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Sustainable energy systems

Achieving 100% renewables Energy systems in Cook Islands

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1 Chapter one (Sarah)

1.1. Abstract:

This study presents the method for reaching 100% sustainable energy systems in cooks islands. It covers the possibility of fulfilling this objective from technical, commercial and environmental aspects. This is based on a model simulation taking into consideration the available resources. This study also focuses on the main Island of Rarotonga. The reason for this is that Rarotonga is the largest populated island and represents 75% of Cook's Island population. (Etches, 2019)

1.2. Overview of Cooks Island:

The total area of Cooks Island is 240 Km^2 and Rarotonga is 67.39 Km2 with a total population of 17,434 located in Rarotonga according to the latest census of 2016 (Office, 2018). Cooks Islands is made up of a total of 15 islands divided into the southern and northern Islands. It's located on the Pacific Ocean between New Zealand and Australia (Office, 2018). Tourism is the main industry in Cooks Island and especially Rarotonga with the highest number of visitors between July and September. The main use of energy in the Cook Islands are transport (43%), aviation (30%) and (27%) for electricity. (Cooksislands economic and development strategy handbook volume 1, 2013)

Until recently, the Cook Islands was mainly dependent on imported refined petroleum fuels, which accounts for 90% of gross energy supply. Biomass provided most of the remaining 10% and is mainly used for cooking (Mirei Isaka, 2013). The energy access in cooks' islands is around 99% (Mirei Isaka, 2013). The share of fossil fuels in 2019 has currently dropped to 79 % with 21% being generated from Renewables and especially solar (World Data.info, n.d.), as the government of Cooks islands has introduced the renewables energy plan. However fossil fuels still represent a very high share of the electricity generation with the current share of renewables only amounting to 15% (New Zealand Ministry of Foreign Affairs & Trade 2016, 2016).

1.3. The problem:

The main dependency in Rarotonga for electricity generation is on fossil fuels (Division, 2012). Which the country imports mainly from New Zealand (Division, 2012). The consumption rate per day for fuel is 22,000 liters (Division, 2012). The current available storage capacity for fuels is three tanks with a capacity per tank of 52,000 liters (Division, 2012). Fuel is delivered by Truck to TAU with a capacity per truck ranging from 4000 Litres to 7000 Litres per truck (Division, 2012). This dependency presents a very economic and environmental burdens and subjects the islands to the fluctuating prices of fuels in addition to the availability (Division, 2012). Additionally, the price of diesel on Cooks islands is higher compared to other pacific islands. The price of diesel on the island of Rarotonga is at $2.52 (Cooksislands economic and development strategy handbook volume 1, 2013). Additionally, the import of fuels amount to 25% of the country's total imports and this represents 9% of the country's gross domestic product (Asian development bank , October 2014). 56% of the imported fuel is used in power generation (Asian development bank , October 2014).

Due to the dependency of the electricity generation on diesel, the electricity rates in Cooks' islands are higher than that of Australia. Accordingly, the residential rates in Rarotonga ranged from $0.53 to $0.79/kWh (Andrews, 2018), (Division, Cook Islands Renewable Energy Chart Implementation Plan, 2012).

In 2011 it announced a plan to achieve 100% renewable energy by 2020 (Olly Norojono, 2017). However, in 2016 the current share of renewable energy systems is only 15% (New Zealand Ministry of Foreign Affairs & Trade 2016, 2016). Currently the 2020 goal has not been fulfilled (Vila times , 2018). In addition, the country is currently facing the huge issue related to the storage due to the dependency on batteries (Vila times , 2018), (Andrews, 2018). This issue has postponed any further plans regarding generation from renewables due to the area limitations of the Rarotonga (Andrews, 2018), (Vila times , 2018). This presents a huge obstacle in further development and postponed the government from achieving their goal set in 2020, due to the current network which can't handle the excess generation from solar (Vila times , 2018). Additionally, the government has announced that they have reached a point where it's not possible to take on more renewable into the current grid (RNZ, 2016). The solution to this as mentioned by the government is the expansion of the grid (RNZ, 2016).

1.4. Rarotonga present power supply:

In the main Island of Rarotonga, power supply is provided by the government authority TAU (TE Aponga Uira) through a single power plant Avatiu Valley Power Station. The most recent data regarding the power status on Cooks islands and especially on Rarotonga is dated 2012 regarding the diesel generators and 2016 for renewables. As such these data are used in this report

In Rarotonga, the installed capacity is 9.5MW connected to six feeders to cover the island (Division, 2012). This installed capacity has dated from 12MW to 9.5 MW due to the depreciation of the nine generators used to generate electricity (Division, 2012). The maximum demand is 5 MW (Division, 2012).

The share of Renewables and especially solar is 3MW (Division, The cooksisalnds renweable energy chart , June, 2016). As shown in table 1, which represents 13% of the total energy share (Division, The cooksisalnds renweable energy chart , June, 2016). This still represents a very low percentage in comparison with the government goal of achieving 100% renewables by 2020 (Vila times , 2018). The electricity tariff in Rarotonga ranges from $053/Kwh for the residential sector to $0.79/Kwh for the commercial, with fuel representing 90% of the tariff cost (Division, Cook Islands Renewable Energy Chart Implementation Plan, 2012).

Table 1.4-1: Rarotonga electricity production and demand

Diesel installed capacity	**9.5MW**
Peak demand	5MW
Renewables installed capacity	3MW
Renewables share	13%
Annual energy generation	33 MWH
Electricity Tariff	$0.53 to $0.79/kWh.
Kwh/person	2201
Kwh/household	9581

1.5. Aim of the report:

The aim of this study is to present a possible and feasible solution towards the transition of the energy system to 100% sustainable energy systems. This has been done by analyzing different renewable energy technologies such as solar, wind, hydro and Biomass. Also, this study presents storage options to overcome the current issue impending further development of renewable technology especially on the main island of Rarotonga which is the main focus of the is study. The study also covers the commercial aspect of the proposed solution in addition to the environmental and social aspects and analysis of the current policies. Additionally, this study will provide recommendations for implementing this study.

2 Chapter two (Sarah)

2.1. Load Curve:

For the building of the model, it is necessary to define the demand per hour for a complete year. This is important for ensuring that the demand can be met and for defining the needed generation per hour from each renewable resource. This chapter illustrates the load curve calculation methodology in addition it provides an estimate to the load projection and forecast till 2040.

2.2. Load curve calculation methodology

The load profile for each hour of the year was calculation methodology was based on several steps. To begin with, a reliable source for the load profile for a typical day had to be found. This information was retrieved from “Cooks Island Renewable energy chart implementation plant “ (Division, Cook Islands Renewable Energy Chart Implementation Plan, 2012). This report is published by Renewable development division by the prime minister’s office. This is shown in figure 2.2-1. Its assumed based on the date of the report that the load curve is for the year 2011.

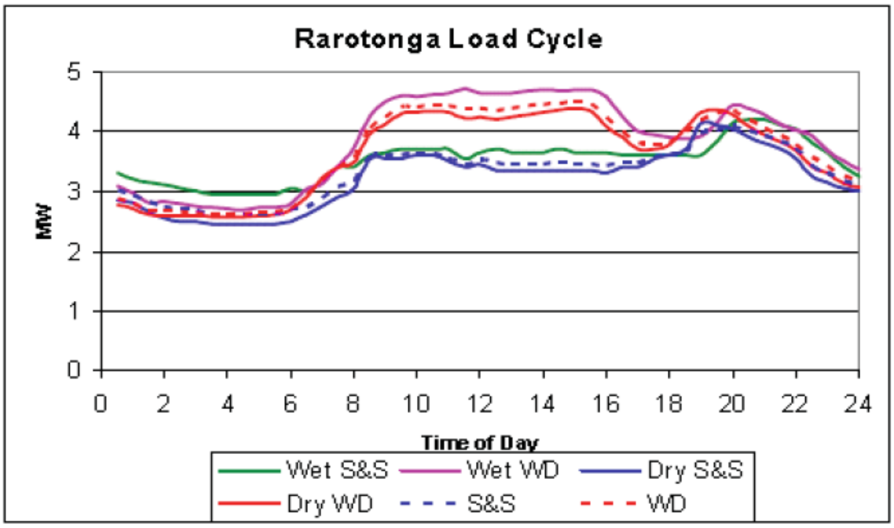


Figure 2.2-1: Rarotonga Load profile for a typical day as per CI renewable energy implementation plan.

From this figure, the load profiles were extracted using excel for S&S season (shoulder seasons) and WD (winter dry) season as shown in figures 2.2-2 and 2.2-3.

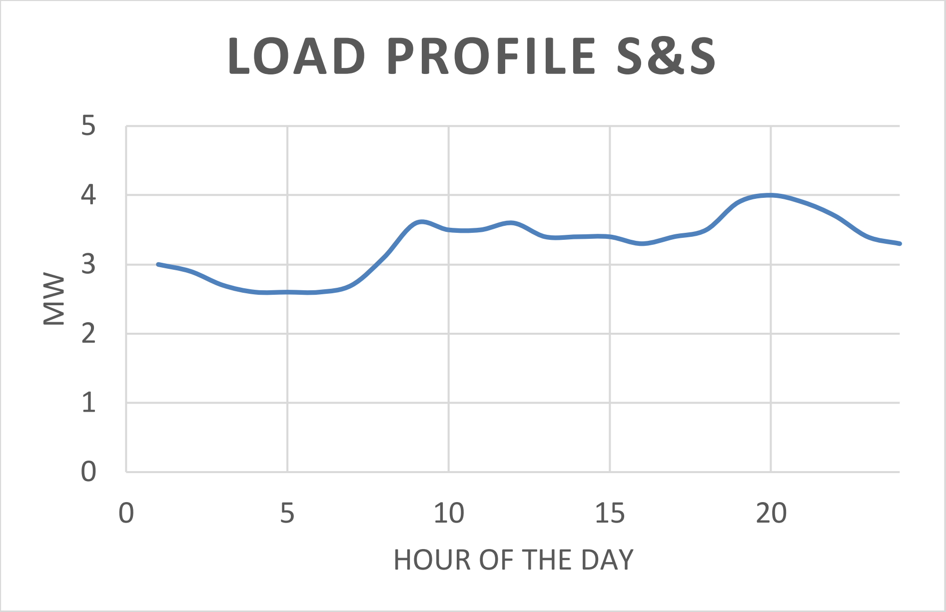


Figure 2.2-2: Rarotonga extracted load profile for S&S Season

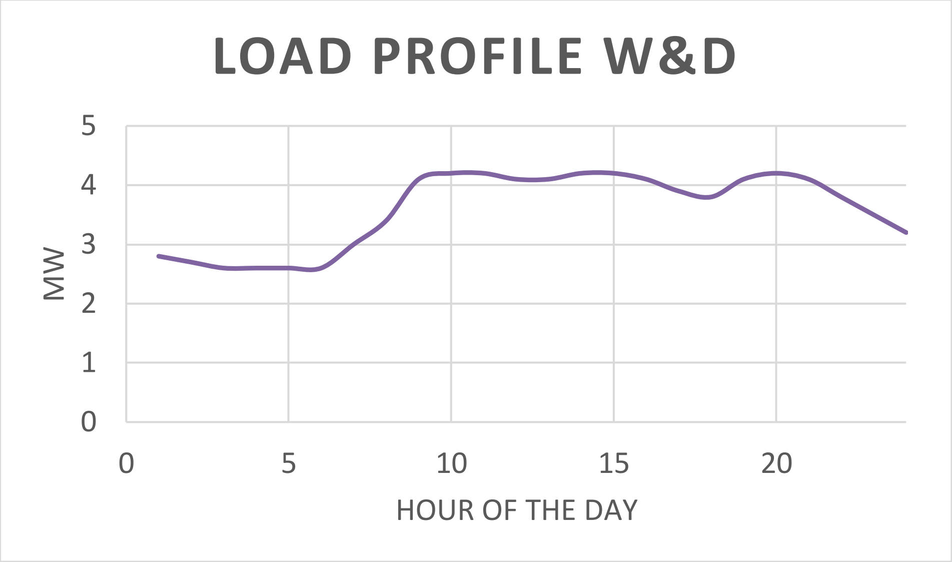


Figure 2.2-3: Rarotonga extracted load profile for WD Season

The extracted data show the same trend as the original trend shown in Figure 2-1. Following that, the number of days and thus the number of hours were defined for each season. For S&S season, the number of days is 153 and thus the number of hours is 3672 in a year. For the WD season, the number of days is 212 and thus the number of hours is 5088 in a year. This was used to convert from MW to MWH for each hour as shown in Table 2.2-1.

Table 2.2-1: MWH per each hour of Day

Time of Day	S&S MW	WD MW	Demand for SS (June to October) MWH	Demand for WD (Nov. to May) MWH	Demand for whole year (365) MWH
1	3	2.8	459	593.6	1052.6
2	2.9	2.7	443.7	572.4	1016.1
3	2.7	2.6	413.1	551.2	964.3
4	2.6	2.6	397.8	551.2	949
5	2.6	2.6	397.8	551.2	949
6	2.6	2.6	397.8	551.2	949
7	2.7	3	413.1	636	1049.1
8	3.1	3.4	474.3	720.8	1195.1
9	3.6	4.1	550.8	869.2	1420
10	3.5	4.2	535.5	890.4	1425.9
11	3.5	4.2	535.5	890.4	1425.9
12	3.6	4.1	550.8	869.2	1420
13	3.4	4.1	520.2	869.2	1389.4
14	3.4	4.2	520.2	890.4	1410.6
15	3.4	4.2	520.2	890.4	1410.6
16	3.3	4.1	504.9	869.2	1374.1
17	3.4	3.9	520.2	826.8	1347
18	3.5	3.8	535.5	805.6	1341.1
19	3.9	4.1	596.7	869.2	1465.9
20	4	4.2	612	890.4	1502.4
21	3.9	4.1	596.7	869.2	1465.9
22	3.7	3.8	566.1	805.6	1371.7
23	3.4	3.5	520.2	742	1262.2
24	3.3	3.2	504.9	678.4	1183.3
Total demand in MWH					**30,340.20**
Average demand per hour in MW					**3.46**
Average Demand per day in MW					**83.12**

From table 2.2-1, it is calculated that the total demand for Rarotonga per year is 30,340 MWH and the average demand for a typical day is 83.12 MW. Based on Barbados ratio of the Saturdays to weekdays which is 0.89 and Sunday to weekday which is 0.86, the demand for a typical Saturday and Sunday were calculated. Based on that the average demand per typical Saturday is 73.98 MW and Sunday is 71.48 MW. For simplicity, it was estimated that the demand for the holidays is equal to that of a typical Sunday.

Following that the calendar for cooks island was obtained (Calendar for Year 2011 (Cook Islands), 2019) to determine the number of working days, Saturdays, Sundays and holidays per month. Table 2.2-2 shows the calendar for Rarotonga for the year 2011.

Table 2.2-2 Rarotonga Calendar for the year 2011

2011	Days of month	Working days	Saturdays	Sundays	Holidays
January	31	21	4	4	2
February	28	20	4	4	0
March	31	21	5	5	0
April	30	19	4	4	3
May	31	23	4	4	0
June	30	19	5	5	1
July	31	23	4	4	0
August	31	20	5	4	2
September	30	21	4	5	0
October	31	21	4	4	2
November	30	21	5	4	0
December	31	20	5	4	2

Following that, the monthly generation had to be estimated. This was done by obtaining the total generated energy in the year 2011/2012. This information was obtained from the yearly issued report by TAU (Te Aponga Uira O Tumu TE Varovaro , 2012). This value is 28,869 MWH which is close to the calculated value in table 2.

Then using the total generated energy in a year, the monthly generation was calculated by dividing the total days per month by 365 and multiplying the total yearly energy generated by this percentage. Table 2.2-3 shows the results of this calculation.

Table 2.2-3: Rarotonga Generation per month

Month	number of days	number of days per month/ total number of days in a year	Total generation per month MWH
Jan	31	9%	2,458.70
Feb	28	8%	2,220.76
Mar	31	9%	2,458.70
Apr	30	8%	2,379.39
May	31	9%	2,458.70
Jun	30	8%	2,379.39
Jul	31	9%	2,458.70
Aug	31	9%	2,458.70
Sep	30	8%	2,379.39
Oct	31	9%	2,458.70
Nov	30	8%	2,379.39
Dec	31	9%	2,458.70

Based on the calculated values for the average demand of the typical weekday, Saturday and Sunday, and based on the values calculated in table 2.2-3, the demand was calculated for each month of the year. For simplicity the number of holidays per each month were added to the number of Sundays. Table2.2-5 shows the results.

Table 2.2-4: Demand per typical type of days for each month

	Monthly generation in MWH	Number of weekdays	Saturdays	Sundays & Holidays	Holidays	Monthly demand in MWH	ratio generation/ Demand	Saturday	Sunday	weekday
Jan	2,458.70	21	4	6	2	2,470.33	0.995	73.63	71.147	82.73
Feb	2,220.76	20	4	4	0	2,244.24	0.990	73.20	70.735	82.25
Mar	2,458.70	21	5	5	0	2,472.82	0.994	73.55	71.075	82.65
Apr	2,379.39	19	4	7	3	2,375.57	1.002	74.10	71.598	83.25
May	2,458.70	23	4	4	0	2,493.60	0.986	72.94	70.483	81.96
Jun	2,379.39	20	5	6	1	2,461.18	0.967	71.52	69.108	80.36
Jul	2,458.70	23	4	4	0	2,493.60	0.986	72.94	70.483	81.96
Aug	2,458.70	22	5	5	1	2,555.94	0.962	71.16	68.764	79.96

Sep	2,379.39	21	4	5	0	2,398.84	0.992	73.38	70.903	82.45
Oct	2,458.70	22	4	5	1	2,481.96	0.991	73.28	70.813	82.34
Nov	2,379.39	21	5	4	0	2,401.34	0.991	73.30	70.830	82.36
Dec	2,458.70	20	5	6	2	2,461.18	0.999	73.90	71.411	83.04

Table 2.2-5 shows the demand for each type of day per month. In order to drive the timely series for the year a relationship needed to be defined for each hour of the day. This was defined by dividing the total demand for each hour of the day by the total demand per year

Table 2.2-5: Relationship between total demand per each hour to the total demand per year

Time of Day	Demand for whole year for each hour MWH	Demand per hour for a year in MWH / Total demand per year in MWH
1	1052.6	0.0347
2	1016.1	0.0335
3	964.3	0.0318
4	949	0.0313
5	949	0.0313
6	949	0.0313
7	1049.1	0.0346
8	1195.1	0.0394
9	1420	0.0468
10	1425.9	0.0470
11	1425.9	0.0470
12	1420	0.0468
13	1389.4	0.0458
14	1410.6	0.0465
15	1410.6	0.0465
16	1374.1	0.0453
17	1347	0.0444
18	1341.1	0.0442
19	1465.9	0.0483
20	1502.4	0.0495
21	1465.9	0.0483
22	1371.7	0.0452
23	1262.2	0.0416
24	1183.3	0.0390

Total demand in a year MWH	30,340 MWH

Based on this ratio shown in table 2.2-5 and the total demand calculated per each type of a typical day per month the demand for each was hour was calculated by multiplying the ratio for each hour shown in table 2.2-5 by the total demand for each type of day for each month shown in table2.2- 4. Table 2.2-6 shows a sample for a typical Sunday, Saturday and Weekday for the month of January.

Table 2.2-6: Sample of the hourly generation for the three different type of days

Month	annual demand per Hour in MWH/Total demand per year in MWH	Hour of a year	hour of day	day	Type day	Load in MW
January	0.035	241	1	Friday	weekday	2.63
January	0.033	242	2	Friday	weekday	2.54
January	0.032	243	3	Friday	weekday	2.41
January	0.031	244	4	Friday	weekday	2.37
January	0.031	245	5	Friday	weekday	2.37
January	0.031	246	6	Friday	weekday	2.37
January	0.035	247	7	Friday	weekday	2.86
January	0.039	248	8	Friday	weekday	3.26
January	0.047	249	9	Friday	weekday	3.87
January	0.047	250	10	Friday	weekday	3.89
January	0.047	251	11	Friday	weekday	3.89
January	0.047	252	12	Friday	weekday	3.87
January	0.046	253	13	Friday	weekday	3.79
January	0.046	254	14	Friday	weekday	3.85
January	0.046	255	15	Friday	weekday	3.85
January	0.045	256	16	Friday	weekday	3.75
January	0.044	257	17	Friday	weekday	3.67
January	0.044	258	18	Friday	weekday	3.66
January	0.048	259	19	Friday	weekday	4.00
January	0.050	260	20	Friday	weekday	4.10
January	0.048	261	21	Friday	weekday	4.00
January	0.045	262	22	Friday	weekday	3.74
January	0.042	263	23	Friday	weekday	3.44
January	0.039	264	24	Friday	weekday	3.23
January	0.035	265	1	Saturday	Saturday	2.63
January	0.033	266	2	Saturday	Saturday	2.54
January	0.032	267	3	Saturday	Saturday	2.41
January	0.031	268	4	Saturday	Saturday	2.37
January	0.031	269	5	Saturday	Saturday	2.37
January	0.031	270	6	Saturday	Saturday	2.37

January	0.035	271	7	Saturday	Saturday	2.55
January	0.039	272	8	Saturday	Saturday	2.90
January	0.047	273	9	Saturday	Saturday	3.45
January	0.047	274	10	Saturday	Saturday	3.46
January	0.047	275	11	Saturday	Saturday	3.46
January	0.047	276	12	Saturday	Saturday	3.45
January	0.046	277	13	Saturday	Saturday	3.37
January	0.046	278	14	Saturday	Saturday	3.42
January	0.046	279	15	Saturday	Saturday	3.42
January	0.045	280	16	Saturday	Saturday	3.33
January	0.044	281	17	Saturday	Saturday	3.27
January	0.044	282	18	Saturday	Saturday	3.25
January	0.048	283	19	Saturday	Saturday	3.56
January	0.050	284	20	Saturday	Saturday	3.65
January	0.048	285	21	Saturday	Saturday	3.56
January	0.045	286	22	Saturday	Saturday	3.33
January	0.042	287	23	Saturday	Saturday	3.06
January	0.039	288	24	Saturday	Saturday	2.87
January	0.035	289	1	Sunday	Sunday	2.63
January	0.033	290	2	Sunday	Sunday	2.54
January	0.032	291	3	Sunday	Sunday	2.41
January	0.031	292	4	Sunday	Sunday	2.37
January	0.031	293	5	Sunday	Sunday	2.37
January	0.031	294	6	Sunday	Sunday	2.37
January	0.035	295	7	Sunday	Sunday	2.46
January	0.039	296	8	Sunday	Sunday	2.80
January	0.047	297	9	Sunday	Sunday	3.33
January	0.047	298	10	Sunday	Sunday	3.34
January	0.047	299	11	Sunday	Sunday	3.34
January	0.047	300	12	Sunday	Sunday	3.33
January	0.046	301	13	Sunday	Sunday	3.26
January	0.046	302	14	Sunday	Sunday	3.31
January	0.046	303	15	Sunday	Sunday	3.31
January	0.045	304	16	Sunday	Sunday	3.22
January	0.044	305	17	Sunday	Sunday	3.16
January	0.044	306	18	Sunday	Sunday	3.14
January	0.048	307	19	Sunday	Sunday	3.44
January	0.050	308	20	Sunday	Sunday	3.52
January	0.048	309	21	Sunday	Sunday	3.44
January	0.045	310	22	Sunday	Sunday	3.22
January	0.042	311	23	Sunday	Sunday	2.96
January	0.039	312	24	Sunday	Sunday	2.77
January	0.035	313	1	Monday	weekday	2.63

January	0.033	314	2	Monday	weekday	2.54
January	0.032	315	3	Monday	weekday	2.41
January	0.031	316	4	Monday	weekday	2.37
January	0.031	317	5	Monday	weekday	2.37
January	0.031	318	6	Monday	weekday	2.37
January	0.035	319	7	Monday	weekday	2.86
January	0.039	320	8	Monday	weekday	3.26
January	0.047	321	9	Monday	weekday	3.87
January	0.047	322	10	Monday	weekday	3.89
January	0.047	323	11	Monday	weekday	3.89
January	0.047	324	12	Monday	weekday	3.87
January	0.046	325	13	Monday	weekday	3.79
January	0.046	326	14	Monday	weekday	3.85
January	0.046	327	15	Monday	weekday	3.85
January	0.045	328	16	Monday	weekday	3.75
January	0.044	329	17	Monday	weekday	3.67
January	0.044	330	18	Monday	weekday	3.66
January	0.048	331	19	Monday	weekday	4.00
January	0.050	332	20	Monday	weekday	4.10
January	0.048	333	21	Monday	weekday	4.00
January	0.045	334	22	Monday	weekday	3.74
January	0.042	335	23	Monday	weekday	3.44
January	0.039	336	24	Monday	weekday	3.23

2.3. Results:

Based on the calculation methodology presented in section 2.2, the following figures were obtained as follows, figure 2.3-1 shows the demand for a typical weekday of a month. Figure 2.3-2 shows the demand for a typical Saturday and figure 2.2-3 shows the typical demand for a Sunday and Saturday. From these figures, the results show the same trend as the original trend shown in figure 2.2-1. In addition, the total demand for year based on the load profile calculation methodology was found to be 28,480.42 MWH compared with the stated annual demand in the TAU annual report (Te Aponga Uira O Tumu TE Varovaro , 2012) which is 28,869.90 MWh thus the variance between the two values is of 0.01. This is due to the calculation's estimations. However, this variance is of a small value and thus can be accepted.

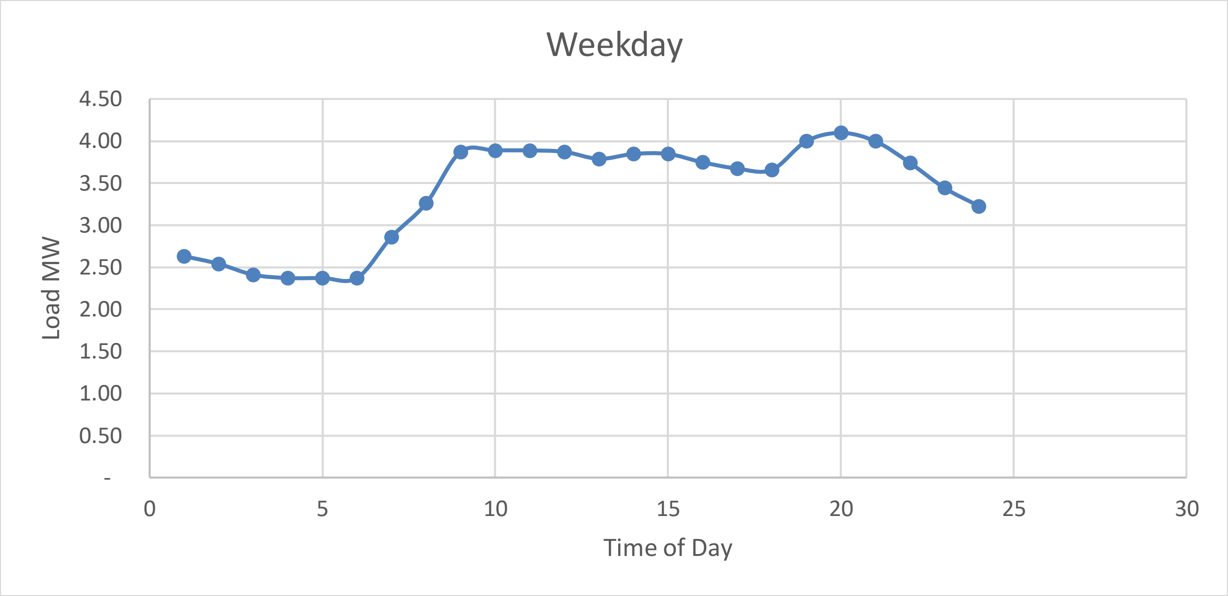


Figure 2.3-1: Demand for a typical weekday of a month

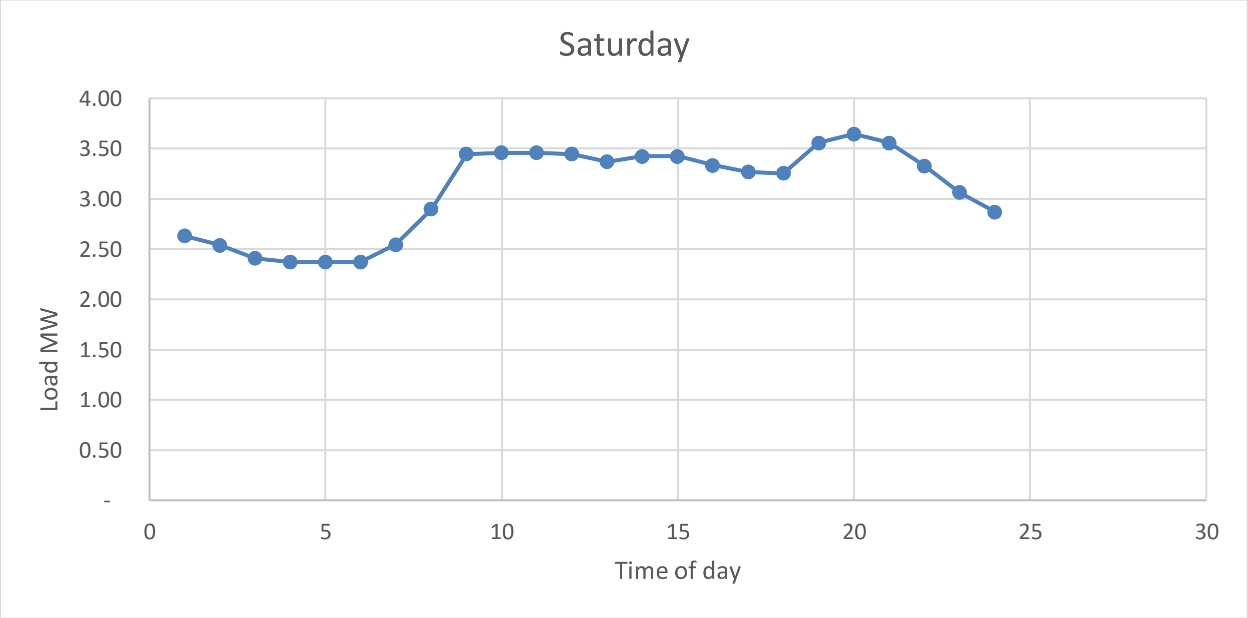


Figure 2.3-2: Demand for a typical Saturday of a month

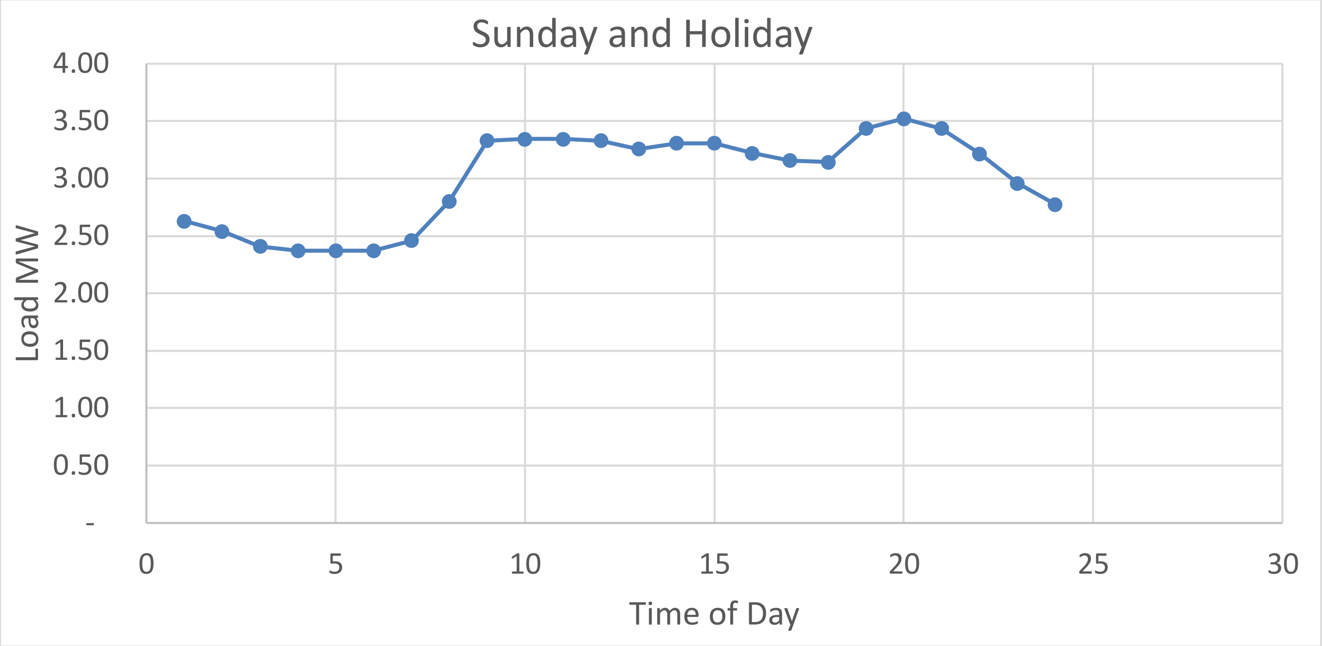


Figure 2.3-3: Demand for a Typical Sunday and holiday of a month

Also figures 2.3-4 and 2.3-5 show the demand for a typical month of a year and the demand for a typical year.

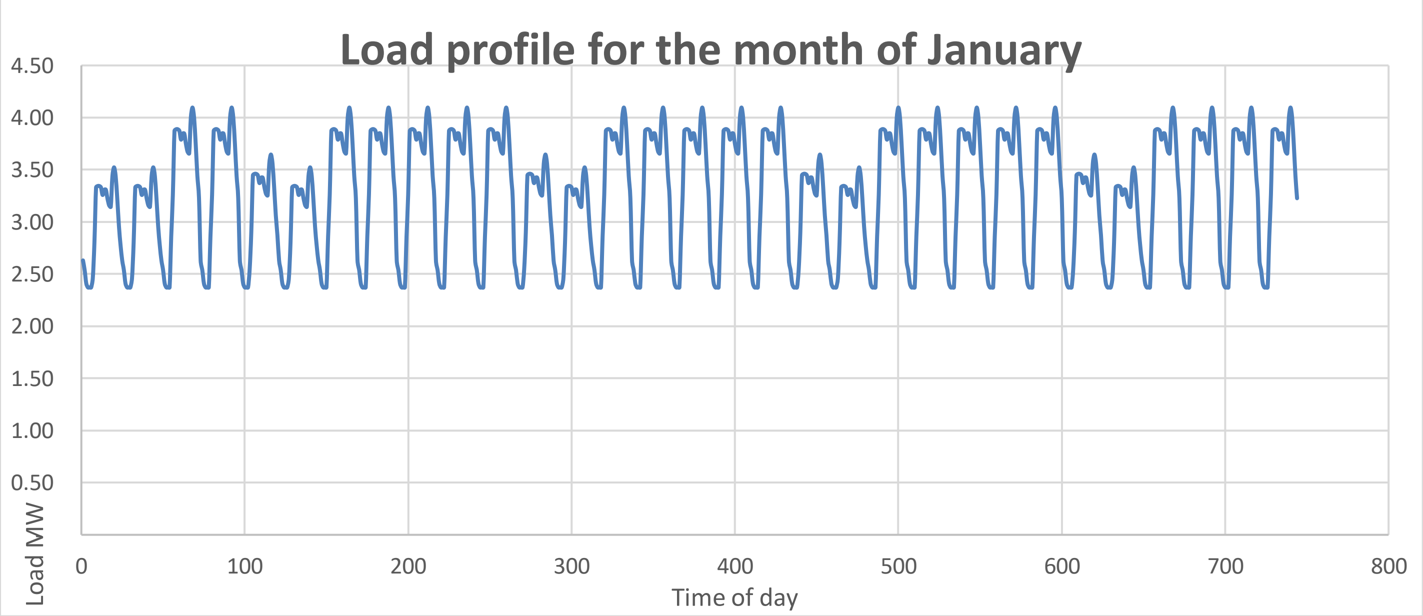
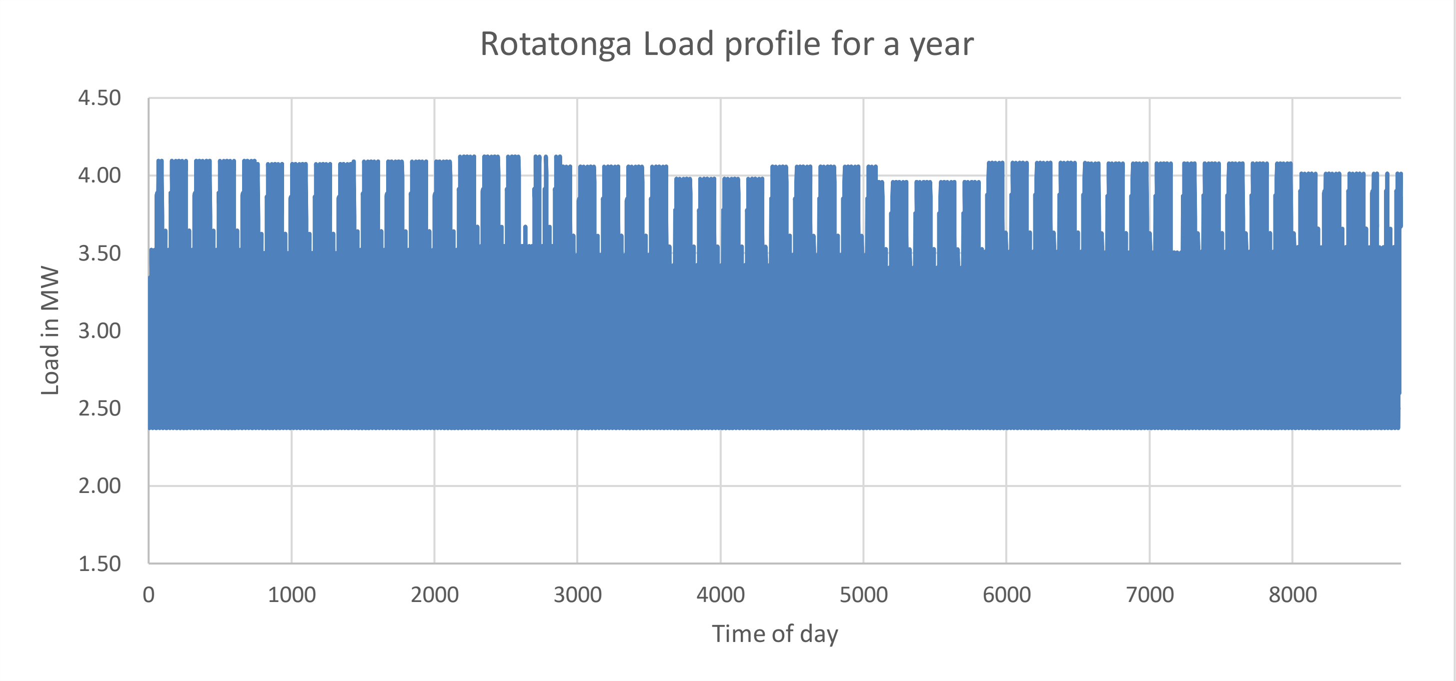


Figure 2.3-4: Demand for a typical month of a year



2.4. Demand projection and forecast:

Since the methodology of the calculation was based on the obtained curve of 2011, thus the demand needed to be projected to the year of 2019. Additionally, since the duration of the project is estimated till 2040, the demand needed to be forecasted till the year 2040. In order to reach these estimations, the following methodology was adapted:

1) Normal GDP data:

First, data regarding the real GDP needed to be obtained. This data was obtained from cook's islands annual national accounts tables (Ministry of fianance and economic managment, cooks isalnds , 2018). The GDP data is published from the year 2006 till 2017, as shown in table 2.4-1.

Table 2.4-1: Gross Domestic Product at Constant 2016 Prices($million)

	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
GDP at Constant 2016 Prices	**391.3**	**398.4**	**393.5**	**392.7**	**373.3**	**376.4**	**379.1**	**380.7**	**401.2**	**424.3**	**445.2**	**487.5**

2) Calculation of the GDP annual growth rate:

Based on these data the annual growth rate of the GDP was calculated. Table 2.4-2 shows the values of this calculation.

Table 2.4-2: annual Growth rate

Year	Real GDP Million	GDP growth rate calculated from 2006 to 2017
2006	391.30	-
2007	398.40	**1.81%**
2008	393.47	**-1.24%**
2009	392.67	**-0.20%**
2010	373.30	**-4.93%**
2011	376.39	**0.83%**
2012	379.06	**0.71%**
2013	380.68	**0.43%**
2014	401.23	**5.40%**
2015	424.30	**5.75%**
2016	445.15	**4.91%**
2017	487.50	**9.51%**

3) Forecasting GDP value and annual growth rate till 2040

Based on table 2.4-2, the GDP value and the annual growth rate till 2040 could be calculated. This was done by taking the average of the annual growth rate form 2006 till 2017. This value is equal to 2.09%. Based on this average annual growth rate the GDP value was calculated till the year 2040.

4) Energy gains

According to the report published by the international institute for energy conservation for the Asian development bank (International insitiute for energy conservastion , 2013), starting from the year 2012 the cooks islands has implemented energy efficiency program to reduce energy use by 836,271 KWH/ year.

The implementation for this program has already proceeded as the streetlights have already been changed to more efficient bulbs. In addition, awareness sessions have been conducted to consumers.

5) The total demand of cooks' islands and Rarotonga:

Based on (Division, Cook Islands Renewable Energy Chart Implementation Plan, 2012) the total demand for Cooks Islands is 33,833 MWH in 2011. Based on (Te Aponga Uira O Tumu TE Varovaro , 2012) the total demand for Rarotonga in 2011 was 28,828.00 MWH. Thus, the demand in Rarotonga represents 87% of the total cooks Islands demand.

6) Demand forecast till 2040:

Since the data related to the demand is available for 2011 and since the implementation of the energy saving program started in 2013, thus it was assumed that the demand for 2012 is same for that of 2011.

Based on the available data regarding the annual growth rate, energy saving % for each year and the demand of Cook’s islands in 2011 and that of Rarotonga in 2011, the demand till 2040 could be forecasted. This was done by multiplying the annual growth rate and the energy saving from the demand of each year to predict the next year starting from the year 2011. Table 2.4-3 shows the results of the final calculations.

According to (Division, Cook Islands Renewable Energy Chart Implementation Plan, 2012), the air conditioner penetration has already reached a saturation in 2011. According, it can be inferred that there will not be a major in demand in future. In addition, to the current situation in Cooks’ islands were most of the young population are immigrating to New Zealand and Australia. Also, according to (UNICEF, 2013) the population growth rate till 2030 is estimated to be by 0.7%. This makes the total population of Rarotonga by 2040 to be 14,228.06 while it was 13, 500 in 2011. Thus, this makes the total increase of the population between 2040 and 2011 5%.

Table 2.4-3: Demand forecast till 2040

Year	GDP growth rate calculated from 2006 to 2017	Cook Islands Demand forecast based on 836,271 KWH/ year energy saving and GDP	Rarotonga demand based on energy saving and GDP MWH
2007	1.81%		
2008	-1.24%		
2009	-0.20%		
2010	-4.93%		
2011	0.83%	33,833.80	28,828.00
2012	0.71%	33,833.80	28,828.00
2013	0.43%	33,140.49	28,237.26
2014	5.40%	34,108.82	29,062.33
2015	5.75%	35,225.21	30,013.54
2016	4.91%	36,083.55	30,744.89

2017	9.51%	38,622.40	32,908.11
2018	2.09%	38,473.02	32,780.84
2019	2.09%	38,324.22	32,654.05
2020	2.09%	38,176.00	32,527.75
2021	2.09%	38,028.34	32,401.95
2022	2.09%	37,881.26	32,276.63
2023	2.09%	37,734.75	32,151.79
2024	2.09%	37,588.80	32,027.44
2025	2.09%	37,443.42	31,903.57
2026	2.09%	37,298.60	31,780.17
2027	2.09%	37,154.34	31,657.26
2028	2.09%	37,010.64	31,534.82
2029	2.09%	36,867.50	31,412.85
2030	2.09%	36,724.91	31,291.36
2031	2.09%	36,582.87	31,170.33
2032	2.09%	36,441.38	31,049.78
2033	2.09%	36,300.43	30,929.69
2034	2.09%	36,160.03	30,810.06
2035	2.09%	36,020.18	30,690.90
2036	2.09%	35,880.86	30,572.19
2037	2.09%	35,742.09	30,453.95
2038	2.09%	35,603.85	30,336.16
2039	2.09%	35,466.15	30,218.83
2040	2.09%	35,328.97	30,101.96

3 Chapter Three: Resource assessment

3.1. Wind Resource Assessment (Ammar)

Assessing the wind resource for any specific area requires deep understanding of the area, its geography, topology, environment, climate and resource of wind available to harness the energy. All these factors and in addition to some more effects the total energy predicted to be generated by wind turbines. Starting with the climate, temperature and humidity directly and air density indirectly effects the performance of turbines.

3.1.1 Temperature

Temperature effects the production of electrical energy from wind turbines. If the temperature is higher above than the technical limits of turbine, it cannot generate the required amount of energy even if we have the wind resource available. So, it is important to analyse temperature of the region. The table below shows the average temperature of island. It is evident that the temperature is quiet constant over the year and no considerable variation can be seen among the hottest and the coldest months. The annual mean temperature is calculated at 21.8 degrees Celsius.

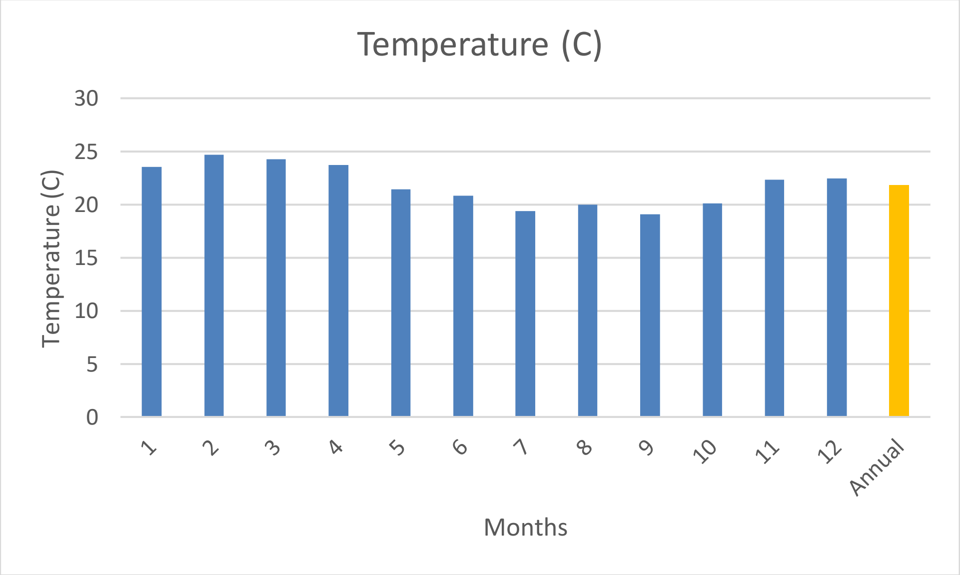


Figure 3.1-1: Annual Mean Temperature

We can say that there is no division of seasons like summers and winters, but we can divide the weathers in rainy and dry seasons.

3.1.2 Wind Speed

Before doing the investment in wind power plant, it is preferable to have on-ground measurements of various metrological parameters including wind speed, direction, pressure, humidity, precipitation at different heights. But at the initial stage to get an estimate of available resource, data available through different remote sources like EMD ERA, MERRA2, or simulation data based on historical data. For the analysis, we have used simulation data available for hourly resolution and satellite data by EMD ERA available on 6-hourly resolution. A correlation was built for both data as shown in the graph below.

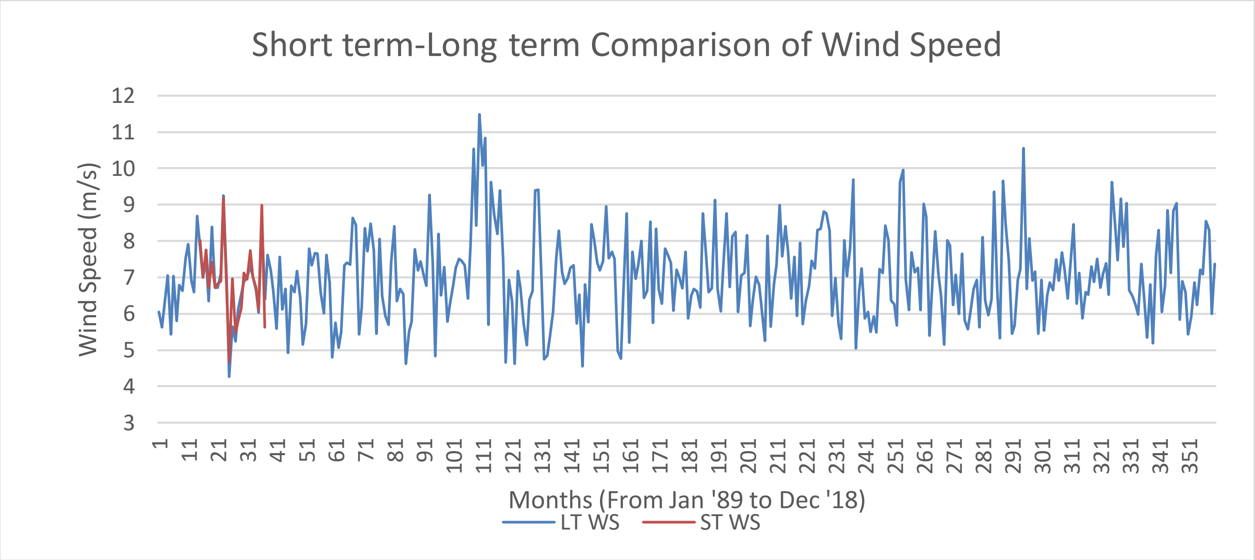


Figure 3.1-2: Correlation of Wind Speed by Different Sources

From the above graph, we can see the trend of both lines are similar when data is available for both sources. Based on the correlation, we can use our short-term wind data as long-term wind data and estimate the energy yield from wind turbines.

Further analysis of wind speed shows the annual mean values of wind speed which are used for resource assessment and energy yield estimations. Annual mean wind speed in 6.6m/s.

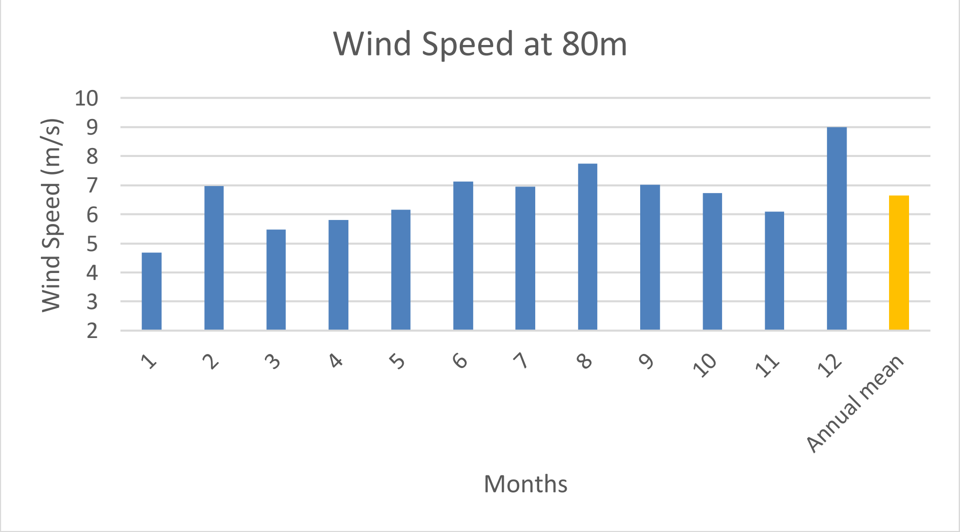


Figure 3.1-3: Annual mean wind speed in m/s

It is also important to know the frequency of different wind speed bins. We can see in the below graph that most of the times wind is blowing in the range of 5-8 m/s. It helps us in finding and selecting a suitable wind turbine for assessment and installation. Different turbines are designed for different wind speed ranges. So, when we know the most frequent wind speeds, we can select those turbines which have higher Power Coefficient Cp in these wind speed range.

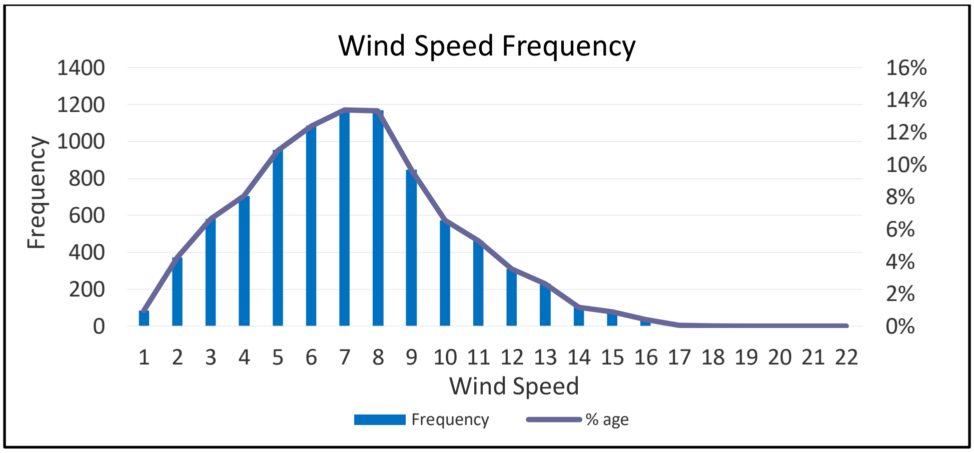


Figure 3.1-4: Wind speed frequency in 1m/s bins

If we look into resource map of wind, it shows that there are some locations on island where the wind speed is very high. These locations usually lie on the tips of mountains. The below image shows us the different wind speeds in different locations of the island. The outer periphery in orange colour show the area which cannot be utilized for installing wind turbines as it is used for other purposes.

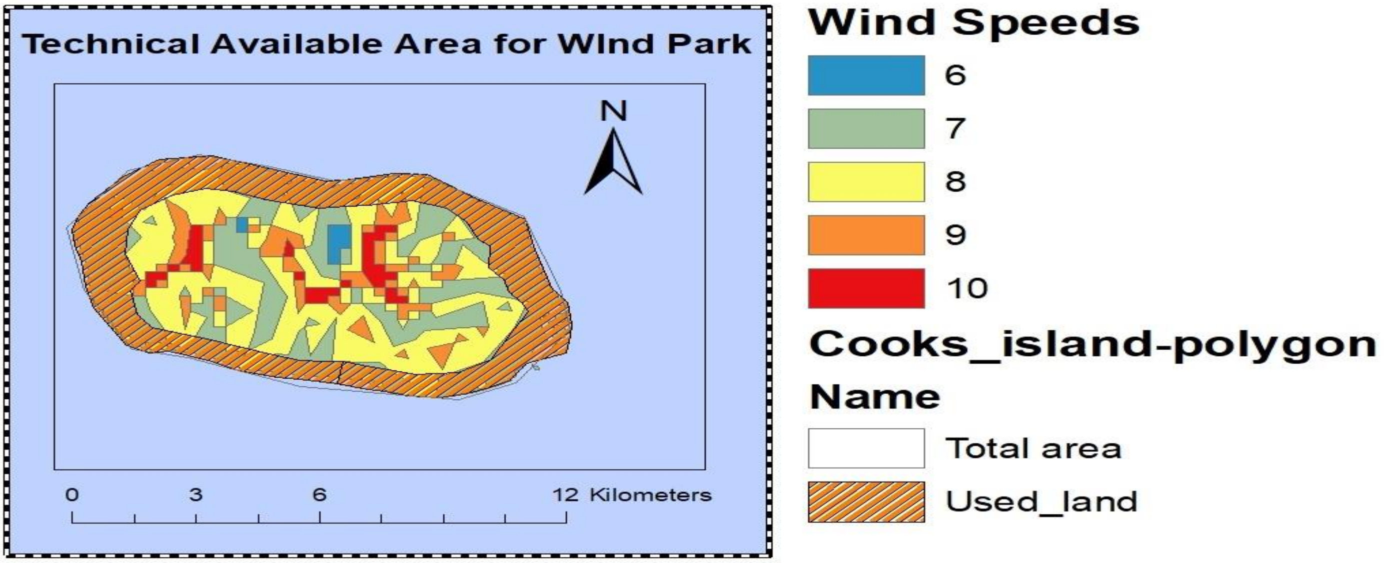


Figure 3.1-5: Wind Resource map and Available Area

This map can be visualized in conjunction with elevation map of the island. The darker colours show the higher elevations whereas blue colour shows the sea level elevation.

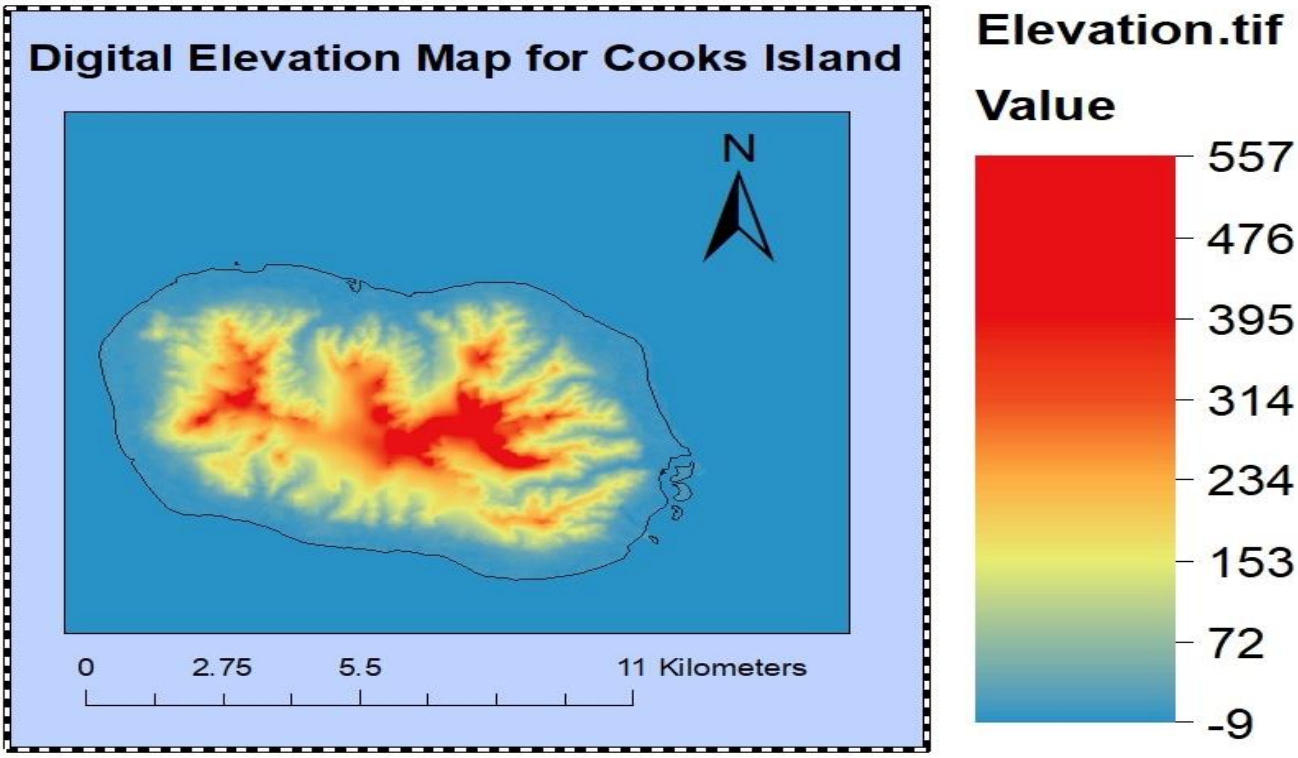


Figure 3.1-6: Digital Elevation Model of Island

3.1.3 Energy Yield Estimations

After getting the resource assessment, annual energy yield estimations can be performed. Now we have to analyse theoretical potential as well as economic potential keeping in my the constrains of demand and initial investment required. The total area of island is approx. 70km^2. Different assumptions are being followed worldwide for area requirement of wind farms. According to NREL, 4MW of wind turbines can be installed on area of 1km^2. But if the resource is good, we can take assumption of 10MW for 1km^2. Following this assumption, we get to a theoretical potential of 70*10=700 MW.

Keeping in mind that it is theoretical potential and all of it cannot be utilized. So, in order to get economical potential, we have to remove the area which are either protected or very near to residential areas to avoid NIMBYism. After removing such areas, we are left with around 30km^2 of area. We can install 300MW of wind turbines in this area. Keeping in mind the peak demand on the island which is approx. 6 MW, this potential of 300MW is too much. So, depending on the investment and other renewables energy mix, we can install any quantity to meet our total demand.

3.1.4 Power Curve

To get the actual Energy prognosis, we have to select the turbine which is best suited for the environment. Every environment has different elevations, temperatures and Wind speeds and each turbine reacts differently by changing these parameters. If we take Wind speeds into account at the moment, we can guess the output by looking at the below power curve of Gamesa G114-2.0.

Table 3.1-1: Power Curve G114-2.0

Wind speed [m/s]	Power [kW]	Cp
3	32	0.187
4	146	0.336
5	342	0.437
6	621	0.46
7	1008	0.47
8	1487	0.464
9	1858	0.408
10	1984	0.317
11	1995	0.24
12	2000	0.185
13	2000	0.146
14	2000	0.117
15	2000	0.095
16	2000	0.078
17	2000	0.065
18	2000	0.055
19	2000	0.047
20	2000	0.04
21	2000	0.035
22	1906	0.029
23	1681	0.022
24	1455	0.017
25	1230	0.013

Same can be visualized in graphical form as below:

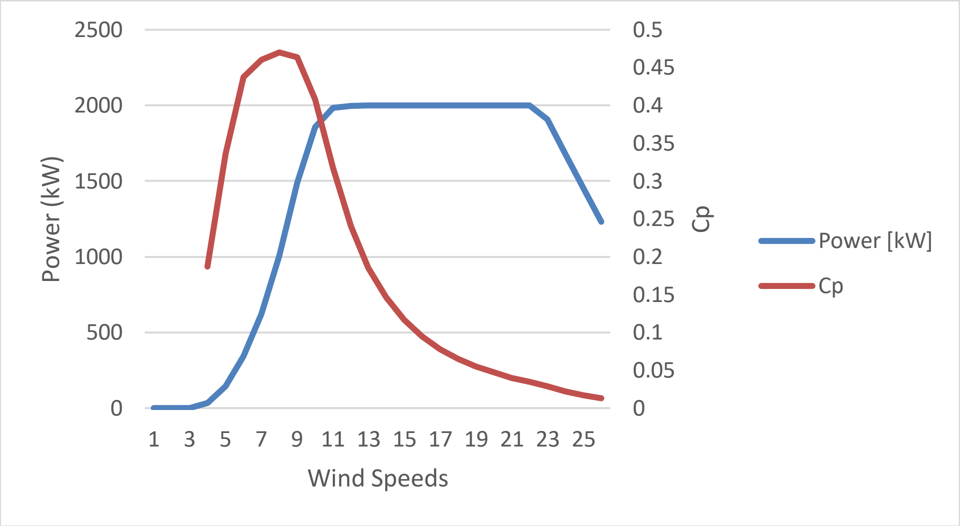


Figure 3.1-7: Power Curve and Cp of G114-2.0

It can be seen that Cp is highest in that range where the frequencies of wind speed are higher. In this case we will not be targeting the rated capacity of turbine but the best partial load operation of the turbine.

If we plan to install Wind farm of 5MW, following Capacity Factor can be expected.

Table 3.1-2: Energy Generation from different turbines

Turbine	GW90-2000	GE2000	Gamesa G114-2.0
Production GWh	9.78	10.61	11.14
Capacity Factor	22%	24%	25%

From the table we can say that installing Gamesa G114-2.0 turbine will be best suited for installation technically. But we also have to take a look at the costs of installation and O&M.

Now in order to find the best locations for installation of turbines, we need to look into elevation as well as good resourceful areas of wind. The below map shows those area where elevation is higher, and it will be beneficial to install the turbines in such areas.

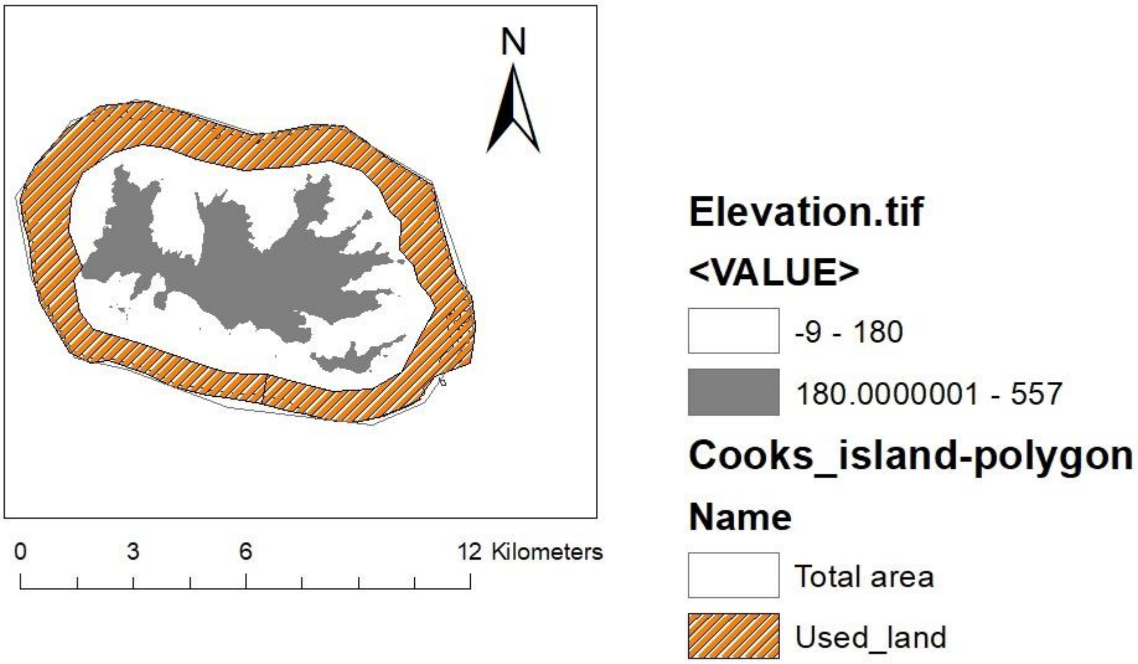


Figure 3.1-8: Places with high elevations

The second important factor which need to be catered while selecting the location is high wind speeds. We converted the wind speed in binary (0= not good, 1=good) and plotted them on the map. All the points with wind speed 7 or below are in white whereas higher windspeeds are shown in grey colour.

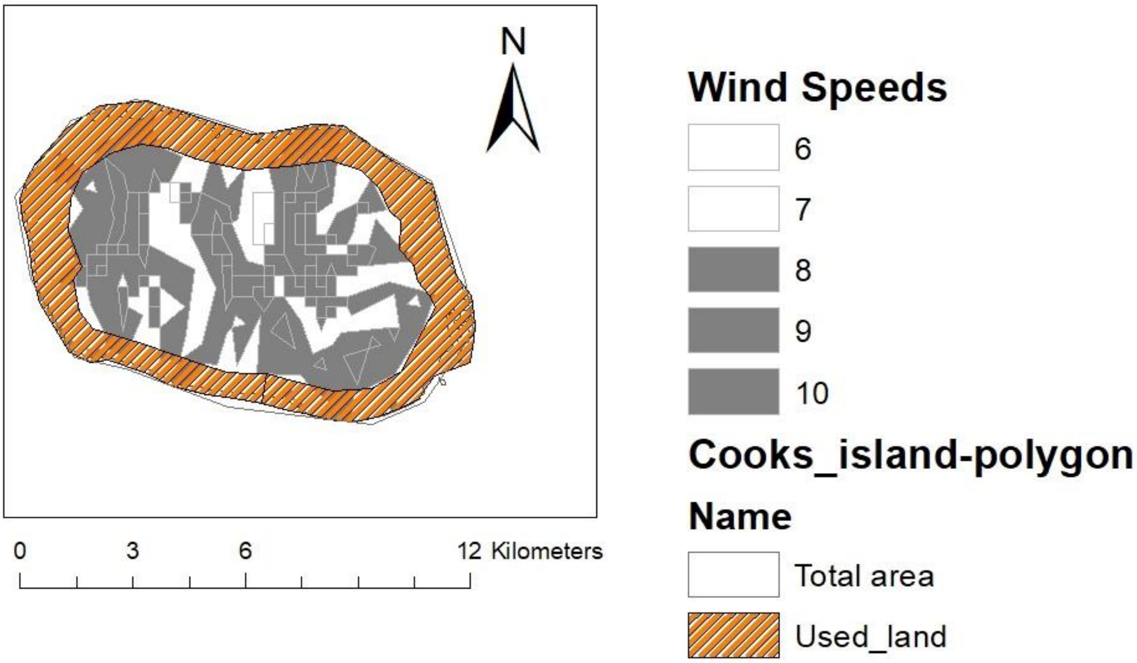


Figure 3.1-9: High Wind speed Areas

So, when we put both of these layers together, their intersection gives us the best elevated as well as best wind resource locations. Those areas can be used to place the turbines to get highest output from wind all around the year. The results are shown below with possible location for 2 turbines.

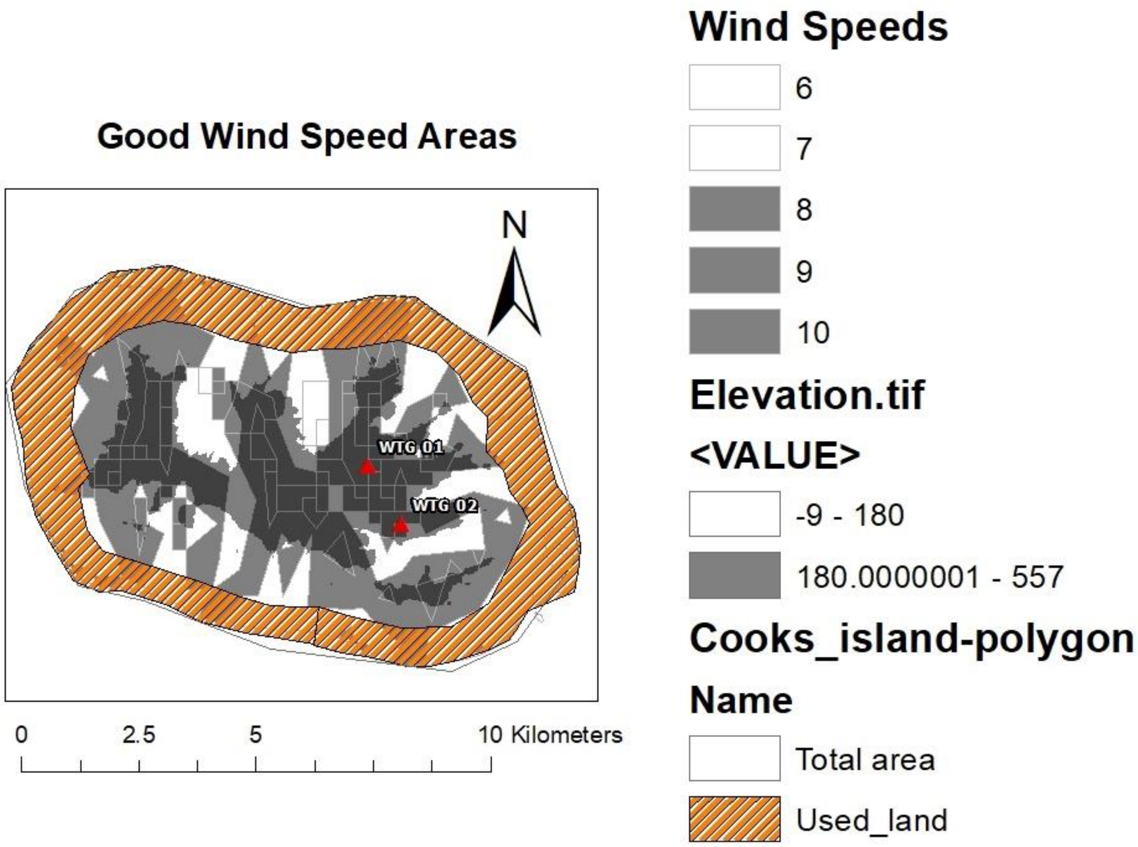


Figure 3.1-10: Best possible locations of wind turbines

3.2 Hydro Resource Assessment (Sarah)

In order to reach 100% renewable energy supply on Rarotonga, all possible renewable resources had to be analyzed. Due to the high elevations on the Rarotonga island, which is 653m, and the available water streams, a hydro potential presented as a possibility.

3.2.1 Methodology

Hydro assessment was done using ARCGIS. The Aster map for Rarotonga was downloaded from NASA earth data website. The ASTER map showed the highest elevation to be 575m. However, this map was used in the analysis as it presented the best quality amongst the other ASTER maps checked from other websites such as Earth Explorer website.

The simulation resulted in three possible locations for catchment areas as per figure 3.2-1. For Catchment area 1, the head difference is 250m and the total area is 148.4meters squared. For catchment area 2, the head difference is 300m and the total area is 152.198meters squared, and the head for catchment area 3 is 200m while the total area is 408.95 meters squared. Figures 3.2-2, 3.2-3 and 3.2-4 illustrates the different heads for the three catchment areas.

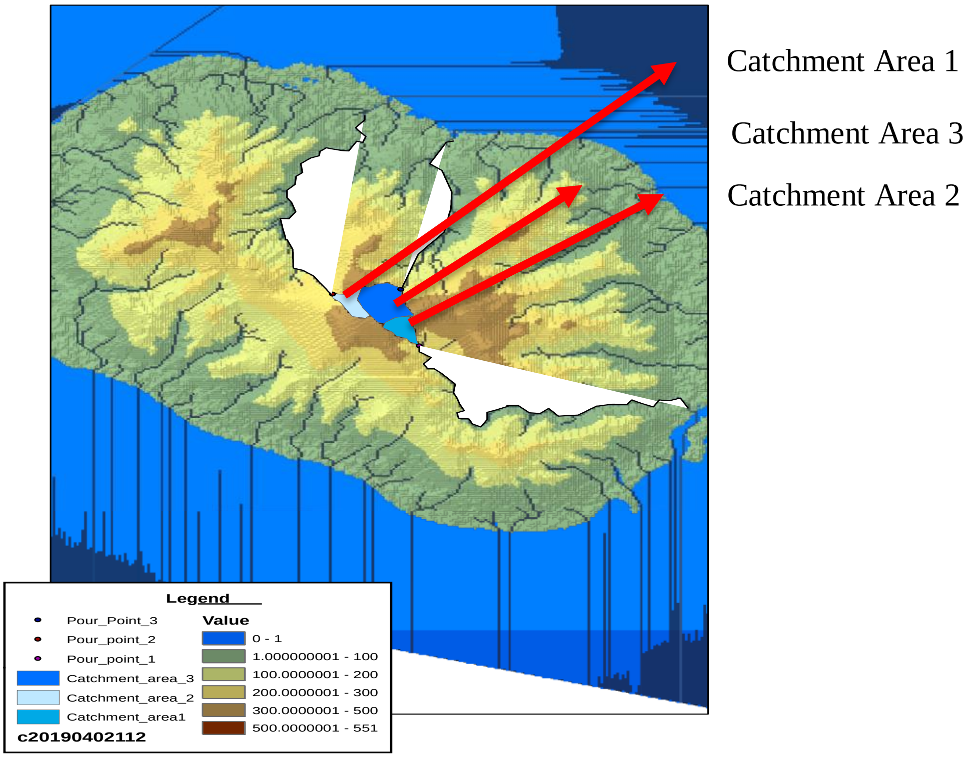


Figure 3.2-1: three catchment areas defined by ARCGIS

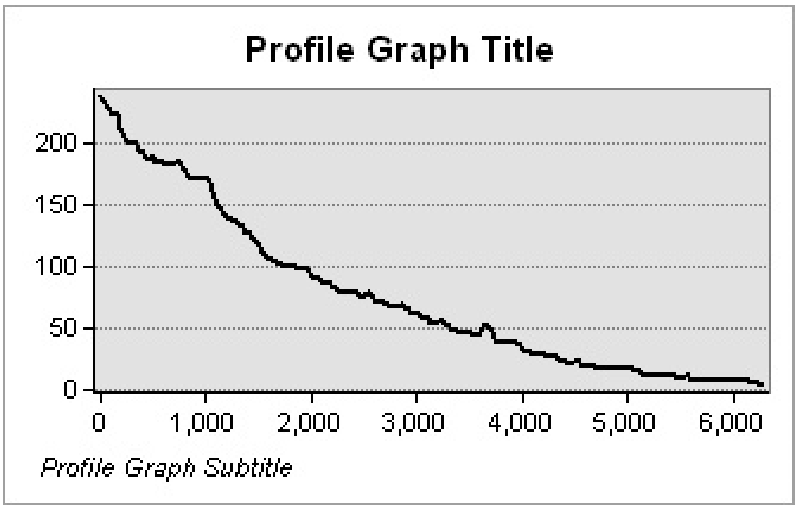


Figure 3.2-2 :Head difference for catchment area 1

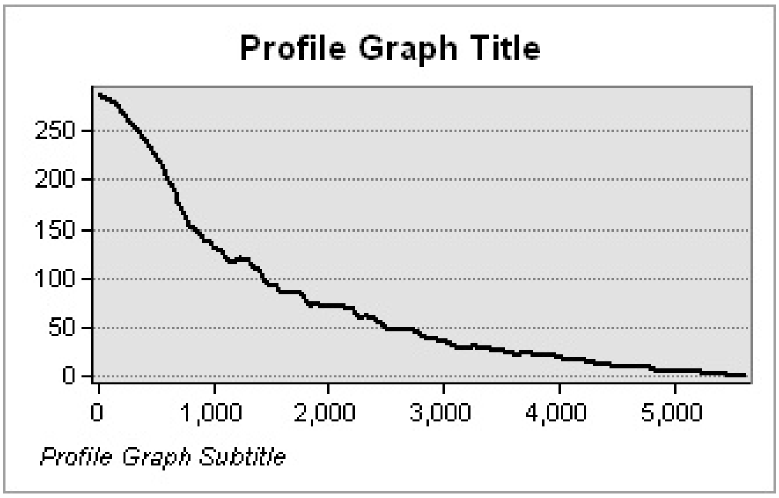


Figure 3.2-3 Head difference for catchment area 2

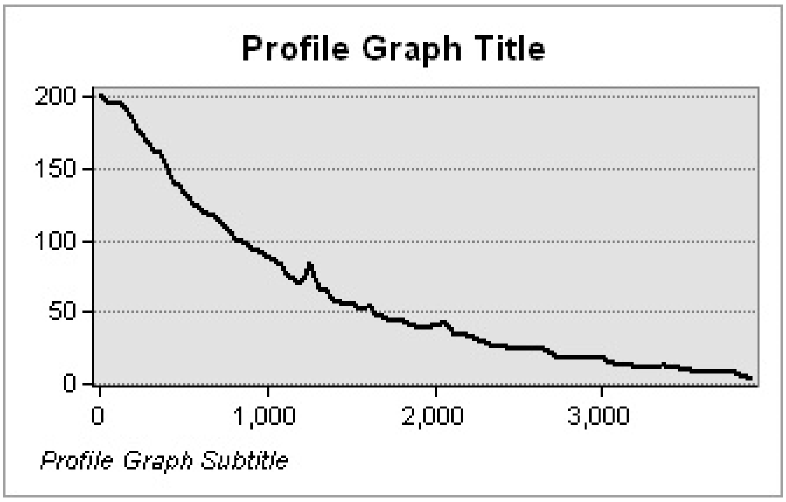


Figure 3.2-4: Head difference for catchment area 3

Following the simulation of the catchment areas, it needed to be checked that the locations of the catchment areas are not within any touristic or residential area. As such the coordinates of the locations were checked on google maps. Figure 3.2-5 to figure 3.2-7 shows the locations of the areas on google maps.

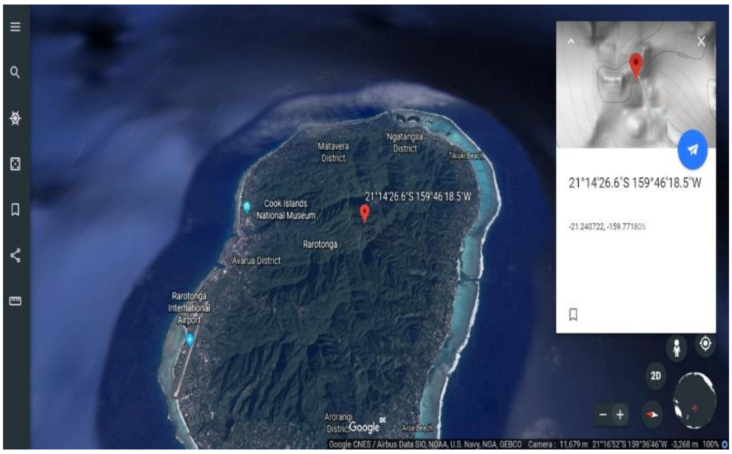


Figure 3.2-5: location of catchment area 1

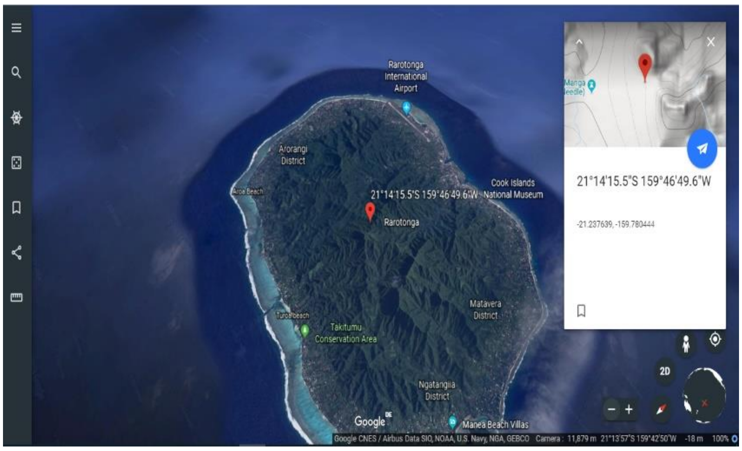


Figure 3.2-6: Location of catchment area 2

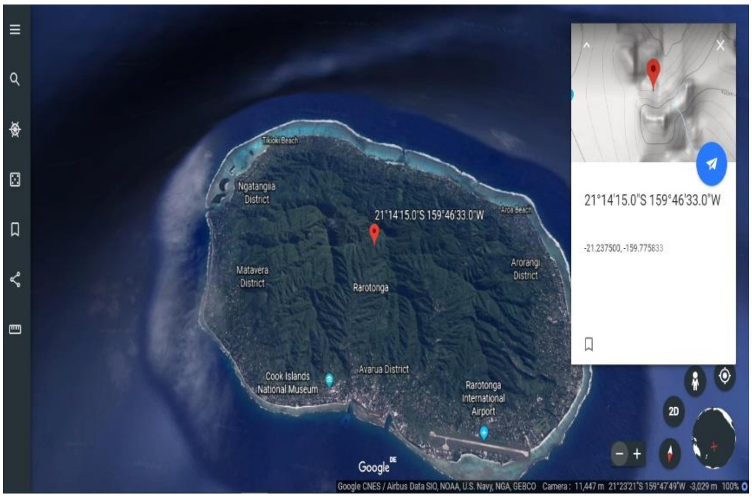


Figure 3.2-7: Location of catchment area 3

3.2.2 Calculations:

The flow needed to be calculated in order to calculate the power. In order to calculate the flow, the below equation 3.2-1 was used.

$$Q\left[\frac{m^3}{s}\right] = (P\left[\frac{mm}{y}\right] X\, rXA[km^2])/3156[m^3y/(km^2 s\, mm)]$$

Equation 3.2-1

Where P is the precipitation per year, r is the runoff coefficient and A is the catchment area. For r, the value used for calculation is that for the New Zealand uncultivated land which represents the nearest country to our target island. Here r is equal to 0.3. for the precipitation the value was obtained from Power data access viewer website developed by NASA. The interannual data was obtained for the years starting 1981 to 2017 and the average was calculated which is 4.29mm/day.

Following the calculation of the flow, the power was calculated for the three catchment areas as per the below equation number 2.

$$P = Q \times \rho \times H \times g \times \eta$$

Equation 3.2-2

Where Q is the flow, ρ is the density, H is the head difference; g is the gravity and η is the efficiency which is estimated 0.7.

3.2.3 Results:

Finally, the Output power was calculated for the three catchment areas. Based on the calculations which show very low power values, it can be stated that there is no hydro potential on Rarotonga.

Table 3.2-1: Flow & Power calculations

Location	**Catchment area (m^2)**	**Catchment area Km^2**	**Head (m)**	**Precipitation (mm/day)**	**Precipitation (mm/year)**	**Run_OFF**	**Q flow(m^3/s)**	**density (Kg/m^3)**	**g (m/s^2)**	**n**	**Power (KW)**
Pourpoint 1	*148329.0514*	*0.148329051*	250	4.29	1565.85	0.3	0.022078046	1000	9.81	0.7	37.9
Pour Point 2	152198.2047	0.152198205	300	4.29	1565.85	0.3	0.022653951	1000	9.81	0.7	46.7
Pour Point 3	408905.2861	0.408905286	200	4.29	1565.85	0.3	0.060863531	1000	9.81	0.7	83.6

3.3 Solar Resource assessment (Precious)

Our goal to deploy 100% renewable energy requires the estimation of the solar resources potential in Rarotonga which would be used for proper energy planning on the Island.

Solar resources have a significant potential in large parts of Rarotonga because of its favorable latitude that is 21 degrees south of the Earth's equatorial plane and its long hours of daylight.

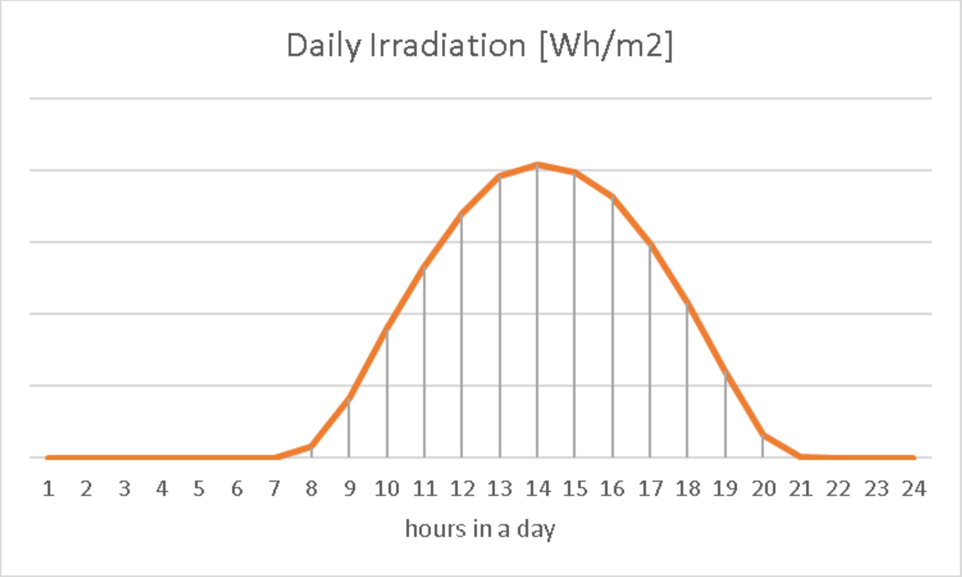


Figure 3.3-1: Daily Irradiation Curve (MeteoBlue, 2019)

The daily irradiation curve in Figure above shows that the Island receives an average of 12 hours Daylight.

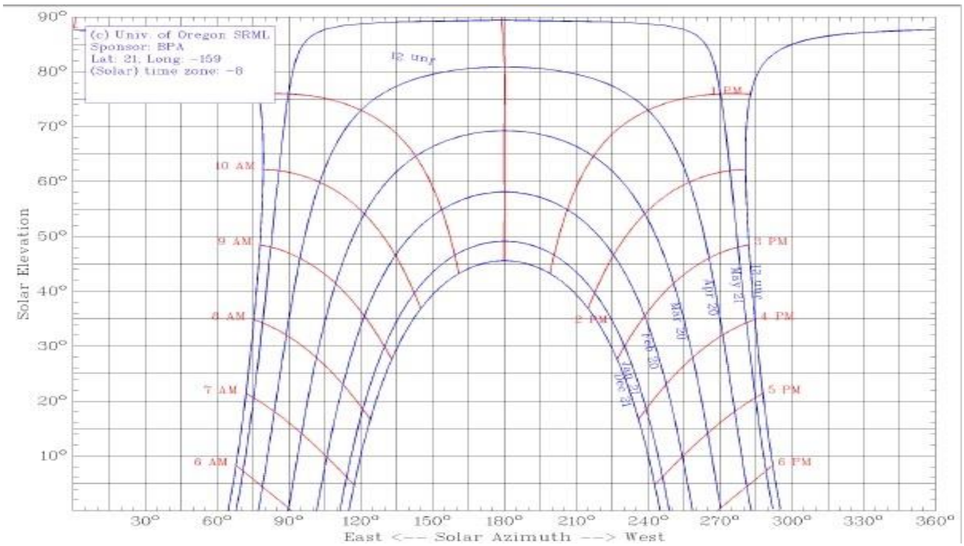


Figure 3.3-2: Sun Path in Cartesian Coordinates (Oregon)

The Cartesian sun path in figure 2 further explains the sun position and the sun elevation angle which defines the length of daylight and the average daylight received throughout the year in Rarotonga. The Red Lines depicts the Hours of Day while Blue Lines portray Sun Position.

The PV power potential is about 1400 kWh/kWp /year and 3.836 kWh/kWp per day on the island (Global Solar Atlas, 2016) .

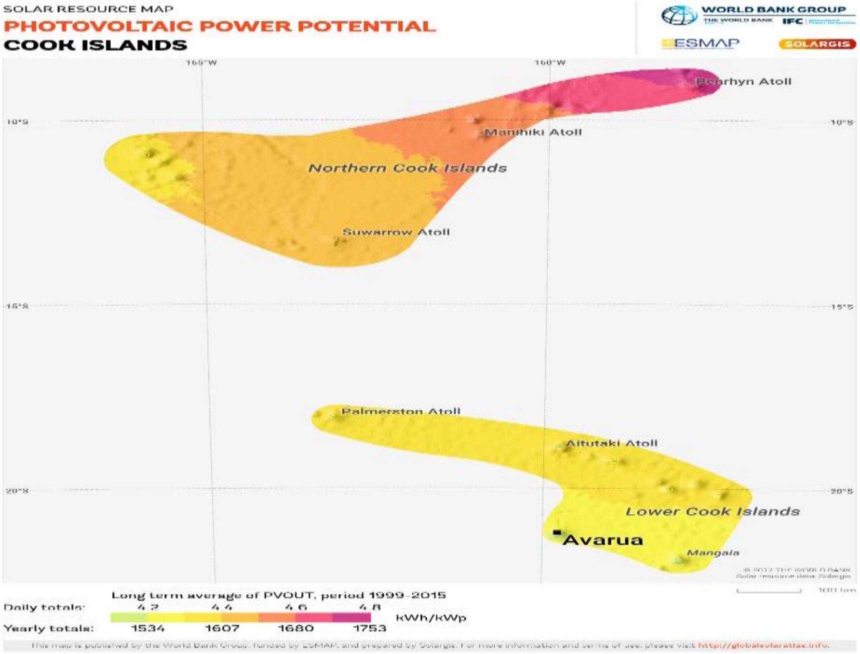
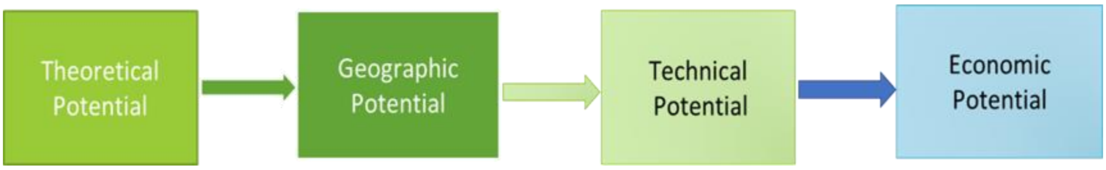


Figure 3.3-3: Solar PV potential in the Cook Island (Global Solar Atlas, 2016)

The Photovoltaic Power Potential represents the average daily/yearly sum of electricity production from a 1kW peak grid connected solar PV power plant (SOLARGIS, 2019).

3.3.1 Methodology

The analysis of the solar resource's potential was evaluated in the following sequence:



The maximum solar potential is the theoretical while the lowest is the Economic Potential that is the proportion of the technical potential that can be utilized after considering economic constraints.

3.3.1.1 Theoretical potential

The solar energy potential assuming all the land area could be used for solar energy system installation is called theoretical solar energy potential. The theoretical potential describes the total amount of solar resources available without the consideration of conversion efficiencies and losses (IRENA). This is equal to the total solar radiation received on the total area of the island.

Theoretical PV potential is calculated by the formula below:

Table 3.3-1:Basic formula for the calculation of theoretical solar PV potential

Equation	Total Land Area	/	Land area per kWp	= Theoretical PV Potential
Units	(m^2)		(m^2/kWp)	(GW)

Where, the total land area of Rarotonga = $67.39*10^6$ m^2, Land area for polycrystalline modules is approximately 8 m^2 /kWp (Prof Olav, 2015)

Theoretical PV Potential =8,42GW

Theoretical PV Potential which equals 8.42GW, portrays a very high potential in solar energy, however, the total area of Rarotonga cannot be assigned solely for PV due to natural geographic features and constraints, infrastructures and land use. Therefore, the geographical potential was estimated to exclude the land use constraints.

3.3.1.2 Geographical potential

The geographic potential takes into account areas only areas that are suitable for solar energy technology for optimum evaluation of the geographic potential the following conditions were taken into account:

- Protected areas- All forest reserve was excluded
- Water bodies- rivers, lakes and seas were not included in the consideration of sites because of high cost of construction of RET
- High Sloped Areas-Land areas with high slopes of more than 45 degrees were also excluded (IRENA)
- Agricultural land- Viable agricultural lands were also excluded to avoid conflicting land -use
- Highly populated areas –areas with population density higher than 5people/km2 were excluded.

Based on the Land Use Map obtained from Global Forest Watch, the environmental designations such as protected area, military zones, forests and other restricted land use were taken into account and excluded to determine the available suitable land areas for the deployment of solar systems technology.

Furthermore, threshold parameters were defined on ArcGIS to define the most eligible sites. The following parameters and thresholds were defined;

- Population density

The population density of island was extracted from the World population density map (Möller, 2019) with the tool ‘extract by Mask’ on ArcGIS.

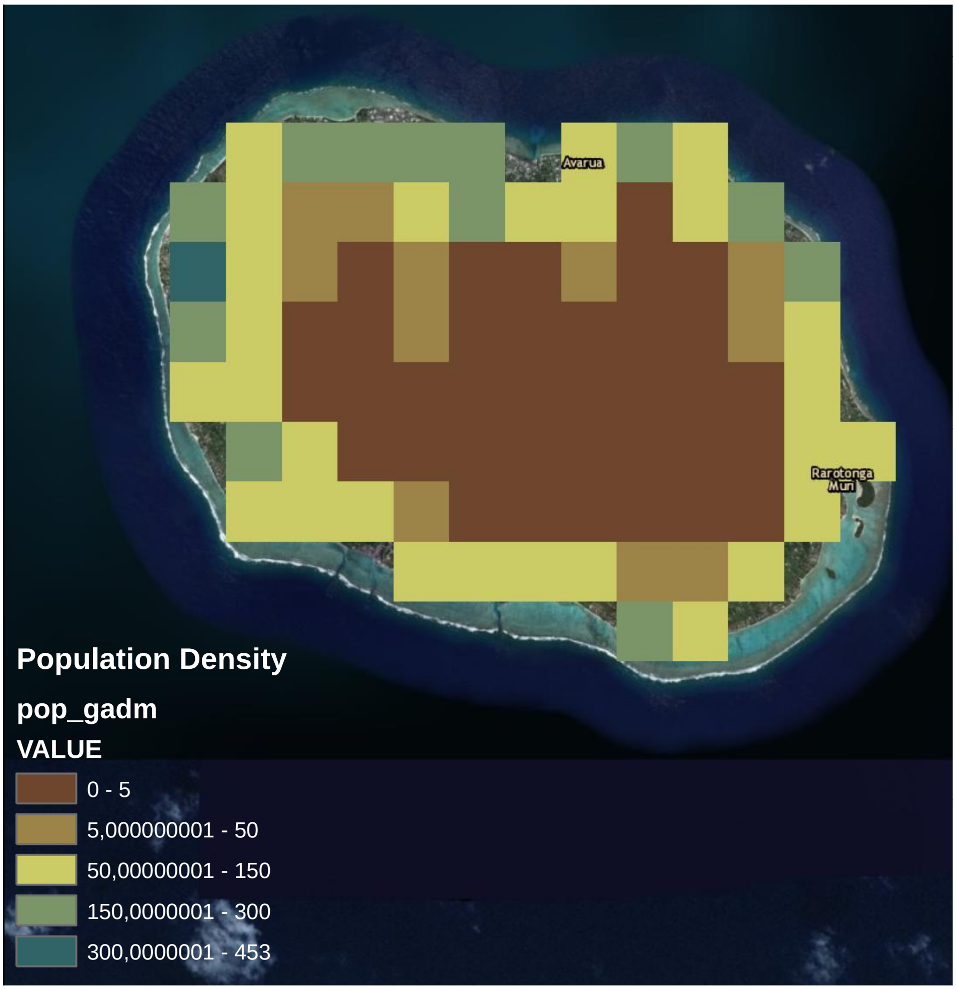


Figure 3.3-4: Population Density map of Rarotonga

A threshold of 5 people/km² was defined to eliminate areas with higher population density to secure enough land space. The result is represented in the figure below.

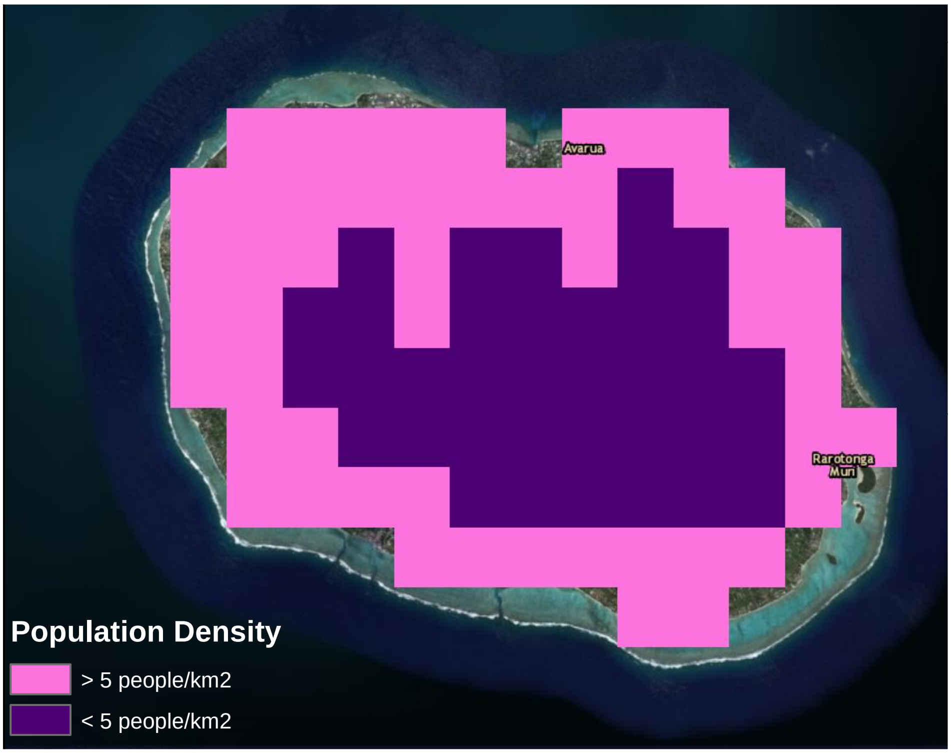


Figure 3.3-5:Population Density with defined Threshold

- Slope Areas

The slope or terrain of the island was extracted from the Elevation Map downloaded from Global Data Explorer with the tool ‘extract by Mask’ on ArcGIS.

Figure 3.3-6:Slope map of Rarotonga

A threshold of 45 degrees was defined to eliminate areas with high slopes which is quite important to reduce the costs of construction and land preparation during the deployment of solar technology (IRENA, 2014). The resulting map from ARCGIS is represented in the figure below.

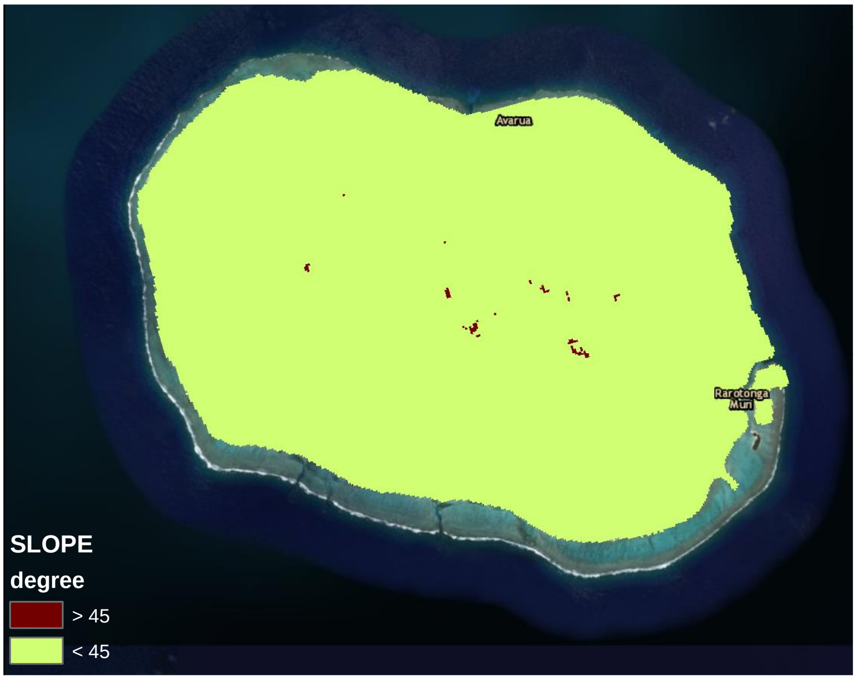


Figure 3.3-7:Slope map with slope Threshold

For optimum selection, the thresholds values were combined on ARCGIS using the tool “Combine” to have the aggregated results of the selection criteria.

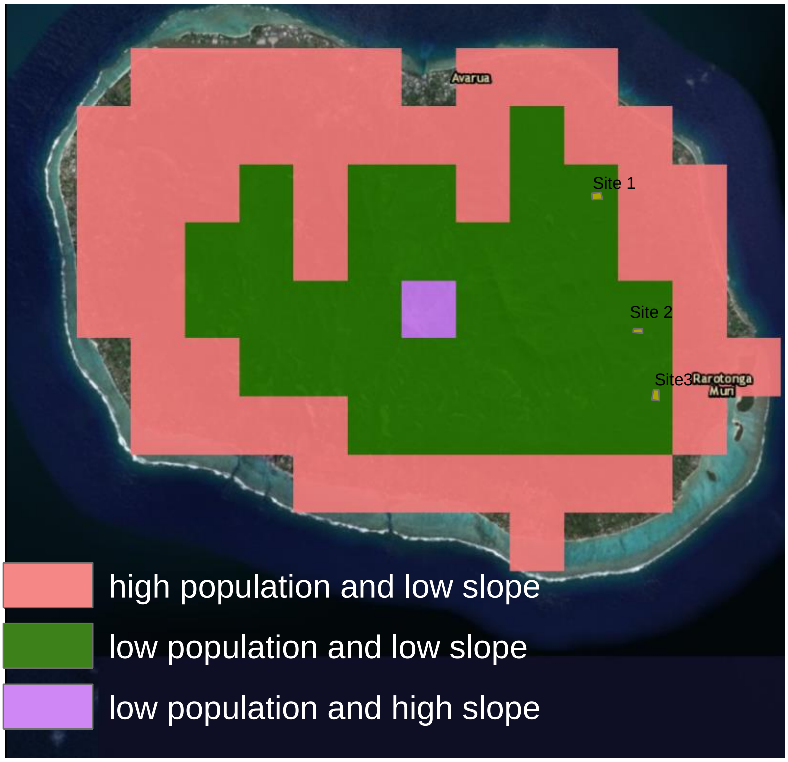


Figure 3.3-8:Potential Sites selected based on all the Threshold criteria

The green colour in the Figure above shows represents the areas that fulfil the threshold conditions while the other colours do not meet all of the selection criteria.

The first potential site (Site 1) with a total area of 18,002.67 m^2,the second potential site (Site 2) is in the North of Rarotonga with a total area of 38580,54 m^2 and the third potential site (Site 3) with a total area of 11422,7 m^2.The Areas of the potential sites was determined by the ArcGIS 'Identify tool'. The sum of the land area is presented in the table below.

Table 3.3-2:Sum of Land Area Available for PV

	Site 1	+	Site 2	+	Site 3	=	Total Land Area
Units	m2		m2		m2		m2
Rarotonga	18,002.67		38,580.54		11,422.70	=	68000

After determining the sum of the available areas, the Geographical PV potential for the three sites is calculated with equation below.

Equation	Solar Resource	x	Available Area	=	Geographic Potential
Units	kWh/m^2/year		m^2		MWh

Equation 3.3-1

The solar resources data was obtained from the Meteoblue company. The solar irradiation =1560kWh/m2/year. The geographic potential of the potential sites is presented in the tables below.

Table 3.3-3: Geographic Solar PV potential for the chosen sites

Potential Sites	**Solar Resource kWh/m2/year**	**x**	**Area (m^2)**	**=**	**Geographic Potential (GWh)**
Site 1	1560		18,002.67		28,1
Site 2			38,580.54		60,2
Site 3			11,422.70		17,8
Total Geographic Potential					106 GWh

the resulting sum of the three potential sites areas analyzed above is equal to 68,006 m^2 which the total area available and suitable for solar energy production and the total geographic potential is around 106GWh.

3.3.1.3 Technical Potential

The technical potential takes into account losses and efficiency of the solar resources. It can be defined as the geographic potential energy minus the conversion efficiency of the solar irradiation into electricity.

Equation:	Solar irradiation	x	Efficiency	x	Total Area	=	Technical potential
Units	($kWh/m^2/year$)		(%)		(m^2)		(MWh)

Equation 3.3-2: Formula for the calculation of technical solar potential energy.

The total area available for solar PV (m2) (which is already derived from the sum of the potential sites,) equals 68,006.0m2, the conversion efficiency coefficient of solar irradiance to electricity assumed to 20% and the solar irradiation data was obtained from Meteoblue.

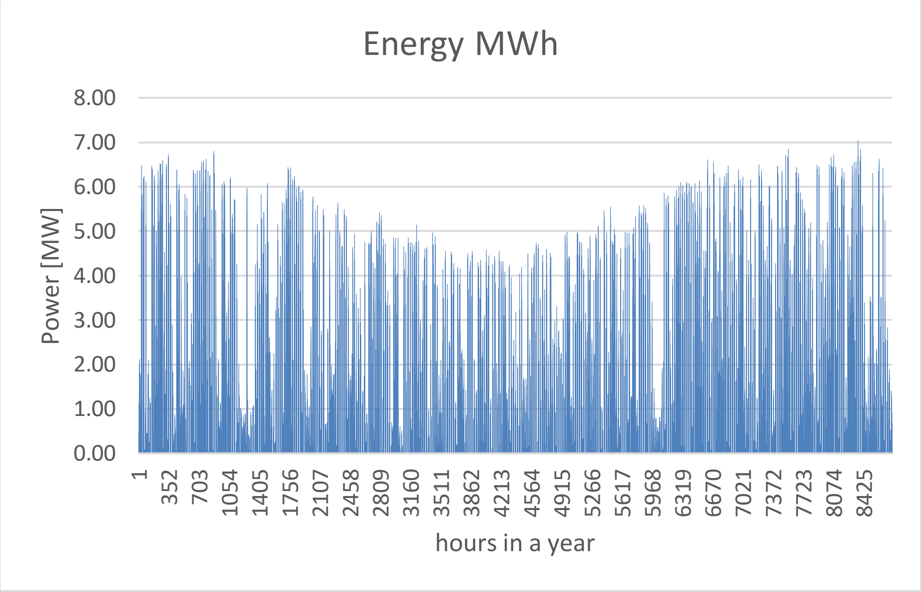


Figure 3.3-9: Annual Solar Energy in Rarotonga

The annual solar energy = 21208,95MWh

While the installed capacity = 14 MW

3.3.1.4 Economical Potential

The economic potential is the most important for the deployment of solar energy systems because all constraints are taken into consideration. (Mominul Hasan, 2019).

The economic solar potential was determined with the assistance of our energy model. The energy model optimized the installed capacity with the lowest amount of overproduction. we played with the model to derive the least over production outcome. Our model results show that decreasing the installed capacity from 13.7MW to 8MW would lead to a decreased overproduction value from 22% to only 7% respectively. Although, it is possible to install all the 13,68MW technical capacity, we decided to install only 8MW because it provides the least over production scenario. The 8MW capacity would generate an annual energy of 10.9GWh which will meet a good percent of the annual electricity demand on the island alongside with the installed capacity from wind.

3.3.1.5 Results

The summary of the solar potential estimation represented below:

I. The power potential (MW)

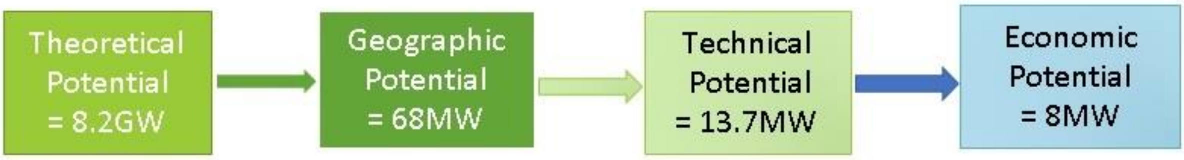


Figure 3.3-10: Summary of Solar Power Potential for Ground Mounted PV

II. The energy potential (GWh)

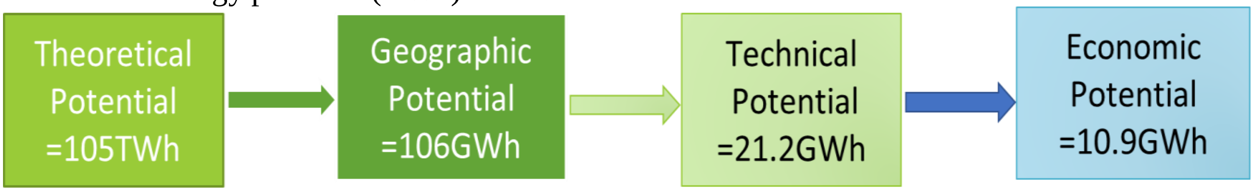


Figure 3.3-11: Summary of the solar energy potential for Ground mounted PV

3.4 Biomass (Diana)

3.4.1 Waste to Energy

Waste to energy technology, with sufficient resource, is capable of providing base load capacity as well as other environmental benefits. Waste to energy can provide energy 24/7 throughout the years and is limited by the amount of feedstock.

Solid Waste (SW) can be transform into electricity, heat or chemical products. The most common and used technology is thermal conversion, which includes incineration, gasification and pyrolysis (EPIC, 2004).Another option is bioconversion like anaerobic digestion and landfill gas.

3.4.2 Waste to Energy in Rarotonga

In Rarotonga waste collection services of households are provided by private operator under the Ministry of Infrastructure Cook Islands (ICI). All the waste collected is taken to Rarotonga´s Waste Management Facility, a sanitary landfill constructed in 2006 that is close to reach its full capacity. According to ICI´s estimations around 80 ton per week, or 4,200 tons per year, of solid waste is deposited in the Rarotonga landfill. In other areas they have four incinerators; three for burning garbage and one for medical wastes. (Asian Development Bank, 2014).

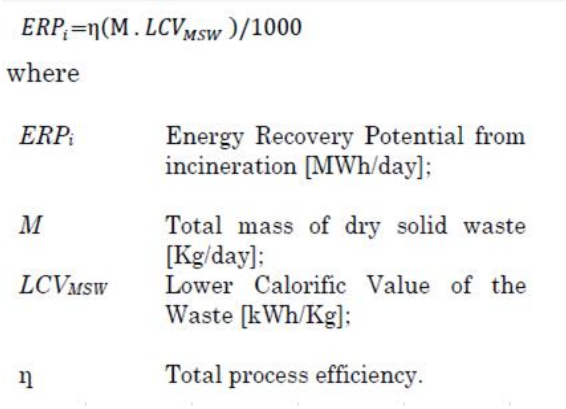
3.4.3 Incineration

In 2012, the electricity utility Te Aponga Uira (TAU), was provided with a grant from New Zealand to carry out a feasibility study to determine the viability of a waste to energy facility on Rarotonga. This study was conducted by KEMA a global energy consultancy company headquartered in Arnhem, Netherlands.

Based on their research and analysis they estimate a total of 43-52 tons per week of combustible material for the Waste to Energy (WTE) plant with a potential of approximately 200 kW (KEMA Australia Pty Ltd, 2012).

For this capacity, a Biomass Gasification technology was suggested. Specifically, they suggested a Biomass Gasifier Operation on Pellets called IST GEM that could produce electricity and hot water.

In the study mentioned above, there was no explanation about how they calculated the 200 kW potential. That is why we made calculations estimate the amount of the electric power that can be obtained by incineration of the SW collected in Rarotonga.



$ERP_i = \eta(M \, . \, LCV_{MSW})/1000$

where

ERP_i	Energy Recovery Potential from incineration [MWh/day];
M	Total mass of dry solid waste [Kg/day];
LCV_{MSW}	Lower Calorific Value of the Waste [kWh/Kg];
η	Total process efficiency.

Figure 3.4-1: Energy recovery potential formula (Alzate Arias, 2018)

Figure above shows the formula for calculating the energy recovery potential, which is a product of the total mass of dry solid waste in kg/day, the Lower Calorific Value of the Waste in kWh/kg and the total efficiency of the process.

With the Knowledge from ICI of the annual waste delivered in Rarontonga´s landfill the electricity potential was calculated. Following important assumptions were made to assist the calculation:

- The Calorific Value of municipal solid waste considered was 7.10–19.90 MJ/kg or 1.97–5.53 KWh/kg (Li, 2017).
- In this case, an efficiency of 26% was used (Alzate Arias, 2018).

The total amount of solid waste available according to ICI is 4,200 tons per year. According to feasibility study of waste to energy in Rarotonga the amount of plastic and glass that is currently being recycled is on average 702 tons per year (KEMA Australia Pty Ltd, 2012).That makes a total amount of 3498 tons available for combustion.

Based on the formula on Figure 1 the estimated electrical potential calculated, using two different Calorific Values are 207- 581 KW.

3.4.4 Cost Analysis

According to the Feasibility study mentioned above, the costs of implementing the IST GEM technology would be approximately $3.4 M US.

Due to high requirement on environmental protection; the operation and maintenance costs are high while the calorific value of municipal solid waste burned is relatively low (Schneider.D.R, 2010).

Also, the Gate Fee, which is the payment that a waste processing facility collects per ton of waste received, has to be taken into consideration. WTE gate fees are usually higher than landfill gate fees.

3.4.5 Conclusion

Even though the complexity of an incineration plant is low, the main disadvantages are that it is not viable for volumes under 100 T/day of SW and its high investment value. It is also not recommendable for SW with high contents of humidity and low calorific value (Alzate Arias, 2018).

Based on our calculations to estimate the electricity power that can be obtained by incineration of solid waste and the potential suggested in the Te Aponga Uira-Final Waste to Energy Feasibility Study; we can conclude that waste to energy technology it is not recommended for this scenario of 100% Renewable energy in the Cook Islands due to the high investment costs for such low potential of energy (around 200 KW).

3.4.6 Biogas

There have been no surveys of biomass energy resources in the Cook Islands since the 1980s. Approximately 65% of the land has light to dense tree cover with biomass energy potential. However, this should not be used for energy purposes, other than meeting existing demand for fuel-wood (IRENA, 2013).

Even though some countries in the Pacific utilizes waste products from agriculture or wood industries for producing energy, in the Cook Islands this is not likely to be developed. According to an agricultural census conducted in 2000, there are about 43 000 coconut trees but 97% of production is already used for households' purposes (IRENA, 2013).

Also, the use of coconut husks and coconut shells is common and widely used for cooking in the traditional 'umu'.

We explored the potential of producing biogas from the 3% of unused coconut Biomass. This means that we made calculations for the energy potential from the husk and shells from the 3% of the 43 000 coconut trees available in the Cook Islands.

The average weight of one Coconut is 1.2 kg and the average number of coconuts per tree is 50. (Raghavan, 2010)

*Total weigh (kg) = 43 000 trees * 50 coconuts per tree * 1.2 kg*

*Total weigh (kg) = 2580000 kg * 3%*

Total Biomass Available = 77 400 kg

Figure 3.4-2 shows the composition of Dry Coconut by weight. For our calculations we only assumed that we can use the coconut residues (husk and shell) of the coconut tree.

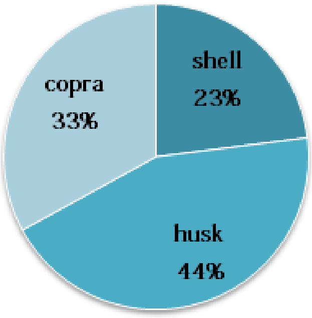


Figure 3.4-2: Composition of Dry Coconut by weight (Raghavan, 2010)

To find the energy potential from the husk and the shell we considered the calorific values of 18.62MJ/kg and 20.8MJ/kg respectively (Zafar, 2019).

- Calculations for energy recovery potential from Coconut Shell:

*Mass of dry Residual Shell= 77 400 kg * 23 %*

Mass of dry Residual Shell = 17 802 kg

*Energy Potential = 17 802 kg * 20.8 MJ/kg*

Energy Potential = 370281.6 MJ = 370.2 GJ

Energy Potential from Shell = 102.85 MWh

- Calculations for energy recovery potential from Coconut Husk:

*Mass of dry Residual Husk= 77 400 kg * 44%*

Mass of dry Residual Shell = 34 056 kg

Energy Potential from Husk = 176.14 MWh

Total energy potential from Husk and Shell is: 279MWh

If we consider an efficiency of 35% the total energy potential is reduced to only 97.65 MWh.

3.4.7 Conclusion

Even though there is potential to produce energy form the residues of the coconut tree, this amount is still too low to invest in a gas engine or CHP plant. Also, the cost of biogas storage increases in proportion to the pressure needed. Further, there are a lot of parameters like temperature, which has to be taken into account. This would represent a big problem for considering it as backup.

3.4.8 Biodiesel

To meet continuously the electricity demand in Rarotonga for our case scenario of 100% renewable energy system, backup is extremely important when the storage is empty.

Energy generation using biogas plants in our case it is not recommendable. Moreover, the use of coconut oil produced from copra as a fuel it is no longer feasible because the cost of re-establishing a copra production would be extremely high. (IRENA, 2013).

Using available space for oil palm instead, is a better option. Oil palm has the highest oil productivity per unit of land on earth. (Jawad Nagi, 2008, pág. 83) Its calorific value (41.3 MJ/kg), is only slighter smaller than fossil diesel (46.8 MJ/kg) (Jawad Nagi, 2008, pág. 85).

There are other advantages in using palm oil for the production of biofuel such as the fact that biofuel is carbon neutral because the combustion of palm oil biofuel does not increase the level of CO2 in the atmosphere as this was obtained earlier through photosynthesis. Another advantage is that this biofuel can be used in any diesel-motor.

The yield varies depending on the region. In most regions the potential oil palm yields are greater than 8 ton oil per ha per year (Lotte S.Woittiez, 2017) .

On average 1 hectare of oil palms can produce 4,000 liters per year. Taking into account the lower energy content of biodiesel of 32.65 MJ/L due to the density and 34% efficiency of an old diesel generator we can obtain 12.09 MWh/ha per year.

For a 5% backup of the annual demand of Rarotonga around 135 hectares of palm oil will be needed. This represents around 2%% of the total area of Rarotonga.

3.4.9 Conclusion

We made a land analysis and nearly 70% of land area consists of steep slopes and hills. Rarotonga has eight reserve areas. With approximately 62 % of intact natural forest;

It is also observed that there is an increase in developmental projects like residential housing. It is apparent that land available for development and public use is very limited.

Moreover, in the 1980s, the Government of the Cook Islands rejected a proposal of developing a 1.7 MW biomass-fuelled steam generation system for Rarotonga, mainly for land use and logistic reasons. These factors continue to prevent large-scale biomass-based generation. (IRENA, 2013).

We conclude that we will import biodiesel.

3.5 Hydro Pump Storage (Maryam)

The Assessment of the different renewable energy technologies shows that wind and PV are mature and practical technologies for implementing 100% renewables in Rarotonga. But they are intermittent in nature and therefore must be utilized when they are available, otherwise they're wasted, this attribute limits the ability of wind and solar to consistently provide power during peak demand periods when it is most needed and beneficial, thus Plant and grid operators cannot order wind or solar plants to produce energy when it is needed as they were used to do so in the conventional electricity system, therefore an energy storage capacity is required to store the energy when there's excess and release it in the case of deficit , to assure the balance between load and generation and to stabilize the supply of electricity to the grid (Te Aponga Uira- Final Waste to Energy Feasibility Study, 2012) .

3.5.1 Rarotonga Load Shape:

The annual consumption of Rarotonga does not change much and the load shape is relatively flat however as noticed in the provided (*Figure 3.5.1-1*) when comparing the RE generation shape (solar and wind combined) to the load shape ,the intermittent of Solar and wind is demonstrated and the generation does not consistently match demand through the year , as a result there's a deficit in generation in some periods of the year and excess in generation on other periods , these deficit and excess define the amount of storage needed to balance out this fluctuations .

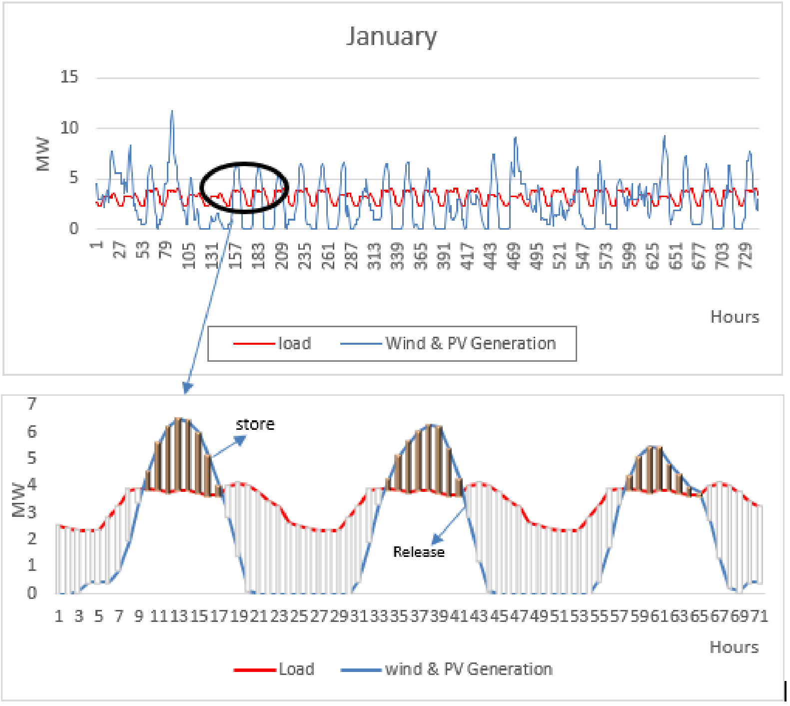


Figure 3.5-1 The intermittent in RE generation and the unmet load in some time during the year (January)

3.5.2 Storage Technologies options in Rarotonga:

Based on modern technology there are several energy storage technologies currently available. These technologies include: (Ibrahim, 2007)

- **Pumped storage hydropower**: Discussed later in this section.
- **Thermal energy storage**: There are two types of thermal energy storage. One type uses sensible heat and the other type uses latent heat. Sensible heat thermal storage heats in a bulk material, then energy is recovered via water vapor, which drives a turbo-alternator system. Latent-fusion-heat makes use of the liquid-solid transformation of a material at constant temperature; during storage the material becomes a liquid and during retrieval forms a solid. System efficiencies of about 60%.
- **Compressed air energy storage (CAES):** There are both large and small CAES applications. Energy is stored by compressing air during times when low-cost energy is available, then a generator is used to retrieve the power during peak demand periods. Efficiencies of about 50% for small scale projects and 70% for large scale projects.
- **Flow battery energy storage**: A two-electrolyte system in which chemical compounds are in their liquid state in solution with the electrolyte and have an efficiency of about 75%.
- **Flywheel energy storage**: There are both low and high-speed flywheel energy storage applications. Flywheel energy storage projects consist of a flywheel, motor generator, and special brackets housed inside a low-pressure environment. This technology has good instantaneous efficiencies of 85%; however long-term storage capabilities are poor, diminishing to 48% after 24 hour
- **Superconductor magnetic energy storage (SMES)**: There are both traditional and micro SMES applications. A direct current (DC) is induced into a coil made of superconducting cables of low resistance, with the current increasing during charging and decreasing during discharge. Good instantaneous efficiency of approximately 95%.
- **Supercapacitor energy storage**: For this technology there is no chemical reaction. An electrical field between two electrodes is used to storage energy, with short term efficiencies of 95%.
- **Electrochemical batteries**: These systems can transform chemical energy into electrical energy by using electrochemical reactions.

Energy storage systems come in many different sizes with varying power output and energy storage capacity. The quantity of energy stored relative to the power output for the energy storage systems described above are shown on *Figure 3.5-2,* As the figure shows, compressed air energy systems and pumped storage hydropower are the two primary large-scale technologies currently available. And *Figure 3.5-3* shows the capacity cost in $ per KWH and also it's noticeable that PHS & CAES have the lowest cost .

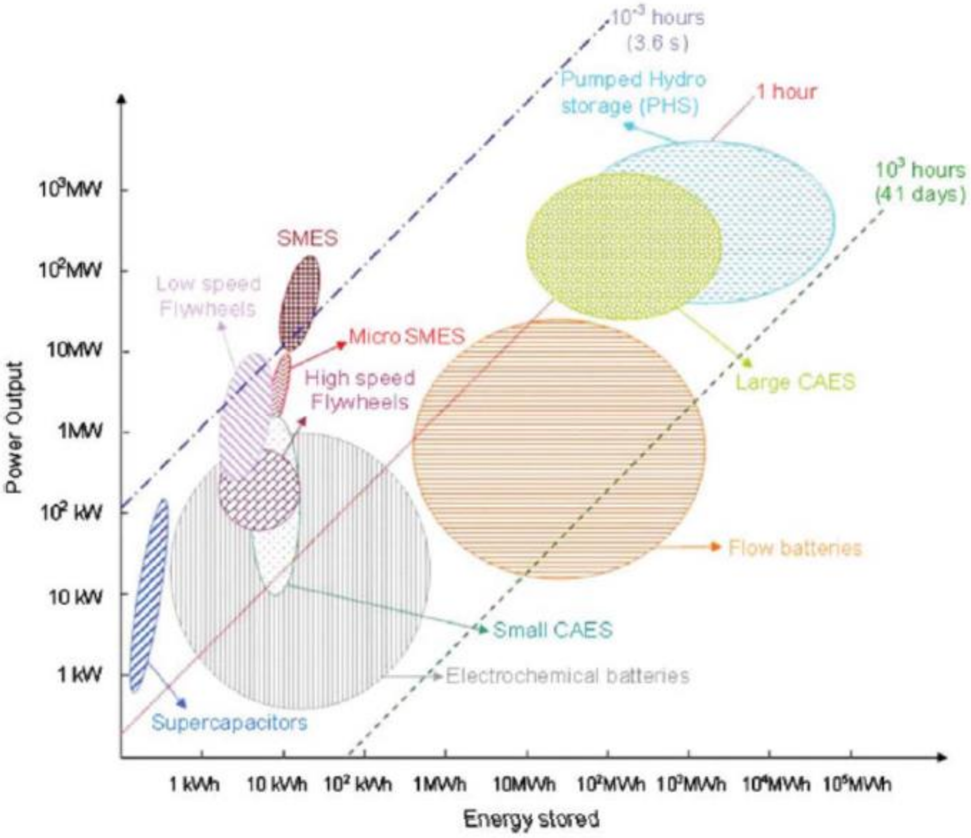


Figure 3.5-2 ***Different Energy Storage Techniques – Energy Stored and Power Output*** *(Ibrahim, 2007)*

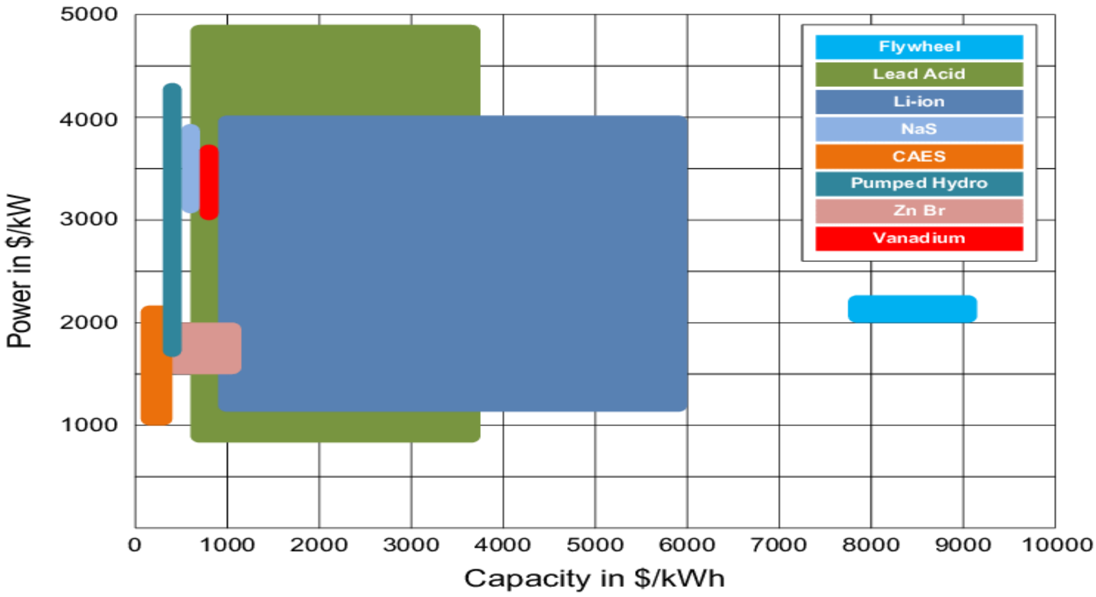


Figure 3.5-3 Comparison of different storage technologies regarding to the investment costs for power and capacity

compressed air energy systems and pumped storage hydropower are the two primary large-scale technologies currently available with a low cost as well. There are presently only a few compressed air energy system plants that are operational; therefore, pumped storage hydropower has the longest history of successful operation for large scale storage systems. While there are numerous benefits and negatives related to each energy storage for Rarotonga, we have chosen Pumped hydro storage (PHS).

3.5.3 Pumped hydropower storage (PHS):

PHS is a mature technology and has been implemented in over 200 locations around the world since the 1890's. A PHS system consists of an upper reservoir and a lower reservoir with a hydro turbine/generator station and a pump station. The turbine/generator can be like normal hydroelectric plants. Water is pumped to the upper reservoir when demand is low and discharged later for power generation when demand is high. The water can be kept in a closed loop so that water loss can be minimal. A PHS can turn intermittent renewable power into high quality base load when properly integrated.

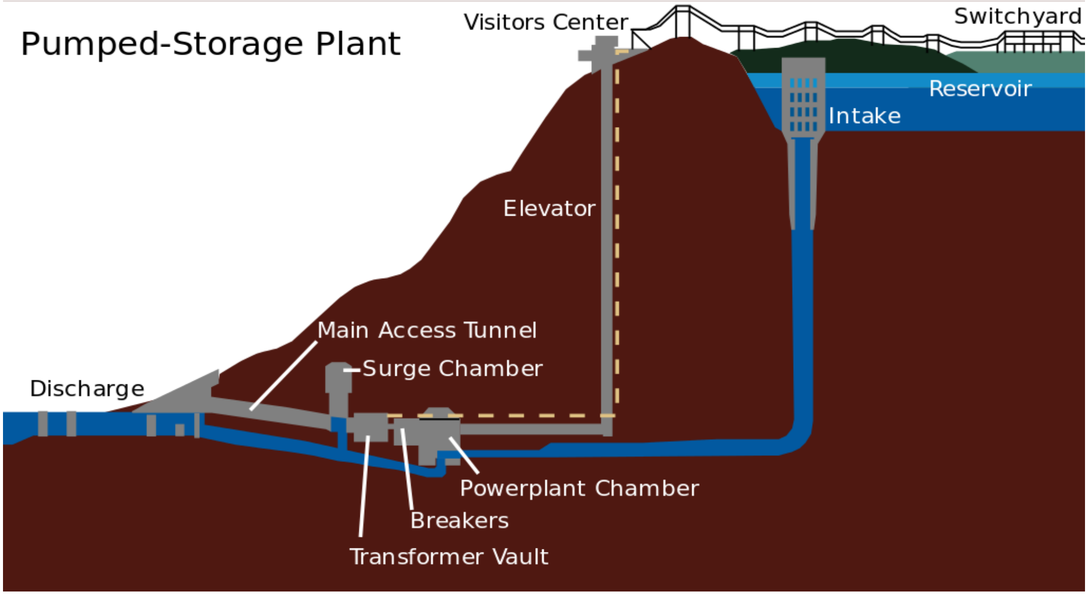


Figure 3.5-4 Pumped Hydro Storage (wikipedia)

3.5.4 Methodology of the location selection:

Since the PHS scheme is highly dependent on the location the below technical elements were considered while looking for suitable Locations : (Deane, 2010)

- Topographic conditions that provide adequate head between the upper and lower reservoir.
- Favorable geotechnical conditions.
- Availability of enough quantities of water (water quality can also be a concern).
- Access to electrical transmission networks (Grid) and low-cost power.
- Distanced from the populated and inhabited areas.

Considering the above points and using ArcGIS google earth pro and google maps the following locations for the upper and lower reservoir has been chosen.

First a 3D design for the elevation of Rarotonga is made to see the topography and possible locations of PHS as in the *Figures (3.5-5)* below.

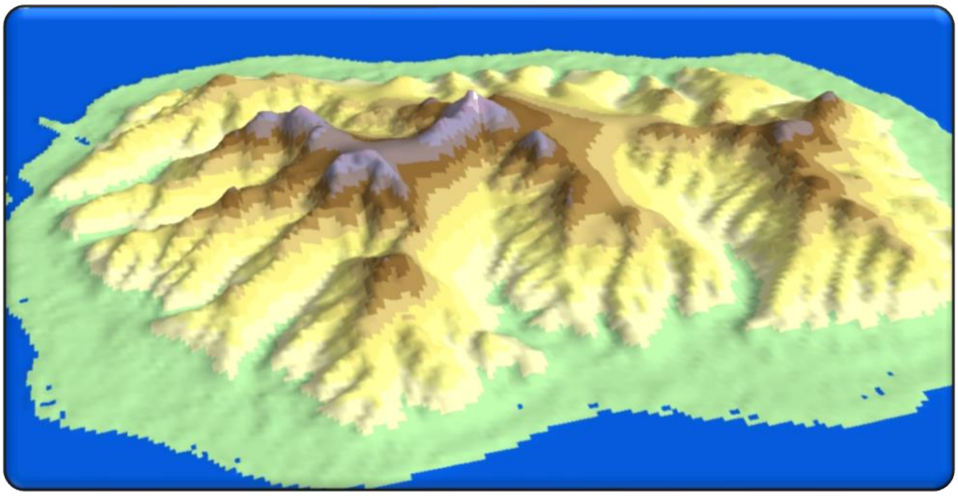


Figure 3.5-5 3D Elevation for Rarotonga, 'Source =own design'

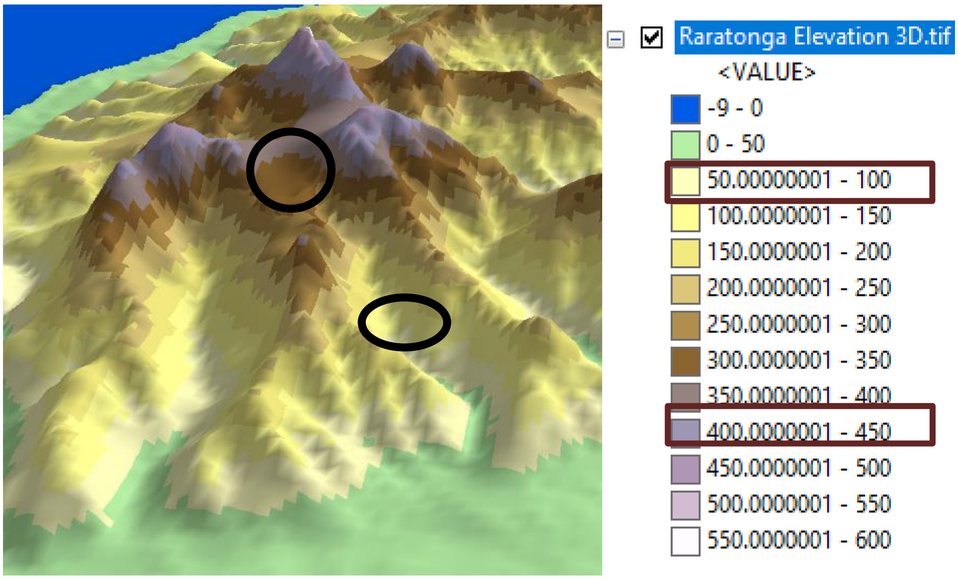


Figure 3.5-6: Possible location for the reservoirs 'source=own design'

Then using google map to calculate the size of the Catchment Area (Lower RESOEVOIRS)

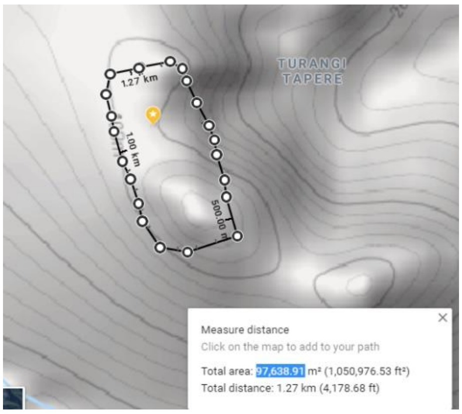
Measure distance

Click on the map to add to your path

Total area: 329,649.00 m² (3,548,312.34 ft²)

Total distance: 2.20 km (1.37 mi)

Figure 3.5-7 lower reservoir size calculation using google map



Measure distance

Click on the map to add to your path

Total area: 97,638.91 m² (1,050,976.53 ft²)

Total distance: 1.27 km (4,178.68 ft)

Figure 3.5-8 upper reservoir size calculation using google map

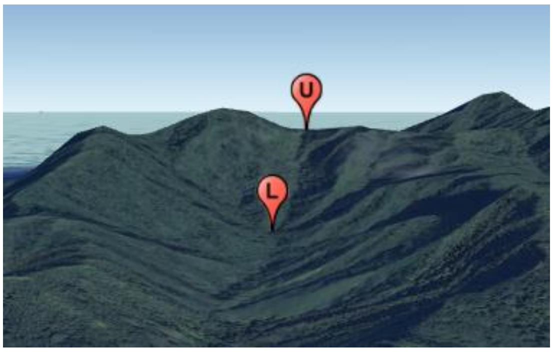


Figure 3.5-9 Location of lower and upper reservoirs using google earth

The table below shows the results:

Table 3.5-1 area and height of the upper and lower reservoirs

Description	**Value**	**Unit**
Upper Reservoir Area	87,638.90	m^2
Lower Reservoir Area	329,649.00	m^2
Upper reservoir height	380	m
Lower reservoir height	80	m
Calculated head – 5%	285	m

The selected upper reservoir is at a height of 400 m above sea level and area of 87,638.91 m^2 , the size of the lower catchment area is 329,649 m^2 with a height of 80 m above sea level a 5% measurement error calculations has been taken into account given an 285 m effective height between the upper and lower reservoirs . As from Rarotonga distribution Grid the east coast feeder is the nearest to the location of the reservoirs and the site can be accessed by Ngati au Rud. The reservoir will be filled by rain water.

3.5.5 Calculations

The storage size is determined after the optimization between the wind and solar PV technologies Considering the future scenarios, the calculation of the storage size is done considering the projection of the demand in 2040 and the load from the transport.

3.5.6 Precipitation:

As mentioned above the reservoir will be filled by rain water, therefore the precipitation data from Nasa has been studied between the years 1989 and 2017 as shown on *figure 3.5-10*, taking the average between the years gives precipitation per day which is 4.3 and that means 1565.85 mm per year

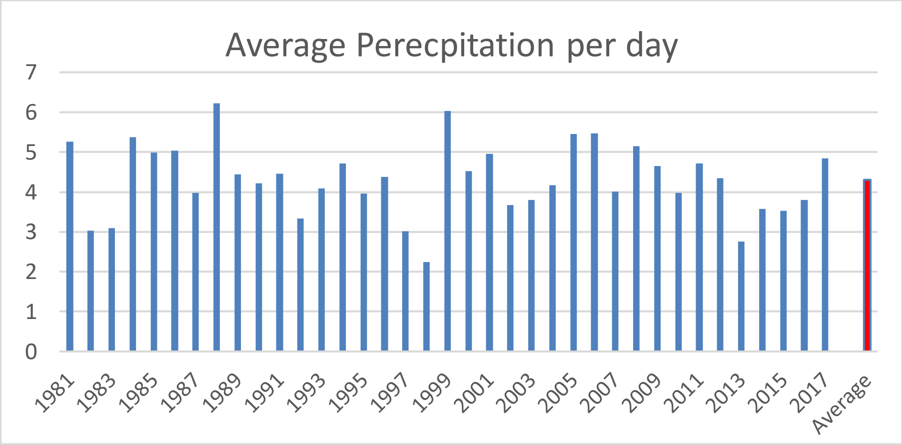


Figure 3.5-10average precipitation per day from 1981 to 2017

Time to fill the Reservoir

Table 3.5-2 Time needed to fill the reservoir

Parameter	Value	Unit
Precipitation	1,569.50	mm/y
50 % from precipitation Considering the evaporation and absorption	784.75	
Area of the Upper Reservoirs	87,638.90	m^2
Depth of the Upper Reservoir	10	M
Volume of the upper Reservoir	876,389.00	m^3
Area of the lower Reservoir	329,649.00	m^2
Depth of the lower Reservoir	20	M
Volume of the upper Reservoir	6,592,980	m 3
Collected water in the lower Reservoir	258,692	m 3
Time to fill the upper reservoir	3.387769321	Years

The product of the total volume of water and the head difference between the reservoirs is proportional to the energy stored.

Thus, the energy stored is calculate according to the equation **E(j)= V*h* ρ* η**

Energy Stored

Table 3.5-3 Energy stored

Parameter	**Value**	**Unit**
Area of the Upper Reservoir	87,638.900	m^2
Height	10	m
Volume **V**	876,389.00	m^3
Head h	285	m
Density **(ρ)**	1000	Kg/m^3
Gravitational acceleration	9.8	m/s^2
Efficiency **(η)**	0.80	
E(j)= V*h* ρ* η	1,958,203,581,600.00	$Kg\ (m/s)^2$
Maximum Generated Energy	543.9454393	MWH

3.5.7 Storage Optimization:

The size of the storage in MWH was 200MWH and the size was determined using the model by optimization between wind , PV Capacitates and Storage size to achieve the lowest LCOE and to avoid the over production, as we can see from the below graph there's still un met demand after the storage which have been covered by bio diesel .

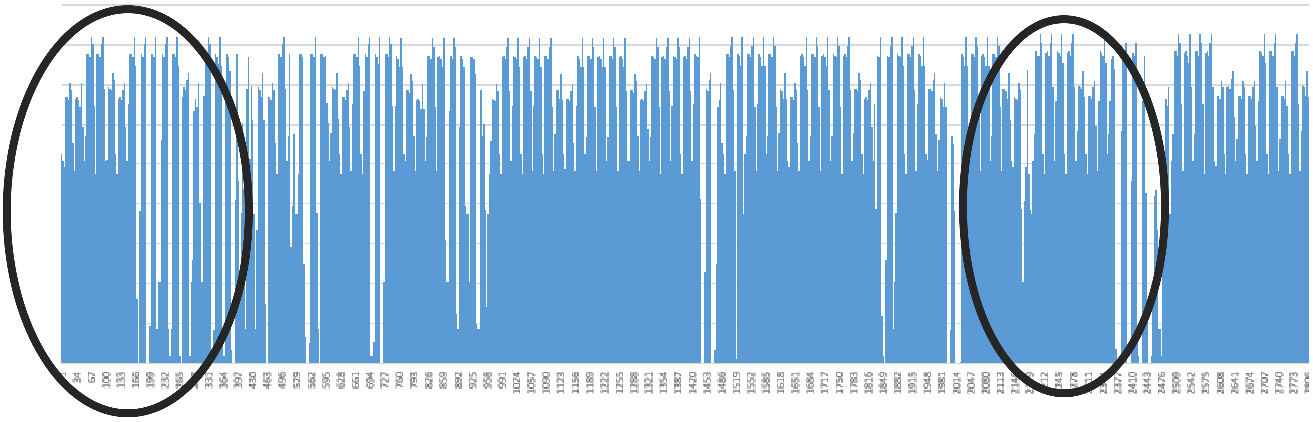


Figure 3.5-11 load curve after the storage

Note:

The 200 MWH needed energy from the storage can be done as well using the battery storage instead of pumped of Hydro storage , but as mentioned the size of the storage will increase according to the demand projection as well as the deploying of E mobility therefore the pumped hydro storage was the reasonable choice

4 Chapter 4: Cost Analysis

In this chapter we will analyse the cost of the different resources which have been identified to have a potential on Rarotonga.

4.1 Wind (Sarah)

To calculate the cost of the wind the following costs needed to be identified: Investment cost, Operation and maintenance cost and interest rate. These costs are needed to calculate the LOCE or the wind using the following equation obtained from Barbados model (Hohmeyer, 2015):

$$LOCE = {}^{Total\ costs}/_{wind\ Total\ generation\ KWH}$$

Equation 4.1-1

However, annuity of the investment costs needed to be considered as they are usually paid over the project years. Since, its estimated that that our project lifetime is 20 years thus the annuity needs to be calculated over 20 years.

Based on chapter three the total installed capacity of wind is 12000 KW and the total generation is 26,751.55 MWh.

Based on IRENA, renewable power generation costs in 2017 (IRENA, 2018) the costs for wind installation for the Oceania region is $1700/Kw. Based on the total installation capacity and the investment cost, the total investment cost is $ 20,400,000.

The annuity of the total investment was calculated based on the below equation obtained from Barbados LCOE calculations model (Hohmeyer, 2015)

$$annuity = \frac{(1+r)^{20} * r}{((1+r)^{20} - 1) * total\ investment\ cost}$$

Equation 4.1-2

The operation and maintenance costs were also retrieved from (IRENA, 2018) for the Oceania region. It was found that the cost for operation and maintenance is 45 $/kW/year. The annuity for the operation and maintenance costs does not need to be calculated as these costs are usually paid over every year.

Regarding the interest rate, in Cooks islands its 2% based on (ANZ, 2015). However, for the calculations the interest rate used was 5%. As the 2% is a very small value.

According to all these parameters the LOCE for wind was found to be $0.081377/Kwh. Table 4.1-1 shows the calculation steps and the results.

Table 4.1-1: LCOE for wind

	Total generation	**Installed capacity**	**Investment cost**	**Total Invest**	**Annuity**	**O&M**	**Total costs**	**LCOE**
	MWH	KW	$/kW	$	$	$/a	$/a	$/kWh
Wind Power	26,751.55	1200	1700	20,400,00	1,636,948	540,000	2,176,948	0.0813

4.2 Solar (Precious)

The Levelized cost of electricity comprises of the total costs, which is incurred during the lifetime of the solar PV power plant for its operation and construction, with the sum of the generated amount of energy throughout its operation cycle (Christoph Kost et al, 2018). The simplified LCOE formula is presented in the equation below (Hohmeyer, 2015):

$$LCOE = {}^{Total\ costs}/_{solar\ PV\ Total\ generation\ KWH}$$

Equation 4.2-1

The financial lifetime of the solar PV power plant is 20 years, this would be considered in the annuity calculation of the total investment cost. The annuity was evaluated with the aid of the formula obtained from the Barbados LCOE calculations model (Hohmeyer, 2015):

$$annuity = \frac{(1+r)^{20} * r}{((1+r)^{20} - 1) * total\ investment\ cost}$$

Equation 4.2-2

The installed capacity of Rooftop and Ground mounted solar PV equals 13,000 KW with the total energy generation of 18,700 MWh.

The installation costs for solar PV for the Oceania region is about $1400/KW (IRENA, 2018). Therefore, the total investment cost is $ 18,200,000 considering the total solar PV installed capacity and the investment cost.

The solar PV operation and maintenance costs for the Oceania region is 18 $/kW/year (IRENA, 2018). A interest rate of 5% was assumed in the calculation.

Table 4.2-1: LCOE for solar PV

	Total generation	**Installed capacity**	**Investment cost**	**Total Invest**	**Annuity**	**O&M**	**Total costs**	**LCOE**
	MWH	**KW**	**$/kW**	**$**	**$**	**$/a**	**$/a**	**$/kWh**
Solar PV	**18,700.00**	**13,000**	**1,400**	**18,200,000**	**1,586,758**	**234,000**	**1,820,760**	**0.097**

The Table above summarizes all the parameters considered in the LCOE calculation, the LCOE for solar is 0.097$/kWh.

4.3 Biodiesel (Diana)

Since there is already diesel generators installed in Rarotonga, no big investment has to be made for that. In general, for many power plants, investments cost of about 430 $/kW is assumed (Sedlak, 2009).

For operation and maintenance of diesel generator, costs 2% of investment were assumed. In Rarotonga the peak demand of 5MW is expected, cost of $2,150,000.00 is estimated as investment. Therefore, the operation and maintenance cost calculated is 43,000.00 USD/a. For cost of biodiesel from vegetable oils 0.96 $/l, equivalent to 0.216 $/kWhel was assume.

Sum up the total cost of producing biodiesel as backup per year is around $358,000.00; divided into $43,000.00 for O&M of the diesel generators and $315,000.00 for importing biodiesel.

4.4 Storage (Maryam)

The costs for a proposed pumped hydropower storage project are separated into two categories: Total investment costs and operation and maintenance cost .According to IRENA Cost of service tool 2017 the total investment cost per usable kwh storage was 696.4 $/kWh, operation and maintenance costs can be highly site specific as well as investment or capital cost, and depend on a number of factors. First, operational costs depend on the owners’ operational philosophy. Second, the age of the project will affect operation and maintenance costs with costs generally increasing with the life of the plant. Third, the number, type, and size of the pump/turbine units will affect operation and maintenance costs. Finally, operation and maintenance costs will depend on the size, type of and configuration of the project reservoirs. According to to IRENA Cost of service tool 2017 O & M cost are usually consider to be 1.5% of the total investment, the cost per usable Kwh along with the O&M cost were taken as input to the developed model to calculate the total LCOE .

5 Chapter Five: Modelling (Ammar)

In a 100% renewable energy system, there is no concept of base load or minimum load which has to be met all the time. Usually there is always intermittency in the generation of renewables whether they are wind, solar or hydro. So, there can be no source which can provide the bae load all the times. So, in order to meet the demand for all the 8760 hours of the years, a model simulation is performed to see whether the load requirement is met all the time or not. There are instances when solar is generating at peak and covering most or all of the load and there is no wind and vice versa. This variation is analysed by a simulation. The simulation has several inputs, then calculations are performed on those inputs and then outputs are generated. These steps are further explained in below sections.

5.1 Inputs of the simulation

To perform the annual simulation, first thing is to decide the resolution of which we can work to get the outputs. As higher the resolution is, more accurate and precise the results with less uncertainty. The problem with high resolution is the availability of data and limitation of the computers performing these calculations. Mostly the load, wind speed, solar radiation and other metrological parameter data is available on hourly resolution. So it is convenient to work on at-least hourly data.

The first input is the hourly load profile. The original hourly profile is taken from the electric utility document from Cooks island. In that load of year 2012, annual percentage increase and load of electric vehicle can be added by giving a percentage for load increase and total energy demand in MWh for E-mobility on the main interface in input & Output tab.

Then we have a tab for Wind Generation. It takes the input of wind speed at measured height. This wind speed can be transformed to any hub height depending on the selection of technology. You need to give the new hub height and roughness coefficient to transform the measured wind speed to height of our selected turbine. Then this wind speed is used to get the power from power curve of the turbine. Power curve of one turbine is given in tab ‘Power Curve” and hourly power is calculated against wind speed of each hour.

For the inputs of solar, we need the available area on which we need to install the solar modules. Our model has option to work either only for Ground Mounted GM, Roof top RT or both. You just input the available area and energy can be calculated against the irradiance data available for each hour. The overall efficiency of solar generation can be entered to see the desired results.

We also have resource of pumped hydro storage in our model. Its size and initial quantity of water can be changed to see the effect on un-met demand and LCOE.

The next resource is biomass. The production of biomass is limited so when deciding the capacities of other sources, it has to be kept in mind that biomass can generates only limited energy. The generation based on biomass is added as input and results can be seen on the main interface page.

For calculation of LCOE, input parameters for cost are also very important. For different resources, investment cost, O & M cost, project life is taken as input to calculate the LCOE. The total generation from these resources are already in the model.

5.2 Calculations

After having the inputs from the user, the simulation performs several calculations for each resource individually as well as for the complete system collectively. These calculations include calculating wind speed at hub height from the measured wind speed. This is done using the power law in which we need the measured height and the unknown height as well as roughness coefficient. These parameters are used to get transform the wind speed to desired hub height. The cost of wind generation is also calculated similarly using total generation from wind, investment cost, interest rate and operations cost.

The input for solar energy is taken in terms of area. this area is then used to calculate the total capacity which can be installed on this input area. Area, efficiency and irradiation gives the maximum generation which can be achieved. The cost of solar generation is also calculated similarly using total generation from solar, investment cost, interest rate and operations cost.

The basic number used for storage calculations is its maximum capacity. The initial content is defined by user and further calculations are performed based on the load and generation from solar and wind. If the total generation from solar and wind is less than the load, the remaining is taken from hydro storage. Similarly, if the load is less than solar and wind, extra is pumped into hydro storage. The efficiency of pump storage is counted while pumping the water up into storage from lower reservoir or while generating electricity from upper reservoir. If there is some instant when generation from solar and wind is less then load, and also there is no storage volume left in upper reservoir, this residual is calculated as the difference of all 4 and this has to be met by biomass generation.

The calculations for biomass are performed based on the resource available. The peak generation can also be determined from pear residual from hydro storage. The LCOE is calculated from fuel cost only. No investment cost is counted for the calculation as the same diesel generators with minor improvisation can be used to run on biomass.

The other major calculations are for the load profile. The load profile is taken from base year of 2012. The load is always changing with time. Usually it increases with passage of time if there is no major change in circumstances. This change is usually in percent of peak load. This number is taken, and percent increase is applied on all the load of each hour. There is another change in load profile. If we plan to shift vehicles to E-mobility, there will be a big change in demand. Our model can calculate such scenarios too. The total energy requirement is calculated for all the vehicles in the island which is given in transportation section. This number can be changed in the model and calculations will tell us the change in capacities required. The energy requirement for e-mobility is only applied to those hours when we have sun. this is in contrast to how model behaves to percentage increase in demand.

5.3 Outputs

Based on the inputs and calculations listed above, outputs are generated. The output of wind generation is the hourly generation from installed capacity. The result of generation over 8760 hours of years looks like this.

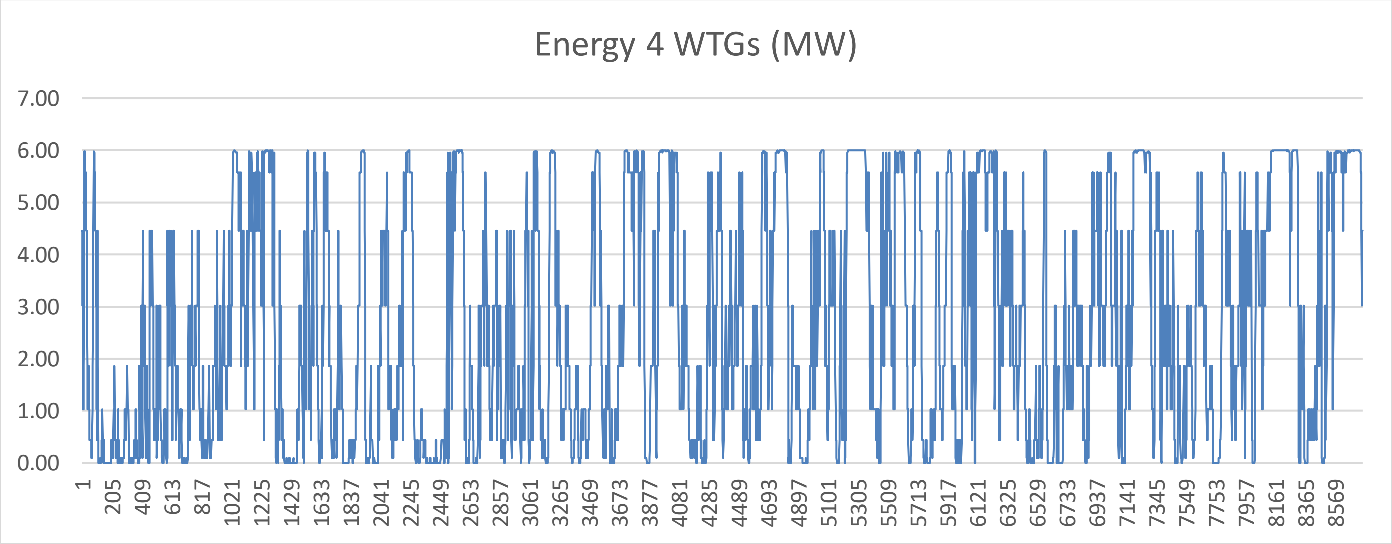
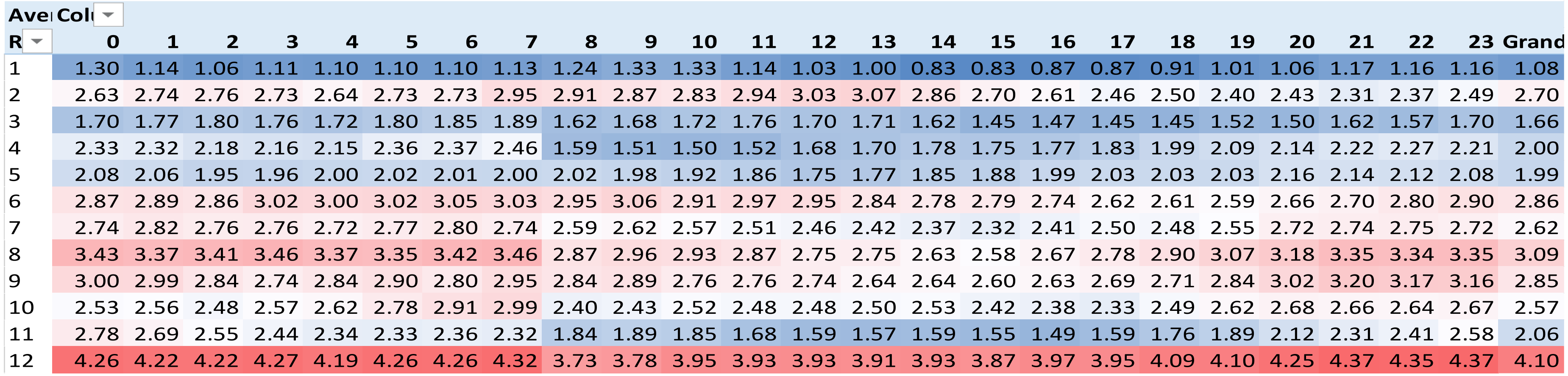


Figure 5.3-1: Wind Generation Output in complete year

The output changing during different hours of a day can be seen by below heat map.

Table 5.3-1: Wind Generation during Hours of months



Ave	**Col**																								
R	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**Grand**
1	1.30	1.14	1.06	1.11	1.10	1.10	1.10	1.13	1.24	1.33	1.33	1.14	1.03	1.00	0.83	0.83	0.87	0.87	0.91	1.01	1.06	1.17	1.16	1.16	1.08
2	2.63	2.74	2.76	2.73	2.64	2.73	2.73	2.95	2.91	2.87	2.83	2.94	3.03	3.07	2.86	2.70	2.61	2.46	2.50	2.40	2.43	2.31	2.37	2.49	2.70
3	1.70	1.77	1.80	1.76	1.72	1.80	1.85	1.89	1.62	1.68	1.72	1.76	1.70	1.71	1.62	1.45	1.47	1.45	1.45	1.52	1.50	1.62	1.57	1.70	1.66
4	2.33	2.32	2.18	2.16	2.15	2.36	2.37	2.46	1.59	1.51	1.50	1.52	1.68	1.70	1.78	1.75	1.77	1.83	1.99	2.09	2.14	2.22	2.27	2.21	2.00
5	2.08	2.06	1.95	1.96	2.00	2.02	2.01	2.00	2.02	1.98	1.92	1.86	1.75	1.77	1.85	1.88	1.99	2.03	2.03	2.03	2.16	2.14	2.12	2.08	1.99
6	2.87	2.89	2.86	3.02	3.00	3.02	3.05	3.03	2.95	3.06	2.91	2.97	2.95	2.84	2.78	2.79	2.74	2.62	2.61	2.59	2.66	2.70	2.80	2.90	2.86
7	2.74	2.82	2.76	2.76	2.72	2.77	2.80	2.74	2.59	2.62	2.57	2.51	2.46	2.42	2.37	2.32	2.41	2.50	2.48	2.55	2.72	2.74	2.75	2.72	2.62
8	3.43	3.37	3.41	3.46	3.37	3.35	3.42	3.46	2.87	2.96	2.93	2.87	2.75	2.75	2.63	2.58	2.67	2.78	2.90	3.07	3.18	3.35	3.34	3.35	3.09
9	3.00	2.99	2.84	2.74	2.84	2.90	2.80	2.95	2.84	2.89	2.76	2.76	2.74	2.64	2.64	2.60	2.63	2.69	2.71	2.84	3.02	3.20	3.17	3.16	2.85
10	2.53	2.56	2.48	2.57	2.62	2.78	2.91	2.99	2.40	2.43	2.52	2.48	2.48	2.50	2.53	2.42	2.38	2.33	2.49	2.62	2.68	2.66	2.64	2.67	2.57
11	2.78	2.69	2.55	2.44	2.34	2.33	2.36	2.32	1.84	1.89	1.85	1.68	1.59	1.57	1.59	1.55	1.49	1.59	1.76	1.89	2.12	2.31	2.41	2.58	2.06
12	4.26	4.22	4.22	4.27	4.19	4.26	4.26	4.32	3.73	3.78	3.95	3.93	3.93	3.91	3.93	3.87	3.97	3.95	4.09	4.10	4.25	4.37	4.35	4.37	4.10

Similarly output from solar generation is also obtained on hourly basis for complete year. This profile is for the ground mounted solar only.

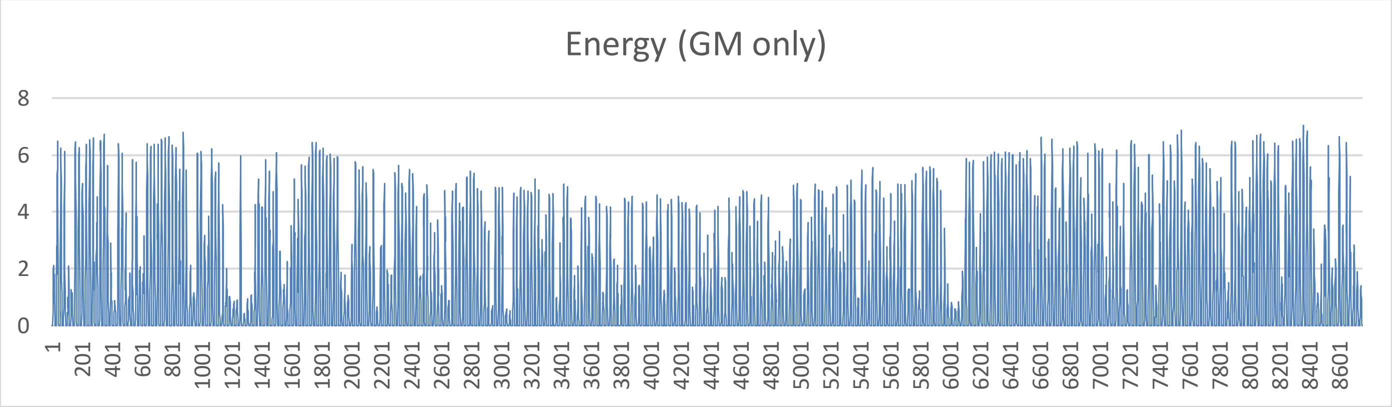
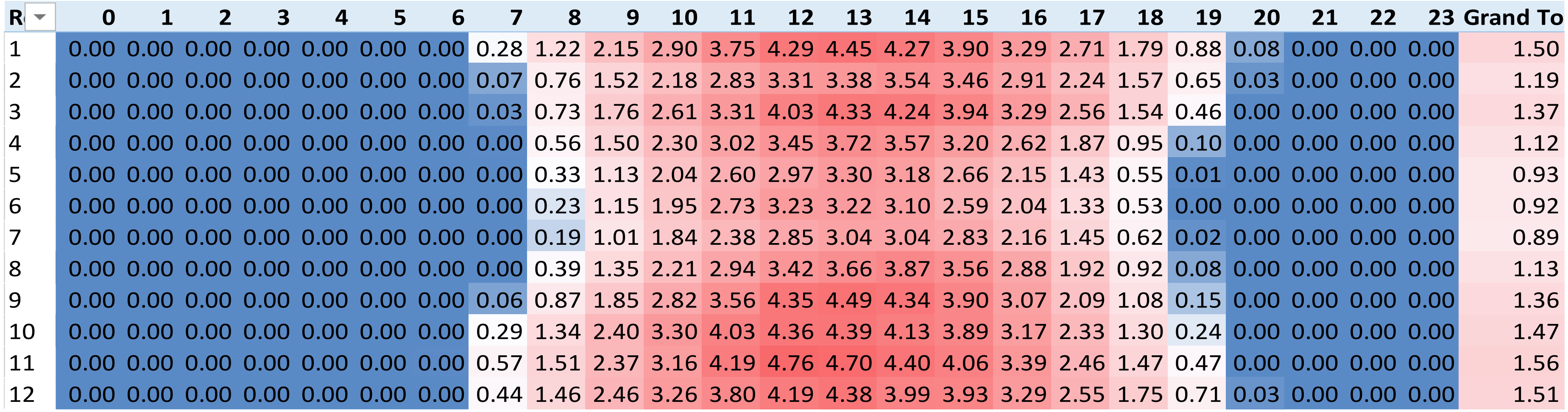


Figure 5.3-2: Solar Generation Output

Generation of Solar during different hours of day can be visualised in the table below. The seasons can also be visualised from the outputs. We can see that we have less sun hours during the months of April-August which is the winter season there.

Table 5.3-2: Generation from Solar during different hours



R	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Grand To
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.28	1.22	2.15	2.90	3.75	4.29	4.45	4.27	3.90	3.29	2.71	1.79	0.88	0.08	0.00	0.00	0.00	1.50
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.76	1.52	2.18	2.83	3.31	3.38	3.54	3.46	2.91	2.24	1.57	0.65	0.03	0.00	0.00	0.00	1.19
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.73	1.76	2.61	3.31	4.03	4.33	4.24	3.94	3.29	2.56	1.54	0.46	0.00	0.00	0.00	0.00	1.37
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.56	1.50	2.30	3.02	3.45	3.72	3.57	3.20	2.62	1.87	0.95	0.10	0.00	0.00	0.00	0.00	1.12
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	1.13	2.04	2.60	2.97	3.30	3.18	2.66	2.15	1.43	0.55	0.01	0.00	0.00	0.00	0.00	0.93
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.23	1.15	1.95	2.73	3.23	3.22	3.10	2.59	2.04	1.33	0.53	0.00	0.00	0.00	0.00	0.00	0.92
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.19	1.01	1.84	2.38	2.85	3.04	3.04	2.83	2.16	1.45	0.62	0.02	0.00	0.00	0.00	0.00	0.89
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.39	1.35	2.21	2.94	3.42	3.66	3.87	3.56	2.88	1.92	0.92	0.08	0.00	0.00	0.00	0.00	1.13
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.87	1.85	2.82	3.56	4.35	4.49	4.34	3.90	3.07	2.09	1.08	0.15	0.00	0.00	0.00	0.00	1.36
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.29	1.34	2.40	3.30	4.03	4.36	4.39	4.13	3.89	3.17	2.33	1.30	0.24	0.00	0.00	0.00	0.00	1.47
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.57	1.51	2.37	3.16	4.19	4.76	4.70	4.40	4.06	3.39	2.46	1.47	0.47	0.00	0.00	0.00	0.00	1.56
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.44	1.46	2.46	3.26	3.80	4.19	4.38	3.99	3.93	3.29	2.55	1.75	0.71	0.03	0.00	0.00	0.00	1.51

The outputs from hydro could be in different ways. It has one output in terms of storage level.

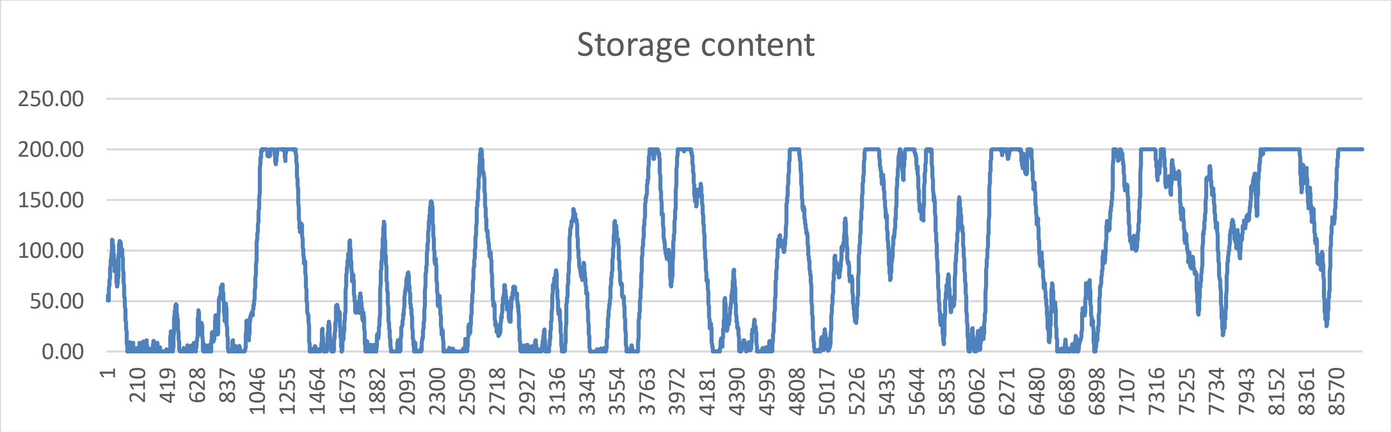


Figure 5.3-3: Storage content

The other output is the amount of residual load covered by hydro.

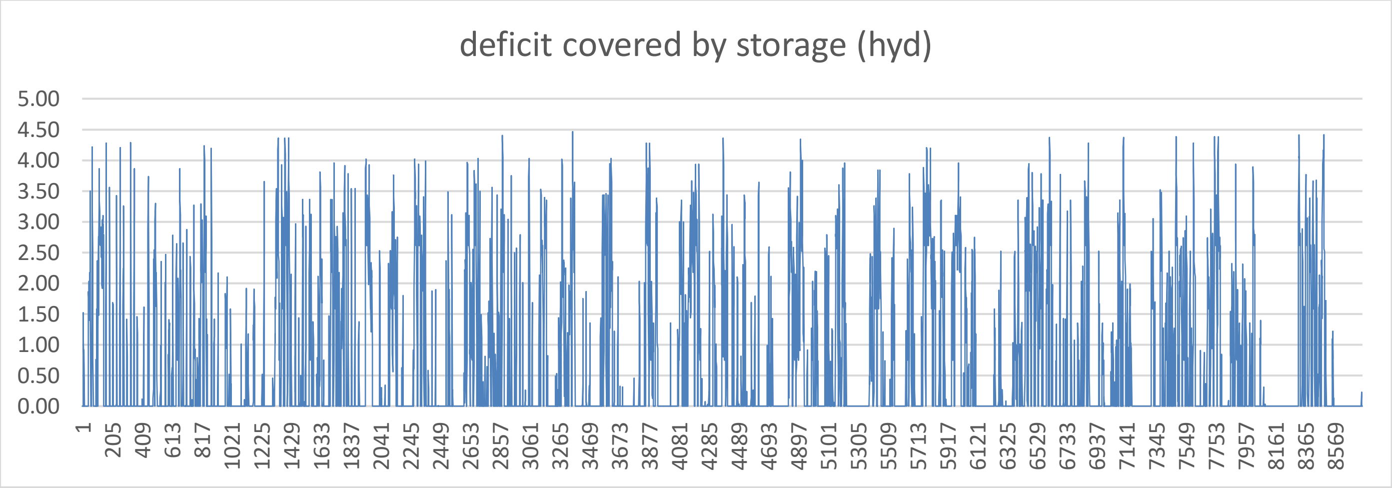
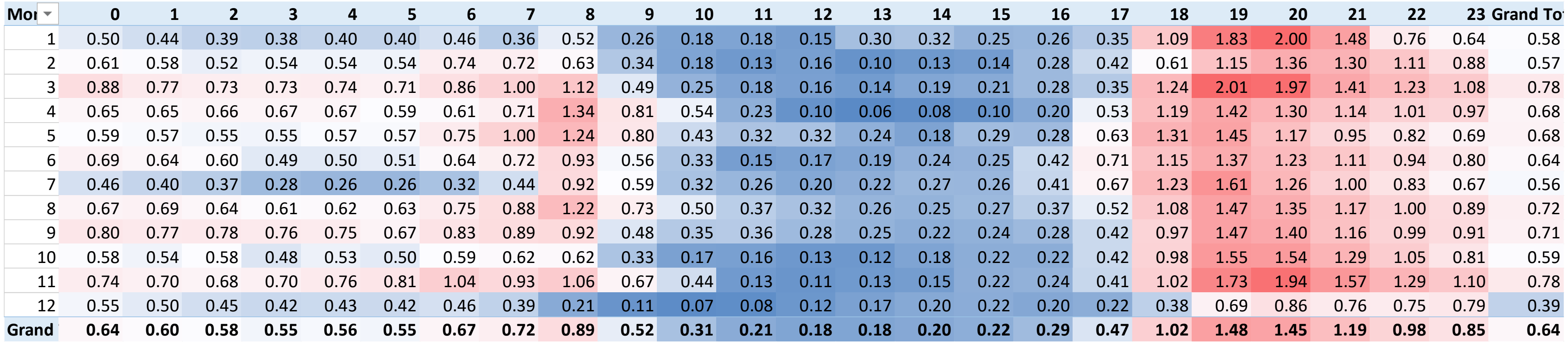


Figure 5.3-4: Deficit covered by hydro

Generation from hydro can be visualised as below:

Table 5.3-3: Generation from pump Hydro



Mor	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**Grand To**
1	0.50	0.44	0.39	0.38	0.40	0.40	0.46	0.36	0.52	0.26	0.18	0.18	0.15	0.30	0.32	0.25	0.26	0.35	1.09	1.83	2.00	1.48	0.76	0.64	0.58
2	0.61	0.58	0.52	0.54	0.54	0.54	0.74	0.72	0.63	0.34	0.18	0.13	0.16	0.10	0.13	0.14	0.28	0.42	0.61	1.15	1.36	1.30	1.11	0.88	0.57
3	0.88	0.77	0.73	0.73	0.74	0.71	0.86	1.00	1.12	0.49	0.25	0.18	0.16	0.14	0.19	0.21	0.28	0.35	1.24	2.01	1.97	1.41	1.23	1.08	0.78
4	0.65	0.65	0.66	0.67	0.67	0.59	0.61	0.71	1.34	0.81	0.54	0.23	0.10	0.06	0.08	0.10	0.20	0.53	1.19	1.42	1.30	1.14	1.01	0.97	0.68
5	0.59	0.57	0.55	0.55	0.57	0.57	0.75	1.00	1.24	0.80	0.43	0.32	0.32	0.24	0.18	0.29	0.28	0.63	1.31	1.45	1.17	0.95	0.82	0.69	0.68
6	0.69	0.64	0.60	0.49	0.50	0.51	0.64	0.72	0.93	0.56	0.33	0.15	0.17	0.19	0.24	0.25	0.42	0.71	1.15	1.37	1.23	1.11	0.94	0.80	0.64
7	0.46	0.40	0.37	0.28	0.26	0.26	0.32	0.44	0.92	0.59	0.32	0.26	0.20	0.22	0.27	0.26	0.41	0.67	1.23	1.61	1.26	1.00	0.83	0.67	0.56
8	0.67	0.69	0.64	0.61	0.62	0.63	0.75	0.88	1.22	0.73	0.50	0.37	0.32	0.26	0.25	0.27	0.37	0.52	1.08	1.47	1.35	1.17	1.00	0.89	0.72
9	0.80	0.77	0.78	0.76	0.75	0.67	0.83	0.89	0.92	0.48	0.35	0.36	0.28	0.25	0.22	0.24	0.28	0.42	0.97	1.47	1.40	1.16	0.99	0.91	0.71
10	0.58	0.54	0.58	0.48	0.53	0.50	0.59	0.62	0.62	0.33	0.17	0.16	0.13	0.12	0.18	0.22	0.22	0.42	0.98	1.55	1.54	1.29	1.05	0.81	0.59
11	0.74	0.70	0.68	0.70	0.76	0.81	1.04	0.93	1.06	0.67	0.44	0.13	0.11	0.13	0.15	0.22	0.24	0.41	1.02	1.73	1.94	1.57	1.29	1.10	0.78
12	0.55	0.50	0.45	0.42	0.43	0.42	0.46	0.39	0.21	0.11	0.07	0.08	0.12	0.17	0.20	0.22	0.20	0.22	0.38	0.69	0.86	0.76	0.75	0.79	0.39
Grand	**0.64**	**0.60**	**0.58**	**0.55**	**0.56**	**0.55**	**0.67**	**0.72**	**0.89**	**0.52**	**0.31**	**0.21**	**0.18**	**0.18**	**0.20**	**0.22**	**0.29**	**0.47**	**1.02**	**1.48**	**1.45**	**1.19**	**0.98**	**0.85**	**0.64**

Similarly, we can also plot the data for excess electricity to storage.

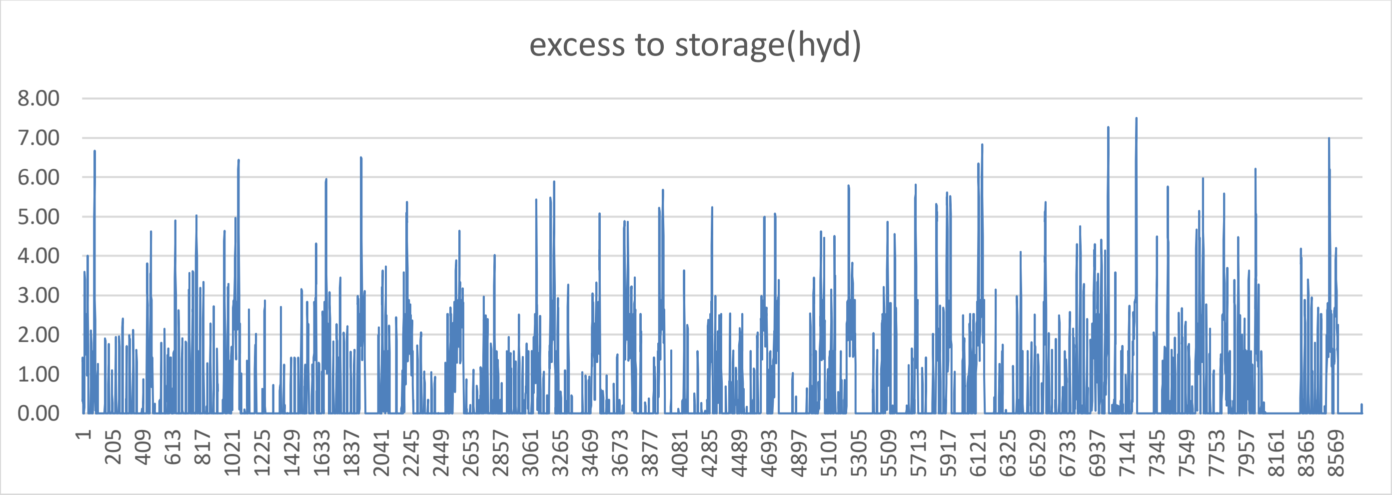


Figure 5.3-5: Excess to hydro storage

Then comes biomass after pumped hydro. If there are some instances when we don't have enough storage content to meet the residual, this load is met by biomass generation. The generation from biomass is shown below:

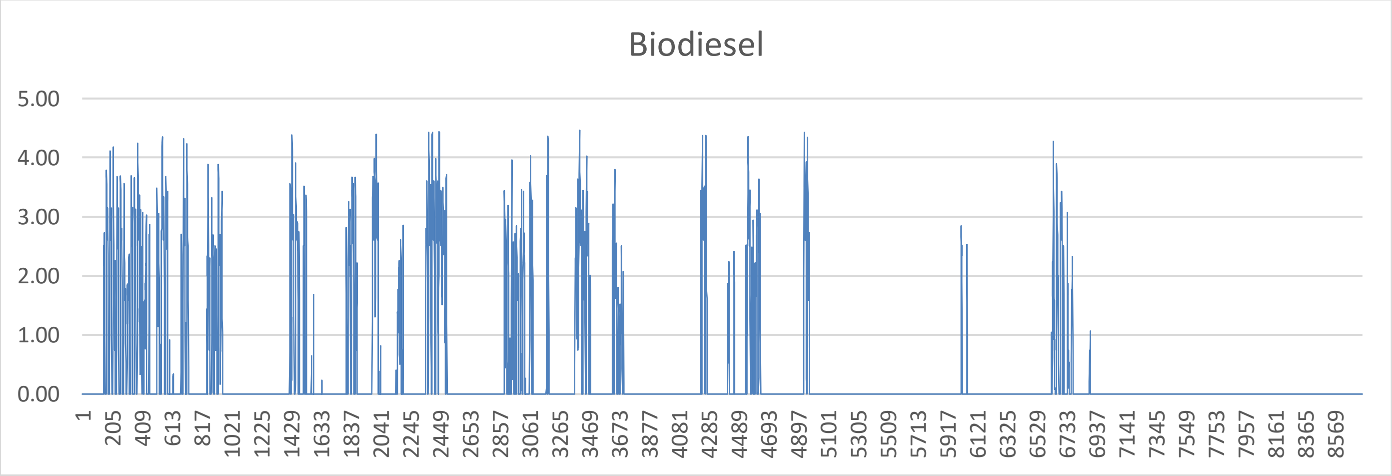
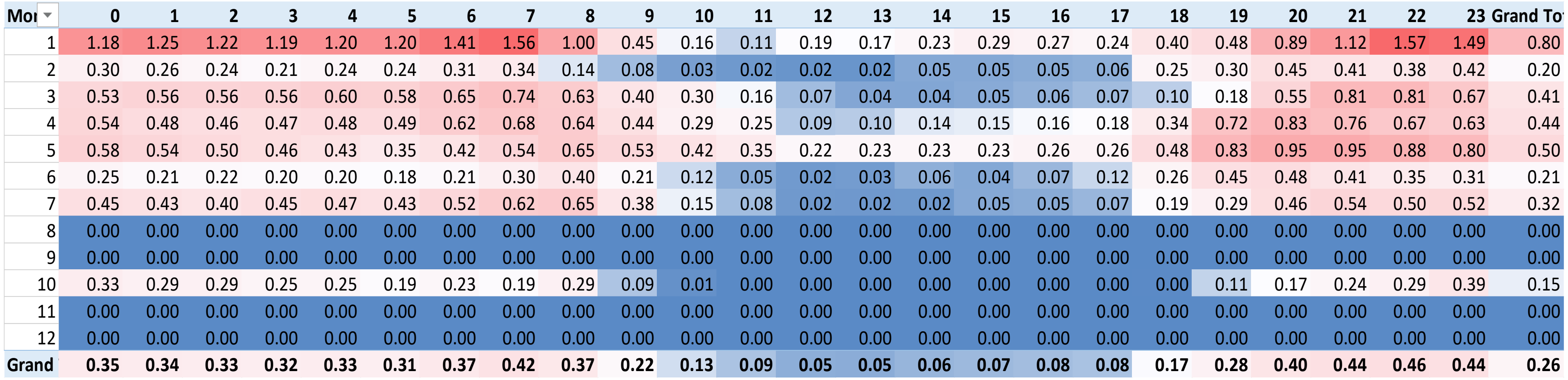


Figure 5.3-6: Biodiesel generation

Biomass will only work when there is no output from pumped hydro. Heat map of biodiesel generation will be similar to hydro during the hours because mostly hydro and biomass are required when there is no solar:

Table 5.3-4: Production of Biodiesel



Mor	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Grand To
1	1.18	1.25	1.22	1.19	1.20	1.20	1.41	1.56	1.00	0.45	0.16	0.11	0.19	0.17	0.23	0.29	0.27	0.24	0.40	0.48	0.89	1.12	1.57	1.49	0.80
2	0.30	0.26	0.24	0.21	0.24	0.24	0.31	0.34	0.14	0.08	0.03	0.02	0.02	0.02	0.05	0.05	0.05	0.06	0.25	0.30	0.45	0.41	0.38	0.42	0.20
3	0.53	0.56	0.56	0.56	0.60	0.58	0.65	0.74	0.63	0.40	0.30	0.16	0.07	0.04	0.04	0.05	0.06	0.07	0.10	0.18	0.55	0.81	0.81	0.67	0.41
4	0.54	0.48	0.46	0.47	0.48	0.49	0.62	0.68	0.64	0.44	0.29	0.25	0.09	0.10	0.14	0.15	0.16	0.18	0.34	0.72	0.83	0.76	0.67	0.63	0.44
5	0.58	0.54	0.50	0.46	0.43	0.35	0.42	0.54	0.65	0.53	0.42	0.35	0.22	0.23	0.23	0.23	0.26	0.26	0.48	0.83	0.95	0.95	0.88	0.80	0.50
6	0.25	0.21	0.22	0.20	0.20	0.18	0.21	0.30	0.40	0.21	0.12	0.05	0.02	0.03	0.06	0.04	0.07	0.12	0.26	0.45	0.48	0.41	0.35	0.31	0.21
7	0.45	0.43	0.40	0.45	0.47	0.43	0.52	0.62	0.65	0.38	0.15	0.08	0.02	0.02	0.02	0.05	0.05	0.07	0.19	0.29	0.46	0.54	0.50	0.52	0.32
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.33	0.29	0.29	0.25	0.25	0.19	0.23	0.19	0.29	0.09	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.17	0.24	0.29	0.39	0.15
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Grand	**0.35**	**0.34**	**0.33**	**0.32**	**0.33**	**0.31**	**0.37**	**0.42**	**0.37**	**0.22**	**0.13**	**0.09**	**0.05**	**0.05**	**0.06**	**0.07**	**0.08**	**0.08**	**0.17**	**0.28**	**0.40**	**0.44**	**0.46**	**0.44**	**0.26**

6 Chapter 6: Scenarios

6.1 Transport (Diana)

The aim of this study was to evaluate the feasibility of 100% E-mobility by 2040 in Rarotonga. We evaluated the potential of using electric vehicles (EVs) as the main forms of transport option in order to reduce the reliance on imported fuels.

6.1.1 Transport Sector in Rarotonga

The Cooks Islands is heavily dependent on imported fossil fuels; around 43% of the total imported fuel is used by transport. In 2009, around 5.5 million litters of diesel and 4.2 million litters of petrol were imported for land transport (Reegle, 2012). This large proportion of the transport sector shows the benefits of switching to electrical mobility based on renewable energy produced in the island.

The main forms of transport for the residents on Rarotonga are motor bikes, followed by motor vehicles (Zhong, 2015). There is also the option for the Round Rarotonga bus service that runs, from Monday to Saturday, clockwise and anti-clockwise.

Figure 6.1-1 shows the main bus stops around the island of Rarotonga.

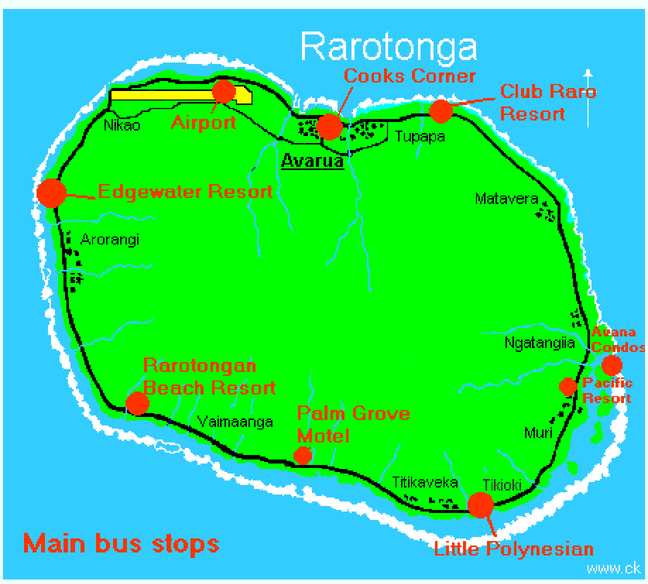


Figure 6.1.1-1: Main bus stops in Rarotonga (Jarvy Web)

The island of Rarotonga is a circumference of 32 km and has two parallel roads (coastal and inland) encircling most of the perimeter of the island. Due to the mountainous interior, there is no road crossing the island. The speed limit is 50km/hr and reduces to 30km/hr in the main centre, Avarua the capital. (Cook Islands Road Safety Council, 2015)

6.1.2 Demand Assessment

In 2016 there were 16,297 motor vehicles registered in the Cook Islands; about 60% represented motor bikes while the rest were cars and trucks (Cook Islands Road Safety Council, 2015). Table 6.1.2-1 shows the number of vehicles by type.

Table 6.1.2-1: No. of Vehicles registered in Cook Islands, 2016 (Own calculations)

Type	**Number of vehicles**
Motorbikes	9 778
Motor-vehicles	6 519
Total	16 297

According to the census of 2016, there were 17,434 people in the Cook Islands. Compared to the figure of number of vehicles, we can conclude than on average there is one vehicle per habitant in the Cook Islands.

Around 75% of the total population lives in Rarotonga. We used this percentage to estimate the number of vehicles in the islands. We also considered the same ratio of Motor-bikes and Motor-vehicles. Table 6.1.2-2 shows the number of vehicles by type in Rarotonga in 2016, based on our own calculations.

Table 6.1.2-2: Estimated No. of Vehicles in Rarotonga, 2016 (Own calculations)

Type	**Number of vehicles**
Motor-bikes	7 334
Motor-vehicles	4 889
Total	12 223

To estimate the number of vehicles in Rarotonga by 2040, we took the forecast population growth in the island. Table 6.1.2-3 shows the estimated number of vehicles by type in Rarotonga in 2040.

Table 6.1.2-3 : Estimated No. of Vehicles in Rarotonga, 2040 (Own calculations)

Type	**Number of vehicles**
Motor-bikes	8 140
Motor-vehicles	5 427
Total	13 567

Another important consideration for further calculations is the 'Vehicles Kilometres Travelled' (VKT), this is the distance travelled by a vehicle in a given period of time.

There is no information about this figure for the Cook Islands. For this scenario, we used the circumference of Rarotonga as a reference, as it is unlikely that a local resident travel more than a full circle around the island on average per day. We assumed an average VKT of 30 km/day.

6.1.3 Techno-Commercial Feasibility

The global Electric Vehicles market is growing faster. They are gaining more attention in recent years, mainly because of tougher emissions targets. Several countries around the world are announcing end dates for the sale of diesel and gasoline powered vehicles. France and the United Kingdom, for example, have proclaimed that they will end sales of Internal Combustion Vehicles (ICEVs) by 2040 (Patrick Hertzke, 2018).

On 2016, the Ministry of Transport from New Zealand announced its Electric Vehicles Program. They set a goal of reaching approximately 64,000 EVs on their roads by the end of 2021. The Government wants to develop the EV market by reducing some of the barriers such us misconception about electric vehicles, and limited public charging infrastructure (Ministry of Transport New Zealand, 2019). This is very important as well for the Cook Islands. As mention on previous chapter, they depend on New Zealand in terms of aids and exports. For Example, New Zealand is its major donor in terms of funding projects to achieve 100% renewable energy target by 2020 (Zhong, 2015).

The Cook Islands, as well, is starting to switch to E-mobility. There are more than 40 electric vehicles owners in Rarotonga and one charging station located at the Te Aponga Uira office in Avarua (Lacanivalu, 2019).

6.1.4 Performance comparison

Currently a Battery Electric Vehicles (BEV) is more expensive than an Internal Combustion Engine Vehicles (ICEV) but, this is likely to change as the EVs industry is moving rapidly. With more technological advances in the production of batteries, manufactures are developing EVs for the mass market, making it much more cost effective.

If charged with a renewable energy source, EVs have zero emissions to the environment. Other advantages of EVs are:

- Low maintenance cost
- Electric motors are quitter, so noise pollution is reduced
- Fuel cost savings

The model selected for this study for the Electric car is the 2018 Nissan Leaf. This mainly because it is rated as the best affordable EV in the market and the basic model with 40kwh battery can provide up to 240 km of range on a single charge (Nissan LEAF 2018). Moreover, the model is available for sales in New Zealand.

The model selected for the electric Motorcycle is a ZERO S because is light, economic and the basic model of 46 HP with a 7.2 kWh max capacity can provide up to 97 KM of range on a single charge (ZERO Motorcycles).

6.1.5 Fuel Economy and Electric Load

The fuel economy of a vehicle relates to the distance travelled and the amount of fuel consumed. For an electric vehicle can be measured in terms of kWh/ 100 km. This value varies depending on the manufacturer. Sample values from the two models mentioned before were adopted for the year 2040.

Table 6.1.5-1 : Fuel Economy Estimates for Electric Vehicles

Fuel Economy	Electric Car	Electric Motorcycle
kWh/100 km	18.64	6.6

The VKT was maintained at 30 km/day. The charging efficiency based on a range estimate for level 2 charging was estimated at 96% by 2040 (Sears, 2014)

Table 6.1.5-2: Electric Annual Load Estimated for Electric Cars

Parameters	**2040**
No. of Electric Cars	5,427
No. of Conventional Cars	0
Total No. of Vehicles	5,427
Percentage of EVs	100%
Fuel Economy (kWh/100 km)	18.64
Average VMT (km/day)	30
Daily load per vehicle (kWh)	5.592
Total Daily Electric Load due to vehicles (kWh)	30,348.16
Annual Electric Load due to vehicles (kWh)	**11,077,078.93**
Charging Efficiency	0.96
Annual Electric Load due to Electric Cars + Efficiency(kWh)	**11,538,623.89**

Table 6.1.5-3 : Electric Annual Load Estimated for Electric Motorcycles

Parameters	**2040**
No. of Electric Motorcycles	8,140
No. of Conventional Motorcycles	0
Total No. of Motorcycles	8,140
Percentage of EVs	100%
Fuel Economy (kWh/100 km)	6.6
Average VMT (km/day)	30
Daily load per vehicle (kWh)	1.98
Total Daily Electric Load due to Motorcycles(kWh)	16,117.57
Annual Electric Load due to Motorcycles (kWh)	**5,882,911.70**
Charging Efficiency	0.96
Annual Electric Load due to Electric Motorcycles+ Efficiency(kWh)	**6,128,033.02**

Added the two values of Annual Electric Load from table 6.1.2-5 and table 6.1.2-6, the total annual demand from Transportation is 17.667 GWh.

6.1.6 Charging Infrastructure

The EV charging infrastructure is highly dependent on the cities' needs. For our case scenario of 100% e-mobility, enough access to efficient charging station should not be a barrier; this would require a robust infrastructural support from the Government of the Cook Islands.

Nowadays, an average electric vehicle needs to recharge its battery after 200 km of driving. Due to the size of Rarotonga and the fact that the island is encircled by a main road of approximately 30 km long, the longest distance travelled by a vehicle in the island will most likely be considerably less than 60 kilometres. Designing a charging system for EVs in Rarotonga should not be very difficult.

Also, considering that it can take between to 1 to 6 hours to charge a battery from complete empty to completely full on an average EV. This can easily be accommodated for charging during the working day on public charging stations.

6.1.7 100% E-mobility Scenario

For the 100% E-mobility Scenario, the shift from classic diesel vehicles to electric vehicles will generate an extra annual demand of 17.667 GWh; this represents 37% of the total forecast electricity and transport demand for 2040, reaching a total value of 47.768 GWh.

For this study we only considered a Controlled Charging System. This means a scenario of public charging infrastructure as well as tariff structure, which encourages EV owners to charge their vehicles during peak hours of solar energy production.

Based on the electricity demand forecast for 2040, the transport demand for the same year and the parameter of charging hours only from 10 am to 3 pm, we generated an hourly load profile and run it in our Excel energy model.

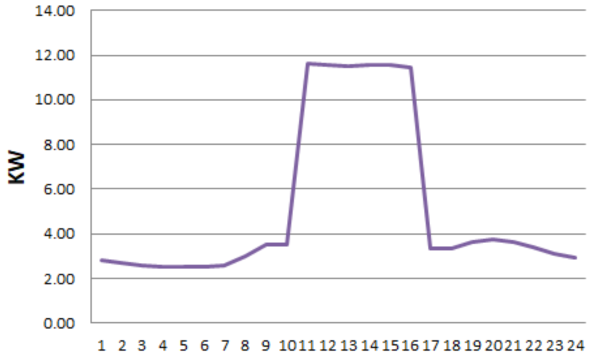


Figure 6.1.7-1: Load in kW for one day with E-Mobility scenario

If the renewable energy consumption for 2040 includes the transport sector a demand of 47.768 GWh has to be met. For this, the installed capacity of solar energy has to be increased from 6MW to 14 MW. The wind energy capacity and the pump storage volume are not affected.

This extra installed capacity of solar energy causes new costs. Although the specific cost for the storage go down because of more generated kWh, the total LCOE goes up to 0.35$/kWh.

6.1.8 Calculations for comparison of fuel cost

A rough estimation of fuel cost of a combustion engine vehicle and an electrical vehicle running on renewable energy produced on Rarotonga gives the following results.

Cars

Table 6.1.8-1 : Cost comparison of Electric car vs Conventional car

Model	Nissan Leaf 2018		Conventional Car	
Fuel Cost	0.24	$/kWh	1.41	$/l ***
Fuel Consumption	0.1864	kWh/ km	0.061	l/km *
Cost per km	0.044736	$/km	0.08601	$/km
Cost per 100 km	**4.4736**	**$/100km**	**8.601**	**$/100km**

Motorcycles

Table 6.1.8-2: Cost comparison of Electric Motorcycle vs Conventional Motorcycle

Model	ZERO S		Conventional Motorcycle	
Fuel Cost	0.24	$/kWh	1.41	$/l ***
Fuel Consumption	0.066	kWh/ km	0.03	l/km **
Cost per km	0.01584	$/km	0.0423	$/km
Cost per 100 km	**1.584**	**$/100km**	**4.23**	**$/100km**

* The conventional car used for comparison is the Toyota Corolla Ascent Hatch, the bestselling car in New Zealand in 2015 and available in Rarotonga (Zhong, 2015).

** The conventional Motorcycle used for comparison is the Yamaha Cygnus, as is available in Rarotonga rental cars. (Zhong, 2015).

*** Price for January 2018 (Cook Islands NEWS, 2018), rate conversion used 1NZD =0.66USD.

Based on Table 6.1.2-7 and Table 6.1.2-8, we can conclude that the cost of driving an electric vehicle is substantially below than driving a conventional vehicle. Moreover, shifting to Electrical Mobility after Cook Islands has reached 100% Renewable electricity, could contribute to the reduction of imports, which will translate in an economic boot for the island.

6.2 PV Roof Top (Precious)

Our aim of achieving a 100% renewable energy and diminishing fossil fuel use in the transport system of the island with the use of e-mobility vehicles requires an increase of the renewable energy technology capacity. The deployment of rooftop solar photovoltaics technologies was considered to meet the increase energy demand from e-mobility. Electricity supply from rooftop PV technologies would serve a good and viable sustainable energy solution (L.K.Wiginton, 2010).

The installed capacity from rooftop PV would complement the energy supply from the already installed capacity of the 8MW ground mounted solar PV and the 6MW wind turbines.

The analysis of solar potential from rooftops would enhance effective energy planning in terms of determine the extra amount of energy capacity required to complement the increased energy demand alongside with cost factors and also to develop policies which would serves as a framework for the advancement of renewable energy projects on the island. Policy such as Feed-In-Tariffs which has shown to be very effective in increasing the use of RES in different countries. For example, Germany increased to 12.5% renewable energy mix in 2007 (Peter&Weis, 2008).

6.2.1: Methodology

To estimate the solar rooftop power and energy potential, the total roof area and the solar PV available roof area was analyzed and calculated.

6.2.1.1: Total roof top areas

The total roof area was estimated from the relationship between per capita rooftop area and number of houses on the Island.

The number of private houses on the island is about 3200 (Statistics Department, 2011).The average roof top area is about 100 square meters for every residential building which was measured with the assistance of Google Earth. The total roof area is calculated with the equation below

Equation	Rooftop area	x	Number of houses	=	Total Rooftop Area
units	(m^2)				(m^2)
	100	x	3200	=	320,000

Total Rooftop Area = 320000m^2

Equation 6.2-1: Total Roof Area formula

6.2.1.2: Available Roof area for Solar PV

The roof top material of most building is mainly from corrugated iron sheets on the islands (Statistics Department, 2011).

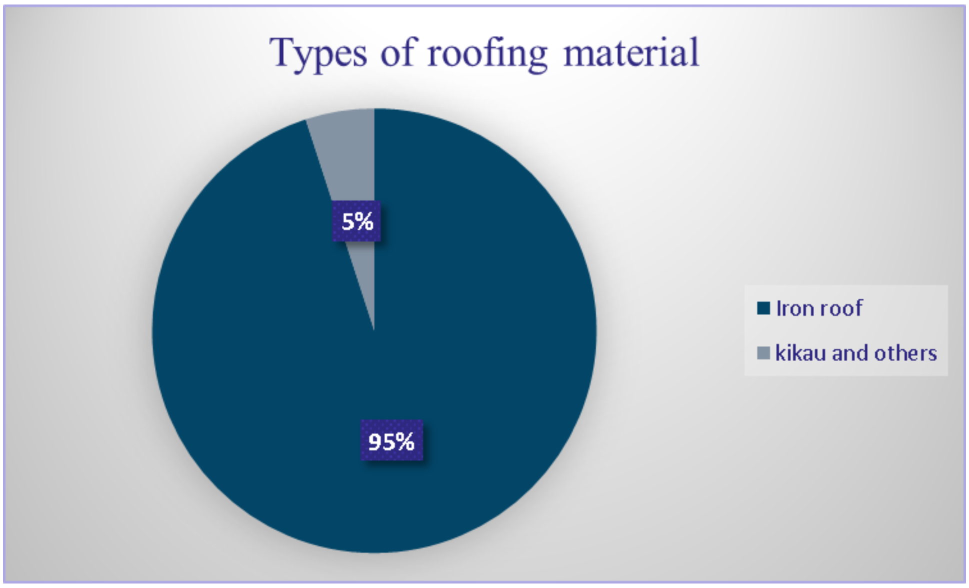


Figure 6.2-1: Types of roofing materials on the island

These implies that a significant amount of the roof top will be suitable for the deployment of rooftop PV. We made an optimistic assumption of 82% suitable roof top areas which would result in 262400 m² available area.

We also made assumptions about the maximum roof space required for solar PV installations on rooftops per capita to estimate the total available roof area for solar PV.

Equation	Suitable Rooftop area	x	maximum roof space required	=	Total Rooftop Area
units	(m²)		%		(m²)
	262400	x	50	=	131,200

Total available Rooftop Area for Solar PV = 131,200(m²)

Equation 6.2-2

6.2.1.3: Solar Energy Potential on Rooftops

The Figure below shows the range of the global horizontal irradiation on the rooftop from 1,600-1,800 kWh/m²/year.

Figure 6.2-2: Global Horizontal Irradiation on Rarotonga Rooftops

The formula used for estimating the energy potential is presented in the equation below.

Equation:	Solar irradiation	x	Efficiency	x	Total Rooftop Area	=	Rooftop Solar Energy potential
Units	(kWh/m^2/year)		(%)		(m^2)		(MWh)
	1560	x	20	x	131,200		40934

the annual rooftop PV energy =40,9 GWh

Equation 6.2-3: Formula for the calculation of rooftop solar potential energy

The solar irradiation was obtained from the Meteoblue company. The solar irradiation =1560kWh/m2/year; the total area available for solar PV equals 131,200 m2, the conversion efficiency coefficient of solar irradiance to electricity assumed to 20%.

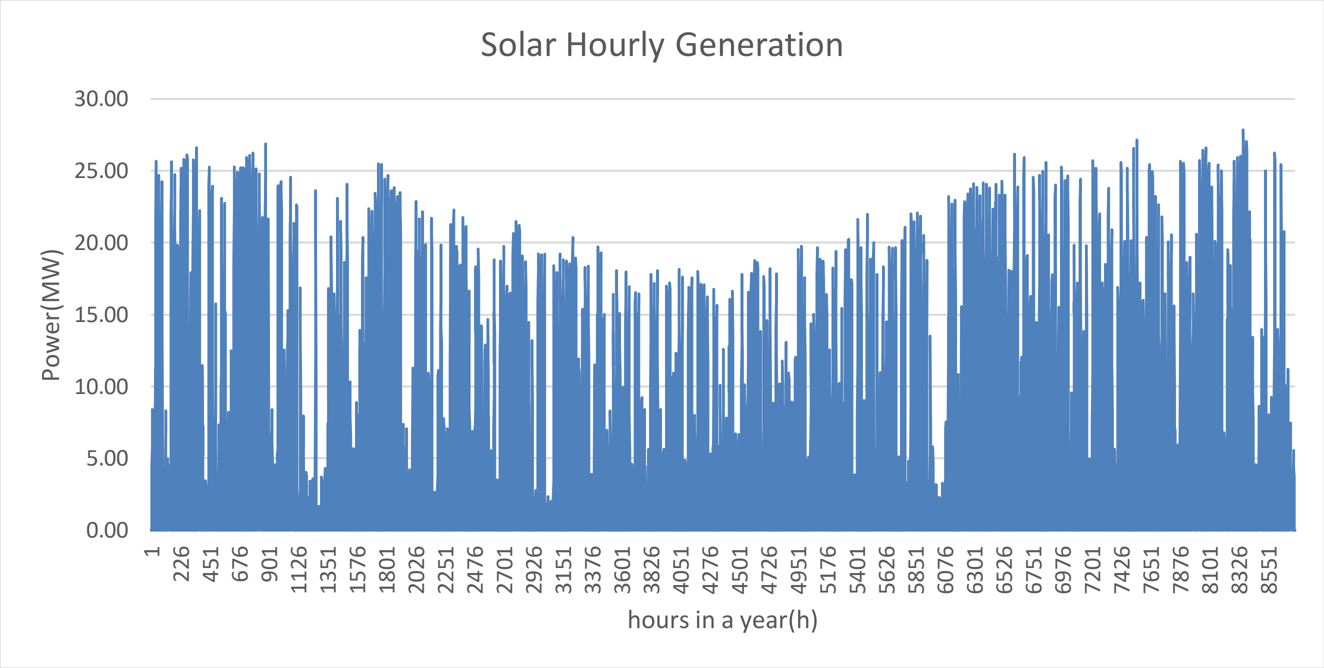


Figure 6.2-3: Hourly generation from solar PV rooftops

From the hourly PV generation, the PV power potential = 26,40MW

Finally, we determined the actual installed capacity that would meet our extra demand from e-mobility with the aid of our energy model. Our model results show that installing solar PV on from the total available rooftop area will be sufficient to meet the increased demand from e-mobility. The solar energy potential was estimated for the optimized area using the equation below.

Equation:	Solar irradiation	x	Efficiency	x	Total Rooftop Area	=	Rooftop Solar Energy potential
Units	(kWh/m^2/year)		(%)		(m^2)		(MWh)
	1560	x	20	x	25000		7,800

the annual rooftop PV energy =7,8 GWh

Equation 6.2-4: Formula for the calculation of rooftop solar potential energy

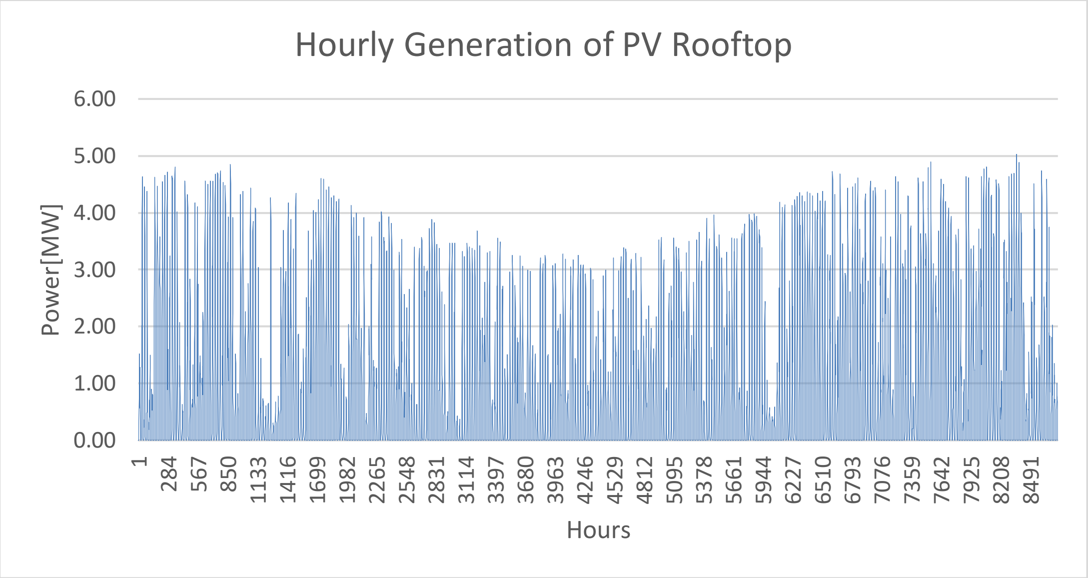


Figure 6.2-4: Hourly generation of 6MW PV on rooftops

With optimized result from the model, roof tops covered with PV, the potential PV peak power output from the island considered is 6MW and the potential annual energy production is 7.8 GWh

6.2.1.4 Aggregated Solar PV Technology Potential

Aggregated sum of the Solar potential is the sum of solar energy potential from ground mounted and rooftop source. The values are presented in the table below:

Table 6.2-1: Aggregated Sum of Solar PV potential

	Installed Capacity [MW]	Annual Energy Generation [GWh]
Rooftop solar PV	8	7.8
Ground Mounted PV	6	10.9
Total	13	18.7

7. Chapter 7: Road Map (Maryam)

As mentioned earlier in *chapter 1* the government of Cook Islands was planning to be 100% dependent on renewable energy generation by 2020 but this goal up until now is clearly out of reach , One of the basic reasons behind not achieving the goal of the 100% RE was the Integration of renewables to the grid without sufficient planning and control which caused instability and reduce quality of power delivered , Another problem that facing Rarotonga now is storing the excess energy from the solar arrays that are already installed

In this chapter an energy transition roadmap for Rarotonga is presented , the goal of this road map is to illustrate how Rarotonga can 100% dependent on renewable energy technologies (in particular Wind and Solar PV) for generating electricity by 2030 and to deploy the Electrical Vehicles by 2040 ,Afterword the obstacles that may appear and influence implementation will be presented along with the recommendation and policies that would support these goals .

7.1 Roadmap:

A roadmap aims to develop and promote renewable sources of energy as an alternative to conventional forms of energy for generating electricity in Rarotonga. This roadmap focuses not just on renewable power technologies, but also technology options transport. To achieve 100 % renewable energy resources in Rarotonga by the year 2030 and to transfer the energy used by the transport sector from diesel to electricity by 2040 (Electric vehicle deployment), this road map proposed in order to be followed and verified , its divided into two phases : planning phase and implementation phase will be described as follows

7.1.1 First Phase: Planning Phase

The planning phase is developed into four stages the first stage is to analyze and study current energy situation and forecast over 20 years ,defining detailed assessing of the most suitable Renewable Energy resources and in a pathway that will lead to 100% renewable energy (which have already been done and analyzed in *chapter 3*) , accompanied by a site investigation and analysis to allow the implementation of the pumped Hydro storage , another important step in this stage is the assessment of the existing grid and examine the capability of it .

This stage is to be followed by a second stage where the suppliers and construction contractors should be identified and engaged, the consultancy should be done in all the levels, also engaging with a wide range of stakeholders early and often should be done here in order to build momentum, and to create the synergies and partnerships across society which will make the strategy success.

The importance of the above two stages is to decide what actions will best help achieving the goal of 100% RE generation, so in the third stage analyzation and optimization between the different technologies. should be done with the help of the developed model in this report the model will come up with the best technical and economic combination of renewable energy resources.

Finances plays a major role in implementing any project, in this stage an appropriate financial analysis techniques such as (Simple Payback Period ,Return on Investment (ROI) ,Return on Equity (ROE),Internal Rate of Return , Net Present Value) should be done so that a final strategy and plan is defined and aligned with the financial Situation . (Financial analyisi principles for energy efficiency and renewable energy project, n.d.)

7.1.2 Second Phase: Implementation phase (Time line)

One of the challenges that faced cooks island in achieving there 100% renewable energy national goal is that the grid is not technically advanced enough to accommodate all renewables being developed. The Cook Islands' rapid pace of integrating renewables into their electricity mix is primarily constrained by limitations of the grid. The country's grid further innovation and investment are required for grid stabilization and grid upgrades to manage the fluctuations in generation and to allow for more renewable energy generation to be integrated into the grid whilst maintaining the reliability of power generation. This is an essential factor for Cook Islands to meet there goal, so between 2020 and 2025 as shown in the figure below, the first step to start with after considering the results of the grid assessment which have been done in the planning phase is to strength and expand the existing grid , building the pump hydro storage should come in this period as well because of the filling time the reservoirs needs and the construction time ,also the plan is to finish implementing 50% of RE by the end of 2025 , between the years 2025 and 2030 the other 50% of renewables should be implemented and the charging stations infrastructure should be started preparing for the deployment of E mobility , between 2030 and 2035 % of the E mobility should be deployed along with starting the implementation of solar roof tops to cover the demand needed for the transport sector , and finally by 2040 100 % E-mobility .

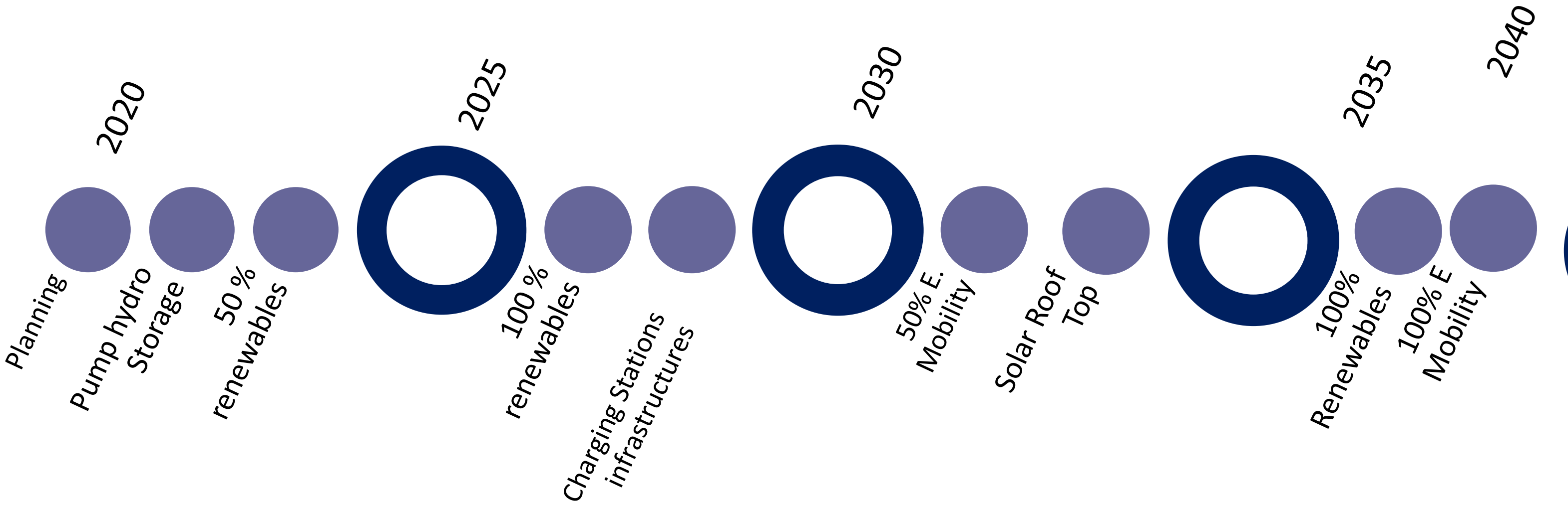


Figure 7.1.2-1 Time line for achieving 100% renewable energy by 2030 and 100% E mobility by 2045

7.2 Risks and Challenges:

The decision to move to 100% Renewable Energy can be fraught with some non-technical issues, therefore its essential to pay attention to them during the planning in order not to be a hurdle to reach the desired goal, these issues required careful and creative policy arrangements, innovative financing and collaboration between a wide variety of stakeholders .Some of these issues considering Rarotonga as below:

- **Climate Change** is a cross cutting issue that will require coordinated policy response from the public sector and civil society in addressing adaption measures, The Cook Islands as a Pacific small island developing state is extremely vulnerable to the most severe and immediate effects of climate change – that being the increased severity of extreme weather conditions, which for the Cook Islands means the annual threat of destructive cyclones for five months of the year. (The Cook Islands National Report for the 2014 Small Islands Developing State, 2015)
- Depopulation and the increase of immigrant labor in Rarotonga will significantly result in altering the context for policy in Rarotonga, which will affect the energy policy .
- Social acceptance and awareness While the public has a positive attitude towards renewable energy in general, individual projects regularly face resistance from the local community. People tend to resist change in their environment, out of a personal fear for a loss of quality of life. Instead of disregarding local views as NIMBY behavior, both rational and emotional parts of the local debate should be taken seriously. Both rational objections to projects and specific fears and emotions should be identified, discussed and dealt with. (Social Acceptance renwable energy, n.d.)

7.3 Policies and Recommendation

- Integration of renewable Energy into the daily life of consumers and prosumers, as well as into the institutional framework, to allow them to be part of the overall energy transition. (Raising awareness programs and Training).
- **Commitment of stakeholders**: Getting to 100% is a journey. More so than just a simple application of technology, it takes time to vary widely with electricity use on the island. Successfully navigating this path creates buy-in from stakeholders and investment in systems which have a significant place in local communities for many years.
- The availability of data and the strong engagement of national stakeholders have proved to be the key preconditions for a meaningful, insightful roadmap
- **Skills:** more complex system also requires more skilled and trained operators, and time to adapt and optimize the system after each development stage .
- **Community Education and training** that creates in consumers a willingness to pay for the conversion of infrastructure from fossil-fuel based energy to renewable energy, with a very strong narrative aligning renewable energy with improved quality of life.
- Understanding local requirements (social, environmental, technical and economic)
- Affordability of electricity should be maintained, with national expenditure on electricity to be no more than without renewable energy.
- (feed-in) tariffs
- Eliminating fossil fuel subsidies and implementing carbon and energy taxes
- Make Electric Vehicles competitive with conventional vehicles in the form of tax breaks, rebates or exemptions in favor of low emissions. (Differentiate taxes on vehicle registration based on their fuel economy or CO2 emissions performance).

Finally, it can be said that with good planning and supporting policies 100% renewable in Rarotonga is achievable.

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