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"Analysing the technical and economic potential of solar photovoltaic energy technologies for the island state Tonga."

Master's Thesis

of

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Affidavit

I declare on my honour that I have written this thesis independently and without external help, that I have not used any sources other than those indicated, and that I have marked the passages taken verbatim or in substance from the sources used as such.

Abstract

The Pacific Island Nation "Kingdom of Tonga" holds ample potential for switching from an expensive diesel-supplied electricity production towards renewable energy driven electricity generation. The high solar insolation and a current fossil fuel dependency of 87% is an obvious indication for its socioeconomic potential. Nevertheless, in many sectors, the existing renewable energy potential is hardly utilised. The national energy policy framework "Tonga Energy Road Map 2010-2020" outlines the ambitious target to replace half of the diesel-generated electricity with solar and wind energy until 2020. The study further indicates that solar will contribute slightly more than half of the needed RE production, which equals an amount of 14,5 MW installed solar capacity. In theory, 35,3 MWp of solar, 16,6 MW wind and 108 MWh of battery storage is sufficient to completely supply Tonga with renewable electricity throughout most days of the year. Based on literature research and a field study in cooperation with the Pacific Centre for Renewable Energies & Energy Efficiency (PCREEE), the developments and potential of solar energy were analysed. We identified the private sector as a profiteer and key contributor to a comprehensive RE development. The outcome of a questionnaire conducted among hotels, as representatives of the private sector, showed that an overwhelming majority of the hotel owners are interested in applying solar technologies, but only a minority are actually already using them. The results of the semi-structured interviews indicate that a lack of communication, information and governmental support are key barriers among the private sector stakeholders, hindering the cooperation with the local energy provider Tonga Power Limited (TPL). Based on a comprehensive analysis of two case studies, this gap will be covered in detail. As Tonga is the third-largest recipient of development aid in the Pacific, without the inclusion of the private sector, the country is very much depending on aid support to achieve its renewable energy targets. The actual developments in the Kingdom of Tonga are moving in the right direction to become more independent of fossil fuels and utilise the potential of renewable energy energies. However, a stronger focus on the private sector is needed to enhance sustainable development for these technologies in the long-term.

Keywords: Solar energy; Tonga; Pacific Island Nation, Renewable Energy, Energy Storage

Kurzfassung

Das Potenzial durch Umstellung von einer teuren dieselbetriebenen Stromerzeugung auf eine Stromerzeugung aus erneuerbaren Energien (EE) ist für den pazifischen Inselstaat "Königreich Tonga" von sozioökonomischem Nutzen. Die hohe Sonneneinstrahlung und eine derzeitige Abhängigkeit von fossilen Brennstoffen zu 87% ist ein offensichtlicher Indikator. Dennoch wird das EE-Potenzial in vielen Sektoren kaum genutzt. Das nationale energiepolitische Rahmenwerk "Tonga Energy Road Map 2010-2020 (TERM)" beschreibt die ehrgeizigen Ziele, bis 2020 die Hälfte des Dieselstroms durch Sonnen- und Windenergie zu ersetzen. Aus dieser Forschungsarbeit geht hervor, dass Solarenergie etwas mehr als die Hälfte der benötigten erneuerbaren Energieproduktion beisteuern wird, was einer Menge von 14,5 MWp installierter Solarkapazität entspricht. Theoretisch reicht eine installierte Menge von 35,3 MWp Solar, 16,6 MW Wind und 108 MWh Batteriespeicher aus, um Tonga an den meisten Tagen des Jahres vollständig mit erneuerbarer Elektrizität zu versorgen. Auf der Grundlage einer Literaturrecherche und einer Feldstudie in Zusammenarbeit mit dem Pacific Centre for Renewable Energies & Energy Efficiency (PCREEE) wurden die Entwicklungen und das Potenzial der Solarenergie analysiert. Der Privatsektor wurde als möglicher Hauptprofiteur und in seiner Schlüsselrolle für den Beitrag einer umfassenden EE Entwicklung identifiziert. Das Ergebnis einer Umfrage, welche unter Hotelanlagen als Vertreter des privaten Sektors durchgeführt wurde, zeigte, dass eine überwältigende Mehrheit der Hotelbesitzer an der Anwendung von Solartechnologien interessiert ist, aber nur eine Minderheit diese Technologien tatsächlich bereits einsetzt. Die Ergebnisse der durchgeführten Interviews deuten darauf hin, dass ein Mangel an Kommunikation, Information und Staatlicher Unterstützung ein wesentliches Hindernis für die Zusammenarbeit mit dem lokalen Energieversorger Tonga Power Limited (TPL) und den Akteuren des Privatsektors darstellt. Auf der Grundlage einer umfassenden Analyse von Zwei Fallstudien soll diese Lücke gefüllt werden. Tonga ist der drittgrößte Empfänger von Entwicklungshilfe im Pazifik. Ohne die Einbeziehung des Privatsektors, ist das Land zur Erreichung seiner Ziele im Bereich der erneuerbaren Energien in hohem Maße auf Hilfe angewiesen. Die aktuellen Entwicklungen im Königreich Tonga bewegen sich in die richtige Richtung, um unabhängiger von fossilen Brennstoffen zu werden und das Potenzial der erneuerbaren Energien besser auszuschöpfen. Allerdings ist ein stärkerer Fokus auf den privaten Sektor erforderlich, um eine nachhaltige Entwicklung dieser Technologien langfristig zu fördern.

Schlüsselwörter: Solarenergie; Tonga; Pazifischer Inselstaat, erneuerbare Energie, Energiespeicherung

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Abbreviations and Acronyms

SPC	South Pacific Community		UNESCO	United Nations Educational Scientific and Cultural Organization
TTI	Tupou Tertiary Institute		MoA	Memorandum of Arrangement
TPL	Tonga Power Limited		DFAT	Department of Foreign Affairs and Trade, Australia
TERM	Tongan Energy Road Map		MFAT	Ministry of Foreign Affairs and Trade, New Zealand
IPCC	Intergovernmental Panel on Climate Change		UNDP	United Nation development Programme
RE	Renewable Energies		PICTS	Pacific Island Countries and Territories
GHG	Green House Gas		UNISDR	United Nations Office for Disaster Risk Reduction
SHS	Solar Home System		ADB	Asian Development Bank
IPP	Individual Power Producer		UNFCCC	United Nations Framework of Climate Change
SDG	Small Distributed Generation		DoE	Department of Energy
PPA	Power Purchase Agreement		GDP	Gross Domestic Product
kWh	Kilowatt Hour		GEF	Global Environment Facility
BESS	Battery Energy Storage Systems		TERM-C	TERM Committee
kWp	Kilowatt-Peak		TERM-A	TERM-Agency
EC	Electricity Commission		TERM-IU	TERM Implementation Unit
SIDS	Small Island Development States		PCREE	Pacific Centre for Renewable Energies and Energy Efficiency
EEZ	Exclusive Economic Zone		GoT	Government of Tonga
O&M	Operation & Maintenance		EE	Energy Efficiency
MEIDECC	Ministry of Meteorology, Energy, Information, Disaster Management, Environment, Climate Change and Communication		CTCN	United Nation's Climate Technology Centre and Network

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1 Introduction

The island nation "Kingdom of Tonga" is located in the south pacific and is part of the Pacific Island Countries and Territories[1] (PICTs), which are mostly characterised by a vast number of small islands with small populations large distances between them. These islands are covered by cities, villages, and energy-consuming tourism facilities. The great distance between the islands makes a centralised energy supply impossible. Therefore, the main part of the energy production is done decentralised in the form of diesel generator systems. As a result, the Kingdom of Tonga currently has an energy fossil fuel dependency of 87% (New Zealand Ministry of Foreign Affairs and Trade 2016). Tonga consumes more than 13 million litres of diesel annually to cover its electricity consumption at a cost equivalent to approximately 10% of the total gross domestic product and 20% of national imports. On the one hand, the large share of expensive fossil fuel produced electricity is reflected in the Tongan electricity tariff. In 2018 and 2019 the kWh price was 0,32 Euro/kWh (0,8129 Pa'anga/ kWh), which is more than one third higher than the average Austrian electricity tariff (Tonga Power limited 2019b; Ingrid 2018; TPL 2018a). On the other hand, this leads to a very high dependency on fossil fuel imports and makes the country vulnerable to oil price fluctuations and problems in the supply chain (IRENA 2013b). In the case of Tonga, the electricity prices in the past twenty years have been impacted by oil price shocks several times. Occasionally, the electricity tariff increased by 60% due to the strong fluctuations in the oil barrel price (Fonua and Essau 2017). Furthermore, the Kingdom of Tonga is considered a fragile state, as it is ranked the second place among the countries considered most at risk from natural disasters (World Economic Forum 2019). The exposure to extreme natural events such as cyclones or earthquakes is amongst the highest in the world. In addition, sea-level rise and an increase in floods caused by climate change are expected (ADB 2016b). Concurrently, the country is subject to a very high level of societal vulnerability to such disasters (Radtke et al. 2018). Besides the risk of natural disasters, the remoteness and small size put fundamental constraints on its economic development, especially for the private sector. The entire country can be considered remote from most markets, lying in the Pacific approximately 1,000km from Fiji and over 2,000 km from New Zealand (Green Climate Fund 2017). As a consequence, Tonga counts to the third-largest development aid recipient in the Pacific (Keeley 2017).

In recent years, innovative solar technologies and energy storage systems have been developed, prices of solar panels have dropped significantly, and the efficiency of solar panels is continuously increasing. This

[1] The PICTs referred to in this document are: Cook Islands, Federated States of Micronesia, Republic of Fiji, Kiribati, Republic of the Marshall Islands, Republic of Nauru, Niue, Republic of Palau, Papua New Guinea, Samoa, Solomon Islands, Kingdom of Tonga, Tokelau, Tuvalu and the Republic of Vanuatu.

fact renders solar energy more and more economically attractive compared to diesel-generated electricity. The tropical belt around the equator, in which most of the Pacific island states like Tonga are located, is characterised by one of the highest solar radiation rates worldwide (World Bank 2017a). Hence, the conditions for solar energy production through photovoltaic systems are theoretically perfect. Still, the Pacific Island states mostly use such RE technologies in small quantities. However, with the manifestation of the national energy policy document "Tonga Energy Road Map 2010-2020 (TERM)" in 2010, the Kingdom of Tonga has set ambitious targets to replace 50% of the common diesel-generated electricity with wind and solar energy until 2020 and 70% until 2030. The overall objective of "TERM" is to layout a least-cost approach and stepwise implementation plan to reduce Tonga's vulnerability to oil price shocks and achieve an increase in access to modern energy services in an environmentally and financially sustainable manner. The TERM-Report states that solar and wind technologies are "most universal" and therefore are intended as the primary RE sources eligible for energy generation in transforming the Tongan energy sector (GoT 2010b, p. 14). Photovoltaic will be holding a share of 30,4% and wind turbines a share of 19,6% of the needed RE capacity to ensure a 50% renewable energy supply. According to the TERM targets, the national energy policy aims to encourage the RE private sector development (GoT 2010b, p. 62). However, in reality, such encouragement is not evident in Tonga. There is no possibility to purchase or design solar systems for the private application within the country. The private sector is highly undeveloped, and almost all of the planned RE capacity will be implemented by the public sector.

This master thesis analyses the potential of modern solar PV technologies to move the island state Kingdom of Tonga towards a maximum of RE generation and fossil fuel independence. Based on literature research and the conducted field study, the following research questions have been addressed:

1. *How is the current energy generation structured in Tonga?*
2. *What is the current application status of renewable energies, in particular solar energy, in Tonga?*
3. *What strategies are existing to increase the share of renewable energies in Tonga?*
4. *What is the technical and economic potential of modern solar energy technologies to support Tonga in decreasing its dependency on fossil fuel?*
5. *What are the socioeconomic benefits for Tonga of increasing its renewable energy generation?*
6. *What are potential barriers for renewable energies in Tonga?*

Therefore, the "state of the art" of the energy sector in the Kingdom of Tonga was examined in 2019 to present the country's RE transformation progress throughout the last ten years and sketch out possible future developments. To better understand the remote island nation's actual situation, the author conducted field research in the country in strong cooperation with the locally based "Pacific Centre for Renewable

Energy & Energy Efficiency" (PCREEE). The two main research threads were set to be differentiated between the "private sector" and "public sector".

The dialogue with the private sector was sought among shareholders of the hotel industry. Feedback and comparable data on the awareness about the solar PV potential were received through a questionnaire. The tourism industry contributes 15% to Tonga's Gross Domestic Product (GDP) and represents a significant private sector industry (Stone et al. 2019). As representatives for Tonga's tourism industry, guesthouses and hotels in the island group of Vava'u were visited and interviewed. The public sector is represented by governmental institutions and development actors and was surveyed with semi-structured interviews. The overall target was to gain a deeper understanding of the development work of key regional and international institutions such as the *World Bank*, *Asian Development Bank (ADB)*, *Department of Foreign Affairs and Trade (DFAT) and Ministry of Foreign Affairs and Trade (MFAT)*, as well as to pinpoint potential donors and financial supporters for the realisation of privately initialised RE projects. Therefore, all mentioned institutions were contacted and visited in their branch offices in the Kingdom of Tonga.

As a result of the conducted field research, two case studies are analysed to illustrate a case for the economic and technical potential of solar PV systems in Tonga. In the first case study, the *Longo Longo Police station's* solar PV system is presented, which is the largest locally owned third-party PV system in the country and a unique example for the benefits of using large rooftop and ground space for solar installations. The second case study is the technical college *Tupou Tertiary Institute (TTI)*, which is part of the educational institutions of the *Free Wesleyan Church*, the state church of Tonga and also the largest Christian denomination in the country (World council of churches n.d.). As a positive outcome of the field research, the TTI college is currently assessing its rooftop potential and preparing an application to implement a school-owned solar PV system. While TTI's primary target is to offset its electricity costs, a possible next step is to generate a surplus for the college. Therefore, the second case study provides an accurate representation of a solar PV project currently being developed.

Besides solar energy, wind energy represents an additional RE source with high potential for electricity production in Tonga. However, wind turbines have high upfront costs, and therefore its application in Tonga so far depends on external investors or development aid funds. Nevertheless, it needs to be highlighted that diverse sources of energy generation create even more energy security and that wind turbines hold an essential share in Tonga's RE development plans. As solar PV is not the only promising RE, the term “Renewable Energies” (RE) is used interchangeably throughout the remainder of the thesis. Nevertheless, the potential of solar energy as an affordable technology for Tonga's citizens to contribute to the national RE targets is enormous and thus the main object of focus.

2 Methodology

This thesis was conducted in two phases. Its core is composed of data obtained in a field study in the Kingdom of Tonga between the 1st of July and 1st of September 2020 in strong cooperation with the Pacific Centre for Renewable Energies and Energy Efficiency (PCREEE). In the initial phase, a comprehensive literature review was carried out, surveying academic literature relevant to energy policy, national energy planning, development aid, project documentation of donors and the development of RE resources in Tonga, in order to explore both the rationale for ambitious RE targets and the interplay between aid and energy policy in RE development. Tonga is a comparably small country and the literature review about the energy situation is highly depending on online sources. Databases such as BOKU: Lit-search, Google Scholar, ScienceDirect, Scopus and Reports from energy officials and development agencies provided a comprehensive overview. Also, numerous governmental reports have been provided by the employees of the PCREEE. Documents and reports with exceptional impact on the thesis are the "Tongan Energy Road Map" (TERM) and the "TPL annual report 2019". The TERM-Report outlines Tonga's approach reaching its target to move towards 50% renewable energy production from 2010 to 2020. The annual report of the national energy provider Tonga Power Limited (TPL) offers an excellent overview of the energy sector and partly provided the data for the solar potential calculations made in chapter 8.3.

In the second phase, interviews with officials of Tonga's public energy and development sector were conducted, and a questionnaire was designed and circulated to the private sector hotel industry during the field study within Tonga. Through the cooperation with the PCREEE, a variety of significant decision-makers in the energy sector were interviewed. In total, eight public authorities were visited and interviewed and eight site visits were conducted (list see Appendix 1). As a result of the research, the case studies "Longo Longo Police station" and "Tupou Tertiary Institute" are analysed, which are concerned with the illustration of the solar potential in the practical field.

According to Kohlbacher (2006), the two main approaches in social research and scientific fieldwork are the qualitative- and the quantitative method. Quantitative methods mainly focus on transforming data into values or statistical representatives. Qualitative methods focus on interpretation rather than quantification, emphasising subjectivity and are flexible during the process of the research (Kohlbacher 2006, p. 3). The qualitative approach is the chosen method for the evaluation for both the interviews among the public sector and the questionnaire developed for the private sector stakeholders. Its flexibility facilitates the accumulation of information from the interview partners, especially on topics unknown to the questioner.

The interviews were all undertaken in accordance with the semi-structured qualitative research methodology. Before the interviews, a guideline had been prepared to ensure that the dialogue remains on the topic of interest. The guide contains a simple list of individual questions with relevance to the objective of the interview. The questionnaire was intentionally designed to gather feedback from the private sector hotel industry regarding its awareness and interest of solar PV. It was structured according to a three-step scheme: (i) identify the awareness of solar energy, (ii) gather technical background to evaluate the solar potential, (iii) identify already existing solar installations in the private sector (questionnaire see Appendix 10). However, only results from (i) and (iii) have been of importance because a solar potential assessment for each institution exceeded the scope of this thesis. The personal visits of the sampled hotels on the outer islands were feasible by accompanying employees of the PCREEE on a mission on the island group of Hapai, Eua and the Niuas. The data of the questionnaire has been evaluated qualitatively and by using a descriptive analysis approach in a tabular form (see chapter 8.2). The intention was to visualise contrasts and similarities among the hotel private sector samples. The tourism industry in Tonga belongs to the most economically relevant industries; however, the number of hotels is small. According to a qualitative market analysis conducted via *Google Search*, the country counts a total of 91 hotels. The questionnaire was sent out via email to 15 "hotels of interest" of which a total of two questionnaires had been returned. "Hotels of interest" were those characterised by a decentralised energy generation, since it was apparent that solar technologies are most common for the off-grid institutions. After receiving small feedback from the remote hotels, the research focus was extended to grid-connected hotels. Therefore, two more hotels and one café have been interviewed personally, leading to a total of five filled-out questionnaires (List see Appendix 2). As the number of questionnaires is small, no robust statistical analysis was possible. Therefore, these results are also to be evaluated qualitatively.

The *Longo Longo Police* and *TTI* case studies presented in this thesis are located in the capital city Nuku'alofa on Tongatapu. Throughout the field study, both cases were identified as unique examples for outlining the implementation process for private solar applications as well as the benefits of solar technologies for the people of Tonga. The *Longo Longo Police* station represents the most extensive third-party solar system in the country and generates substantial annual profits. During a site visit on the 13.08.2019, the solar system was presented by the responsible police officers. The Tupou Tertiary Institute (TTI) was visited several times between 18.08.2019 and 28.08.2019. In various meetings with the school principal Mrs Ungatea Kata and through email correspondence after leaving Tonga, the developments of the project have been documented. At the current research stage in 2020, TTI is in the application phase with TPL to implement a school-owned PV system to decrease its annual electricity costs. The development of the TTI solar system is carried out in close cooperation with the thesis research. Therefore, both case studies were analysed carefully and will be presented in detail in the thesis, to function as a guide for third-party solar projects in Tonga.

There is hardly any literature about the technical scenario of supplying an island nation like Tonga with a maximum RE share. Therefore, two scenarios are presented in the thesis based on derivations of local conditions combined with technical background data received from the cooperation with TPL and TTI. For calculating the first scenario, which is the case of a maximum RE penetration through solar, technical parameters of the TTI solar system application were used and scaled up for the whole of Tonga. The outcome presents a theoretical approach, which may lay the basis for a conceptualisation of what could be possible. The second scenario is a more realistic approach based on calculations made by TPL with the *HOMER* software. This scenario combines solar and wind technologies with battery storage systems and therefore represents a moresecure energy mix solution.

3 Background Information about the Kingdom of Tonga

This chapter presents critical background information about the *Kingdom of Tonga* to gain an understanding of the overall picture of the research scope and outcome. The local socioeconomic and cultural environment differ significantly from European conditions, which impacts immensely the development of RE.

3.1 Kingdom of Tonga Country Profile

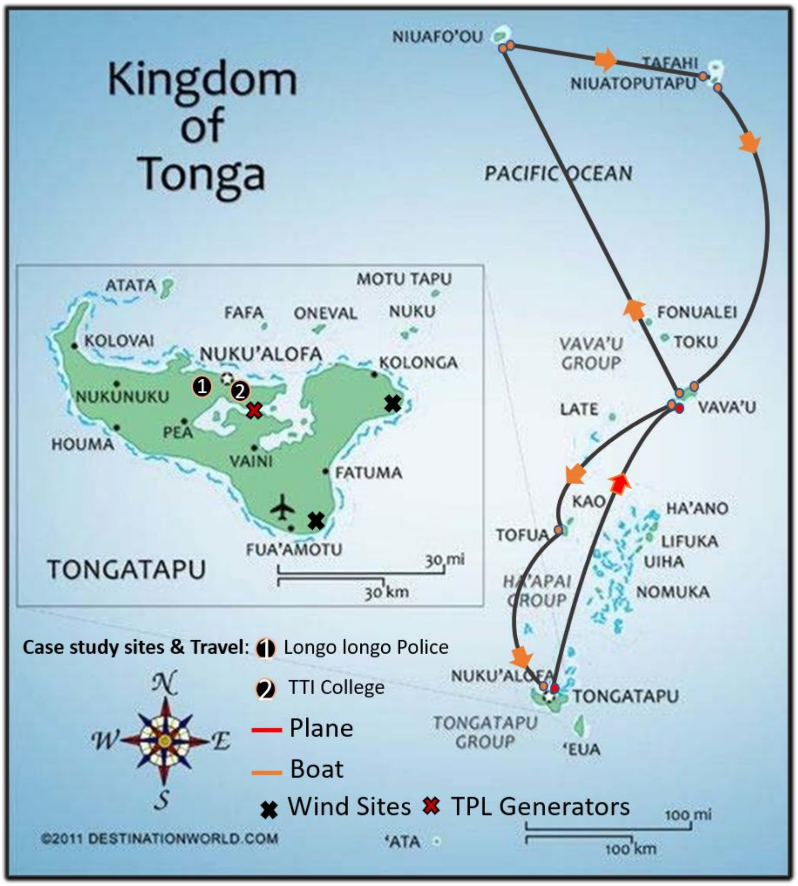

Figure 3.1: Map of the Kingdom of Tonga, showing the case study sides and research travels (Own representation) source: (Destinationworld 2018).

The small developing island nation *the Kingdom of Tonga* is located to the south of Samoa, south-east of Fiji and northeast of New Zealand and belongs to the Polynesian countries. The Tongan archipelago is comprised of 176 islands, of which a population of approximately 101,000 Tongans inhabits 36. Tongas total land area is 748 km^2, with an additional Exclusive Economic Zone (EEZ) of about 660,000 km^2. More than 75% of the country's people live on the largest island Tongatapu, which is also the main island as well as the location of the capital, *Nuku'alofa*. The island state is divided into four main groups – Tongatapu, Ha'apai and Vava'u and the Niuas. The remote islands of Tonga are called *Outer Islands*. Most of the islands have a limestone base formed from an uplift coral formation, while some islands have a limestone overlaying a volcanic base such as "*Niuatoputapu*" (Australian Department of Foreign Affairs and Trade 2019). Presently there is some volcanic activity, and there have been several eruptions over the past century. Also, since 2015 the earth's newest piece of land is evolving in Tonga, the volcanic island named *"Hunga Tonga"* (Garvin et al. 2018). Figure 3.1 displays the main points of interest on the main island of Tongatapu described in this thesis, as well as the field study rout undertaken by the researcher within Tonga.

Tonga's currency is called *Pa'anga* (short=TOP), *Seniti* (= Cents); 1 TOP = 0,44 USD = 0,40 Euro (checked on 24.04.2020)

3.2 Government

Tonga has a constitutional monarchy with a reigning king, *King Tupou VI*, making it political unique in the Pacific (IBP 2011). It is the only pacific country that avoided formal colonisation. In 2006 pro-democracy demonstrations turned into riots and lootings, which destroyed a large part of the infrastructure and buildings of the capital Nuku'alofa. The reason for this development was the modest effort and action of the Tongan Legislative Assembly towards the advancement of democracy in the government. As a result of the riots, the country's first democratic election was held in 2010. Since then, Tonga is declared a constitutional monarchy and a parliamentary democracy with a unicameral Legislative Assembly consisting of 26 elected members (Commonwealth n.d.).

Under the current political background, a variety of government ministries are responsible for the different areas related to the energy sector in Tonga. Most of these ministries are embedded under the acronym MEIDECC and located in the *Carl Sanft Building* in Nuku'alofa. MEIDECC are the Ministry of Meteorology, Energy, Information, Disaster Management, Environment, Climate Change and Communication (ADB 2016c). MEIDECC is responsible for the outer island energy policy formulation as well as the implementation of rural electrification programmes on the remote outer islands of Tonga (ADB and GCF 2017). The Electricity Commission (EC) is located separately in Nuku'alofa and regulates the electricity tariff setting on the four main islands covered with TPL's national electricity grids (Electricity Comission 2020). Together with the national energy provider Tonga Power Limited (TPL), these ministries are the primary governmental institutions impacting the countries RE development.

3.3 Land Resources

Tonga has specific rules on land ownership. All land is either owned by the King, the government or the nobles and is passed on in the form of a *Hereditary Estate.* Only they have the right to allocate land to the people according to the constitution. Meaning that land ownership can only be gained by a land lease from the government or nobles if there is no hereditary lease possible. The *Minister of Lands* is the representative of the Crown in all matters regarding land concerns in Tonga (Schaumkel 2017). According to the *Land Act 1903*, the land leaser has no secure land ownership rights and might be expropriated or evicted after investing in infrastructure on the land. Immigrants may lease land or housing but with unsecured ownership claims. This form of permit poses a significant problem for private investment, visible through many unfinished building complexes in the island state and low presence of foreign investors (Veikune et al. 2017).

3.4 Religion

Religion is playing a significant role in the pacific island nation. Religious institutions are among the wealthiest and most powerful in the country. After the arrival of London missionaries in 1797, followed by missionaries of the *Wesleyan Mission Society* at the beginning of the 19th century, Tonga became comprehensively Christianised (Urbanowicz 1977). The *Free Wesleyan Church* is the state church of the monarchy, and several other churches exist, such as the Church of Tonga, the Free Church of Tonga, the Seventh Day Adventis, the Angelican Church and the Pentecost Church (Tatafu 2008). Religion plays a significant role in the daily life of the Tongan population. For example, Sundays in Tonga are celebrated as a strict sabbath on which no shops are allowed to open, and any form of activities besides going to church is seen grudgingly. Furthermore, churches function as the primary social hub in the country, strongly influencing the Tongans' daily social life (Forman 2005).

3.5 Migration and Emigration

The internal migration from the outer islands to the main island of Tongatapu began to rise after World War 2, due to the better access to modern amenities and increased demand for education and job opportunities. Hence, on average, almost 7 out of 10 Tongans reside on the main island Tongatapu where Nuku'alofa is located (Brown et al. 2014). As a consequence of the movement, people on the main island started to face a shortage of agricultural land resources and job opportunities. Therefore, in the early 1930s Tongans began to move overseas for work purposes, primarily to New Zealand, Australia, the United Kingdom and the United States. At present, an estimated number of 110.000 Tongans live abroad, which is more than living in Tonga. The emigrated Tongans mostly financially support their relatives in Tonga, which results in a strong economic dependency. Remittances from overseas contribute an essential part of Tonga's income and represent a significant source of foreign currency exchange (see chapter 3.6 Economy). However, the emigrational activities of Tongans to overseas countries might lead to a problematical demographic development in the long term, since the populations' growth rate in the country is 0,3% compared to the emigration rate of -8% between 2010 to 2015 (Bedford and Hugo 2012; Small and Dixon 2004; UNICEF 2017).

3.6 Economy

Tongas economy confronts a variety of barriers, namely limited natural resources, geographic isolation, heavy dependence on remittances as well as fossil fuels and foreign aid. In 2019 the gross domestic product (GDP) was 0,46 billion USD; its main components are displayed in Figure 3.2. The economy can be described as small, open and vulnerable to external shocks due to its narrow export base mainly of agricultural goods, which account for 17,21% of the GDP (World Bank 2019b). The tropical climate provides fertile soils, and agricultural land covers about 43,1% of the land resources. The main crops are squash, vanilla, beans and yams. Agricultural exports, including fish, make up two-thirds of the total exports. The country also must import a high proportion of its food, mainly from New Zealand. Therefore, Tonga has a negative trade balance, equivalent to three times (USD) of the export incomes in 2017 (World Bank 2017b).

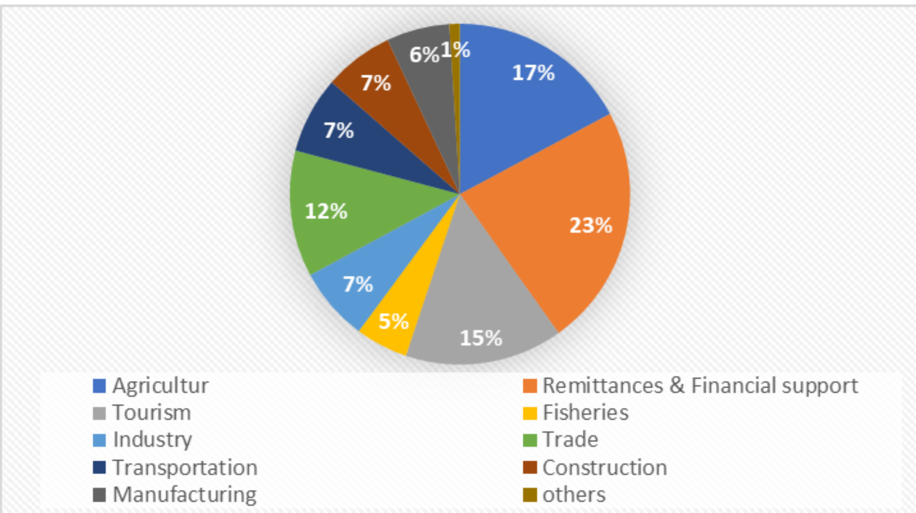

Figure 3.2: GDP composition for the year 2019, own presentation based on data from (Government of Tonga 2019; Lin 2011; ADB 2016a)

As mentioned before, Tonga's economy is heavily reliant on remittances from emigrants and foreign aid as an essential source of income, also to offset its negative trade balance. The largest share of remittances comes from the USA, followed by New Zealand and Australia and make up in average 15% to 30% of the country's GDP (Lin 2011). However, from a macroeconomic perspective, remittances are a stable and essential source of development finance for poor, labour-exporting countries like Tonga (Brown et al. 2014). Besides, foreign development assistance in the form of loans, grants, and direct aid is a crucial component of the Tongan economy (Australian Department of Foreign Affairs and Trade 2019).

According to a sample survey done by Brown, Connell, and Jimenez-Soto (2014), 91% of the Tongan households receive remittances. Brown explains that short term labour contracts lead to increased migration to Australia and New Zealand for agricultural work purposes since 2007 (Brown et al. 2014). Besides remittances, tourism is the second-largest source of hard currency earnings. In 2015 Tonga had 53,800 visitors, and the tourism sector contributes directly and indirectly for about 15% to Tongas GDP (Matangi 2017; GoT 2019). The manufacturing sector consists of handicrafts, mainly traditional goods produced by the outer islands, and contributes only about 6% to the GDP. The retail sector on the main island Tongatapu, the urban landscape of Tonga, is influenced by many small businesses owned by recent Chinese immigrants who arrived under the cash-for-passports scheme, which ended in 1998. Also, Tonga is ranked the sixth most corrupt country globally, which is one reason for the lack of foreign investments in general. Tongas economic growth in the future will be heavily depending on climatic and political events (IBP 2011).

3.7 Climate

The climate of Tonga is tropical throughout the year due to its position within the South Pacific wind trade zones. An alternating climate characterises the weather with a contrast between the wet season from November to April and the dry season from May to October. During the wet season, about 60% to 70% of the annual rainfall is recorded. The rainfall in Tonga is mainly caused by the movement of the South Pacific Convergence Zone and therefore closely linked with tropical cyclone activities. Most of the northern islands receive more rainfall with 2500 mm/year, while the southern islands receive almost one third less with 1700 mm/year. The monthly average rainfall is between 80 mm and 230 mm, as shown in Figure 3.3.

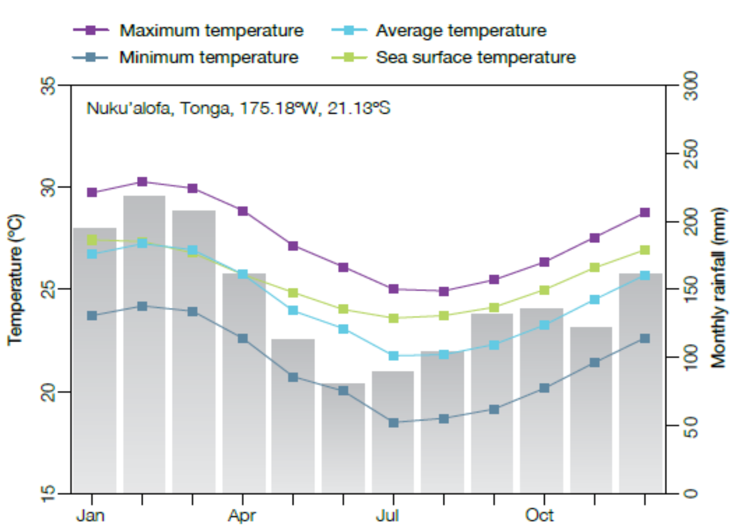

Figure 3.3: Seasonal rainfall and temperature at Nuku'alofa, source: (Tonga Meteorological Service and Australian Bureau of Meteorology, CSIRO 2015)

The winds over Tonga are usually dominated by the south-east trades all around the year. These trade winds prevail from May to November with easterlies the rest of the year. From May to October, the trade wind tends to be strongest. The average wind speed ranges from around 3.5 m/s to 5.5 m/s. Tonga's climate varies from year to year due to the *El Niño* Southern Oscillation (Tonga Meteorological Service, Australian Bureau of Meteorology, CSIRO 2015).

The mean annual temperature for Tonga ranges from 23°C to 28°C, while the mean humidity is about 75%. As the tropical climate is characterised by a dependence upon latitude (see Figure 3.1), the annual temperature of the northern islands "Niuafo'ou" is slightly higher with 27°c compared to the southern part of the country with 24 °C. In general, Tonga's temperatures are strongly linked to changes in the surrounding ocean surface temperature and water temperature continues to increase by 0.0004°C annually since 1993 due to climate change. The dry months are considerably cooler than the warm and wet months (GoT 2019).

3.8 Tropical Cyclones

Tonga is exceptionally vulnerable to the impact of cyclone events. Tropical cyclones appear in Tonga between November to April, while the highest frequency of occurrence is recorded in February (Tonga Meteorological Service, Australian Bureau of Meteorology, CSIRO 2015). The high interannual variability in the number of tropical cyclones makes it challenging to identify any long-term frequency trends in the Southwest Pacific. However, tropical cyclones have become more intense than historical records of cyclone occurrences. Since 1960, 76 cyclones have crossed the area of Tonga, and since the beginning of this century, 11 cyclones have hit the small island nation (Tonga Meteorological service 2020; JICA 2017). Among those, the most destructive cyclones occurred just within two seasons, which are cyclone Gita in 2017/18 and cyclone Harold in 2019/20. Cyclone Gita was the most destructive storm hitting Tonga in the last 60 years. It was a category four cyclone with peak wind speeds up to 233 km/h causing significant damage and injuries across Tonga and damaging 40% to 50% of Tongatapu's electric grid. Tonga declared a state of emergency, 969 buildings got partially damaged and 95 were destroyed, causing the evacuation of 3900 people. Also, characteristic Tongan landmark buildings have been badly damaged, such as the parliament and the Free Church of Tonga in the capital Nuku'alofa. The damage of cyclone Gita is still partly visible in the country (European Commission JRC 2018). The infrequent occurrence of tropical cyclones represents a significant challenge for project development in Tonga. According to a study on the wind generation potential in Tonga by the Ministry of Foreign Affairs and Trade (MFAT, 2015), the potential of damages from tropical cyclones is one of the least quantifiable project risks. Even wind turbines designed to withstand strong wind conditions can be damaged or destroyed through tropical cyclones, as it has occurred in New Caledonia in 2003 (MFAT 2015). Global and regional studies show a decadal trend in which the Southwest Pacific is heading towards lesser severe occurrence for tropical cyclones. However, the current data for Tonga is showing the opposite trend. The total numbers of tropical cyclones that have crossed into Tonga's waters and those reaching severe have both increased (GCF and MEIDECC 2018).

3.9 Climate Change Impact

Small island developing states (SIDS), including Tonga and other PICTs, are recognised by the United Nations Framework of Climate Change (UNFCCC) treaty and the Intergovernmental Panel on Climate Change (IPCC) fifth assessment report as among the most vulnerable countries to climate change worldwide (Weir 2018). The United Nations Office for Disaster Risk Reduction (UNISDR) (2012) described the situation as followed: *"Pacific people face the greatest risk of becoming poorer, getting displaced from their homes and regressing in their development as a result of climate change"*. The PICTs are highly vulnerable to the effects of climate change due to their low lying nature, small size, low height, dependence on natural resources and coastal populations (UNISDR 2012).

According to Tonga Meteorological Service (2015), the country records an increase in annual maximum and minimum temperatures of 0,10 °C per decade since 1950. The yearly rainfall shows a declining trend, especially in the wet season. Satellite data and tide gauges indicate a sea-level rise by about 7 mm per year since 1993, which is larger than the global average of 2,8 to 3.6 mm per year. If this trend continues, the sea level will have risen by 27.8 cm until 2030 (Tonga Meteorological Service, Australian Bureau of Meteorology, CSIRO 2015). Besides, the acidification of the ocean is increasing due to rising carbon dioxide levels in the atmosphere. Therefore, climate change directly affects the functions of individual organisms and ecosystem structures in Tonga, e.g. decomposition, nutrient cycles, water flows, species composition and species interactions. In combination with the rising sea temperature, the balance of the local reef ecosystems is critically impacted and put under stress, for instance, an enhanced coral bleaching is recorded (GoT 2019). Global climate models predict the sea-level rise combined with natural climatic year-to-year changes will increase the impact of storm surges and coastal flooding. Also, particularly low lying coastal areas are affected by saltwater intrusion, which leads to an increase in groundwater salinity and reduces the availability of sufficient freshwater (Government of Tonga 2018). Tongas main island Tongatapu already experienced several inundations and erosions at the northern and western coastlines. Especially the coastal villages between Ha'atafu and Kolovai on the west side of Tongatapu are low lying, 2m to 5m above sea level, and therefore highly at risk of erosion from rising sea levels.

Climate change and natural disaster critically impact the Tongan agricultural sector, which forms an integral part of Tonga's economy. Agricultural production was severely affected by Tropical cyclones in recent years. In 2018 cyclone Gita caused damage costs to the Tongan agriculture of more than 300 million TOP (129 million USD). Also, severe droughts have affected Tonga in recent decades, for instance, in 1983, 1998, 2006 and 2015, with a dramatic impact on the agricultural sector, mostly enhanced by the climatic effect of *El Niño*. In 2015 the targeted export of agricultural products to Japan such as pumpkins and squash was reduced by 69% (Government of Tonga 2018).

From Tonga's viewpoint, there is an urgent need to mitigate climate change before its effects are exacerbated. Climate change adaptation in the developing Pacific Island Nations is more complicated than in the developed countries due to limited adaptive capacity (IPCC 2007). Furthermore, the contribution of the Pacific Islands to climate change is comparatively low, since they are low emitters of carbon dioxide gas. Hence, the Pacific Island countries cannot mitigate these problems by themselves without having assistance from developed countries. Tonga is planning to reduce its greenhouse gas emissions to contribute to climate change mitigation and respond to the Paris Agreement. Targeting much cleaner energy generation became a nationally determined policy. Reaching this target is only feasible by reducing the use of fossil fuels through an increase in the utilisation of RE sources and the application of energy-efficient technologies in the energy sector (Government of Tonga 2018).

4 Solar Photovoltaic Energy

The sun emits energy at a rate of 3.8x10 ^{23} kW per second, and the solar radiation reaching the earth's surface in a year is approximate to 3,400,000 EJ which is 7,500 times the world's total annual primary energy consumption of 450EJ in 2011 (576 EJ in 2019) (Kuang et al. 2016, p. 506).

4.1 Introduction to Solar Energy

The photovoltaic effect was discovered in 1839 by the French physicist Alexandre-Edmond Becquerel and describes the conversion of radiation energy into electric current and voltage in photovoltaic elements. It is directly related to the photoelectric effect, which relates to the discharge of electrons from the surface of semiconductor material upon exposure to radiation (Torner 2014).

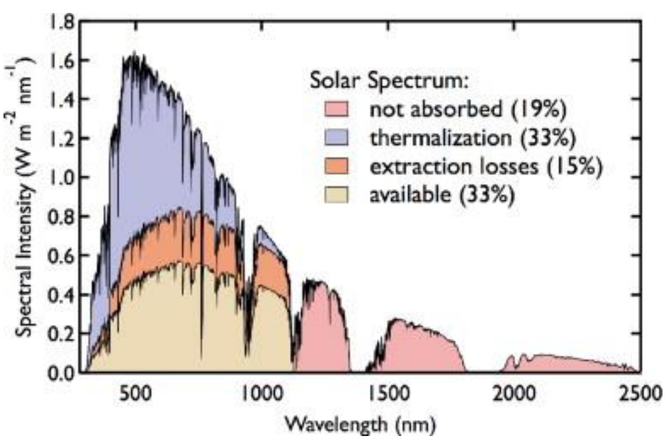

Figure 4.2: Absorption spectrum for solar cell (Semonin et al. 2012)

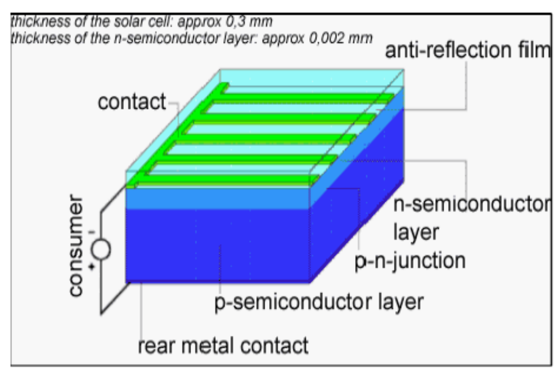

Figure 4.1: Functionality of solar PV cell (Eierstock 2012)

A solar PV cell consists out of two semiconductor layers which are doped with impurity atoms to alter their properties. Solar PV modules are divided into a n-type and p-type layer, while for the commonly applied modules, the n-type layer is doped with Phosphorus und the p-type layer with Boron (see Figure 4.1). The doping with Boron creates an electron shortage and thus a positively charged layer and the doping with phosphorus creates an electron overflow making the cell negatively charged. The combination of these two layers is called the *'p-n junction'*, which serves as an isolating layer between the positive and the negative pole inducing an electric field. The antireflection coating prevents reflectance and therefore increases the transmission of the light. Photons of a wavelength up to 1,130 nm (see Figure 4.2) are absorbed by the semiconductor leading to the ejection of electrons from the upper layer moving through the material into the p-layer. The process induces a corresponding positive charge which is called 'hole'. Through the separation of the p-n junction, an electric field is generated, and the charges are collected in the form of DC current by the metallic contacts on each side of the solar cell. The resulting voltage depends on the semiconductor material. For silicon, which is the commonly used material for PV cells, the voltage is 0.5 V (Torner 2014; Semonin et al. 2012). The electric current increases with the irradiation intensity, while the voltage is hardly influenced by irradiation. The resulting power, the product of voltage and electric current, depends on the cell temperature and decreases with rising temperatures (Eierstock 2012). The characteristics of photovoltaic modules are given at standard test conditions (STC). STC refer to irradiation of 1,000 W/m² with a light spectrum air mass of 1.5 and a cell temperature of 25 °C.

Electrical characteristics at STC are commonly displayed on the datasheet of a panel. The following shown data originated from the solar panels of the TTI-case study example in chapter 8.3.2 (datasheet see Appendix 5).

1. Maximum power (maximum output at STC) = 320-340 W
2. Module efficiency (19.9 %)
3. Temperature coefficient (-0,37%/°C)

4.2 Cell Types

An estimation made by Frauenhofer ISE (Institute for Solar Energy Systems) (2020) indicates that a total of 133 GWp of PV modules was produced in 2019. The resulting worldwide installed cumulated module power reached 628 GWp by the end of 2019 (VDMA 2020). Since in 2019, the market share of photovoltaic modules made on a silicon basis was over 95%, only these cell types are described in detail in this section. Besides, the silicon-based PV technologies, several other cell types are available, such as organic solar cells (OPV) made from hydrocarbon molecules or multi-junction (MJ) with several p-n junctions allowing a broader range of light wavelength absorbance. Within the silicon wafer-based solar cell technologies, three main cell types are distinguished: polycrystalline (or multi-crystalline), monocrystalline and thin-film/amorphous. Among the silicon-based modules, monocrystalline cells are currently holding a share of 66% and count to the commercial best-performing modules with an average efficiency of 19-24,4% under laboratory conditions. This cell type is made of one block of silicon crystal, which requires qualitative high semiconductor material. Since 2015 the global share of monocrystalline panels was continuously rising and exceeded the former leading multi-crystalline modules (see Figure

4.3) The reason for this development was the higher cell efficiency and fallen cell prices due to a decrease in production costs (Fraunhofer ISE 2020; Torner 2014). This development is also in line with the applied

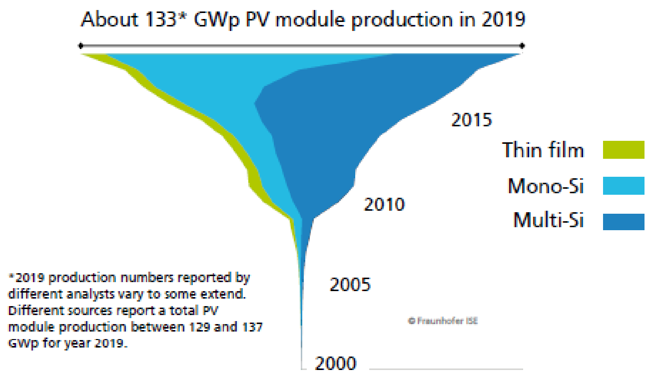

Figure 4.3: Annual PV Production by Technology Worldwide (Fraunhofer ISE 2020)

modules in the case scenario in section 9.3.2 in which monocrystalline panels are used for the solar PV rooftop installation for the Tongan TTI college.

Polycrystalline silicon cells, also known as multi-crystalline, are produced from silicon wafers which are made from blocks founded through the process of silicon smelting. During the solidification, many small silicon crystals are formed, giving the cell the denomination polycrystalline. In recent years this form of cell production has been more economical since less pure semiconductor material is needed, but the formation of different sized crystals leads to defects that create a lower cell efficiency with an average of 15-22%. This fact currently leads to a substitution of polycrystalline cells by higher efficiency cells on the market (Sendy 2020).

Thin-film (TF) cells are produced of a different type of silicon, known as amorphous silicon (a-Si) and other semiconductor materials such as CIGS (copper indium gallium selenide) or CdTe (Cadmium Telluride). The cell thickness varies between a few nanometres (nm) to several micrometres (µm), allowing thin cells to be flexible and lower in weight and, therefore, mainly used as integrated photovoltaics in buildings or semi-transparent photovoltaic glazing material for example on windows. The TF type solar cell is one of the most economical options within the silicon-based technologies but due to its low efficiency of around 16.1% only represents 5% of the world market (US DOE n.d; Fraunhofer ISE 2020).

4.3 Functionality of a Solar PV System

The single solar cells are interconnected to a solar module to provide a suitable voltage and electricity output for the power-consuming applications. A solar module consists out of typically 48-60 cells in series, which are embedded in Ethylene Vinyl Acetate (EVA) foils, a glass cover on the front, a frame made of aluminium and a back-sheet with a junction box for cables (see Figure 4.4).

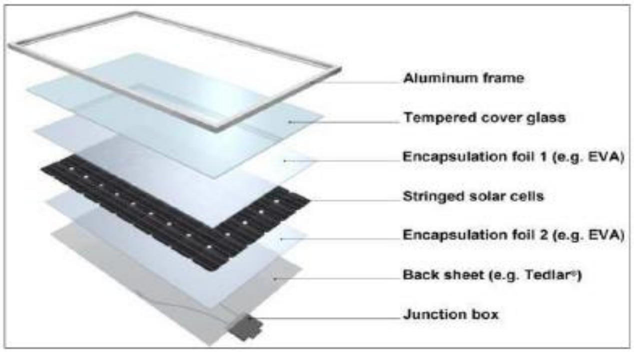

Figure 4.4: Components of a glass-foil PV panel (Swimsol 2010, as cited in Eierstock 2012)

Double glass panels have an additional glass cover on the backside instead of the back sheet and are more resistant against corrosion. Currently, the global PV industry is converting production from an aluminium back-surface field (Al-BSF) to "Passivated Emitter and Rear Cell" (PERC) solar cells, in which the back of the cell is coated with a dielectric layer, e.g. AlOx/SiNy, and the Aluminium layer is only locally in contact the Si wafer (VDMA 2020).

The applications of solar PV energy can be divided into two main categories, which are *Off-Grid* and *On-Grid connected*. The relation of these categories to the Tongan energy sector is further explained in chapter 6.1. Figure 4.5 displays, a typical residential grid-connected solar PV system.

A grid-connected residential solar PV system consists of five essential components (not including battery storage):

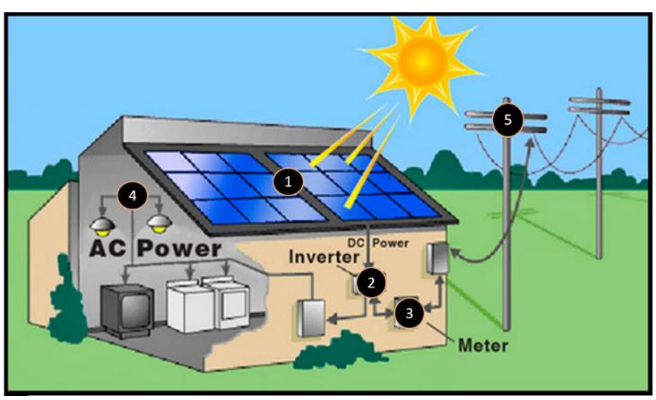

Figure 4.5: Components of a solar PV system, (own representation according to graphic from (Tiyou 2016))

Legend:

1. Solar panels
2. DC/AC Inverter
3. Electricity meter
4. Appliances
5. Electrical grid

The electrical output of the roof-mounted solar panels (1) (DC) is converted to alternating current (AC) by the DC/AC inverter (2), which then can be used by standard electrical appliances (4) or fed into the public electrical grid. The amount of generated electricity is recorded by the electricity meter (3), the energy that is not used by the appliances is directly fed into the electrical grid (5) while at times when electricity production does not meet the demand, electricity is drawn from the electrical grid. Within the application of grid-connected solar PV, large-scale ground-mounted systems with areas of several hundred hectares and output powers of hundreds of megawatts represent a common form of solar energy production (Tiyou 2016; Torner 2014).

Off-grid PV systems typically operate in remote areas such as isolated islands or thinly populated regions where a public electrical grid is not available or uneconomical. These solar PV systems are applied as *stand-alone* or *hybrid systems*. The hybrid system describes a mix between renewable energy production and diesel generators that meet part of the load demand and therefore offer greater reliability. Additionally, depending on the load requirements and size of the renewable energy generator a battery bank is included in the hybrid system, sized to store and provide energy for a certain amount of time mostly in the evening. A typical PV/diesel/battery hybrid system consists of a PV array, a control device (charge controller), a backup diesel generator, an inverter and a battery bank. Off-grid stand-alone PV systems typically consist of a PV array, a control device and a battery bank. The control device manages the power distribution and state of charge of the batteries, while the excess energy is stored in the batteries and discharged in times when the solar PV array output does not meet the load requirements (Torner 2014; Eierstock 2012; Vezzoli et al. 2018).

In the case of the Kingdom of Tonga, hybrid systems are the commonly applied form of power generation. However, yet the share of diesel-generated electricity far exceeds that of renewable energies. The challenge to supply these islands with a maximum amount of RE is to promote these technologies among the people of Tonga - an attempt undertaken in this thesis.

4.4 Solar Price Development

The first solar cells made from silicon were produced in 1954, just after the discovery of the semiconductor technology. Due to increasing environmental awareness and triggered by the energy crisis in the 1970s, the commercial application of solar cell technology commenced. In the beginning, the costs for PV modules was reasonable high due to the enormous investment costs for silicon mines and manufacturing facilities. As a result, the silicon prices slowly started to reduce when the global demand kept on rising and with it, the prices for solar systems (Torner 2014). Between December 2010 and December 2019, the total average cost of a utility-scale PV system has reduced by 75% from 4,90 USD/Watt in 2010 to 1,19

USD/Watt in 2019, while the price differences vary significantly depending on the country. In countries like China and India, the system costs for utility-scale PV have even reduced below 0,80 USD/Watt (see Figure 4.7). Also, the prices of crystalline silicon solar modules declined on average in the order of 90% in the same period. Figure 4.6 displays the price development for the main types of solar modules sold in Europe and visualises the enormous downwards drop in cell prices over the last ten years. A wide range of cost exists while the price difference varies significantly depending on the type of module, with average costs in December 2019 from 0.21 USD/Watt for the lower cost modules to 0.38 USD/Watt for all-black modules, while the cost for high-efficient crystalline modules is 0.37 USD/Watt (IRENA 2020, 2017). This price transition is highlighted in the cost difference of about 80% for a solar PV array installed in Tonga in 2012 and the reported cost for a similar facility completed in 2017 (IRENA and PCREEE 2018).

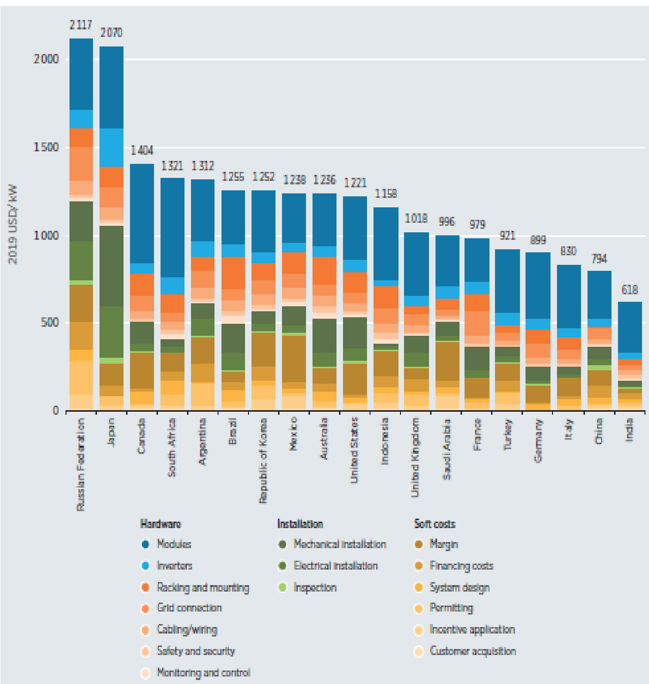

Figure 4.7: Detailed breakdown of utility-scale solar PV total installed costs by country, 2019 (IRENA 2020)

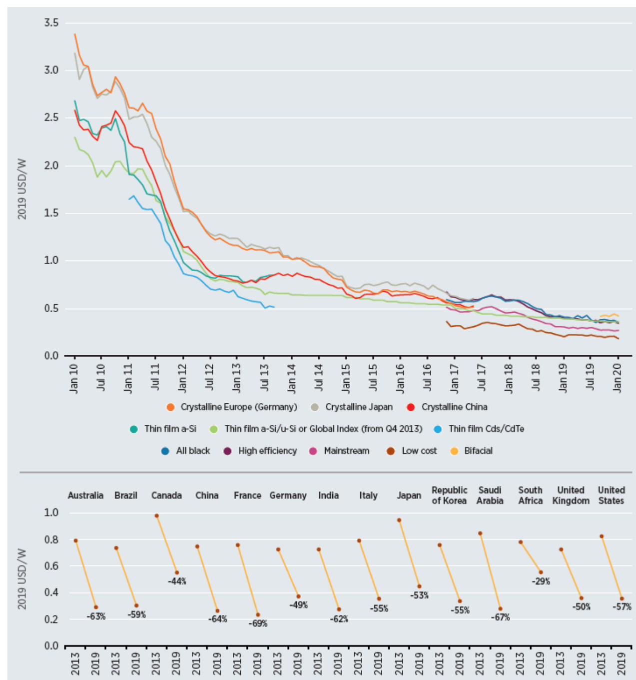

Figure 4.6: Average yearly solar PV module prices by technology and manufacturing country sold in Europe, 2010 to 2020 (top) and average yearly module prices by market in 2013 and 2019 (bottom) (IRENA 2020)

Several important factors influence the reduction of module prices in the period of 1980 until 2020. The improving module efficiency is the largest contributor until the beginning of the 21st century and is then replaced in its importance by improvements of new technologies and processes such as surface passivation, anti-reflective coating, texturing of the wafers and development of encapsulant materials. Lastly, reductions in the silicon consumption per cell due to more efficient technologies and falling polysilicon prices contributed to decreasing module costs (Kavlak et al. 2018).

According to the International Renewable Energy Agency (2019), the developments of recent Power Purchase Agreements (PPA) indicates that photovoltaic provides one of the cheapest options of electricity supply. The electricity cost from utility-scale solar PV decreased by 82% between 2010 and 2019 and is competing for energy generation costs of existing coal-fired power plants. This fact renders PV increasingly economically attractive, especially in areas with high conventional electricity generation costs such as in Tonga. The sustained dramatic decline in the price of utility-scale solar PV leads to a significant expansion of global capacity. Since 2014 the global-weighted average cost of solar PV electricity has fallen into the costs range of fossil fuel. In 2018, 98 GWp of PV capacity was added globally, representing 55% of the total additional RE power generation capacity. The largest markets for new capacity addition in 2018 were China (44 GW), India (9 GW), the United States (8 GW), Japan (6 GW), Australia and Germany (4 GW), Mexico, Turkey and the Republic of Korea (2 GW each) (IRENA 2019, 2020).

4.5 Battery Storage

The inherent characteristics of renewable energy sources, such as the intermittence of wind and solar energy, can lead to the imbalance between energy supply and demand in electricity grids and, consequently, fail to guarantee the continuity and reliability of energy supply. Energy storage technologies are effective approaches to cope with the stochastic and volatile behaviours of RE generation (Kuang et al. 2016). The most common form of energy storage technologies in hybrid systems like in Tonga are Battery Energy Storage Systems (BESS). BESS are integral to scale up RE systems in Tongatapu and provide TPL with a greater range of options for a sustainable and reliable energy generation (Cole and Banks 2017). Also, the growth of intermittent electricity generation from solar PV and wind is leading to a need for energy storage for grid stabilisation and load shifting purposes (Perkins 2018). Providing load shifting requires large battery storage, which currently accounts for the highest share of cost in a solar PV/battery system. An example of peak load shifting with BESS is charging a battery bank during peak production times and discharging it during the operational hours when there is insufficient power output from RE generators. As in the case of Tonga, the battery storage system is applied for load shifting purposes and is required to cycle once per day. It is charged by the solar PV plant during daytime and then discharged in the afternoon and at night to deliver electricity in accordance with the daily energy demand curve (Corson et al. 2014). A significant improvement of using BESS for Tonga is that diesel generators have a prolonged life, as they do not need to frequently cut in and out to sustain energy feed into the distribution grid (TPL and MEIDECC 2019).

A battery bank is a collection of one or more batteries connected to strings to achieve the desired voltage. Larger storage systems can be constructed by multiplying the number of battery strings. A variety of battery technologies exist and are under development. The currently most prominent battery storage systems are based on lithium-ion (Li-ion), lead (Pb) and Vanadium Redox Flow (VRF) technologies. In particular, the use of lithium-ion (Li-ion) batteries in utility-scale applications has grown in recent years due to the technology's attractive cost and performance characteristics. Li-ion batteries use an intercalated lithium compound as one electrode material and have attracted significant interest as supporting devices in the grid because of their remarkable advantages, namely relatively high energy density (up to 200 Wh/kg) and long life-cycle. Multiple lithium-ion battery chemical variants are available with the most important characteristics being cell voltage, energy density, rate capability, cycle life and costs. Lithium-ion batteries can be divided into two categories based on the type of anode – Graphite or Lithium Titanium Oxide (LTO). According to a research study by Jaiswal (2017), seven main lithium-ion battery types have been selected for the purpose of off-grid renewable energy storage. The costs of the battery types vary enormously, depending on factors such as life cycle, safety, and cell voltage (Jaiswal 2017). Table 4.1 displays the seven different lithium-ion battery types, including the essential criteria in comparison to a conventional Flooded Lead Acid Battery (pbA).

Historically, high costs have been a barrier to the application of storage systems, but improvements in technologies are continually reducing these costs. In the last decade the prices for lithium-ion batteries reduced by 80-85 %, and the average kWh price for battery storage in 2017/18 was indicated with 220 USD/kWh up to 630 USD/kWh

depending on the battery type. Moreover, a recent study reports that stationary storage is expected at a cost level of approximately 100 €/kWh by 2025 (Chen et al. 2020; Nedjalkov et al. 2019).

Battery type		Nominal cell voltage (V)	Battery voltage	Cell capacity	Round trip efficiency (%)	Cycle Life	Cost (USD/kWh)	No. Of cells in series
Flooded Lead Acid		2.0	12.0	10	80	500	100	6
Graphite anode	LMO	3.6	14.4	2	95	1,200	220	4
	NCA	3.6	14.4	2	95	4,500	270	4
	NMC	3.6	14.4	2	95	900	275	4
	LFP	3.3	13.2	2	95	4,400	310	4
Lithium titanium oxide anode	LMO/LTO	2.5	12.5	2	95	6,000	325	5
	NMC/LTO	2.3	13.8	2	95	27,000	550	6
	LFP/LTO	1.8	12.6	2	95	20,000	630	7

Table 4.1: Parameters of flooded lead-acid batteries and seven lithium-ion battery types used for Off-Grid energy storage purposes, according to the research study of (Jaiswal 2017)

5. Energy Overview

5.1 Energy Supply

Tonga uses three primary sources of energy: indigenous biomass, renewable energy (e.g. solar and wind) and imported petroleum products (e.g. unleaded fuel, diesel, kerosene). The countries current energy consumption is almost wholly depending on imported fossil fuel. The imported liquid and gaseous fossil fuels dominate Tonga's energy sector since it took over from indigenous biomass in 1949, when the first electrical grid in Tongatapu was built, followed by Vava'u in 1970 and Hapai and Eua in 1982 and 1983 (ADB and TECB 1996). Today, the national electricity provider Tonga Power Limited (TPL), an utterly state-owned enterprise solely governing the Tongan electricity sector, is operating four distinctly separated island grids. Despite the islands' geographic dispersion, which makes it impossible to connect all islands to one single grid, each of the four islands Eua, Tongatapu, Ha'apai, and Vava'u contain a separated grid. The total energy consumption of Tonga consists of 73% fossil fuel energies, including the sectors electricity and transportation, and 23,84% biomass, while the remaining energy is generated with solar PV and wind energy technologies (see Figure 5.2).

Fossil energy sources mainly drive Tonga's electricity sector. 87% of the annual electricity is produced by diesel generators, which is equivalent to an estimated 13 million litres of diesel and equals 20% of the total import value in 2011 and makes up the cost of 10% of the total GDP. In 2019, 11% of the electricity was generated with solar energy and 2% with wind turbines (see Figure 5.1). So far, wind turbines are only applied in the grid of the main island Tongatapu (ADB and GCF 2017; IRENA 2013a).

Tonga's transportation sector includes *jet fuel for in-country flights* and *diesel fuel for land and sea transportation* which holds a share of 48 % of the total energy consumption, and thus consumes more fossil fuels compared to the electricity sector with a share of 25%. Transportation consumes 25 million litres at a cost close to 20% of GDP (CTCN 2018). Tonga's electricity sector currently holds a total installed diesel generators capacity of 17.276 MW together with 6 MWp solar PV and 1,3 MW of wind turbines for all four island grids. Of these, the main island Tongatapu has the largest grid with an installed diesel capacity of 15,2 MW, 4,8 MWp solar and 1,3 MW wind energy and consumes on average 30.000 litres of diesel daily. The total electricity generation for Tonga in 2017 was about 57,9 GWh and is estimated to increase to 107 GWh by 2030 (TPL 2018a). The two international oil companies *TOTAL* and *Pacific Energy* are the leading fossil fuel suppliers for Tonga. The inland distribution of fossil fuel to the outer islands is done by the *Uata Shipping* company and the *Friendly Island Shipping Agency*. *Pacific*

Energy is also the only with solar energy and 2% with wind turbines (see Figure 5.1). So far, wind turbines are supplier of aviation fuels for Tonga (GoT 2019).

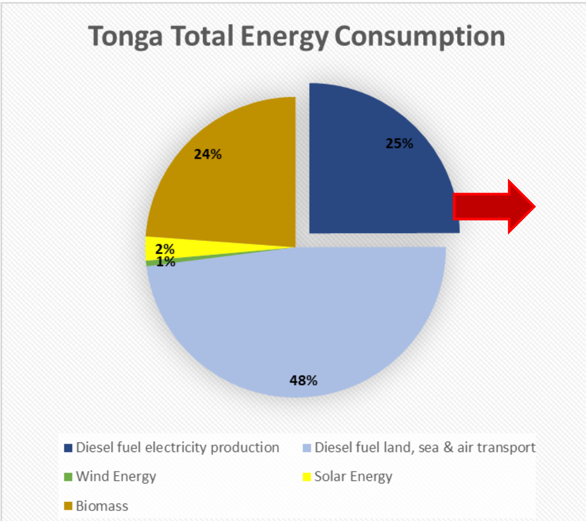

Figure 5.1: Tonga Total Energy Mix , own representation based on data from (Government of Tonga 2019; IRENA 2013)

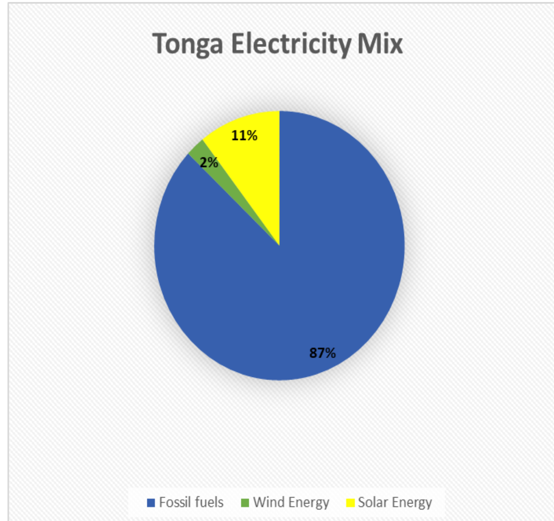

Figure 5.2: Tonga Electricity Mix, own representation based on data from (Tonga Power

The *Department of Energy* (DoE) of the Ministries of *MEIDECC* is responsible for the Off-Grids, which means the non-TPL grid, electrification planning in the rural areas and is not involved in policy or strategic planning for grid-based electricity supply. The Electricity Commission and TPL are responsible for the On-Grid regularities. In general, the Tongan energy sector is characterised by a variety of different areas of competence, which makes the implementation of RE projects more complex. The sector is divided into the four main components electricity, petroleum, RE and energy efficiency, which involves eight different ministries, and is covered by eight legislations. For further details on the exact involvement on the areas of the energy sector, see Appendix 4. As of 2020, the energy policy document "Tonga National Energy Bill" is under development, which pursues the goal of bundling the different energy sector areas under one framework and thus simplifying actions and development processes in the future (ADB and GCF 2017).

The almost total dependency on imported fossil fuels, high transportation costs and comparatively small scale of the electricity generation systems negatively impacted the Tongan economy with high electricity generation cost. Particularly the electricity consumers were exposed to high and volatile electricity prices over the last fifteen years due to the high share of diesel-generated electricity. The impact is more acute than in other larger Pacific Island countries, such as Fiji, and can be found in the fewer alternatives to offset the diesel consumption with hydropower plants. Therefore, Tonga is still reliant on imported fossil fuels for its overall energy needs (Government of Tonga 2018).

5.2 The Tongan Electricity Sector

"Providing safe, reliable, affordable and sustainable services for Tonga with at least 50% of electricity requirements through renewable sources by 2020 whilst remaining financially stable."

The official mission statement of the national electricity provider Tonga Power Limited (TPL) is in line with the Government of Tonga's energy policy, according to the TERM (TPL 2019b, p. 5). TPL was established in 2008 after a governmental restructuring of the electricity sector. TPL's core business is generating, distributing and retailing electricity. Its financial performance in 2018 is approximately 46 million TOP in revenue, with 4.7 million TOP (1,74 Million Euro) net profit after tax deduction. The vertically integrated utility owns and operates most of Tonga's in-front-of-meter electricity generation, transmission and distribution assets (CTCN 2018). Approximately 94% of the Tongan population has access to electricity, of which 89% are connected to the TPL utility grid and 5% are connected to small-scale mini Off-Grids in the outer islands. About 90% of outer island households are electrified via Off-Grid solar systems (MEIDECC 2015; Lucas et al. 2017). The largest grid is found on the island of Tongatapu. The island's grid accounts for about 85% of the total grid-supplied energy in Tonga, followed in size by the islands of Vava'u, Ha'apai, and Eua. On average TPL's island grids have a fuel efficiency of 4,05 kWh per litre of diesel, except the grid of Vava'u, mainly because the generators operate on low loads leading to reduced fuel efficiency. TPL serves approximately 25,000 customers, of which 19,8% are commercial customers such as public services, religious and governmental institutions, and 80,2% are residential customers such as households. The number of customers continually increases, by a rate of 2,7% in 2019, mainly due to network and infrastructure upgrades (TPL 2018a). In 2018, the residential sector accounted for 44% of electricity consumption, while commercial customers accounted for 56% (CTCN 2018). Besides the fluctuations in global fossil fuel prices, also line losses lead to inefficiencies and impact the electricity tariff. High line losses mean that more fuel needs to be consumed for electricity generation, which makes improving the efficiency of the country's power system a matter of interest for both, the power utility TPL and Tonga's consumers. In 2009, line losses accounted for 17,5% of electricity loses and were reduced to 10,12% until 2019. This development was mainly made possible by network upgrades such as the TVNU (Tongan Village Network Upgrade) in the period from August 2013 to August 2018, NNUP (Nuku'alofa Network Upgrade Project) which commenced in 2018 and OIEEP (Outer Island Energy Efficiency Project) which finished in 2019. These infrastructural development projects were financed by the World Bank, Asian Development Bank and New Zealand Aid. Besides, reducing line losses, they also paved the way for the expansion of renewable energies in the future by modernising the grid. As part of the network upgrade programmes, all obsolete meters in Tongatapu and to a larger extent in the other grids have been replaced by smart meters, enabling digital grid monitoring for TPL and simplifying the feed in of RE from third parties. The new meters intend to improve smart metering capabilities, provide alternative billing methods, and allow TPL to detect faults and power quality issues remotely (TPL et al. 2016; TPL 2018a).

5.2.1 Electricity Tariff

Pacific Island Nations, including Tonga, have one of the world's highest electricity generation costs (Lucas et al. 2017). The electricity tariff in Tonga is divided into two components, the fuel and non-fuel component. Since more than 87% of the electricity in the TPL grid is generated by diesel, fuel price displays a major component of the electricity tariff. The electricity tariff fluctuates according to the global diesel price and as of 2019 was at a price of 81.20 seniti/kWh (0,32 €/kWh).

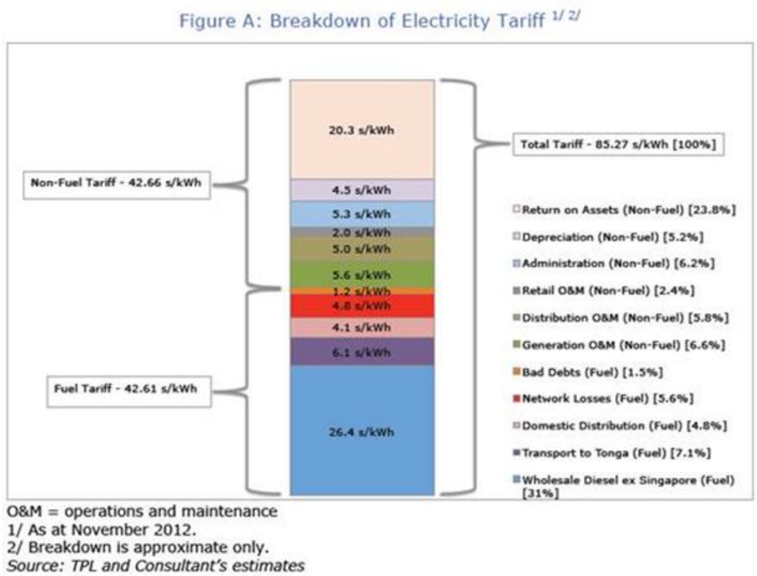

Figure 5.3: composition of the Tongan electricity tariff, source (Fonua 2019)

In 2019, the fuel component had a monetary share of 38.53 seniti/kWh and the non-fuel component of 42.67 seniti/kWh. Figure 5.3 displays the composition of the electricity price in 2012, which was slightly higher due to increased diesel costs, but nevertheless reflects the individual components. The fuel component's largest share is the diesel wholesale with 31%, while network losses contribute to 5,6%, transportation to 11,7%, and domestic distribution to 4,8% of the tariff. The largest share of the non-fuel component consists of asset investments with 23,6%, followed by Operation and Maintenance (O&M) of Distribution/Generation/Retail with 14,6%, administrational costs with 6,2% and depreciation 5,2% (Fonua 2019). An important issue in the future is the transition from an electricity tariff structure based on diesel fuel cost as a variable component to a tariff that incorporates the different cost structure associated with a significant share of RE (Taibi et al. 2016). It is anticipated that the fuel-component will be reduced through an increase in RE generation. Besides, the non-fuel O&M costs for the generators should decrease simultaneously, while the administrative effort to manage the intermittent RE increases. According to an interview with the Strategic Development Manager of TPL (2019), a large-scale expansion of RE will lead to decreasing electricity prices, but how exactly this will influence the tariff is not predictable yet (Fonua 8/15/2019).

The electricity generation costs vary from island to island due to transportation costs. In 2009 the tariff structure "*one tariff for all*" was adopted, making the tariff consistent across all the four island groups. However, in response to the high electricity tariff resulting from expensive fossil fuels, in April 2017 the GoT approved *lifeline support* for all residential customers consuming power of up to 100 kWh to maintain the tariff at 70 seniti/kWh. The fuel component regularly requires changes of the tariff according to the cost of diesel, which is determined by the *Electricity Commission* based on the Concession Contract at intervals of three months (ADB 2016c). According to the Concession Contract, the non-fuel tariff will be reviewed and updated on a five-yearly basis and subjects of inflationary changes are reviewed on an annual basis (Tonga Power limited 2019a).

5.2.2 Tongan Grids

In 2019, TPL had a total installed firm diesel capacity of 17.1 MW in all four island groups. Tongatapu's generator capacity is 15,2 MW and makes up approximately 85% of the Tongan electric grid capacity. Its average peak demand is about 9.7 MW, while in February 2019 absolute peak demand was at 10.4 MW. Tongatapu’s grid consists of 197 km overhead line, 9 km of underground cables, and 0.8 km of submarine cable, in addition to 567 km of low voltage lines (single and three phase). The diesel generators of Tongatapu are located at the Popua Power Station (see Figure 5.4), holding sufficient capacity to meet current peak demands. The 11kV switchboard in the power station helps to provide flexibility and reliability of supply.

Figure 5.4: TPL's Popua Power Station and Caterpillar (CAT-1750kVA-50Hz-CP_C) Generator, own representation

Currently, Tongatapu is transforming into a hybrid grid, including larger shares of RE and battery storage. In 2019, in addition to the existing generators, 4,3 MWp of solar PV in the form of larger plants, 540 KWp of rooftop and ground-mounted solar PV, and 1,3 MW of wind turbines were installed in Tongatapu. Appendix 8 shows a detailed list of RE installed in the country. The total renewable energy generation for 2018/19 was 6,4 MWh, a 12.2% increase from the previous year 2017/18. Figure 5.5 compares the share of each RE plant of the year 2017/18 and 2018/19: Of the total RE generation in 2018, Matatoa's Singyes solar PV contribution was the highest with 38.0%, followed by Mata'o e La'a at 19.5% and Maama Mai at 17.6%, while third party micro solar plants contributed 7.9% (TPL 2019a). In 2019 a lithium-ion BESS of 5 MWh/10 MW was integrated into the grid to improve grid stability and a second lithium-ion BESS of 23,4 MWh/6 MW will be installed at the end of 2020 for the purpose of load shifting to alleviate the intermittent RE and further stabilise the grid (Akuo 2019). Through the increasing energy storage possibilities, the technical barriers for the feed in of RE are reduced. Table 5.1 displays the exact electricity generator composition of the four Tongan grids.

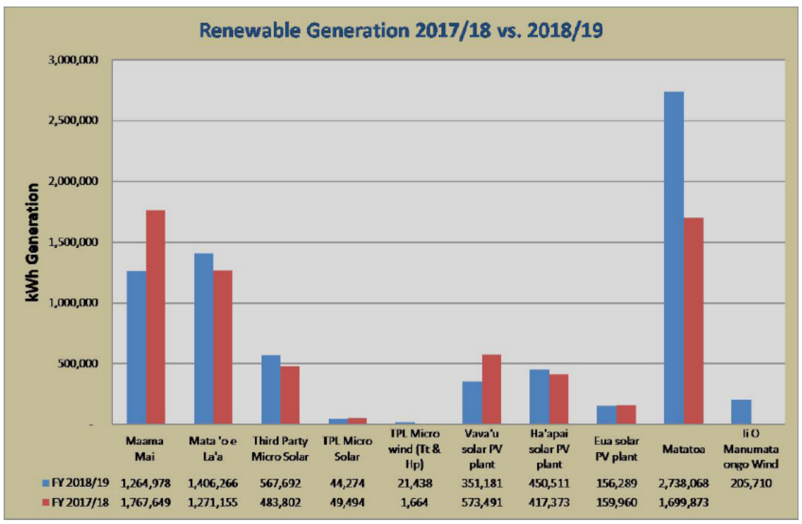

Figure 5.5: renewable energy generation of each RE plant in Tonga (TPL 2019a)

The three TPL grids of the other island groups are relatively smaller compared to Tongatapu. Vava'u holds a total of five generators with a capacity of 1,87 MW and an installed solar PV capacity of 420 KWp, paired with a 200 kWh battery storage facility. Vava'u has a 6.6 kV distribution network, 76 km of overhead line, 2 km of underground cables, and 95 km of low voltage lines. The TPL grid of Ha'apai consists of four generators with a capacity of 6,9 kW, has an 11kV distribution network, 14 km of overhead line, 2 km of underground cables, and 38 km of low voltage lines. The grid of Eua consists of two generators with a total capacity of 370 kW, an 11 kV distribution network, 13 km of overhead line and 42 km of low voltage lines. The Eua grid is the most inefficient of all Tongan grids with an average efficiency of 3,5 kWh/litre, compared to the total average fuel efficiency of 4,05 kWh/litre. The peak demand at Eua is such that for a small number of hours both Cummins generators need to be operational and work on inefficient loads to meet the peak demand. All TPL grids can offer single and three-phase configurations. Low voltage reticulations for all islands are at 400/240 volts (TPL and MEIDECC 2019). Some of the large scale RE installations connected to the Tongan grid are Individual Power Producers (IPPs), which are third-party owned entities selling the produced energy to TPL. The exact role of IPPs for the Tongan electricity sector is going to be explained in chapter 7.

Figure 5.6 and 5.7 show the approximate daily load curve of a weekday and weekend in Tongatapu (data obtained from IRENA 2013, modified to the current consumption of 2019). In general, there are two electricity peak demands on weekdays, which are late morning to early afternoon peak and then an evening peak. Analysis of the load profile shows that the major contributors to daytime load are commercial customers, primarily air-conditioning, computers and lighting. The decrease in commercial sector activities in the afternoon, at around 4 pm, is replaced by the increase in the residential sector activities, which are primarily lighting and cooking, resulting in an evening peak at around 8 pm. In general, mid-day peak demands during weekdays are higher than weekends, while the differences are estimated to be about 30% or more, significantly in the hot season. Furthermore, it is observed that the load on weekends follows approximately the same pattern compared to weekdays but at a lower level at each time of the day. Unfortunately, solar generation cannot address this timing of peak load without adding substantial storage facilities (Tonga Power limited 2019a).

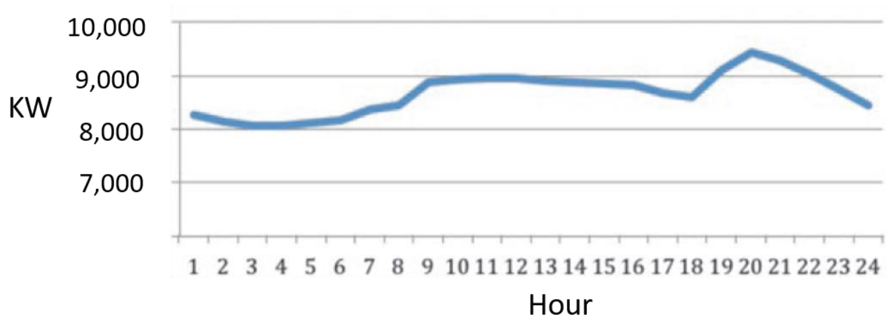

Figure 5.7: Typical weekday load pattern for Tongatapu 24/03/2013 (IRENA 2013)

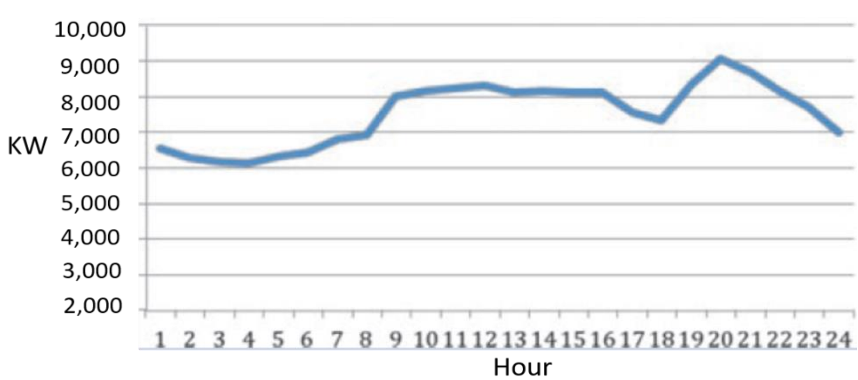

Figure 5.6: Typical load profile of a Saturday in Tongatapu (IRENA 2013)

As displayed in Table 5.1, six other grids on remote islands are existent, which do not belong to TPL and are under the DoE’s management. Some islands obtain generators or hybrid systems, a mixture between small generator units and solar PV capacities, or just separated Solar Home System (SHS) at the individual houses. Besides, some tourist resorts on the outer islands maintain their personal electricity generation systems, mostly solar PV hybrid systems. Under the programme *Outer Island Renewable Energy Project* (OIREP), the grids of the remote islands mainly in the island group Ha’apai and Niuas are upgraded and extended with RE. The overall objective of OIREP is to install approximately 1.32 MWp of solar PV power systems across nine outer islands of Tonga until 2021 (MEIDECC 2019).

Island Group	**Island**	**Grid Status**	**Description**	**Conventional capacity (MW)**	**RE Capacity (MW)**	**BESS Capacity (MW)**	**Expected fuel savings (thsnd litres per annum)**
Tongatapu	Tongatapu	TPL grid (11kV)	Popua Power station 6x 1,6 MW Diesel + 2 x 2,8 MW diesel	15,2			
			Maama Mai solar PV Plant/ TPL facility		1,3	10,5	460
			Vaini solar PV plant/ TPL facility		1	0,5	327
			Matatoa Singyes solar PV/ IPP		2		680
			1 x 1,35MW wind/ TPL facility		1,35		
			Distributed PV rooftop installations		0,54		
Tongatapu	Eua	TPL grid (11 KV)	Power station 2 x 186 KW diesel	0,37			
			Huelo ‘o e Funga Fonua PV plant (no battery storage)		0,2		73
Vava'u	Vava'u	TPL grid (6,6 KV)	Taumu'aloto power station 2 x 600 kW, 1 x 300 kW, 2 x 186 kW diesel	1,87			
			La'a Lahi solar PV facility and VRLA batteries		0,42	0,2	180,9
Ha'apai	Lifuka	TPL grid (11kV)	Panga Power station 1 x 320 kW + 2x186 kW diesel	6,92			
			Ha Mai Solar Facility		0,55	0,66	160,3
TOTAL TPL Grid				**24,36**	**7,36**	**11,2**	**1881,2**
Ha'apai	Nomuka	Non-TPL grid (6.6 kV)	Power station 1 x 37 kW and 1 x 55 kW diesel	0,92	0,7		
	Ha'afeva	Non-TPL grid (6.6 kV)	Power station 1 x 37 kW and 1 x 27 kW diesel	0,64	0,7		
	Ha'ano	Non-TPL grid (6.6 kV)	Power station 1 x 37 kW and 1 x 27 kW diesel	0,64	0,7		
	Uiha	Non-TPL grid (6.6 kV)	Power station 1 x 37 kW and 1 x 55 kW diesel	0,92	0,7		
Niua	Niuafo'ou	Non-TPL grid	SHS Systems, size unknown		unknown		
	Niuatoputapu	Non-TPL-grid	Solar PV plant (under construction)		0,15	0,295	
TOTAL Non-TPL Grid				**3,12**	**2,95**	0,295	
Projects planned or under construction 2020/2021							
Tongatapu	Tongatapu	TPL Grid (11 kV)	Additional Solar PV Extension/ IPP		6		
			Additional Wind Extension		8		
			Battery storage for load shifting			23,4	
Total added capacity					14	23,4	

Table 5.1: Status of Generation and Storage Capacities in Tonga, own representation based on data from (Tonga Power limited 2019a; TPL and MEIDECC 2019)

5.2.3 CO_2 Emissions

The highest among all greenhouse gas (GHG) emissions in Tonga is CO_2. Unfortunately, there is no data available on current circumstances. However, in a national GHG inventory in 2006 a total of 300,55 Gg CO_2 emissions was measured of which 62,35% are attributed to the Land Use, Land-Use Change and Forestry Sector (LULUCF) and 37,55% to the energy sector. The two most significant sources of GHG emissions within the energy sector are transportation, mainly road and air transportation, and fossil fuel-based electricity generation. The road transportation accounts for 60% of the sectors GHG emissions, while the energy transformation from fossil fuels accounts for 40% (GoT 2019). However, the total amount of greenhouse gas emissions from both sectors has not changed significantly in the last two decades. The emissions of the LULUCF sector are still similar in scope today as in 2006 as well as the emissions of the energy sector. This can be explained through the cancelling effect of increasing energy demand and decreasing line losses (Yamaguchi 2019).

A recent study by the United Nation's Climate Technology Centre and Network (CTCN) which targeted to reduce the Tongan greenhouse gas emissions, analysed suitable GHG reduction policy options and concluded that the three sectors; Transportation, Energy Efficiency and RE generation offer the largest potential for an emission reduction. The study concludes that a total of 43% emissions, equivalent to 106 Gg CO_2, could be reduced until 2030 compared to the Business as Usual (BAU) scenario. The targeted CO_2 emission reductions through policy reforms are distributed in percentage terms among the following areas; ground transportation is responsible for 30,4%, RE electricity generation is responsible for 40%, and EE in the electric sector is responsible for 29,6% of the projected emissions targets. The GHG reduction potential of RE is calculated for the national target of 70% RE generated electricity generation until 2030 and holds the largest share of GHG reduction potential, which indicates the importance of RE technologies in terms of CO_2 reductions (CTCN 2018). The contribution of the current objective of 50% RE generation equates to a reduction of 9,4 million litres of diesel per annum, which amounts to approximately 27 Gg CO_2 and is equivalent to a decrease of 25% of emissions (GoT 2015).

5.3 Fossil Fuel Dependency and Vulnerability

The dependency on imported fossil fuels places Tonga in a vulnerable position due to volatile fuel prices, which have a downstream effect on electricity, transportation, and cost-of-living expenses (GoT 2015). As shown in Figure 5.8, between March 2002 and March 2015, the country was significantly affected by unpredictable fluctuations of global diesel prices, directly influencing national electricity prices. An outstanding example of Tonga's extreme vulnerability to barrel price fluctuations were the oil price shocks during 2001, 2004 and 2008, leading to an increase in electricity prices of 60% caused by the rising oil barrel prices from around 25 USD to about 40 USD. In the following four years until 2008, the average barrel price more than doubled to a peak of around 100 USD, which in consequence led to electricity rates exceeding 1.00 TOP/kWh (equals 0,5 USD/kWh). The dramatic fall in crude oil prices that continued into 2009 led to a relaxation of this situation. These huge volatilities resulted in the highest electricity tariffs Tonga had ever experienced and dramatically impacted economic activities and the quality of life for all Tongans (GoT 2010b).

A recent example for the impact of fossil fuel fluctuations is the financial performance of TPL in the fiscal years 2018/2019. For two years TPL stabilised the national electricity tariff at 0,812 TOP/kWh, while at the end of June 2019 the diesel prices started to rise. As a result of the increased fuel costs in 2019, Tonga Power Limited recorded a net profit of only 2,2 million TOP, a significant decline of 53% of net profit compared to 2018 (TPL 2018a, 2019a).

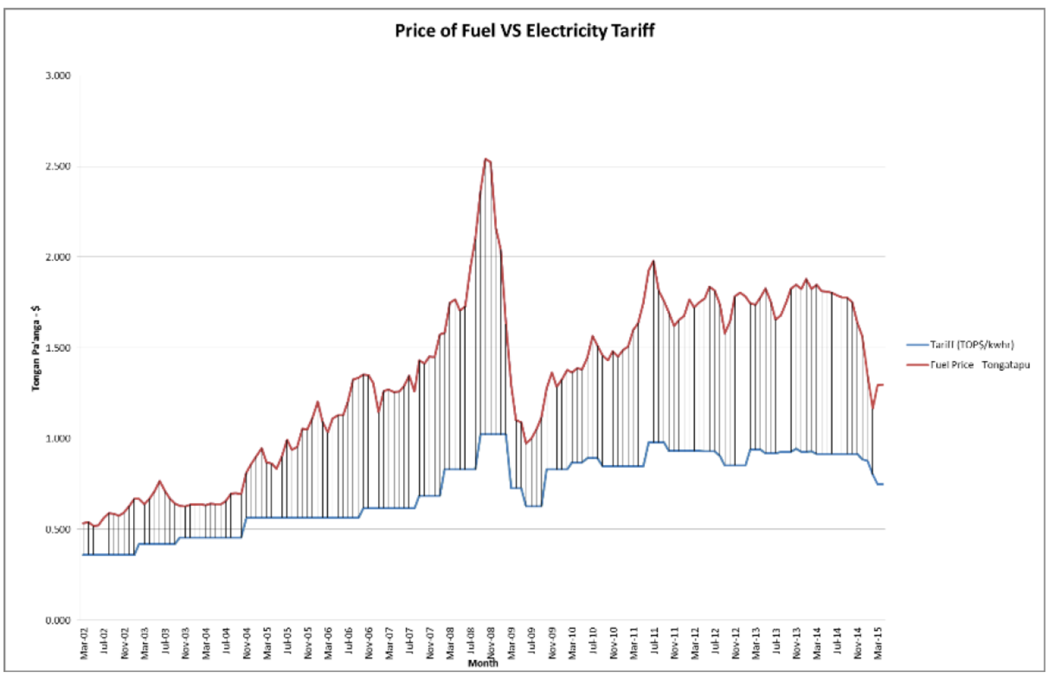

Figure 5.8: Price of fossil fuel in comparison to Electricity Tariffs in Tonga (Fonua and Essau 2017)

5.4 Impact of RE Generation on Fossil Fuel Savings

The successful widespread deployment of RE technologies in Tonga increases energy and economic security through significantly reducing the dependence on imported oil. Because TPL's tariff is the same for all four islands, the financial savings generated by the renewables are equally shared by all grid-connected consumers. As displayed in Figure 5.9, the increase in RE production between July 2014 and May 2018

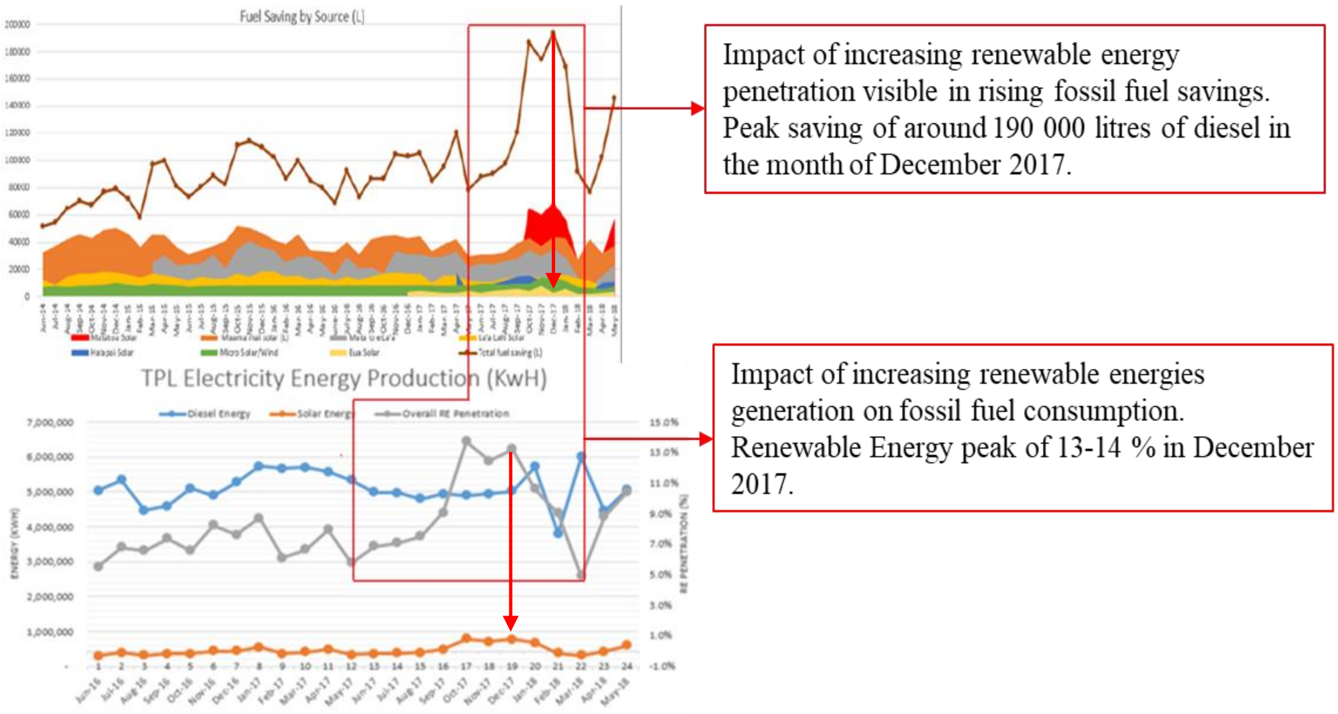

Figure 5.9: Comparison of energy production and fuel savings in Tonga for 2017 and 2018, source (Fonua and Essau 2017)

led to a significant reduction in fossil fuel consumption, which peaked in May 2017 to December 2017 when the *Matatoa Solar Farm* was connected to the grid (TPL 2018b). The Figure also reflects the impact of annual solar PV fluctuations. The months between September and January provide the highest solar insolation in Tonga. The subsequent decline in 2018 was due to an unexpected increase in power demand and due to Cyclone Gita's damage in February 2018, leading to an overall increased diesel fuel consumption of 6 % (Yamaguchi 2019). For the twelve months from July 2018 to June 2019, fuel-saving from renewable energy was about 1.6 million litres. The fuel-saving for the same period of the year before was about 1.5 million litres. The 50% RE target would equate to a reduction of 9,4 million litres of diesel per annum (TPL 2019a; GoT 2015).

6. Renewable Energies in Tonga

6.1 Applied Solar Types in Tonga

According to the national energy framework *Tongan Energy Road Map 2010-2020,* the RE technologies of most interest for Tonga are wind and solar energy. The TERM describes the role of solar energy as one that *"… can be developed across all parts of Tonga, it represents the most universally available renewable energy resource for the Kingdom" (GoT 2010b, p. 14)*. The ADB completed a feasibility study in the 1990s for developing diesel power generation systems on the most remote island group, the two Niua Islands (see map chapter 3.1). According to the study outcome, the investment to cover the potential loads of 15 kW exceeded the benefits for both islands, leading to a gradual application of Solar Home Systems (SHS) on the outer islands. Photovoltaic technologies already have been introduced to Tonga in the 1980s and provided the first basic energy supply to the inhabitants of Tonga's remote outer islands of Ha'apai. The beginning of PV implementation in Tonga was donor-funded by the World Bank and contributed to better life quality, improved education and health standards and cultural development for the rural areas. These first solar projects also paved the way for a long and distinctive development of RE. Nevertheless, the solar projects between the 1980s and 1990s are also an excellent example of the challenges encountered in implementing rural development projects, especially regarding the management of solar PV systems (MEIDECC 2015).

The vast number of islands in Tonga make it economically impossible to provide a national electricity grid on most islands. Hence, the two characteristic different types of energy supply for Tonga are: i) On-Grid electricity supply and ii) Off-Grid electricity supply.

i) On-Grid: Supplied electricity is provided by the national energy provider Tonga Power Limited on the country's four primarily populated islands. These are Tongatapu, Eua, Hapai and Vava'u. All four grids are currently hybrid-grids, including RE technologies and battery storage systems (TPL 2019a).

ii) Off-Grid: Systems are predominantly applied at the remote outer islands, where a standard grid is not existent. Each RE system represents an individual electricity grid.

Figure 6.1 presents an overview of the six most common application forms of solar PV systems in Tonga and is divided into Off-Grid or On-Grid usage. The decentralised Off-Grid application of solar PV offers a variety of application scenarios and has a clear advantage for the remote islands. However, the role of large-scale Independent Power Producers (IPP) is becoming increasingly crucial for the island nation. Tonga's target of 50% RE generation will be achieved mainly by using IPP projects which therefore are becoming increasingly represented on the landscape of Tongatapu. By the year 2020, TPL aims to achieve a total capacity of 17.7 MW in RE generation, of which 8 MWp of solar PV and 3,8 MW of wind energy shall be accomplished as an IPP (TPL 2019a).

Figure 6.1: Off and On-Grid Solar system types applied in Tonga, pictures own representation.

The four island groups of Tonga belong to the most remote places globally, which makes the supply of fossil fuels very difficult. In 2019 some of the outer islands are still supplied only once a month with a cargo boat. Besides the capital island Tongatapu, electricity supply for many outer islands of Tonga has a brief history. For instance, the first-time electrical power in the form of SHS was introduced to four outer islands of the Ha'apai group was in 2001-2003 (Tatafu 2008). The SHS and solar-powered satellite communication systems are only applied throughout the outer islands, while the solar water pump systems and solar streetlight are also part of the infrastructure on the main island. For example, in 2015 diesel-powered water pumping machines still consumed 1.3% of Tonga's annual imported diesel fuels and are therefore replaced continuously with solar PV products throughout the country (MEIDECC 2015).

Sahu et al (2016) divides the application of large-scale solar energies into five categories (1) ground-mounted, (2) roof-top, (3) canal-top, (4) offshore and (5) floating. Of these applications, the technologies (1) and (2) are already applied in Tonga, and the potential of floating solar will be analysed in chapter 8.5 (Sahu et al. 2016).

In Tonga, the solar resource has a reasonable radiation rate and is consistent throughout the year across the whole island nation. The average yearly solar radiation is about 1873 kWh/$m^{2,}$ which is more than 42% higher than in Austria (1100 kWh/m^2) (Fonua and Essau 2017; Solargis 2020). Table 6.1 displays the optimal tilt, cardinal direction, and exact irradiation data for all four Tongan island groups. Additionally, the data for wind energy is presented, including the hub height and correlating wind speeds.

Solar Energy		
Island system	Optimal tilt	Irradiation on the tilted plane kWh/m2
Eua	22° N	1,878
Ha'apai	20° N	1,882
Vava u	19° N	1,876
Niuas	17° N	1,856

Wind Energy		
Hub height (m)	Lapaha, Tongatapu, wind speed (m/s)	Niutoua wind speed (m/s)
55	6,89	7,45
45	6,5	6,72
38	6,15	6,16

Table 6.1: Solar and wind energy attributes for the different Tongan island groups, own representation based on (Fonua and Essau 2017).

6.2 Existing Solar Systems

Besides the continuous expansion of solar PV in the outer islands since the 1980s, Tonga's first large scale solar PV system was established in 2012 on Tongatapu and is called *Maama Mai Solar Farm*. At the end of 2019, three large scale solar PV systems with a capacity of 4,3 MWp have been finalised on the main island, while an additional 6 MWp of solar PV will be installed in 2020 (TPL 2019a; ADB and GCF 2017; TPL 2017).

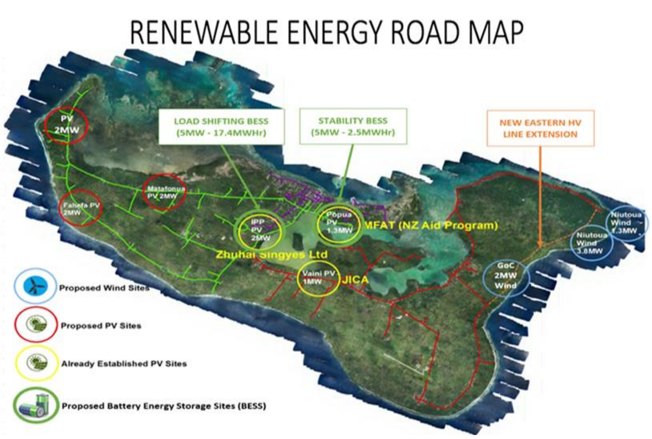

Figure 6.2: Project sites for large scale solar PV and wind installations on Tongatapu, sources (TPL and MEIDECC 2019)

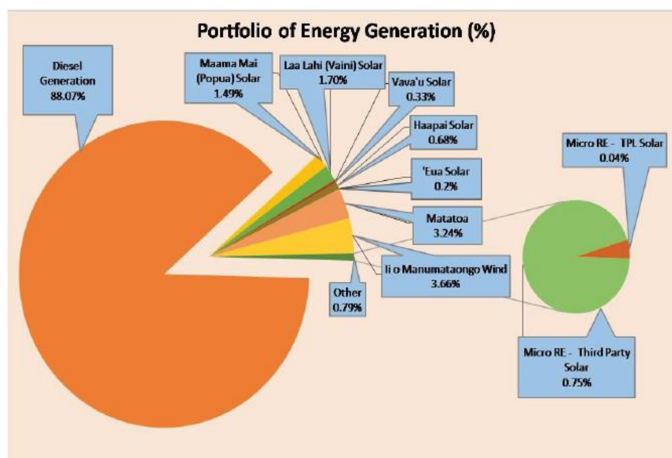

Figure 6.3: Contribution of wind and solar technologies to the total energy consumption in Tonga, source (TPL 2019a)

In the following, the four different island grids will be analysed, including their solar PV application. Figure 6.3 displays the exact locations of the solar and wind plants, and Figure 6.2 shows the systems' contribution to overall energy consumption.

Tongatapu

The *Maama Mai Solar Farm* has an installed solar PV capacity of 1,32 MWp which provides about 1,76% of Tongatapu's energy consumption and is located next to the Popua Power Station, south-east of the capital Nuku'alofa (See Figure 6.3). The system was fully donor financed by the NZ aid programme at a total of 5.68 million USD. In 2015 the second large scale ground-mounted solar PV system in Tongatapu was built named *Vaini solar facility,* with a capacity of 1 MWp. This facility represents the first introduction of microgrid control systems to ensure a cooperative electricity feed-in into the TPL grid together with the Maama Mai solar facility. Therefore, the project included the first applied BESS in Tonga with a total capacity of 1 MWh in lithium-ion battery banks, serving 1,7% of Tongas energy demand. The government of Japan fully financed the system at a total of 15 million USD (TPL 2017).

The *Matatoa Solar Farm* is the third large scale ground-mounted system and the first IPP installation for Tonga. TPL signed a 25 years agreement with the Chinese company *Singyes Technologies Holding Limited* in 2016. The 2 MWp system is currently Tongas largest solar plant and entirely financed and owned through a third-party private investment by Singyes Technologies. The company sells the electricity to TPL at an unpublished Power Purchase Agreement (PPA) rate. The system contributes 3,24% to the Tongan electricity demand and represents the introduction of third party financed systems.

In 2020 the largest solar plant in the south pacific is under development in Tongatapu. The 6 MWp solar PV system, is the second RE project designed under an IPP concept. The company *Sunergise New Zealand Limited* finances and operates the system and will sell the electricity to TPL for the official PPA tariff (see chapter 6.5). The solar plant is distributed over three locations with 2 MWp each and is expected to cover another 15% of tonga's electricity consumption (See Figure 6.3, red circled areas) (ADB 2019b).

Vava'u

The *La'a Lahi Solar Facility* is the first solar farm constructed in Vava'u and the second to be operating in Tonga. The solar farm was commissioned in November 2013 and fully financed by the United Arab Emirates. The system has a capacity of 420 kWp, including a 185 kWh battery storage and supplies 1,7 % of Tongas energy demand (TPL 2017).

Ha'apai

The *Ha Mai* Solar Farm at Lifuka, Ha'apai is operating since 2015 and has a total capacity of 550 kWp and a 660 kWh battery storage. The system was fully funded by the ADB, DFAT and the European Union under the Outer Island Renewable Energy Project (OIREP) (see chapter 7.2). The island of Lifuka is the first island of Tonga to reach the target of 50% RE generation (TPL 2017).

Eua

The *Huelo 'o e Funga Fonua* solar plant was commissioned in 2017 and had a capacity of 200 kWp which generate around 15-20% of the electricity for the people of Eua and 0,2% of the total Tongan energy demand. The system was grant funded by the ADB, DFAT and European Union (TPL 2017).

Additionally, several comparatively small micro and third-party solar systems already exist in Tongatapu (see summary Appendix 8). The TPL owned micro solar systems have a total capacity of 49,4 kWp and are primarily installed at educational institutions, including *Takuilau College*, *Tupou College, Beulah High School, Alonga roof-top solar, Tailulu College, and ʻApifo'ou College.* The third-party micro solar systems are privately owned and sell the generated energy to TPL under the given IPP regulations. A total capacity of 483,8 kWp exists in third-party ground-mounted and rooftop solar PV plants. The most important of these are the *Longo Longo Police Station* with 225 kWp (see case study chapter 8.3.1), the Vava'u hospital with 20 kWp and the NZ High Commission with 10 kWp.

According to the official OIREP programme of MEIDECC (2019) and documented through the conducted field study, five large scale solar PV projects are under construction in 2019 to ensure the electricity supply on the outer islands. These include mainly the islands of the Hapai group; Uiha (80 kWp and 420 kWh BESS), Nomuka (80 kWp and 420 kWh BESS), Ha'ano (80 kWp and 420 kWh BESS), Ha'afeva (50 kWp and 220 kWh BESS). Besides, the first electrical solar PV hybrid grid on the island Niuatoputapu of the Niua island group is under construction in 2020. This system is funded by the Global Environment Facility (GEF) and consists of a 122 kWp ground-mounted solar PV plant and a 590 kWh BESS including a diesel back-up generator (ADB 2016a; MEIDECC 2019).

6.3 Wind Energy Potential

This thesis's primary focus is set on the potential of solar energy for the pacific island state Tonga. Nevertheless, wind-based electricity production is of high interest for the Tongan energy sector and the role of wind energy for Tonga needs to be discussed. As described in the TERM-Report, there is an enormous potential for wind energy, especially on the main island Tongatapu. However, this technology is only interesting for large-scale investors or development aid-funded projects due to the high upfront costs. Also, wind turbines are vulnerable to damage from cyclones and need to be demountable and constantly stay under supervision, resulting in higher O&M costs than solar PV (Cole and Banks 2017).

In 2014, the GoT requested wind turbines and a grid stabilization system as a Japanese grant aid project (JICA). A preliminary survey by JICA identified the potential wind generator systems locations in Tongatapu. Besides, in 2015 a feasibility study was carried out under the New Zealand government's cooperation, which analysed potential wind turbine sites (MFAT 2015). In this way, with the support of the Japan International Cooperation Agency (JICA) and other donors, the introduction of this RE technology is progressing, also in order to secure more diverse electric power sources (JICA 2017). According to the JICA wind potential assessment, the eastern side of Tongatapu offers the most attractive conditions for larger wind turbine installations. The possible locations are limited to the coastal areas of the east coast and a small site on the west coast (see Figure 6.5). The first wind turbine was installed in 2013 in the area of *Nakolo*, the eastern part of Tongatapu, with a capacity of 11 kW. In 2019 the largest wind turbine project was accomplished by the Japanese aid donor JICA in Tongatapu. The project was installed in the area of *Niutoua* and comprises five wind turbines with a total capacity of 1,3 MW (260 kW each) and implementation costs of 20 million USD (see Figure 6.4). Apart from strong winds such as cyclones, the described area offers sufficient constant winds with an average of 7 m/s in the height of 50 metres (Sharma and Ahmed 2014). The estimated generation per turbine is 785 MWh/annually, which equals to the total generated electricity of 3925 MWh annually for five turbines. The total electricity demand of Tonga in 2017 was 57,6 GWh. Hence, the JICA wind farm can supply about 7% of the Tongan energy demand (Halatuituia 2014; TPL 2018a).

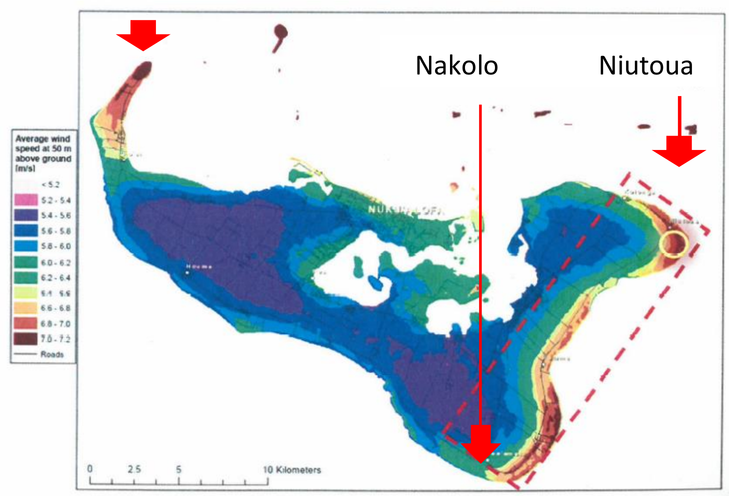

Figure 6.5: Jica wind Farm turbines in Niuatoua, source (TPL 2019a)

Figure 6.4: Area of highest potential for wind farms on Tongatapu, red marked, the location of the JICA wind farm is yellow circled, source (Halatuituia 2014)

6.4 Models for Outer Islands Solar PV Maintenance

The solar electrification in Tonga dates back to the 1980s when the first pilot solar PV projects of Taunga and Mango in 1987 and 1988 paved the way to the broader recognition and widespread application of solar electricity for lighting in the outer islands. The number of SHS installations in the outer islands increased rapidly over the years, and by 1999, the total number of installed SHS has reached 528. Until 2002 there was no policy framework existing to guide the donor financed SHS development and maintenance. At that time, the SHS systems have been managed based on a community cooperative model supervised by the GoT, which was responsible for instalment, maintenance and fee collection. However, experience showed that this government and cooperative based model had weaknesses. The sustainability of the systems in the long term could not be ensured, mainly due to the lack of experience in managing these new technologies. Experiences showed that the community cooperative's maintenance is unreliable and has to be carried out by specially trained technicians. Furthermore, the community managed concept is not very successful at collecting tariffs and scheduling appropriate maintenance and replacement tasks. Also, the design of the SHS system components needs to show low failure rates and a good performance in the demanding environment of pacific islands (Lucas et al. 2017; MEIDECC 2015; Outhred et al. 2004).

In 2002, the GoT formalised a new institutional structure under the *Tonga Incorporated Society Act*, which marked a new era in institutional arrangements for SHS projects in remote island communities. This act formed an improved management body, involving the communities and the local and central government to oversee the rural electrification projects on each island. The management concept forms a legal body of the SHS supplied households and is structured as a governmental owned solar electrification utility. The main difference is that the utility providing the services is a government-owned and supported institution rather than a cooperative. As a result, the utility has better access to capital and support services and is more flexible in its operations. The solar utility is called *Renewable Energy Service Company (RESCO)* and owns the solar panels, batteries and controllers up to the circuit breaker, while the households privately own the lights, switches and cables and are responsible for the maintenance from the circuit breaker to the load (see Figure 6.6). In this way, the systems are entirely accessible by the island technicians, since the panels, controllers and batteries are safely installed outside of the house so that maintenance of PV components can be provided at any time. The *RESCO* management committees are registered under the *Incorporated Society Act* and represent the governance body of PV electrification in the outer islands. The primary function of the RESCOs management committees is to liaise between the users and the DoE, which involves appointing island technicians for each RESCO and reporting to the DoE on any malfunctions in the systems. The RESCO's island technicians are responsible for collecting monthly payments, stocking spare parts, doing essential maintenance on the systems, and reporting to the committee on the status of the systems. Technicians are paid monthly from the collected revenue through user installation fees and monthly fees (MEIDECC 2015; Weir 2018). The RESCO model is the applied maintenance concept of the OIREP programme, further described in chapter 7.2.

There are currently five islands participating under the RESCO programme in Tonga: the Ha'apai Outer Islands Solar Electricity Society, Vava'u Outer Islands Solar Electricity Society, Niuatoputapu Outer Islands Solar Electricity Society, Niuafo'ou Outer Islands Solar Electricity Society and Tongatapu Outer Islands Solar Electricity Society. The process for households to become a RESCO member and get access to SHS is simple in theory:

1. Consumers apply to local RESCO to be provided with solar electricity.
2. Consumers pay an installation fee of TOP 200 (86,5 USD)
3. Monthly fee of TOP 13 (5,5 USD)

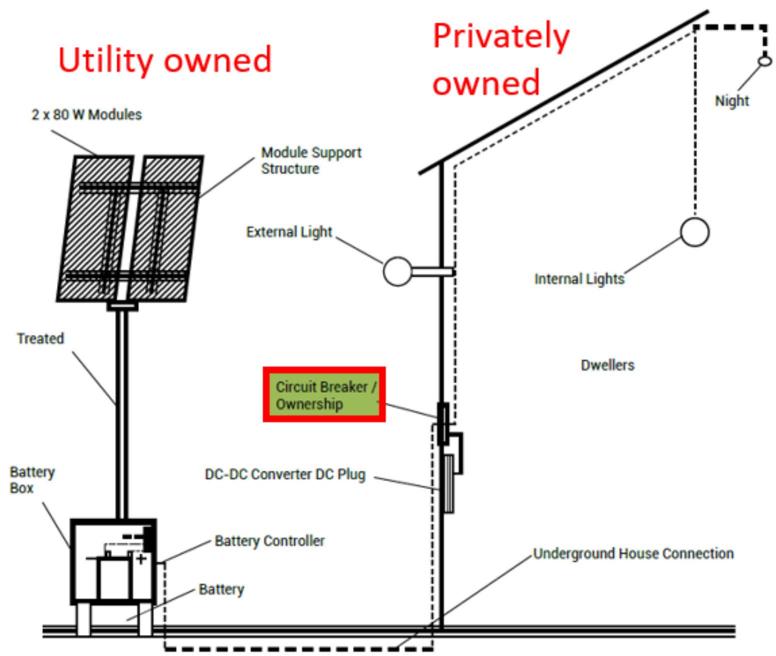

Figure 6.6: Schematic Layout of Standard Solar Home System, circuit breaker (green) is boundary of ownership, source (MEIDECC 2015)

6.5 Independent Power Producer Regulations

The Independent Power Producer (IPP) is a third-party entity that is not publicly owned and contains facilities to generate electricity and sell it to the public utilities and end consumer. IPPs can be privately owned or belong to a corporation or cooperative (Kashi 2014). The price of the sold electricity is based on a Power Purchase Agreement (PPA). The PPA is a long-term contract between the electricity generator and the electricity purchaser and defines all the commercial terms for selling electricity between the two parties. According to Thumann and Woodroof (2009), over two-thirds of all commercial solar projects are financed using this structure. In practice, this means the government of Tonga allows third parties, e.g. foreign firms or local institutions, to enter the electricity generation sector and sell their electricity to the public grid of the energy provider TPL, which is also to be considered as partial privatisation of the energy sector (Bayliss and Hall 2000; Thumann and Woodroof 2009, p. 93). The third-party entity provides the capital to build, operate and maintain the solar system according to the contract period, mostly between 15 to 20 years. It allows the customers to preserve their capital budget on the core business and still benefit from lower electricity costs than conventionally generated electricity (Thumann and Woodroof 2009). Hence, the customer TPL is only responsible for purchasing the electricity produced instead of investing upfront into a large upfront capital consuming RE installation.

Looking at the future of Tonga's RE targets, it is evident that IPP projects are the next strategic step for the GoT to expand its RE share. The planned 6 MW solar PV plant, the largest in the south pacific, is currently under construction in Tonga and was developed through an IPP contract between Tonga and the New Zealand company *Sunergise*. Furthermore, in 2019 the GoT published a tender request for a 3,8 MW Wind Farm IPP (TPL 2019a). Tender means the invitation of governments, companies or financial institutions to offer bids on larger scale projects. By applying a Tender Process, TPL can choose between offers of different companies and select the one that best fits their expectations (ADB 2019a).

The IPP concept is not only applicable to large scale solar systems. Any individual utilising solar systems can be considered a mini IPP or Small Distributed Generation (SDG). In the case of Tonga, the individual has to enter a contract with TPL and needs to install the solar system according to TPL's metering policy to acquire permission to feed the generated electricity into the grid. TPL institutionalised a *Gross Metering Policy* and developed a guideline to ensure a secure connection to the grid (TPL 2019c). Figure 6.7 explains the step by step guideline for an SDG to connect to the grid. The process follows eight steps, while step 2 to 5 are significant from an SDG perspective. It is decisive for the successful project implementation to fulfil the *operation and equipment standards* according to TPL's requirements.

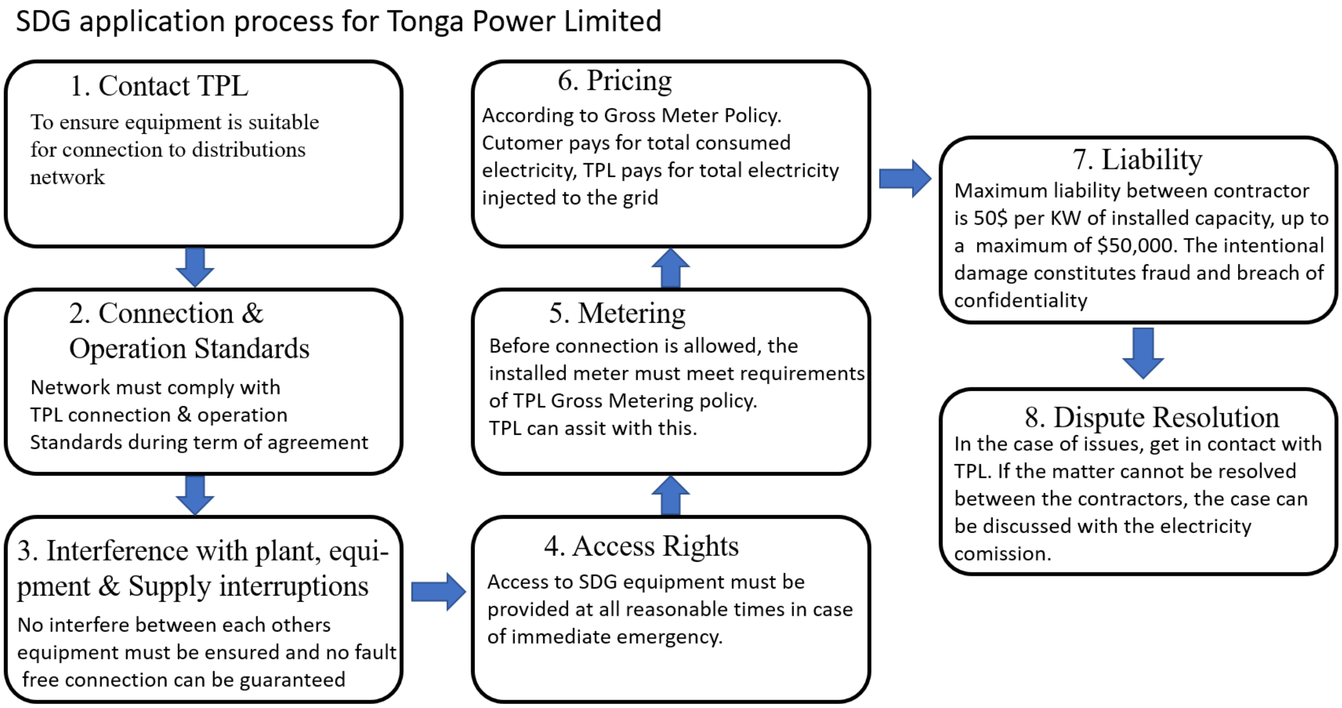

Figure 6.7: Process for SDG application on cooperation with Tonga Power Limited, own representation based on (TPL 2019c)

6.6 Metering Policy

The currently applied *Gross Metering Policy* is an arrangement in which the third party electricity provider has to feed in the total number of generated energy units to the grid accounted by an unidirectional 'gross meter'. The SDG is compensated at a fixed feed-in tariff according to the PPA and has to pay the electricity distribution company at retail supply tariff for the total electricity consumed from the grid. The feed-in-tariff is typically at a lower rate than the retail supply tariff (CEEW 2019).

Currently, the consumer price of TPL for 1 kWh of electricity is 0,81 TOP/kWh while the feed-in tariff for which TPL buys 1 kWh is 0,34 TOP/kWh (0,15 USD/kWh), resulting in a gross feed-in ratio in comparison with power supply cost of *(34/81)*100 = 42%*. A consumer needs to sell 2,38 kWh of electricity to compensate for the consumption of 1 kWh from TPL, according to the calculation of Table 6.2 (TPL 2018a).

TPL tariff	0,81	Pangi/ kWh
TPL Feed in	0,34	Pangi/ kWh
TPL tariff/TPL Feed in	2,382352941	kWh ratio

Table 6.2: Calculation of ratio between TPL tariff and TPL feed-in tariff, source (own representation)

7. Renewable Energy Strategies

7.1 Tonga Energy Road Map

"Reducing Tonga's vulnerability to oil price shocks, and achieve an increase in quality access to modern energy services in an environmentally sustainable manner" official mission statement of TERM, (GoT 2010b, p. 11)

In 2009 the Government of Tonga (GoT) developed the first national energy policy to respond to the twin challenges of global Greenhouse Gas emission (GHG) reduction and the countries energy security, the Tonga Energy Road Map 2010-2020 (TERM). TERM is the response to the global oil price shocks in 2008, which significantly affected the Pacific region. The planning and implementation of the "TERM" energy policy strategy has been substantially developed by the GoT, the national energy provider TPL, and development partners. Especially the financial and technical support by development partners International Renewable Energy Agency (IRENA), Australian Aid, New Zealand Aid, Asian Development Bank and World Bank enabled the realisation of the national energy guideline (GoT 2010b). The GoT developed TERM as a proposal to donors to map out the future of energy use in the country. Tonga developed the ten-year plan as a result of an intensive dialogue between development partners and the GoT. The discussions with the development partners were led by the World Bank, which forwarded inputs from many organisations, including all the *Pacific Region Infrastructure Facility (PRIF)*[2] development partners (TERM-IU 2015; UN 2019).

The TERM has the intention to create a guiding policy framework to mark a shift from conventional diesel-driven energy generation to RE based energy production. The document is designed as a guideline for the government action and development partner support to reach the target of 50% electricity generation through RE resources by 2020, which recently was increased to 70% by 2030. At the state of research, the target of 50% is expected to be reached in 2021. The overall goal of TERM is to layout a least-cost approach and implementation plan to reduce Tonga's dependency on fossil fuels by focusing on; energy efficiency, improved supply chains to mitigate the effect of price fluctuations in imported products, improved national energy security, reduced GHG emissions and access to modern energy services in a financial and environmentally sustainable manner (TERM-IU 2015; GoT 2010b). Within this research, the focus is set exclusively on the last target, *access to modern energy services*. It needs to be noted that the transport sector, which is responsible for two-thirds of Tonga's petroleum consumption, is

[2] PRIF supports infrastructure development and maintenance in twelve Pacific Island Countries (PICs) through providing a framework for better engagement of countries and development partners to ensure more effective use of available funding and deliver better infrastructure services (UN 2019.

not included in the TERM. The given reason is that currently, there are no RE alternatives to fossil fuels in this sector at a large scale (Yamaguchi 2019; Lucas et al. 2017; GoT 2010b).

The road map's first version of 2010 aims to meet its objective in three strategic phases. *Phase 1* defines the most urgent steps that need to be undertaken, including policy, institutional, legal, regulatory, capacity strengthening and data gathering actions. *Phase 2*, which can proceed parallel with *phase 1*, includes work designed to implement the first set of RE projects for the On-Grid electricity supply. The defined approach to move towards the overall set energy goals is formulated as followed: *"The recommended approach is to design a system with both centralized and distributed components and a Proof-of-Concept PV system with battery storage on one of the smaller grids"* (GoT 2010b, p. 14). *Phase 3* aims to achieve the private sector participation to generate sustainable investments and lead to full-scale development of RE projects on an IPP basis.

The actual implementation of TERM is characterised by many difficulties and delays (TERM-IU 2015). The framework has continuously developed throughout the last ten years and reached the end of its timeframe without fulfilling its primary target. An updated version of the 3 phases of TERM according to the TPL annual report of 2018 is presented in Figure 7.1. As it can be seen, the two major programmes in order to expand the share of RE in the energy sector are the *Outer Island Renewable Energy Project* (OIREP) in phase 1 and *Tonga Renewable Energy Project* (TREP) in phase 3.

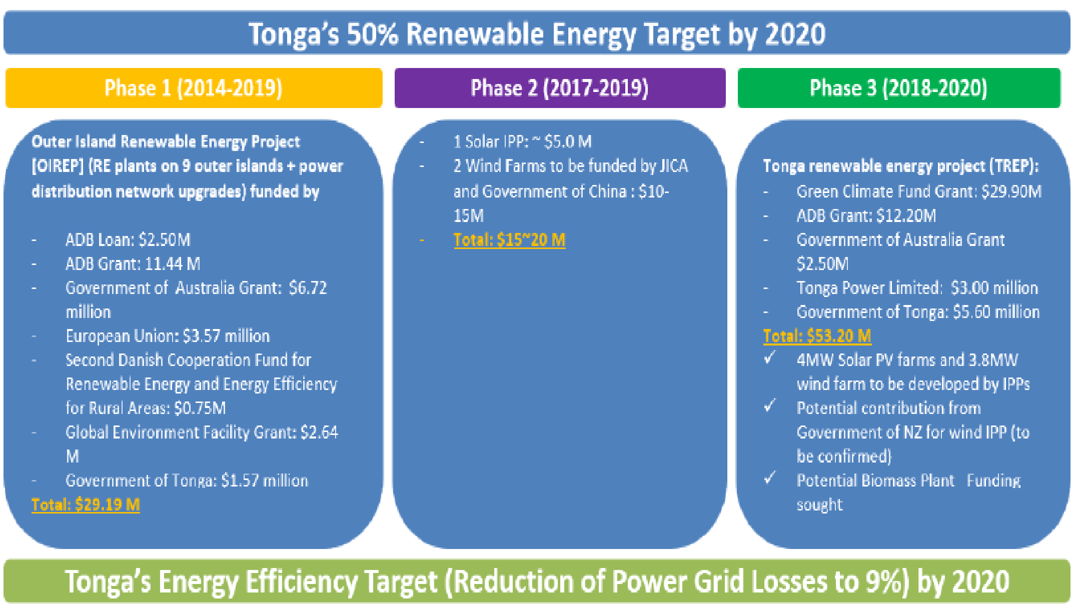

Figure 7.1: TERM phases to reach a 50% RE generation, including donor participation(TPL 2018b)

OIREP focuses primarily on the remote islands of Tonga and, therefore, is supervised by the DoE, while TREP focuses on the four national grids and is co-supervised by TPL. Both programmes are executed through the financial support of development funds by the Global Green Climate Fund (GCF) and Asian Development Bank (ADB). Besides, projects included in TERM to reach Tonga's energy targets are the Climate Technology Centre and Network Project, Pacific Appliance Labelling and Standard, Tonga Village Network Upgrade Project and the Pacific Centre of Renewable Energy and Energy Efficiency (PCREEE) (GoT 2019). The total expenses for the projects' execution amount to approximately 102 million USD, which is provided through a variety of donors, including the Asian Development Bank, Green Climate Fund, Japan Aid, MFAT and partly by the GoT.

A total capacity of 13,5 MWp of solar PV and 7,4 MW of wind turbines and a reduction in line losses of 9% is needed to meet the 50% RE generation target. As it is possible to see from Figure 7.2, Tonga still has to install 6 MWp of solar PV, 6,05 MW of wind turbines and 23 MWh of BESS. The funding is secured and the projects are about to be implemented. However, due to the delays, the finalisation of the TERM is expected to take until 2021 (TPL 2019a).

Figure 7.2: RE projects needed according to TERM to reach a 50% RE generation, Green thumbs indicated completion of the Project, source (TPL 2019a)

7.2 Outer Islands Renewable Energy Programme (OIREP)

OIREP targets the expansion of RE in the outer islands of Tonga, a group of 25 inhabited islands which are holding 4% of Tongas population and are scattered throughout the four primary main island groups, the island of Eua, Hapai, Vava'u and Niuatoputapu. The funding of 29 million US dollars is joint funded by the ADB, DFAT, European Union, Denmark and the Global Environmental Facility (see Figure 7.1). The overall objective of OIREP is to construct an approximate 1.32 MWp of solar PV power systems and

945 kWh of battery storage across nine outer islands of Tonga. Furthermore, the programme comprises the rehabilitation of the On-Grid network of Eua and Vava'u, including the laying of 189 km of conductor cables and replacing transformers and electrical equipment (MEIDECC 2015). The DoE of MEIDECC is the implementing arm of the OIREP programme and is responsible for identifying and coordinating donor funding for the programme, carrying out pre-installation surveys and user training, planning, designing, installing, monitoring project performance, and reporting to donors. As described in chapter 6.4, the outer island RE installation is maintained under the RESCO model. The engagement of the DoE in all outer island RESCOs serves as the main contribution of the Tongan government to the programme. The DoE also ensures that the contracts between the island RESCOs and the users comply and that the programmes' sustainability is guaranteed in terms of system maintenance. All installations included in OIREP were successfully executed at the beginning of 2020. However, several outer islands still lack an essential electricity supply (ADB 2018b).

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7.3 Tongan Renewable Energy Project (TREP)

TREP is part of the *Pacific Islands Renewable Energy Investment Programme* of the GCF and financed through the ADB. The programme's objective is to help seven pacific island nations in their transition towards a RE future and transform the electricity sector to low carbon and climate-resilient pathways. In October 2018 the GCF approved the financial support of 64,37 million USD, to assists the TREP programme in its mission to fill the gap of needed RE capacity for a 50% renewable electricity production. The GoT contributes 9 million USD and TPL 6,1 million USD to the TREP programme. The funding organisations describe the programme as a "response" to the Renewable Energy Act established by the GoT in 2008 (see chapter 7.4). The implementing agencies of TREP are the DoE as a part of MEIDECC

Sub-project no., location and technology	Generation capacity	Storage capacity	No. of beneficiaries
1. Tongatapu: 3 units of BESS	-	6.9MW/18.30MWh	Indirectly: 75,000 (all island)
2. Tongatapu: grid connected solar PV	4MW	1.4MW/0.7MWh	Indirectly: 75,000 (all island)
3. 'Eua: solar PV and BESS	0.4MW	0.5kWh	Indirectly: 5,000 (all island)
4. Vava'u: solar PV BESS	0.5MW	1.1MW/1.5MWh	Indirectly: approx. 10,000 (all island)
5. Tongatapu: grid connected wind farm	5.3 MW	1.8MW/0.9MWh	Indirectly: 75,000 (all island)
6. 4 outer islands (Nomuka, Ha'afeva, Uiha and Ha'ano): solar mini-grid and BESS	0.32MW	1.68MWh	1-2,000
7. Niuafo'ou: solar mini-grid and BESS	0.122MW	0.52MWh	650
8. Capacity building	n/a	n/a	n/a

Figure 7.3: Tongan Renewable Energies Project composition in the different locations, source (ADB and GCF 2017).

and TPL. The programme's target is to lead to a tipping point, after which RE become a more default investment for the private and public sector. As a part of TREP, seven outer islands that are not included in OIREP will receive RE technologies investments. The programme represents phase 3, the last phase of the TERM approach (ADB and GCF 2017). Figure 7.3 displays its exact project composition.
TREP targets to achieve the following four outputs:

- Output 1: Multiple units of BESS systems will be installed to provide storage capacity for the existing and upcoming RE systems through IPP agreements.
- Output 2: Installation of grid-connected solar PV on the islands Eua and Vava'u coupled with small BESS systems.
- Output 3: Installation of RE based hybrid systems and mini-grids coupled with small scale BESS in five outer islands.
- Output 4: Capacity building for the implementing agencies MEIDECC and TPL to manage the assets, undertake O&M, improve community engagement, support the project management, and supervise the procurement and construction. TPL requires expertise to manage the more complex mixed power generation system for Tongatapu as outlined in the TERM. Having a high renewable energy penetration requires a multi-level control strategy to maintain power stability and quality, whilst achieving economic and environmental objectives.

In total TREP will lead to approximately 10.65 MW of installed RE capacity and almost 28 MWh of BESS capacity, which will consume 23 hectares of land. This capacity should lead to fossil fuel savings of 7,027 million litres per year equivalent to a CO_2 reduction of 19030 tons per year with an expected lifespan of 25 years. According to the electricity act of 2007, all plant and machinery required for setting up public

Figure 7.4: Overview of TREP final RE & BESS implementation locations in Tongatapu, source (Akuo 2019).

power plants in Tonga are exempt from taxes and duties. Therefore, the ADB financed projects in Tonga do not include any taxes. Figure 7.4 displays the final locations of the RE technologies that are implemented throughout TREP, while the marked red areas show the currently unfinished installations (TPL and MEIDECC 2019).

7.4 Legislation Background of Tongan Electricity Sector

Before the creation of the TERM, the institutional responsibility for the energy sector in Tonga was extremely fragmented. There was no GoT entity existing with the mandate and capacity to maintain a strategic overview of the electricity and petroleum sub-sector. The results were inefficient and diverse regulations of the electricity sector by the parliament. In 2012 the cabinet approved the creation of the TERM-Agency (TERM-A) to provide policy and planning advice to the government as well as monitoring and reporting on the energy sector. TERM-A is a government agency accountable directly to Cabinet and responsible for achieving the objectives of TERM. Within TERM-A, the GoT created a policy advisory body by establishing the TERM Implementation Unit (TERM-IU). The TERM-IU plays a critical role in the coordination and technical advice and is the focal point for all Development Partners on behalf of the Government. The TERM-IU is headed by a director that reports directly to the TERM Committee (TERM-C). TERM-C's role is to oversee and govern the planning and implementation process of the Road Map. TERM-C is chaired by the Office of the Prime Minister and includes all Chief Executive Officers (CEOs) of GoT agencies that are relevant to the TERM, including; Ministry of Finance and National Planning, Ministry of Labour, Commerce and Industry, Ministry of Environment and Climate Change, Ministry of Public Enterprises, Ministry of Infrastructure, Ministry of Foreign Affairs, Crown Law Office and Public Service Commission. In July 2014, the GoT established the DoE to become part of a more comprehensive ministry under the leadership of the Prime Minister and fulfil the tasks of collecting, analysing, and disseminating energy data required for identification and monitoring of demand-side efficiency improvements, and implementing national energy efficiency programmes and public awareness campaigns with a focus on the outer islands (IRENA 2015; TERM-IU 2015).

The development of TERM displays a crucial starting point for the transformation of the national energy sector. The institutional changes were accompanied by various policies and initiatives that have been implemented besides the creation of TERM and impact the energy sector development. In 2007 the *Electricity Act* was established, under which the Electricity Commission (EC) was founded, and the former privately-owned energy provider *Tonga Electric Power Board (TEPB)* was transformed into the governmental owned *Tonga Power Limited (TPL)* in 2008. Under the Electricity Act, the EC aims to reflect the best international practice for public utility regulation and balance consumers' interests regarding fair tariffs and the receipt of high-quality power against private investors' need to minimise their risks regarding adequate returns on their investment. The EC is legally required to regulate tariffs, consumer service standards and electrical safety (GoT 2010b; IRENA 2015). In 2008 the *Renewable Energy Act* was established to provide a legal framework to promote the utilisation of renewable energy in Tonga by creating a conducive and enabling market environment. A *Renewable Energy Authority* was created to deal with matters concerning renewable energy. Also, a distinction is made between electricity that comes under the Renewable Energy Authority and electricity subjected to the Electricity Commission's authority, according to the *Electricity Act 2007*. The Renewable Energy Authority is responsible for all RE, including electricity in the *direct current* form, which is the case for RE technologies. When electricity is converted to *alternate current*, it then becomes subject to the Electricity Commission. These legislation frameworks paved the way for the development of the TERM (GoT 2008; TPL and MEIDECC 2019).

7.5 Role of Development Aid

Development aid displays a central role in the development of Tonga, especially for the energy sector. According to a case study made by the GoT (2015) about the outer islands' energy development, the early influence of aid-based solar PV projects was decisive, particularly because they provide substantial proof of concept examples in markets technologies are still novel. The installations' multi-year performance has strengthened the utilities and governments' confidence about their ability to rely on solar as a power source. This demonstration could also reassure investors and financiers that the Pacific energy sector is a market with a strong future (MEIDECC 2015; IRENA and PCREEE 2018).

RE technologies typically require high upfront capital, which cannot be provided by the GoT and private households and therefore, they depend on external funding and aid (Betzold 2016). Since 1972, Tonga is successfully attracting donor-financed projects on solar electrification. Grant funding has provided approximately 1,5 billion USD for RE's deployment in the Pacific Small Island Development States (SIDS) until 2017. Making Tonga being ranked on the third place of the PICTs receiving financial aid for energy sector development (Keeley 2017). The most crucial development actors in Tonga are the Asian Development Bank (ADB) and the World Bank. Besides them, there are multiple other institutions providing development services in Tonga, such as; South Pacific Community (SPC), United Nations Educational Scientific and Cultural Organization (UNESCO), Japan International Cooperation Agency (JICA), United Nations Development Programme (UNDP), Green Climate Fund (GCF) as a part of the United Nations Framework of Climate Change (UNFCCC), New Zealand Ministry of Foreign Affairs and Trade (MFAT) and Australian Department of Foreign Affairs and Trade (DFAT) (SPC n.d; UNESCO 2020; JICA 2020; DFAT 2020b; UNDP 2020; Green Climate Fund 2019; MFAT 2020).

The ADB has the most extensive energy portfolio amongst development partners in the Pacific, covering electricity generation, transmission, and distribution. Currently, the regional energy portfolio consists of 14 projects in 8 countries for a total investment of over 1 billion USD until 2021 (Martín 2019; ADB 2018a). The ADB began working with Tonga in 1972 and has since committed 70,2 million USD in loans, 207,9 million USD in grants, and 23,3 million USD in technical assistance. In the PICTs international development partners prioritise the investments in the energy infrastructure and innovations. For instance, the share of ADB investments that flow into the energy sector is equivalent to one-third of the total grant and technical assistance commitments. As part of this investment, activities continue to provide energy sector reform and capacity building to enhance the market conditions to increase private sector participation. Independent private sector investment cannot be established in isolation and a relatively immature market for renewables (Michalena and Hills 2018; ADB 2020).

The World Bank holds the second-largest share of financial support in Tonga. Since Tonga joined the World Bank in 1985, the World Bank has provided 233,82 million USD in financing comprised of 55 million USD in International Development Association credits and 178,8 million USD in grants. The World Bank has also significantly scaled up its financial and technical support to Tonga. In 2019, the World Bank supported seven active projects in Tonga with 129,17 million USD in commitments (World Bank 2019a).

The promotion of renewable energy for the PICTS has been motivated by several factors. A desire to lessen dependence on fossil fuels, attract development assistance in the energy sector and strengthen SIDS position in climate change negotiations. The official RE target and prioritization in energy policies indicate to donor agencies that their support for RE's deployment is in line with Tonga's development plan. More than half of SIDS have established higher targets than 40% RE generation, including 14 of 15 Pacific SIDS. Additionally, SIDS have a prominent international platform in climate change negotiations, and while their GHG emissions share is negligible, by setting ambitious RE targets, they highlight the urgency for action. This is acknowledged in their special treatment by successive IPCC reports and the establishment of unique funding streams dedicated to SIDS such as the Green Climate Fund (Dornan and Shah 2016).

In 2016 the Pacific Centre for Renewable Energy and Energy Efficiency (PCREEE) was founded in Tonga, as a part of the SDG-7[3] and in cooperation with the European Union, to work on common sustainable energy solutions for the SIDS in the pacific region (PCREEE 2016). The PCREEE was established by "*The United Nation Industrial Development Organization"* (UNIDO) and belongs to the "Global Network of Regional Sustainable Energy Centres" programme, which in total includes seven renewable energy centres around the globe. It aims to accelerate the moderate growth rates of "*Sustainable*

[3] Sustainable Development Goal 7 "Ensure access to affordable, reliable, sustainable and modern energy for all " (UN 2016.)

Energy and Climate Technology" on a regional base and represents an essential player in renewable energy development for the whole pacific. Therefore the PCREEE acts on an international level superordinate to only national affairs (GNSEC 2018). Also, it has a strong focus on supporting and promoting activities with high relevance of the domestic private renewable energy sector and industry, including the promotion of sustainable energy solutions and technologies to enhance the productivity and competitiveness of Tonga's industries with high value and job creation potential for example in the sectors of agriculture, tourism, fishery, manufacturing and the creative industry, as well as domestic sustainable energy entrepreneurship, industrial development and innovation (PCREEE 2017).

8 Technical and Economic Potential of Solar Energy

A large part of Tonga's import expenditures is made to ensure the energy supply in the country. Through the application of RE technology, the energy provider TPL expects to reduce the energy tariff in the next years (Fonua 8/15/2019). A key benefit is a separation from fossil fuel fluctuations, creating a more stable energy tariff and enabling the Tongan people to plan their financials according to the fixed tariffs. This renders RE technologies not only environmentally attractive, but their economic and socio-political impact is considered the main benefit. However, the country's current situation indicates that the private sector is almost not included in the RE developments.

The question deriving from looking into high electricity tariffs and the comparable low PPA tariff is: How economically beneficial and technically feasible is the investment into solar energy in Tonga? This question will be elaborated in two case studies in chapter 8.3, in which the technical and economic parameters will be analysed, and based on the outcomes, predictions for potential new stakeholders can be made.

8.1 Tongan Private Sector

The New Zealand Ministry of Foreign Affairs & Trade (2016) estimates the possible RE capacity of the Tongan private sector to be 11 MW, which could be provided as IPPs. An installed capacity of this size would contribute to between 15% to 18% of Tonga's total energy demand. Currently, all small-scale solar PV systems together contribute 0,79% in total. In fact, there are no possibilities to purchase RE technologies for the private use in Tonga and with a total solar PV capacity of 483 kWp solar systems are distributed rarely among the private sector stakeholders (TPL 2019a; New Zealand Ministry of Foreign

Affairs & Trade 2016). In 2009, the Pacific Islands Forum leaders highlighted at the *Cairns Compact2*[4] conference that broadly based private sector led growth is essential to achieve faster RE development progress and donors and governments should encourage the private sector, including micro-finance and support for larger-scale private sector projects. The high electricity tariffs in the regions, coupled with the sustained decrease in RE technologies' cost, create the expectation that the private sector could play a leading role in RE hardware deployment if the necessary infrastructure were previously put in place (MEIDECC 2015). To date, the private sector has not participated effectively in the provision, operation and maintenance of RE and almost no political will is evident in Tonga to incentivise the private sector of Tonga in its RE development. The prevailing barriers to RE development for Tonga and the Pacific Island Nations in general, are evaluated in chapter 10.

Throughout the field study, the private sector was identified as a pivotal contributor to RE's expansion in the future. Especially educational and religious institutions, hotels and hardware stores have stable and cyclone proof roofs and therefore display a significant target group for applying solar PV technologies in the country. For this reason, a questionnaire was applied among the hotel-industry. In general, this industry is characterised by high energy consumption, financial resources and partial isolation on segregated islands. The questionnaire intends to collect primary data and feedback about the general awareness of REs, the willingness for its usage or investment, possible obstacles for its implementation and to determine the already existing PV-system installations.

8.2 Survey on the Tongan Private Sector

The questionnaire was applied among private sector stakeholders of the tourism hotel industry between July 2018 and August 2018, including four hotels and one coffee shop (see Figure 8.1). These institutions were visited or contacted through email to create a dialogue about the local experiences with RE and public authorities. The questionnaire is divided into three sections (see Appendix 10). Section A aims to understand the institution's relation to solar energy and to receive general feedback on their experiences on this topic. Section B aims for the technical background needed to evaluate the solar potential for the institution. Section C is interested in information from those institutions that have already installed solar PV. All surveyed institutions are located on the island group of Vava'u. Besides TPL's primary grid in Tongatapu, Vava'u displays the second-largest grid in Tonga. Therefore, it is necessary to limit the survey results on the electricity sector of Vava'u, which might look different for other areas in the country.

[4] Cairns Compact Forum targest the Strengthening Development Coordination of the Pacific Island Nations (UN 2014.

The chosen form of evaluation is qualitative, which enables the integration of individual feedbacks. The small number of questionnaires does not allow empirical statements to be made. In the whole country's context, the questionnaire has little meaning due to a small number of interview partners. However, an impression of the private tourism sector can be gained and first conclusions can be drawn. At this point, further research is needed to develop concrete solutions.

The primary outcomes of the questionnaire are summarized in Table 8.1. The questionnaire shows that especially in the TPL grid of Vava'u, there is a substantial lack of communication leading to barriers from public authorities. All stakeholders connected to the national grid, three of the five surveyed institutions, mentioned complaints about obstacles in the application process for private solar rooftop systems. *Café Tropicana* and *Whale Waters Retreat* noted problems with TPL for installing the smart meters, which are necessary for feeding-in the electricity into the grid. There is no clear evidence for the reasons. According to the TPL website, there should be no differences between the feed-in regulations of the different island grids (TPL 2019c). One anticipated reason could be the missing BESS storage in Vava'u, which could affect the grid stability due to the intermittent RE fluctuations. However, the cooperation with TPL in Vava'u was strongly criticised in the personal feedback. A second outcome of the research was that all interviewed institutions are interested in solar energy, which indicates that the awareness about the solar PV potential is already existent. The *Café Tropicana* is the only grid-connected entity which already applied a solar rooftop system, while the *Mandala Resort* and *Mounu Island Resort* use solar PV in their private Off-Grid hybrid systems. Both Off-Grid remote resorts indicated that solar PV leads to significant energy cost reduction, due to the reduced diesel fuel purchases for the back-up diesel generators. All three solar PV equipped institutions indicated that the purchase, import and installation of the solar systems had been managed by the owners, due to the lack of a RE technologies market in Tonga. Furthermore, all three institutions criticized the import tax regulations for private RE systems. To sum up, for the grid-connected institutions such as *Café Tropicana*, *Hilltop Hotel* and *Whale Waters Retreat* the bureaucratic cooperation with TPL and the gross feed policy make the application of solar PV unattractive. The remote institutions benefit most of solar PV and also recommend this technology. Whale Waters retreat did not apply solar PV yet but tend to recommend this technology, while *Hilltop Hotel* and *Café Tropicana* do not recommend investing in such technologies under the current circumstances.

Questionnaire	Cafe tropicana	Hilltop Hotel	Whale Waters Retreat	Mandala Resort	Mounu Island Resort	total			
						YES	NO	YES	NO
already installed solar	Yes	No	No	Yes	Yes	3	2	60%	40%
are interested in solar	Yes	Yes	Yes	Yes	Yes	5	0	100%	0%
Own installation of Solarsystem	Yes	No	No	Yes	Yes	3	2	60%	40%
complaints about barriers for solar	Yes	Yes	Yes	No	No	3	2	60%	40%
connected to grid	Yes	Yes	Yes	No	No	3	2	60%	40%
off grid	No	No	No	Yes	Yes	3	2	60%	40%
recommend solar	No	No	Yes	Yes	Yes	2	3	40%	60%

Table 8.1: Outcomes of the questionnaire applied among electricity sector stakeholders in Vava'u, Tonga, own representation.

8.3 Case Studies

8.3.1 Longo Longo Police Station

The *Longo Longo Police Station* case study represents the largest existing third-party solar PV project in Tonga (see Figure 8.1. The police station was visited on the 13.08.2019 and displays a police Training College including large buildings, qualitative roof space and several land areas. The solar PV system capacity is 225 kWp and partly roof and ground-mounted and includes a battery system that is able to discharge 25 kW over six hours. The system was funded by the *Australian* and *New Zealand Governments* and is part of the *Tonga Police Development Program (TPDP)*. Under the TPDP another five police

Figure 8.1: Longo Longo police solar PV system, left: rooftop solar system on barracks, middle: battery and inverter container, right: ground mounted system behind the barracks. own representation

stations have been equipped with small scale solar PV rooftop systems with a total capacity of additional 45 kWp. All seven police stations are combined under the *Tongan Police Solar Sustainability Trust Fund* which targets to ensure the system maintenance through the generated revenues. The Longo Longo police station is an excellent example of solar PV's economic and technical benefits (TPDP 2016; Bardwell 2018).

Figure 8.2: Longo Longo Police Station solar PV system, source: google maps.

The system design uses the roof of the police barracks and the land area behind for the system. Besides, the battery storage container is adjacent to a bypass road, allowing convenient access for TPL to read the meters (see Figure 8.2). The ground-mounted system comprises of solar array frames connected to five tiers of above-ground concrete pads. A converted container is placed next to the ground-mounted solar array to house the batteries and inverters including a TPL metering box. The roof space of the barracks as well as of the battery container is wholly equipped with solar panels. The system's technical stability has been proven when the category four *cyclone Gita* hit Tonga in 2018, the entire solar array has survived unscathed (TPDP 2016; Bardwell 2018).

The 225 kWp system has an expected average daily output of 328,5 kWh. According to TPL's gross feed-in policy, the total amount of electricity is stored in the batteries and from there fed into the TPL grid. The electricity is compensated according to an individual PPA agreement based on a signed *Memorandum of Arrangement* (MOA) between TPL and Tonga police. During the daytime, the PPA tariff is 0,48 TOP/kWh and during the evening 0,679 TOP/kWh from 6.30 pm to 9.30 pm. This tariff is comparatively higher than the current official PPA tariff of 0,34 TOP/kWh, which results in higher revenues for the Tongan police station. On average, the police station generates a monthly income of 13,288 TOP which equates to an annual income of 159,458 TOP (equivalent to 69,567 USD) after off-take of the electricity costs (TPL and TPDP 2015).

The Tongan Police Sustainability Trust Fund represents a well-designed economic model to ensure the solar PV system's longevity. A set amount of annual revenues is reserved sufficient to meet the expected asset replacement terms as set out in Table 8.2. According to the Financial Management Proposal of the TPDP (2018), funds must first be applied for the following purposes:

- Annual maintenance costs of the solar systems, such as engagement of a contractor to oversee the maintenance of the system and arrange any necessary repairs or adjustments.

- Solar asset replacement, according to the *TPDP Solar Asset Register* and the *Asset Replacement Programme* at the following schedule (Bardwell 2018):

Period	Assets	USD	TOP approx
Every 7 years	Longo Longo system batteries	$106,142.00	$243,360.00
Every 10 years	frames, inverters, isolator, batteries, balance of system	$204,416.00	$468,660.00
Every 25 years	Solar modules	$208,820.00	$478,757.00

Table 8.2: TPDP Solar Asset Replacement Schedule for Longo Longo Police Station, source: (Bardwell 2018)

Any excess funds have to be authorized by the Police Commissioner and in accordance with TPDP Governance have to be allocated for other projects under the TPDP Annual Work Plan or supplement TPDP projects. At the same time, it is prohibited to reallocate generated funds from the solar system which have the purpose of solar asset replacement. These funds have to remain in the TPDP trust fund and need to be applied for asset replacement in accordance with the asset replacement schedule. Assuming a consistent average annual revenue, TPDP can anticipate a yearly income of excess funds of 58,707 TOP (25,590 USD) (Bardwell 2018; TPDP 2015). The annual replacement costs and excess funds are calculated according to the following depreciation.

Period	Depreciation	Result
7 Year	(TOP 243,360.00 ÷ 7)	**34,735.00**
10 Years	(TOP 468,660.00 ÷ 10)	**46,866.00**
25 Years	(TOP 478,757.00 ÷25)	**19,150.00**
Total per year		**100,751.00**
Annual revenue		**159,458.00**
Excess funds		**58,707.00**

Table 8.3: Calculation of annual depreciation of revenues for Longo Longo police station solar system maintenance. Source: own representation based on: (Bardwell 2018b)

8.3.2 TII and Wesleyan Church Solar PV Project

The Tupou Tertiary Institute college (TTI) case study represents a solar PV system which is under development in 2020. TTI is part of the “Free Wesleyan Church” educational institutions, the state church of Tonga and the largest Christian denomination in the country. The development of the TTI college PV solar project found its beginning throughout the field study for this thesis. Through the intense dialogue with the private sector about the potential of Solar PV, in this case with local education and religious institutions, the principal of TTI college showed strong interest in developing a solar system for the college. The TTI institute was visited several times between 16.08.20 and 22.08.20 to discuss the implementation plan with the college's principal Mrs Ungatea Kata. As a result of research for companies capable of developing a rooftop solar PV system, the Tongan companies *"Kingdom Energy"* and *"Solar Island Technology"* were commissioned to assess the college's solar potential. Both companies already worked together and implemented seven small scale solar roof systems in Tonga and therefore found to be compatible with the project's implementation. In a second step, the solar PV potential for another four educational institutions has been assessed, which are the *Tupou College*, *Queen Salote College, Tupou High School* and the *Sia'atoutai Theological College*. All five institutions are currently paying between 1,5 million to 2,0 million TOP annually to TPL for their electricity bill. The project's overall target is to reduce all educational institutions' electricity bills to lessen the dependency on donors and governmental subsidies for the school's educational infrastructure. The total targeted system size for all five institutions is 1,19 MWp of solar PV, representing the largest solar PV project under development through a local initiative. For the exact allocation of the institutions, see Appendix 7. However, this case scenario is explicitly analysing the solar PV potential for the TTI college case study (Solar Island Technology 2020).

Figure 8.3: Roofs of TTI college, determined for solar PV application, source (own representation)

The TTI college has three compatible roofs which offer sufficient roof space for a 90,64 kWp solar PV system. The system is designed for two roofs with the size of 27,2 kWp and one roof with 42,24 kWp (see Figure 8.3). According to *REID Technologies*, the company designing the system for *Small Island Technology*, has a calculated annual energy yield of 161,95 MWh at an average performance ratio of 85% (see Appendix 6). In 2018 TTI had an energy consumption of 73 MWh equivalent to the electricity bill of 59,259 TOP (26014,7 USD). Implementing the solar PV system will lead to average annual electricity sales of 50,207 TOP (22040 USD), which reduces the total electricity costs by 85%. The reduction is displayed in Figure 8.4. At the current stage of project development, the system costs are estimated to be 288,235 TOP (126535 USD) (estimation based on (Johnson 8/20/2019)). The system's payoff time is calculated with 5,7 years, not including costs for maintenance (economic calculations see Table 8.4).

The complete system design was made by New Zealand company *Reid Technologies* since there is no Tongan company compatible for this task. To gain a better understanding of the technical aspects of solar PV, see chapter 4.3. The applied products comprise the latest state of the art technology in the field of solar PV. In total, 156 solar panels will be mounted on the roofs. The applied modules are monocrystalline and supplied by the company *Trinasolar* and have an efficiency of 19,9% and a power output range of 320-340 Watt with the dimensions of 169x1004x35 mm (see Appendix 5). The applied railing system for the roof mounting is the *PV-ezRack Solar Roof* of the company *Clenergy*. Two inverters are applied from the company *SMA,* the *Sunny Tripower Core1 STP 50-40* and the *Sunny Tripower 20000TL / 25000TL* with an efficiency of 98,4%. For the overvoltage protection, the *TELE - RE NA003* device is used. The cabling between the panels and the inverters is applied from the company *Tricab* (Small Island Technologies 2019). *Small Island Technologies* carries out the bureaucratic SDG application process with TPL for feeding the generated electricity into the grid (compare chapter 6.5). As a guideline for interested stakeholders, the TTI application form is attached in Appendix 9.

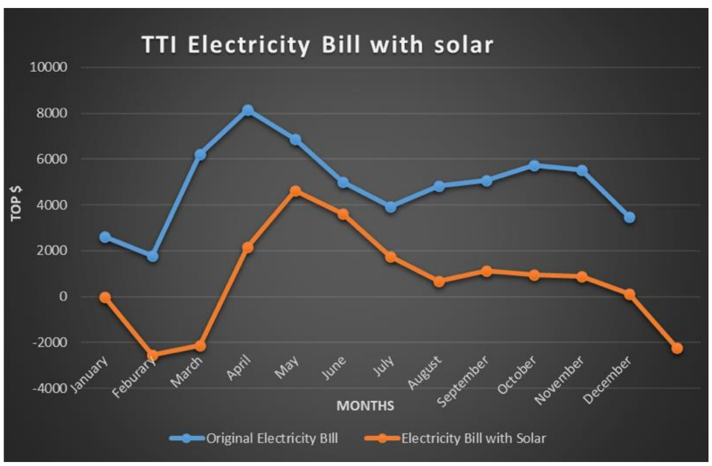

Figure 8.4: TTI annual electricity bill reduction with 90,64 kWp solar system (orange), own representation

Economical calculations for TTI solar PV system	
	TOP
Annual electricity costs	59259,93
Annual electricity sells	50207,8
Savings through solar in %	85%
Pay Off time of system	
system cost	288235,2
saving or cash inflow	50207,8
Formula	Payback Period = Initial Investment Or Original Cost of the Asset / Cash Inflows
Years	5,740845048

Table 8.4:Economical calculations for TTI solar PV system, own representation

Local educational institutions, such as colleges and universities, can play a significant role in helping the transition to RE by serving as a key institutional player with regards to the creation of a regional market for RE experts (Taibi et al. 2016). As the largest church in Tonga, the "Free Wesleyan Church" comprises several hundreds of religious and educational buildings, which can be considered the highest quality roofs amongst Tonga buildings. Therefore, the TTI college solar PV project could trigger further RE initiatives in the private sector.

8.4 Technical Potential of RE for Total Electricity Production

The following two case scenarios display a theoretical approach that does not consider the underlying economic conditions. Instead, the intention is to give a technical outlook on two possible scenarios for a maximum RE penetration in Tonga. Other Pacific Island nations like Niue, Cook Island and Tuvalu already work on achieving a 100% RE target (NDC 2019). Therefore, it can be assumed that this will also be a similar target for Tonga, after reaching 70% RE penetration in 2030. However, this case analyses a 99% RE generation approach, since diesel generators already exist and are needed as a back up to ensure a functioning grid on days with strong RE fluctuations.

Both given scenarios simplify the local conditions and assume the energy generation in Tonga as one interconnected network. Also, it is anticipated that constraints such as social, institutional or financial barriers are non-existent. The first scenario analyses the capacity of photovoltaic to substitute the diesel-generated electricity entirely. The second scenario models a wind and solar-based approach to ensure a maximum RE penetration for Tonga. The correspondence with Nikolasi Fonua, the Engineering Manager of the national energy provider TPL, was significant support for the comprehension of the energy situation in Tonga and obtaining the technical parameters to depict the second case scenario for a maximum electricity generation through wind and solar technologies. Through an internal request to Nikolasi Fonua (2020), the battery storage dimensions for both scenarios and the technical parameters for modelling the second scenario were given as followed: *“A fairly recent study indicates that in addition to our current committed projects an additional 29MWp of Solar PV, 90MWH of BESS and 10MW of wind would be required to achieve 99% Renewable Energies (Fonua 7/12/2020)”*. Currently, 28 MWh of BESS are commissioned (see chapter 7.3), applying an additional 90 MWh of BESS a total of 118 MWh BESS is required to ensure an energy supply at day and night.

1. Maximum electricity penetration with Solar PV

According to the TPL annual report (2018), the total electrical generation in 2017 was 57,9 GWh, which is equivalent to an average daily production of 158,63 MWh. The specific photovoltaic power output for Tonga is indicated with 1566 kWh/kWp per year (TPL 2018a). The calculation based on the average daily production data suggests that a solar system size of 37 MWp would be sufficient to produce the required daily electricity (Table 8.6). It is assumed that three modules (330-340 W per panel) with a space requirement of 1.7 m² each have to be used to reach one kWp of installed capacity (module types of the

TTI project, see data sheet Appendix 5). Hence, for the capacity of one kWp, an area of 5,1 m^2 is covered, which equals a surface of 188.547 m^2 to reach a total of 37 MWp.

Tonga 100% Solar	YEAR	DAY	
Solar Output	1566 kW/kWp	4,2 kW/kWp	
Energy generation TPL	57,9 GWh	158,63 MW	
Total solar needed	158,63 MW/4,2 Kw/kwp		36,97 MWp

Table 8.5: Solar capacity required to supply 100% RE, source: own representation.

Figure 8.6: Map of Nuku'alofa, showing the area needed for 99% RE solar generation. Source: Google maps, own representation.

Figure 8.5: Dimensions of Matatoa Solar Farm by Singyes ldt, 2 MWp. Source: Google maps.

Square 1 (Figure 8.6) displays the area of solar capacity calculated in Table 8.5. In reality, between the solar panels rows a particular space is required. Therefore, the area of *Square 1* is equivalent to one large solar panel.

Henceforth, in a second step, the Matatoa Solar Farm dimensions have been scaled up for the case of a 36,97 MWp solar system (Figure 8.5). The Matatoa Solar Farm is a 2 MWp IPP by the Chinese company *Singyes ldt* with a dimension of 23.180 m^2, located on Tongatapu. Implementing a large-scale solar system with the equivalent m^2/kWp output as it is the case for Matatoa, the required area is calculated with 428 517 m^2, displayed as *Square 2*. Increasing solar panel efficiencies are positively affecting the size of the necessary area. The Matatoa panels' output is 260 W, which leads to an increased surface of *Square 2* of 25% compared to a modern panel efficiency as in *Square 1*.

This theoretical approach intends to give an impression of the required solar system scales for a complete solar energy supply of the country's current energy demand. However, several reasons disagree with an energy supply only by photovoltaic. The entire electricity generation with solar PV leads to difficulties in the constant energy supply due to solar insulation fluctuations (GoT 2010b). Therefore, Tonga does pursue the strategy of applying a mixed approach of wind and solar energy.

2. Maximum electricity penetration through a combination of wind and solar

This more realistic approach is modelled based on data and calculations created with the *HOMER* software by the Tongan energy provider TPL. As the analyses indicate, the most effective approach is a wind and solar combination. According to Nikolasi Fonua, reaching a maximum RE generation case scenario needs a total installed capacity of 35,3 MWp solar PV and 16,6 MW of wind energy (Fonua 7/12/2020). The approach already takes rising electricity demand for five years in the future into consideration and therefore has a significantly larger total RE capacity than the first scenario.

Solar share: 35 MWp **Wind share: 16,6 MW** **Battery storage: 118 MWh**

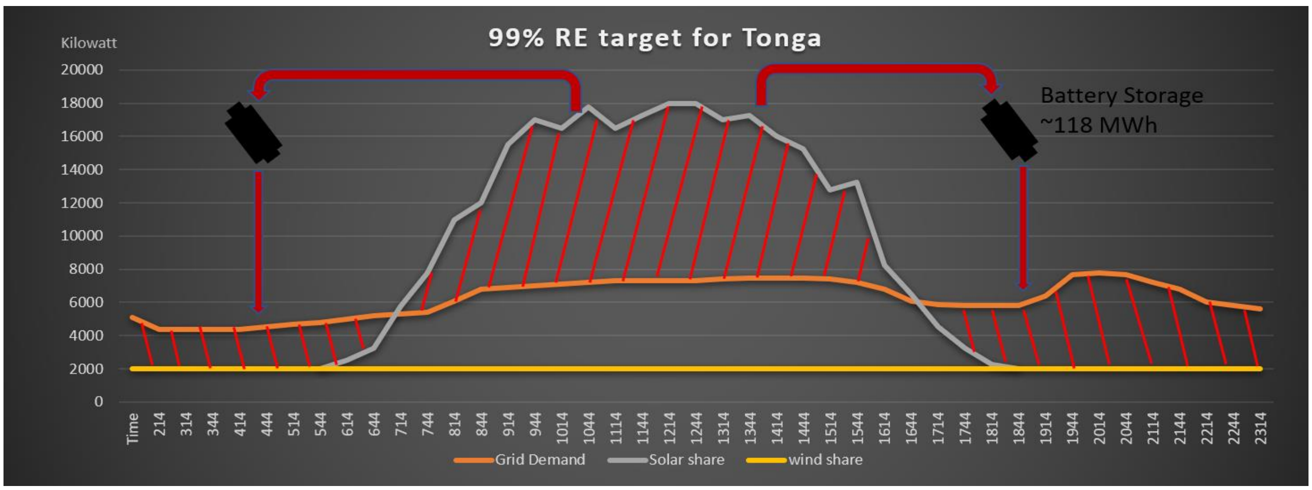

Figure 8.7: Case scenario of a complete RE energy supply of Tonga with wind and solar, source: own representation

The scenario model displayed (Figure 8.7) explains the principal of the complete RE energy production case and is based on following simplified assumptions:

- Steady winds (yellow). The average daily production of the 1,3 MW *JICA Wind Farm* (see chapter 6.3) has been taken and scaled up for a wind farm with 16,6 MW. Wind generation was calculated on an average value and assumed to be constant in order to simplify the graph.
- The load profile (orange) of an average weekday in February 2013 is applied, according to data of TPL (Fonua and Essau 2017).
- Solar production (grey) is based on the average daily output of the 1 MWp *Maama Mai* solar facility located in Tongatapu and scaled up according to a 35 MWp solar system (TPL 2017).

- Battery storage of 118 MWh is indicated as sufficient by TPL to ensure a load shift of RE for day and night time.

This case scenario is a futuristic approach at the current stage of Tonga's energy transition. The economic feasibility implementation is currently not yet given. Therefore, this theoretical approach intends to give an impression of how a 99% RE case might look like to stimulate policymakers. After successfully achieving the 70% target in 2030, Tonga could continue to implement such a goal. At this time, the technical situation on the RE market will most likely be a different one.

8.5 Potential of Floating Solar Technologies

Floating solar systems are an innovative solar technology, which could become of growing interest for small pacific island nations like Tonga. As land on remote tropical islands is scarce, the implementation of large-capacity photovoltaic systems displays a significantly growing problem. Floating solar technologies address this problem using the space on water, which is nearly unlimited (Sahu et al. 2016). The number of companies around the world developing this relatively new technology is increasing. Currently, the leading companies represented on the market are Ciel & Terre (France), Seaflex (Sweden), Sunfloat (Netherlands), Swimsol (Austria), Solaris Synergy (Israel) and REC Solar (Singapore), implementing solar systems in the range of several MWp. In 2017 Ciel & Terre accounted for 59,7% of all developed floating solar projects worldwide (Thi 2017).

Figure 8.9: Floating solar technology for inland, source: (FOEN 2020)

Figure 8.8: Floating Swimsol "Solar Sea" platform for the sea, on Dharavandhoo island, Maldives, source: (Swimsol 2016)

However, a distinction must be drawn between floating technologies for sweet water inland lakes and maritime conditions. Most companies are developing floating solar technologies conceptualized for inland lakes or lagoons characterised by low wave heights (See Figure 8.8). These systems do not need to resist substantial environmental impacts, which leads to a cost reduction for the floating body, mainly designed out of plastic components. A few companies have developed technologies for maritime environments as well. This technology differs significantly in the materials used for the floating structure (Sahu et al. 2016). The Austrian company Swimsol has been selected for a closer floating solar potential analysis due to existing platforms in the Maldives, an environment in theory comparable to Tonga.

Swimsol has developed the “SolarSea” series (Figure 8.9), a corrosion-resistant floating technology suitable for applications at and in the sea. The system is available in different sizes. The size currently used includes the dimensions 192 m^2, weighs 4,9 tons and carries 96 panels (260 W) with a total output of 25 kWp. The floating construction consists of aluminium profiles and stainless-steel nodes and the floats consist of a cylindrical body of expanded polystyrene, a polyethylene film and two aluminium plates for sealing. The ground anchoring is accomplished with a steel cable which consists of stainless steel/chrome-nickel. The “SolarSea” platforms are especially suitable for locations between islands or islands with an offshore reef, because they are protected from high waves and the water depth is shallow. The water depth and the type of seabed, in turn, are relevant for the type of mooring. According to marine biological observations in the Maldives, the platforms do not significantly impact the marine ecosystem. It has been observed that small fish increasingly use the shade below the platforms and corals cover the structure. Both aspects are seen as a positive effect from a marine biological point of view. The electromagnetic field of the power cable, which is conducted to land on the seabed, could affect larger fish and sharks in the immediate vicinity and lead to avoidance behaviour. According to expert opinions, the probability of sharks or other large fish in such a shallow lagoon area is considered very unlikely (Kriechhammer 2017).

Besides saving land, an additional benefit from using solar systems on the ocean surface is the water's natural cooling effect. It allows the PV panels to operate more efficiently and produce more output than traditional land-based systems. The efficiency of solar panels is drastically reduced with rising temperatures, which is indicated by the producers with the “Peak Power Temperature Coefficient“ (Sahu et al. 2016). The panels used for „SolarSea“ have a coefficient of -0,37% per degree Celsius, measured from a standard panel temperature of 20 degree Celsius. The “SolarSea” photovoltaic system on water has a maximum temperature difference of 18,5 degree Celsius compared to rooftop PV systems. As a result, the energy output of floating solar is 5-10% higher (Kriechhammer 2017).

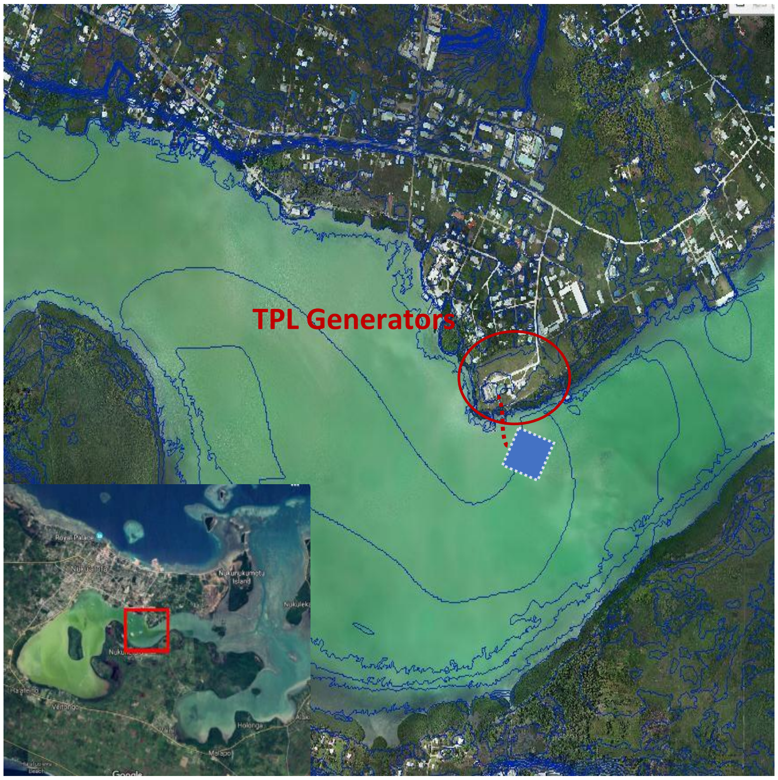

Figure 8.10: Potential location for Floating Solar in Tongatapu, Tonga, blue lines indicated areas with depth of 5 meters; own representation, source: (Ministry of Lands & Natural Resources 2019)

The location most appropriate for applying a floating solar system in Tong has been determined on the Fanga'uta Lagoon, Tongatapu island (Figure 8.11). The inland lagoon pervades Tongas's main island with a 12,3 km canal (see also Figure 3.1). Following criteria lead to the assumption that this location offers the highest potential for floating solar:

1. Tongatapu has the largest population with approximately 75 000 inhabitants, accounting for 85% of the entire Tongan electricity generation.
2. The suggested area is located next to the TPL generators, which provide the island grid with an installed generator capacity of 17,26 MW. The floating platforms' generated energy can be conveniently fed into the network at this point and support the island RE production. Also, the maintenance and operations of the platforms could be managed more comfortably by TPL.
3. According to the topographic map of the Ministry of Land (2019), the water depth around the area of interest (see Figure 8.11, blue platform) is between 5 to 10 meters, while the mean depth is indicated with 13 meters (Ministry of Lands & Natural Resources 2019). The operation depth range of the SolarSea is indicated with 1 to 60 meters. Previous installations of "SolarSea" in a depth of up to 10 meters have delivered good results in the Maldives.
4. Due to the lagoons' great length, the chosen location protects the solar system from waves and winds. According to a Hydrodynamic Model of the Fanga'uta lagoon conducted by *Pacific Island Applied Geoscience Comission* (2008), the annual mean wind speed is 4 m/s, tidal current regime 0,65 m/s and mean wave height 0,3m (Damlamian 2008).

The described local conditions let assume that the application of such a technology could have a great benefit. However, at the current development stage of the technology, the environmental conditions in Tonga are hard to withstand for the system. The *"SolarSea"* technology belongs to the most resistant systems on the market, developed for the maritime application with wave heights up to 2 m and wind speeds up to 120 km/h (Eierstock 2012). Due to the strong wind events in the annual cyclone seasons, their limit will be exceeded more than twice (See chapter 3.8). Nevertheless, it can be assumed that higher wind speeds can be withstood in the future due to further technical development, which could make this technology attractive to the island state in the future. Some of the smaller outer islands could also benefit from applying floating solar technologies for electricity production. Besides, the problematic landowner regulations could make this technology potentially even more attractive (see chapter3.3). Appendix 3 is listing three additional potential locations for floating solar systems on the outer islands.

9. Socio-Political and Economic Aspects of an Increase in RE

The Kingdom of Tonga is divided into four different island groups. Considering the socio-political and economic aspects, one must distinguish between the remote outer islands and the main island of Tongatapu. While the main island is supplied with electricity from a diesel-powered grid for more than 50 years, RE technologies represent the first and only feasible form of electrical energy supply for many outer islands. However, both of the aspects “development” and “independence from fossil fuels” are interrelated and impact the whole country. The research has shown that an increase in solar PV influences the three levels of sustainable development, the environmental, economic and social level, for the whole country (ADB and GCF 2017).

9.1 Development Aspects

The electrification of the outer islands with RE technologies displays an overall socio-political target of the GoT, leading to tremendous socio-economical aspects for the outer islands' inhabitants. RE technologies represent the only long-term feasible energy supply source on most outer islands and therefore have a significant development character. In the past 20 years, the government of Tonga has included electrification of the outer island as one of its key development priorities. Since the 1980s, when the first SHS were introduced at two remote islands, until now, were 90% of the outer island's households are supplied with solar PV technologies, a lot of development work was applied. These aid-based projects paved the way to providing proof of concept in regions where such technologies are still novel. The installations' multi-year performance positively impacted the confidence of the people, utilities, and the government about the reliability of solar as a power source for the future (IRENA and PCREEE 2018).

A case study analysis by the Tongan Government (2015) summarizes the observed socioeconomic impacts of the outer island electrification programmes. Based on these past experiences in Tonga, rural electrification is accompanied by a substantial increase in living quality. The significant benefits for the outer island population are the opportunity to have access to better lighting and electrical appliances such as mobile phones and sewing machines. For instance, handcraft manufacturing displays a substantial income opportunity for the people on the outer islands. Therefore, an improvement in income-generating activities due to the possibility of nightwork, especially for woman, is observed. Also, improved lighting leads to a rise in social activities such as community meetings and has an effect of mitigating conflicts. An improve in lighting also has a positive impact on education. It allows students to study at night times and enables the use of audio devices such as radios for classroom presentations. Additional new educational opportunities, such as evening adult classes become feasible. RE technologies also have environmental and health benefits for the people of the outer islands. For older people with visual problems, the much higher quality of lighting is expected to reduce accidents and increase their capacity to do tasks, which requires good visual acuity. Health aspects within households are impacted by reducing air pollution and lowering the risk of fire from kerosene lighting. For instance, the introduction of PV lighting on the remote islands of Vava'u has reduced kerosene consumption for lighting by about 70% (Outhred et al. 2004). Also, a reduction in firewood consumption is ensured, which leads to the preservation of the natural environment. One of the essential socio-political aspects is the interconnection of the outer islands with the outside world. Solar PV technologies ensure the telecommunication systems' energy supply on remote islands, enabling them to communicate and receive internet (MEIDECC 2015). The exact technologies applied to the remote islands are shown in chapter 6.1.

9.2 Independence from Fossil Fuels

Besides the tremendous benefit of RE technologies for the inhabitants of the outer islands, the currently largest share of political interest is set on the main islands Tongatapu, with its 75.000 inhabitants. The promotion of RE has been motivated by several factors: a desire to lessen dependence on fossil fuels, to attract development assistance in the energy sector, to increase economic activity within the country and to strengthen the position of SIDS in climate change negotiations (Dornan and Shah 2016). Climate change mitigation and the national target to become independent from fossil fuel electricity is a political key driver for acquiring development aid funds for Tonga. The international donors recognise the pacific island states' vulnerable role in the fight against climate change and support them in their mitigation and adaptation efforts. Therefore, prioritizing RE in energy policies and setting an official RE target constitutes an indication to donor agencies that their support for the deployment of RE in the country is in line with its development plan (Keeley 2017). As explained in chapter 7.5, the country is highly dependent on development aid for implementing its RE targets, which as well, represents a source of income for the country and has a significant economic impact. The expansion of RE technologies offers the most efficient option to reduce fossil fuel dependencies and electricity expenses, stabilising the energy tariffs by decoupling them from their correlation on volatile oil prices. Therefore, the increase of RE leads to numerous socio-economic aspects for all Tongan inhabitants. According to the governmental report *Tongan Renewable Energy Project (TREP)* (2017), various socio-economic aspects are expected through a further increase in RE technologies. An increase in national energy security will lead to reduced and stable electricity prices, ensuring income savings for all involved stakeholders connected to the national grid and further enabling entrepreneurial activities, including household income generation and small local businesses. Considering the high cost of electricity generation from imported diesel, and the fact that the retail tariffs often are subsidized and do not reflect the actual generation costs, power utilities could experience a net saving scenario if the share of renewables in the generation mix increases. Reduced expenditure on fuel imports will also reduce pressure on the national budget, due to the stabilization of net profits from TPL, which is releasing funds for other economic investments (ADB and GCF 2017). Energy is considered a significant factor for economic growth and a clear relationship between Gross Domestic Product (GDP) per capita and energy consumption is evident across pacific island nations like Tonga. Therefore an increase of the national GDP due to RE extension in the long term is anticipated (Cole and Banks 2017; Zafar et al. 2019).

10. Barriers and Solutions to RE Expansion

The Intergovernmental Panel on Climate Change (IPCC) defines a barrier for RE as: *"Any obstacle to developing and deploying a renewable energy potential that can be overcome or attenuated by a policy, programme or measure"* (Weir 2018, p. 7). The barriers to the development of RE in Tonga are identified on the three levels *1. Infrastructural and Technological, 2. Institutional and Political*, and *3.Social Behavioural.* These levels are described in the literature as typical *Lock-In's* for human development processes, hindering the transition from conventional paths to new paths. Therefore, a Lock-In is path-dependent, favouring the status quo and developing inertial resistance to large scale systematic shifts (Seto et al. 2016). The presented barriers in Tonga are divided according to this Lock-In framework. Each type of Lock-In has its own set of processes, which can be tightly intertwined and contribute to the inertia of RE technologies in Tonga. These barriers apply in general for many of the SIDS in the pacific; therefore, the following section addresses not only Tonga's case. A survey among the main stakeholders of the energy sectors in 11 Pacific SIDS was conducted by Lucas et al. (2017) to identify specific characteristics of these barriers and gather recommendations to overcome them. This survey will function as a guiding document for this section.

10.1 Infrastructural and Technological Lock-In

Lack of Skilled Human Resources

The importance of skilled human resources as a technological capacity is a crucial factor for a proper enabling environment in which RE can be developed. Two factors are decisive for the lack of human resources. Educational quality training on RE at the national level, from policymakers down to O&M training for technicians, is still scarce in the small island pacific states like Tonga. It seems to be a common reason for the lack of qualified energy professionals. Furthermore, especially the emigration of qualified engineers with technical expertise from government agencies and power utilities to higher paid jobs abroad or in the private sector leads to a significant lack of technological capacity. Consequently, the capacity of skilled human resources dedicated to REs in national institutions and maintenance tasks in the field is unavailable (Taibi et al. 2016; Lucas et al. 2017).

The respondents to the survey of Lucas et al. (2007) on this particular section pointed out that the most common technical skills missing in the private sector and public utilities are: drafting of feasibility studies, costing studies of viable RE technology; project planning and design; project development and installation of RE systems. The private sector actors further lack skills and knowledge to develop a business plan, design investments proposals, write funding proposals and understand different finance models, cost analyses, financing structures, and marketing skills to increase awareness among potential consumers about RE products and their benefits. Government and public institutions often lack skills on, project budget and finance management, raising awareness and public relations. Responsible government agencies do not have sufficient expertise and experience for the development of RE projects. This fact is often aggravated by the absence of capacity building initiatives within the public sector (Lucas et al. 2017).

Technical Barriers

RE sources, especially wind and solar, are inherently stochastic and unreliable power sources. The integration of such technologies into the national grids entails some technical difficulties. The increasing share of RE possibly impacts the efficiencies of the existing diesel generators as it is currently the case for Tonga. According to the survey of Lucas et al. (2017), representatives from the utilities highlighted the challenge of grid management when integrating large shares of variable renewable-based power into the existing electricity grid infrastructure, and the need to assess the impact of the efficiency of the existing fuel generation. Due to the irregularities in wind and sun, the generators run at sub-optimal capacities, negatively affecting the diesel consumption (Michalena and Hills 2018; Lucas et al. 2017). A technical solution to the obstacle of variability and randomness of weather-dependent RE utilization is the addition of more extensive battery storage technologies, as it is planned for the Tongan grid.

The knowledge of the local power utilities on understanding the following technical interrelationships is lacking; Grid stability concepts, storage technologies for solar and wind to ensure stable power, dynamic modelling of the power generation, transmission and distribution infrastructure, deferrable loads, advanced inverters, and eventually electricity of the other renewable energy resources. As a solution, further capacity building for the local power utilities is needed to ensure reliable operations (Lucas et al. 2017; Taibi et al. 2016). A lack of technical standards and regulations compromises the quality of the deployment of RE technologies for Pacific Island nations like Tonga. Limited adoption of internationally recognized standards and regulations contributed to failures in several RE projects in the history of the pacific island nations (Taibi et al. 2016).

Geographical and Environmental Barriers

The small size and geographical isolation display a limiting barrier for Tonga. Characteristics of the barriers entail limited economies of scale, reduced land area, high transportation cost, long distances on precarious ways and significant vulnerability to natural disasters and sea-level rise caused by global climate change. The large distances hinder equipment maintenance in case of failure, which ultimately increases the RE project's overall cost. Due to small economies of scale, remoteness, and climatologic and geographical conditions, infrastructure costs in small island states are likely to be higher. The lack of road transport infrastructure is an impediment to access project sites. Destructive tropical cyclones display a significant environmental hazard for RE systems, particularly wind turbines. Any device operating for a sustained period in the islands has to contend with corrosive warm, humid salty air (Weir 2018).

10.2 Institutional and Political Lock-Ins

National policies and regulatory frameworks have a clear positive or negative impact on the expansion of RE technologies in the private and public sector. Keely (2017) highlights that political aspects contribute the most to enhancing the RE enabling environment. Whereby complicated and inefficient institutional structures are a significant hindrance for introducing RE in SIDS like Tonga. Donors consider island states to lack skilled human resources and efficient energy institutions to implement RE projects (Keeley 2017). According to Lucas et al. (2017), the presence of well-designed incentives as a success factor for RE upscaling is wide and well understood (Lucas et al. 2017). In the case of Tonga, the national energy policy of “TERM” targets to transform the pathway of conventional diesel energy generation, but in its implementation mainly focuses the RE expansion on a public scale. There are no incentives for the growth of renewable energies in the private sector from Tonga's governmental side. Regulatory barriers for RE are evident in various areas such as in duties and taxes on imports, lack of financial assistance through funding, and bureaucratic hurdles for the private sector to connect RE technologies to the grid. According to the *Electricity Amendment Act 2010,* there is no tax exemption existing on the import of RE technologies if it is not performed by a concessionaire. Therefore, only public authorities like the national energy provider TPL are exempt from import taxes (GoT 2010a). At the time of research, there is no financial assistance available on a governmental level for private individuals who want to apply RE technologies, only two possible subsidies from external institutions are available. The local development aid branch of Australia DFAT (2020) runs the *direct aid programme* with the financial support of 8000 TOP for projects on a municipal basis, which could be used for RE projects (DFAT 2020a). The PCREEE offers the *Pacific Sustainable Energy Entrepreneurship Facility* grant as financial support for the private sector of SPC members to invest in RE technologies or Energy Efficiency. The grant is available for Small and Medium Businesses and NGOs and covers 25% of the project costs (PCREEE 2019).

The bureaucratic hurdle for the private sector to apply RE technologies and feeding into the national grid is strongly connected to the lack of information (Keeley 2017). At the time of research, TPL is not communicating the benefits and exact step by step processes to the people of Tonga, causing a significant lack of awareness. The process of becoming a third-party energy producer described in chapter 6.5, was only received on a direct request from TPL. The consumers connected to the three smaller TPL grids (Ha'apai, Eua, Vava'u) face even more considerable bureaucratic difficulties when trying to feed into the grid, as it could be seen throughout the interviews.

As described in chapter 8.2, a questionnaire was given to five stakeholders of the private hotel sector in the island group of Vava'u. The results showed that all institutions are interested in solar energy, of these, 60% are connected to the TPL grid, and the rest generates its electricity through hybrid solar systems in self-sufficient Off-Grids as the hotel facilities are located on independent islands. A significant outcome of the survey is that all grid-connected private sector institutions have indicated complaints on the process and cooperation with the competent authorities about the implementation of solar PV technologies. Mentioned complaints include that requested smart meters were not implemented by TPL, and grid access cost charges were considered too high by the institution. Since there is no infrastructure for the procurement of private solar PV systems in Tonga, all private sector institutions that already installed solar PV had to import and install them on their own initiative. The private sector is highly dependent on cooperating with the energy provider TPL to apply solar PV systems. It needs to be noted that the applied information represents only a small part of the whole picture. Therefore, it should only be understood as a note on possible barriers in the Tongan energy sector.

In the survey, Lucas et al. (2017) outline that experts highlight the importance of setting up a regulatory framework for renewable power generation through IPPs in the PICTs energy sectors. Among the essential capacity needs, the experts highlighted; practical and analytical guidance for the implementation of feed-in tariffs, a clear and transparent framework for power purchase agreements (PPAs) between IPPs and the utilities, net metering policies, supporting generation at consumption point, and tax/duty exemptions. Finally, specific grid connection regulations need to be developed and the implementation of mechanisms for integrating variable electricity sources (Lucas et al. 2017). In the case of Tonga, a gross metering policy is dominant, and fixed PPA tariffs have already been manifested in recent years, which is a significant advantage. However, the successful expansion requires greater support from local authorities at the financial and regulatory policy level. Incentives such as tax credits and subsidies have been the primary drivers in the development of RE worldwide. They are needed to provide favourable market conditions for RE deployment and mainly attract financial resources from the private sector to overcome the economic barriers of the limited market ("Economy of Scales") (Zafar et al. 2019).

Financial Barrier

Financial resources are a significant constraint for the implementation of RE technologies in SIDS. In the case of Tonga, development aid represents the primary source of monetary funding for the implementation of RE technologies. These technologies have high upfront costs and often must go through costly assessment phases before their implementation, in contrast to fossil-fuel generators, while there rarely are funding opportunities for phases before implementing RE projects for the private sector. Therefore, specific areas such as resource assessments and feasibility studies, need stronger financial support from government and donors. Besides, the small scale energy sector often limits international investors' interest (Taibi et al. 2016). To overcome the high upfront capital costs, Lucas et al. (2017) highlight the need for meaningful public finance programmes that offer flexible finance packages instead of single or fixed mechanisms. Also, to overcome the lack of capital, the involvement of IPPs through financially attractive PPAs should play a significant role. The financial barrier is closely related to regulatory barriers. For instance, setting the right regulatory framework to create incentives for big consumers such as tourist resorts to invest in RE technologies for self-consumption or feeding into the grid, has also been seen as a successful solution case in several islands (Lucas et al. 2017). To further enhance a private RE sector's growth, a holistic approach will be needed, including reforms in the regulatory and policy environment, business development support, and risk mitigation instruments to improve projects' bankability. Commercial banks' interest rates and the risk for equity investors need to be reduced, which usually consider small developing countries as high risk for lending (Taibi et al. 2016).

Financial institutions that facilitate loans for RE projects belong to the key players in the deployment of RE in small island nations, including financial players from the public and private sectors and microfinance institutions. These players must have the required knowledge to evaluate the financial aspects of RE projects, such as; profitability margins, intrinsic risks, technology viability, industry standards, and social and environmental benefits of the project. The lack of this expertise makes financial institutions, especially in developing countries, reluctant to provide the necessary resources to support RE projects costly infrastructure. An analysis based on the feedback provided by financial institutions indicated that all the Pacific SIDS rely on grant funding for the development of RE (Lucas et al. 2017; Michalena and Hills 2018).

Informational Barrier

The lack of information and data on RE technologies displays a significant barrier to developing these technologies in Tonga. The PCREEE (n.d.), which has the mission to strengthen the awareness and knowledge base of local key institutions and stakeholder groups on RE and Energy Efficiency in the PICTs, describes the situation as follows: *"The non-availability of reliable and updated energy information creates a major constraint for investors and project developers in the sustainable energy sector in PICTs. Key energy country data on existing policies, laws, stakeholders, prices, generation costs, resources, investments, and potential project sites is, in many cases, not available or not up to date. The lack of quality information is perceived as a major investment risk by investors and project developers. Information on good practices of successful or unsuccessful projects is not readily available. Moreover, the awareness of key market enablers and the public on the opportunities offered by RE&EE technologies and services is low (PCREEE n.d.)*".

The Pacific SIDS often do not gather energy data systematically. In particular, long time series of detailed and accurate energy data are rarely existing, which makes energy planning very difficult. Data from RE resource assessments and RE equipment retail cost for each island are not available. The lack of quality data affects all areas of the energy sector, including the absence of a comprehensive and updated energy balance and detailed electricity data from power utilities. The lack of data on RE resources is also a significant hurdle for project and policy development by not informing the prioritisation and optimal location of projects and preventing the development of the necessary quantitative policy support tools. For enhancing the policy recommendations, it is imperative to improve energy data collection, processing and dissemination processes. Simultaneously, the training of national statistical experts in the area of energy data is essential (Lucas et al. 2017).

Development Aid as a Barrier

Development aid displays the main driving force and primary financial resource for the development of RE in Tonga. Consequently, donor funding is competing with the natural market-driven development of the private energy sector. As Keely (2017) discussed, a large amount of foreign development aid on SIDSs like Tonga leads to an over-reliance on funding for the deployment of RE technologies and is not sustainable in the long-term. Even though international organisations and donor agencies encourage market-oriented policies, their large amount of international aid might have an adverse effect on enhancing an enabling environment for private investment (Keeley 2017). Rickerson et al (2012) describe the situation as follows: *"The growing dominance of donor funding in RE projects in the Pacific is, if anything, moving the majority of RE applications away from commercial RE provision and further distorting the real pricing of electricity supply, and making it harder for the private sector to compete on a level playing field (Rickerson et al. 2012)"*.

Development aid funds are undoubtedly an essential support for expanding RE technologies in Tonga and needed to promote energy transition. However, considering international aid effectiveness, it should be evaluated as effective when it compensates for the investment capital that is not provided by foreign investors and supports processes to implement structural reforms that make a country more business-friendly or used to improve the infrastructure. From this perspective, the effectiveness of the growing dominance of donor funding in RE projects in SIDS like Tonga is questionable. Therefore, according to Lucas et al. (2017), experts consider that donor support should move away from the delivery of grant financed turn-key projects to focus on expanding the capacity building and technical assistance (Keeley 2017; Lucas et al. 2017). It is evident that these national renewable energy targets cannot be achieved sustainably through grant aid alone. There is a recognition that the private sector needs to be empowered to play a central role in delivering these renewable resources (IRENA and PCREEE 2018).

Private Sector Barrier

The Tongan RE private sector is highly undeveloped. There was no retail store for solar PV equipment existent in the country at the time of research. The reasons can be considered as the product of the collective sum of all barriers together. So far, there is only little experience with the private sector's engagement in the electricity market. The lack of clear institutional and regulatory frameworks has already been identified as one of the main limiting factors for the private sector participation, which is in contrast with official statements from the GoT to expect IPPs to play an essential role in the financing of RE deployment (GoT 2010b, p. 62). Several reasons negatively influence the investment decisions of the private sector. For instance, the investors' risks to enter a long-term PPA with the local power utility because of political and commercial instability due to unsecured landownership rights (see chapter 3.3)

(Taibi et al. 2016; Weir 2018). Small consumer markets constrain the ability of energy suppliers to benefit from economies of scale in power generation and limit the extent to which it is possible to have multiple competing generations and retail companies supplying electricity. This fact creates a monopoly market without competition in which the private sector finds it difficult to establish itself. Besides, insufficient knowledge in financial institutions is creating the perception of RE as a high-risk investment. Implementing public support mechanisms and regulations such as feed-in tariffs and net metering will provide security for investments (Lucas et al. 2017).

The outcome of the applied survey on the Tongan private tourism sector showed that all the surveyed institutions indicated the interest of implementing solar PV systems. However, all respondents who are already connected to the national grid mentioned complaints about institutional and bureaucratic regulations. Besides the not existent infrastructure to obtain RE products in the country, the feedback indicates why the private sector has such a small contribution to the RE share in Tonga. As outlined before, the private sector development is strongly connected with regulatory incentives and capacity building and is needed to design, install, operate and maintain RE projects independently (Weir 2018).

10.3 Social and Behavioural Lock-In

Achieving social acceptance is a crucial barrier to overcome for the successful implementation of RE projects in a rural environment. In remote islands with limited access to operation and maintenance, the system's sustainability depends on the adequate project design according to the conditions in the local communities and needs the users' active cooperation. Especially in Tonga, many people are still not aware of RE technologies and their benefits, leading to a lack of local community support and commitment (Keeley 2017). As disruptive technologies, RE technologies are exposed to people's reaction to the change of their established ways of life. Therefore, socio-cultural impediments are intrinsically linked to societal and personal norms and values. Such values and norms affect the perception of RE technologies and their deployment, which means that people are locked-in in their current traditional social behaviour. Experiences from stakeholders show that insufficient consultation and poor communication often result in misunderstandings or lack of information on the part of the communities. Consequently, this can create false expectations among community members, such as the idea of being connected to a traditional On-Grid instead of implementing Off-Grid RE systems. Such problems are frequently reported and lead to widespread ownership issues, land tenure problems and unwillingness to pay for energy services (Taibi et al. 2016). The great challenge of bridging this barrier can only work through capacity building in combination with the right system maintenance management models. As described in chapter 6.4, the current approach is to create governmental utilities consisting of local community members to ensure the PV equipment's maintenance.

11. Discussion

The overall goal of this thesis was to analyse the technical and economic potential of solar PV energy technologies for the island state Kingdom of Tonga. The chosen methodology for conducting the research was qualitative and characterised by an intensive dialogue with the private and public sector throughout a field study and the cooperation with local institutions. The answers to the identified research questions posed in chapter 1 are as follows:

How is the current energy generation structured in Tonga?

The current energy generation of Tonga is highly dependent on the consumption of fossil fuels, which make a total of 30% of the country’s GDP, including the energy and transportation sector. In 2019 RE generation contributes only 11% to the generated electricity, while 89% is produced through diesel generators by the national energy provider TPL, consuming 13 million litres of diesel annually. The Tongan economy is highly impacted by its large electricity tariffs which are more than one third higher than the average Austrian tariff. The scattered and remote island groups display a significant burden for TPL to establish equally efficient and reliable electricity grids for the country. Therefore, the electrical grid infrastructure is upgraded through development programmes to reduce line losses and provide smart meters to the customers for digital grid monitoring. In total on four of 36 inhabited islands, national grids are existent and owned and managed by TPL. The outer islands are characterised as “non-TPL” grids and are managed by the Energy Department. The only form of energy supply for the outer islands are SHS or small solar PV hybrid grids. The capital island Tongatapu displays the largest grid in Tonga serving 75.000 people.

Currently, the Tongan energy sector is transforming, and the RE share is expected to reach 50% by 2021. In 2019, a capacity of 4,84 MWp of solar PV and 1,3 MW of wind turbines were installed in Tonga. In 2008 the crude oil price shock led to an increase in the fuel component so that the entire electricity price rose by 60%. The electricity tariff is structured into a fuel and a non-fuel component, while the fuel component represents almost half of the total tariff and will decrease with rising RE shares. The dialogue with the energy provider TPL indicates that the expansion of renewable energy will positively impact the electricity tariff, but it is not yet predictable to which extend. However, the increase of renewable energies already displays a significant reduction in fossil fuel consumption of 1,6 million litres of diesel in the period of July 2018 to June 2019. The Tongan electricity sector's current structure indicates that the transformation to a 50% RE generation further reduces the countries dependency on fossil fuels, which is in line with the GoT national energy framework “Tongan Energy Road Map 2010-2020”.

What is the current application status of renewable energies, in particular solar energy, in Tonga?

Since the 1980s solar PV systems provide the first essential energy supply for the outer islands of Tonga and contributed to better life quality, improved education and health standards and cultural development. The costs to implement diesel generator systems on the outer islands exceed its benefits, and therefore solar PV represents the only economical form of energy. Solar PV requires less maintenance and has cheaper upfront costs than wind energy, making it economically more attractive for the private sector. However, both technologies suffer from intermittences. The RE generation in Tonga is divided into On-Grid and Off-grid. Off-Grid RE systems are mainly found on the remote islands in the form of SHS, Water Pump Systems, Street lights and Satellite Communication Systems. Experiences from the past showed that the most reliable maintenance concept for solar PV projects on the outer islands is a governmental owned and community-supported solar utility model. The utility is called *Renewable Energy Service Company (RESCO)* and owns the solar panels, batteries, and controllers up to the household's circuit breaker. This ensures that the systems are entirely accessible by the island technicians because the panels, controllers and batteries are safely installed outside of the house.

On-Grid RE systems represent the most significant share of installed solar PV capacity in the form of large governmental or IPP owned solar plants. Especially the contribution of large scale IPPs is becoming increasingly crucial to expanding the renewable electricity share further to reach the 50% target or higher. In 2019, only one IPP existed while all other RE installations have been financed by development aid, which shows how deeply Tonga is dependent on aid funding for its RE expansion. IPPs represent a partial privatisation of the electricity sector and have the benefit that the GoT does not need to provide the upfront capital for the RE systems and still receives lower electricity costs compared to the conventional diesel-generated electricity. In 2020 the largest solar PV IPP installation of the southwest pacific was under development in Tonga, which can be seen as a step in the right direction to achieve independence from development aid. In theory, the feeding in of RE to the TPL grid is applicable for any individual in Tonga. TPL pays the IPP owner for the electricity at a fixed PPA tariff of 0,34 TOP/kWh and according to the gross metering policy. The applied gross feed-in metering policy has been a significant criticism on the cooperation with TPL for many stakeholders throughout the field study. Experts recommend the net metering policy to make the application of RE more attractive for the private sector since stakeholders can consume their own cheaper produced electricity rather than buying it from TPL (see chapter 6.6). However, the Tongan private sector is currently not involved in the utilization of solar PV. There is no infrastructure for purchasing RE equipment existing in Tonga, meaning that all technical materials need to be imported from overseas. It is anticipated, that the design of an attractive fixed PPA tariff and a net metering policy as part of a well-designed policy mechanism stimulates the RE energy sector, leads to an extended application of solar PV and wind energy, and may further break the dependencies on fossil fuels and development aid.

What strategies are existing to increase the share of renewable energies in Tonga?

The promotion of renewable energy has been motivated by three factors: a desire to lessen dependency on fossil fuels, to attract development assistance in the energy sector, and to strengthen the position of Tonga in climate change negotiations. Therefore, in 2010 the GoT developed the Tongan Energy Road Map 2010 – 2020 to create a policy framework to transform the energy sector towards a 50% RE production. The TERM approach targets a mix of different RE energies, in which a combination of 13,5 MWp of solar PV and 7,4 MW of wind energy supply the needed energy to reach the target of 50%. Based on the TERM framework, the cooperation with donors and international development agencies was extended. Having an official RE target and prioritizing RE in national policies indicate to donor agencies that their support for the deployment of RE in the country is in line with its development plan. The primary strategy of the GoT for the last ten years to increase the share of RE is an aid driven approach including the development of programmes such as TREP and OIREP, which then become funded by donors. Within these two main TERM programmes, the strategic focus is divided into the four existing island grids and the outer islands of Tonga. TPL is in charge of the On-Gid RE electrification projects as a part of TREP, and the Energy Department is in charge of the outer island's projects as a part of the OIREP programme. In total, the TERM framework received funding worth 102 million USD by various donors such as ADB, World Bank, Green Climate Fund, Japan Aid and MFAT. Therefore, Tonga is highly dependent on development aid as a source for its energy transformation, which is also evident through its position on the third rank of most development aid receiving pacific island nations. However, the TERM framework does not include small third-party domestic and commercial rooftop solar PV systems to contribute to the countries RE targets, indicating that the private sector does not hold a part of the development aspect.

It is proven that the inward investment by development partners for RE demonstration projects failed to be upscaled by the government-facilitated private sector. On the one hand, development aid is essential to open the markets for RE expansion, on the other hand, a large amount of financial assistance might have an adverse effect to enhance an enabling environment for private investments. The growth of RE leads to an increase in fluctuations in the grid's energy load due to shadings and varieties in winds. Therefore, the government needs to ensure a resilient energy infrastructure capable of balancing out these effects. Thus, high upfront capital is required to invest in BESS, which can only be provided by international donors. From the perspective of the bigger picture, it can be concluded that the aid driven approach is the economically most attractive one for Tonga to achieve its renewable energy target. The Tongan energy sector's current development shows that the next strategic step for the GoT is the cooperation with international companies to develop large scale IPPs to expand the RE share to reach the 70% target until

2030. However, the private sector's incentivisation to contribute to the RE transformation needs to be included in the development aid programmes to establish a substantial RE market and ensure that the people of Tonga have access to RE in the future.

What is the technical and economic potential of modern solar energy technologies to support Tonga in decreasing its dependency on fossil fuel?

Tonga has a development character, a vulnerable economy and is heavily reliant on foreign aid and remittances. It is in the interest of all stakeholders to ensure a stable energy grid with involatile and affordable energy tariffs. Constantly decreasing solar module prices and permanently fluctuating diesel prices are an obvious indicator of solar PV's growth potential. The technical and economic potential of RE for Tonga has been officially recognized by the GoT through creating the TERM framework. In general, an increase in RE will bring benefits for all Tongans. However, the solar PV potential needs to be divided into the public sector's perspective on Tonga as a country and the private sectors' perspective as the individual inhabitants. While the number of larger-scale public RE systems is rising, residents hardly utilize the potential of solar PV. From a governmental strategic point of view, it may lead to an overall benefit for the people of Tonga if the high upfront investment costs for large-scale renewable energy projects and especially battery storage systems are funded by development aid and not by international investors. Development funding is related to certain obligations but can be seen as an endowment to the country, while large-scale investors plan to generate profits from the PPA tariffs. Hence, the financial savings from the fuel reduction is to be considered as revenue for the state's treasury, which could then be used to promote maintenance of the systems, develop additional RE-projects and reduce the national electricity tariffs.

A key finding of the research in connection with local surveys is that in particular the solar PV potential of rooftop and ground-mounted systems for the private sector, the people of Tonga, is enormously high. However, it is far from being fully exploited at present. The estimated potential of Tonga's private sector solar capacity could contribute 15-18% to Tonga's total energy demand compared to the current contribution of 0,79 %. A questionnaire among the private sector stakeholders of the hotel tourism industry showed that a lack of cooperation in the installation of smart meters and further barriers from institutional site hindered the implementation of private solar PV systems in the island group of Vava'u. The exact reason could not be clarified in a dialogue with TPL. However, it is anticipated that the grid infrastructure is not yet ready to balance larger external RE input amounts. In 2020 therefore 23 MWh of BESS will be implemented in the main grid of Tongatapu, which allow the feeding in of larger quantities of RE from the private sector.

However, the questionnaire's comparable small response rate indicates that there was hardly any access to the private hotel sector possible. As a result, this sector's statements are not particularly meaningful, which makes a representative conclusion for the whole country difficult. Nevertheless, it offers an insight into a small circle of people in the industry and allows assumptions to be outlined for the rest of the hotel industry. This paves the way for future research which can address this situation in more detail. Besides, the private sector's feedback has made an essential contribution to approach the national energy provider TPL with further questions.

In cooperation with Longo Longo Police Station and the TTI college, two case studies are presented, and the technical implementation and economic aspect are elaborated. It could be shown that the Longo Longo Police Station, the largest third-party IPP of Tonga is generating significant excess funds of 25,590 USD annually after taking off of all system maintenance costs for the police trust fund model. It needs to be highlighted that the Longo Longo Police station operates under comparatively better conditions due to a higher PPA tariff, but also higher implementation costs through battery storage. However, it is one of the first systems in Tonga to be developed, and discussions between TPL and TTI show that the PPA tariff is possibly negotiable.

The case study of the TTI college outlines the feasibility of implementing a solar PV system that is fully developed by a local initiative and in a second step could become the largest IPP in the country. The annual income savings of the 90,64 kWp solar PV system at TTI are calculated with 22,040 USD, not including maintenance costs, which would result in a pay-off time of 5,7 years, after which it will generate reasonable savings for the college to invest in its education infrastructure. The TTI college is part of the Wesleyan church, the largest Christian denomination in Tonga, holding several hundreds of buildings with high-quality roofs. Religious and commercial institutions obtain buildings with the highest potential for solar PV systems. The successful development of the first self-initiated large-scale PV system could enhance further RE projects in the private sector. Theoretically, such a payback scenario can be assumed for every private solar PV installation in Tonga. However, awareness needs to be created to motivate the people of Tonga to participate in the energy sector, driven by the profitability of RE and innovations in the delivery of business models.

Besides, the technical potential's research focus is set on the innovative floating solar technology as a new method to solve the problematic scenario of scarce land for large-scale solar PV systems on small islands. In a theoretical approach, the topography of Tonga offers enormous potential for the application of floating solar. Especially the Fanga’uta Lagoon next to the TPL generators at the Popua Power Station provides an excellent location for the application of such a technology. However, at the current development state, floating platforms are not considered technically resistant to the devastating cyclone wind speeds which occur in Tonga almost annually.

In cooperation with TPL, a theoretical 99 % RE energy mix scenario was developed to create an outlook on how future RE scenarios could look. The scenario outcome outlines that 35,3 MWp of solar PV, and 16,6 MW of wind turbines linked with 118 MWh of batteries would be sufficient for a complete energy supply of the country, including potential growth in electricity demand for five years. However, further research on various unknown factors is needed to transform such a scenario into reality. For example, how long will it take to implement this amount of RE, and how will the load grow during that time? How sustainable is this case scenario? On a holistic viewpoint, an increase in RE will lead to economic benefits for all Tongans by reducing the electricity tariff's fuel component, and through decreasing prices in RE equipment, such a scenario will become increasingly economically feasible.

What are the socioeconomic benefits for Tonga of increasing its RE generation?

The increase of RE has a significant beneficial socioeconomic impact on aspects of Tonga's development and fossil fuel independence. Solar PV represents the first electrical power supply for the remote islands of Tonga and brought life-changing socioeconomic benefits for its inhabitants. The access to electricity promotes economic activities on the remote islands. For instance, it enables the application of sewing machines for handcraft manufacturing, which displays a substantial income. Also, improved lightning leads to a rise in social activities such as community meetings, supports educational activities, enables the use of electronic devices such as radios and mobile phones and comes with environmental and health benefits. Therefore, solar PV technologies contribute positively to the development of the outer island, increase the inhabitants' living conditions, and the socio-economic benefits of the inhabitants.

The expansion of RE on the main island Tongatapu in the form of large-scale systems reduces the total fossil fuel consumption, leading to a reduction in the countries fossil fuel dependency. Similar to the RE strategies, the following three socio-economic aspects function as a political key driver to pursue the target of becoming fossil-fuel independent: i) Attracting development assistance, which also increases economic activities within the country ii) Increase in national energy security which leads to reduced and stable electricity prices, ensures income savings for all involved stakeholders and further enables entrepreneurial activities iii) Strengthen the position of the SIDS in climate change negotiations to receive more extensive support from western countries. Every percent of saved fossil fuel importing cost due to better energy policy and planning will pay back a reasonable additional budget allocation to strengthen the public and private stakeholders. The high electricity tariffs in the regions, coupled with the sustained decrease in the cost of RE technologies, create the expectation that the private sector could play a leading role and in RE hardware deployment and receive an economic benefit. This expectation has been proven by analysing the two case studies of the Longo Longo Police Station and the TTI college, showing economic and social benefits from applying solar PV technologies. As a part of an existing diesel grid, RE provides immediate fuel savings to pay back the investment. Therefore they are generally financially viable without grant funding if there is a smart design of financing packages provided. This implies that well-designed policy mechanisms that are stimulating the private sector may break Tonga's grant dependency.

What are potential barriers to renewable energies in Tonga?

Understanding the barriers for RE in Tonga allows proposing possible improvements to better integrate RE in the future. The barriers have been analysed based on the three defined Lock-In levels: i) Infrastructural and Technological Lock-In, ii) Institutional and Political Lock-In, iii) Social Behavioural Lock-In. As a consequence of these Lock-Ins, there is no possibility to purchase RE products within the country. Overcoming these barriers will have a significant impact on the social acceptance of RE in Tonga. When people become aware of RE technologies' benefits, it can be anticipated that local community support and commitment will enhance.

The technological and human skilled dependency on foreign countries represents a significant barrier. Valuable skills for the development of RE projects in the country are missing, which is also due to a brain drain to higher-paid professions abroad. Educational qualitative training top-down from policymakers to O&M for technicians is needed to counteract the lack of qualified energy professionals. Consequently, it is anticipated that particularly the fulfilment of technical tasks by local technicians is an enrichment of the Tongan energy market in the following fields: drafting of feasibility studies and cost studies of viable RE technology; project planning and design; project development and installation of RE systems. Currently, the technical integration of large-scale solar PV projects creates difficulties for the small island grid due to its inherent characteristics of intermittence and fluctuations. The grid stability management concept in relation to the application of BESS needs to be strengthened through capacity building. Besides, the remoteness of Tonga displays a limitation for economic equality in comparison with other land-based countries, which increases the cost of technical equipment for RE systems and its maintenance in case of failure.

Political and institutional Lock-Ins display the largest barrier to the expansion of RE at the state of research. National energy policies clearly impact the development of the energy market positively or negatively. In Tonga, the complicated and inefficient institutional structures display a significant hindrance for introducing RE technologies in the private sector. For instance, tax and duties are imposed on private imports of RE technologies, while the public sector imports them tax-free. There are no government incentives given, such as subsidises or funding of RE technologies. Instead, bureaucratic hurdles of TPL make it difficult for the private sector to connect to the grid as an IPP. Besides, the only two potentially available sources for private individuals to receive potential subsidisation for the application of RE are the “direct aid” programme by DFAT and the Pacific Sustainable Energy Entrepreneurship Facility grant by the PCREEE. However, both programmes are generally unknown to the local people and may not be sufficient in the amount of their support.

The outcome of a questionnaire applied among five stakeholders of the private hotel sector in Vava’u showed, that all grid-connected private sector institutions have indicated complaints on the process and cooperation with the competent authorities about implementing solar PV technologies. For the purpose clarification and awareness creation, the process of feeding-in electricity into the primary grid is elaborated in this thesis. Chapter 6.5 offers a step by step process description. The exact process for connecting to the grid was received from TPL on a direct request and was not available online at the state of research.

The lack of reliable and updated energy information and data represents a significant barrier to the private sector's RE development and creates a constraint for investors and project developers. The local centre PCREEE has the mission to strengthen the local key institution and stakeholder groups' awareness and knowledge base on RE and Energy Efficiency and created the first online server for the collection of information. However, the PCREEE is responsible for the pacific region and cannot provide all information necessary for the Tongan private sector to be adequately informed. To further incentivise the Tongan private sector to expand the share of RE, official support is needed to create awareness, procure quality equipment at fair prices and manage the bureaucratic registration of the solar PV system with TPL. Therefore, it is suggested that TPL or a comparable institution, in cooperation with local technicians, should support the private sector by regularly holding free awareness workshops about the requirements of the solar PV system application for households and further provide the possibility to import the certified products exempt from taxes and duties as it is the case for the public sector.

Financial resources display a major constraint on the implementation of RE due to its high up-front costs. The small Tongan consumer markets constrain the ability to benefit from the economy of scale of having multiple competing retail companies offering RE products as well as the electricity generation constitutes a monopoly by TPL. Financial institutions from the private and public sector need to provide flexible finance packages to overcome the lack of capital of the people of Tonga, which also requires knowledge to evaluate the financial aspect of RE projects. Currently, Tonga is over-reliant on development aid for the expansion of RE, which leads to the situation in which donor funding is competing with the open market and hindering private sector investments. In general, aid is an essential driver for expanding RE and to possibly kick start the energy transition. However, the effectiveness of development aid preventing the enhancement of the local RE market is questionable. It is equally clear that these national energy targets cannot be achieved sustainably through grant aid alone. There is a recognition that the private sector needs to be empowered to play a central role in delivering these renewable resources. Therefore, this thesis highly recommends that the GoT revises its national energy policies to provide a favourable environment for investors through providing property rights, developing human expertise, enhancing macroeconomic stability, transparency and removing political barriers.

12. Conclusion

The Pacific Island Nations, including the Kingdom of Tonga, have established the world's most ambitious renewable energy targets. In the case of Tonga, the national framework "*Tonga Energy Road Map (TERM)"* targets a 50% renewable share until 2020 and 70% until 2030. Energy is a fundamental building block for Tonga in its social and economic development and enhancing its inhabitants' livelihood and well-being. The country's extreme dependency on expensive fossil fuels is threatening the small and fragile economy. The island nation's characteristics of high solar insolation and remoteness combined with a reduction of solar panel's prices by ninety percent in the last ten years create the expectation that solar PV has the potential to substitute the predominant conventional fossil fuel-driven electricity production. Besides the officially defined targets, the actual status quo of renewable energy development within the country is hardly described in the literature. Therefore, field research has been conducted in Tonga with the goal to analyse the technical and economic potential of solar photovoltaic energy technologies for the island state. The research has shown that especially a combination of solar PV and wind turbines has the potential to support Tonga in becoming independent from fossil fuels for energy generation. Through the dialogue with the public and private tourism sector in the form of qualitative interviews and applied questionnaires, it could be shown that no renewable energy retail infrastructure exists and mostly only off-grid hotel owners use solar PV. At the same time, on-grid facilities are interested in solar PV but face institutional barriers. As an outcome of the research, two case studies are introduced as unique examples for solar PV application. The *Tupou Tertiary Institute* solar PV system started in cooperation with the research study and displays the country's largest privately initiated solar PV system under development in Tonga. Together with the currently largest private solar PV system of the *Longo Longo Police Station*, these two analysed case studies prove that the implementation of private solar PV systems is economically and technically feasible and provides a reasonable system pay off within five to six years.

The TERM framework shows that the Government of Tonga is increasingly aware of the potential to supply a part of Tonga's energy needs from renewables in a reliable, affordable and more secure manner.

Currently, the country is designing and implementing large-scale solar PV and wind turbine systems as well as policies and support measures to achieve its renewable energy targets on a public scale financed by development aid. However, the Tongan private energy sector is not yet promoted by these policies and is still lagging behind. The research's key outcome is the identification of the potential of renewable energy for the Tongan private sector and the importance to create integrating incentives on the political level. Through providing incentives such as flexible financial support systems, moving from a gross feed-in policy towards a net feed-in policy, and attractive power purchase agreements, by the government and the national energy provider TPL, the private sector could be stimulated to take on a significant role in reaching a complete renewable energy generation in the long term. Estimations indicate the potential capacity of the Tongan private sector to be 11 MW. A decrease in fossil fuel consumption also contributes to climate change mitigation, since Tonga as a part of the Pacific Island Nations belongs to the countries most threatened by climate change globally. The high renewable energy targets are strengthening the Small Island Development States position in climate change negotiations to receive more extensive support from western countries.

Today, multiple barriers hinder the comprehensive expansion of these technologies at various levels, leading to the present situation, in which the private sector rarely uses solar PV. Significant barriers are not technological but institutional, social and financial. Tonga's most predominant barriers are unsupportive policies, the lack of awareness, lack of financial resources, and the bureaucratic processes for the private sector to feed in electricity into the national TPL grid. A holistic approach will be needed to overcome these barriers and further enhance the growth of a private-led renewable energy sector, including reforms in the regulatory and policy environment and in business development support. Most importantly, the private sector must be included in the donor programmes to counteract the competition between private investments and development aid to expand renewable technologies. Hence, the inclusion of the private sector displays a possible pathway to reduce Tonga’s aid dependency. Significant benefits deriving from an increase of renewable energies are particularly evident in the country's socio-political development. Among many other benefits, an increase in renewable energies will lead to reduced and stable electricity prices, enhancing economic activities in the country and positively impacting the Gross Domestic Product. The research outcomes can help create a better understanding of the common barriers, solutions, and benefits of renewable energy expansion in Small Pacific Island Nations. The awareness of essential background understanding and interrelationships of the energy sector are needed to overcome the informational barrier.

In the future, technological innovations will play a significant role in enhancing the energy transition on all levels. For instance, more robust floating solar PV technologies could make water areas accessible, if more land space for renewable technologies is required due to rising loads. It is anticipated, that political incentive regulation combined with continually decreasing cost of renewable energy and storage technologies will make a completely renewable energy supply increasingly feasible in the future. In a next step, to ultimately reach the goal of a total independency of fossil fuels, the Government of Tonga needs to develop a comparable Energy Road Map for the transportation sector, which has a higher fuel consumption than the electricity sector. The next decades' most crucial challenge will be to encourage the private sector to participate in this technological energy revolution. Therefore, further research needs to be conducted in the private sector's integration and stimulation to contribute to renewable energy targets. The expansion of RE displays an essential contribution to breaking the Pacific Islands dependency on fossil fuels, increasing the population's well-being, and contributing to climate change mitigation.

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14. Appendix

Appendix 1: Conducted site visits

List of site visits	
JICA Windfarm (1,3 MW)	17.07.2019
Matatoa Singyes IPP (2MW	17.07.2019
TPL Generators	12.08.2019
Nikolasi Fonua TPL	15.08.2019
Longo Longo Police station	13.08.2019
Tupou Tertiary Institute	16.08.2019
Tevita Tukunga DoE	16.08.2019
Meeting with Graham (TTI)	07.07.2019
Tupou College visit	17.08.2019
Queen Salote College visit	17.08.2019

List of public sector visits	
Tongan Development Bank	09.08.2019
Reserve Bank	08.08.2019
World Bank Office	08.08.2019
Asian Development Bank	08.08.2019
Australian High Comission	12.08.2019
New Zealand High Comissio	12.08.2019

Appendix 2: List of conducted questionnaires

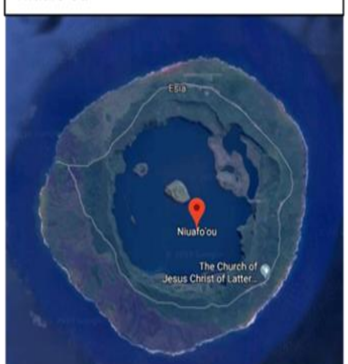
List of Questionnaire	Name of Contact	Date
Whale Waters Retreat	Axel & Eska	21.07.2019
Hilltop Hotel	Vaasi	20.07.2019
Cafe Tropicana	Greg Tust	20.07.2019
Mandala Resort	Lisa	19.07.2019
Mounu Resort	Kirsty Bowe	19.07.2019

Appendix 3: Three potential additional floating locations in Tonga, source: google maps

Nomuka island, Lake Ano'ava on

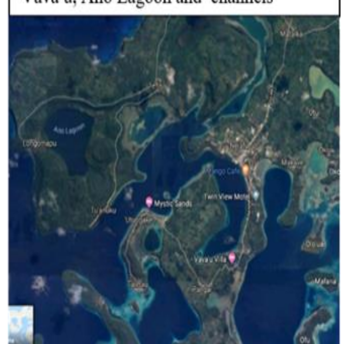
Population: 400-500
Island group: Ha'apai

Niuafo'ou



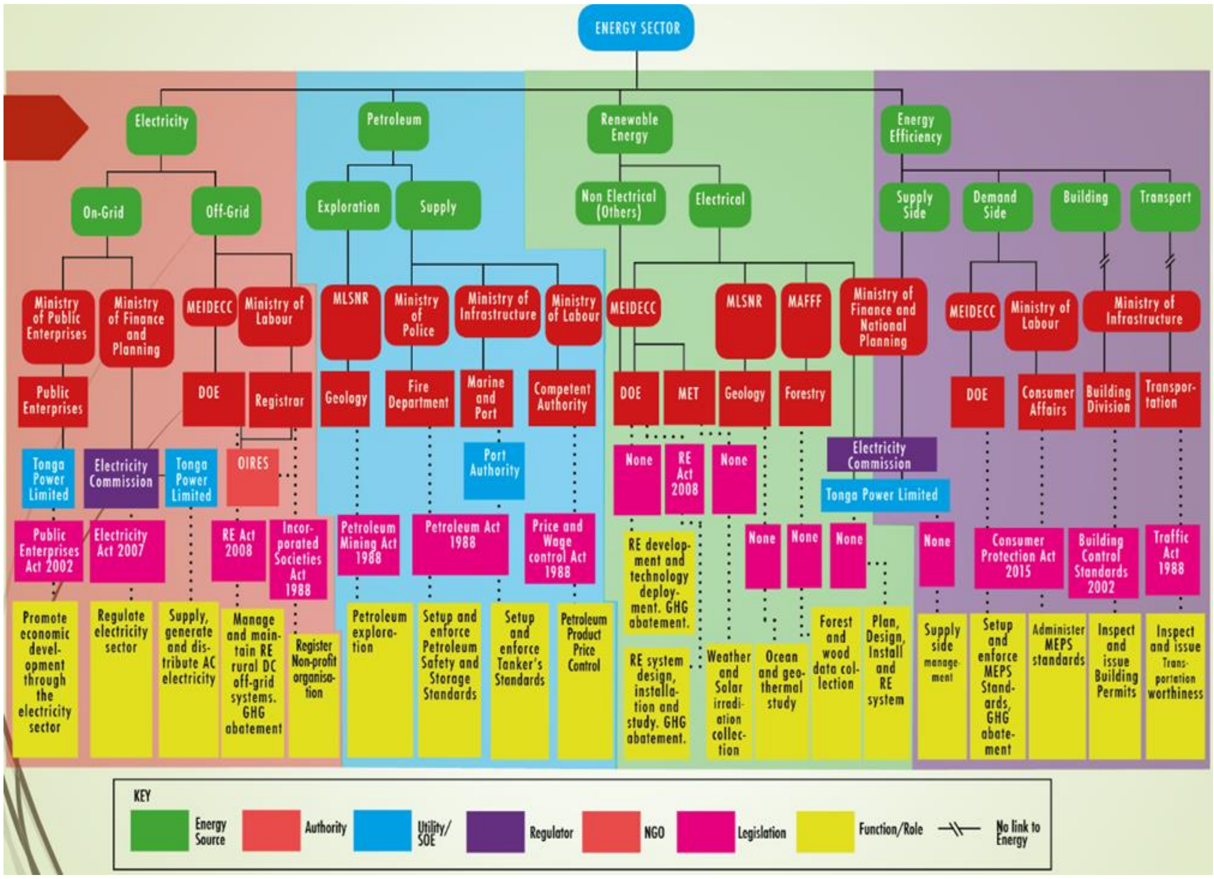
Population: 650
Island group: Niua, most north

Vava'u, Ano Lagoon and channels



Tourism centre of Tonga: 22 Hotels, resorts, guesthouses
Population: 13,740

Appendix 4: Involvment of ministries in Tongan energy sector, source: *(TERM-IU 2015)*

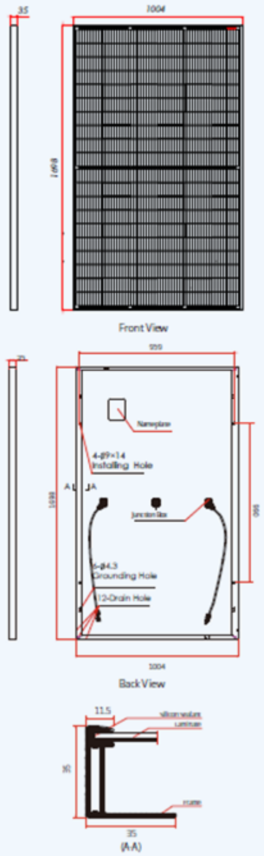


Appendix 5: Solar panel data sheet of TTI college project

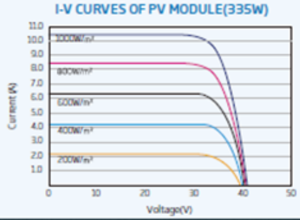
HoneyBlack

60LAYOUT MODULE

DIMENSIONS OF PV MODULE(mm)



I-V CURVES OF PV MODULE(335W)



ELECTRICAL DATA (STC)

Peak Power Watts-PMAX (Wp)*	320	325	330	335	340
Power Output Tolerance-PMAX (W)	0 ~ +5				
Maximum Power Voltage-VMPP (V)	33.4	33.6	33.8	34.0	34.2
Maximum Power Current-IMPP (A)	9.58	9.67	9.76	9.85	9.94
Open Circuit Voltage-VOC (V)	40.3	40.4	40.6	40.7	41.1
Short Circuit Current-ISC (A)	10.20	10.30	10.39	10.48	10.55
Module Efficiency η m (%)	18.8	19.1	19.4	19.7	19.9

STC: Irradiance 1000W/m², Cell Temperature 25°C, Air Mass AM1.5.
*Measuring tolerance: ±3%.

ELECTRICAL DATA (NMOT)

Maximum Power-PMAX (Wp)	241	245	249	253	256
Maximum Power Voltage-VMPP (V)	31.1	31.3	31.5	31.7	32.0
Maximum Power Current-IMPP (A)	7.75	7.84	7.90	7.96	8.02
Open Circuit Voltage-VOC (V)	38.0	38.1	38.2	38.3	38.7
Short Circuit Current-ISC (A)	8.23	8.31	8.38	8.45	8.50

NMOT: Irradiance at 800W/m², Ambient Temperature 20°C, Wind Speed 1m/s.

MECHANICAL DATA

Solar Cells	Monocrystalline
Cell Orientation	120 cells (6 × 20)
Module Dimensions	1698 × 1004 × 35 mm (66.85 × 39.53 × 1.38 inches)
Weight	18.7kg (41.2lb)
Glass	3.2mm (0.13 inches), High Transmission, AR Coated Tempered Glass
Encapsulant Material	EVA
Backsheet	White (.08) / Black (.05)
Frame	35 mm (1.38 inches) Anodized Aluminium Alloy
J-Box	IP 68 rated
Cables	Photovoltaic Technology Cable 4.0mm² (0.006 inches²), Portrait: N 140mm/P 285mm(5.51/11.22inches) Landscape: N 1200 mm/P 1200 mm (47.24/47.24 inches)
Connector	MC4 / TS4

TEMPERATURE RATINGS

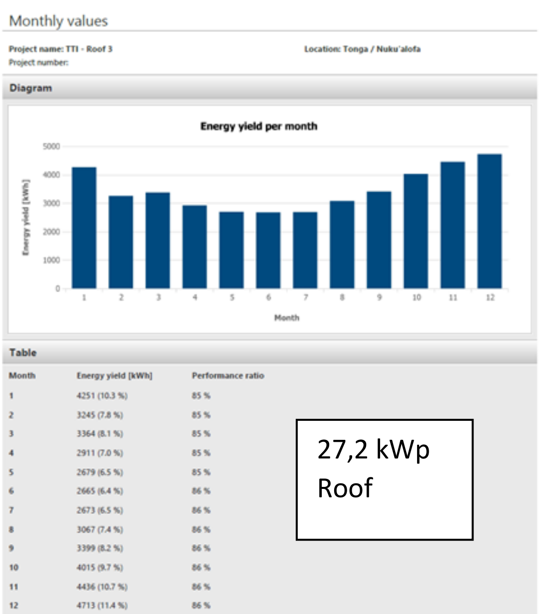
NMOT (Nominal Module Operating Temperature)	41°C (±3°C)
Temperature Coefficient of PMAX	- 0.37%/°C
Temperature Coefficient of VOC	- 0.29%/°C

MAXIMUM RATINGS

Operational Temperature	-40~+85°C
Maximum System Voltage	1000V DC (IEC) 1000V DC (UL)

Appendix 6: Calculation of TTI 161,95 MWh/annually, source: (Small Island Technologies 2019)

Institution	Roof 1	Roof 2	Roof 3	**Total kWp**	
TTI college	27,2	42,24	27,2	**96,64**	
TTI REID data					
month	roof1	roof2	roof3	total	90,64
1	4251	6654	4251	15156	167,210944
2	3245	5085	3245	11575	127,703001
3	3364	5267	3364	11995	132,336717
4	2911	4567	2911	10389	114,61827
5	2679	4200	2679	9558	105,450132
6	2665	4177	2665	9507	104,887467
7	2673	4190	2673	9536	105,207414
8	3067	4807	3067	10941	120,708297
9	3399	5322	3399	12120	133,715799
10	4015	6265	4015	14295	157,711827
11	4436	6937	4436	15809	174,415269
12	4713	7363	4713	16789	185,227273
total	41418	64834	41418	147670	
Total kWp for TTI annually					**1629,19241**


Monthly values

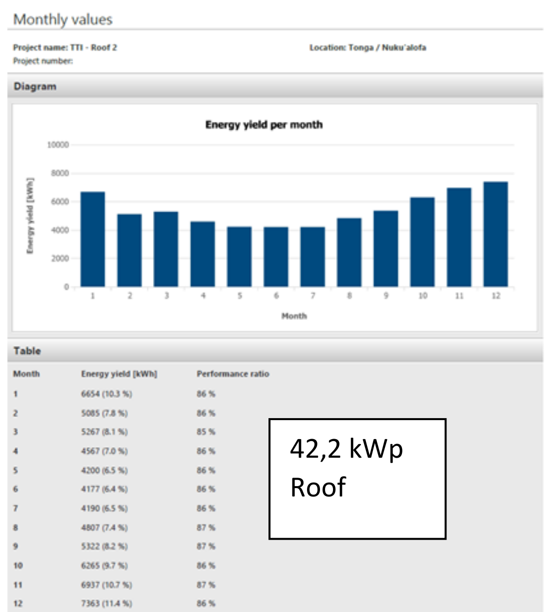
Project name: TTI - Roof 3 Location: Tonga / Nuku'alofa
Project number:

Diagram

Table

Month	Energy yield [kWh]	Performance ratio
1	4251 (10.3 %)	85 %
2	3245 (7.8 %)	85 %
3	3364 (8.1 %)	85 %
4	2911 (7.0 %)	85 %
5	2679 (6.5 %)	85 %
6	2665 (6.4 %)	86 %
7	2673 (6.5 %)	86 %
8	3067 (7.4 %)	86 %
9	3399 (8.2 %)	86 %
10	4015 (9.7 %)	86 %
11	4436 (10.7 %)	86 %
12	4713 (11.4 %)	86 %

27,2 kWp Roof


Monthly values

Project name: TTI - Roof 2 Location: Tonga / Nuku'alofa
Project number:

Diagram

Table

Month	Energy yield [kWh]	Performance ratio
1	6654 (10.3 %)	86 %
2	5085 (7.8 %)	86 %
3	5267 (8.1 %)	85 %
4	4567 (7.0 %)	86 %
5	4200 (6.5 %)	86 %
6	4177 (6.4 %)	86 %
7	4190 (6.5 %)	86 %
8	4807 (7.4 %)	87 %
9	5322 (8.2 %)	87 %
10	6265 (9.7 %)	86 %
11	6937 (10.7 %)	87 %
12	7363 (11.4 %)	86 %

42,2 kWp Roof

Appendix 7: Exact allocation of proposed solar PV systems in Tonga, source (google

FACILITY	TYPE	ISLAND	STATUS	CAPACITY (kW)
Maama Mai	Solar PV	Tongatapu	Commissioned	1332
La'a Lahi Solar Facility (420kW) actua	Solar PV	Vava'u	Commissioned	420
Mata 'ae La'a Solar Facility (1MW) ac	Solar PV	Tongatapu	Commissioned	1000
Huelo 'o e Fungafonua	Solar PV	Eua	Commissioned	200
Ha Masani	Solar PV	Ha'apai	Commissioned	550
Matatoa Singyes IPP	Solar PV	Tongatapu	Commissioned	2000
Owen Muller	Roof-top Solar PV	Tongatapu	Commissioned	15
Molisi Fasi	Roof-top Solar PV	Tongatapu	Commissioned	11
St Andews College	Roof-top Solar PV	Tongatapu	Commissioned	8
Sitani Mafi Bakery	Roof-top Solar PV	Tongatapu	Commissioned	5
Soane Ramanlal Residence	Roof-top Solar PV	Tongatapu	Commissioned	10
Sefo Ramanlal	Roof-top Solar PV	Tongatapu	Commissioned	5
Liahona High School	Roof-top Solar PV	Tongatapu	Commissioned	100
NZ High Commission Office	Roof-top Solar PV	Tongatapu	Commissioned	10
Café Tropicana	Roof-top Solar PV	Vava'u	Commissioned	3
Michael Lani 'Ahokava Res	Roof-top Solar PV	Tongatapu	Commissioned	1
Murray Sheerin Res	Roof-top Solar PV	Tongatapu	Commissioned	2
LDS 'Eua	Roof-top Solar PV	Eua	Commissioned	13
LDS Ma'ufanga	Roof-top Solar PV	Tongatapu	Commissioned	10
LDS Havelu	Roof-top Solar PV	Tongatapu	Commissioned	10
Catholic Residents (Fangaloto)	Roof-top Solar PV	Tongatapu	Commissioned	10
Police Longolongo	Solar PV	Tongatapu	Commissioned	150
Police Tatakamotonga	Roof-top Solar PV	Tongatapu	Commissioned	10
Police Nukunuku	Roof-top Solar PV	Tongatapu	Commissioned	10
Police Vaini	Roof-top Solar PV	Tongatapu	Commissioned	10
Police Kolofo'ou	Roof-top Solar PV	Tongatapu	Commissioned	10
Domestic Wharf	Roof-top Solar PV	Tongatapu	Commissioned	90
Davina Bar actual	Roof-top Solar PV	Tongatapu	Commissioned	5
Sea View Lodge	Roof-top Solar PV	Tongatapu	Commissioned	8
Solomone Fifita (Mohokoi)	Roof-top Solar PV	Tongatapu	Commissioned	1
Solomone Fifita (Heilala)	Roof-top Solar PV	Tongatapu	Commissioned	1
Prince Wellington Ngu Hospital	Roof-top Solar PV	Vava'u	Commissioned	20
Channel College	Roof-top Solar PV	Vava'u	Commissioned	8
Apifo'ou College	Roof-top Solar PV	Tongatapu	Commissioned	8
Tailulu College	Roof-top Solar PV	Tongatapu	Commissioned	8
Tupou College	Roof-top Solar PV	Tongatapu	Commissioned	8
Beulah College	Roof-top Solar PV	Tongatapu	De-commissioned	8
Takuilau College	Roof-top Solar PV	Tongatapu	Commissioned	8
Alonga	Roof-top Solar PV	Tongatapu	De-commissioned	10
Pole	Roof-top Solar PV	Tongatapu	Commissioned	15
Nakolo	Micro-Wind Turbine	Tongatapu	De-commissioned	11
Ha'apai	Micro-Wind Turbine	Ha'apai	Commissioned	11
Japan Wind Farm	Wind Turbines	Tongatapu	Yet to be	1325

			Commissioned	
Sunergise IPP	Solar PV	Tongatapu	Yet to be Commissioned	6000
China Wind Farm	Wind Turbines	Tongatapu	Planned RE	2200
Wind IPP	Wind Turbines	Tongatapu	Planned RE	3800
TREP 'Eua	Solar PV	Eua	Planned RE	300
TREP Vava'u	Solar PV	Vava'u	Planned RE	300
Vete Green Cold Storage Warehouse	Solar PV	Tongatapu	Planned RE	150

Summary of RE info

Appendix 8: Detailled summary of exisitng RE in Tonga

Appendix 9: Filled out TTI application for TPL

2.5 APPLICATION FORM B1 FOR OVER 4 KW UP TO 160 KW

The following applies to generation greater than 4 kWp but not larger than 160 kWp.

You must provide Tonga Power with enough information to enable your distributed generation to successfully connect to our network without affecting other connected customers. Please note that an application fee may be payable if we need to carry out significant research and analysis to assess the potential impact of your proposed distributed generation on our network.

You must obtain our written agreement before you can connect distributed generation to our network

5. Details of Applicant

Customer Name:	Tupou Tertiary Institute		
TP Account Number:	91102080C2300 (Meter # - 32237/9011)		
Party responsible for application:	Ungatua Fonua Kata		
Contact phone:	Office - (676) 25093/25890	Facsimile:	None
Mobile:	(676) 7778973		
Email address:	Hayden.braddock@mgrouptonga.com		
Postal address:	Tupou Tertiary Institute, P.O. 117, Nuku'alofa, Tongatapu, TONGA ISLANDS		

6. Proposed location of embedded generation

Address:	Loviola Road, Nuku'alofa, Tongatapu Island

Is the property owned by the applicant?	YES ☐ NO ☐ (If YES continue to 8)		
Name of owner:	Free Wesleyan Church of Tonga		
Contact phone:	Office (676) 25890/28890	Facsimile:	None

3

TONGA POWER LIMITED 2016

Appendix 10: Questionnaire applied at Tongan private sector

Questionnaire for the Master-Thesis Research on

"Analysing the technical and economic potential of modern solar and battery storage technologies for the island state Tonga"

Nicolas Meier
BOKU – University of Life Science, Vienna
LU – Lincoln University, New Zealand

The Questionnaire is divided into Section A, B and C. Section A is meant to gain a first understanding about the Lodge/Hotel/Guesthouse, while section B aims for the technical background needed to evaluate the solar potential. Therefore, section B is preferable filled out by the researcher in a personal dialogue. If this form is completely filled out by the interviewee through email, please do not hesitate to come back to me with questions. Section C is only relevant to you if you already have installed Solar energy at your place.

Note: To be able to give a solar potential estimation, the roof capacity needs to be measured by the researcher.

Organization:	**Name:**	**Date:**

Section A (multiple selection possible)

1. Have you already implemented Solar energy in your Lodge/Hotel/Guesthouse?

   Yes (please enter system size) ☐ [kWp]
   No ☐

   *If yes, proceed with question number 4 and later section C.

2. Have you ever considered solar energy as a source for energy generation for the Lodge/Hotel/Guesthouse?

   Yes ☐
   No ☐

3. What are possible reasons that have kept you from not implementing solar energy?

   High investment ☐
   No supply of solar products ☐
   Energy policies ☐
   No solar companies for maintenance ☐
   Strong weather events ☐
   Other reasons ☐

Explain other reason:

4. Have you ever calculated the cost saving potential of solar energy for your lodge/Hotel/Guesthouse?

Yes ☐
No ☐

5. When was the last time you renovated your roofs?

Year ☐

6. Would you consider your roof constructions as cyclone proof?

Yes ☐
No ☐
Not all ☐

7. Did you ever experience heavy damages on your roof construction by cyclones?

Yes ☐
No ☐

8. How many buildings are part of your lodge/Hotel/Guesthouse?

Number ☐

9. How many of the roofs do you consider as suitable for solar panels? *(And have no solar panels installed yet)*

Number ☐

To estimate the solar potential for your resort I need a few technical details.

Section B

10. What is your current source of energy?

Generator ☐

Main Grid ☐

Solar ☐

11. If a generator is included, what is the generator's efficiency and how many litres of diesel do need per day?

kWh/l ☐

litres of Diesel ☐

No Generator ☐

12. What is your average daily or monthly energy consumption in kWh.

kWh. ☐

13. Alternatively, how much do you pay for energy monthly.
(Energy consumption can be calculated through the energy bill)

TOP or other ☐

14. What time of the day do you expect to have the highest energy demand?
(Simply, when is the most electricity consuming time of a day, in terms of running ACs, and other highly electricity consuming appliances)

Time ☐

15. If possible, what is the maximum energy load around that time?

kW ☐
I don't know ☐

16. Difference of demand in high and low season. *(simply, lowest power bill and highest power bill of a year)*

Highest consumption ☐

Lowest consumption ☐

Section C (only if you have solar installed already)

17. Do you feed the solar energy into the grid?

Yes ☐
No ☐

18. Do you use a battery storage system?

Yes (please enter system size) ☐ kWh
No ☐

19. How did you manage the supply of the solar system?

By myself ☐
Foreign company ☐
Tongan company ☐
Other.. ☐

Explain other reason:

20. How did you managed to install the solar system?

By myself ☐

Foreign company ☐

Tongan company ☐

Other.. ☐

Can you please note company name:

21. What obstacles did you face when installing your solar system?

Please explain reason:

22. Would you recommend using solar energy in Tonga?

Yes ☐

No ☐

Please explain reason:

23. If possible, can you give a general feedback about your experiences with using solar energy in Tonga.

Thank you very much for taking the time

Kind regards

Nicolas Meier