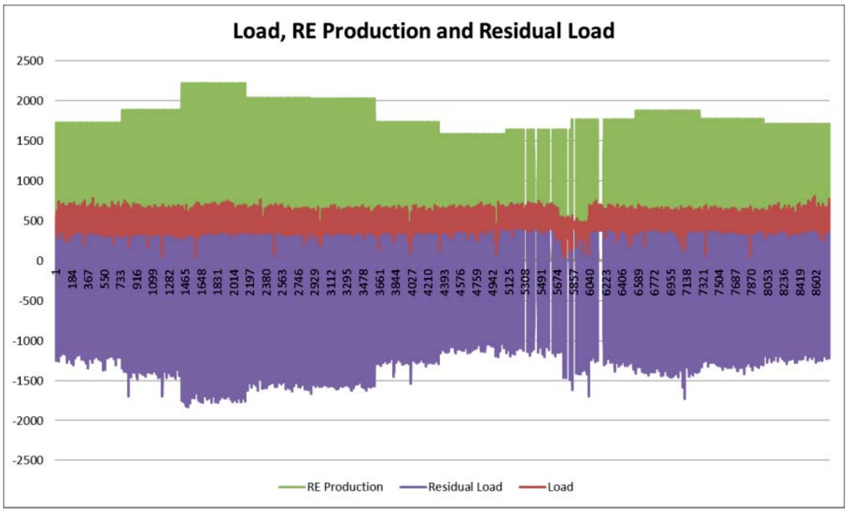

Figure 26 – Load, RE production and residual load for Maio Island, Battery Storage, 1WS and 2020 (KE, 2015)

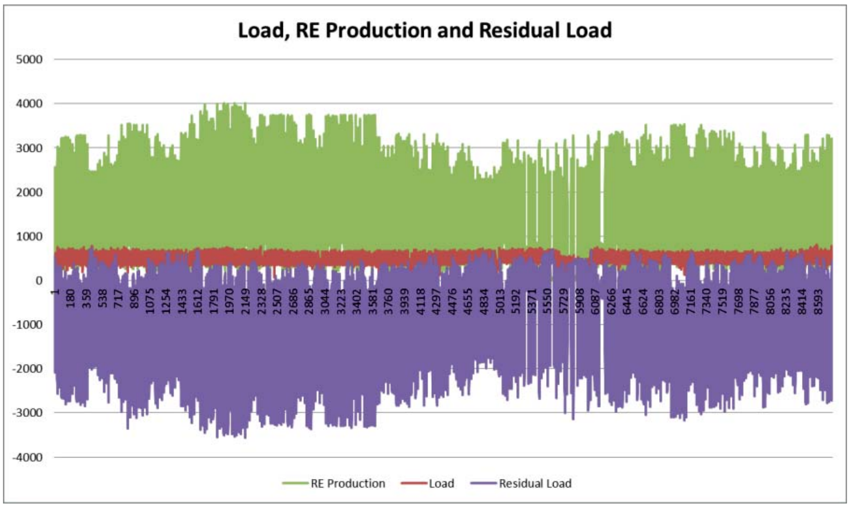

Figure 27 – Load, RE production and residual load for Maio Island, P2G Storage, 1,5DS and 2020 (KE, 2015)

3.3.1.6 Storage

The storage part of the analysis takes into account four different storage technologies, namely pumped hydro storage, power to gas, battery storage and thermal energy storage in connection with a CSP plant. Thermal energy storage was only considered in connection with CSP. For each of the different possibilities of storing energy an individual efficiency rate was determined from the literature review (see chapter 2.5 and Table 24). For the calculations, I used an average value of the indicated intervals below.

Table 24 – Efficiencies of Energy Storage (sources see Table 3)

	Batteries	Pumped Hydro	Thermal Energy Storage	Power to Gas
Efficiency	70-95%	75-85%	98,5%	35%
Applied Value	82,50%	80%	98,5%	35%

Every island provides different challenges regarding energy storage. As was identified previously by GESTO (2011) only Santiago and Sao Vicente provide reasonable locations for pumped hydro. These two and additionally Sal, Santo Antão and Boavista also prove too big to be powered by battery storage. Therefore, the following energy scheme scenarios were applied. CSP Thermal Energy Storage is only applied proportional to the share of CSP of the energy mix (e.g. 10% of Santiago's electricity is produced based on CSP which means also 10% of its storage capacity is thermal energy storage). Sao Nicolau and Santo Antão, due to their small electricity demand (less than 10MW installed capacity even in 2030), do not allow for the deployment of CSP although the DNI values would be sufficient (Trieb et al., 2009b: p.76).

Table 25 – Applied storage schemes

	Storage Scheme(s)
Boavista	100% Power to Gas
Brava	100% Battery; 100% Power to Gas
Fogo	100% Battery; 100% Power to Gas
Maio	100% Battery; 100% Power to Gas
Sal	100% Power to Gas
Santiago	CSP-TES+PHS; CSP-TES+P2G
Santo Antao	100% P2G
Sao Nicolau	100% Battery; 100% Power to Gas
Sao Vicente	100%PHS; 100% P2G

As was already indicated above two scenarios have been considered (1,5DS, 1WS). In both cases, it was assumed that full storage capacity was available in the beginning of the year. From there, depending on the residual load (negative or positive) the chosen storage devices were charged or discharged. However, the maximum (1,5 days or 1 week worth of energy) and obviously the minimum (no energy) could not be exceeded (above the maximum and below the minimum). Furthermore, in the calculation, the efficiency was applied "during the charging process" for the sake of less complexity. The overall efficiency of the storage scheme is calculated depending on the shares of the applied storage technologies in the individual scheme (see chapter 3.3.2). There might be a certain bias due to the efficiency deduction "during the charging process". In real, efficiency is lost consistently during the entire process. Also, changing the application of efficiency to the discharging process could have altered results.

3.3.2 Island Specific Analysis

In the following paragraphs I will assess each island individually based on the methodology described in the previous chapter (chapter 3.3.1) and the knowledge laid out in the theoretical part of this thesis (chapter 2).

3.3.2.1 Maio

The natural conditions in terms of renewable energy deployment are average on Maio (see Table 26). 268W/m² of solar irradiation is a relatively high value in comparison to the other islands. Maio's wind resource (8,25m/s) is on the lower side when compared with other Cape Verdean islands but still strong enough to support WTGs. Also, the deployment of CSP on Maio will not be considered due to the low DNI value of 250W/m² which sums up to 1696kWh/m²/year and thus stays way below the designated threshold value of 2000kWh/m²/year.

Table 26 – RE Characteristics for Maio Island

Maio RE Characteristics		
Average Irradiation	Average Wind Speed	Average DNI
268 W/m²	8,25 m/s	250 W/m²

Maio's energy sector will have a still rather small amount of annual electricity demand of roughly 4GWh by 2020 and 8GWh by 2030. The peak loads will be 0,8MW and 1,3MW respectively. More importantly, the maximum 24 hour load demand is predicted to be around 13MWh by 2020 and 22MWh by 2030.

Table 27 – Characteristic Data for Maio Island

Maio Characteristics				
	Annual Electricity Demand	Peak Load	Minimum Load	Maximum 24 hour load
2020	3.973.775 kWh	804 kW	37 kW	12.894 kWh
2030	6.722.720 kWh	1.360 kW	62 kW	21.815 kWh

Taking a look at the distribution of RE potential and the load over a year (see Figure 28 and Table 28), it is observable that the load runs rather constantly while RE potential is highly volatile. Maio's wind resource peaks in May and experiences its weakest month in September. PV's and CSP's resource are both peaking in spring (February to May) while they are rather low during the summer and winter months. In conclusion, RE potential does not follow Maio's load curve at any time. Consequently, excess energy rates during the spring months will be significant as electricity supply has to be based on summer, fall and winter values (highest demand although lowest RE potential).

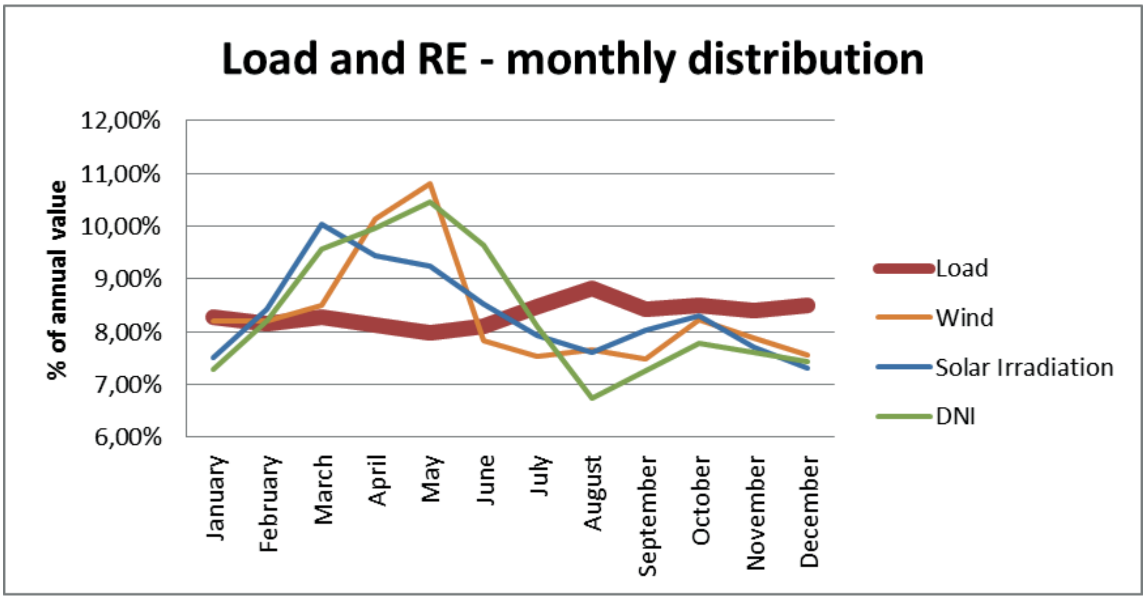

Figure 28 – monthly distribution of load and RE values in per cent of yearly value for Maio

The volatility of the load curve is backed up by Table 28. The power variation is almost as strong as the peak power of 804kW. Additionally, the strongest change of load within one hour (load gradient) will be 541kW and 914kW by 2020 and 2030. When taking a look at the consecutive hours of either positive or negative loads we can see two different scenarios on top. On the one hand, 100% battery storage in 1WS will yield the most consecutive positive residual hours, thus longest time relying on storage will be 63 hours. Although, energy storage capacity is only designed to meet 24 hours of storage it can still sustain longer periods without newly added renewable energy supply. This can happen when demand during this period is way below the maximum 24 hour electricity demand. On the other hand, 100% P2G in 1WS will provide the possibility of consecutively charging energy storage for 109 hours. This also means that, there is no need for electricity from storage during this time.

Table 28 – Load Characteristics for Maio Island

Maio - Load Characteristics							
	Load Factor	Power Variation	Maximum Load Gradient	Maximum consecutive hours of positive Residual Loads		Maximum consecutive hours of negative Residual Loads	
2020	0,56	767 kW	541 kW	63	100% Battery - 1WS	109	100% P2G - 1WS
2030		1.298 kW	914 kW	63	100% Battery - 1WS	108	100% P2G - 1WS

Based on the observations and calculations made I could derive an energy mix for Maio for both years 2020 and 2030 respectively. For each year 1,5DS and 1WS will be presented in one chart including the respective value for the total excess energy produced over the course of the year (see

Figure 29 and Figure 30).

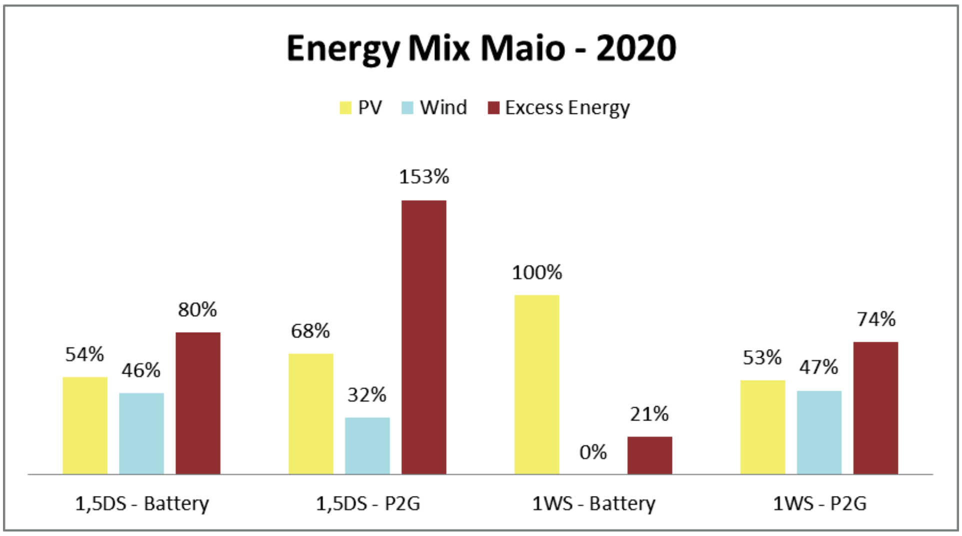

Figure 29 – Energy Mix Maio 2020 based on 1,5DS and 1WS

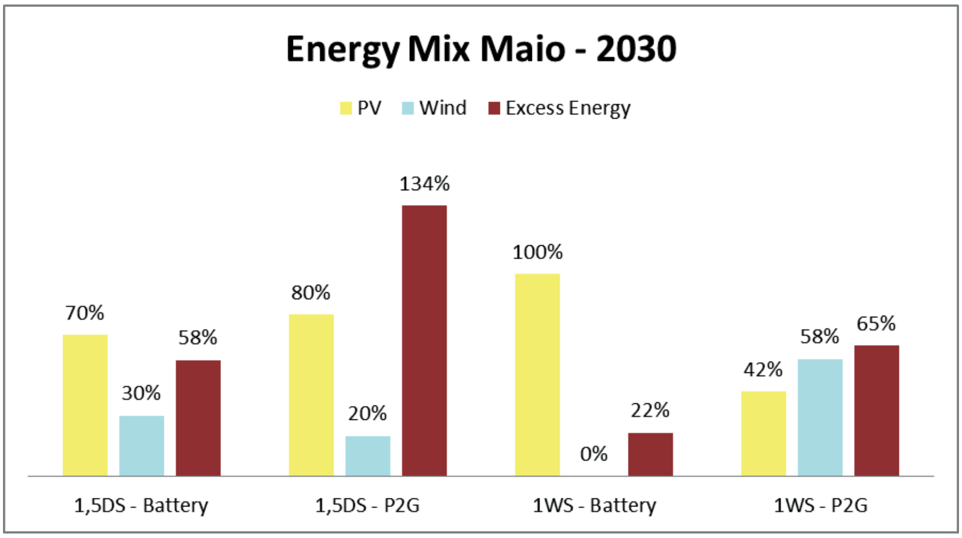

Figure 30 – Energy Mix Maio 2030 based on 1,5DS and 1WS

Both years, 2020 and 2030, show a similar pattern in terms of shares of renewable energy technology. In all cases, PV makes up the largest share of the energy mix – except in 1WS in 2030. The biggest contribution by PV to the energy mix is made in 2020 and 2030 in 1WS with battery storage. This can be explained due to the high efficiency of the storage technology and the constant irradiation penetrating the island. Furthermore, this scenario can overcome (due to the aforementioned characteristics) the days without any solar irradiation due to the large storage capacity and still have less excess energy produced than any other scheme (21% and 22% respectively). However, a very one-sided production always bares risks in case of malfunction or change of climatic conditions. In 2030 (1WS, battery storage), one added wind turbine and less PV panels would come very close to the most energy efficient scenario (0,75% more). In this case, PV would only get a share of 61% compared to 100% in the one shown in Figure 30. There is a scenario in which output of the two technologies is almost equal which is 1WS and P2G. Here, wind takes shares of 47% and 58% respectively. Furthermore, excess energy values are still within certain limits reaching 74% in 2020 and 65% in 2030. Finally, the most inefficient scenario in terms of excess energy is 1,5DS with P2G in 2020 - surplus production of 153%. This means more than double the needed electricity produced in this year.

Table 29 – Installed capacities for Maio Island based on different scenarios

Installed Capacity								
Year	**2020**				**2030**			
Scenario	1,5DS - Bat	1,5DS - P2G	1WS - Bat	1WS - P2G	1,5DS - Bat	1,5DS - P2G	1WS - Bat	1WS - P2G
PV	1,8 MW	3,2 MW	2,2 MW	1,7 MW	4,1 MW	6,0 MW	3,8 MW	2,2 MW
Wind	0,9 MW	0,9 MW	0,0 MW	0,9 MW	0,9 MW	0,9 MW	0,0 MW	1,7 MW
CSP	-	-	-	-	-	-	-	-
Total RE	**2,6 MW**	**4,0 MW**	**2,2 MW**	**2,5 MW**	**5,0 MW**	**6,9 MW**	**3,8 MW**	**3,9 MW**

Table 30 – Storage characteristics for Maio Island based on different scenarios

Storage Characteristics				
Year	**2020**		**2030**	
Power	0,8 MW		1,36 MW	
Scenario	**1,5DS**	**1WS**	**1,5DS**	**1WS**
Capacity	19,3 MWh	90,3 MWh	32,7 MWh	152,7 MWh

3.3.2.2 Brava

Brava's solar irradiation values can be considered comparatively weak when seen among the other islands. 246W/m² is the lowest value of all the islands although Boavista and Sal pose the same solar conditions. Consequently, also the DNI score is among the least favourable for CSP deployment. The annual value amounts to 1721kW/m² which is way below the threshold value of 2000kW/m². The average wind speed experienced on Brava is average with a value of 8,61m/s. Due to its natural conditions we will see that wind plays a more important role than on Maio although still limited in output.

Table 31 – RE Characteristics for Brava Island

Brava RE Characteristics		
Average Irradiation	Average Wind Speed	Average DNI
246 W/m²	8,61 m/s	197 W/m²

The electricity demand by 2020 and 2030 – similar to Maio – will be around 4GWh and 6,5GWh respectively. These increases come with a rise in peak load to 819kW and 1386kW depending on the year. Both values are still very low compared to electricity demands on Brava or Sao Vicente and can easily be managed. Furthermore, peak loads and maximum 24 hour electricity demands allow for the application of battery storage. Additionally, power to gas storage will be assessed. The cost effects of these two storage options will be assessed in the subsequent chapter.

Table 32 – Characteristic Data for Brava Island

Brava Load Characteristics				
	Annual Electricity Demand	Peak Load	Minimum Load	Maximum 24 hour load
2020	3.852.595 kWh	819 kW	156 kW	13.171 kWh
2030	6.517.711 kWh	1.386 kW	263 kW	22.282 kWh

Figure 31 shows an almost completely levelled load curve for Brava with no distinct peaks in any month. Still, a slight increase from the 8,33% average production can be observed from June to November. Again, these are the same months in which conditions for the harvesting of renewable energy are the worst. Especially, solar irradiation and DNI curves are extremely volatile – more so than the wind resource. To sum up, load curve and resource curves having promising characteristics for the majority of months but show significant discrepancies in the rest.

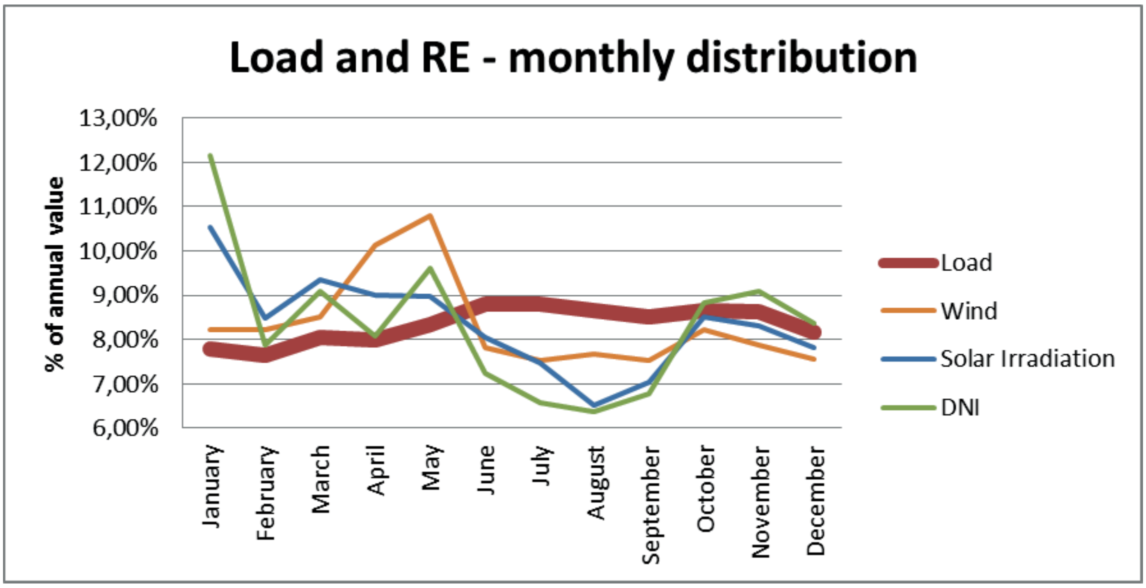

Figure 31 – Monthly distribution of load and RE values in per cent of yearly value for Brava

Although Brava's load curve looks consistent its load factor is at 0,54 which means that average demand is only half as strong as the maximum value. The power variation gives the same information considering the fact that it is more than 75% of the peak load. However, the gradient in change from one hour to another is low. It makes up only half the peak load value. Other distribution systems on various islands experience gradients as big as their peak loads. The amounts of consecutive hours of positive or negative residual loads transmit the same image as described above. Both values follow the normal pattern observable on other islands. 186 hours of excess energy production mean more than a week electricity could be used otherwise once storage is full. Additionally, this could provide the opportunity of increasing the energy storage reservoir for longer term storage.

Table 33 – Load Characteristics for Brava Island

Brava - Load Characteristics							
	Load Factor	Power Variation	Maximum Load Gradient	Maximum consecutive hours of positive Residual Loads		Maximum consecutive hours of negative Residual Loads	
2020	0,54	664 kW	406 kW	62	100% Battery - 1WS	186	100% P2G - 1,5DS
2030		1.123 kW	687 kW	62	100% Battery - 1WS	185	100% P2G - 1WS

The energy mix for 2020 and 2030 based on all information gathered and consequently processed are shown in Figure 32 and Figure 33. For each year 1,5DS and 1WS are presented in one chart including the respective value for the total excess energy produced over the course of the year.

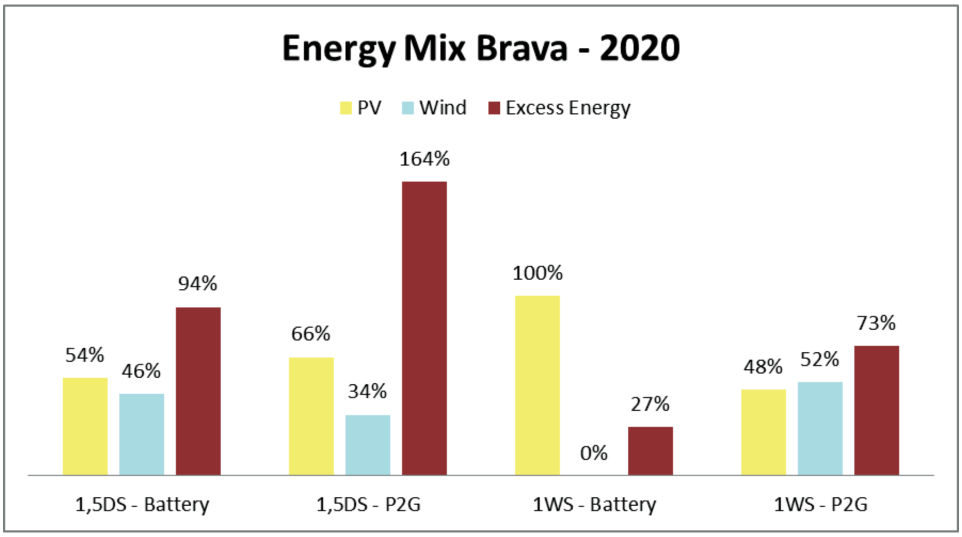

Figure 32 – Energy Mix Brava 2020 based on 1,5DS and 1WS

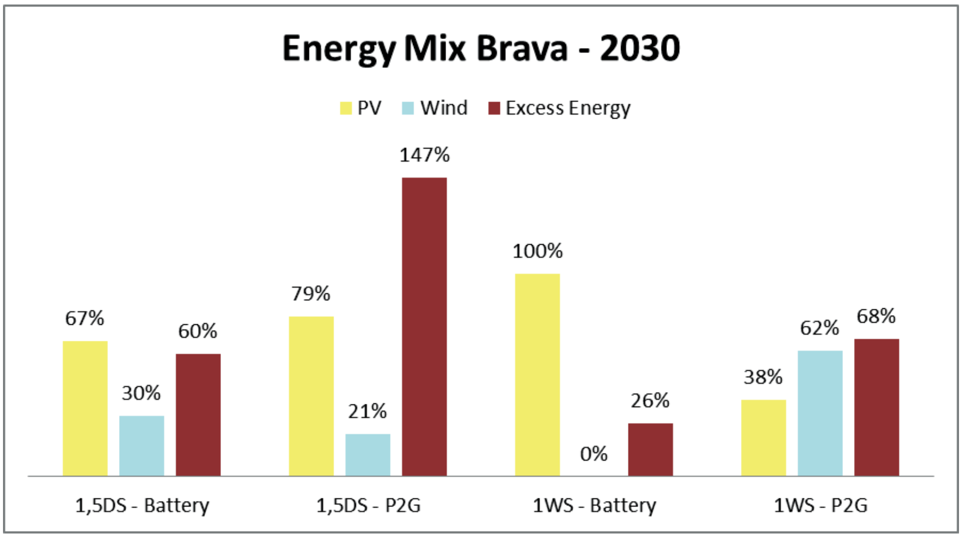

Figure 33 – Energy Mix Brava 2030 based on 1,5DS and 1WS

Energy mixes for both years, 2020 and 2030, follow the same trend. We can see PV dominate in all scenarios except 1WS-P2G. The low efficiency of power to gas storage is responsible for this effect. The contrary is visible for 1WS-Battery for the opposite reason. Here, it has to be said that installing one wind turbine would only marginally lower overall efficiency of this scenario while diversifying energy sources. Again, 1,5DS-P2G is the scheme with most inefficient outcome from an energy perspective due to P2G's efficiency and the huge size of installed capacity which is necessary as energy cannot be stored long.

Table 34 – Installed capacities for Brava Island based on different scenarios

Installed Capacity								
Year	**2020**				**2030**			
Scenario	1,5DS - Bat	1,5DS - P2G	1WS - Bat	1WS - P2G	1,5DS - Bat	1,5DS - P2G	1WS - Bat	1WS - P2G
PV	2,0 MW	3,4 MW	2,4 MW	1,6 MW	3,6 MW	6,7 MW	4,1 MW	2,1 MW
Wind	0,9 MW	0,9 MW	0,0 MW	0,9 MW	0,9 MW	0,9 MW	0,0 MW	1,7 MW
CSP	-	-	-	-	-	-	-	-
Total RE	**2,9 MW**	**4,3 MW**	**2,4 MW**	**2,4 MW**	**4,5 MW**	**7,5 MW**	**4,1 MW**	**3,8 MW**

Table 35 – Storage characteristics for Brava Island based on different scenarios

Storage Characteristics				
Year	2020		2030	
Power	0,8 MW		1,39 MW	
Scenario	1,5DS		1WS	
Capacity	19,8 MWh	92,2 MWh	33,4 MWh	156,0 MWh

3.3.2.3 Fogo

Fogo, as most other islands, is not eligible for the deployment of CSP due to its relatively low value of DNI (227W/m²). The normal solar irradiation, however, is at average levels. Finally, the wind resource is the lowest measured among all islands. One reason is the volcano in the middle of the island which makes it harder for the air to flow constantly. All in all, Fogo is the island with the least favourable RE conditions in Cape Verde. Nevertheless, Cape Verde's overall quality to sustain renewable energy production is very high.

Table 36 – RE Characteristics for Fogo Island

Fogo RE Characteristics		
Average Irradiation	Average Wind Speed	Average DNI
259 W/m²	8,08 m/s	227 W/m²

The electricity demand of 2020 and 2030 is predicted to be around 17GWh or 29GWh accordingly. Fogo's peak load will reach levels of over 3 respectively 5 MW while minimum load is very low at below 500kW in both years. The maximum 24 hour load has to be considered for the design of the storage device and is at roughly 56 respectively 94MWh.

Table 37 – Characteristic Load Data for Fogo Island

Fogo Load Characteristics				
	Annual Electricity Demand	Peak Load	Minimum Load	Maximum 24 hour load
2020	17.149.924 kWh	3.188 kW	211 kW	55.549 kWh
2030	29.013.759 kWh	5.394 kW	357 kW	93.976 kWh

Fogo's load curve compared to resource curves looks quite promising given that no big discrepancies can be identified. Nevertheless, from June to September all three renewable sources experience their minimum strength while electricity demand is slowly increasing. Different to other islands, Fogo has its peak load in December only for it decreases to the minimum in January where the solar resource has its maximum power. In comparison to Brava and Maio, this island's load curve is closer to the resource lines.

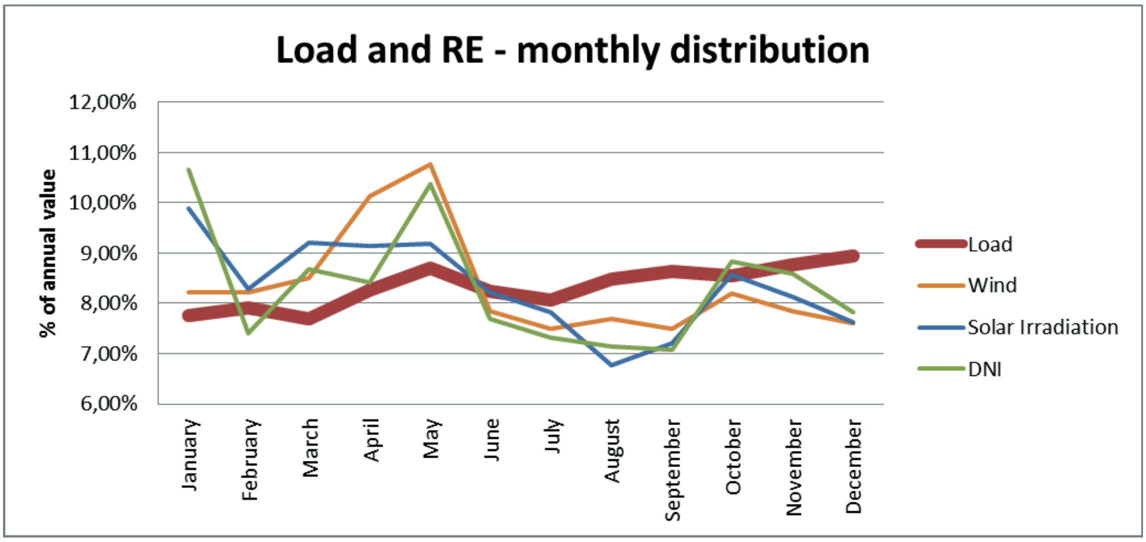

Figure 34 – Monthly distribution of load and RE values in per cent of yearly value for Fogo

In contrast to the rather volatile load curve the load factor is higher than we have seen on Brava indicating a more levelled demand. Fogo's load gradient reaches already significant values which should be considered in the short term balancing of supply (not part of this thesis). The amount of hours of the electricity sector spent without the need for storage is 111 hours and thus similar to Santiago Island.

Table 38 – Load Characteristics for Fogo Island

Fogo - Load Characteristics							
	Load Factor	Power Variation	Maximum Load Gradient	Maximum consecutive hours of positive		Maximum consecutive hours of negative Residual Loads	
2020	0,61	2.977 kW	2.449 kW	62	100% Battery - 1WS	109	100% P2G - 1WS
2030		5.037 kW	4.143 kW	62	100% Battery - 1WS	111	100% P2G - 1WS

The energy mix for 2020 and 2030 based on all information gathered and consequently processed are shown in Figure 32 and Figure 33. For each year 1,5DS and 1WS are presented in one chart including the respective value for the total excess energy produced over the course of the year.

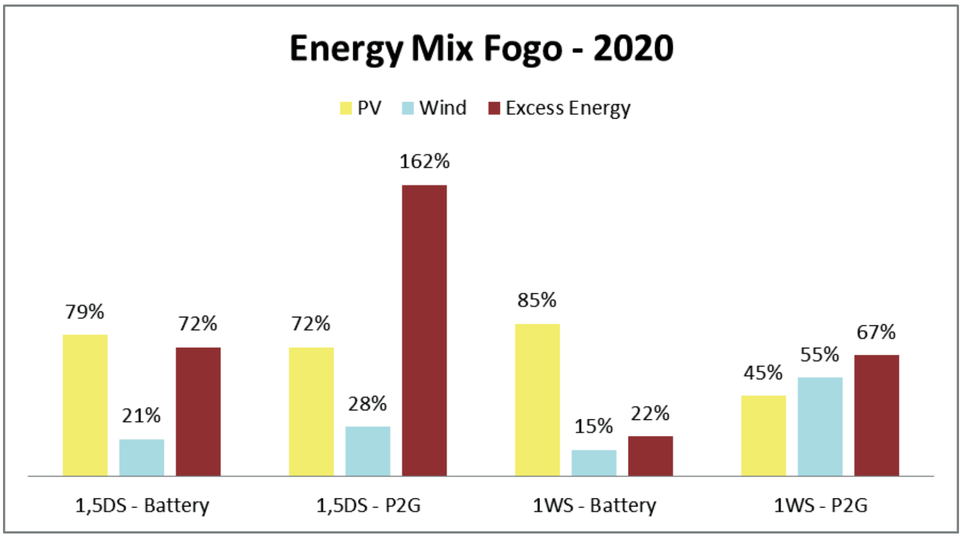

Figure 35 – Energy Mix Fogo 2020 based on 1,5DS and 1WS

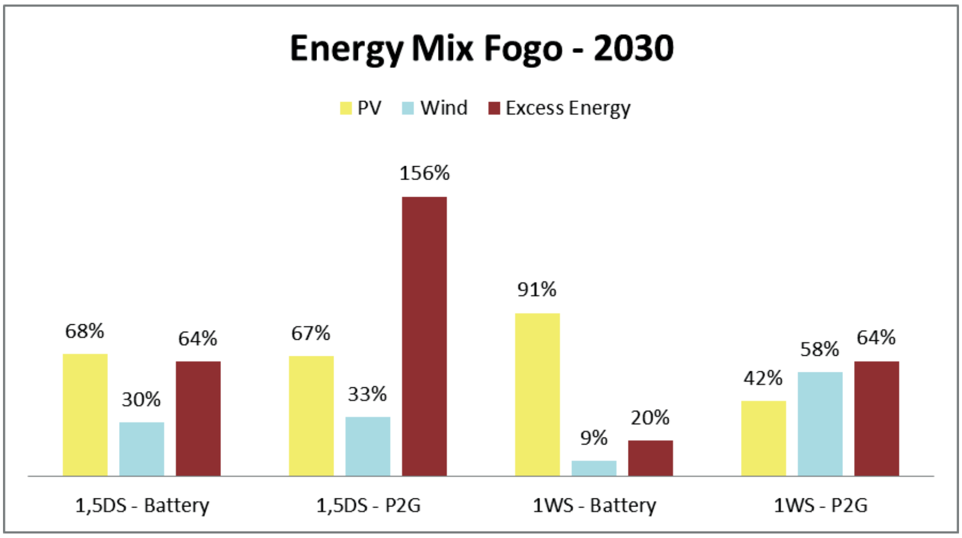

Figure 36 – Energy Mix Fogo 2030 based on 1,5DS and 1WS

Due to the low wind speeds on Fogo Island the share of wind energy in the energy mix is even smaller for the 1,5DS scenarios than on other islands. However, 1WS-Battery adds some 9-15% wind energy to its energy mix depending on the year which is – in comparison to Brava and Maio – owed to the size of grid. While the smaller islands were not made for the deployment of this size of turbine, Fogo can handle the power output. Still, Fogo could have increased its wind energy share taking into account a little decrease in output efficiency.

Table 39 – Installed capacities for Fogo Island based on different scenarios

Installed Capacity								
Year	**2020**				**2030**			
Scenario	1,5DS - Bat	1,5DS - P2G	1WS - Bat	1WS - P2G	1,5DS - Bat	1,5DS - P2G	1WS - Bat	1WS - P2G
PV	11,1 MW	15,6 MW	8,4 MW	6,2 MW	15,6 MW	24,9 MW	15,1 MW	9,7 MW
Wind	1,7 MW	3,4 MW	0,0 MW	0,9 MW	4,3 MW	6,8 MW	0,0 MW	1,7 MW
CSP	-	-	-	-	-	-	-	-
Total RE	**12,8 MW**	**19,0 MW**	**8,4 MW**	**7,0 MW**	**19,9 MW**	**31,7 MW**	**15,1 MW**	**11,4 MW**

Table 40 – Storage characteristics for Fogo Island based on different scenarios

Storage Characteristics				
Year	**2020**		**2030**	
Power	3,19 MW		5,39 MW	
Scenario	**1,5DS**		**1WS**	
Capacity	83,3 MWh	388,8 MWh	141,0 MWh	657,8 MWh

3.3.2.4 Sal

Sal's solar irradiation values can be considered comparatively weak when seen among the other islands. 246W/m^2 is the lowest value of all the islands although Boavista and Brava pose the same solar conditions. Consequently, also the DNI score is among the least favourable for CSP deployment. The annual value amounts to 1702kW/m^2 which is way below the threshold value of 2000kW/m^2. The average wind speed experienced on Sal is also far from the best value (Sao Vicente) with a value of 8,23m/s.

Table 41 – RE Characteristics for Sal Island

Sal RE Characteristics		
Average Irradiation	Average Wind Speed	Average DNI
246 W/m^2	8,23 m/s	194 W/m^2

The electricity demand by 2020 and 2030 will be around 58GWh and 99GWh respectively. These increases come with a rise in peak load to approximately 12MW and 20MW depending on the year. The only feasible option of storing energy on Sal on based my starting variables is P2G as no significant elevation allows for a reasonable application of PHS. Additionally, the island's electricity demand is too large to power it by battery storage. Finally, Sal (also Boavista) experiences a high amount of tourism which should rely on secure energy supply. P2G incorporates this characteristic despite its low efficiency.

Table 42 – Characteristic Data for Sal Island

Sal Load Characteristics				
	Annual Electricity Demand	Peak Load	Minimum Load	Maximum 24 hour load
2020	58.890.994 kWh	11.881 kW	425 kW	217.702 kWh
2030	99.630.128 kWh	20.099 kW	718 kW	368.302 kWh

Figure 37 shows a very volatile load curve with peaks in March, August and October. The overall peak is witnessed in March which makes up more than 10% of the total consumption. Resource curves (solar irradiation, wind and DNI) do not strongly deviate from the load curve.

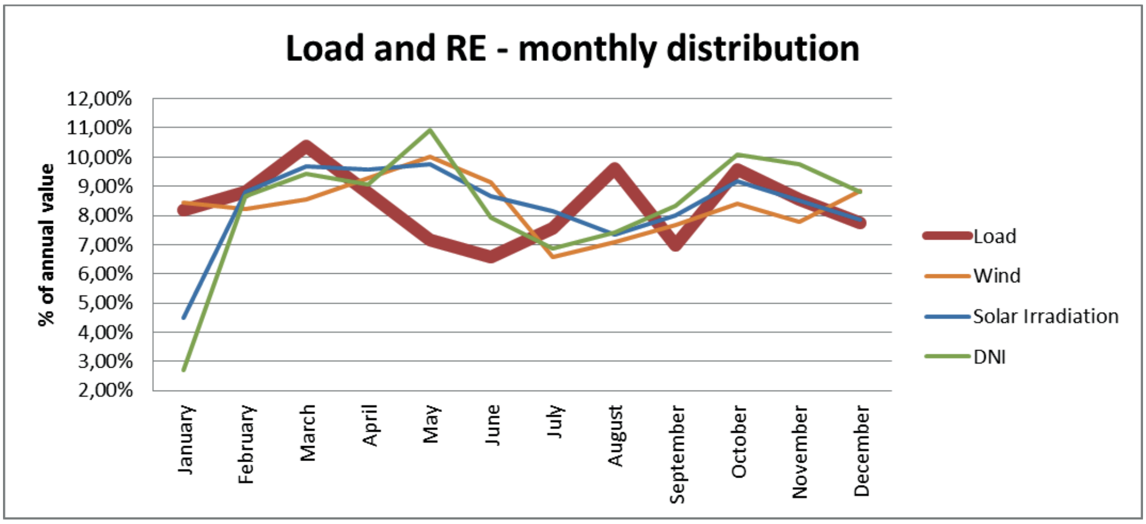

Figure 37 – Monthly distribution of load and RE values in per cent of yearly value for Sal

Although Sal's load curve does not look consistent its load factor is at 0,57 which means that average demand is half as strong as the maximum value. The power variation paints a different image considering the fact that it is almost at level with the peak load. Also, the gradient in change from one hour to another is high. The amounts of consecutive hours of positive or negative residual loads show a low value for positive loads (energy from storage) and a high value for negative loads (filling up energy storage). 208 hours of excess energy production mean more than a week of excess electricity could be used otherwise. Additionally, this could indicate extending energy storage is reasonable. As we can see from the scenarios, an increase in stored energy results in considerable increases in efficiency.

Table 43 – Load Characteristics for Sal Island

Sal - Load Characteristics							
	Load Factor	Power Variation	Maximum Load Gradient	Maximum consecutive hours of positive Residual Loads		Maximum consecutive hours of negative Residual Loads	
2020	0,57	11.456 kW	9.870 kW	38	100% P2G - 1WS	208	100% P2G - 1,5DS
2030		19.381 kW	16.697 kW	38	100% P2G - 1WS	208	100% P2G - 1,5DS

The energy mix for 2020 and 2030 based on all information gathered and consequently processed are shown in Figure 38. Both years and scenarios are presented in one chart including the respective value for the total excess energy produced over the course of the year.

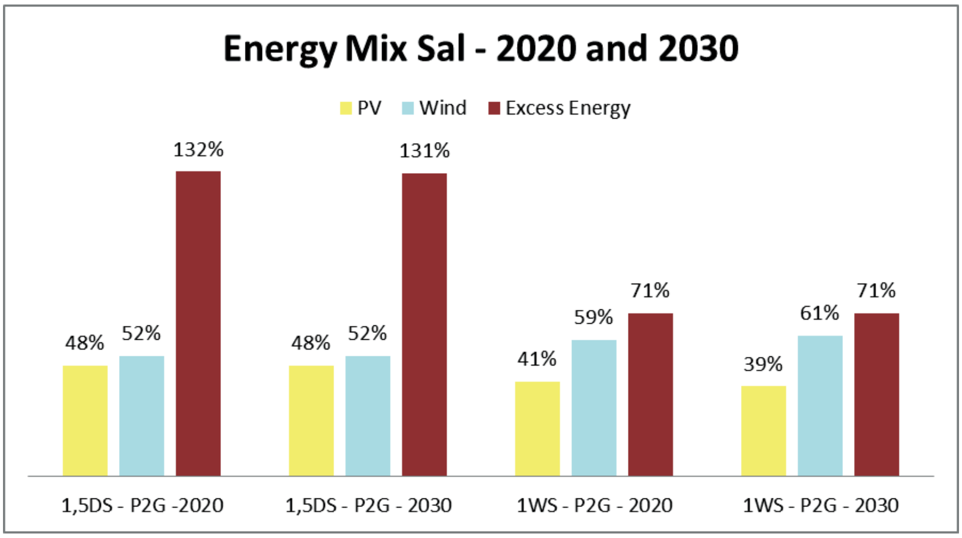

Figure 38 – Energy Mix Sal 2020 based on 1,5DS and 1WS

In the case of Sal, only P2G has been considered a reasonable option of storing energy. Thus, the comparison of storage option is not possible. However, we can see a similar pattern as we see with all the other islands. While efficiency rates are extremely high for 1,5DS, they are limited for 1WS. Interestingly and owed to the low irradiation value, wind power makes up the majority share in all scenarios with the maximum in 1WS-P2G-2030.

Table 44 – Installed capacities for Sal Island based on different scenarios

Installed Capacity				
Year	**2020**		**2030**	
Scenario	1,5DS - P2G	1WS - P2G	1,5DS - P2G	1WS - P2G
PV	23,8 MW	20,9 MW	39,0 MW	35,5 MW
Wind	21,3 MW	13,6 MW	36,6 MW	23,0 MW
CSP	-	-	-	-
Total RE	**45,0 MW**	**34,5 MW**	**75,6 MW**	**58,4 MW**

Table 45 – Storage characteristics for Sal Island based on different scenarios

Storage Characteristics				
Year	**2020**		**2030**	
Power	11,9 MW		20,1 MW	
Scenario	**1,5DS**		**1WS**	
Capacity	326,6 MWh	1523,9 MWh	552,5 MWh	2578,1 MWh

3.3.2.5 Boavista

Boavista and Sal's situation are very similar (also see chapter 3.3.1). The only main difference is the wind resource which is one of the strongest in Cape Verde. Solar irradiation and DNI, both, have low levels relative to the other islands.

Table 46 – RE Characteristics for Boavista Island

Boavista RE Characteristics		
Average Irradiation	Average Wind Speed	Average DNI
246 W/m²	8,83 m/s	194 W/m²

Electricity demand by 2020 and 2030 will be around 45GWh and 76GWh respectively. Consequently, also peak loads rise to 9 and roughly 15MW. In comparison, the minimum loads are very low. Also, the maximum 24 hour load is low for the annual electricity demand.

Table 47 – Characteristic Data for Boavista Island

Boavista Load Characteristics				
	Annual Electricity Demand	Peak Load	Minimum Load	Maximum 24 hour load
2020	44.892.107 kWh	9.056 kW	324 kW	165.952 kWh
2030	75.947.204 kWh	15.321 kW	547 kW	280.754 kWh

Figure 39 gives an overview of the load curve in comparison to the monthly strength of the resources. In total, the lines are quite levelled with only January having a strong discrepancy between solar resource and load curve.

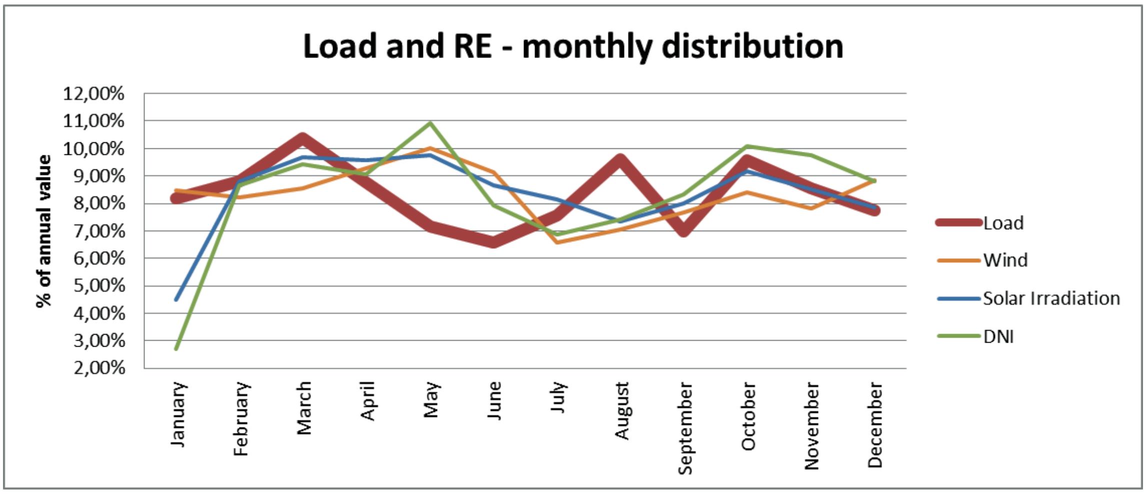

Figure 39 – Monthly distribution of load and RE values in per cent of yearly value for Boavista

The load characteristics of Boavista (see Table 48) show standard values. It is indicated that 208 hours of power are directly produced by the renewable energy plants without the need of storage. On the other hand, 38 hours – as the maximum of all scenarios – are taken straight from storage reserve.

Table 48 – Load Characteristics for Boavista Island

Boavista - Load Characteristics							
	Load Factor	Power Variation	Maximum Load Gradient	Maximum consecutive hours of positive Residual Loads		Maximum consecutive hours of negative Residual Loads	
2020	0,57	8.733 kW	7.524 kW	38	100% P2G - 1WS	208	100% P2G - 1,5DS
2030		14.774 kW	12.728 kW	38	100% P2G - 1WS	208	100% P2G - 1,5DS

The energy mix for 2020 and 2030 based on all information gathered and consequently processed are shown in Figure 40. Both years as well as 1,5DS and 1WS are presented in one chart including the respective value for the total excess energy produced over the course of the year.

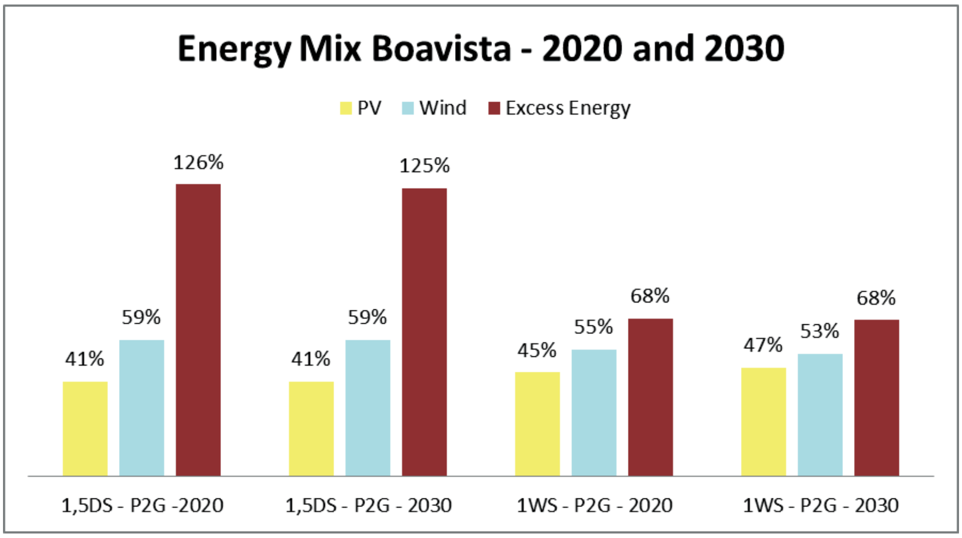

Figure 40 – Energy Mix Boavista 2020 and 2030 based on 1,5DS and 1WS

Table 49 – Installed capacities for Boavista Island based on different scenarios

Installed Capacity				
Year	2020		2030	
Scenario	1,5DS - P2G	1WS - P2G	1,5DS - P2G	1WS - P2G
PV	17,5 MW	14,6 MW	29,6 MW	25,6 MW
Wind	13,6 MW	9,4 MW	23,0 MW	15,3 MW
CSP	-	-	-	-
Total RE	**31,1 MW**	**23,9 MW**	**52,6 MW**	**40,9 MW**

Table 50 – Storage characteristics for Boavista Island based on different scenarios

Storage Characteristics				
Year	**2020**		**2030**	
Power	9,1 MW		15,3 MW	
Scenario	**1,5DS**		**1WS**	
Capacity	248,9 MWh	1161,7 MWh	421,1 MWh	1965,3 MWh

3.3.2.6 Sao Vicente

Sao Vicente is the most suitable island for the deployment of wind as its average wind speed exceeds the 10m/s value – observed over a year. This rate is far better than any other island. In terms of solar resource, Sao Vicente exhibits similar conditions as other islands. The deployment of CSP will not be assessed for Sao Vicente due to aforementioned reasons (annual value is 1895kW/m^2). The yearly DNI value is below the threshold value of 2000kWh/m^2. However, it might be of interest to evaluate the potential in more detail as Sao Vicente has one of the biggest energy sectors of Cape Verde. Any available source for the production of electricity will be helpful in the future.

Table 51 – RE Characteristics for Sao Vicente Island

Sao Vicente RE Characteristics		
Average Irradiation	Average Wind Speed	Average DNI
253 W/m²	10,24 m/s	216 W/m²

Almost 92GWh of electricity demand by 2020 and 155GWh by 2030 makes Sao Vicente the second largest grid in Cape Verde. Also, peak load is high with values around 27MW or 47MW. To store the maximum 24 hour load indicated in Table 52 it will need big reservoirs.

Table 52 – Characteristic Data for Sao Vicente Island

Sao Vicente Load Characteristics				
	Annual Electricity Demand	Peak Load	Minimum Load	Maximum 24 hour load
2020	91.987.468 kWh	27.735 kW	637 kW	330.126 kWh
2030	155.621.811 kWh	46.920 kW	1.077 kW	558.497 kWh

Figure 31 shows an almost completely levelled load curve for Sao Vicente with no distinct peaks in any month. Still, a slight increase from the average production can be observed in June and from October to December. Renewable energy production is most promising from February to June peaking in May. Another peak can be observed in October. Only from June to September (and also January) are limited in their wind and solar resources.

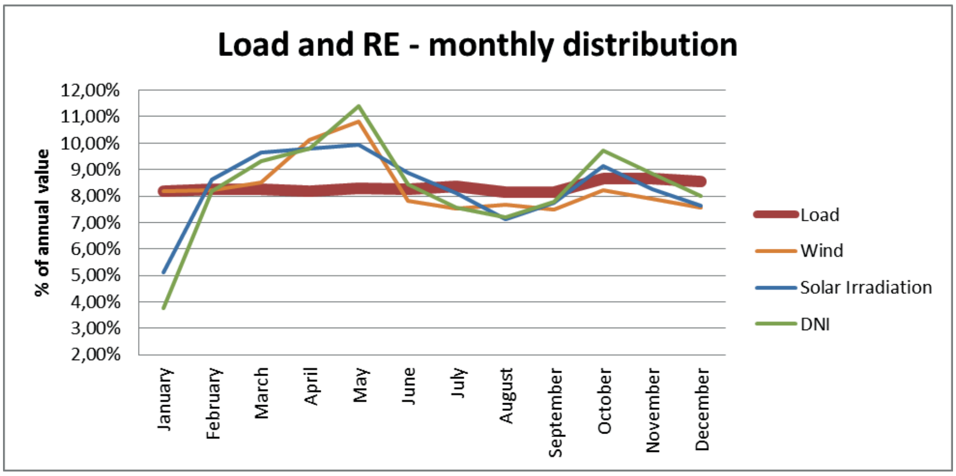

Figure 41 – Monthly distribution of load and RE values in per cent of yearly value for Sao Vicente

Although Sao Vicente's load curve looks consistent its load factor is at low 0,38 which means that average demand is almost down to a third of the peak value. The power variation gives the same information considering the fact that it is more than 90% of the peak load. However, the gradient in change from one hour to another is low. It makes up only half the peak load value. Other distribution systems on various islands experience gradients as big as their peak loads. The amounts of consecutive hours of positive or negative residual loads can be considered average to low. Both values follow the normal pattern observable on other islands. 185 hours of excess energy production mean more than a week electricity could be used otherwise once storage is full. Additionally, this could provide the opportunity of increasing the energy storage reservoir for longer term storage.

Table 53 – Load Characteristics for Sao Vicente Island

Sao Vicente - Load Characteristics							
	Load Factor	Power Variation	Maximum Load Gradient	Maximum consecutive hours of positive Residual Loads		Maximum consecutive hours of negative Residual Loads	
2020	0,38	27.098 kW	14.575 kW	67	100% P2G - 1WS	185	100% P2G - 1WS
2030		45.843 kW	24.657 kW	67	100% P2G - 1WS	185	100% P2G - 1WS

The energy mix for 2020 and 2030 based on all information gathered and consequently processed are shown in Figure 32 and Figure 33. For each year 1,5DS and 1WS are presented in one chart including the respective value for the total excess energy produced over the course of the year.

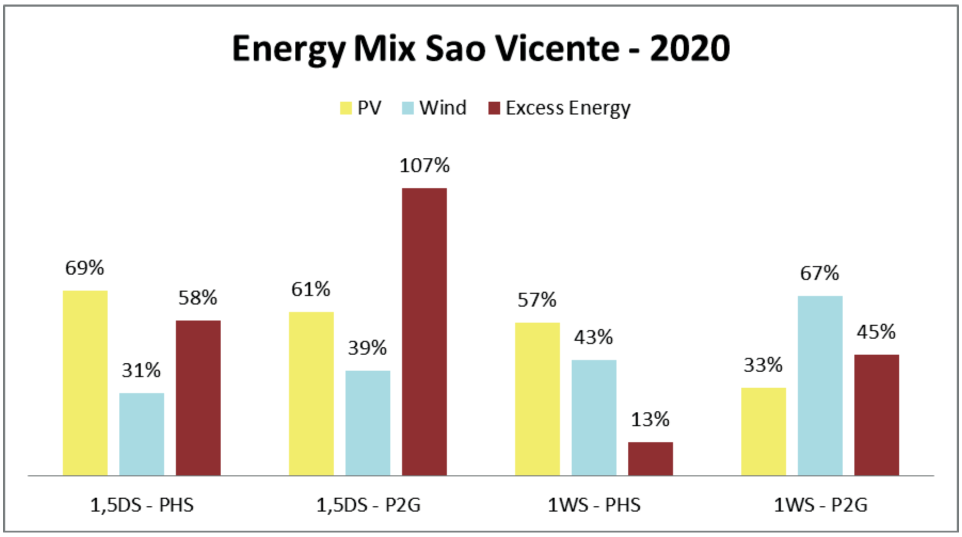

Figure 42 – Energy Mix Sao Vicente 2020 based on 1,5DS and 1WS

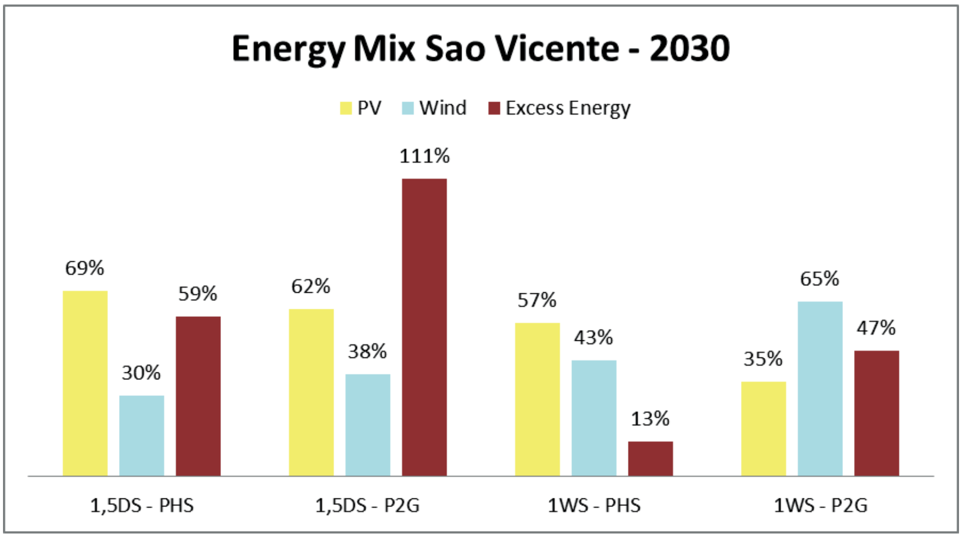

Figure 43 – Energy Mix Sao Vicente 2030 based on 1,5DS and 1WS

Sao Vicente provides the most efficient scenario of all islands with an excess energy production of only 13%, both in 2020 and 2030, for 1WS-PHS. The energy mix for this scenario is made up of 57% PV and 43% wind. It is somewhat surprising that wind will not play a bigger role for Sao Vicente's energy production. Nevertheless, individual islands and scenarios depend highly on the specific load values as well as RE production values. Therefore, it is not possible to depict trends based on wind or solar resource. Still, one consequence of the good wind resource (and the use of pumped hydro as storage option) is the low excess energy rate observed in Sao Vicente. In conclusion, Sao Vicente's various energy mixes for the different schemes and years do not considerably deviate from other islands. What however deviates is the efficiency rate which is way below average, even for 1,5DS-P2G.

Table 54 – Installed capacities for Sao Vicente Island based on different scenarios

Installed Capacity								
Year	**2020**				**2030**			
Scenario	1,5DS - PHS	1,5DS - P2G	1WS - PHS	1WS - P2G	1,5DS - PHS	1,5DS - P2G	1WS - PHS	1WS - P2G
PV	43,9 MW	51,8 MW	25,8 MW	19,3 MW	73,9 MW	89,8 MW	43,5 MW	32,2 MW
Wind	8,5 MW	13,6 MW	8,5 MW	17,0 MW	14,5 MW	22,1 MW	14,5 MW	28,9 MW
CSP	-	-	-	-	-	-	-	-
Total RE	**52,4 MW**	**65,4 MW**	**34,3 MW**	**36,3 MW**	**88,4 MW**	**111,9 MW**	**57,9 MW**	**61,1 MW**

Table 55 – Storage characteristics for Sao Vicente Island based on different scenarios

Storage Characteristics				
Year	2020		2030	
Power	27,7 MW		46,9 MW	
Scenario	1,5DS		1WS	
Capacity	2310,9 MWh	10784,1 MWh	3909,5 MWh	18244,2 MWh

3.3.2.7 Sao Nicolau

278W/m² solar irradiation, 9,3m/s average wind speed and 278W/m² DNI are among the best values of whole Cape Verde. Hence, Sao Nicolau experiences very satisfying conditions for the deployment of RE. Taking a look at Table 57, however, will show that Sao Nicolau does not need a lot of electricity. It is in fact, the third smallest power grid after Maio and Brava. Consequently, limited peak loads of 1,8MW and 3,1MW will be observable in the future (2020 and 2030).

Table 56 – RE Characteristics for Sao Nicolau Island

Sao Nicolau RE Characteristics		
Average Irradiation	Average Wind Speed	Average DNI
278 W/m²	9,30 m/s	273 W/m²

Table 57 – Characteristic Data for Sao Nicolau Island

Sao Nicolau Load Characteristics				
	Annual Electricity Demand	Peak Load	Minimum Load	Maximum 24 hour load
2020	7.821.131 kWh	1.845 kW	212 kW	25.885 kWh
2030	13.231.569 kWh	3.122 kW	359 kW	43.792 kWh

In contrast to the promising resources (see above), the load curve shows a different image. In months of low demand, wind and solar resource are strong while vice versa during the rest of the year. Only, November and January exhibit a more matching pattern. Figure 44 clearly shows the peak demand during summer months (June to October).

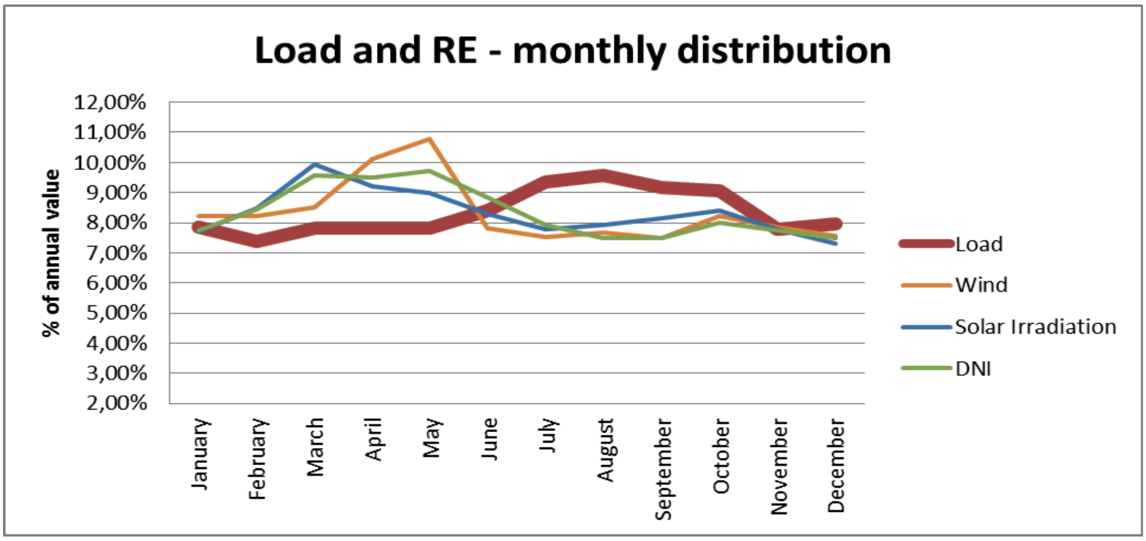

Figure 44 – Monthly distribution of load and RE values in per cent of yearly value for Sao Nicolau

One thing that comes across immediately from Table 58 is the small amount of consecutive hours with either negative or positive loads. Although the maximum (186 hours) is comparable to other islands, all other values fall below average values observed on other islands. This means - especially the little hours of dependence on energy storage – that production almost always meets the load. Interestingly, efficiency rates are not higher than usual but rather below the average.

Table 58 – Load Characteristics for Sao Nicolau Island

Sao Nicolau - Load Characteristics							
	Load Factor	Power Variation	Maximum Load Gradient	Maximum consecutive hours of positive Residual Loads		Maximum consecutive hours of negative Residual Loads	
2020	0,48	1.633 kW	874 kW	39	100% Battery - 1WS	186	100% P2G - 1,5DS
2030		2.763 kW	1.479 kW	16	100% Battery - 1WS	137	100% P2G - 1WS

The energy mix for 2020 and 2030 based on all information gathered and consequently processed are shown in Figure 32 and Figure 33. For each year 1,5DS and 1WS are presented in one chart including the respective value for the total excess energy produced over the course of the year.

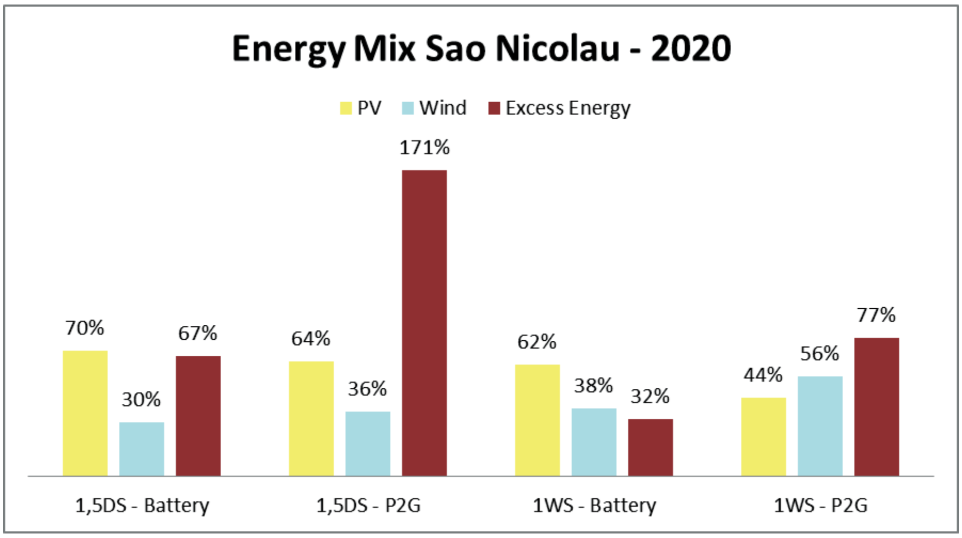

Figure 45 – Energy Mix Sao Nicolau 2020 based on 1,5DS and 1WS

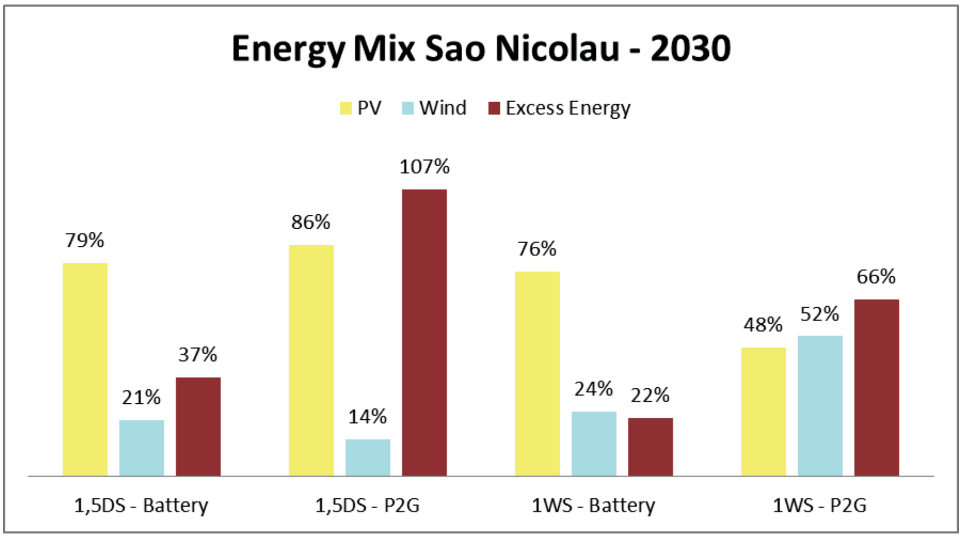

Figure 46 – Energy Mix Sao Nicolau 2030 based on 1,5DS and 1WS

Table 59 – Installed capacities for Sao Nicolau Island based on different scenarios

Installed Capacity								
Year	2020				2030			
Scenario	1,5DS - Bat	1,5DS - P2G	1WS - Bat	1WS - P2G	1,5DS - Bat	1,5DS - P2G	1WS - Bat	1WS - P2G
PV	4,3 MW	6,4 MW	3,0 MW	2,9 MW	6,6 MW	11,2 MW	5,6 MW	5,0 MW
Wind	0,9 MW	1,7 MW	0,9 MW	1,7 MW	0,9 MW	0,9 MW	0,9 MW	2,6 MW
CSP	-	-	-	-	-	-	-	-
Total RE	**5,1 MW**	**8,1 MW**	**3,8 MW**	**4,6 MW**	**7,5 MW**	**12,1 MW**	**6,5 MW**	**7,5 MW**

Table 60 – Storage characteristics for Sao Nicolau Island based on different scenarios

Storage Characteristics		
Year	**2020**	**2030**
Power	1,8 MW	3,1 MW
Scenario	**1,5DS**	**1WS**
Capacity	38,8 MWh	306,5 MWh

3.3.2.8 Santo Antão

Santo Antão's situation regarding the installation of PV and CSP is good. Both values (average irradiation and DNI) are among the best observed on Cape Verde. Unfortunately, the energy sector of Santo Antão is too small to install commercial size CSP plants. Hence, CSP will not be considered for this island. Nevertheless, the wind resource (8,75m/s average wind speed) experienced is also promising.

Table 61 – RE Characteristics for Santo Antão Island

Santo Antao RE Characteristics		
Average Irradiation	Average Wind Speed	Average DNI
274 W/m²	8,75 m/s	275 W/m²

The electricity demand by 2020 and 2030 will be around 22GWh and 36GWh respectively. These increases come with a rise in peak load to approximately 8,8MW and 15MW depending on the year.

Table 62 – Characteristic Data for Santo Antão Island

Santo Antao Load Characteristics				
	Annual Electricity Demand	Peak Load	Minimum Load	Maximum 24 hour load
2020	21.472.086 kWh	8.751 kW	109 kW	188.664 kWh
2030	36.325.871 kWh	14.805 kW	185 kW	319.176 kWh

The load curve of Santo Antão is the most volatile of all islands. This can also be seen in

Table 63 which shows a value of 0,28 for the load factor. Hence, average demand is only a third of peak demand. Moreover, Figure 47 shows that February is the absolute low point in demand (5% of yearly production takes place during this month) while July and August experience production rates of over 12% of the yearly value. Resource curves (wind, solar irradiation and DNI) are rather constant and do not have a significant peak or low value.

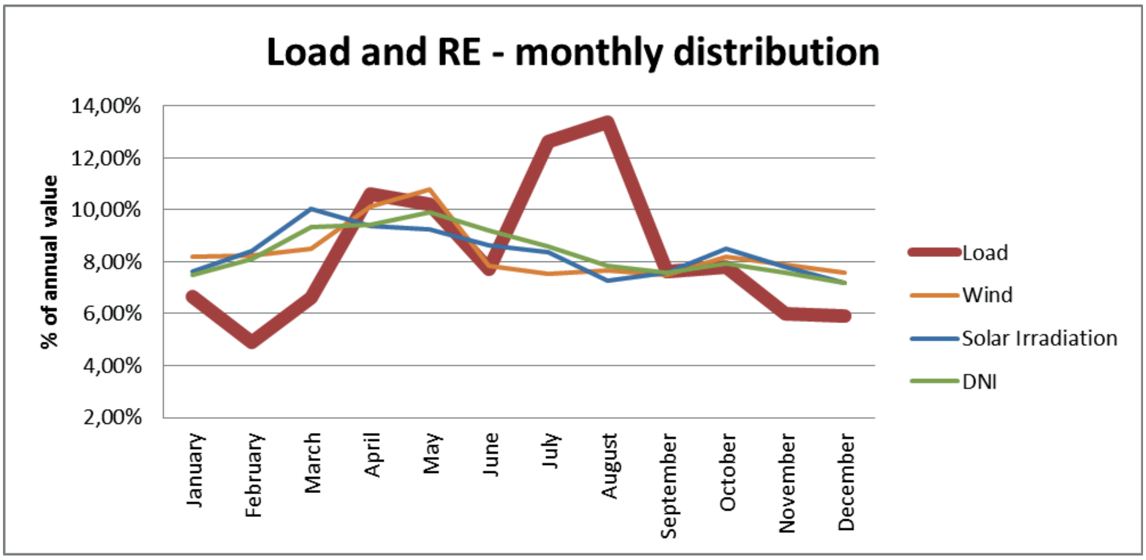

Figure 47 – Monthly distribution of load and RE values in per cent of yearly value for Santo Antão

Table 63 – Load Characteristics for Santo Antão Island

Santo Antao - Load Characteristics					
	Load Factor	Power Variation	Maximum Load Gradient	Maximum consecutive hours of positive Residual Loads	Maximum consecutive hours of negative Residual Loads
2020	0,28	8.642 kW	6.556 kW	40 100% P2G - 1WS	357 100% P2G - 1WS
2030		14.621 kW	11.091 kW	41 100% P2G - 1WS	357 100% P2G - 1WS

The energy mix for 2020 and 2030 based on all information gathered and consequently processed are shown in Figure 48. Power to gas storage for both years is presented in one chart including the respective value for the total excess energy produced over the course of the year.

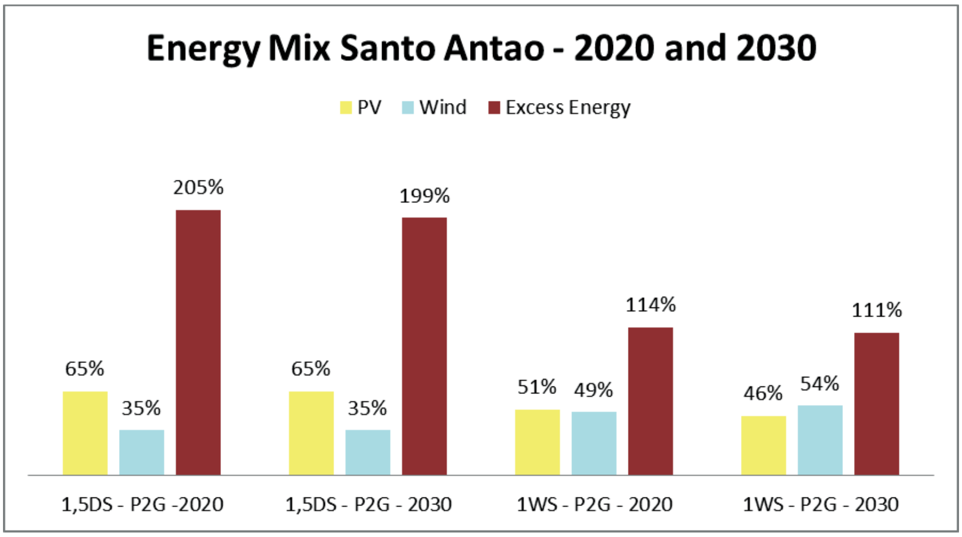

Figure 48 – Energy Mix Santo Antão 2020 based on 1,5DS and 1WS

Figure 48 shows very high values for the excess production. Considering the load curve and load factor this does not surprise. Annual production has to be designed to meet the load in summer months (July and August). Thus, the energy system is over dimensioned for the needs during the remainder of the year. The same trend is observable looking at the maximum consecutive hours of negative residual loads in Table 63. 357 hours (this period takes place in beginning of February) clearly indicate that storage above requirements for some months. In conclusion, Santo Antão sees the lowest efficiency in terms of production due to its volatile behaviour of the load.

Table 64 – Installed capacities for Santo Antão Island based on different scenarios

Installed Capacity				
Year	**2020**		**2030**	
Scenario	1,5DS - P2G	1WS - P2G	1,5DS - P2G	1WS - P2G
PV	18,1 MW	10,0 MW	30,8 MW	15,5 MW
Wind	5,1 MW	5,1 MW	8,5 MW	9,4 MW
CSP	-	-	-	-
Total RE	**23,2 MW**	**15,1 MW**	**39,3 MW**	**24,9 MW**

Table 65 – Storage characteristics for Santo Antão Island based on different scenarios

Storage Characteristics				
Year	2020		2030	
Power	8,8 MW		14,8 MW	
Scenario	1,5DS		1WS	
Capacity	1320,6 MWh	6163,0 MWh	2234,2 MWh	10426,4 MWh

3.3.2.9 Santiago

Santiago is the only of the nine populated islands which will be considered for CSP deployment. First of all, due to the fact that DNI values exceed the threshold value and secondly, Santiago's electricity demand is greater than all the other islands together which makes the installation of a reasonable size of CSP plant possible. Additionally, average irradiation and wind speeds (especially considering the successful operation of Cabeolica's wind farm) makes this islands one of the most diverse in terms of energy supply. In consequence, storage schemes had to be adapted to this island. Santiago will be analysed based on a mix of thermal energy and pumped hydro storage as well as thermal energy storage and power to gas. In both cases, thermal energy storage is limited to supply only the base load of power, as was stated above already in section 3.3.1. In consequence, I calculated an overall total of 500.000m^2 of collector surface for 2020 and 700.000 for 2030. In terms of solar multiple (see 2.4.3) this means 2,17 times the collector surface needed (230.000m^2) to sustain nominal output of 15MW during sunshine hours in 2020 and 2,33 (300.000m^2) to sustain nominal output of 20MW during sunlight hours in 2030.

Table 66 – RE Characteristics for Santiago Island

Santiago RE Characteristics		
Average Irradiation	Average Wind Speed	Average DNI
263 W/m²	8,51 m/s	246 W/m²

Santiago's electricity demand by 2020 and 2030 will be around 308GWh and 522GWh respectively. Also, peak loads rise to almost 60MW or 100MW depending on the year. Moreover, 24 hour demand reaches significant values and has to be considered when talking about energy storage. However, Santiago poses various ways of storing energy which simplifies the issue.

Table 67 – Characteristic Data for Santiago Island

Santiago Load Characteristics				
	Annual Electricity Demand	Peak Load	Minimum Load	Maximum 24 hour load
2020	308.662.312 kWh	58.355 kW	56 kW	1.107.399 kWh
2030	522.186.219 kWh	98.723 kW	94 kW	1.873.466 kWh

Figure 49 shows the load curve for Santiago in addition to the resource curves. We see that demand almost constantly increases over the course of the year until November. Basically, the opposite happens to the resource curves which decrease starting in March.

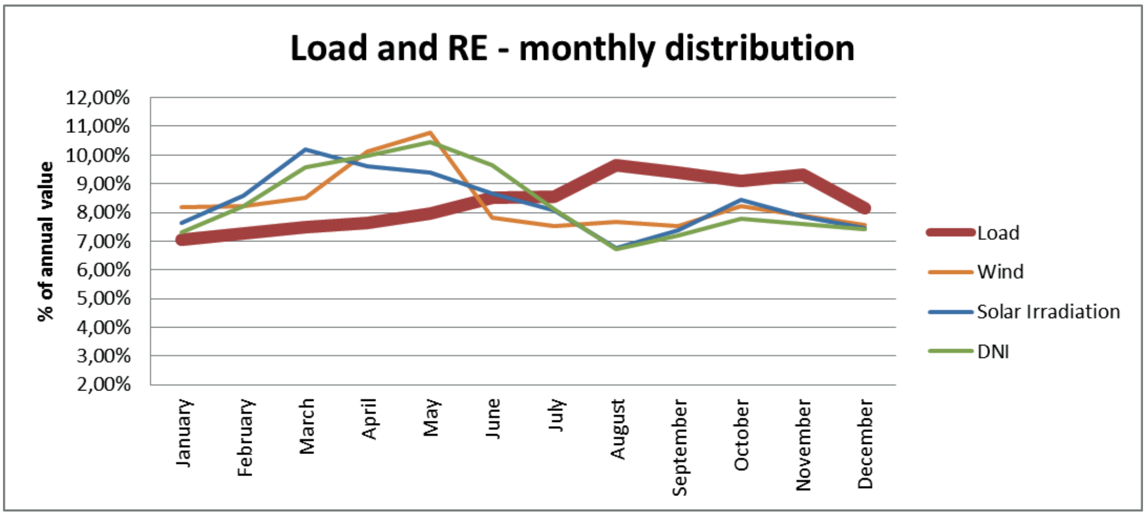

Figure 49 – Monthly distribution of load and RE values in per cent of yearly value for Santiago

Power variation and maximum load gradient are close to peak load which means measures have to be implemented in order to balance supply in the short term. Due to the above average load factor (consistent load), also, consecutive hours of negative or positive loads are limited.

Table 68 – Load Characteristics for Santiago Island

Santiago - Load Characteristics							
	Load Factor	Power Variation	Maximum Load Gradient	Maximum consecutive hours of positive Residual		Maximum consecutive hours of negative Residual	
2020	0,60	58.299 kW	49.915 kW	62	CSP + PHS - 1,5DS	93	CSP + P2G - 1WS
2030		98.629 kW	84.445 kW	89	CSP + PHS - 1WS	111	CSP + P2G - 1WS

The energy mix for 2020 and 2030 based on all information gathered and consequently processed are shown in Figure 50 and Figure 51. For each year 1,5DS and 1WS are presented in one chart including the respective value for the total excess energy produced over the course of the year.

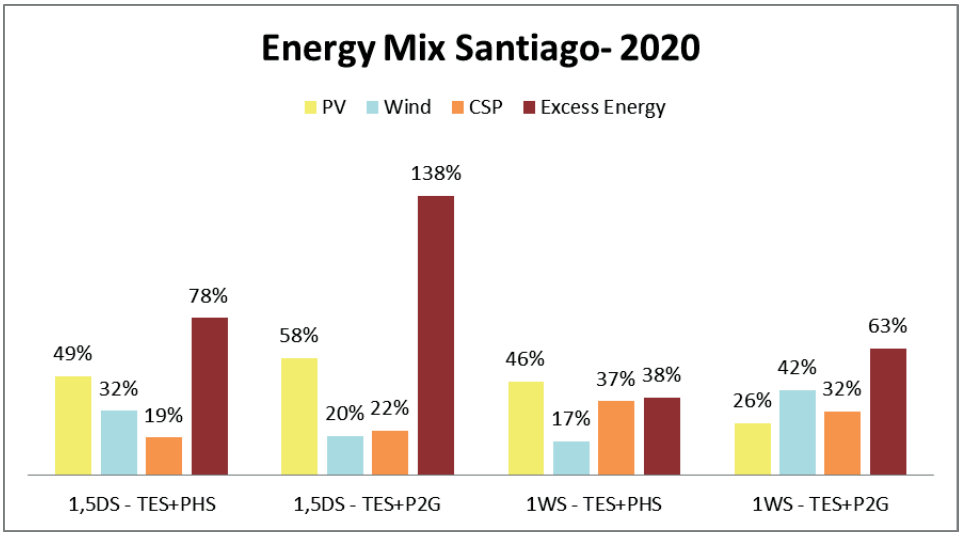

Figure 50 – Energy Mix Santiago 2020 based on 1,5DS and 1WS

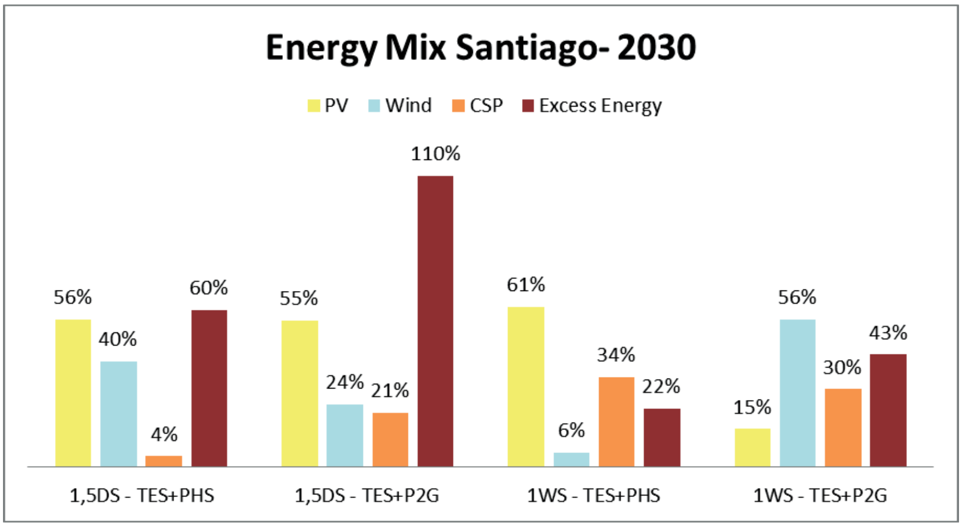

Figure 51 – Energy Mix Santiago 2030 based on 1,5DS and 1WS

Santiago's energy mix deviates from all other eight islands due to the application of CSP with thermal energy storage. Additionally, excess energy produced throughout various scenarios is within certain limits. Only 1,5DS – TES+P2G exceeds the 100% mark. This, however, can also be observed for all other islands and is based on the low efficiency rate of P2G. This means an installed capacity of 227,6MW and 338,6MW respectively (see Table 69). The largest share of CSP to the mix comes with 1WS-TES+PHS in 2020 and reaches 37% as overall installed capacity is the lowest with 119,4MW deployed (see Table 69). Moreover, the biggest contribution of wind turbines to the mix is observed for 2030 and 1WS-TES+P2G which has also a surprisingly low over-supply of electricity. The two different scenarios – 1,5DS and 1WS – will require a storage reservoir of 1,7GWh and 13,1GWh. The peak load coming from storage based on loads and RE production is 58,4MW (2020) and 98,7MW (2030) which also determines power of the storage device (see Table 70).

Table 69 – Installed capacities for Santiago Island based on different scenarios

Installed Capacity								
Year	**2020**				**2030**			
Scenario	1,5DS - PHS	1,5DS - P2G	1WS - PHS	1WS - P2G	1,5DS - PHS	1,5DS - P2G	1WS - PHS	1WS - P2G
PV	116,1 MW	179,9 MW	87,0 MW	56,4 MW	202,0 MW	259,0 MW	172,5 MW	47,5 MW
Wind	27,2 MW	32,3 MW	17,0 MW	49,3 MW	34,0 MW	59,5 MW	8,5 MW	97,8 MW
CSP	15,4 MW	15,4 MW	15,4 MW	15,4 MW	20,1 MW	20,1 MW	20,1 MW	20,1 MW
Total RE	**158,7 MW**	**227,6 MW**	**119,4 MW**	**121,1 MW**	**256,1 MW**	**338,6 MW**	**201,1 MW**	**165,3 MW**

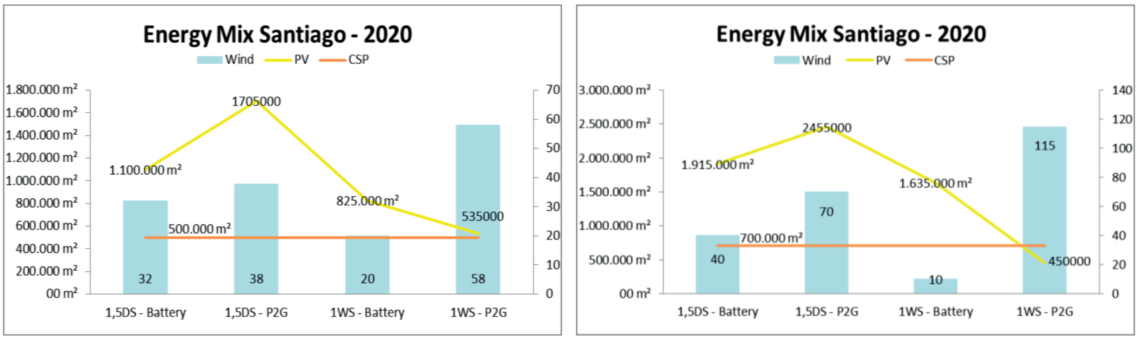

Figure 52 – Energy mix of Santiago for 2020 and 2030 showing number of WTGs, collector surface and reflector surface

Table 70 – Storage characteristics for Santiago Island based on different scenarios

Storage Characteristics				
Year	**2020**		**2030**	
Power	58,4 MW		98,7 MW	
Scenario	**1,5DS**		**1WS**	
Capacity	7751,8 MWh	36175,0 MWh	13114,3 MWh	61199,9 MWh

3.4 Island specific costs analysis

In this section I want to give an overview of the prospective costs of the energy mixes derived above. The costs per kW and kWh respectively LCOE were derived from an extensive literature review. In order to minimize complexity I used the mean value of identified lower and upper limits. Using both would not give a better overview of the costs due to the fact that many factors play an essential role when determining expenses for specific locations (accessibility, labour, etc.). Furthermore, the range of costs for each category of RE technology is huge and incorporates project which turned out to be very cost intensive or which had extremely favourable conditions. Cape Verde itself does not pose the most accessible situation. Cabeolica's numbers allowed me to estimate average costs per kW to be approximately 2350€ (25,5MW of wind turbines at an investment cost of €60 million). This value is comparatively very high and should be understood considering that Cabeolica's wind farm was the first of its size in Cape Verde. Moreover, the project is spread out over four islands making installation costs even higher. It was important to include one value from a local project in order to make this approach more realistic. The value for CSP in Table 71 already incorporates costs for energy storage. Hence, thermal energy storage is not mentioned again in Table 72. This section does not claim to be an accurate financial calculation for prospective RE projects in Cape Verde but wants to provide a tendency. Most importantly it will facilitate comparing scenarios. It has to be noted that scenarios applied (1,5DS and 1WS) were not designed to be cost effective but to be energy efficient - contrary to what was done in the IfaS study. Finally, total costs for individual scenarios will change massively (factors of 0,5 to 50 possible) when altering the costs due to the small unit size of kWh and kW.

Table 71 – Overview of RE costs (sources see respective chapters in theory part)

Overview of RE Technology Costs				
		PV	Wind	CSP
Installed capacity	USD/kW	3120	1863	8050
LCOE	USD/kWh	0,1325	0,1075	0,2625

Table 72 – Overview of Energy Storage Costs (sources see respective chapters in theory part)

Overview of Energy Storage Costs				
		Battery	Pumped Hydro	Power-to-Gas
Costs	USD/kW	1060	1000	1375
	USD/kWh	560	80	0,9

In the subsequent part tables for each individual island will be given. A holistic summary will be made in the end of the chapter.

3.4.1 Maio

Table 73 – Costs of RE deployment for Maio based on different scenarios

Costs of RE deployment (in million US-$)								
Year	2020				2030			
Scenario	1,5DS - PHS	1,5DS - P2G	1WS - PHS	1WS - P2G	1,5DS - PHS	1,5DS - P2G	1WS - PHS	1WS - P2G
PV	$4,8 M	$8,4 M	$5,9 M	$4,5 M	$10,9 M	$16,0 M	$10,1 M	$5,9 M
Wind	$3,0 M	$3,0 M	$0,0 M	$3,0 M	$3,0 M	$3,0 M	$0,0 M	$6,1 M
CSP	-	-	-	-	-	-	-	-
Total RE	**$7,8 M**	**$11,5 M**	**$5,9 M**	**$7,5 M**	**$14,0 M**	**$19,0 M**	**$10,1 M**	**$12,0 M**

Table 74 – Costs for Energy Storage for Maio based on different scenarios

Costs of Storage (in million US-$)					
Year		2020		2030	
Scenario		1,5DS	1WS	1,5DS	1WS
Battery	Power	$0,9 M		$1,4 M	
	Capacity	$10,8 M	$50,5 M	$18,3 M	$85,5 M
PHS	Power	-		-	
	Capacity				
P2S	Power	$1,1 M		$1,9 M	
	Capacity	$0,017 M	$0,081 M	$0,029 M	$0,137 M

3.4.2 Brava

Table 75 – Costs of RE deployment for Maio based on different scenarios

Costs of RE deployment (in million US-$)								
Year	2020				2030			
Scenario	1,5DS - Bat	1,5DS - P2G	1WS - Bat	1WS - P2G	1,5DS - Bat	1,5DS - P2G	1WS - Bat	1WS - P2G
PV	$5,4 M	$9,0 M	$6,5 M	$4,2 M	$9,6 M	$17,8 M	$11,0 M	$5,7 M
Wind	$3,0 M	$3,0 M	$0,0 M	$3,0 M	$3,0 M	$3,0 M	$0,0 M	$6,1 M
CSP	-	-	-	-	-	-	-	-
Total RE	**$8,4 M**	**$12,1 M**	**$6,5 M**	**$7,3 M**	**$12,7 M**	**$20,8 M**	**$11,0 M**	**$11,7 M**

Table 76 – Costs for Energy Storage for Maio based on different scenarios

Costs of Storage (in million US-$)					
Year		2020		2030	
Scenario		1,5DS	1WS	1,5DS	1WS
Battery	Power	$0,9 M		$1,5 M	
	Capacity	$11,1 M	$51,6 M	$18,7 M	$87,3 M
PHS	Power	-		-	
	Capacity				
P2G	Power	$1,1 M		$1,9 M	
	Capacity	$0,018 M	$0,083 M	$0,030 M	$0,140 M

3.4.3 Fogo

Table 77 – Costs of RE deployment for Maio based on different scenarios

Costs of RE deployment (in million US-$)								
Year	2020				2030			
Scenario	1,5DS - Bat	1,5DS - P2G	1WS - Bat	1WS - P2G	1,5DS - Bat	1,5DS - P2G	1WS - Bat	1WS - P2G
PV	$29,4 M	$41,5 M	$22,3 M	$16,4 M	$41,5 M	$66,1 M	$40,1 M	$25,7 M
Wind	$6,1 M	$12,2 M	$0,0 M	$3,0 M	$15,2 M	$24,3 M	$0,0 M	$6,1 M
CSP	-	-	-	-	-	-	-	-
Total RE	**$35,5 M**	**$53,7 M**	**$22,3 M**	**$19,4 M**	**$56,8 M**	**$90,5 M**	**$40,1 M**	**$31,8 M**

Table 78 – Costs for Energy Storage for Maio based on different scenarios

Costs of Storage (in million US-$)					
Year		2020		2030	
Scenario		1,5DS	1WS	1,5DS	1WS
Battery	Power	$3,4 M		$5,7 M	
	Capacity	$46,7 M	$217,8 M	$78,9 M	$368,4 M
PHS	Power	-		-	
	Capacity				
P2G	Power	$4,4 M		$7,4 M	
	Capacity	$0,075 M	$0,350 M	$0,127 M	$0,592 M

3.4.4 Sal

Table 79 – Costs of RE deployment for Maio based on different scenarios

Costs of RE deployment (in million US-$)				
Year	2020		2030	
Scenario	1,5DS - P2G	1WS - P2G	1,5DS - P2G	1WS - P2G
PV	$63,3 M	$55,6 M	$103,8 M	$94,4 M
Wind	$76,1 M	$48,7 M	$130,8 M	$82,2 M
CSP	-	-	-	-
Total RE	**$45,0 M**	**$34,5 M**	**$75,6 M**	**$58,4 M**

Table 80 – Costs for Energy Storage for Maio based on different scenarios

Costs of Storage (in million US-$)					
Year		2020		2030	
Scenario		1,5DS	1WS	1,5DS	1WS
Battery	Power	-		-	
	Capacity				
PHS	Power	-		-	
	Capacity				
P2G	Power	$16,3 M		$27,6 M	
	Capacity	$0,3 M	$1,4 M	$0,5 M	$2,3 M

3.4.5 Boavista

Table 81 – Costs of RE deployment for Maio based on different scenarios

Costs of RE deployment (in million US-$)				
Year	**2020**		**2030**	
Scenario	1,5DS - P2G	1WS - P2G	1,5DS - P2G	1WS - P2G
PV	$46,5 M	$38,8 M	$78,8 M	$68,2 M
Wind	$48,7 M	$33,5 M	$82,2 M	$54,8 M
CSP	-	-	-	-
Total RE	**$45,0 M**	**$34,5 M**	**$75,6 M**	**$58,4 M**

Table 82 – Costs for Energy Storage for Maio based on different scenarios

Costs of Storage (in million US-$)					
Year		**2020**		**2030**	
Scenario		1,5DS	1WS	1,5DS	1WS
Battery	Power	-		-	
	Capacity				
PHS	Power	-		-	
	Capacity				
P2G	Power	$12,5 M		$21,1 M	
	Capacity	$0,224 M	$1,046 M	$0,379 M	$1,769 M

3.4.6 Sao Nicolau

Table 83 – Costs of RE deployment for Maio based on different scenarios

Costs of RE deployment (in million US-$)								
Year	**2020**				**2030**			
Scenario	1,5DS - Bat	1,5DS - P2G	1WS - Bat	1WS - P2G	1,5DS - Bat	1,5DS - P2G	1WS - Bat	1WS - P2G
PV	$11,4 M	$17,0 M	$7,9 M	$7,6 M	$17,6 M	$29,8 M	$14,9 M	$13,2 M
Wind	$3,0 M	$6,1 M	$3,0 M	$6,1 M	$3,0 M	$3,0 M	$3,0 M	$9,1 M
CSP	-	-	-	-	-	-	-	-
Total RE	**$14,5 M**	**$23,1 M**	**$10,9 M**	**$13,7 M**	**$20,6 M**	**$32,9 M**	**$18,0 M**	**$22,3 M**

Table 84 – Costs for Energy Storage for Maio based on different scenarios

Costs of Storage (in million US-$)					
Year		**2020**		**2030**	
Scenario		1,5DS	1WS	1,5DS	1WS
Battery	Power	$2,0 M		$3,3 M	
	Capacity	$21,7 M	$101,5 M	$36,8 M	$171,7 M
PHS	Power	-		-	
	Capacity				
P2G	Power	$2,5 M		$4,3 M	
	Capacity	$0,035 M	$0,163 M	$0,059 M	$0,276 M

3.4.7 Sao Vicente

Table 85 – Costs of RE deployment for Maio based on different scenarios

Costs of RE deployment (in million US-$)								
Year	**2020**				**2030**			
Scenario	1,5DS - PHS	1,5DS - P2G	1WS - PHS	1WS - P2G	1,5DS - PHS	1,5DS - P2G	1WS - PHS	1WS - P2G
PV	$116,7 M	$137,7 M	$68,6 M	$51,2 M	$196,7 M	$238,8 M	$115,7 M	$85,6 M
Wind	$30,4 M	$48,7 M	$30,4 M	$60,9 M	$51,7 M	$79,1 M	$51,7 M	$103,5 M
CSP	-	-	-	-	-	-	-	-
Total RE	**$147,1 M**	**$186,3 M**	**$99,0 M**	**$112,1 M**	**$248,4 M**	**$317,9 M**	**$167,4 M**	**$189,1 M**

Table 86 – Costs for Energy Storage for Maio based on different scenarios

Costs of Storage (in million US-$)					
Year		**2020**		**2030**	
Scenario		1,5DS	1WS	1,5DS	1WS
Battery	Power	-		-	
	Capacity				
PHS	Power	$27,7 M		$46,9 M	
	Capacity	$184,9 M	$862,7 M	$312,8 M	$1459,5 M
P2G	Power	$38,1 M		$64,5 M	
	Capacity	$2,080 M	$9,706 M	$3,519 M	$16,420 M

3.4.8 Santo Antão

Table 87 – Costs of RE deployment for Maio based on different scenarios

Costs of RE deployment (in million US-$)				
Year	**2020**		**2030**	
Scenario	1,5DS - P2G	1WS - P2G	1,5DS - P2G	1WS - P2G
PV	$48,2 M	$26,7 M	$82,0 M	$41,3 M
Wind	$18,3 M	$18,3 M	$30,4 M	$33,5 M
CSP	-	-	-	-
Total RE	**$66,4 M**	**$44,9 M**	**$112,4 M**	**$74,7 M**

Table 88 – Costs for Energy Storage for Maio based on different scenarios

Costs of Storage (in million US-$)					
Year		**2020**		**2030**	
Scenario		1,5DS	1WS	1,5DS	1WS
Battery	Power	-		-	
	Capacity				
PHS	Power	-		-	
	Capacity				
P2G	Power	$12,0 M		$20,4 M	
	Capacity	$1,189 M	$5,547 M	$2,011 M	$9,384 M

3.4.9 Santiago

Table 89 – Costs of RE deployment for Maio based on different scenarios

Costs of RE deployment (in million US-$)								
Year	**2020**				**2030**			
Scenario	1,5DS - PHS	1,5DS - P2G	1WS - PHS	1WS - P2G	1,5DS - PHS	1,5DS - P2G	1WS - PHS	1WS - P2G
PV	$308,7 M	$478,5 M	$231,5 M	$150,1 M	$537,4 M	$688,9 M	$458,8 M	$126,3 M
Wind	$97,4 M	$115,6 M	$60,9 M	$176,5 M	$121,7 M	$213,0 M	$30,4 M	$349,9 M
CSP	$41,5 M	$49,3 M	$25,9 M	$75,2 M	$51,9 M	$90,8 M	$13,0 M	$149,2 M
Total RE	**$447,6 M**	**$643,4 M**	**$318,3 M**	**$401,9 M**	**$711,0 M**	**$992,8 M**	**$502,2 M**	**$625,4 M**

Table 90 – Costs for Energy Storage for Maio based on different scenarios

Costs of Storage (in million US-$)					
Year		**2020**		**2030**	
Scenario		1,5DS	1WS	1,5DS	1WS
Battery	Power Capacity	-		-	
CSP+PHS	Power	$58,4 M		$98,7 M	
	Capacity	$620,1 M	$2894,0 M	$1049,1 M	$4896,0 M
CSP+P2G	Power	$80,2 M		$135,7 M	
	Capacity	$7,0 M	$32,6 M	$11,8 M	$55,1 M

3.4.10 Summary

The tables on costs of RE deployment clearly show that 1WS is by far the cheaper version than 1,5DS. Obviously, this comes as less excess energy is produced which in turn means less installed WTGs, PV panels or CSP collectors. The average gap between 1,5DS and 1WS is almost 30%. For Santiago Island this already means more than $200M by 2020 and around $350M by 2030. At the other end of list Maio witnesses costs around $6M for the least cost option (1WS in 2020). As we will see subsequently, costs by RE deployment are easily upset by certain storage schemes.

The small islands (Maio, Brava, Fogo and Sao Nicolau) with relatively small demand of electricity have been assessed regarding battery storage. Already Table 72 gave an indication of the costly installation of this technology. For the islands of Maio and Brava costs are still within certain boundaries. Sao Nicolau and especially Fogo with a larger energy sector experience huge costs for these scenarios. This comes mostly as scaling up the size of the storage reservoir (kWh) is cost intensive (560USD/kWh). Fogo witnesses peak installation costs for battery storage options at $5,7M for 1WS in 2030.

Besides, battery storage also pumped hydro storage was assessed, although only for Sao Vicente and Santiago which accommodate reasonable conditions. In both cases we can see that PHS is a very cost intensive option mainly due to high costs for the reservoir. For 1WS in 2030 on Santiago Island almost $5 billion would have to be financed. The same trend can be observed for Sao Vicente although to a smaller extent. In favourable conditions which can be found on some of the islands it might be possible to reduce costs significantly and to a more competitive value. However, this would need more detailed and site specific analysis.

Finally, I evaluated the power-to-gas storage. It turned out to be the least cost option of all scenarios. Again, this is mainly due to the costs for capacity increases. We can observe that P2G has higher costs in terms of power ($/kW) but has very low costs per kilowatt hour stored ($0,9/kWh). In the case of Santiago, installation costs for P2G would be almost 40% higher than for PHS ($80,2M instead of$58,4M in 2020). However, costs per kWh are lower by a factor of 89. Consequently, storing energy based on P2G is by far the least cost option. Additionally, P2G is the most modular storage option with possible transport of gas.

4 Conclusion

In the following, I will summarize the findings of the previous chapters and point out key results. Furthermore I will give a few alternatives to the problem of excess energy. Finally, a short outlook on what could be done as a follow up study to complement this thesis will be presented.

The electricity sector of Cape Verde has been fully and is still mainly dependent on fossil fuels. This lack of sovereignty comes with a price, to be exact €62,7 million in 2012. Luckily, the trend has been negative due to the installation of Cabeolica's wind turbines (see chapter 3.1.4). Nevertheless, with an increasing amount of customers and rising consumption rates the annual sum for the procurement of fossil fuels is going to increase. In consequence to high procurement and production costs also electricity tariffs passed on to the population of Cape Verde are significant. In 2012, the national electricity tariff exceeded the €0,3 mark again. This is especially high considering that Cape Verde is still a developing market with a low GDP and little purchasing power. Another consequence of high procurement costs and therefore high tariffs is that electricity theft is on the rise. This among other factors (technical losses, etc.) was responsible for more than 28% losses of the total production in 2012 and allegedly more than 40% in 2014.

In the course of analysing the different electricity grids on Cape Verdean islands it became obvious that each individual system has to be carefully analysed based on its very own characteristics. There is no one-fits-all approach to such a sensitive issue like power grids. Naturally, there are islands (Brava and Maio) similar in their electricity needs and consumption behaviour. However, there are also islands that experience completely different load curves like Santo Antão which has a load factor of only 0,28. Low values as this one indicate that consumption behaviour is very volatile and dependent on the season. On the other hand, Santiago has a load factor of 0,6 which is relatively high and points at a consistent consumption behaviour. As we can see from the different energy mixes these key indicators give a first impression of the complexity of one grid. Santo Antão has the highest excess energy rate while Santiago one of the lowest.

The literature review on RE technologies shows clearly that cost competitiveness of RE technologies is almost around with some countries already experiencing it. Nevertheless, it has also been shown that some technologies which theoretically have a huge potential did not demonstrate to be applicable in Cape Verde as of yet. The best example is ocean wave technologies. The underlying science predicts great energy yields as energy density within water is way above the value for air. Still, no commercial successful project has been observed until now. Moreover, other renewable technologies such as biomass and geothermal energy have shown their feasibility multiple times but cannot be deployed in Cape Verde due to resource scarcity or lack of sufficient research. The same was shown for energy storage. Various technologies have found commercial application for many years while others not.

Despite the problems with several RE and energy storage technologies, there are still enough left to fully power electricity grids. In chapter 3.2 the renewable potential (wind and solar PV) has been shown based on annual electricity demand. Even on Santiago where more than 50% of all installed capacity and thus electricity consumption takes place it would be feasible to produce the required amounts of energy based solely on RE. As shown only 7,3km² or 264 WTGs would be sufficient to meet the annual load. This comes as no surprise as the sun shines all year long peaking in February and March and wind penetrates the islands almost as consistently. More than 4380 hours of solar irradiation prove this fact impressively. Of course, it is not enough to produce annual electricity demand but rather it has to be supplied at the right time.

In chapter 3.3 an individual energy mix for each island was developed. Here, hourly load and resource data were used to work out different scenarios based on RE and energy storage technology in a more timely accurate manner than it was done before. The first issue was to solve which technologies are applicable on which of the nine islands. Only one of them (Santiago) proved to be able to accommodate CSP plants while all nine are eligible for solar PV and wind energy deployment. Additionally, two islands were considered for pumped hydro storage, namely Sao Vicente and Santiago and four islands (Maio, Brava, Fogo and Sao Nicolau) could theoretically be powered by battery storage. The resulting energy mixes were clearly in favour of solar PV – 40 out of all 60 scenarios found solar PV as the biggest contributor. Only, Sal and Boavista experience a completely different behaviour as all eight scenarios for both islands see wind power as the strongest technology in terms of energy produced. This, however, is owed to a poor solar irradiation value and a wind resource curve which is closer to the load curve than the solar irradiation curve is.

Still, no amount of PV panels, wind turbines or solar reflectors will realistically supply sufficient amount of energy without some kind of energy storage. For that reason two different approaches were chosen: storage to supply sufficient electricity for 1,5 days and

1 week. These storage schemes reduced excess energy to values still very high for our understanding. The average excess energy throughout all 60 scenarios is 82% while the maximum reaches 205% in the case of Santo Antão and the minimum is experienced on Sao Vicente with only 13% excess energy. Although energy storage is absolutely necessary it comes at high costs.

The financial calculation based on values taken from the literature showed that value of above a billion US-$ are easily possible if storage is not chosen correctly. From the experience of the four islands with battery storage it could be concluded that this way of storing energy is definitely feasible but only up to limited values of MWh stored. Fogo and Sao Nicolau, already experience very costly scenarios. This, however, would have to be evaluated in a context of economic power for the individual islands. Also, it has been established that P2G is clearly the least cost option for energy storage. Although, installed capacity per MW comes at considerable prices, costs for the energy reservoir (MWh) are so convincing that not even an increase of a factor of 50 could make it less favourable. Additionally, this way of storing energy is the most module one which could even allow for transport of energy in between the islands or allow for the sale of excess gas.

In conclusion, the supply of Cape Verde’s electricity only based on renewable production is definitely feasible but comes at a price which is significant. The least cost alternative of the developed scenarios for each island sum up to $514 million for 2020 and $816 million for 2030. Moreover, the 1WS scenario proves to be the less cost intensive one for almost all islands. Nevertheless, some islands favour the 1,5DS scenario.

The results concluded above lead me to the following recommendations:

First, the next step in Cape Verde’s pursuit of 100% renewable energy penetration will be the implementation of first storage facilities. These could be used to collect excess energy produced by the currently operating wind parks. Doing this would also grant first experiences with storage and could provide valuable information for future and higher penetration rates of renewables.

Secondly, it will be important for Cape Verde to reduce the loss rates which were witnessed during the last years. More than 28% of total electricity produced was lost in 2012. This number is ridiculously high and has to see a decline immediately. By finding a solution to this problem it will be possible to decrease required capacity in the future (in case of mostly technical losses and thus less actual consumption) or at least generate more revenue which in turn reduces electricity tariffs (in case of mostly commercial losses and theft).

The third issue which needs exploring is a more decentralized approach to the power generation. This model would make it possible to more accurately tackle the individual problems and demands of the local loads. Therefore, less excess energy rates would be observed which in consequence reduces costs and land used.

As a last remark I want to point out two issues that should be explored in a follow up study. It is imperative to get more accurate results before engaging in a renewable energy or energy storage project. Therefore, specific technologies at specific sites should be explored in detail. This would pave the road to attracting more foreign investors interested that kind of projects but are discouraged by the lack of data and fear the costs and risks of starting a feasibility study. It has been shown that Cape Verde is a promising location for renewable energy projects (Cabeolica). However, more could be done to by the government to entice investors capable of conducting such projects. As a second recommendation I suggest to conduct a study on different sizes of renewable penetration from 50-100%. When we take Santo Antão as an example, 6805 hours of the year (77%) have a load which reaches less than 35% of Santo Antão's peak load. In consequence, the energy sector is designed for a load that almost never occurs. It would make sense to research other shares of renewable penetration while meeting peak loads by traditional methods in order to get a substantially more economic outcome. Energy storage could be considerably sized down while still most of production would be renewable.

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List of tables

List of figures