Assessing the Carbon Footprint of RARCC and Papua Diving in Raja Ampat, Indonesia

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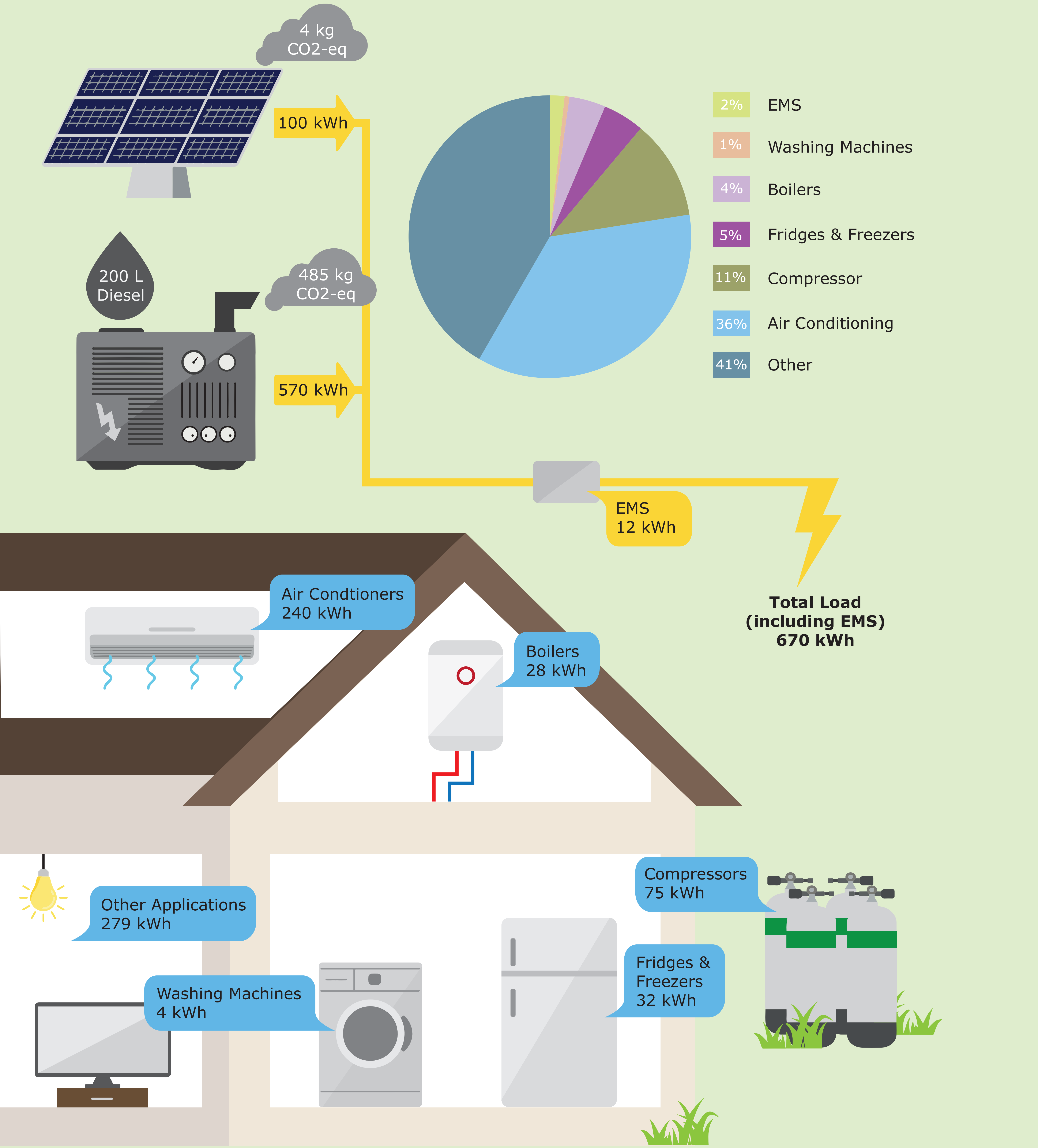
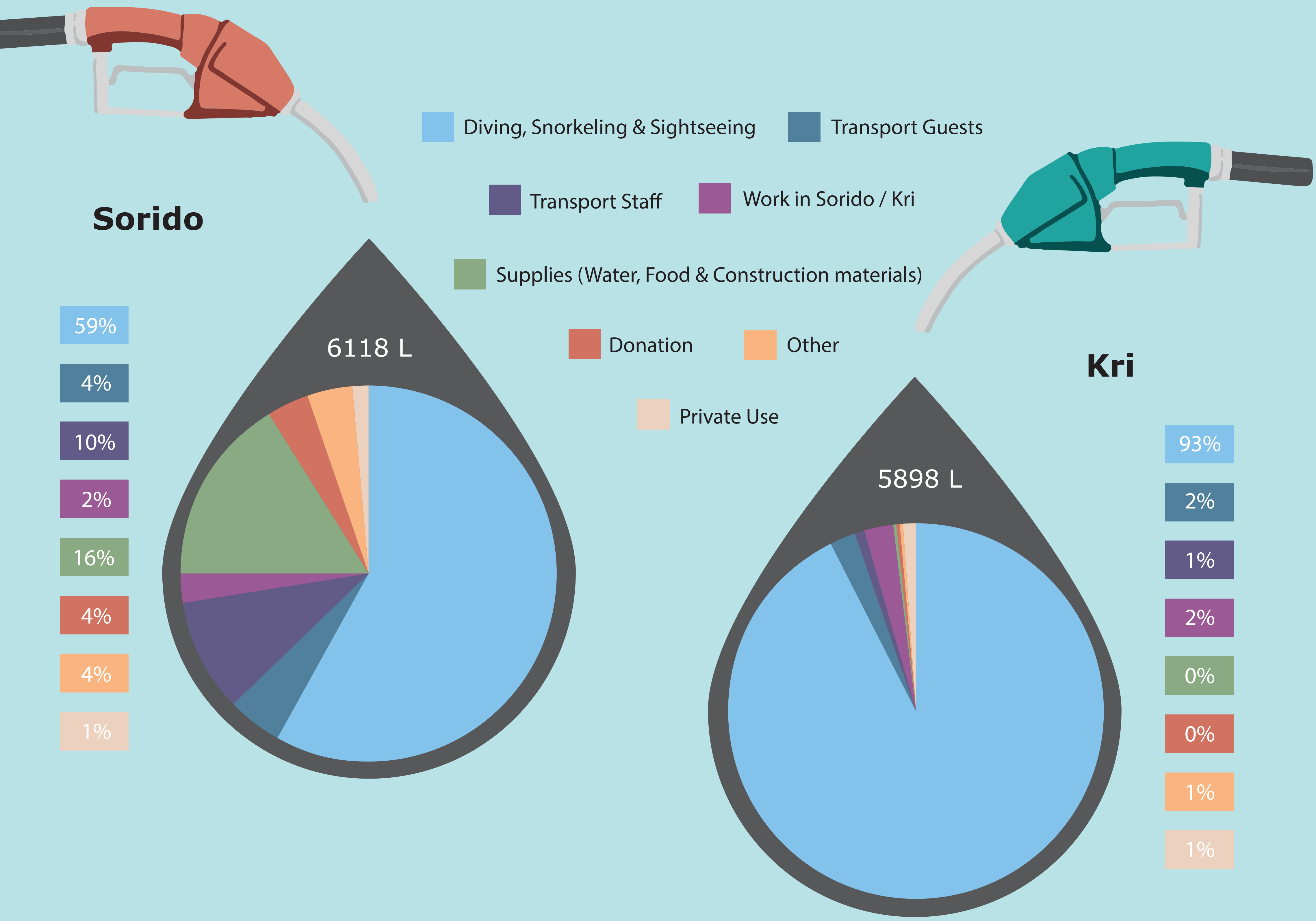
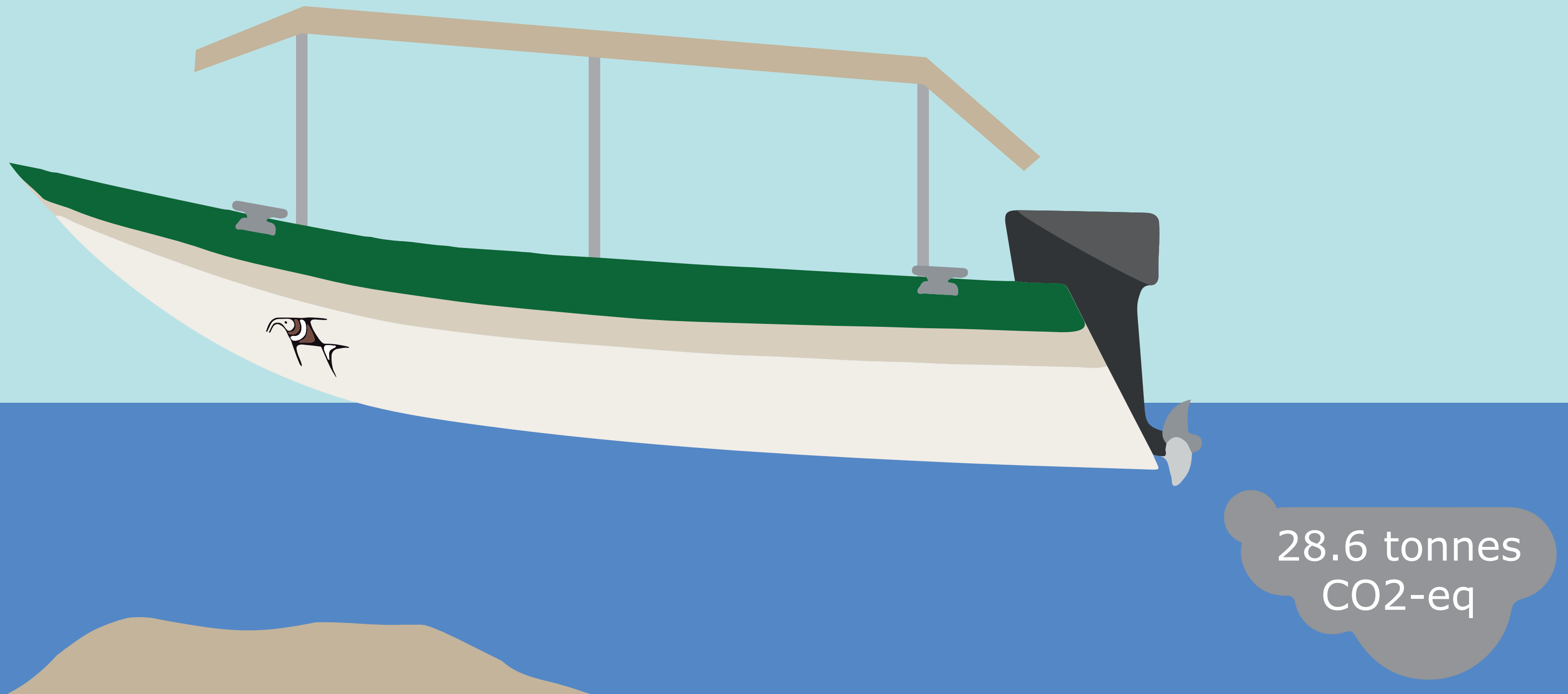
October – December, 2018

Executive Summary: Average Electricity Usage Per Day



Executive Summary: Average Gasoline User Per Month For Boats





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1 Introduction

The Indonesian archipelago consists of roughly 17500 officially listed islands within the Republic of Indonesia. However, the exact number of islands is questionable, as well as number of inhabited island. Over 12000 remote villages are underdeveloped and disconnected to the grid where over 2000 villages or 10% of the population have no electricity at all. The lack of electricity restrains the quality of life and will prevent economic growth [1]. Particularly in the eastern islands of Indonesia, the electrification rates are less than 50%. In those villages where people want economic growth, electrification is very important. The government of Indonesia plans to increase the national electrification rate from 84% to 100% by 2020 [2].

Unfortunately, the investment in the generation of renewable energy in Indonesia has always lagged that of other neighbouring counties. The electricity regime in Indonesia is almost exclusively a state-run affair where generation, transmission, and distribution are mostly controlled by Perusahaan Listrik Negara (PLN) since the independence of Indonesia in 1945. Big failure was known for the Indonesia Solar Home System Project (ISHSP), which ran from 1997 to 2003. The goal was to reach one million rural Indonesians by selling and installing 200.000 solar home systems. However, in 2003, only 8.054 units were installed [2] [3].

Thereafter in 2015, the Indonesian solar power section received a lot of attention from international developers and investors. Planned projects from 2017 should increase the installed capacity from 9 MW to over 240 MW, still short of Indonesia's target of 3.6 GW of solar PV by 2019. However, it still suggests a significant shift in Indonesia's electricity sector and a potential start of the transition form fossil fuels to renewable energy sources [2].

Raja Ampat Research & Conservation Centre (RARCC) and the Papua Diving resorts are located on the island Kri (Pulau Mansuar), in west Papua. The island, just like many others in the region, is not connected to the grid. The electricity to power all the facilities of the resorts on Kri is generated by diesel generators and a small photo voltaic (PV) field. The goal of RARCC is to decrease the islands' carbon footprint and possibly with that, increase their renewable energy factor (RF).

This report describes an assessment of the carbon footprint and suggestions on how the carbon footprint can be reduced. First the system as was present on the island during the internship will be described. Second, the carbon footprint will be analysed and mapped by collecting data of the electricity consumption of the island along with the gasoline consumption for the boats that provide all the transportation from and to the island. Third, methods to reduce the electricity consumption will be analysed and described. In addition, suggestions will be made on how the renewable energy factor can be increased and how the resorts on the island could be more self sustainable in the future.

2 Current Electricity State

Nowadays, RARCC and the Papua Diving resorts rely mostly on electricity generated by three diesel generators. Being self sustainable and not rely on diesel combustion would be ideal for the near future since islands are very sensitive to climate change. Next to renewable energy sources, water harvesting and waste management are important aspects for being self sustainable. A photo voltaic (PV) system is already present on the island but this is not sufficient for all the facilities. This chapter will describe the current layout of the island and its electricity state.

2.1 Island layout

The Papua Diving resort can be divided into three locations. The Sorido Bay resort including the RARCC facilities, Kri Eco resort, and a Helicopter hangar slightly up hill on a cleared area. All these locations are supplied with electricity generated by the diesel generators, of which at least one runs all day, and a PV system that generates electricity during daytime.

The total load of the island can be divided into three categories. The resort load (both resorts and RARCC), a carpenter workshop and a compressor room where compressors are used to fill dive tanks. Both carpenter workshop and compressors operate on three phases.

2.2 Air Compressors

Four air compressors (2x 7.5 kVA and 2x4 kVA rated) are installed in the compressor room, providing compressed air and Nitrox, a mixtrure of nitrogen and 32% oxygen, for 24 dive tanks and a 350bar storage tank. The compressors operate on three phases and a meter board is present in the compressor room displaying the voltage, current and frequency.

2.3 Diesel Generators

Mentioned before, three diesel generators are providing most of the electricity on the island. Their capacities are 42.5, 42.5 and 60 kVA. These generators have a specific function where the 60 kVA rated generator is often used for the resort load and the 42.5 kVA generators for the compressors and carpenter workshop. However, the loads are sometimes switched between the generators. An overview of the specifications of the 42.5 kVA and 60 kVA diesel generators can be seen in Table 1 and Table 2 respectively.

Table 1: HARTECH 42.5 kVA

Diesel Generator			
Model	HT - 42,5 Y	Output	42,5 kVA
Serial Number	170116-O-035	Voltage	220 / 380
Engine	YANMAR	Current	64.57
Engine Type	4TNV98T-GGEA	PF / Phase	0.8 / 3
Engine S/n	W6267	Speed	1500 RPM
Generator	HARTECH	Frequency	50 Hz
Generator Type	HTG224C	Rating cont.	80%
Generator S/n	16071281	Reference	HPL

With a performance factor of 0.8, the total power of the 42.5 kVA generator results into roughly $42.5*0.8 = 34$ kW. Furthermore, according to the manufacturer, the fuel consumption is 6.99 Litres per hour for a 75% load and 9.31 Litres per hour for a 100% load [4]. The second 42.5 kVA generator is also manufactured by HARTECH. The main difference is the generator type, which is manufactured by Stamford.

Table 2: HARTECH 60 kVA

Diesel Generator			
Model	HT - 60 Y	Output	60 kVA
Serial Number	091005-O-001B	Voltage	220 / 380
Engine	YANMAR	Current	91.2 Amp
Engine Type	4TNE 106 TG1A	PF / Phase	0.8 / 3
Engine S/n	V17352	Speed	1500 RPM
Generator	STAMFORD	Frequency	50 Hz
Generator Type	UCI 224 E14	Rating cont.	80%
Generator S/n	X09H330420	Reference	WL9/336/AKT

With a performance factor of 0.8, the total power of the 60 kVA generator results into roughly $60*0.8 = 48$ kW. Furthermore, according to the manufacturer, the fuel consumption is 9.79 Litres per hour for a 75% load and 13.05 Litres per hour for a 100% load [4].

Especially the 60 kVA generator runs far below optimal, which is considered to be roughly 80% of the rated capacity. This is caused by the PV system that takes over a big part of the load during a sunny day around noon, leaving sometimes only a 10kW load to be covered by a 60 kVA generator.

2.4 Solar PV

The solar modules present at Sorido are manufactured by Jskye, formerly known as PT. Sky Energy Indonesia. The manufacturer claims that the panels have an excellent performance under low light conditions. For example, in the morning, evening and on cloudy days. In addition, the modules are durable and independently tested for harsh environmental conditions, such as exposure to ammonia, salt mist and known PID risk factors. The reliability of the ST72M200, the PV modules on the island, as stated by the manufacturer can be seen in Figure 1 [5]. The PV modules have a maximum power of 200W under standard conditions. The nominal cell temperature is 45 degrees Celsius ± 2 degrees Celsius. The temperature coefficients of Pmax, Voc and Isc are -0.45, -0.344, and +0.021 percent per degrees Celsius respectively [5].

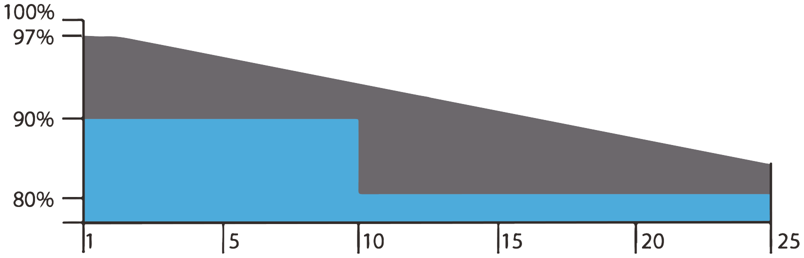


Figure 1: Reliability PV module ST72M200 [5].

At RARCC, 144 solar modules are present with a total of 28.8 kWp of which 48 are mounted roughly one meter from the ground under a 12 degrees angle and 96 are mounted on a pitched rooftop under a 16 degrees angle. Of the rooftop mounted modules, half is facing north where the other half is facing south. The modules close to the ground consist of 3 groups of 16 modules connected in series and the modules on the rooftop consist of 2 times 3 groups of 16 modules connected in series, where the three groups form one phase each. In addition, the PV modules run in parallel with one diesel generator at a time. A photo of the PV system can be seen in Figure 2.

Figure 2: PV system at RARCC.

2.5 Battery System

A small battery system is present on the island and owned by Murata (previously Sony Battery prior to 2017). However, the battery pack is not connected to the PV system and not in use. In total twelve IJ1000M Murata Lithium Ion batteries are present with a total capacity of 13.2 kWh.

2.6 Online Monitoring

An online monitoring system is installed on the island and owned by Murata. However, much improvement is needed as the system is very inaccurate. The system records the resort load, the generated solar energy and generated energy of three diesel generators. The resort load consists of both the resorts (Sorido Bay and Kri Eco) combined, where a part of Kri Eco is supposedly not taken into account. In addition, the carpenter workshop is not included in the resort load and the three generators are denoted as 42, 60, and 80kVA where in fact the 80kVA broke down and was replaced with another 42 kVA generator. An example of the interface of the EMS can be seen in Figure 3.

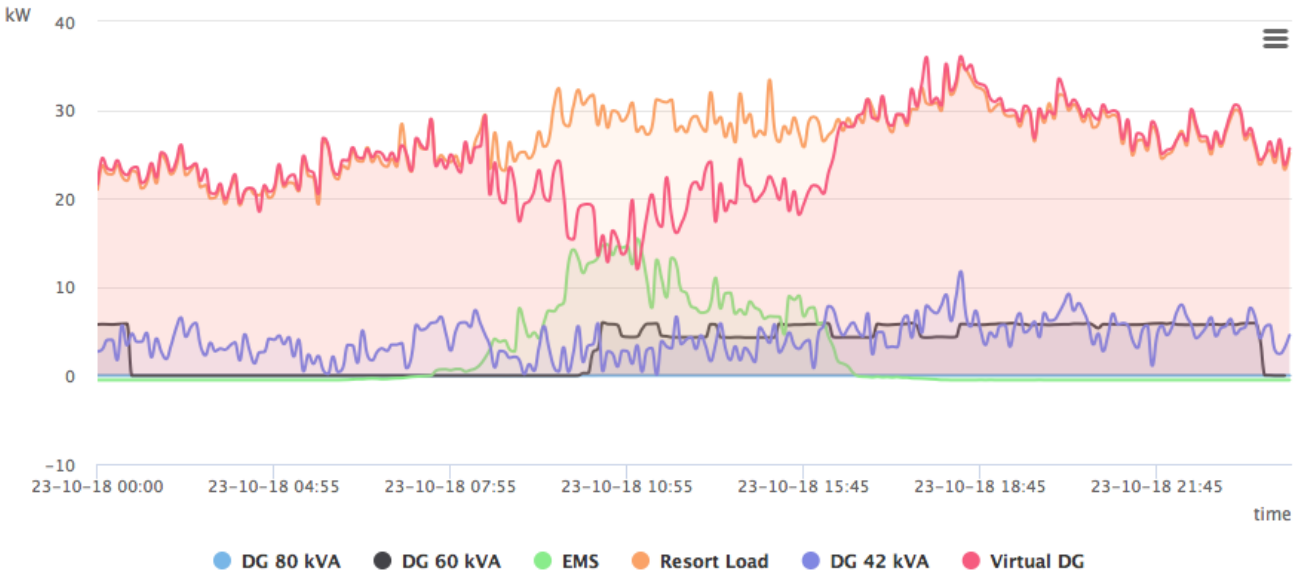


Figure 3: Example of Murata's interface on 23 October 2018.

By analysing the daily load of every first Tuesday and Saturday of the month since November 2017, it was concluded that the generated power by the solar modules never exceeded the load and that the average load lies between 20 and 35kW.

As of December 2018, the online monitoring system is out of order due to a fire in the generator room, causing the connection of the measurement system to burn down. This also resulted in the disconnection of the PV system to the load.

2.7 Transportation

All transportation from and to the island is provided by boats. These boats run mostly on dual 40hp 2-stroke gasoline engines and have function ranging from picking up food and supplies to taking guests to dive locations. In addition, motorcycles and a helicopter are present on the island but these will be omitted in this report due to their unpredictable and undocumented usage.

3 Carbon Footprint

The challenge of RARCC is to lower the carbon footprint as much as possible keeping all the facilities of the research centre and resorts operable. Therefore, the energy use has to be documented before it can be optimised. This chapter will describe the life cycle assessment of both solar PV panels and diesel generators. In addition, an analysis of the electricity use and gasoline use for the boats will be performed. Different type of renewable energy systems will then be evaluated in the next chapter and compared with respect to the carbon footprint for the island and feasibility along with suggestions on how to lower the energy consumption and thus the carbon footprint.

3.1 Life Cycle Assesement of the PV System

A life cycle assessment (LCA) is a framework for defining the environmental impacts caused by all stages of a product's life cycle, meaning, from raw material extraction to the product's end of life disposal. This includes raw material mining, component and chemical manufacturing, product manufacturing, transportation, installation, usage, maintenance, decommissioning and disposal and/or recycling if applicable [6].

First, to fabricate PV modules, materials need to be mined, refined and purified, including the silicon cells, glass, module frame, inverters and other electronics. This includes the petroleum extraction to create plastics, natural gas extraction for heating and electricity from the grid to create all the necessary parts. Second, the PV modules can be assembled by using the electricity in the grid as well. Third, the PV modules need to be transported from the manufacturer to the installing site, most likely by different means of transportation. Fourth, the PV modules need to be installed along with the Balance Of System (BOS) materials, which will be further explained in the next section. Fifth, during the time the PV system is used, maintenance should be performed. Minor replacements can be necessary along with frequent cleaning. The final stage is the end of the PV modules' lifetime. Decommissioning includes deconstruction, disposal and recycling where possible. When parts are recycled, the green house gases (GHGs) produced will decrease over the system's life cycle [6] [7].

A complete life cycle analysis will not be performed due to the large number of researchers that already published their work. However, an assessment will be made based on literature. A complete life cycle analysis describes the energy payback time (EPBT), energy return on investment (EROI) and the greenhouse gas emissions (GHG emissions), which will be introduced in the next sections.

3.1.1 Energy Payback Time

The energy payback time can be defined as the the time needed for a renewable energy source to generate the same amount of energy for the system to be produced itself. To calculate this, the cumulative energy demand (CED) during the PV system's lifetime is needed. For photo voltaics, the CED is the amount of primary energy used within the complete life cycle from cradle to grave, or in other words: The sum of the mining and production of raw materials, material processing and purification, manufacturing of the solar cells, the solar modules and the balance of system (BOS) components (wiring, transformers, inverters, supports etc., excluding batteries), the transportation of the system, the usage of the system (including operation), and the decommissioning, disposal and recycling if applicable [6] [8] [9].

The CED can be calculated by adding all the primary energy demands using equation 1 [6] [8].

$$CED[MJ_{PE-eq}] = E_{materials} + E_{manufacturing} + E_{transport} + E_{installation} + E_{O\&M} + E_{endoflife} \tag{1}$$

With $E_{materials}$ the energy demand to mine and produce materials for the PV modules, $E_{manufacturing}$ the energy demand to manufacture the PV modules $E_{transport}$ the energy demand for the transportation of materials, machines and the PV modules, $E_{installation}$ the energy demand for the module installation,

$E_{O\&M}$ the energy demand for operation and management of the system, and $E_{endoflife}$ the energy demand for the system disposal.

The energy payback time can then be calculated with the annual electricity generation, the energy demand for operation and maintenance and the conversion efficiency at the demand side. This can then be calculated by using equation 2 [6] [8].

$$EPBT[years] = \frac{CED}{\frac{E_{generation}}{\eta_{conversion}} - E_{O\&M}} \tag{2}$$

With $E_{generation}$ the electricity generation per year, $\eta_{conversion}$ the energy to electricity conversion from the grid (approximately 0.3), and $E_{O\&M}$ the energy demand for operation and management.

Different solar PV technologies result in different energy payback times. The purification and crystallisation process of silicon is very energy intensive, resulting in a higher EPBT. Studies showed that mono-Si had the greatest range of CED (1123-8050 MJ/m2) and the longest EPBT (1.4-7.3 years) compared to other PV technologies [8].

3.1.2 Energy Return On Investment

The energy return on investment can calculated by dividing the time period of system operation over the energy payback time as can be seen in equation 3 [6].

$$EROI_{PE-eq}\left[\frac{MJ_{PE-eq}}{MJ_{PE-eq}}\right] = \frac{T}{EPBT} \tag{3}$$

In contrast to the EPBT that measures the point in time after which the system provides net energy in return, the EROI describes the overall energy performance of the PV system over it's lifetime [6] and has values ranging from roughly 30 to 75.

3.1.3 Green House Gas Emissions

The greenhouse gas emissions are usually described with respect to their global warming potential, CO_2 equivalent, in a time-horizon of 100 years, where 1 kg CO_2 = 1 kg CO_{2-eq}, 1 kg CH_4 = 23 kg CO_{2-eq}, and 1 kg $N_2O = 296$ kg $CO2 - eq$. For solar PV, almost all green house gases are emitted during the up and down stream process where the mixture of fossil fuels in the grid are determining the greenhouse gas emissions [6]. However, literature shows a big disparity in the estimates of solar PV due to resources, technologies, manufacturing, transportation, location, size and capacity, lifetime and additional equipment [7].

For example, different PV technologies as mono-crystalline (Mono-Si), poly-crystalline (Poly-Si), multi-crystalline (Multi-Si) and thin-film technologies as cadmium telluride (CdTe) all require different material inputs and therefore different processing requirements and different conversion efficiencies where Mono-Si has the highest estimated average emissions [7], [8]. However, even though Mono-Si has a more energy intensive process considering its production, the efficiency advantage of Mono-Si might balance this out [9]. In addition, studies have not focus much on transportation, being a large weakness in literature. Fabrication and manufacturing are highly dependent on the mixture of the electricity grid, where electricity from renewable energy sources accounts for a significant low GHG intensity and coal fired electricity causes a significant high GHG intensity [7].

Furthermore, the geographic location is very important for the PV emissions, since solar irradiation is very location dependent and can change on a daily and seasonal basis. In addition, shading, vegetation and structures play a big role on the performance of a PV system where most studies presumed a solar irradiance of 1700 kWh/m^2/year [7]. A less obvious factor perhaps is the size and capacity. Efficiency increases with a large scale PV application due to logistics and transportation. More obvious however is the lifetime of the PV system. For this, maintenance, manufacturing quality and the usage conditions are very important, but also, difficult to measure. Studies showed that a lifetime of 5 years results in GHG emissions of 106.25g CO_{2-eq}/kWh where a lifetime of 20 years results in GHG emissions of 17.5 g CO_{2-eq}/kWh, showing that good maintenance is very important [7]. Research by Hsu et al. [9] evaluated different life cycle greenhouse gas emissions of crystalline silicon PV and harmonised these results to decrease the variability caused by inconsistent performance characteristics. 397 PV references were screened for quality, transparency, usability and relevance. Thirteen references relevant to c-Si ranged from 20 to 217 g CO_{2-eq}/kWh. The harmonisation methodology to calculate the GHG emissions is described with equation 4 [9].

$$GHG[gCO_{2-eq}] = \frac{W}{I * \eta * PR * LT * A} \tag{4}$$

With W the GWP-weighted mass of greenhouse gases emitted over the PV system's lifetime (g CO_{2-eq}), I the irradiation (kWh/m^2/year), eta the lifetime average module efficiency (%), PR the performance ratio, LT the system's lifetime (year), and A is the module are (m2) [9]. To harmonise the results, standard values for equation 4 were found in literature studies where an irradiation of 1700 kWh/m2/year, a module efficiency of 14.0% and 13.2% for Mono-Si and Multi-Si respectively, a lifetime of 30 years and a performance ratio of 0.75 and 0.80 for roof and ground mounted systems were used respectively. The lifetime of the PV system was set to 30 years instead of the more common 25 years due to recommendation guidelines by the International Energy Agency. Results from both studies can be seen in Figure 4 and Figure 5 [9] [10].

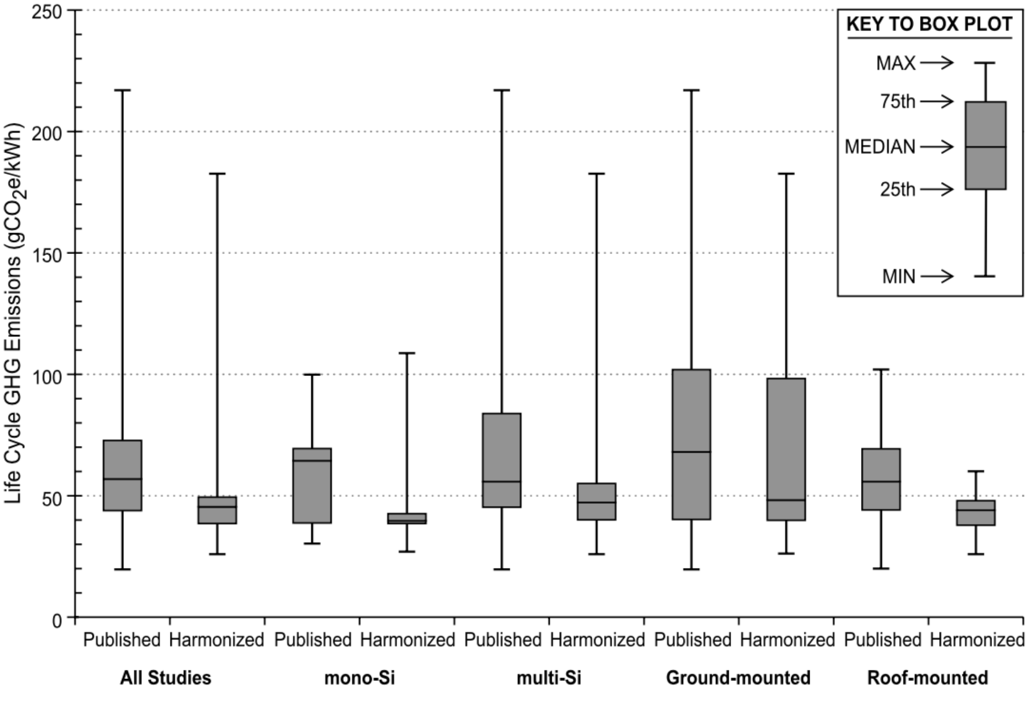


Figure 4: Life Cycle GHG eEissions of PV Technologies as Stated by Hsu et al. [9].

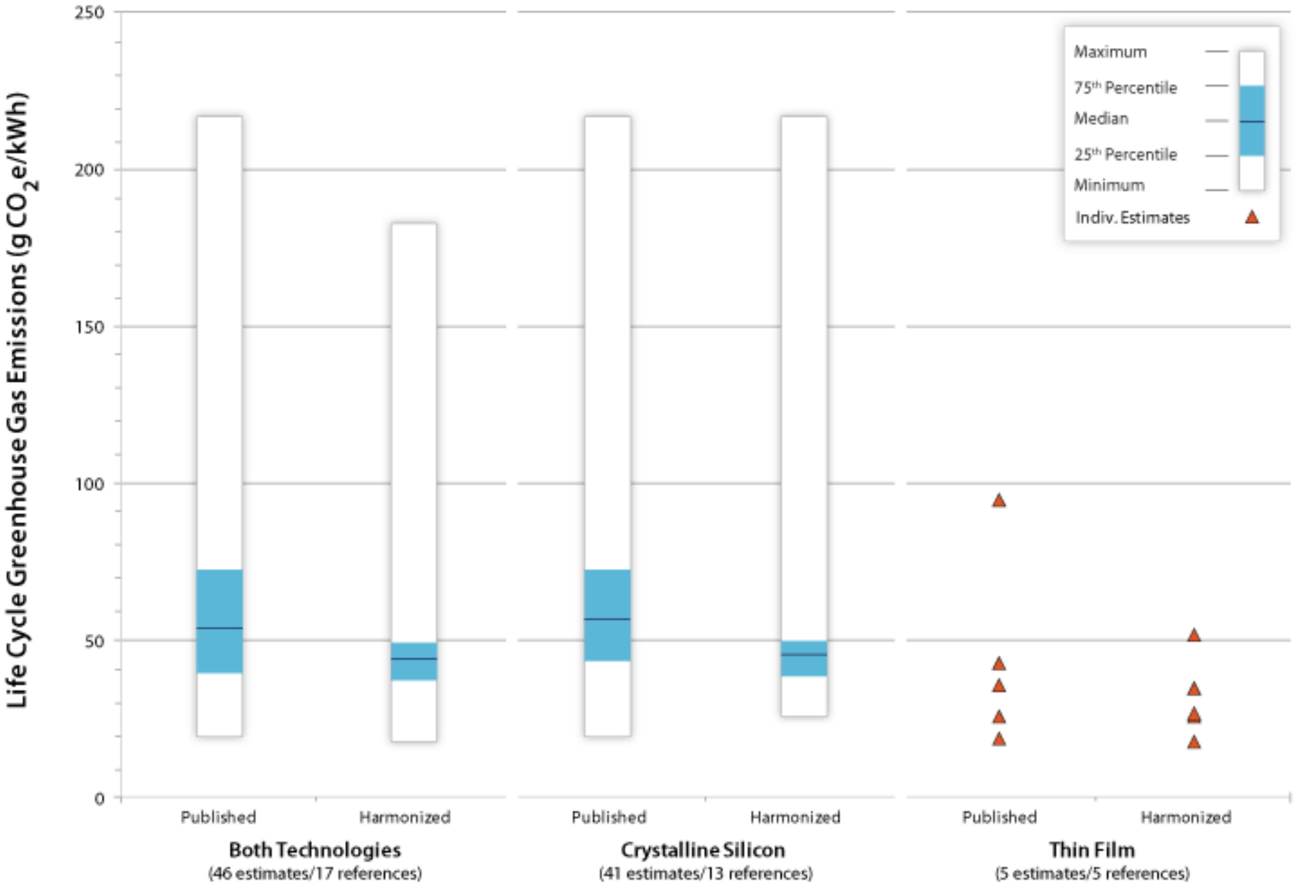
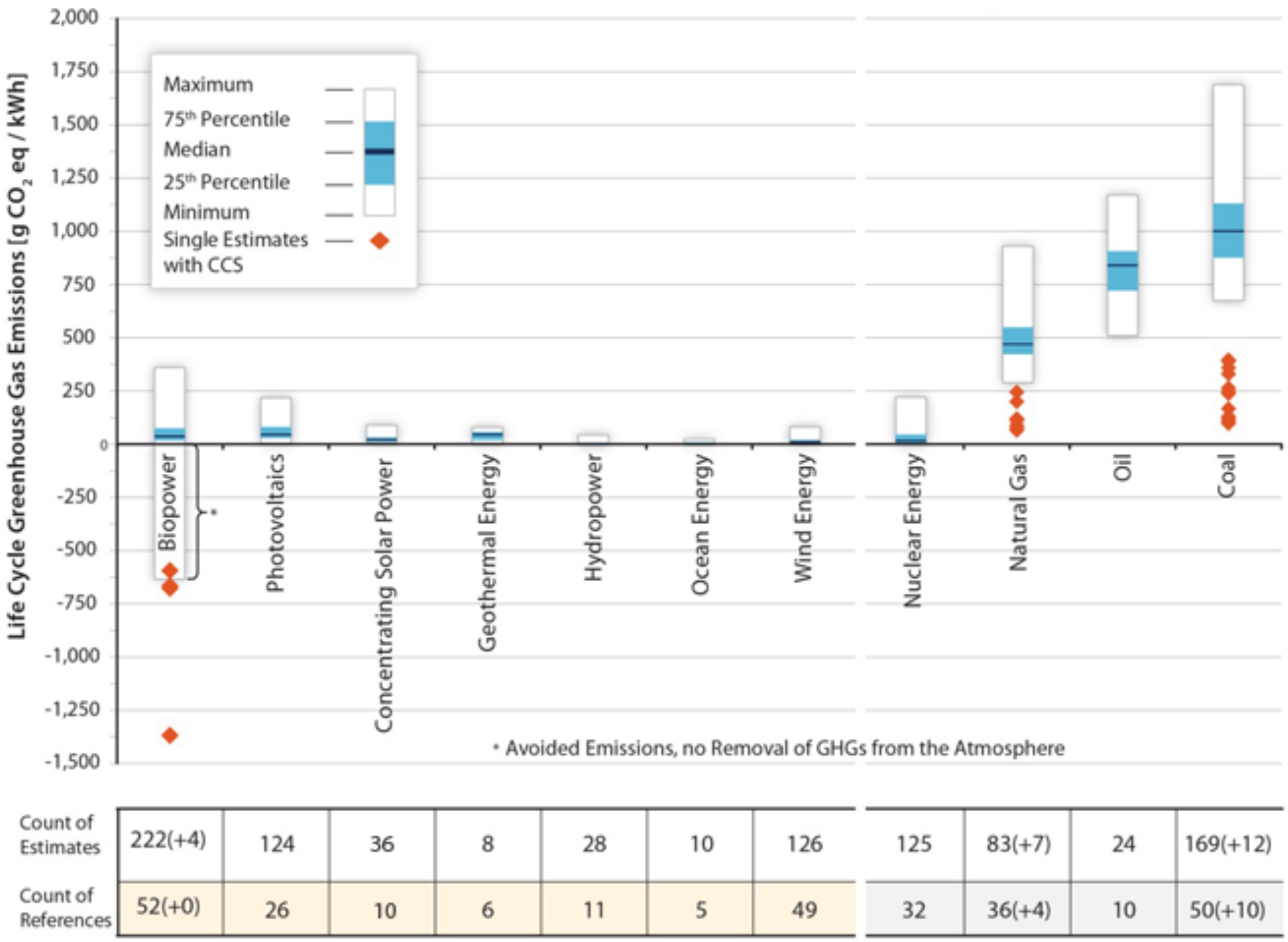


Figure 5: Life Cycle GHG Emissions of PV Technologies as Stated by NREL [10].

From Figure 4 and Figure 5 can be seen that the GHG emissions for Mono-Si is roughly 40 g CO_{2-eq} per kWh, significantly lower than the GHG emissions of coal fired power plants as can be seen in the summary of Figure 6 based on data from NREL [10].

With a PV yield of 100kWh on a sunny day, the GHG emission for the PV system on the island results in to 4 kg CO_{2-eq}/day.



	Biopower	Photovoltaics	Concentrating Solar Power	Geothermal Energy	Hydropower	Ocean Energy	Wind Energy	Nuclear Energy	Natural Gas	Oil	Coal
Count of Estimates	222(+4)	124	36	8	28	10	126	125	83(+7)	24	169(+12)
Count of References	52(+0)	26	10	6	11	5	49	32	36(+4)	10	50(+10)

Figure 6: Life Cycle Process Summary of Electricity Generation Technologies Powered by Renewable and Non-Renewable Resources [10].

Research by NREL found that the irradiation had a greater effect on decreasing the GHG than the system lifetime and that both irradiation and lifetime had a greater effect on decreasing the GHG than the module efficiency [9]. However, Hsu et al. also described difficulties in harmonisation. Many studies did not go into the end of life process of the PV system since decommissioning and recycling has not been well studied. However, the studies that did include the end of life process described them as only 4% as the total GHG emissions and therefore not influencing the results significantly. In addition, recent studies use the Intergovernmental Panel on Climate Change (IPCC) 2007 Global Warming Potential (GWP) for methane and nitrous oxide. Older studies however might have used different numbers and toxic gases with very high GWPs have not been taken into account [4]. However, the Crystal Clear database estimated these emissions to contribute for less than 1 g CO_{2-eq}/kWh to the PV life cycle and therefore would be unable to significantly change the GHG emissions. Over time, the module efficiency of PV systems will improve as well as the production technology where silicon wafers become thinner. If the energy requirements remain the same while the module efficiency improves, the GHG emissions will decrease, resulting in different LCA studies. In addition, when PV electricity is used instead of grid electricity for the manufacturing of the modules, the GHG emissions will be reduced significantly (70% for Multi-Si) [9].

3.2 Life Cycle Assessment of the Diesel Generators

Unlike solar PV, the life cycle assessment of diesel generators is hardly documented in literature. A lot of attention went to the combustion of fuels, thus the operational process, rather than the up- and downstream processes.

3.2.1 Lifetime

The lifetime of a diesel generator is dependent on the rpm of the generator. Two most common types have either four poles with 1500 rpm or two poles with 3000 rpm characteristics. A general rule is that the 3000 rpm have a simpler structure with 2-poles. They are most suitable for low duty applications, have low acquisition costs and are usable for operation of less than 400 hours per year. The 1500 rpm generators have 4 poles and are used for heavy duty and suggested when more than 400 hours of operation per year are needed [11] [12]. The higher the rpm the easier wear and tear occurs to the bearings, resulting in more maintenance requirements. The life time of diesel generators varies therefore from 5000 to 50000 hours with an average of 20000 hours but is dependent of the engine quality, installation and maintenance operations [11].

3.2.2 Efficiency

The efficiency of the diesel generator itself is specified by the ratio of the rated power to the output power, where the overall efficiency depends on the generator, thermal and mechanical efficiency. The typical values for the generator en mechanical efficiency are 95% to 98% and 80% to 85% respectively. The thermal efficiency however depend on the quality of the diesel oil that is being used [11]. The specific fuel consumption [l/kWh] can be defined as the fuel consumption required to produce 1kWh of energy wit a rate of 1 litre per hour. When the diesel generator operates at for example 20% of it rated power, the specific fuel consumption will be very high (roughly 0.64L/kWh) due to the low efficiency of the generator. When the diesel generator operates between 70% and 89% of its rated power, the specific fuel consumption will be minimal. In general, between 0.32 and 0.53 L/kWh is consumed by a diesel generator when operated at its rated power [11]. Research by Jakhrani et al. concluded that the efficiency of diesel generators is inversely proportional to the fuel consumption, rated power and the CO_2 emissions of the generator. Ideally, the rated power of the diesel generator should be close to the load demand, taking the power factor into account to prevent undersizing. In addition, the selection of the diesel generator should always be based on the peak power demand, even when the difference between the peak demand and average demand is very high in order to sustain the load. In this case however, the efficiency of the generator drops and more fuel will be consumed resulting in more greenhouse gas emissions [11] [12].

3.2.3 Energy Demand

A life cycle energy assesment of a standby diesel generator set has been performed by Benton et al. [13]. However, this model has a heavy duty 15L engine with a 355 kW rating and is thus significantly bigger than the diesel generators present on the island. In general, a diesel generator can be divided into 5 subsections, the engine, radiator, alternator, skid and electronic controls, as can be seen in Figure 7.

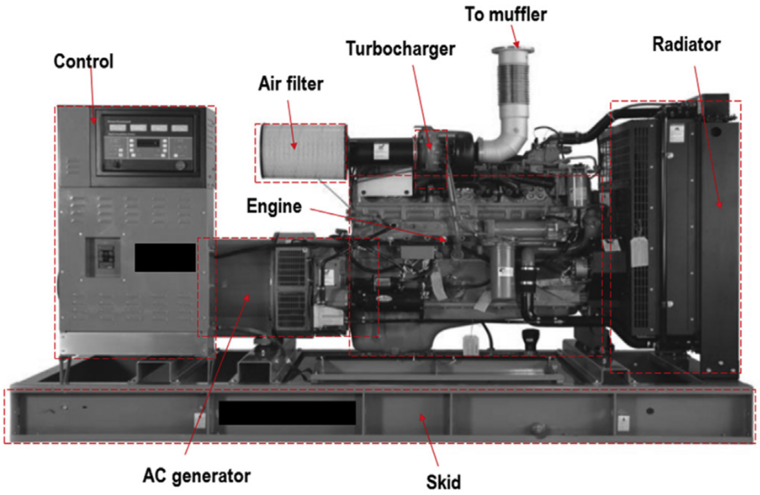


Figure 7: Diesel Generator Components [13].

Similar to the LCA of PV modules the production process of a diesel generator can be described as: Material mining & material assembly, manufacturing, transportation, usage, and disposal. Again, it should be noted that energy used for each stage (except for the use stage) could be coming from either renewable energy or unsustainable sources like coal, which can have a significant impact [13].

Benton et al. concluded that the use phase is dominating the energy demand with almost 95%, second is the material extraction stage at 4%, third the transportation stage at 1% and finally the manufacturing which accounts for less than 1% of the total energy demand as can be seen in Figure 8.

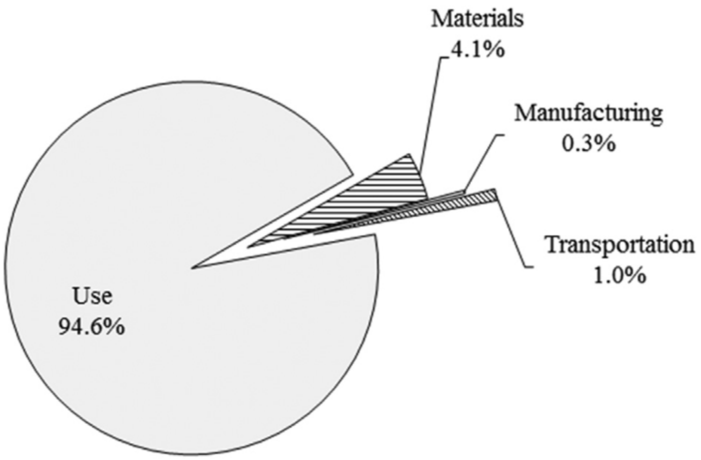


Figure 8: Energy Demand Diesel Generator [13].

Decommissioning was excluded due to the uncertainties towards the end of life stage of diesel generators. The energy used for the specific parts described before is dominated by the controls with almost 36%, second is the engine at 27.5%, third the alternator with 22.3% and both the energy needed for the radiator and skid is 7% each, as can be seen in Figure 9.

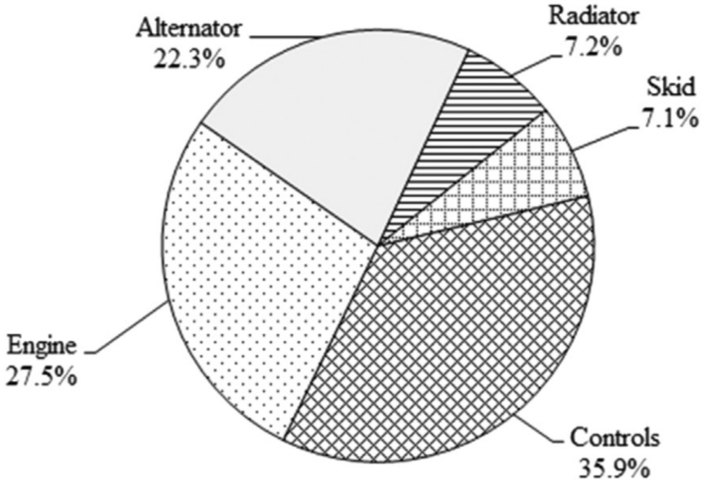


Figure 9: Energy Demand by Parts for a Diesel Generator [13].

3.2.4 Greenhouse Gas Emissions

The total amount of greenhouse gases emitted through the complete life cycle of diesel generators is not well documented in literature. According to Jakhrani et al. [11] and Ali et al. [12], one litre of diesel emits roughly 2.4-2.8kg of CO_2 where the emission factor considered for a diesel generator is roughly 1.27 kg CO_2/kWh. With an average diesel consumption at Kri of roughly 6385 litres per month or 210 litres per day, as can be seen in Table 3, the emissions would vary between 504 and 588 kg CO_2/day respectively.

Table 3: Diesel Usage

Month	**Liter Used**	**Avg L/Day**
January	5660	182,6
February	5560	198,6
March	6520	210,3
April	7230	241,0
May	6520	210,3
June	5700	190,0
July	6580	212,3
August	6595	212,7
September	5365	178,8
October	7216	232,8
November	7290	235,2
Total	70236	
Avg / Month	3685,1	209,5

According to the Department of the Environment and Energy [14], electricity generated from diesel can be calculated by formula 5.

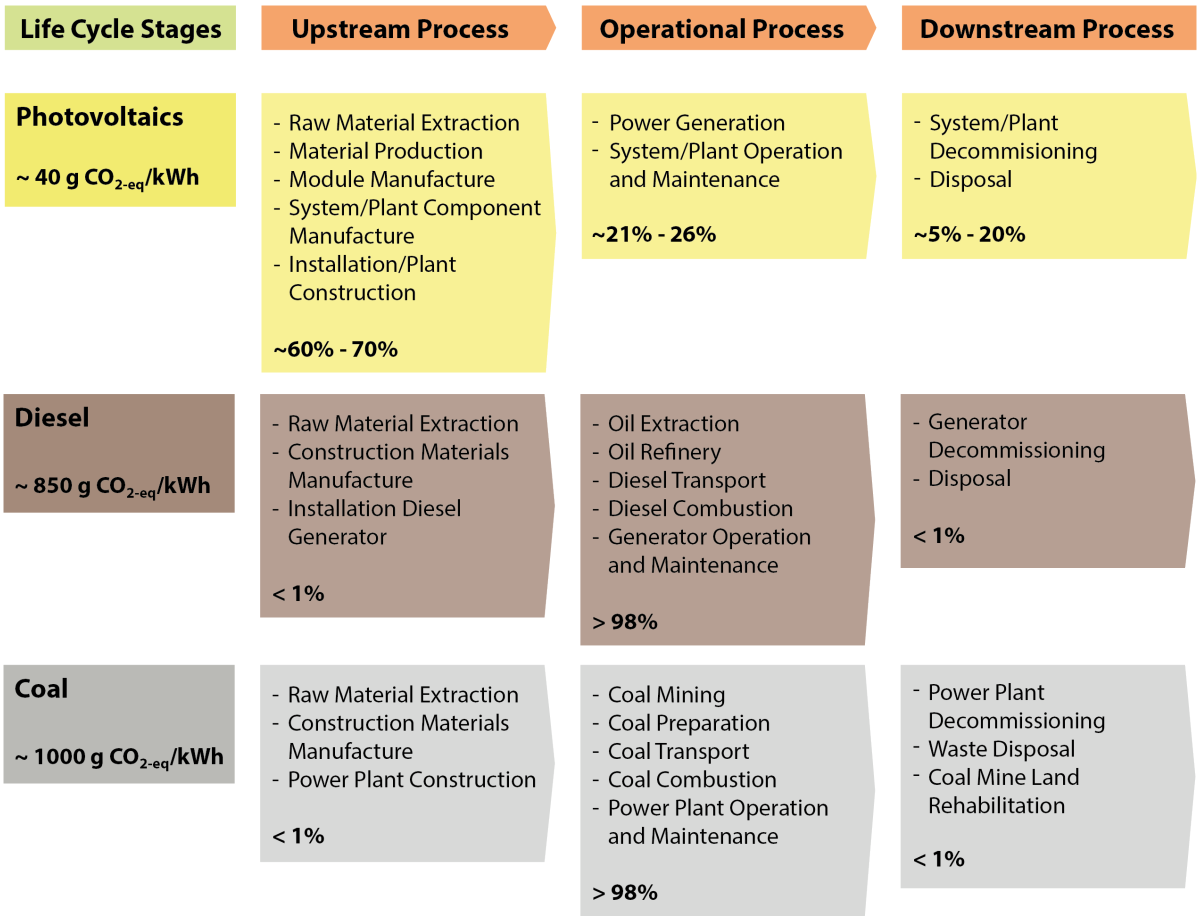
$$E_{ij} = Q_i * EC_i * EF_{ijoxec} \tag{5}$$

With E_{ij} the emissions of gas type (j) (carbon dioxide (CO_2), methane (CH_4) or nitrous oxide (N_2O), from fuel type (i) [g CO_{2-eq}], Q_i the quantity of fuel type (i) [litres], EC_i the energy content factor of fuel type (i) (Mega joules per litre), and EF_{ijoxec} the emission factor for each gas type (j) for fuel type (i) [grams CO_{2-eq} per Mega joule]. For diesel oil, EC = 38.6, EF(CO_2) = 69.9, EF(CH_4) = 0.1, and EF(N_2O) = 0.2. The average diesel consumption is 6385 litres per month, resulting in emissions of 17.3

tonnes CO_{2-eq} per month or 567 kg CO_{2-eq} per day, corresponding to the range defined by Jakhrani et al. and Ali et al. [11] [12].

In addition, harmonisation studies could not be found in literature. The harmonisation data from NREL [10] has a harmonised value of 850 g CO_{2-eq} per kWh. However, from this graph, as was presented in the previous section in Figure 6, it is uncertain what type of oil they are referring to and its composition. In order to be consistent with the harmonisation studies, the GHG emissions for the diesel generator will be assumed to be 850 g CO_{2-eq} per kWh instead of the 1.27 kg CO_2/kWh proposed by Jakhrani et al. and Ali et al. [11] [12]. With an estimated average electricity load of 570 kWh/day supplied by the diesel generators, this would result into emissions of 485 kg CO_{2-eq} per day.

An overview of the life cycle stages of photovoltaics and diesel compared to coal fired electricity can be seen in Figure 10 based on data of the National Renewable Energy Laboratory [10].



Life Cycle Stages	**Upstream Process**	**Operational Process**	**Downstream Process**
Photovoltaics **~ 40 g CO_{2-eq}/kWh**	- Raw Material Extraction - Material Production - Module Manufacture - System/Plant Component Manufacture - Installation/Plant Construction **~60% - 70%**	- Power Generation - System/Plant Operation and Maintenance **~21% - 26%**	- System/Plant Decommissioning - Disposal **~5% - 20%**
Diesel **~ 850 g CO_{2-eq}/kWh**	- Raw Material Extraction - Construction Materials Manufacture - Installation Diesel Generator **< 1%**	- Oil Extraction - Oil Refinery - Diesel Transport - Diesel Combustion - Generator Operation and Maintenance **> 98%**	- Generator Decommissioning - Disposal **< 1%**
Coal **~ 1000 g CO_{2-eq}/kWh**	- Raw Material Extraction - Construction Materials Manufacture - Power Plant Construction **< 1%**	- Coal Mining - Coal Preparation - Coal Transport - Coal Combustion - Power Plant Operation and Maintenance **> 98%**	- Power Plant Decommissioning - Waste Disposal - Coal Mine Land Rehabilitation **< 1%**

Figure 10: Life Cycle Stages of Photovoltaics, Diesel and Coal

3.3 Gasoline Boats

Boats are the only transportation method from and to the island and are excessively used for dive trips. An inventory was made of the gasoline usage of the boats for both resorts and can be seen in Table 4 and Table 5 for Sorido and Kri respectively.

The following categories were selected: Diving/snorkeling/hiking, transport guests, transport staff, Kri/Sorido, supplies, donation, other, and private. Where Diving/snorkeling/hiking include all guest related activities like diving, snorkeling, sightseeing, bird watching etc. Transportation of guests and staff is the transportation to Waisai where guests and staff can take the ferry or the transportation to another island where staff need to be for work. Supplies include food, water, building materials and other goods, often taken from Waisai. Donations include water or oil donations to villages and the private category includes the gasoline bought by staff for personal usage.

In addition, the data form Table 4 and Table 5 have been converted into a pie chart and can be seen in Figure 11 and Figure 12 respectively. It can be clearly seen that the boats in Kri are mainly used for diving activities where Sorido arranges transportation and supplies as well.

Table 4: Gasoline distribution in Sorido

	Diving/ Snorkeling/ Hiking	**Transport Guests**	**Transport Staff**	**Kri**	**Supplies**	**Donation**	**Other**	**Private**	**Total**
Jan	3173	486	242	273	1031	40	85	58	**5388**
Feb	3539	543	610	294	849	665	116	74	**6690**
Mar	3818	235	511	245	862	155	144	44	**6014**
Apr	4198	228	561	119	1009	85	76	75	**6351**
May	4033	226	310	158	987	35	220	113	**6082**
Jun	1943	227	555	21	811	480	83	54	**4174**
Jul	1533	90	733	79	975	158	286	180	**4034**
Aug	5483	127	583	67	1028	130	1014	5	**8437**
Sep	2206	159	951	3	781	25	0	42	**4167**
Oct	5055	368	949	86	1258	245	625	20	**8606**
Nov	4585	209	721	97	1265	261	135	86	**7359**
	Diving/ Snorkeling/ Hiking	**Transport Guests**	**Transport Staff**	**Kri**	**Supplies**	**Donation**	**Other**	**Private**	**Total**
Year	**39566**	**2898**	**6726**	**1442**	**10856**	**2279**	**2784**	**751**	**67302**

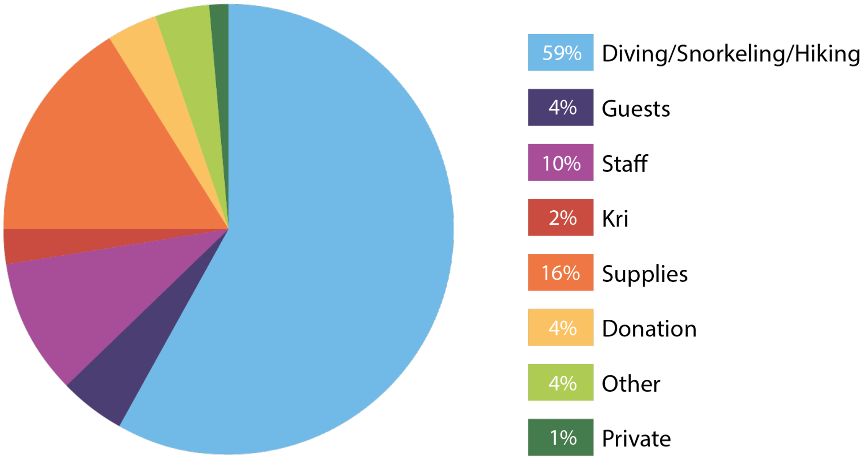


Figure 11: Gasoline Distribution for Boats at Sorido

Table 5: Gasoline distribution in Kri

	Diving/ Snorkeling/ Hiking	**Transport Guests**	**Transport Staff**	**Sorido**	**Supplies**	**Donation**	**Other**	**Private**	**Total**
Apr	4957	130	55	115	0	15	10	20	**5302**
May	5186	260	0	118	0	15	104	69	**5752**
Jun	4696	0	35	70	0	15	5	50	**4871**
Jul	5469	115	55	176	70	45	2	35	**5967**
Aug	5786	185	190	138	0	0	20	71	**6390**
Sep	4030	56	0	139	0	15	10	83	**4333**
Oct	6008	175	0	198	0	15	0	10	**6406**
Nov	7429	0	0	70	0	35	80	68	**7682**
Dec	5994	0	190	58	70	45	5	20	**6382**
	Diving/ Snorkeling/ Hiking	**Transport Guests**	**Transport Staff**	**Sorido**	**Supplies**	**Donation**	**Other**	**Private**	**Total**
Year	**49555**	**921**	**525**	**1082**	**140**	**200**	**236**	**426**	**53085**

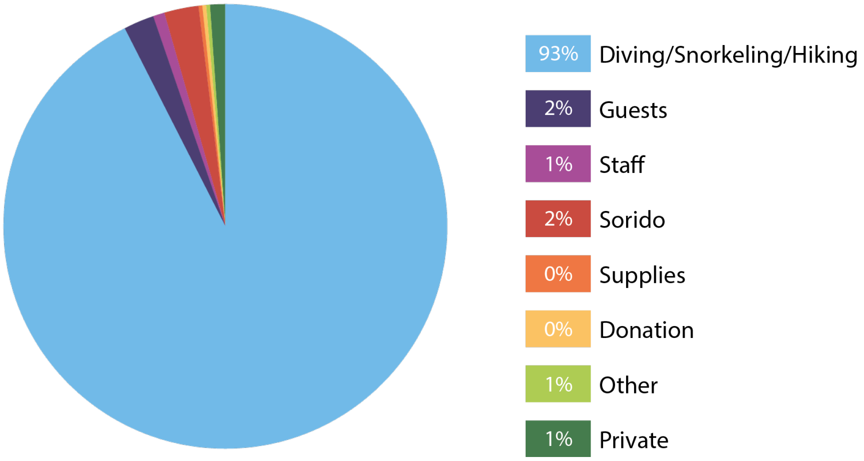


Figure 12: Gasoline Distribution for Boats at Kri

Knowing the total amount of gasoline used, an estimation for the greenhouse gas emissions of the gasoline boats can be made by using equation 6 [14].

$$E_{ij} = Q_i * EC_i * EF_{ijoxec} \tag{6}$$

With E_{ij} the emissions of gas type (j) (carbon dioxide (CO_2), methane (CH_4) or nitrous oxide (N_2O), from fuel type (i) [g CO_{2-eq}], Q_i the quantity of fuel type (i) [litres], EC_i the energy content factor of fuel type (i) (Mega joules per litre), and EF_{ijoxec} the emission factor for each gas type (j) for fuel type (i) [grams CO_{2-eq} per Mega joule]. For gasoline, EC = 34.2, EF(CO_2) = 67.4, EF(CH_4) = 0.5, and EF(N_2O) = 1.8. The average gasoline consumption is roughly 12000 litres per month for both resorts together, resulting in emissions of 28.6 tonnes CO_{2-eq} per month or 940 kg CO_{2-eq} per day.

Very little attention has been paid towards air pollution by combustion outboard boat engines over the years. This resulted in the lack of filtering technologies included in the engines to reduce the pollutants. In addition, it should be noted that these calculations are rough estimates. Here, no distinguish has been made between engine types, which is very important for the determination of the emissions. The boats on the island have two-stroke engines which are far more polluting than four-stroke engines, where a news article claims that a 2-stroke engine has 30-50 times more emissions compared to a 4-stroke engine due to the large amount of hydrocarbons [15].

Furthermore, Torqueedo claims that a new 80 HP, four-stroke gasoline outboard engine emits the equivalent of 350 new cars at highway speed, both operated for one hour. In addition, they claim that letting a 5 HP dinghy motor run for an hour emits hydrocarbons and nitrogen oxides equivalent to driving 38 cars [16].

According to the U.S. Department of Energy, a gasoline car emits roughly 5187 kg CO_{2-eq} per year, corresponding to 432.25 kg CO_{2-eq} per month. Comparing this to the emissions of the boats on the island, all the boats together have emissions equivalent to roughly 66 cars.

3.4 Energy Measurements

This section describes the process and results of measuring the energy consumption of several specific devices. The data from the energy measurement system on the island was used as a basis for the energy consumption where a sunny day with a load of 670 kWh/day was chosen as reference day.

The biggest contributors to the carbon footprint were selected and analysed. Potential solutions on how to lower the carbon footprint, based on their feasibility, were analysed and can be found in the next chapter.

3.4.1 Method

The allocation of the energy usage of island was executed by measuring the energy use that is needed for the activities and facilities. With the amount of energy, the carbon footprint was calculated and documented.

Several electrical devices were selected to be measured with the expectation that these devices would be the major consumers of the load. These were the air compressors, air conditioners, boilers, fridges and freezers and washing machines. Another big consumer would be the lighting, however, the lights were not measure due to the difficulty.

First, an inventory was made to find out how many devices needed to be measured. Due to the limitation of equipment and the availability of 2 energy meters, it was decided that every device would be measured for minimum of 24 hours and a maximum of one week to capture the full day and night cycle or the full week cycle. For example, boilers at the guest bungalows were measured for one week and washing machines on a weekday and the weekend since most employees do their laundry on a Saturday. Other devices like fridges and freezers for example were only measured for 24 hours since their usage is not deviating much throughout the week.

3.4.2 Measurement Equipment

Due to the lack of a proper cable network on the island, measuring the current through the cables would have been a difficult task as it would have been impossible to find out to which load a certain cable would be supplying. Therefore, direct energy meters have been used and applied directly on the devices that were measured.

The equipment that was used for the energy measurements was the Voltcraft '4500Advanced' Energy Monitor. This energy monitor has a standard European 2-pin type-C plug and socket that can be installed between the power socket and and the plug of the to be measured device. It records the amount of kWh as well as the time that the device has been consuming energy.

In addition, the Uni-Trend Infrared Thermometer UT300 was used to measure the surface temperature of the solar PV panels to determine the amount of losses.

3.4.3 Measurement Results

Mentioned before, several devices were selected to be measured including the compressors, air conditioners, boilers, fridges and freezers, and washing machines.

The compressors operate on three phases with a monitor present in the compressor room displaying the voltage and current that is supplied to the compressors. During the time of the internship, only one of the four compressors was in operation with a rated apparent power of 7.5 kVA. During operation the power supplied to the compressor ranged between 5 and 9 kVA, where 7.5 kWh/hour was used for the estimation of the energy consumption of the compressor with an operation time of 10 hours per day. This resulted in an energy consumption of roughly 75 kWh/day.

At the Sorido side of the island, 33 air conditioners were present of which 6 are not in use. This is either due to the air conditioners being installed as reserve or that they needed repairing. Furthermore, 11 boilers, 3 top load- and 3 front load washing machines, 7 minibars, 8 fridges, and 4 freezer were found at Sorido. The total inventory list and results can be found in Table 6 - 9 and a summary of the measured energy consumption can be found in Table 10.

Table 6: Electricity Consumption Electric Boilers

Number	**Location**	**Rated Power [W]**	**Measured kWh/day**
1	Kaimana 1	1200	2
2	Kaimana 2	1200	2
3	Sentani 1	1200	2
4	Sentani 2	1200	2
5	Sentani 3	1200	2
6	Sentani 4	1200	2
7	Sentani 5	800	2
8	Restaurant	1200	5,458
9	RARCC	1200	3,177
10	Girls Dorm	1200	3,367
11	Chris	800	1,616
Total			**27,618**

Table 7: Electricity Consumption Washing Machines

Number	**Specification**	**Measured kWh/day**	**Comments**
1	Left Grey Machine	1,582	Both grey machines, washing with cold water only.
2	Right Grey Machine	1,582	Average 4-5 washes per day
3	White Machine	0,15	Washing with cold water only. Less used than grey machines
4	Left Red Machine	0,714	0,052 kwh / 15 min wash
5	Right Red Machine	0,1	Mostly used for handwash
6	Green Machine	0,104	0,033 kWh / 15 min wash. 0,021 kWh / 5 min spin. Saturday measurement failed
Total		**4,232**	

Table 8: Electricity Consumption Air Conditioners

Number	**Location**	**Measured kWh/day**	**Comments**
1	Kaimana 1	6,582	
2	Kaimana 2	6,582	
3	Sentani 1	6,582	
4	Sentani 2	6,582	
5	Sentani 3	6,582	
6	Sentani 4	6,582	
7	Sentani 5	6,582	
8	Logistic	8,11	
9	Logistic Sotrage	18,303	
10	Dive Office	6,819	
11	PD Office	7,675	
12	Museum	5,034	
13	Mechanic	6,524	
14	Murata 1	6	No electricity after the fire, assumed to be 6 kwh/day
15	Murata 2	6	
16	Murata 3	0	Not in use, reserve
17	Murata 4	0	
18	RARCC Office	9,599	
19	RARCC Wetlab	5,106	
20	Andreia	0	Too noisy to use
21	RARCC Storage	6,879	
22	Attic (S&D)	11,297	
23	Attic (H&F)	3,785	
24	Max 1	19,837	
25	Max 2	0	Not in use
26	Communal Room	0	Not frequently in use
27	Hangar Computer Room	11,319	
28	Hangar Storage 1	15,289	
29	Hangar Storage 2	15,032	
30	Kitchen	12,225	
31	PD Staff (F&A)	0	Broken
32	PD Staff (F,H,...)	8,037	
33	Guys Dorm	11,291	
Total		**240,235**	

Table 9: Electricity Consumption Fridges and Freezers

Number	**Location**	**Specification**	**Measured kWh/day**
1	Kaimana 1	Minibar	0,298
2	Kaimana 2	Minibar	0,298
3	Sentani 1	Minibar	0,298
4	Sentani 2	Minibar	0,298
5	Sentani 3	Minibar	0,298
6	Sentani 4	Minibar	0,298
7	Sentani 5	Minibar	0,298
8	Restaurant	Fridge	1,979
9	Guest Kitchen	Left Fridge	2,766
10	Guest Kitchen	Right Fridge	2,289
11	Guest Kitchen	Standing Freezer	1,866
12	Guest Kitchen	Left Chest Freezer	1,85
13	Guest Kitchen	Right Chest Freezer	1,62
14	Guest Kitchen	Large Chest Freezer	5,191
15	Staff Kitchen	Left Fridge	2,287
16	Staff Kitchen	Right Fridge	5,808
17	Communal	Grey	0,972
18	Communal	White	1,739
19	Dorm	Grey	1,416
Total			**31,869**

Table 10: Measured energy consumption

Device	**Measured kWh/day**
Compressor	75
Energy measurement system	12.5
Air conditioners	240
Boilers	28
Fridges and freezers	32
Washing machines	4
Total measured	**391.5**

With the reference load being 670 kWh/day, the total measured energy consumption in Tables 10 covers only about 59% of the total load. It should be noted that the big energy consumers at Kri Eco resort have not been taken into account. This resort has no air conditioners and no electric boilers. The boilers at Kri Eco run on LPG and in total, 3 front load washing machines, 6 fridges, 4 freezers and 4 minibars (of which one always in use) are present. However, due to the limitation of the amount of energy meters and the uncertainty of the inclusion of the load of Kri in the online monitoring system, these devices were not measured. Therefore, the remainder of the load measured by the online monitoring system partially consists of the load at Kri Eco, lighting and other applications like water pumps, computers, televisions and water dispensers. According to TNO (prior ECN), 13% of the electricity consumption in a household is assigned to lighting [17]. However, in a company environment, this percentage would be a lot higher.

In addition, several wood working machines, each rated around 4kVA are present in the carpenter workshop and only used during specific construction projects.

4 Increasing The Sustainability

Ideally, all the energy needed on the island would be generated by renewable energy sources. However, as described before, diesel generators generate most of the electricity needed and the fuel consumption by the boats is significant. Therefore, other renewable energy sources could be considered on the island. This chapter describes how the sustainability on the island can be increased in terms of energy efficiency, supply and savings.

This chapter excludes the potential of electric boats, due to it being already an ongoing project at RARCC.

4.1 Reducing the Energy Consumption

Instead of trying to generate all electricity by renewable energy sources, the sustainability can be increased by trying to decease the energy consumption. Measured in the previous chapter, the air conditioners consume the largest amount of energy. It was noticed that many air conditioners operate all day long and on a relative low temperature (18 degrees Celsius) compared to the outside air temperature (27 degrees Celsius).

Tests have been executed with a guest room where the air conditioner consumed 8.92 kWh/day, set to 20 degrees Celsius compared to 6.58 kWh/day, set to 25 degrees Celsius. Not only will the energy consumption be reduced if the air conditioners are set to a higher temperature, but health conditions might also improve. Studies show that a temperature difference from cold to warm with a maximum of 6 degrees is tolerable by the human body. Increasing this temperature difference can give a shock on the human body cause stomach aches. With an outside average temperate of 27 degrees Celsius it would be recommended to set air conditioners to a minimum temperature of 21 degrees Celsius.

In addition, all electric devices consume less energy for a shorter operation time. Therefore it would be suggested that timers are used for the air conditioners. Instead of letting air conditioners run all day, air conditioners in staff rooms for example can be turned on after working hours, making them operate at least 35 hours less per week.

An alternative to air conditioners can be proposed by dehumidifying certain rooms instead of cooling them. At least four rooms (two storage rooms at the hangar, mechanic's room and the storage room next to the gasoline storage), are rather in need of dehumidification than cooling. The high humidity can cause corrosion on parts and tools and the air conditioners in those rooms are currently installed to decrease the humidity. Dehumidifiers consume less energy than air conditioning units, however, they should not be used in combination with air conditioners as dehumidifiers add heat to the environment, resulting in more work for the air conditioners.

Besides the air conditioners, it was noticed that two fridges present at RARCC were almost always empty. Letting an empty fridge run can be considered as a waste of energy and therefore it is suggested that at least one of these fridges would replace an inefficient older fridge at the staff kitchen. Furthermore, many fridges are showcase fridges with a see-through glass front panel. These types of fridges are less isolated compared to fridges with a non-glass front panel. However, their advantage is that ingredients can be easily found without opening the fridge for a long time. Therefore, in cases where a see-through front panel is not necessary, it is suggested that these fridges will not be replaced with another show case fridge when the old fridge is broken.

Another point of attention should go towards lighting at the resort and RARCC. The exact amount of energy consumed by lighting is unknown but it was noticed that a decent amount of lights are turned on throughout the whole day. It is suggested that lights outside are replaced by lights with a motion sensor, saving a decent amount of energy. Furthermore, in the office building and bedrooms, lights are used as well during the day instead of using the available daylight by opening the blinds. This custom can be easily changed by making employees more aware about sustainability.

Finally, green rooftops could be considered. This however might be more relevant for new building that have to be constructed rather than existing buildings due to the type of support that is needed for the rooftop. Several studies show that green rooftops are also applicable in tropic climates with a significant amount of downpour [18], [19], [20]. Not only can vegetation on a rooftop contribute to less warming of the indoor space, and thus reducing the air conditioning usage, but it also contributes in water purification. A green roof positively influences the temperature of the roof and insulation effect for the indoor climate. Rain water is retained which creates cooling effects and some of the pollutants are absorbed by the vegetation, improving the rainwater quality and thus making it easier convertible to potable water [19], [21].

4.2 Alternating the PV Setup

Discussed in Chapter 3, generating electricity with photo voltaic modules less polluting in terms of greenhouse gas emissions when compared to electricity generation from diesel generators. Therefore, expansion of the PV generation on the island might be a solution to increase the sustainability.

First, data of the solar irradiance was needed in order to make calculations for the sizing of the PV. Irradiation data from the Global Solar Atlas [22] and Homer Energy [23] (NASA database) have been compared can can be found in Table 11 and Table 12 respectively.

Table 11: PV output by Global Solar Atlas

Installed Capacity [kWp]	**Azimuth [degrees from north]**	**Inclination [degrees from horizontal plane]**	**Generated Energy [kWh/day]**	
9.6	0	12	37.58	
9.6	0	16	37.16	
9.6	180	16	36.82	+
			111.56	

Table 12: PV output by Homer

Installed Capacity [kWp]	**Azimuth [degrees from north]**	**Inclination [degrees from horizontal plane]**	**Generated Energy [kWh/day]**	
9.6	0	12	39.6	
9.6	0	16	39.1	
9.6	180	16	39.2	+
			117.9	

The total generated energy for the installed PV on the island deviates slightly between the two different databases. It should be noted however that these values are averaged and when energy is only generated by PV, the worst irradiance conditions should be taken into account to always be able to supply for the load. Therefore, the data from the online measurement system have been analysed for a optimal (sunny day) and worst case scenario (rainy day).

On a sunny day 24-10-2018

Resort Load	670.32 kWh	± 14%
Diesel	572.19 kWh	
PV	98.18 kWh	

On a rainy day 10-11-2018

Resort Load	665.78 kWh	± 5%
Diesel	644.95 kWh	
PV	34.11 kWh	

Here it can be seen that on a sunny day the PV system only covers 14% of the resort load where on a rainy day the PV system only covers 5% of the resort load, where the generation on a sunny day is almost three times as large when compared to a rainy day. The advantage of using the measured data is that loses are already included. Common voltage losses occur due to shading, reflection, temperature and the wrong inclination angle. For example, the optimum inclination angle is 3 degrees, where the installed PV have inclination angles of 12 and 16 degrees. Temperature losses of -0.45% per degree Celsius occur for cell temperatures above 45 degrees and the measured temperature was found to be 55 degrees during a sunny day. Furthermore, efficiency losses need to be taken in to account as well like the efficiency of the cable, battery, charger, inverter and mismatch. Since the PV system is disconnected from a battery and charger, these efficiencies still need to be taken into account and are assumed to be 0.9 and 0.98 for the battery and charger respectively. Taking a load of 670 kWh per day, the total amount that need to be generated considering the battery and charger efficiency is roughly 670 /(0.9 * 0.98) = 760 kWh.

Comparing the total amount of energy that the PV generate during a rainy day to the energy that needs to be generated each day to sustain the load, it can be found that the PV yield on a rainy day is currently 22.28 times less than the amount that needs to be generated each day. This would result in a PV field 22.28 times bigger than present on the island, meaning that in total roughly 3210 PV panels are needed of the same brand.

However, installing an extra 3066 PV panels is not feasible considering space and the impact on nature on the island. Another alternative could be suggested by letting the compressors run on energy generated by PV. This would result in the shut down of one 42.5 kVA generator, saving diesel for this machine and reducing the strain on the 60 kVA generator that runs below optimum when part of the load is is taken over by PV generation.

Assuming that the compressor uses 75kWh/day, taking into account the battery and battery charger efficiencies again the amount of energy the PV system needs to generate results in to 75/(0.9*0.98) = 85 kWh. Comparing this to the yield of the PV panels during a rainy day, a ratio of 2.5 can be found. This means that roughly 2.5 times the amount of PV panels have to be installed on the island to make the compressor run solely on PV generated electricity. This would result into a total of 144*2.5 = 360 PV panels, which would be feasible.

The battery capacity needed to store the surplus energy harvested by the PV during the peak irradiation hours can be calculated with equation 7 [6].

$$BatteryCapacity[kWh] = \frac{E_{load} * n_d}{d * \eta_b} \tag{7}$$

With E_{load} is the daily energy requirement in kWh, n_d the days of autonomy, d the maximum allowed battery discharge (0.8), and η_b the battery efficiency (0.9).

Filling in the formula gives a battery capacity of 104.2 kWh needed for the system for one day of autonomy. It should be noted however that during sunny days, the yield of the PV would be much higher. For 144 panels this results in to 98.18 kWh/day and thus for 98.18*2.5 = 245 kWh/day. Subtracting the load of the compressors, this would give a remaining of roughly 160 kWh, which could be stored for optimal sustainable usage. This however would result in a battery capacity of 340 kWh for daily storage, which is the equivalent of roughly ten BMWi3 batteries. This surplus generated electricity could then be used for construction work or the main load of the resorts.

4.3 Solar Cooling

Mentioned in the previous chapter, air conditioning takes up a significant part of the total electricity load. All air conditioning units are split systems where all air conditioning systems are inverters. An inverter air conditioning unit is considered to be more energy efficient due to the variable speed option of the compressor. This allows the compressor to run at the needed power to regulate the desired temperature rather than on a fixed speed for a non-inverter air conditioning system where the system is either on or off [24].

Depending on the ground temperature, and the air temperature fluctuations, a heat pump can be used to heat during winter and cool during summer. However, in the tropics, the ground temperature is often even warmer than the outside air temperature, and therefore not suitable for cooling as can be seen in Figure 13.

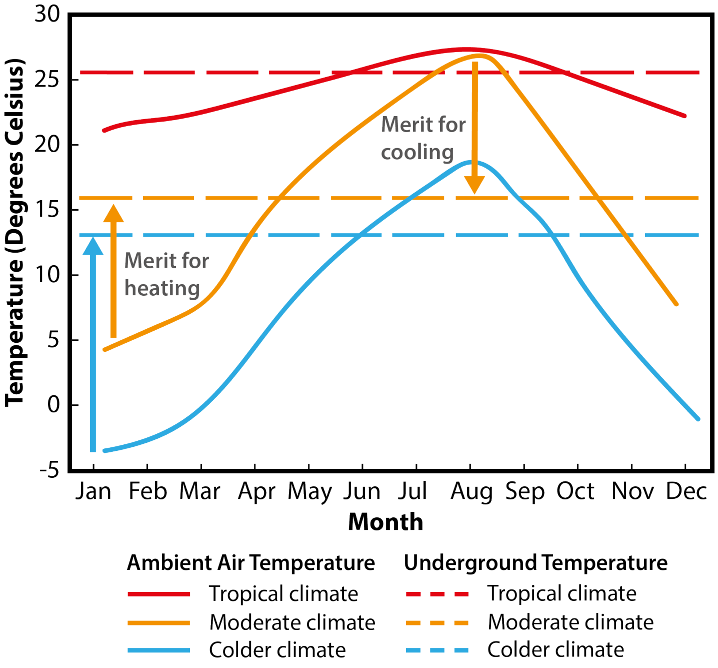


Figure 13: Potential for Heating and Cooling for Different Climates, based on an graph by K. Yasukawa [25].

For tropical environments, absorption air conditioning might be a solution. These systems are powered by heat, usually a waste heat source as exhaust gases or flash steam and hot water. In sunny climates, solar heat captured by solar collectors can be used as well, however, absorption air conditioning is still mainly industrial to date. Using the sun for cooling, either a thermal/work driven system or an electricity driven system can be considered. Since converting solar energy to heat is more efficient than converting solar energy to electricity, a thermal/work driven system would be more efficient. The most developed thermal/work driven system is the absorption system. In certain ways the absorption cycle is similar to an electrically operated vapour compression machine. A refrigerant cycle consists of three components, a condenser, expansion valve, and an evaporator. The refrigerant is thermally compressed by the usage of a heat source and a liquid absorbent/refrigerant solution, replacing the electric power consumption of a mechanical compressor.

The cooling effect of absorption chillers is based on the evaporation of water in the evaporator at a very low pressure. First, the low pressure vapour in an absorbing liquid is being absorbed where vapour is converted into liquid. This means that heat is being rejected during this process. The pressure will be elevated by a pump and the vapour is released from the absorbing liquid by the addition of heat. To date, the most used and researched working fluid for absorption air conditioning is Lithium Bromide in combination with water due to a lower required generator inlet temperature (70-88 degrees Celsius), lower operating pressures and thus pumping power and a simpler system and better safety compared to ammonia and water. In addition, an extra energy source can be added to the system so that hot water can always be supplied to the generator when the solar energy requirements are insufficient to heat up the water to the required temperature [26].

To date solar driven absorption cooling is not widely used yet. Solar absorption is mainly used on industrial scale for commercial buildings. Despite this, absorption air conditioning for residential usage has a great potential for (sub-)tropical areas due to the availability of heat from the sun. However, barriers are still present that need to be overcome. The initial cost would be significantly more than that of conventional air conditioning systems and the efficiency of the solar heat is limited to only a few hours of the day. In additions, collectors that convert solar energy into heat have decreasing efficiencies with increasing temperatures, just like PV panels [27].

4.4 Heat Storage

Heat storage might be a solution for, not only absorption air conditioners, but also for warm water supply for showers, which is currently provided by electric boilers. An alternative to these electric boilers could be proposed since generating heat and storing heat for a short time is more efficient than generating electricity. Water could be warmed by solar collectors that heat up a storage tank. Phase changing materials (PCM), also known as latent heat storage units, are known for their ability of storing and releasing heat. PCMs are characterised by their solid to liquid and liquid to solid phase changes. When heat is added to a PCM, the temperature of the PCM rises. When the PCM reaches its melting temperature, heat can be absorbed at an almost constant temperature and heat continues to be absorbed at an almost constant temperature until it is liquefied. The PCM releases its stored energy in the form of latent heat when the temperature drops to the point where it is solidified.

Therefore, heat can be stored in PCM by heating water with solar collectors and then exchanging this heat with a PCM storage tank. This heat can be released again to supply energy to warm water for kitchens and bathrooms and potentially for absorption air conditioners.

4.5 Consideration of Other Renewable Energy Sources

Indonesia is known for its great geothermal potential due to the large volcanic activity in the country. In the first quarter of 2018, Indonesia reached the total installed capacity of 1925 MW and is expected to grow more over the coming years. However, geothermal power plants are big installations and therefore not suitable to implement on a remote off-grid island [28]. This is also the case for biomass installations. In addition, biomass as fuel is needed which would have to be imported which is not CO_2 neutral.

4.5.1 Wind Energy

Another well developed renewable energy source is wind energy. Wind energy has less carbon emissions than solar PV as the greenhouse gas emissions for wind powered energy generation is rated between 2.2-74.8 g CO_2-eq/kWh. This range is lower than that of mono-Si PV (29-671 g CO_2-eq/kWh) [8].

Wind powered energy generation is however unfortunately difficult to implement in Indonesia due to the low wind velocities in the country. Especially at Kri, wind velocities are on average lower than 3.5 m/s, as can be seen in Figure 14, which is about the cut-in wind velocity of many wind turbines. The cut-in wind velocity is the wind velocity at which the blades starts rotating, meaning that the turbines would always operate below their rated power, and therefore will be very ill-efficient. In addition, guests staying at a resort might not like the view of a wind turbine when they get to a place that is known for its beautiful nature.

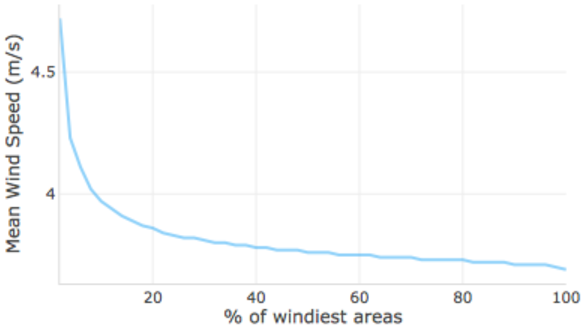


Figure 14: Wind Velocity at 100m at Kri.

4.5.2 Ocean Energy

Another potential, but still under development is ocean energy. Ocean energy can come from different sources like waves, tidal range, tidal currents, ocean currents, ocean temperature differences and salinity gradients. Most interesting forms of ocean energy considering the location of the resort are tidal and ocean currents. Due to the lack of wind and the depth of the water, no waves are present, but currents can still be strong.

Horizontal movements of water generate tidal currents especially close to the shore. The rise and fall of the tide result in tidal current flows of which their magnitude and timing are very predictable and insensitive to climate change influences. However, these tidal current flows can be slightly influenced by short-term weather fluctuations [29].

In contrast to near-coast tidal currents, ocean currents occur in open oceans, flow continuously in the same direction, and have a low variability. Therefore the difference between ocean and tidal currents is that ocean current flow is unidirectional, where tidal current change flow direction between ebb and flood cycles [29].

The technology to generate kinetic energy from tidal and ocean currents is currently still under development, however, several classifications have been proposed. The turbine types can be classified as axial-flow systems, cross-flow systems and reciprocating systems [29]. A representation of a twin turbine horizontal axis device, cross-flow device and a vertical axis device can be seen in Figure 15 from left to right respectively.

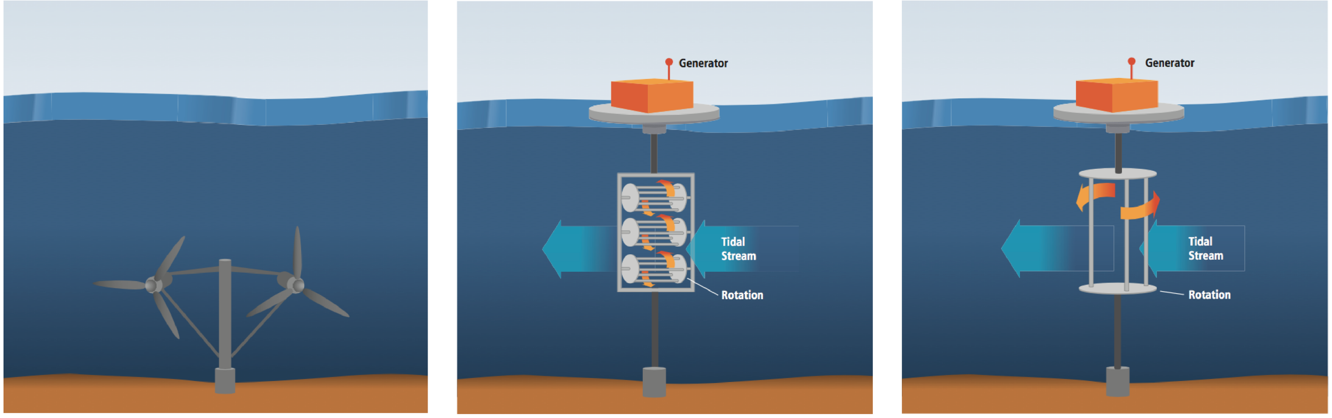
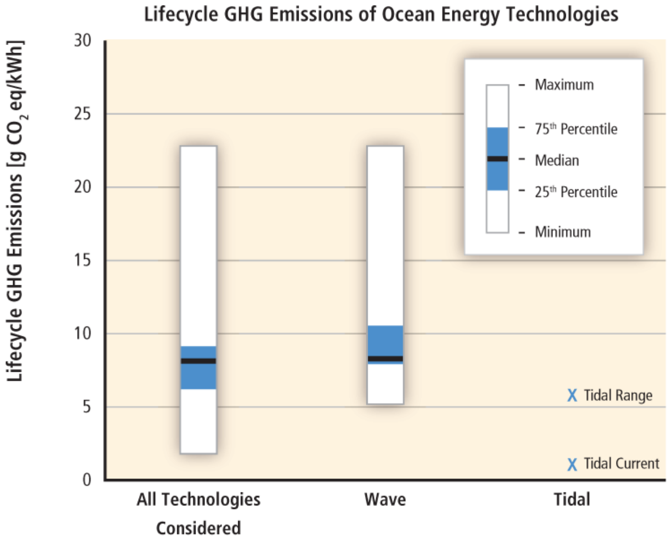


Figure 15: From left to right: a twin turbine horizontal axis device, cross-flow device and a vertical axis device [29].

The systems that convert water current to energy have the same resemblance of wind turbines, however, factors as cavitation, reversing flows and harsh underwater conditions should be taken into account. It should be noted that for deep-water systems neutrally buoyant turbine/generator modules with anchor systems and mooring lines are likely to replaced the fixed bottom structures [29].

The environmental and social impacts have not fully been researched due to the development stage of the technology and the limited amount of prototypes. Ocean energy however does not emit CO_2 during energy generation but it does during the other aspects of the life cycle resembling PV and wind power generation. It is estimated that the life cycle greenhouse gas emissions are less than 23g CO_2eq/kWh as can be seen in Figure 16. However, studies on tidal and ocean currents are still lacking.



	All Technologies Considered	Wave	Tidal
Estimates:	10	8	2
References:	5	3	2

Figure 16: Life cycle GHG emissions of ocean energy technologies [29].

It is assumed that environmental effects are limited due to the location of the systems in moving water environments, where less species are located. Although the fact that current technologies have moving parts like rotor blades or hydrofoils that are capable of harming marine life, no evidence was found in studies up to 2011. This may be due to the slow rotation speeds compared to ship propulsion or due to the limited number and duration of deployment of the systems. In addition, the scale of ocean current devices is expected to be insufficient to alter or scale the ocean circulation or net mass transport. However, mixing processes and meander patterns could be influenced. Furthermore, systems under water can affect the habitats of marine life where animals might get entangled in these systems or the alteration of pelagic habitats [29]. The latter would be especially undesirable for Raja Ampat which is known for their coral reefs and the many reef fish that attract tourism.

5 Discussion

Due to the, sometimes rather poor, internet connection in Indonesia, research was quite limited on certain days, causing the online monitoring system to be offline quite often as well. Furthermore, a fire caused by a lizard burned down the connection of the PV modules and the connection of the online monitoring system in November. Hereafter, the data could not be accessed anymore and the PV output could not be measured. In addition, the fire caused a power outage in the Murata building, making it impossible to measure the energy consumption of two air conditioners that used to run all day before the fire started.

The access to only two energy meters made measuring very slow with long waiting times in between the measurements. It is therefore suggested for future work to get a sufficient amount of measuring devices. In addition, the energy meters sometimes gave false measurement readings, resulting in the repetition of measurements, and therefore leaving less time for other measurements. During the assessment, the data from the online monitoring system was used as a reference. However, it was not known how accurate this data was and what was exactly in- and excluded in the measurements. Therefore, in reality the total load of the resort might deviate from the online measurement system. In order to make definite conclusions on load-based calculations, like increasing the PV setup, it is necessary to find out the real values and what is and is not included in the load. This could be done by improving the measurement system by measuring at both the generation and demand side. By doing so, cable losses can be found and improvement might be suggested (generating closer to the demand side) if these turn out to be significant.

Furthermore, the complete environmental burdens of PV systems, diesel generators and gasoline engines have not been assessed where the use of finite materials, the consequence of material mining, water consumption and land area used should also be considered. For example, a PV field covers a significant amount of land where no vegetation can grow. Several diesel generators in a building occupy less land area and on top of that, rain water falling on the roof can still be harvested where for PV, this becomes more difficult.

In addition, the Singaporean company Energy Renewed [30] is working on a electric boat design for RARCC and Papua Diving and ways to optimise the diesel generators by letting them charge a battery bank. The electric boats would come with an electric charging station, and thus they would increase the electricity demand. Electric boats will not have any gasoline consumption, reducing the CO_2 emissions drastically. However, the extra electricity demand would need to be generated with solar panels, integrated in the boat and charging station design. Research should be executed towards the life cycle emissions of electric boats and compare them to the gasoline engines and boats that are present on the island. Only then conclusions can be made on the reduction of the amount of CO_2 emissions for using electric boats.

Further future research could be done towards the measurement of ocean currents close to the island and the amount of heat that can be harvested from solar collectors and the diesel exhaust. When this is known, calculations can be made concerning heat storage and its feasibility to power absorption air conditioners and provide warm water for showers.

6 Conclusion

The greenhouse gas emissions of photo voltaics and diesel generators during their complete life cycle have been assessed and were found to be 40 g CO_{2-eq} per kWh and 850 g CO_{2-eq} per kWh for PV and diesel generators respectively. For the chosen reference day this results in 4 kg CO_{2-eq}/day for the PV system and 485 kg CO_{2-eq} for the diesel generators. On average, the diesel consumption was found to be 6385 Litres per month and the gasoline consumption for the boats 12000 Litres per month, in total for the two resorts. For the boats, the greenhouse gas emissions were calculated to be roughly 28605 kg CO_{2-eq}/month, equivalent to the emissions of 66 cars. Good research articles on this topic however are lacking.

Big energy consumers were mapped and it was found that the air conditioners take up more than one third of the total load. Their consumption can be easily reduced by using the timer option or reducing the temperature. Surprisingly, laundry machines did not consume a lot of electricity. This is due to the fact that the heating elements are not used and thus only cold washes are done.

Making the whole resort run on solely PV power is rather unfeasible due to the sizing and the consideration of bad weather. Alternatively, the PV supply can be switched from resort load to the compressor load, for which a total of 360 PV modules need to be installed to provide enough electricity during cloudy and rainy weather. This would reduce the strain on the 60 kVA generator that generates electricity for the resort load and makes one of the 42.5 kVA generators obsolete, reducing the diesel consumption. With the PV system supplying to the resort load, the diesel generator runs below optimal, consuming more fuel. The PV system as it is now, never provides enough electricity to sustain the resort load at any given instance but could be able to supply enough for just the compressors when the PV field is expanded. Therefore, switching the PV supply from the resort load to the compressor load would be recommended. Excess generated electricity can be stored in batteries and used for specific uses like the construction or using the laundry machines.

Several applications like absorption air conditioning and ocean energy look very promising but need more research attention before it can be concluded whether they are feasible or not. Right now, they are still in the development phase where only a few prototypes are being used. Once they are available on the market, more information on these system will be available for research after which definite conclusions on these technologies can be drawn.

References

[1] A.W. Putra, E. Kamandika, S. Rosyadi, A. Purwadi, and Y. Haroen. Study and design of hybrid off-grid pv-generator power system for administration load and communal load at three regions in indonesia. In *2016 3rd Conference on Power Engineering and Renewable Energy (ICPERE)*, pages 57–62, 2016.

[2] S.F. Kennedy. Indonesia's energy transition and its contradictions: Emerging geographies of energy and finance. *Energy Research & Social Science*, 41:230–237, 2018.

[3] B. K. Sovacool. Success and failure in the political economy of solar electrification: Lessons from world bank solar home system (shs) projects in sri lanka and indonesia. *Energy Policy*, 123:482 – 493, 2018. ISSN 0301-4215. doi: https://doi.org/10.1016/j.enpol.2018.09.024. URL `http://www.sciencedirect.com/science/article/pii/S0301421518306293`.

[4] HARTECH. Ht 42.5 y, 2018. URL `http://www.hartech.co.id//post/produk/HT-42-5-Y.html#.W9f9di-B36Y`.

[5] Jskye. St72m200 by jskye, 2018. URL `http://www.jskye.com/services/jskye-solar-panels/#1482810472303-37609655-cd58`.

[6] A.H.M.E. Reinders, P.J. Verlinden, W.G.J.H.M. van Sark, and A. Freundlich. *Photovoltaic Solar Energy: From Fundamentals to Applications*. Wiley & Sons, 2016. ISBN 9781118927465. doi: 10.1002/9781118927496.

[7] D. Nugent and B.K. Sovacool. Assessing the lifecycle greenhouse gas emissions from solar pv and wind energy: A critical meta-survey. *Energy Policy*, 65:229 – 244, 2014. ISSN 0301-4215. doi: https://doi.org/10.1016/j.enpol.2013.10.048. URL `http://www.sciencedirect.com/science/article/pii/S0301421513010719`.

[8] N.A. Ludin, N.I. Mustafa, A.M. Hanafiah, M.A. Ibrahim, M.A.M. Teridi, S. Sepeai, A. Zaharim, and K. Sopian. Prospects of life cycle assessment of renewable energy from solar photovoltaic technologies: A review. *Renewable and Sustainable Energy Reviews*, 96:11 – 28, 2018. ISSN 1364-0321. doi: https://doi.org/10.1016/j.rser.2018.07.048. URL `http://www.sciencedirect.com/science/article/pii/S1364032118305574`.

[9] D.D. Hsu, p. O'Donoughue, V. Fthenakis, G.A. Heath, H.C. Kim, P. Sawyer, J.K. Choi, and D.E. Turney. Life cycle greenhouse gas emissions of crystalline silicon photovoltaic electricity generation: systematic review and harmonization. *Journal of Industrial Ecology*, 16:S122–S135, 2012.

[10] NREL. Harmonization, 2018. URL `www.nrel.gov/harmonization`.

[11] A. Q. Jakhrani, A. R. H. Rigit, A. Othman, S. R. Samo, and S. A. Kamboh. Estimation of carbon footprints from diesel generator emissions. pages 78–81, July 2012.

[12] Waqas Ali, Salman Nasir, Abdul Awan, Haroon Rashid, Iqra Ayub, Syed Hamza Gillani, and Muhammad Jawad Latif. Assessment of carbon footprints in terms of co2 of diesel generator. *Earth Sciences Pakistan*, 2:15–17, 2018.

[13] K. Benton, X. Yang, and Z. Wang. Life cycle energy assessment of a standby diesel generator set. *Journal of Cleaner Production*, 149:265 – 274, 2017. ISSN 0959-6526. doi: https://doi.org/10.1016/j.jclepro.2017.02.082. URL `http://www.sciencedirect.com/science/article/pii/S0959652617302962`.

[14] Department of the Environment and Energy. National greenhouse accounts factors – july 2018, 2018. URL `http://www.environment.gov.au/climate-change/climate-science-data/greenhouse-gas-measurement/publications/national-greenhouse-accounts-factors-july-2018`.

[15] D. Kushner. Two strokes and you're out, 2008. URL `http://discovermagazine.com/2008/may/21-two-strokes-and-youre-out`.

[16] Torqueedo. Torqueedo2019, 2008. URL `https://media.torqeedo.com/catalogs/torqeedo-catalog-2019-uk.pdf`.

[17] ECN, Energie-Nederland, and Netbeheer Nederland. Energie trends 2016, 2016. URL `https://energietrends.info`.

[18] G. Tibério Cardoso and F. Vecchia. Thermal behavior of green roofs applied to tropical climate. *Journal of Construction Engineering*, Volume 2013:1–7, 12 2012. doi: 10.1155/2013/940386.

[19] M. Köhler, M. Schmidt, F. Grimme, M. Laar, V. Lúcia de Assunção Paiva, and S. Tavares. Green roofs in temperate climates and in the hot-humid tropics – far beyond the aesthetics. *Environmental Management and Health*, 13:382–391, 10 2002. doi: 10.1108/09566160210439297.

[20] G. Wong and C.Y. Jim. Quantitative hydrologic performance of extensive green roof underhumid-tropical rainfall regime. *Ecological Engineering*, 70:366–378, 09 2014. doi: 10.1016/j.ecoleng.2014.06.025.

[21] C.Y. Jim. Air-conditioning energy consumption due to green roofs with different building thermal insulation. *Applied Energy*, 128:49–59, 09 2014. doi: 10.1016/j.apenergy.2014.04.055.

[22] Global Solar Atlas. Global solar atlas, 2018. URL `https://globalsolaratlas.info`.

[23] Homer Energy. Homer energy, 2018. URL `https://www.homerenergy.com`.

[24] Property24. Solar geysers vs heat pumps: what's best?, 2017. URL `https://www.property24.com/articles/solar-geysers-vs-heat-pumps-whats-best/26262`.

[25] Kasumi Yasukawa, Youhei Uchida, Norio Tenma, Yusaku Taguchi, Hirofumi Muraoka, Takemasa Ishii, Jittrakorn Suwanlert, Somkid Buapeng, and Ha Nguyen. Groundwater temperature survey for geothermal heat pump application in tropical asia. *Bulletin Of The Geological Survey Of Japan*, 60: 459–467, 01 2009. doi: 10.9795/bullgsj.60.459.

[26] V. Mittal, S. Kasana, and N. S. Thakur. The study of solar absorption air-conditioning systems. *Journal of Energy in Southern Africa*, 16:59–66, 01 2005. doi: 10.17159/2413-3051/2005/v16i4a3103.

[27] F. Asdrubali, G. Baldinelli, and A. Presciutti. Solar cooling with small-size absorption chillers: Different solutions for summer air conditioning. 02 2019.

[28] A. Richter. Indonesia reaches 1,925 mw installed geothermal power generation capacity, 2018. URL `http://www.thinkgeoenergy.com/indonesia-reaches-1925-mw-installed-geothermal-power-generation-capacity/`.

[29] A. Lewis, S. Estefen, J. Huckerby, W. Musial, T. Pontes, and J. Torres-Martinez. Ocean energy. *In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*, 2011. URL `http://www.ipcc-wg3.de/report/IPCC_SRREN_Ch06.pdf`.

[30] Energy Renewed. Energy renewed, 2018. URL `https://www.energy-renewed.com`.