Hybrid renewable energy systems for remote locations

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Solar power combined with vegetable oil-driven IC-engine

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Thank you!

Summary

Many locations in Indonesia such as small islands and remote villages on the main islands are not connected to the main electricity grid, and may never be as they are too remote for grid extensions to be economically justifiable. Therefore, many either do not have electricity or are dependent on expensive diesel transports to fuel their stand alone, diesel powered mini-grids. Using a hybrid renewable energy system combining solar power and a diesel engine run on vegetable oil could provide this type of location with cheaper, more reliable energy.

In order to investigate whether this type of system would be feasible, field studies were completed to gain an understanding of how well implemented systems are working and what challenges are connected to them. The field studies were conducted at the Karimunjawa archipelago, where the energy systems of the main island and three smaller islands were studied. The field studies were complemented by running experiments at the university laboratories to analyze the effect of using vegetable oil as fuel in a diesel engine.

The installed solar power was working well on the two islands where it had been implemented recently, whereas another island with an older system had issues with corroding PV-panels. The main island was running on large diesel engines at a newly installed diesel power plant which were not used optimally. Two of the smaller sites also had wind turbines which were all broken.

The experiments showed that it was possible to run the diesel engine with palm and coconut oil. The emissions were slightly lower for the vegetable oils, with palm oil have lower emissions that coconut oil. However, the fuel consumption for the vegetable oils was higher than for diesel, with coconut oil giving the highest result.

Keywords Hybrid, renewable, Karimunjawa, solar power, vegetable oil, diesel engine, remote locations, palm oil, coconut oil, PV

Sammanfattning

Många platser i Indonesien som exempelvis små öar samt avlägsna byar på de större öarna är inte anslutna till elnätet, och kommer eventuellt aldrig vara det eftersom de är för avlägsna för att nätuppkoppling ska vara ekonomisk. Därför är det många som antingen inte har el alls eller är beroende av dyra dieseltransporter till att driva deras fristående nät. Med användning av ett hybridsystem som kombinerar solenergi och en dieselmotor som körs på vegetabilisk olja skulle denna typ av ort kunna tillgodoses med billigare, mer tillförlitlig energitillförsel.

För att undersöka om denna typ av system har potential, har fältstudier gjorts för att få förståelse för hur existerande system fungerar och vilka utmaningar som finns med att implementera dessa. Fältstudierna genomfördes i Karimunjawas skärgård, där energisystemen på huvudön och på de tre mindre öarna studerades. Fältstudierna kompletterades genom att köra experiment på universitetets laboratorier för att analysera effekten av att använda vegetabilisk olja som bränsle i en dieselmotor.

Den installerade solenergin fungerade bra på de två öarna där det hade införts nyligen, medan en annan ö med ett äldre system hade problem med korroderade solcellspaneler. På huvudön kördes stora dieselmotorer på ett dieselkraftverk som inte kördes på ett optimalt vis. Två av de mindre öarna hade också vindkraftverk som alla var trasiga.

Experimenten visade att det var möjligt att köra dieselmotorn på palm- och kokosolja. Utsläppen var något mindre för de vegetabiliska oljorna, där palmolja hade mindre utsläpp än kokosolja. Bränsleförbrukningen var dock högre för de vegetabiliska oljorna än för diesel, där kokosoljan gav det högsta resultatet.

Nyckelord Hybrid, förnyelsebart, Karimunjawa, solenergi, vegetabilisk olja, avlägsna orter, palmolja, kokosolja

List of abbreviations

BDC	Bottom Dead Center
BMEP	Brake mean effective pressure
BOE	Barrel of oil equivalent
BPPT	Agency for the assessment and application of technology
BSCF	Billion Standard Cubic Feet
BSEC	Brake specific energy consumption
BSFC	Brake specific fuel consumtion
BTE	Brake thermal efficency
ESDM	Ministry of energy and mineral resources of republic of Indonesia
FES	Flywheel energy storage
HRES	Hybrid Renewable Energy System
IC	Internal Combustion
IDR	Indonesia Rupiah
ITB	Institut Teknologi Bandung
LA	Lead acid
Li-ion	Lithium ion battery
LPG	Liquefied petroleum gas
NiC	Nickel cadmium
PCO	Pure Coconut Oil
PHS	Pumped hydro storage
PPO	Pure Palm Oil
PV	Photovoltaic
SVO	Straight Vegetable Oil
TDC	Top Dead Center
USAID	United Stated Agency for International Development

Hybrid renewable energy systems for remote locations: Solar power combined with vegetable oil-driven IC-engine

1 Introduction

1.1 Background

Indonesia is a tropical country that is largely spread out geographically, with over 17 000 islands. Indonesia is the world's fourth most inhabited country with over 250 million inhabitants (IEA, 2015) and of them about 30 million do not have enough access to electricity (ESDM, 2016). The many remote islands make it challenging to provide electricity to the whole population. On the main islands there are also remote locations that are not connected to the main electricity grid. Many of the places that do have electricity but are not connected to the main grid use diesel engines to power their local grid, which means they are dependent on deliveries of diesel. This is expensive, both due to diesel prices and because of the extra expense to transport it to the remote location. To solve this issue it would be desirable to implement small-scale hybrid systems that use locally available energy resources.

1.2 Objectives

The main purpose of this thesis is to gain an understanding of the challenges and potential solutions for electrification in Indonesia, specifically for remote, rural areas. The potential for various renewable energy resources will be discussed, as well as the basics of designing and maintaining hybrid energy systems. The effects of using vegetable oil in a diesel engine will also be examined. These objectives can be summarized in the following research questions:

- How are hybrid renewable energy systems built, operated and maintained in Indonesia today and how can this process be improved?
- Is it possible to run a diesel engine on vegetable oil without losing engine performance or causing engine damage?

1.3 Limitations

This thesis will discuss the design of hybrid systems generally, but the main focus is the potential of using the configuration of solar power combined with a diesel engine running on vegetable oil.

For the field studies conducted, all information was collected through translation, which gives room for misinterpretations. Often when questions were asked the answer was completely different information then what was originally asked. Lack of data or other documentation prevented the possibility of collecting detailed information on the loads and energy production.

There are several moral aspects of using biofuel to consider, such as deforestation of rainforest for palm oil production, and whether food or fuel should be prioritized. As it is assumed that type of locations that will use the studied systems are remote and rural areas, any production of biofuel would ideally be local and small-scale. Therefore the environmental impact would be small (but still an important consideration). For this reason the effects of large-scale palm oil production will not be examined further. Ensuring that the production of biofuel does not negatively impact the local inhabitants access to food is also important, but this requires site-specific investigation and will therefore not be included.

The project will focus on electricity generation, and therefore not include energy for transportation. The possibility of using biofuel for running vehicles is however highly relevant as locals will still be dependent on fuel even if a HRES (hybrid renewable energy system) is implemented for vehicular use, and this would have been interesting to look at.

How much land that is required for cultivation for the different options for vegetable oil sources is also an important factor, but will not be covered in this thesis.

1.4 Method

Literature studies were conducted to gain an understanding and background of all the technological components of a hybrid renewable energy system. This was complemented by looking at recent scientific publications on research and projects within the field of renewable energy for remote locations. Previous experimental research involving the use of vegetable oil in diesel engines were also studied. For information regarding electrification in Indonesia, recent reports from governmental institutions were studied.

The field studies at Karimunjawa were executed using case study methodology in order to see how an implemented system works and what issues can arise when installing and operating such a system. The research methods involved were observation combined with interviews. The studied energy systems where located on the main island of Karimunjawa, Parang island, Genting island and Nyamuk island. Home systems, fresh water systems, backup systems and base load systems where observed and the technicians running the systems where interviewed together with other involved locals. The interviews were conducted with the help of translators as the locals were not proficient in English.

In order to evaluate the potential of running an IC-engine (internal combustion) on vegetable oil, experiments were conducted in ITB's laboratories. The experiment was first run on conventional diesel oil in order to be able to compare the results of diesel oil with vegetable oil. The rotational speed was kept constant while varying the load. The experiment was run in the same way for palm oil and coconut oil. The properties of nyamplung oil were analyzed with the help of the chemistry department.

The results from the experiments and the field research were discussed in symbiosis to come to a conclusion of the potential for hybrid renewable energy systems of this configuration in Indonesia.

2 Electrifying Indonesia

Indonesia is a net energy exporter, where globally it is one of the biggest coal exporters. It has great potential for renewable energy but the development of this faces problems, such as the energy infrastructure and the subsidization of fossil fuels. There are plans and policies on expanding the grid, but they are often delayed due to lack of funding and land owner issues. The subsidies take money needed to build up the infrastructure and counteract sustainable mindset among the people.

In 2015 the electrification rate in Indonesia was 84 % (ESDM, 2015). The electrification rate is defined by the number of households with electricity compared to the total number of households. The general goal of electrification made by the Ministry of Energy and Mineral Resources of Republic of Indonesia is to have a rate of 89 % by 2017. The islands Java and Bali have the highest rates, where the capital city Jakarta has a 100 % electrification rate. The islands most remote from central Indonesia have the lowest rates, where Papua had a rate of only 36 % in 2013 (IEA, 2015).

Table 1: Energy production 2014 (ESDM, 2015)

Crude Oil	287 902	Thousand Barel
Natural gas	2 688	BSCF
Coal	458 097	Thousand Tonnes
Hydro Power	217 846	Tera Joule
Geothermal	73 598	Thousand Tonnes Geothermal Steam

Table 2: Energy consumption 2014 (ESDM, 2015)

Source	Million BOE	%
Final energy consumption	1 196	100
Coal	221	18.5
Fuel	396	33.1
Gas	95	7.9
Electricity	122	10.2
Briquette	0.06	0.00050
LPG	52	4.3
Biomass	310	25.9

Table 3: Electricity generation 2012 (IEA, 2015)

Total electricity generation	195.9 TWh
Coal	48.7 %
Natural gas	23.2 %
Oil	16.7 %
Hydro	6.5 %
Geothermal	4.8 %
Biofuels and waste	0.1 %

As seen in table 3, coal provides almost half of Indonesia's electricity generation (48.7%) which is reasonable considering Indonesia is a coal producer, see table 1. The renewable energy contribution in the electricity generation is 11.4 %.

Feed-in tariffs exist for geothermal, solar , waste-to-energy, hydro power and bioenergy. The consumption of these sources, among others, are shown in table 2. In the national management blueprint 2015 a development plan is set up to secure that 15 % of the electricity generation is supplied by renewable energy sources by 2025, with a target of 5000 MW geothermal energy and 500 MW of solar energy (Nachmany et al., 2015).

There is a growing interest in renewable energy sources in the world today, mainly due to the negative aspects of fossil fuels such as greenhouse gas emissions, pollution and depletion of fossil resources. For remote rural areas, an important benefit of using renewables is the possibility of self-sustainability, as using locally available resources decreases dependency on transport of fuel. This could also reduce energy costs as fuel transports can be quite expensive to these types of locations.

2.1 Solar energy

Indonesia is located in the tropics along the equator (latitude 0-9 degrees), giving it good potential for solar power. Proximity to the equator means the seasonal variation of solar radiation is diminished, although it may decrease due to cloud cover during rain season. Figure 1 shows a solar map of Indonesia, indicating that the solar irradiance is quite high over the whole country, particularly over Java island. According to the Indonesia Energy Outlook 2016 (PTSEIK and BPPT, 2016), the solar power potential in Indonesia averages at 4.8kWh/m^2/day.

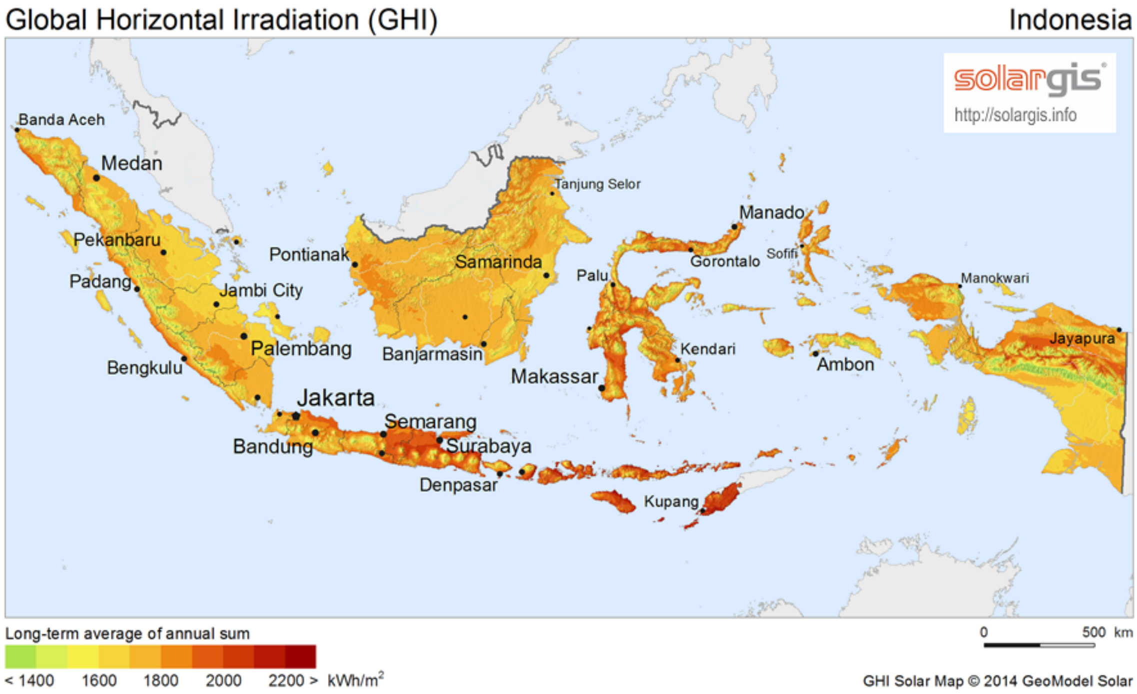


Figure 1: Solar map over Indonesia (Solargis, 2015)

2.2 Diesel fuel

The diesel fuel in Indonesia is called Solar due to its yellow color. For many years fossil fuels have been subsidised in Indonesia. In January 2015 the government removed the subsidies for premium gasoline and limited the subsidies for diesel to 1000 IDR (Indonesian Rupiah) per liter. Every quarter the Indonesian authorities evaluate and determine the prices for the fuels based on the price movements on the international market. During 2016 the price of diesel decreased even though the price of crude oil at the international market increased. (Investments, 2016).

2.3 Alternative fuels

There are a large amount of alternative fuels emerging on the market today as a result of the move away from fossil fuels. These include but are not limited to, FAME (Fatty Acid Methyl Ester), HVO (Hydrogenerated Vegetable Oil) and ethanol. It is problematic to run on these fuels alone, so often they are blended with fossil fuels. As they require chemical processing to produce, they are not optimal for production in remote locations. SVOs (Straight Vegetable Oils) are extracted from a plant source of choice without any major chemical processing.

In Indonesia there are several potential sources for vegetable oil. These include palm oil, coconut oil, nyamplung oil and jatropha oil.

2.3.1 Palm Oil

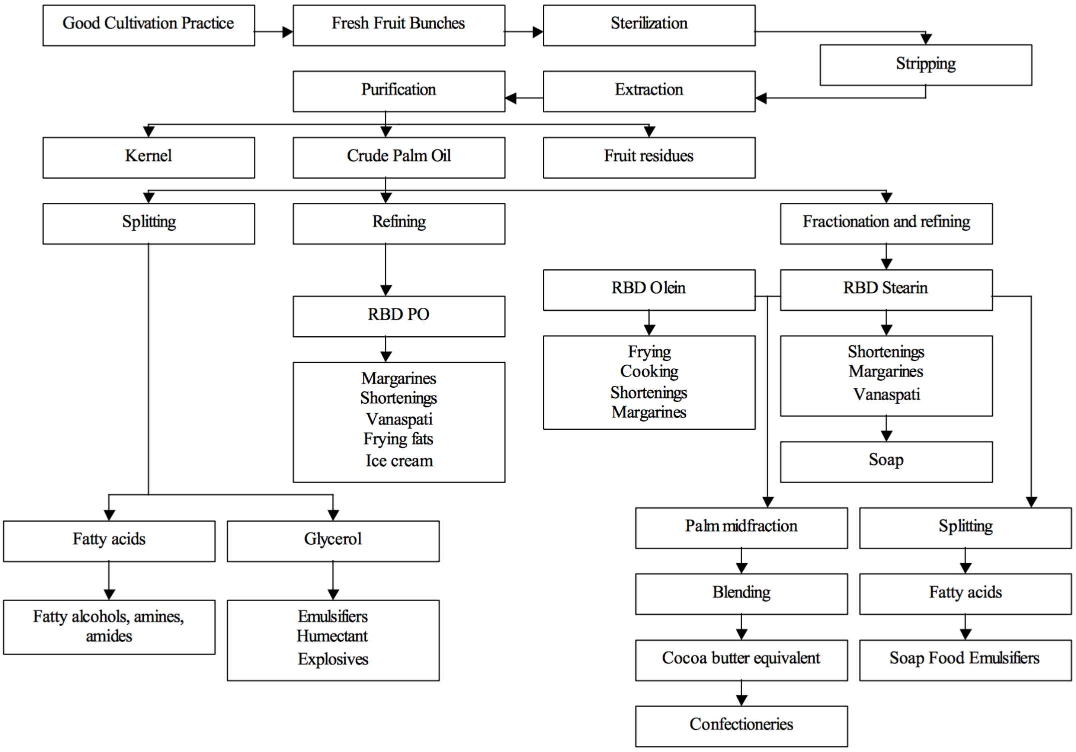
The palm tree has its origin in West Africa, but is today mainly cultivated in Malaysia and Indonesia, with these two countries contributing to about 90% of the global production. Crude palm oil (CPO) is extracted from the mesocarp of the palm tree, and palm kernel oil from the kernel within, as seen in figure 2. After extraction the oil is refined to make it suitable for consumption (Mba et al., 2015).

Figure 2: Cross-section of the palm oil fruit

Today its biggest application is in the food industry, where different refining processes are used to obtain suitable configurations depending on the desired end product, see figure 3. While over 90% of the produced palm oil goes to food such as margarine, frying oil and baby food, the remaining 10% is used for non-edible applications such as soap, cosmetics and biofuel (Sarmidi et al., 2009).

Palm oil has taken over from soybean oil as the most important vegetable oil on the market, with CPO and palm kernel oil accounting for 32% of the global fat and oils market. The growth of palm oil production is mainly due to the low cost as palm oil plantations give a comparatively high yield per unit cultivated land. It also contains many desirable nutrients, such as vitamin E, beta-karotene and its unique fatty acids (Mba et al., 2015).

It may also be possible to extract residual oil from the palm oil mill effluent (oily wastewater) and use for biodiesel (Primandari et al., 2013). As this is a waste product it would ensure



(Sarmidi et al., 2009)

Figure 3: Palm oil production process

that as much oil as possible is utilized, and prevents oil from being released into the local water.

2.3.2 Coconut Oil

The origin of the coconut tree is unclear, but the main producers today are India, the Philippines and Indonesia. Coconut oil, much like palm oil, has it's main use in the food industry, commonly used in snack foods. It is extracted from the coconut using similar techniques as for palm oil, where mechanical and/or chemical processes are used to first separate the oil from the other components of the coconut. After extraction it is usually refined before end consumption. It can also be unrefined and is then referred to as Pure Coconut Oil (PCO) (Marinaa et al., 2009).

2.3.3 Nyamplung Oil

The *Calophyllum inophyllum* tree, referred to as nyamplung locally in Indonesia, has seeds which are not edible but contain high quality oil. It grows in coastal areas where it is used for revitalization, windbreak and as a shield against abrasion. The wood of the tree is also used as boat material, and the plant contains certain chemicals that can be used in cosmetics. It has potential to be used as a biofuel but is not cultivated for commercial use at this point. There have been attempts to encourage communities to start producing nyamplung oil for use as biodiesel, but there have been problems with these trials due to lack of education and information to the farmers and the competitiveness of nyamplung versus diesel (Uripno et al., 2014). Extraction of the oil can be done through a mechanical process using a screw press, followed by degumming and refinement (Fadhlullah et al., 2015).

2.3.4 Jatropha Oil

The *Jatropha curcas* tree originated in Central America, but is today mostly grown in Africa. Historically the seeds were exported to Europe for use in soap, and the trees are today common as live fencing. It gained interest for use as biofuel in the 1980s, it's main advantages being that the seeds are non-edible, meaning it does not compete with the food industry like palm and coconut oil do (Lang and Elhaj, 2013).

The major roadblock for jatropha oil is that the available plants had poor and variable quality of the oil. Research continues to try and find/breed a genetically satisfying jatropha plant. Good results have been achieved in areas were there is good quality soil and rainfall, but at these good sites it is likely more advantageous to grow other, more productive and valuable crops (Lang and Elhaj, 2013). This also diminishes the argument of jatropha oil not competing with food as it may then compete with sites that are suitable for food production.

Jatropha oil can be extracted from its shell and seed either by mechanical extraction using a ram-press or engine-driven expeller, or chemical extraction using solvents (Forson et al., 2004).

2.4 Wind power

The potential for on-shore wind power in Indonesia is limited due to generally low wind speeds. There are some locations with high wind speeds where wind farms are in place and several other potential sites, although these are often far from populated areas which creates difficulties with transmission. Additionally, the infrastructure needed for construction of a wind turbine generator is often not in place at remote places. For on-shore implementations small (up to 10kW) and medium (10-100kW) power plants could be viable, but the suitability of installing wind power is site-dependent (IEA, 2015).

2.5 Future energy sources

There is potential for expanding the use of hydro power in Indonesia, and the possibility of using micro hydro power plants in off-grid locations would be interesting to investigate. Micro hydro by definition has a power output of 5-100kW, and is usually of the run-of-the-river type which means the cost is low compared to larger hydro power plants, and the ecological impact is small. However, the potential of using micro hydro is dependent on the location, as proximity to a suitable site is crucial. For hydro power to be feasible, important factors are head, flow rate and power output (Nasir, 2014).

Indonesia produces 146.7 million tons (470 GJ/y) of biomass per year. The main sources of biomass are rice residues, rubber wood residues, sugar mill residues and palm oil residues. Palm oil sugar and rice residues are considered to contribute to power generation in Indonesia (Zafar, 2015). The most well known process of converting biomass into usable fuel apart from direct combustion is gasification. Gasification is a method with high temperatures used in a controlled environment creating gas suitable for different energy usages by incomplete combustion of the biomass.

2.6 Karimunjawa archipelago

The Karimunjawa archipelago is a group of islands located 90 km north east of Jepara in central Java, at about 5 degrees latitude. It takes 2-5 hours to travel by ferry from the port in Jepara to the main island of Karimunjawa. The populated islands of Parang, Genting and Nyamuk are located about 1-2 hours by boat from the main island. As the archipelago is located far from the mainland, it is not cost effective to connect the islands to the mainland grid, and is unlikely that it ever will be.

(Balai tamal nasional Karimunjawa, 2004)

Figure 4: Archipelago of Karimunjawa

The main occupations of the people on these islands are fishing and farming, mainly of fruits. Production over own consumption is usually exported to the main island of Karimunjawa. The Indonesian government has recently funded hybrid energy systems for these islands, improving the electricity access and hence the quality of life for the local population.

The main island also has fishing as one of the main sources of income. In addition there is a growing tourism on the island. The smaller islands are too remote for tourism at this time, but at Parang island there are plans to build a new harbour to make the island easier to access and there are hopes that this could be a tourist destination in the future (Pt. contained energy Indonesia, 2015).

2.7 Electricity against poverty

Electricity access is one of the most important tools in battling poverty. Used for implementations such as cleaning the water and basic lighting that facilitates activities after sundown, electricity has the ability to greatly improve living standards. It also increases opportunities for education, decreases infant mortality and energy for irrigation helps increase food production (IEA, 2008).

For remote areas where grid connection is not cost effective, the only alternative for gaining electricity access are stand alone systems. Electricity generated from diesel fuel has traditionally been used for this purpose, but with the price of solar panels going down as fossil fuel prices go up, solar power for developing countries, especially for remote areas, is considered a promising solution for the future (Foroudastan and Dees, 2006).

While many projects implementing solar power in developing countries have been successful, failure due to lack of maintenance and after installation services is a common issue. This creates distrust to these systems from the users and discourages further similar projects. Proper training and creating a sense of ownership among the local population are important factors to promote a well working and lasting installation (Urmee et al., 2009).

Another issue is the financing of the system. Upfront costs for solar power installations are often high relative to the income in remote areas, and credit among the locals may not be good. In order to overcome this possible solutions that exist are fee-for-service type models, funding through government or help organizations, or a combination of both (Dornan, 2011).

3 Energy Technologies

Supplying energy to the entire world population presents many difficulties. One is the growing demand for electricity and increase in energy consumption. Another issue is the depletion of traditional fossil fuels. When it comes to remote, rural areas another challenge is the difficulty of connecting to a centralized electricity grid. A solution to these issues are hybrid renewable energy systems (HRES), which strive to combine different energy sources, thereby creating a system that provides a reliable electricity supply.

Renewable energy sources have different characteristics, but several share the advantage of being an undepletable energy source with no fuel required. There are also disadvantages, such as intermittency and difficulty of predicting the varying energy access. This holds true for solar power which is dependent both on time of day and cloud cover, and also varies seasonally. The same holds for wind power which can shift greatly from zero to maximum power over relatively short time spans. Hydro power is also seasonally dependent, although the intermittency of hydro power can be partly handled if dams are utilized. Hydro is however geographically limited as there must be access to an appropriate site for it to be feasible.

There are also non-intermittent renewable energy resources such as biomass, which can be from various different sources such waste from industry or food, or directly from plants. Biomass can be utilized for energy as it is or processed to become biofuel or biogas.

In order to overcome the intermittency issues it is necessary to combine the renewable energy sources with each other, sometimes include a fossil energy source, and/or use energy storage. There are numerous examples of such systems, for example PV/diesel (Bala and Siddique, 2009), PV/wind/battery (Bekele and Boneya, 2011), solar with thermal energy tank (Esen and Ayhan, 1996), solar and biomass (Nixon et al., 2012), and many other possible combinations.

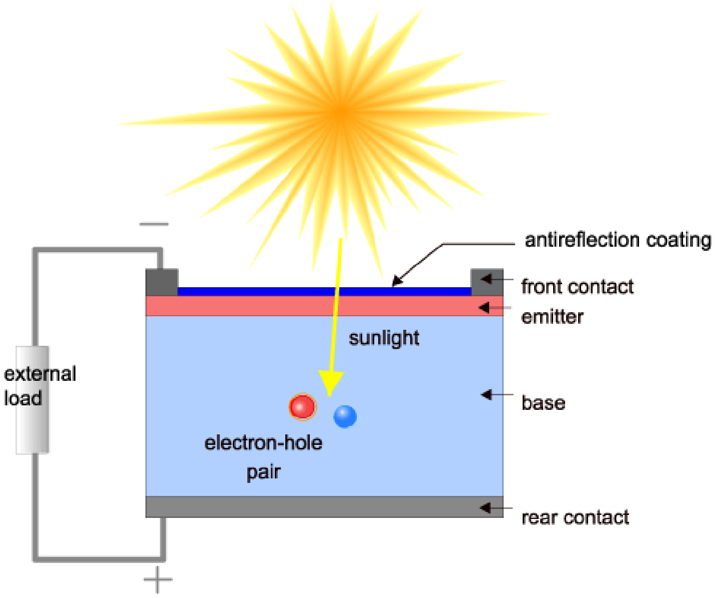
In order to optimize a HRES, the first step is to analyze what resources are available at the particular location. Once the relevant sources have been selected, the system can be cost optimized for the expected load. Determining the load profile is one of the most important steps for dimensioning the system correctly (Mohammed et al., 2014).

As stated in the previous section, for the current case of Indonesia, an interesting hybrid system configuration is to combine PV with a diesel engine, either running on diesel or preferably on vegetable oil or biodiesel.

Operating micro hybrid systems in remote areas faces several challenges. One is that there is often a lack of data for the weather conditions and loads for these areas, which makes it difficult to dimension energy systems. Lack of technical skills among the local population can also present a challenge once the system is up and running, and may cause the system to fail prematurely. Therefore educating the local technicians is essential when implementing these systems. For this reason it is also advantageous to choose components and control systems that are simple and easy to navigate (Mofor et al., 2013).

3.1 Photovoltaics

Photovoltaic panels are devices used to convert solar energy into electricity. The market for solar panels has been rapidly developed over the past few years, with the global rate for new installations increasing with 500% between 2009 and 2013 (IEA, 2014). The basic mechanism of the solar cell is that the solar radiation excites photons in the semiconductor material of the cell, inciting an electrical current which can then generate electricity.



(Honsberg and Bowden, 2014)

Figure 5: Solar cell

Individual solar cells are connected in series and parallell to increase current and voltage respectively, which forms the PV-panel.

The size of a PV-system is commonly given in watt-peak (Wp) or in kilowatt-peak (kWp). Wp is defined as the maximum power output at full radiation at standard test conditions. This entails radiation of 1 kW$/m^2$, a temperature of 25°C and an air mass of 1.5 (Honsberg and Bowden, 2014).

3.1.1 Types of cells

The most common type of PV-module on the market is the crystalline silicon cell. The silicon cells can be either mono- or polycrystalline, where the monocrystalline are more efficient but the polycrystalline are cheaper. Crystalline silicon cells dominate the market with a 90% share (IEA, 2014).

Besides silicon cells there are also thin film solar cells, which can be based on a variety of materials. Typically they have lower efficiency and much shorter lifetime, but are cheaper as well as bendable and therefore easier to place. The thin film cells have however decreased in market shares compared to the silicon PV cells, from 16% in 2009 to 10% today (IEA, 2014).

The monocrystalline silicon cells commonly have efficiencies ranging between 14-20%, polycrystalline between 13-15% and thin film between 6-12% (IEA, 2014). The efficiency of a solar cell is defined as the generated electricity divided by the incoming solar energy, and has a theoretical limit of 30%. Up to 25% efficiency has been achieved in laboratories (Alharbi and Kais, 2015).

3.1.2 Cost development

The growing market and interest in solar panels as well as the development of the technology has led to a large decrease in cost for solar panels. The average cost for PV-modules has been divided by five over the past 6 years, whereas the price for the total PV-system has been divided by three (IEA, 2014).

There are some costs related to maintenance of the solar panels, but the biggest cost is the upfront investment which includes material cost, transportation and installation (IEA, 2014).

3.1.3 Optimizing PV-module placement

The amount of solar power available depends on a number of factors such as geographical location (latitude and longitude), weather, time of day, time of year and the inclination of the solar panel.

The inclination angle is defined relative to the horizontal plane. As a general rule the solar panel should be inclined at an angle equal to the latitude of the location in order to maximize the total radiation received over one year (Castaner and Silvestre, 2002). For Indonesia this means an inclination of around 0-9 degrees (8 degrees for Java Island). As Indonesia is south of the equator, PV panels should be facing true north (Landau, 2015).

Another important factor when designing solar power plants is to ensure that there is sufficient spacing between the rows of panels so that they do not shade each other. This consideration increases in importance with increased inclination angle, as a zero degree angle entails zero shading, and so in this case no spacing is necessary. Avoiding shading from surrounding structures, such as trees or buildings, is also important. Shading of one cell will block an entire row of cells if they are connected in series, meaning that shading of small areas can have a large negative impact of the overall output of the system (Honsberg and Bowden, 2014).

3.1.4 Maintenance

The solar panels themselves do not require that much maintenance once they are installed. However, if the cells are dusty or dirty it will impact the efficiency and therefore the daily energy yield from the cells (Rehman and El-Amin, 2012). Hence it is important to keep the modules clean.

Besides the cleanliness of the panels, another factor that will effect the performance is the operating temperature, where higher temperatures lead to a decrease in conversion efficiency (Rehman and El-Amin, 2012).

It also important to protect the panels from theft, as the solar power system is made up of many expensive components. While alarm systems may be too costly and advanced for remote locations, a simple fence surrounding the solar power plant is a good way to protect the system.

3.1.5 Solar panels in tropical climates

Tropical countries presents several challenges in the process of designing efficient PV-panels. The high humidity, heavy rainfalls, sudden storms and cloudy skys make the conditions different from what most conventional panels are designed for. For every $1°C$ increase of cell temperature the efficiency decreases with 0.45% (Sabera et al., 2014).

Conventional PV-panels in tropical countries have efficiency losses due to the designed operational temperature of 25°C. They are not protected properly against humidity through the backside foil which decreases the lifetime of the panels. Heavy-duty solar panels are designed to withstand extreme weather conditions, with design features such as glass on the front and back side, sealed edges and are tested in humid and salty conditions. They are relative new on the market and use costly materials, which makes them comparatively expensive at this point (Invensun, 2017).

3.1.6 Wind turbine generators

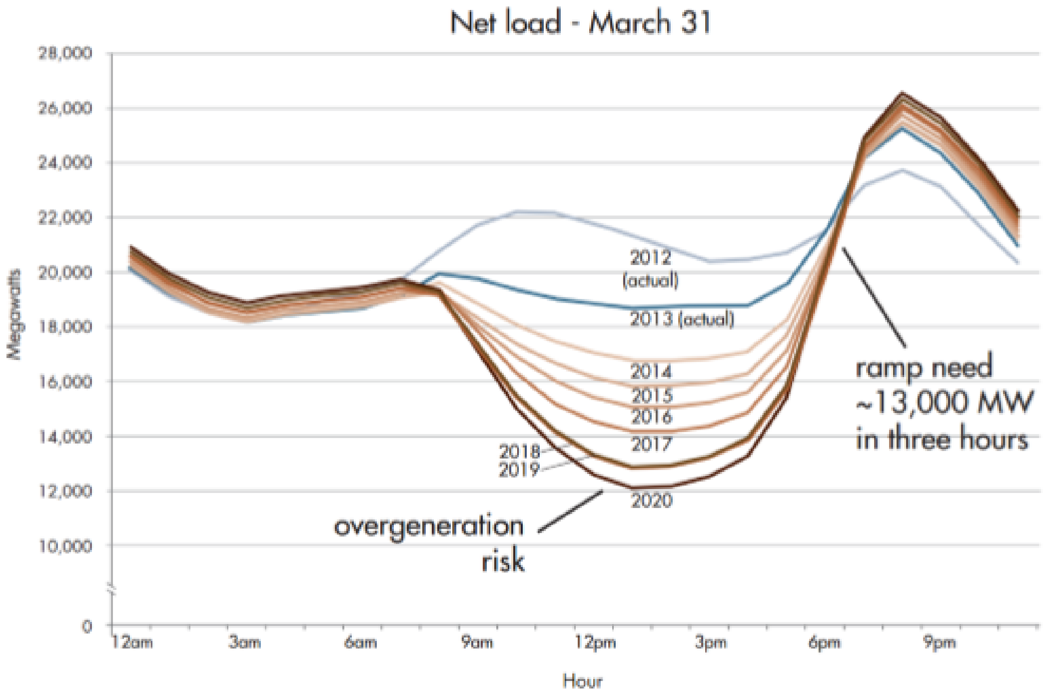
The manufacturers of wind turbines are focused on producing big turbines, as bigger wind turbines have great efficiency and use less material compared to the wind power produced (Caduff et al., 2012). This development means that there are less models to choose from for smaller wind power implementations. There are different methods to ensure that wind turbines are protected from high wind speeds, for example automatic control systems that turn the blades against the wind at dangerous wind speeds. However, a common reason for failure is that the braking system fails at high wind speeds, causing the turbine to spin out of control. Other reasons for structural damage on wind turbines are lack of quality control, lightning and improper installation (Ciang1 et al., 2008).

3.2 Energy storage

With increasing penetration of intermittent renewable energy sources in the world, the importance of energy storage is growing. Solar energy is only available during the day, and most energy is consumed in the evenings. There is a mismatch between the power curve of the solar energy production and the energy consumption, which can be visualized in the so called duck curve, see figure 6. The duck curve shows the load that has to be provided by another energy source than solar power, and indicates that at sundown the drop in solar power combined with increased demand makes a dramatic ramp up of power necessary. The scale of this problem increases with increasing implementation of solar power and the size of the system. In figure 6 for the case of California it can be seen that this will result in many MW of power needed in short time-spans (Denholm et al., 2015). For smaller systems the problem will not be as large-scale, but the ramp up is still an important consideration. A solution to this problem is to use energy storage.

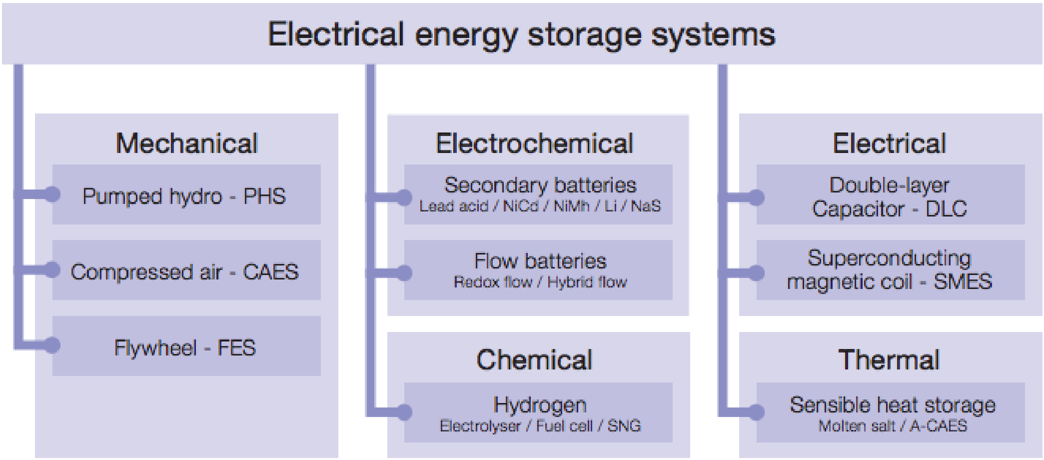
Since solar energy is an unpredictable source of energy, loss of power in the system can happen fast. To ensure a stable electricity supply and to protect the grid from unnecessary wear (voltage and frequency changes) during the time between loss of solar power and the starting up of another energy source, the system needs to be compensated by instant energy. This energy can come from a source stored mechanically, thermally, electrically, chemically or electrochemically, as can be seen in figure 7.

In a micro hybrid energy system incorporating solar panels it is desirable to use as much of



(Denholm et al., 2015)

Figure 6: Duck curve



(IEC, 2011)

Figure 7: Classification of electrical energy storage systems

the solar energy as possible. For this type of system the most common way of storing energy is by using batteries. Another possible but less utilized method is by using mechanical energy storage systems.

3.2.1 Batteries

The main function of the battery is to convert chemical energy to electrical energy by a electrochemical reaction.

The efficiency of a battery is measured as; coulombic/charge efficiency, voltage efficiency and energy efficiency. Coulombic efficiency is the amount of charge retrieved from the battery during constant discharge compared to the amount of charge put in during charging. The voltage efficiency is when charge is retrieved from the battery at constant discharge but at lower voltage than the one needed to put in to the battery. The product of coulombic and voltage efficiency is called the energy efficiency.

The power rating of a battery is the maximum amount of charge and discharge in amperes (A). The capacity of the battery is the amount of energy that can be extracted without the battery voltage getting below a certain value and it is measured at constant discharge rate in either kilowatt-hours (kWh) or ampere-hours (Ah).

The lifetime of batteries varies from three to up to 15 years depending on the operation conditions such as temperature, depth of charge, discharge, how well the electrolyte is managed and other factors. The discharge depth has to be taken into account when optimizing the capacity for a system. If the battery has a capacity of 6kWh and its discharge depth is 50 % then the usable capacity is 3kWh, while with a discharge depth of 75 % gives a usable capacity of 4.5kWh.

Safety is of great importance when choosing a battery, since some electrochemical reactions can generate hazardous substances and high operation temperatures if not cooled properly. Therefore the technical expertise of the operator of the system is as important as the right cost and performance ratio when choosing a battery.

For HRES applications lead acid batteries are most common due to the low investments costs (Wenham et al., 2011). In the future lithium, sodium and flow batteries are expected to dominate the market (Gauchia, 2015).

3.2.2 Lead acid battery (LA)

The Lead Acid (LA) battery is a mature technology that has been utilized commercially since 1890, with applications such as starter batteries in vehicle systems, power supply systems and storage for stand-alone PV-systems.

With a discharge depth of 80 % it can handle up to 1500 cycles (IEC, 2011). Typical efficiencies are; coulombic = 85%, voltage = 85% and energy = 72% (Wenham et al., 2011).The batteries are suitable for medium and large energy storage systems due to their combination of good performance at a low cost.

A LA battery has different types of design features such as deep or shallow cycling, sealed or open, gelled and captive or liquid electrolyte. Normally in a LA battery the positive electrode plates are lead dioxide (PbO_2), the negative electrode plates are lead (Pb), and the electrolyte is sulfuric acid (H_2SO_4) and water. It is constructed with either a vented or a sealing housing (valve-regulated LA batteries, VRLA). The VRLA batteries have catalytic converters that convert hydrogen and oxygen back into water, and in case of extra gas it is vented. Hence the electrolyte can not be added. The open batteries have an excess of electrolyte which needs to be refilled frequently. The housing needs to be properly ventilated to prevent build-up of hydrogen gas.

The components in a LA battery can all be recycled and a new battery contains of 60 % to 80% of recycled lead and plastic. Undercharging, overcharging, low electrolyte level, vibration and high temperature are factors that shorten the lifespan of a LA battery. The rate of self-discharge at a temperature of 20° is 1 % to 5 % per month and rises with increased temperature.

Some disadvantages of the LA battery are low cycle life, relatively low energy density, comparatively large size and the build-up of dangerous hydrogen gas (Rand and T.Moseley, 2015).

3.3 Inverters

The purpose of the inverter is to convert from the direct current (DC) produced by the PV-module to alternating current (AC), as most grids use AC for distribution. It also increases the voltage and helps to keep the voltage and frequency constant despite the varying load. A bidirectional inverter can also receive AC power and convert it to DC power, making it possible to charge batteries using an AC producing energy source. This is an important component in a hybrid energy system. Typical inverter efficiencies are around 80-85%, but can diminish significantly at low loads (Wenham et al., 2011).

3.4 Solar charge controller

In order to prevent the battery from being overcharged or deeply discharged, it is advantageous to use a charge controller connected to the PV system. This will regulate so that if the maximum allowable voltage is reached, the current will be switched off by using either a short or open circuit. Once the voltage is under a certain level, the current will be reconnected. If the voltage is too low, the load will be disconnected in order to avoid deep discharge. At a certain set point, the load will be reconnected. Choice of the points for dis- and reconnecting depend on the battery type, the charge controller type and the temperature (Wenham et al., 2011).

3.5 Monitoring system

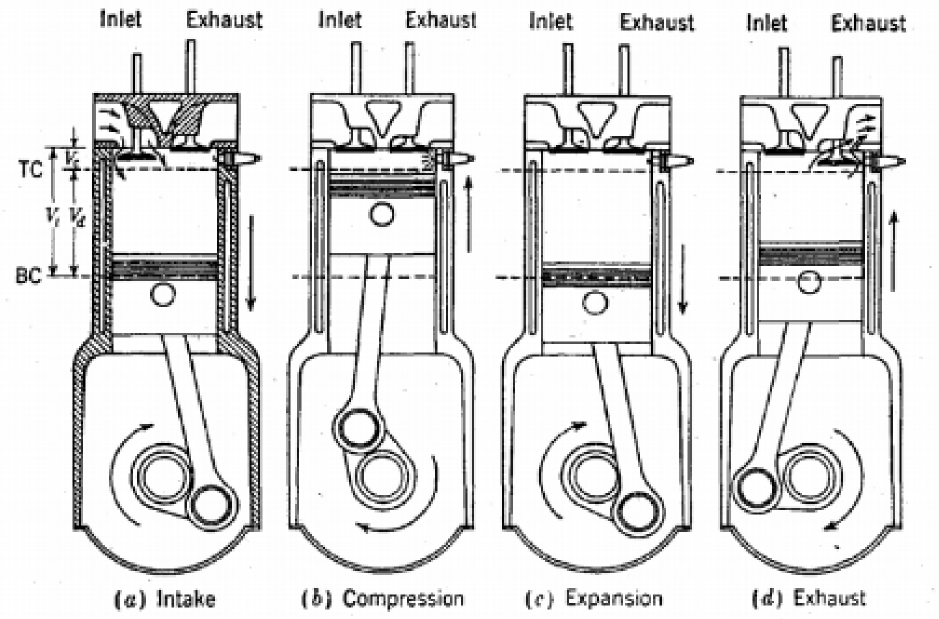
In order to optimize the operation of a HRES, a monitoring system can be used. Its purpose is to collect data from the sources it is connected to, and by using this data the software manages the system to run in the most effective way. The system logs events, historical data and performance in user-friendly ways. The data can then be used to analyse and optimize future settings of the HRES (Schneider Electric, 2013).

3.6 Diesel engine

The diesel engine is a compression ignition (CI) engine, which means that the fuel ignites when it enters the cylinder due to the high pressure caused by compression. In contrast, in petroleum engines the combustion process is started by using a spark plug that ignites a fuel-air mix. The cetane number indicates the ignition quality of the fuel, therefore the diesel engine operates with high cetane number fuels since it needs to self-ignite fast and easy.

There are four-stroke and two-stroke diesel engines, where the more common type is the four-stroke engine. The basic principle of the four-stroke diesel engine is the following:

During the first stroke the inlet valve is open and air is sucked into the cylinder, the piston moves from top dead center (TDC) to the bottom dead (BDC) center and at BDC the inlet valve close.



(Heywood, 1988a)

Figure 8: The four-stroke cycle of a CI engine

The second stroke is the compression stroke. Both valves are closed and the piston moves to its upper position. In the beginning of the compression stroke the pressure is between 30 to 50 bar and the temperature between 550° C to 700° C. At the end of the compression stroke the pressure is between 60 to 100 bar and the temperature can be up to 2000° C, and this is when the fuel is injected at the top of the cylinder.

The third stroke is the power stroke. The heat generated due to high compression ignites the fuel, the process generates pressure that pushes the piston down. The connection rod transfers the reciprocating movement of the piston to rotational movement in the crankshaft that is connected to the generator.

The last stroke is the exhaust stroke. When the piston moves toward TDC the exhaust valve opens, the pressure difference between the exhaust port and the burnt gases in the cylinder allows the gases to escape. Then shortly after TDC is reached the exhaust valve is closed.

When a cycle of a four stroke diesel engine is completed the piston has moved up and down two times and the crankshaft has done two complete revolutions (Heywood, 1988a).

3.6.1 Engine characteristics

The compression ratio (r_c) is defined by the maximum cylinder volume divided by the minimum cylinder volume. Normal compression ratios for diesel engines are between 16-20, where the upper limit is due to weight increase. The high compression ratio is possible due to absence of knock limit. V_d (displaced volume), is the volume between the BDC and TDC and V_c (clearance volume), is the volume of the combustion chamber (min volume), giving the compression ratio as:

$$r_c = \frac{V_d + V_c}{V_c} \tag{1}$$

The mean piston speed (S_p) is important for kinematic and dynamic performance. With increased speed the friction, inertial forces and wear increases, therefore large engines are low-speed and high-speed engines have small dimensions. $L =$ is length of the stroke and $N =$ is the rotational speed of the crankshaft.

$$S_p = 2LN \tag{2}$$

For diesel engines $S_p \approx D^{-1/4}$ where a bore diameter of 0.1m < D < 1m is desirable.

The power the engine supplies to the load is called effective brake power (P_e) and is the product of the effective brake torque (T_e) multiplied by the angular speed:

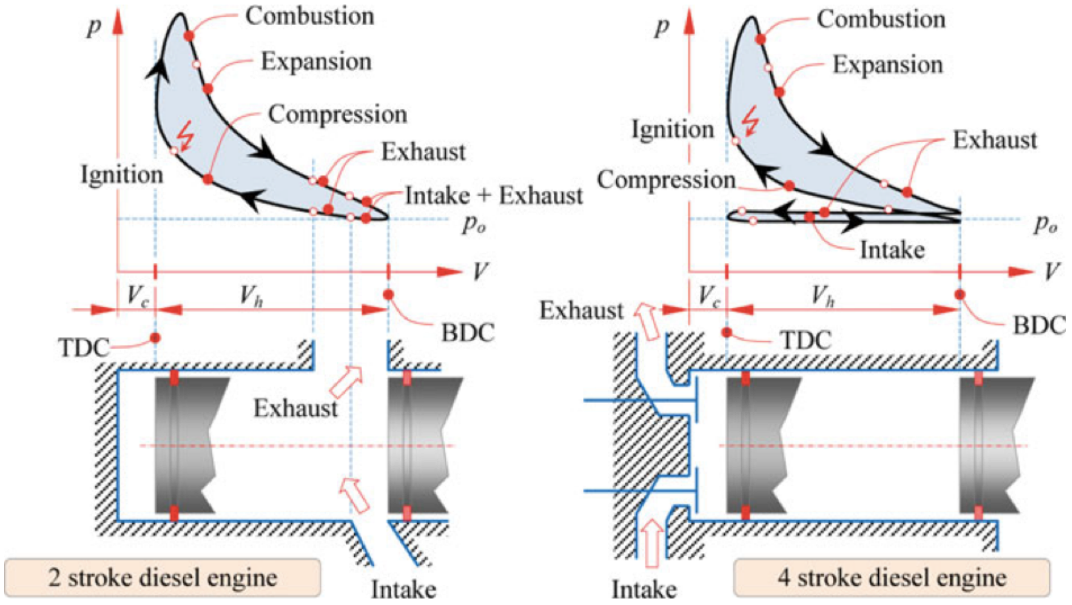
$$P_e = 2\pi N T_e \tag{3}$$

In SI units:

$$P_e(kW) = 2\pi N(rev/s)T_e(Nm)10^{-3} \tag{4}$$

The indicated work per cycle can be calculated with pressure data. By plotting pressure and volume in a so-called pV-diagram (see figure 9), the indicated work can be calculated by integrating the curve (Heywood, 1988b):

$$W_i = \oint_V p\,dV \tag{5}$$



(Kegl et al., 2013)

Figure 9: pV-diagram of diesel engines.

3.6.2 Engine performance parameters

The brake specific fuel consumption (BSFC) is the fuel flow rate per unit power output. The lower the value, the better combustion efficiency.

$$BSFC[g/kWh] = \frac{\dot{m}_f}{P} \tag{6}$$

The brake specific energy consumption (BSEC) is the product of the BSFC and the calorific value, also called lower heating value (LHV), of the fuel. It measures the efficiency of energy obtained from the fuel.

$$BSEC[kJ/kWh] = BSEC * LHV \tag{7}$$

The brake thermal efficiency (BTE) is the ratio between power and the energy the fuel holds.

$$\eta_{BTE}[\%] = \frac{P}{\dot{m}_f * LHV} \tag{8}$$

The mean effective pressure (MEP) is an engine performance parameter that is essential when comparing different engines since it is independent of engine displacement. It is defined as the work done divided by the displacement volume. This gives the average pressure needed to produce the brake power, if it was uniformly spread on the piston(s) from top to bottom for each power stroke. It can also be interpreted as the torque that an engine can give for a certain displacement, and is as such an indicator of the engine efficiency.

$$Work\ per\ cycle = \frac{Pn_R}{N} \tag{9}$$

$$MEP = \frac{Pn_R}{V_d N} \tag{10}$$

$$MEP[kPa] = \frac{P(kW)n_R 10^3}{V_d(dm^3)N(rev/s)} \tag{11}$$

n_R is the number of crank revolutions for each power stroke per cylinder. $n_R = 2$ for a four-stroke cycles and $n_R = 1$ for two-stroke cycles.

In the beginning of an engine cycle the fuel has a certain chemical energy content which is defined as the fuel MEP. The output performance of a cycle is indicated by the last MEP, Brake Mean Effective Pressure. Normal values for naturally aspired diesel engines are 700 to 900 kPa. In a naturally aspired engine the intake of air depends on atmospheric pressure, whereas in a turbocharged engine it is forced to higher pressures.

The air-fuel ratio (AFR) is the ratio between the air mass flow rate $\dot{m}_a$ and the fuel mass flow rate $\dot{m}_f$. For a diesel engine it range between $18 < A/F < 70$.

$$\frac{A}{F} = \frac{\dot{m}_a}{\dot{m}_f} \tag{12}$$

The relative air/fuel ratio λ is the ratio between the actual air/fuel ratio and the stoichiometric air/fuel ratio. Stoichiometric air/fuel ratio exists only for a stoichiometric mixture. The minimum air/fuel ratio for a diesel engine is 1.2-2 (Heywood, 1988b).

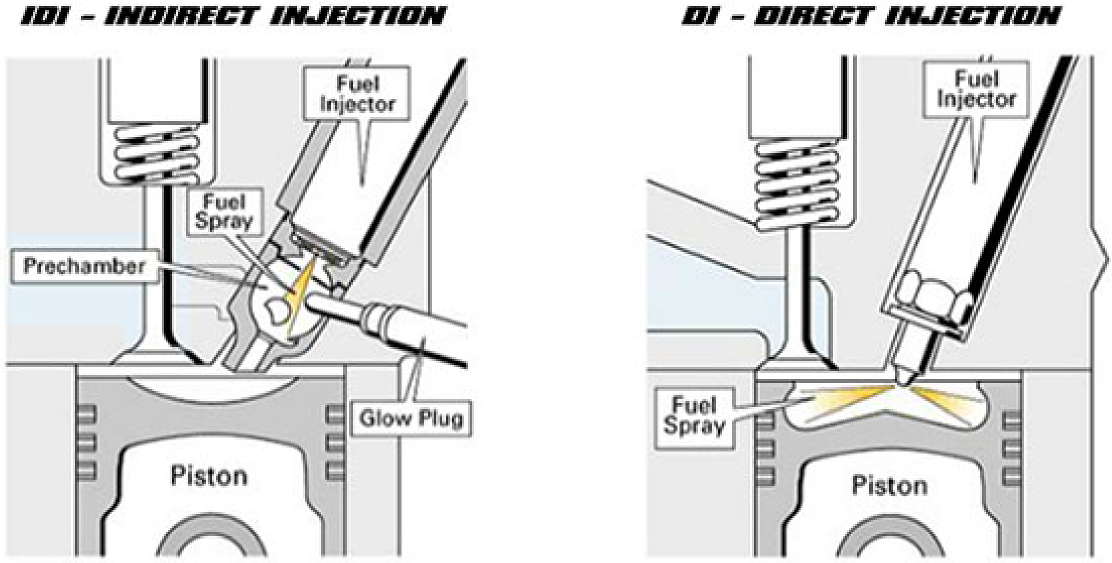
$$\lambda = \frac{(A/F)_a}{(A/F)_s} \tag{13}$$

3.6.3 Fuel injection systems

In the diesel engine the fuel is injected close to TDC. The time to reach a stoichiometric state is short, so to be able to obtain the right combustion it therefore runs with a higher air-fuel ratio. When the fuel vaporises and mixes with the cylinder air it self-ignites due to high pressure and temperature.

Modern diesel engines normally utilize direct injection (DI) systems where the fuel is injected directly into the cylinder with high velocity in the shape of droplets.

Before the DI systems developed to their current precise technology, indirect injection (IDI) fuel systems where common (during the 80s and 90s). Before entering the main combustion the fuel goes into a pre-chamber where it is heated using a glow plug. By using a pre-chamber the fuel gets more time to mix with the compressed air. Today the DI systems are more efficient than the IDI, but since they involve advanced technology they demand more knowledge during operation and maintenance. Therefore in some cases a CI-engine with IDI is the better option when choosing fuel injection system (Mollenhauer and Tschoeke, 2010).



(DieselHub, 2016)

Figure 10: Indirect injection vs direct injection

3.6.4 Combustion

In CI-engines, the fuel is burned with air, which consists of 20.95 percent oxygen, 78.09 percent nitrogen, 0.93 percent argon and low amounts of other gases, where oxygen is the reactive component during combustion. The fuel used in internal combustion engines is composed of different hydrocarbon composites. When an adequate amount of oxygen is available during combustion the hydrogen is converted into water, the carbon into carbon dioxide and if the working temperature is low the nitrogen is not affected by the combustion and therefore preserved. Combustion is referred to as rich when combusted with excess fuel, stoichiometric when combusted with precise amount of oxygen and lean when combusted with excess air. Diesel engines operate with lean conditions, which results in good fuel economy, low hydrocarbon emissions but high nitrogen oxides emissions (Heywood, 1988b).

3.6.5 Emissions

CI-engines run on diesel generate more emissions compared to SI-engines (spark ignition) run on petrol or gas. Compared to petrol engines they emit 30% less CO_2, but give high emissions of particulate matter and nitrogen oxides, though the lean air condition in the CI-engine results in low carbon monoxide (CO) and hydrocarbon (HC) emissions. Nitrogen oxides contribute to respiratory diseases and acidification, and particulates also contribute to respiratory diseases as well as cancer. In modern day engines the exhaust gas control is advanced, minimizing the amount of exhaust gases (Heywood, 1988b).

The legislated emissions of the diesel engines are: CO, HC, NO_x and particulate matter (PM). The emissions that are not legislated of the diesel engine: carbon dioxide (CO_2), water vapor (H_2O), nitrogen gas (N_2) and oxygen (O_2) (DieselNet, 2016).

3.6.6 The advantages of the diesel engine

High compression ratio and unthrottled operation results in high thermodynamic efficiency which leads to a higher fuel efficiency. The higher compression ratio also means it can produce higher power, as more compression will give a more powerful explosion.

Diesel engines operates at a wide range of lean air ratio. Due to the lean air ratio the fuel consumption is low (smaller than SI-engines). Lean mixtures have higher isentropic efficiency and therefore a high thermal efficiency (Heywood, 1988a).

3.6.7 The Lister engine

A common diesel engine used for power supply at remote locations is the Lister type. The Lister engine is an old model that many thought was of the past. Its cold-start and slow rpm characteristics make it a great engine for power supply at rural places, where it is used to produce electricity and to run the water pumping to homes out of reach of the power grids. The engine is started by hand cranking and due to the mechanical start there is no involvement of electrical component, which makes it easy to operate and maintain. It is equipped with an IDI fuel system, and is therefore suitable to run on other fuels than diesel such as bio-diesel, vegetable oil and other waste oils(Canada, 2016).

3.6.8 Effects of using vegetable oil as fuel

When Rudolf Diesel first showed his diesel engine at the world fair 1900, he ran it using peanut oil (Altin et al., 2001). However, modern day engines have been adapted and designed for use with fossil diesel oil.

Hence, there are many issues associated with using vegetable oil as a fuel in modern day diesel engines. Since these engines are designed to run on diesel, alterations must be made for it to be possible to run them on vegetable oil. The alteration can either be made to the fuel, adapting it through chemical processes to make it more similar in properties to diesel, and/or blending it with diesel. Alternatively, one can adapt the engine to make it work for the vegetable oil. For the application of rural hybrid systems, using straight vegetable oil without processing of the fuel is advantageous as it could be difficult to perform advanced processing at such locations. Therefore adapting the diesel engine to run on SVO is more relevant.

When running a diesel engine on SVO, the biggest issue is that vegetable oil has a much higher viscosity compared to diesel. Higher viscosity means the flow of the oil is more sluggish, which changes the pattern of fuel injection, spray duration, and can lead to high pressures and subsequently stresses in the fuel injection system. This can lead to incomplete combustion and result in clogging of the engine, causing damage and shortening the lifetime considerably (Altin et al., 2001).

It also has a lower cetane number than the conventional diesel which means the fuel has a longer ignition delay. The low cetane number leads to incomplete combustion when idling, increased engine noise and difficulties of cold starting the engine. The self-ignition delay decreases when the injection temperature increases. In order to lower the viscosity of the vegetable oil, it should be pre-heated before being used in the engine (Blin et al., 2013).

One method to achieve this is to use only a small amount of diesel for starting up and shutting down the engine. At start-up it helps preheat the vegetable oil, and at shutdown it flushes out any vegetable oil that may be remaining in the engine. If diesel is not used to any extent, the vegetable oil must be preheated in some other manner. Once the engine is running, preheating can be done using the heat of the exhaust gases, so it is mainly preheating at start up that presents a challenge. While it may be possible to run on only vegetable oil, using dual fuelling is recommended for running the engine without issues and has the added advantage of the possibility to revert to running on 100% diesel if desirable. Blends of vegetable oil and diesel oil can be used without dual fuelling with up to 30% vegetable oil (Sidibe et al., 2010).

Besides the issues of low viscosity and high cetane number, using vegetable oil can also lead to unwanted effects such as coke formation and polymerisation (Tunér, 2016).

Despite the many disadvantages of using SVO, there are several examples of it being used successfully to run a diesel engine, such as "do it yourself"-projects where Waste Vegetable Oil (WVO) is used to run vehicles, for fuel cost savings and to lower environmental impact. On the island of Bougainville, Papua New Guinea, the local population was able to use coconut oil to run their cars after being blocked from importing diesel due to civil war with the Papua New Guinea government (Rotheroe, 2000).

IRENA (International Renewable Energy Agency) reported that on several pacific islands pure coconut oil could be used successfully in certain diesel engines, while others had problems with clogging of filters. A blend of 5% coconut oil and 95% diesel was however considered acceptable as a direct replacement for pure diesel for all vehicular engines (Mofor et al., 2013).

The conclusions from previous research on using vegetable oil as fuel show that it will result in a slight drop in power (around 10%). However, other parameters such as emission characteristics, fuel consumption and ignition delays are inconclusive for vegetable oil compared to diesel oil, giving higher values for some cases and lower for some. This can be explained by different testing conditions and that the results depend on the engine and equipment used, as well as the quality of the oil (Sidibe et al., 2010).

3.7 Generator

The generator is composed of a stator and rotor, and uses the mechanical energy from the diesel engine (or other source) to induce an electromotive force in the stator, thereby creating electrical energy in the form of AC (Moyer, 2010).

For industrial use, three-phase distribution is most common as it is more efficient and gives a consistent level of power. Single-phase generators can be used for lighter load applications. Most households have single phase loads for lighting, appliances etc. Usually three-phase is used for distribution and converted to single-phase near the single-phase loads.

4 Execution

Literature studies and previous research showed that many similar systems are in place, but no systems running purely on vegetable oil where found, despite the fact that there is much research showing that it is possible to run diesel engines (with modifications) on vegetable oil. To further investigate the possibilities of such a system, existing hybrid systems in remote locations were studied and experiments were conducted in order to evaluate the potential of using vegetable oil as a fuel.

4.1 Field studies at Karimunjawa

After consulting with a local guide of the main island it was decided that a visit of the solar power plants and other energy system components of the islands was possible. The goal of the trip was to gain further understanding of this type of system, overlook the loads and energy production, and see how the maintenance and operation of the systems was handled. The following research questions were established before the visit as interesting aspects to investigate during the field studies:

- What is the load profile and does it vary between the islands? How does this compare to the produced energy?
- How is maintenance of the systems done?
- Looking at the system components, is the system well-designed and looked after?
- When is there electricity?

All information was collected through observation combined with conversations with operators of the energy systems and the local population. None of the islands had any written records on the energy production or consumption, and much information was not known by the operators. Therefore many assumptions, generalizations and estimations had to be made.

As the local population spoke little or no English, translation was necessary. For the main island, Parang island and Genting island accompaniment by English speakers made this possible. Unfortunately, bad weather prevented visiting Nyamuk island on the planned day, meaning that when it was possible to visit no translator was present. Viewing the system and some simple communication with the operator was still executed.

4.2 Vegetable oil tests

The aim with the first test was to analyze the performance of the system when running on conventional diesel, PPO, PCO and Nyamplung oil. The fuel properties of the tested fuel can be seen in table 4. In the tested systems, it is possible to connect to PV panels and batteries but as this will not be affected by the change of fuel, they will be excluded.

4.2.1 Measuring equipment

The power output from the different energy sources and loads are recorded in a micro SD-card in a comBox, figure 13, which is connected to the inverter. Besides the data from the micro

Table 4: Fuel properties (from LEMIGAS)

Category	Unit	Diesel	Coconut oil	Palm oil	Nyamplung oil
Cetane Number	–	48.8	39.6	42.2	∗)
Lower Heating Value	MJ/kg	42.000	33.843	35.248	32.582
Higher Heating Value	MJ/kg	39.061	34.375	35.352	34.147
Density	kg/m^3	820	908.2	898.5	922.2
Viscosity	cSt	3.32	26.96	39.58	41.67

SD-card, the fuel consumption, emissions and smoke opacity are measured manually. The fuel consumption was measured through channeling the fuel through a measuring cup and recording the time for 50ml of fuel to be consumed, see figure 11. The gas analyzer, figure 14, was used to measure the emissions, and to measure the smoke opacity the smoke opacity analyzer, figure 12, was connected to the gas analyzer.

The rotational speed was measured manually by using a tachometer to ensure a constant rpm, see figure 15.

Thermocouples were connected at five points; the fuel tank of the vegetable oil, the fuel intake, air intake, exhaust gases and cooling water, figure 16.

Figure 11: Fuel cup

Figure 12: Smoke opacity analyzer

Figure 13: ComBox

Figure 14: Gas analyzer

Figure 15: Tachometer

Figure 16: Thermocouple

4.2.2 Specifications

The engine and inverter properties are presented below in table 5 and 6.

Table 5: Engine properties - Powerline 6/1 Listeroid

Power rated	4,4kW
Model	Lister type
Injection type	Indirect Injection (IDI)
Number of cylinders	1
Operational rotational speed	650 rpm
Compression ratio	1:18
Bore x Stroke	11,43 cm x 13,97 cm
Cylinder volume	1,43 L
Cooling system	Water cooling

Table 6: Inverter properties - Schneider Electric Conext XWB 7046 E

Charger Mode (25°C)	
Input Voltage Range	165-280 V
Max Input Current	56A
Input Power Factor	>0.98
Input Frequency Range	40-68 Hz
Output Voltage Range	40-64 V
Nominal Output Range	48.0 V
Max. Output Current	110A
Inverter Mode (25°C)	
Nominal Output Voltage	230V
Nominal Output Frequency	50Hz
Max. Continuous Output Current	24A
Max. Continuous Output Power	5.5 kVA
Input Voltage Range	40-64 V
Nominal Output Range	48.0 V
Max. Continuous Input Current	150A
Operating Temperature range	-25°C to + 70°C

4.2.3 Setup

The 4,4kW one-cylinder diesel engine connected to the inverter has indirect fuel injection and a single phase distribution. Its operational speed is 650rpm, the cylinder volume is 1,43 L with a water cooling system, see table 5. The engine is connected to the generator which is connected to the bidirectional inverter. There are two separate tanks connected to the engine, one for regular diesel fuel and the other for vegetable oil. The vegetable oil tank is equipped with a coil for preheating the fuel to operational temperature. The coil is powered be an external battery and controlled using a switch.

The comBox device monitors the system and can be used to control it, making it possible to limit the current from the energy source to the load. The load comprises of lamps of varying sizes, in order to facilitate the testing of different loads, with a maximum load of 2500 W.

The solar panel system of 1 kWp is connected to the inverter. The system consists of 20 panels. They are placed on the roof of the laboratory at an 8° inclination facing north. The specification of the panel is presented in table 8. In the experiment when testing the vegetable oils the solar panels where disconnected.

The battery capacity is 200Ah, with eight batteries in total where 4 batteries are connected in series and two series are connected in parallel. A solar charge controller is connected in order to operate and maintain the batteries properly.

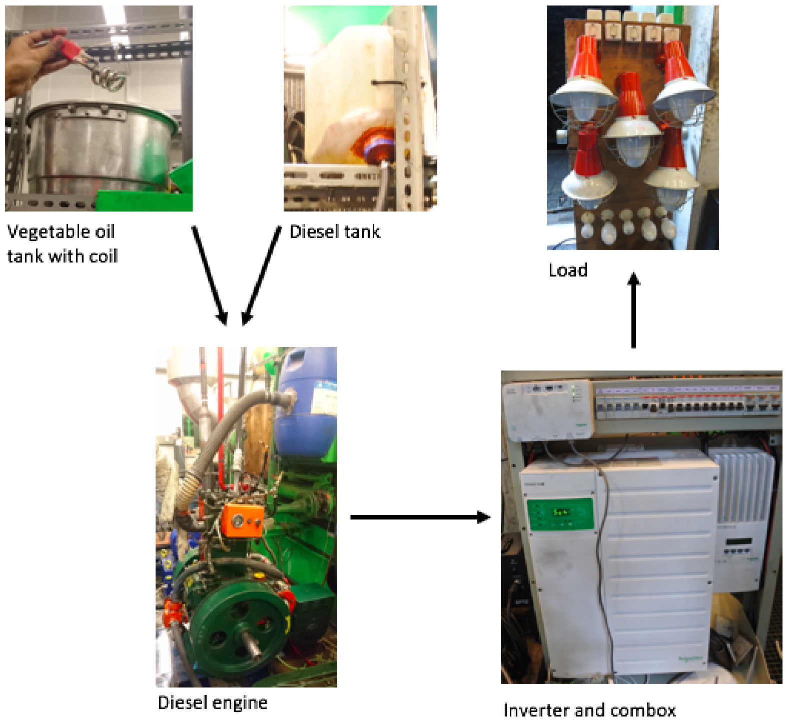


Figure 17: Experimental set-up

4.2.4 Execution of experiments

The engine was run at constant rpm while varying the load. It was run on idle (no load) and then at 1000-2500 W with 500 W intervals. 1000 W was the minimum load for the inverter. When the load was increased the rotational speed was measured manually using a tachometer, and adjusted until running at 650 rpm (design condition for the engine).

The temperatures were measured three times at five minute intervals for each load case. The emissions and smoke opacity were also measured three times each using the gas analyzer. The current, voltage and power where recorded through the SD card in the inverter. The current was adjusted so that the system would not use the batteries in order to get the whole load to be supplied by the engine alone.

When conducting the experiments with vegetable oil the engine was first run on diesel to "warm up " the engine and switched to vegetable oil after a few minutes.

5 Results

5.1 Energy systems of Karimunjawa

All of the studied islands use diesel power and solar power in different configurations. The solar power plants on the remote islands have all been funded by the government. The price of industrial diesel was at 14.000 IDR/L (1.05 USD) after subsidies for all the remote islands, where on the mainland the diesel price was at 8.000 IDR/L (0.60 USD). The locals did not have knowledge about how large the subsidies where. Besides the large scale energy production, solar installations on homes and fishing boats and small engines used as backup are common energy sources.

All of the islands have a similar load profile. Though the exact loads are not known as there is no documentation, the general picture is that there is low load during the day, mostly for refrigeration of food and the fishing industry, and the peak load is in the evenings after sundown as there is need for lighting, television and similar purposes. At night the load is low again.

Regarding maintenance there does not appear to be any regular check-ups on the condition of the systems other than what is observed by the local operators. For cleaning of solar panels, it seems to been done regularly but not according to any specific schedule, but more on an as-needed basis.

Piles of coconut shells could be seen along the roads of the islands, they were used as fuel when barbecuing food.

Table 7: Overlook of the energy systems

Island	Population	Engine capacity	Solar capacity	Electricity access
Main	7000	2x2.2 MW (+backup)	none	24/7
Parang	1169	100 kW	75kWp	24/7
Genting	380	30 kW	10kWp	5:30-11:30 pm
Nyamuk	600	30 kW	25 kWp	24/7

5.1.1 Karimunjawa main island

On the main island of Karimunjawa, a diesel power plant with two engines at 2.2 MW was implemented quite recently, on the 30th of May 2016. The diesel engines are however not new, they were manufactured in 1997 and have been in use previously. There are also two rental engines at 500 kW and 350kW meant for lower loads at the plant, but these are not currently in use as there are synchronization issues between these engines and the grid. Before this plant was put to use, there were six 500kW engines that were used as base load, and these are now used as backup. The backup generation is only activated if a blackout is estimated to last more than 6 hours. The power plant is run by Indonesia Power and the distribution by PLN (Perusahaan Listrik Negara), a state-owned company for electricity distribution in Indonesia. The diesel fuel is not significantly more expensive than on the mainland as Indonesia Power is running the power plant and they have a well-established diesel supply system. Since the implementation of this power plant there is 24h electricity access on the island but blackouts are still common, both at high and low load. During the visit of the power plant it was day-time and consequently low load. It was observed that the exhaust fumes were black as can be seen in figure 18.

Figure 18: The diesel power plant on Karimunjawa main island

On the main island three identical 500W solar home installations located on rooftops at a health centre, school and mosque, installed by the Gadhjah Mada University were observed. The systems consisted of PV-panels, two sealed lead acid batteries, inverter, solar charge controller and a monitoring system. These were only used as back up, meaning that if the batteries are already fully charged, the solar energy is wasted. For the health centre it was not possible to view the actual panels, but at the other locations they appeared to have a good inclination and be correctly turned towards north. These systems are not connected to the main grid and therefore only supply electricity to the facility they are placed on. The inverter of the solar installation at the school had broken and been replaced by a self-built inverter which was working well. The mosque had solar panels running its fresh water system.

The solar home system installations were aided by the organization USAID in collaboration with Gadhjah Mada University (Marwati, 2015b). Year 2014 they installed the solar home system at four locations and a solar water pumping system in eight locations. The calculated potential for the project is that the solar energy can be collected up to 4.5 hour per day and the 12 panels can produce 6.4 kWp therefore 28.8kWh can be generated daily. At the time when the article was written in 2015, Indonesia Power had not yet installed their power plant and the island was only supplied with electricity from the six smaller diesel generators located in five villages at night between 18.00-06.00. The solar power supplying electricity during the day helped the institutions to do their administration work during normal working hours instead of having to do it at night when the diesel generators were operated (Marwati, 2015a).

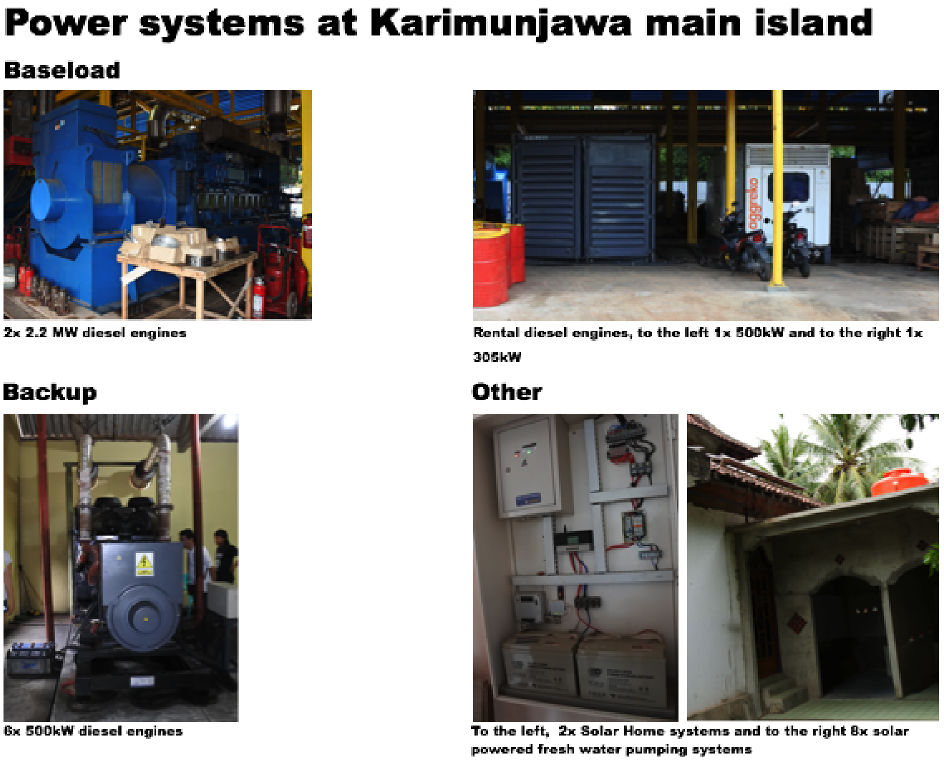


Figure 19: Power supply on Karimunjawa main island

5.1.2 Parang island

Parang island operates a solar power plant of 75kWp, with plans to double the capacity in 2017 with the help of the government through a Danish company. They also have many smaller home installations that they implemented themselves before the government built the solar power plant in 2014. The panels are well placed regarding inclination, spacing and compass direction. Since the installment they have 24/7 electricity access and report that the plant has run smoothly apart from two small inverters breaking due to storms. Why this happened is unclear, but a possible explanation is that some houses may not be grounded.

Figure 20: Solar panels on Parang island

There is also a 100kW diesel engine that runs from 6 to 9 pm at full load. It is hoped that the doubling of the capacity of the solar power plant will eliminate or at least significantly diminish the need for the diesel engine.

Interestingly, the diesel engine is not connected to the solar power system at all, meaning it is not actually a hybrid system per se, but uses two separate grids. For the homes in Parang that also have small solar home installations put in place before the building of the solar power plant, they actually have three separate systems. In a household three different lights hanging in the same place were observed, that were used depending on the currently running energy source.

Figure 21: Solar panel on fishing boat and the three different distribution lines

5.1.3 Genting island

There are two energy systems at Genting Island. One to feed electricity to the grid for six hours every evening (5.30-11.30 pm) and the most recent installation, solar panels to run the pump for the islands fresh water system. There are no solar home systems on the island.

The hybrid system used for supplying electricity to the islands 75 households combines diesel power with solar power. When the government installed the system 2008 it consisted of solar, diesel and wind power. The wind turbines have been broken since 2010, meaning they were functional for only two years. By this time the guarantee had expired and therefore they have not been repaired.

Figure 22: Broken WTGS

The solar power system is also not functioning well. It is currently at 10kWp and there are plans to expand with 30kWp in the near future. On several of the panels the seal appears to be broken causing the aluminium inside the panels to corrode, see figure 23. The panels are manufactured by the Spanish company Isofotón, module number I-110/12. According to the operator of the system, it takes about three days of good weather to charge the batteries using solar power, and only 50% of the batteries are functioning well. The batteries are long overdue replacement as their lifetime was 5 years and they have been in use for 8 years. Hopefully new batteries will be supplied to the island soon. Once the batteries are charged fully to their limited capacity, they can give about three hours of electricity to the system. All remaining time of operation the diesel generator is used.

Figure 23: Corroding solar panels on Genting island

The solar panels providing energy for the fresh water pump were provided through government funding to the locals, but without any instructions or help with the installment. Consequently the panels are not optimally placed. They are inclined at around 45 degrees, and located directly behind a structure that blocks the sun. According to the operator of this system, it has been working well and provides sufficient power to the pump during the day. There are no batteries connected to the system meaning that any energy not used by the pump is wasted.

Research online led to information about which Danish company will responsible for the extension of the solar power plants. In an article documenting a company visit to Genting island the previous year, there was a photo of the solar powered pump system. On the picture in the article the panels were directed the opposite direction, towards south (Pt. contained energy Indonesia, 2015).

Figure 24: Left: pre-feasibility study of 2015 (Contained energy, 2014) Right: during the visit

5.1.4 Nyamuk island

There were 5 wind turbines at the location, none of them functioning. They were installed in 2002, and worked for about two years. Several of them had turbine blades completely broken off. It was not possible to find out exactly what the size of the system was or what had caused the failures. They appeared to be similar but slightly different sizes and 1kW could be read on one of them. They did not appear to be placed in a well designed manner considering spacing and alignment between them.

Figure 25: Diesel engine and broken WTG

The island has 24/7 electricity access supplied by a 25kWp solar power plant installed 2013, and a diesel generator of 30 kW. The diesel engine is operated at full load between 5.30-11 pm and the solar power provides energy the remaining hours. The system has worked well although two of the solar charge controllers were not functioning at the time of the visit, where one of them had been repaired earlier and then broken again. The reason for the failure was not known or not communicated.

Figure 26: Solar power plant on Nyamuk island

5.2 Vegetable oil tests

Originally the plan was to run the engine on diesel, PCO, PPO and nyamplung oil. When it was established that nyamplung oil could not be tested (see next section regarding nyamplung oil), the possibility of testing jatropha oil was investigated. Unfortunately it was found to be too difficult to obtain within the given time-frame. Therefore the experiments were completed only for diesel, PCO and PPO.

5.2.1 Nyamplung

When obtaining the properties of the nyamplung oil, the cetane number was not readable as the viscosity was too high for it to be used in the test engine as it would most likely cause clogging of the engine due to incomplete combustion. An additional test was done to evaluate the viscosity of the oil vs the temperature to see if it could be used if pre-heated to higher temperatures. The results are presented in the figure 27.

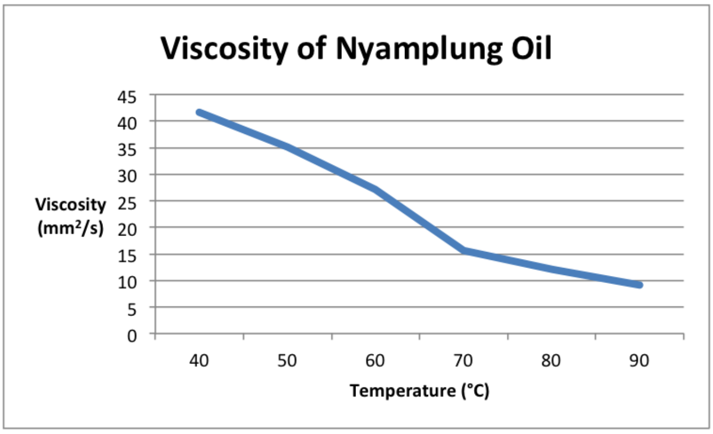


Figure 27: Viscosity of nyamplung oil at different temperatures

As the viscosity was still not at an acceptable level at 90°C, and testing was not possible for higher temperatures, it was not possible to run the experiment using nyamplung oil.

5.2.2 Emissions

The emissions and smoke opacity measured during the experiments for the different load cases and fuels are shown in figures 28-33.

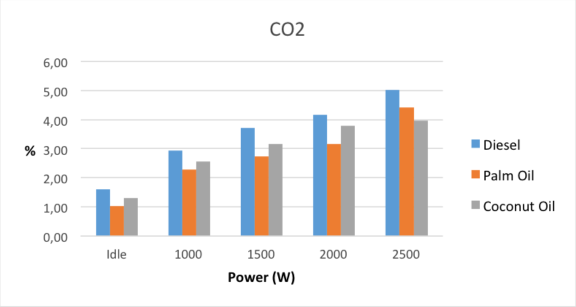


Figure 28: CO_2

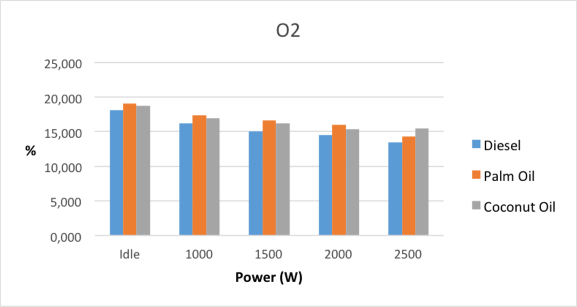


Figure 29: O_2

As seen in figure 28, the CO_2 emissions are highest for diesel in all cases, and higher for coconut oil compared to palm oil for all cases except the highest load. For O_2, we can see in figure 29 that the emissions are opposite from CO_2, being lowest for diesel and highest for palm oil, with the exception of the last value where coconut oil has slightly higher results.

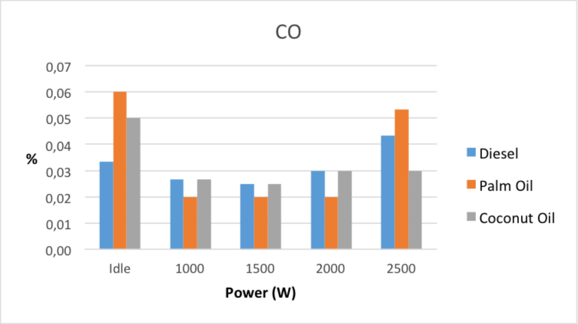


Figure 30: CO

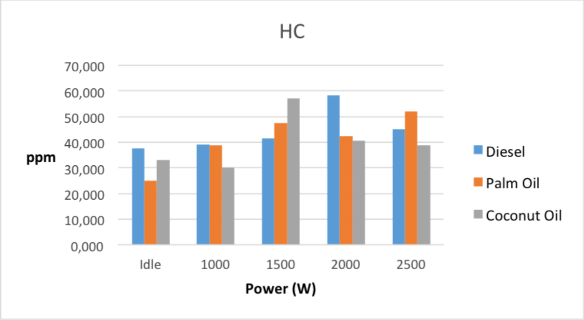


Figure 31: HC

The CO emissions have the highest values at idle and at the highest load, and at 1000-1500 W the values are almost constant, with palm oil having a slightly lower value than the other fuels. For the HC emissions, figure 31, it is difficult to discern any specific pattern with increasing load or when comparing to the fuels to each other. When running the experiment, sometimes the HC emissions did not appear at all at first and the gas analyzer had to be activated through putting it in the diesel jug to trigger the sensor.

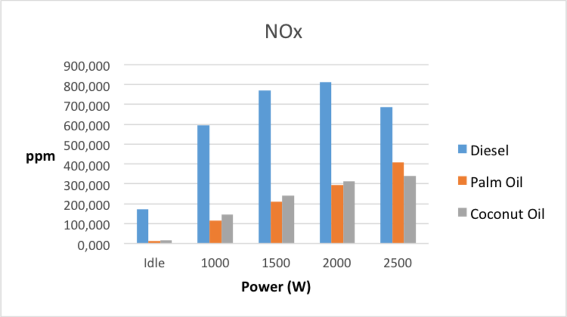


Figure 32: NO_x

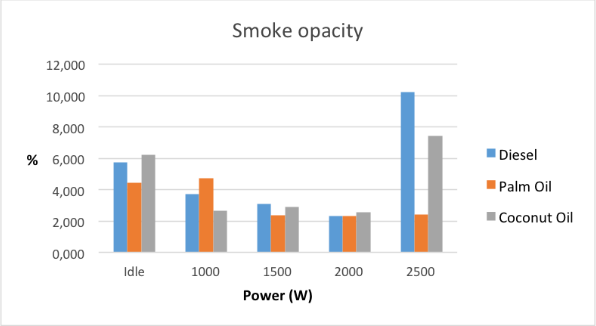


Figure 33: Smoke opacity

The NO_x emissions, figure 32, are significantly higher for diesel compared to palm and coconut oil. The values increase with the load with the exception of the last value for diesel. Coconut oil has slightly higher NO_x emissions than palm oil except for at the highest load.

The smoke opacity first appears to decrease with increasing load, but then it rises sharply for the highest load for diesel and coconut oil, but not for palm oil. When looking closer, the smoke opacity for coconut oil does not decrease continually as the smoke opacity is higher for 1500W compared to both 1000W and 2000W. As for palm oil, the values for the last three loads are almost exactly the same.

5.2.3 Engine performance parameters

The results for the engine performance parameters as calculated from the data that was collected in the experiments are presented below.

The BSFC is lowest for diesel and highest for coconut oil, as seen in figure 34. For the

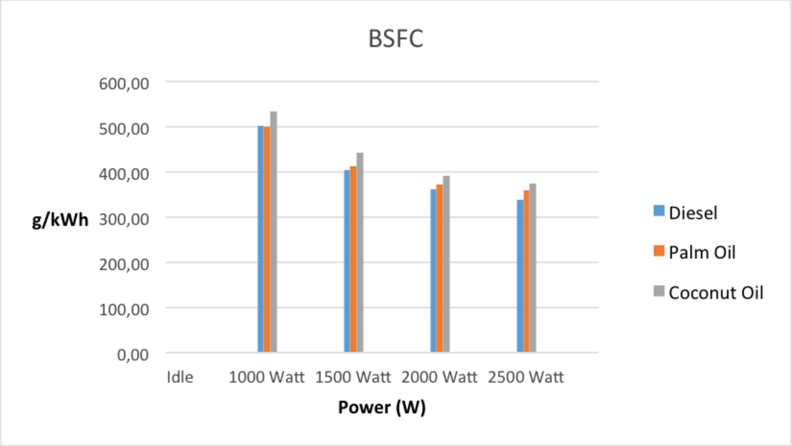


Figure 34: Brake Specific Fuel Consumption (BSFC)

first value of 1000W the BFSC for palm oil appears to be lower than for diesel. The BSFC diminishes as the load increases for all of the fuels.

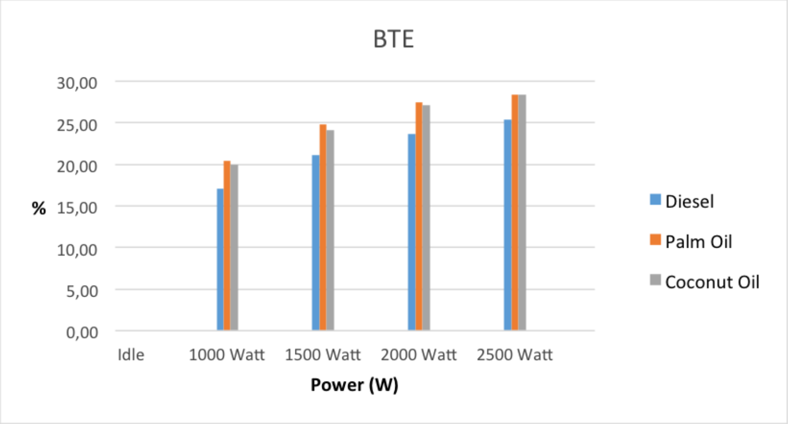


Figure 35: Brake Thermal Efficiency (BTE)

The BTE is lowest for diesel, with coconut oil and palm oil giving similar results although palm oil is slighty higher, see figure 35. The efficiency increases for higher load.

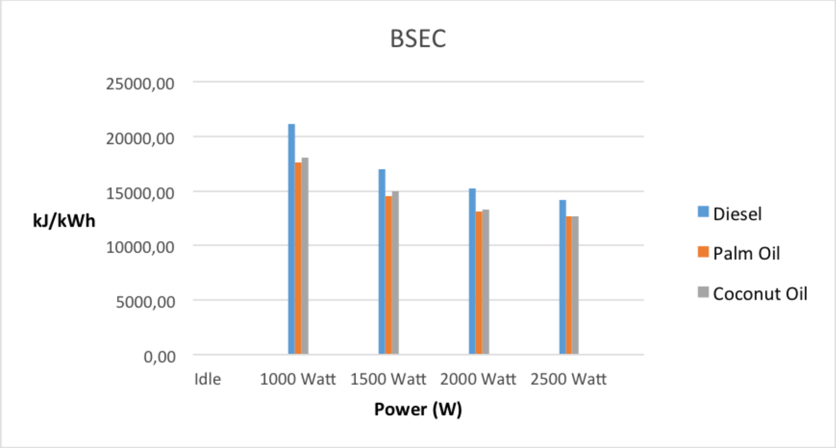


Figure 36: Brake Specific Energy Consumption

The BSEC is higher for diesel than the vegtable oils, with palm oil giving slighty lower BSEC compared to coconut oil. The BSEC decreases as the load increases for all fuels.

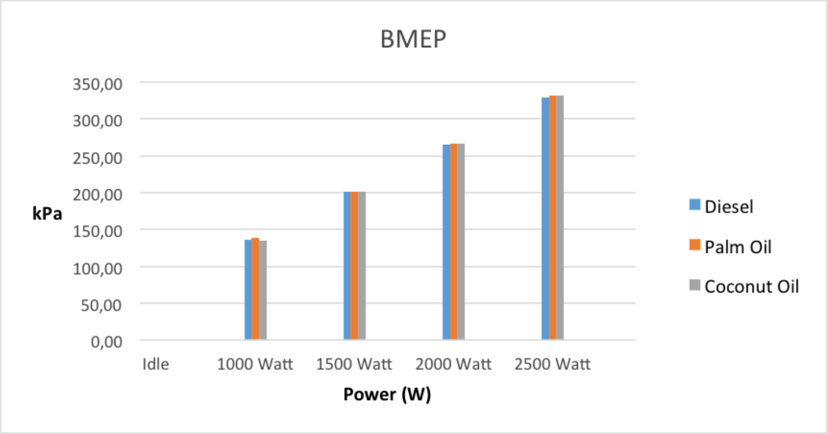


Figure 37: Brake Mean Effective Pressure (BMEP)

The BMEP, figure 37, does not appear to vary significantly between the fuels, giving almost exactly the same value for all the fuels. The BMEP rises with increasing load.

5.2.4 Cooling water

During the experiments the cooling water started reaching very high temperatures, see figure 38. While running the experiment on diesel at 2000 W, the temperature was approaching 100°C, and as the cooling water could not be permitted to reach the boiling point, the engine had to be stopped and cooled with an external fan in order to prevent engine damage. The cooling water also started to reach dangerous levels at 2500 W for palm oil, but as this was the last load it was going to be stopped momentarily anyway, so the experiment was not paused.

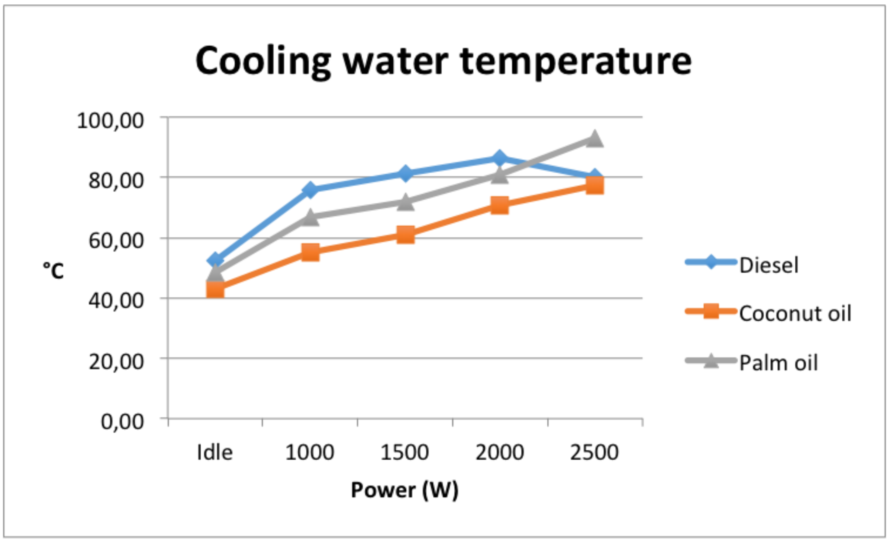


Figure 38: Temperature of cooling water

6 Discussion

6.1 Karimunjawa

Regarding the field studies, the information was mostly collected from locals via translation. This may result in misinterpretations or loss of important information. Hopefully most of the gathered information was correctly understood. Answers were found in part to most of the question formulated before the visit, except for those regarding the load profiles and production curves as there was no information or data about this. Although detailed data was not accessible, information about when and for what purposes electricity was used was still interesting information.

Running the large diesel engines on the main island at low load is not recommendable as the combustion is inefficient, as indicated by the black fumes at the time of the visit. Operation on low load results in lower cylinder pressure, thus lower working temperatures and less fuel combusted which causes problem in the cylinder due to the unburned fuel clogging different parts. Hopefully the synchronization issues of the smaller diesel generators can be resolved before the low load operation wears too much on the larger engines.

On the smaller islands the solar energy system is utilized to the maximum extent and the diesel is operated during peak hours to ensure the electricity delivery to the households when it is needed. This type of configuration is preferable to the completely diesel based energy system of the main island, as the base load is clean energy from an undepletable source. Additionally, with this setup it is possible to ensure that the diesel engines run only on full load when the efficiency is high. It also increases the reliability of the system to have a variety of energy sources.

The solar power plants all appear to be well-designed with regard to inclination, direction, spacing and dimensions, with the exception of the solar panels running the pump system on Genting island. While solar power has been proven to be a well working energy source for these systems in the field, there are some issues that it faces. One such issue is that solar power is generated during the day, but the peak load is in the evenings. This mismatch means there will be losses due to the necessity of energy storage.

In several cases, as for the solar panels running the freshwater pump on Genting island, and the solar home installations on the main island that are used as backup, any extra energy generated will go to waste. This is, for obvious reasons, not an optimal solution. In order to fully utilize all the generated energy, connecting these sytems to the main grid would be advantageous.

The solar power plants of Nyamuk and Parang island worked quite well, while the one on Genting island was in bad shape, considering a modern solar power system usually has a lifetime of 25 years or more and the system was presently around 8 years. This could have several different causes. Poor quality of the solar panels is most likely the main cause of the seal breakage and corrosion of the panels on Genting island. The solar panels are from a Spanish company and of a conventional model manufactured to provide great performance during normal conditions in Europe. To reach optimal efficiency and to secure a long operational life, choosing panels optimized for tropical conditions could be a better solution, but the increased investment costs have to be considered. The knowledge about using solar energy may be better on Parang and Nyamuk as both these islands had solar home installations prior to the building of the power plants. Hence, lack of knowledge could be the reason for the premature degradation of the system on Genting. Another factor is the age of the system, as the system on Genting island is more than double the age of the systems of the other islands. It would be interesting to investigate the state of the systems on the other islands when they reach the same age as the system on Genting island.

Regarding the operation and maintenance, there is no schedule or plan for maintaining the systems. If the panels appear to need cleaning, they are cleaned; if something is broken, it is fixed after failure. Routines for overlooking the system continuously could increase the effectiveness of the system and prevent failure before it happens. In the long run this is also most likely more cost-effective than fixing components after damage has already been done, especially as repairs can take a long time to get done.

The wind turbines at both sites which had them had failed relatively quickly after installation. This may be due to poor quality of the turbines. Most likely they did not have storm protection, and while winds in Indonesia generally are low speed, during monsoon season there are high wind speeds that could lead to breakage. Wind turbines equipped with storm protection may be too costly for these locations.

It is odd that the new solar power plants have not been connected to the existing grid and are not interconnected with the diesel engines. By connecting these systems the cost of cables and wires would have been lessened. Connecting the diesel engine to the batteries could also extend the lifetime of the batteries, as the diesel engine could charge the batteries at times of low yield from the solar panels, preventing deep discharge.

At the present there are not many activities requiring electricity on the islands during the day, but as economy and electricity access grows the demand may increase both in daytime and in general. This may effect the future development and expansion of the energy systems. The electricity access has been greatly improved over the past few years, with 24/7 access on almost all the islands and plans for further expansion of all the power plants on the smaller islands. Considering that electricity was limited to only a few hours a day quite recently, the rate of development is excellent.

6.2 Experiments using vegetable oil

The measuring equipment and engine used in the experiments are old and therefore possibly not completely reliable. The engine would sometimes spontaneously accelerate rapidly, making it necessary to manually brake the engine by adjusting the air intake until the desired rotational speed was regained. As setting the rotational speed was done manually using a tachometer and it had to be checked continuously, the rotational speed may not have been as constant as desired. The rapid accelerations occurred during all experiments, but more often when running on coconut oil.

The temperature of the vegetable oil also had to be checked continually and adjusted manually, and as a result may not have been completely constant as desired in the experiments. The thermocoil connected to the fuel tank gave highly fluctuating temperatures making it challenging to maintain a constant temperature of 90°C. The fluctuations also indicate that the reading may not be valid. It was discovered after the experiment was conducted that in previous experiments an automatic temperature controller was utilized to keep the temperature more stable. It would have been advantageous to use this in this experiment as well.

The cooling system for the engine was not very effective, resulting in dangerously high temperatures of the cooling water. As this necessitated shutting down the engine before testing the highest load of 2500W, the values for this last load may be misleading, and give results that deviate from the expected pattern.

Exhaust gas temperatures are generally very high (see Appendix: Data from experiments), which indicates a large amount of heat loss, most likely due to the engine being inefficient. However, when running on vegetable oil high exhaust temperatures could be utilized to preheat the oil once the engine is running, which would make use of more energy and limit the use of energy from an external source to start up.

6.2.1 Emissions

The diesel engine tested had no emission control device, meaning the emissions are significantly higher than for modern engines. However, the main point of interest is to compare the fuels with each other, and most remote locations that already have diesel engines will have older models without emission control similar to the test engine.

The CO_2 emissions were higher for pure diesel oil compared to the vegetable oils. This is explained by vegetable oil containing more oxygen than diesel oil, which also why the O_2 emissions are higher in the exhaust gases for the vegetable oils. Containing more oxygen is an advantage as is improves the completeness of the combustion.

The HC emissions do not appear to follow any clear pattern, and the gas analyzer behaved strangely for the HC emissions, only registering them after triggering the sensor. Therefore the results from the HC emissions are not considered reliable, and as there is no clear discernable pattern the results are difficult to interpret. It can be observed that they appear to increase slightly with the load, but this in counterintuitive as HC emissions should be higher at low loads as lower temperatures may cause incomplete combustion which results in higher HC formation.

The results from the CO emissions, like the HC emissions, seem a bit strange. They do however follow more of a pattern, giving a higher value at idle, lower at intermediate loads, and higher values at high load. CO formation, similarly to HC, would be expected decrease as combustion temperature rises. That it increases for the highest load could for diesel be explained by the stopping of the engine. The vegetable oils could be expected to give lower CO emissions compared to diesel as they contain more oxygen. Looking at the results, this appears to be the case for palm oil at the intermediate loads, though coconut oil has roughly the same as diesel oil.

In the test results the NO_x values are much lower for the vegetable oils compared to diesel fuel. The main explanation for this is that diesel has a higher LHV, which entails higher temperatures in the combustion chamber which in turn leads to higher NO_x emissions. It is also noted in the results that the NO_x emissions increases with increasing load, which is expected as higher loads result in higher temperatures. The exception is for the highest load of diesel, where the NO_x is lower than before. This is due to the stopping and cooling down of the engine that was necessary due to the dangerously high temperatures of the cooling water. It should be noted that, though NO_x formation is disadvantageous, it is the result of high temperatures which indicates more complete combustion and higher LHV.

The results for the smoke opacity are very inconclusive, not following any pattern between the fuels or with increasing load. The smoke opacity was measured using a specific device, and the strange results suggest that this device may be faulty. Instinctively, the smoke opacity should increase with increasing load, as higher temperatures lead to more particulate emissions. Low loads could however also lead to higher smoke opacity as incomplete combustion also leads to higher particulate emissions.

While some trends can be noted for the emission characteristics, such as vegetable oils containing more oxygen, the difference between the fuels is not extreme, perhaps with the exception of NO_x which is more than double for diesel oil compared with PPO and PCO. Comparing the vegetable oils to each other, palm oil gives lower emissions than coconut oil for almost all instances. However, the difference is not big enough that it could be expected to be a deciding factor when choosing fuel.

6.2.2 Engine performance parameters

The BSFC is an indication of how much fuel is needed, and the results show that it is lowest for diesel, meaning that more fuel will be required when running on vegetable oil, where palm oil has a lower fuel consumption compared to coconut oil. The fuel consumption is in important consideration for future cost calculations, because even if the price per liter is cheaper for the vegetable oils, they may become more expensive than diesel if larger quantities are needed. The cetane number of vegetable oil is lower than for diesel, and as the cetane number is related to the quality of the combustion, this means that vegetable oil gives a lower quality combustion which increases fuel consumption. In order to resolve this the injection system could be modified, for example using a two stage injection which could give the fuel more time to mix well with the air.

The brake thermal efficiency is higher for the vegetable oil. They have a lower LHV which means they contain less energy per kg but still give the same power, even when factoring in that the mass flow is higher for the vegetable oils.

As the BSEC is an indication of how much energy is consumed to produce one kWh, this indicates that when running on diesel, more energy is used to produce the same amount of electricity. This is due to that the LHV of diesel is much higher than for the vegetable oil, so even though the fuel consumption is lower there will still be more calorific energy consumed when running on diesel.

The BMEP is roughly the same for all fuels at a given load, which is expected as it isn't dependent on any fuel specific parameters but on the power and engine dimensions. It only differs a little as the average power measured is not exactly the same for all fuels. The BMEP is very low for this engine, as it ranges between approximately 130-320 kPa, where diesel engines usually should have values between 700-900 kPa. This indicates that the test engine does not have good performance compared to other engines.

6.3 Key considerations

The field studies have proved that implementing solar power presents some challenges but is definitely doable. The experiments have shown that running a diesel engine on PPO or PCO can be done. Therefore building a HRES combining these energy sources would be a viable solution for remote locations, providing locally available, sustainable energy. However, for this type of system to be recommendable, there are several important considerations to make.

There would be many costs associated with changing to this type of system. While it is common to use diesel engines for stand alone applications, meaning a diesel engine is most likely already in place, adjusting the engine to run on vegetable oil will require the adding of an additional fuel line and tank, and ideally equipment to make it possible to use the exhaust gases to heat the vegetable oil. However, the investmest costs related to implementing this type of HRES will most likely be dominated by the solar power installation. Another large investment would be equipment for oil extraction if this is not already in place.

The size of the investment makes it unlikely that the local population would be able to fund these systems on their own, making it necessary for the government or help organizations to aid in funding, as has been the case for Karimunjawa. Some of the studied research did show that this type of funding could be disadvantageous as receiving it for free may lead to the local inhabitants not feeling ownership and responsibility for the system. However, the research also showed that the alternative of using fee-for-service systems has not always been efficient either. Hence, it seems government funding is the best alternative at this point, although other options may be more desirable in the future if problems should arise or the direct funding become to expensive. It is also important to monitor the systems in the future to see how the systems degrade and what lifetime can be expected at this type of location.

Aside from investment issues, implementing a HRES also involves increasing the complexity of the energy system compared to only using a diesel engine. During the field studies it was observed that the components that had the most problems/failures were usually electric. This could indicate that although dual fuelling means more complexity, it is still technology that most technicians are likely familiar with, and any problems would be mechanical which could be easier to understand compared to the solar power system components. At locations where it is considered too risky to modify the engine, another option could be to use blends of vegetable oil and diesel in order to at least achieve some decrease in diesel usage.

Considering that one of the main advantages with these systems is self-sustainability, the most important considerations when choosing which fuel to use are availability and cost efficiency. It is unfortunate that diesel fuel is still necessary for starting up the engine, as this prevents total self-sustainability. However, it is advantageous to have the option to switch between vegetable oil and diesel. As performance will depend on the type of diesel engine and the oil quality of the locally available oil resource, this must also be investigated for each specific application.

When visiting the island and during conversations at the university, it was noted that the main reason for moving towards solar power and biofuels was not environmental concern or a wish to decrease greenhouse gas emissions, but fueled by economical and practical benefits of using renewable energy sources. This attitude towards sustainable energy is very interesting in contrast to the motivations in the western world.

6.4 Future studies

Many improvements can be made to the the experimental setup in order to gain more reliable results. Both the engine itself and the measuring equipment such as gas analyzer are considered slightly unreliable considering the rapid uncontrollable accelerations of the engine and the odd results for some of the emissions. The cooling system for the engine could also use an upgrade. It would be advantageous to have a better method for regulating the oil temperature and rpm of the engine. If engine temperatures allow, the engine should be run on diesel oil at the end of the vegetable oil experiments.

As there is already extensive research showing that it is possible to run an engine on coconut or palm oil, the next step would be to find a suitable location to test the fuels in the field. The best alternative would be to test on several locations over a longer time period in order to see what environments are compatible with this type of system and whether or not the increased complexity of implementing a dual fuel system will be manageable. Regarding the testing of nyamplung, the issues regarding oil quality and how to achieve commercial production must be resolved before it can be properly tested in the field.

A HRES can consist of many different sources, and apart from the studied configuration using vegetable oil, another source that could complement solar power well could be gasified biomass used to run a gas turbine. Using hydro power is more limited to only certain sites but could still be used in some parts of Indonesia.

7 Conclusions

- Using the HRES configuration of combining solar power with a vegetable oil-driven IC-engine would be functional and could provide reliable, clean energy for remote communities.
- The systems on Parang and Nyamuk island prove that adding solar power to create hybrid energy systems is possible to do in a sucessful way and a viable energy solution for future projects.
- Visit to sites confirmed that wind power in Indonesia is problematic as the turbines were all broken. Most likely they must be equipped with storm protection which will lead to higher cost relative to the generated power, which may not be economically justifiable.
- Nyamplung oil does not appears suitable for direct use in diesel engines at this time and has had issues with cultivation, therefore it is not a good option for implementation in energy systems today. More research and resources are necessary to establish whether this oil holds potential or not.
- It is possible to run diesel engines on vegetable oil, but it requires some alterations for pre-heating and addition of dual fuelling equipment. This increases the complexity of the system which may be a disadvantage in remote locations if technical knowledge is lacking. A trade off between cost reduction and increased complexity leading to risk of failure of the system must be made for each specific case.
- Palm oil gives less emissions, lower BSFC and higher BTE compared to coconut oil, suggesting it is a slightly better choice as a biofuel. The difference is however not monumental and the deciding factor will most likely be which oil is available at best quality at the specific site.
- The test and measuring equipment was not completely reliable and as such the experimental results should be regarded more as overall guidelines. Doing the tests in a more standardized and controlled test environment would have been advantageous, but they were completed the best way possible in the given situation.
- While the potential of using vegetable oil is dependent on available resources, which necessitates in-depth site investigation, solar power has good potential for all of Indonesia, although it is recommendable to have a back up for solar to increase relability and flexibility. At sites where vegetable oil is judged not to be viable, adding solar power to a diesel powered system like on the smaller Karimunjawa islands is still a good idea as it will improve the system and help the local population decrease fossil fuel dependency.

7.1 Recommendations

The following courses of action are important in order to make the future developments of renewable energy systems in Indonesia as successful as possible.

- Start documenting and collecting data as this is valuable information for evaluating implemented systems and as a basis for other similar future sytems.
- Implement regular scheduled maintenance of the systems to prolong the lifetime and to decrease the costs.

- Increase education about the energy systems including all components for the local population.
- Build systems that are all connected to the same grid, rather than several separate systems.
- If possible, expand the energy system of the main island of Karimunjawa to include a solar power plant to increase reliability by having multiple energy sources and avoid running the large diesel engines inefficiently on low load.

The most important recommendation is to start collecting data as this will show any flaws in existing systems which gives the opportunity to avoid making the same mistakes in future systems.

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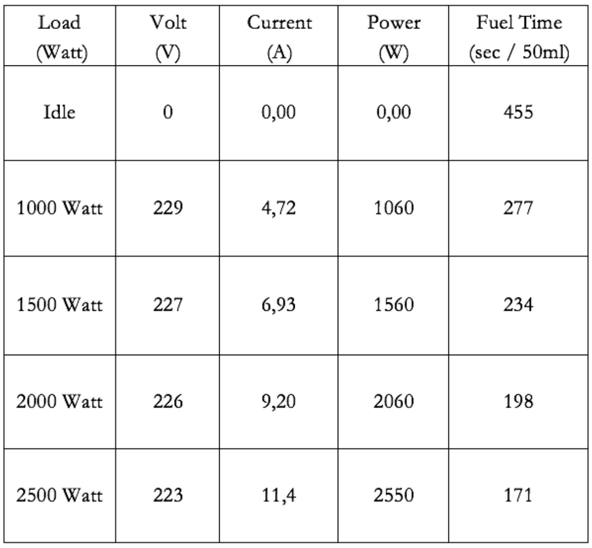
Appendix

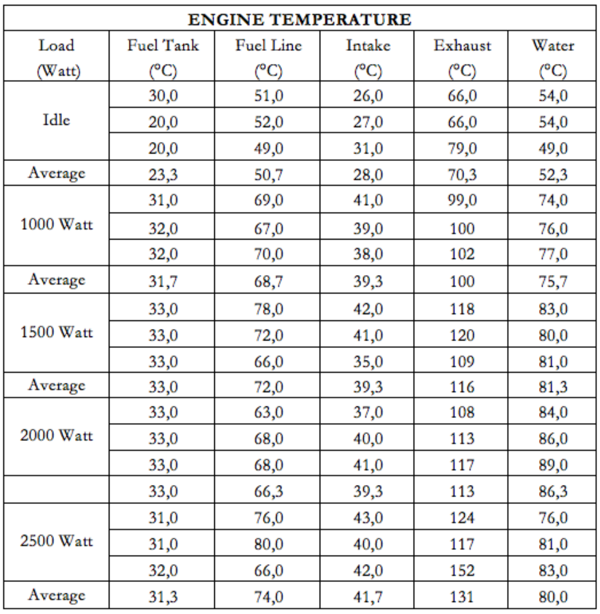
Appendix: Data from experiments

1 Diesel oil



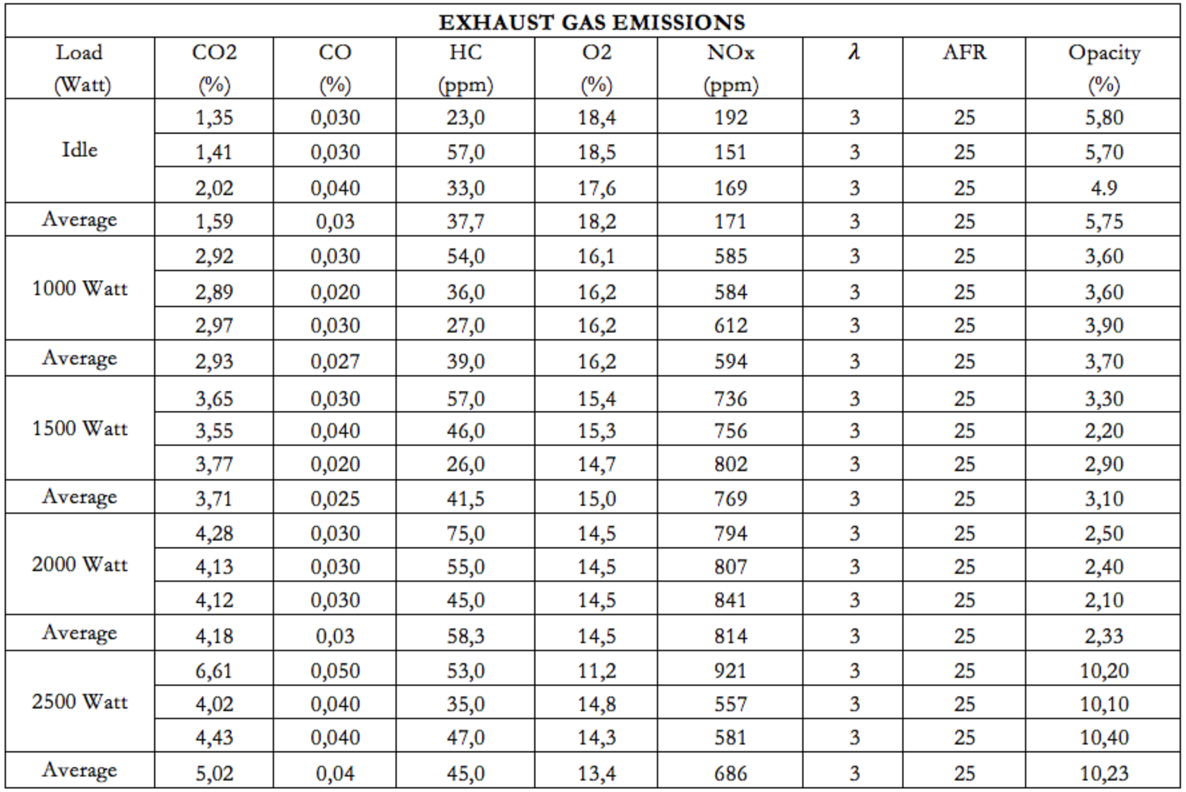
Load (Watt)	Volt (V)	Current (A)	Power (W)	Fuel Time (sec / 50ml)
Idle	0	0,00	0,00	455
1000 Watt	229	4,72	1060	277
1500 Watt	227	6,93	1560	234
2000 Watt	226	9,20	2060	198
2500 Watt	223	11,4	2550	171

Figure 39: Data used in calculations



ENGINE TEMPERATURE					
Load (Watt)	Fuel Tank (°C)	Fuel Line (°C)	Intake (°C)	Exhaust (°C)	Water (°C)
Idle	30,0	51,0	26,0	66,0	54,0
	20,0	52,0	27,0	66,0	54,0
	20,0	49,0	31,0	79,0	49,0
Average	23,3	50,7	28,0	70,3	52,3
1000 Watt	31,0	69,0	41,0	99,0	74,0
	32,0	67,0	39,0	100	76,0
	32,0	70,0	38,0	102	77,0
Average	31,7	68,7	39,3	100	75,7
1500 Watt	33,0	78,0	42,0	118	83,0
	33,0	72,0	41,0	120	80,0
	33,0	66,0	35,0	109	81,0
Average	33,0	72,0	39,3	116	81,3
2000 Watt	33,0	63,0	37,0	108	84,0
	33,0	68,0	40,0	113	86,0
	33,0	68,0	41,0	117	89,0
	33,0	66,3	39,3	113	86,3
2500 Watt	31,0	76,0	43,0	124	76,0
	31,0	80,0	40,0	117	81,0
	32,0	66,0	42,0	152	83,0
Average	31,3	74,0	41,7	131	80,0

Figure 40: Data from thermocoils



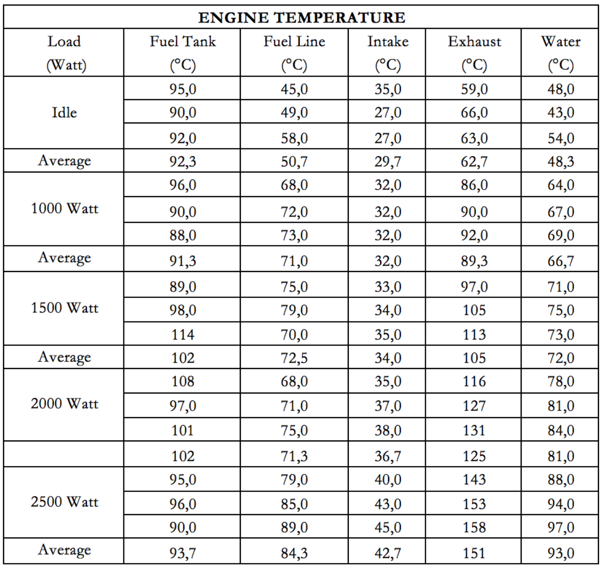
EXHAUST GAS EMISSIONS								
Load (Watt)	CO2 (%)	CO (%)	HC (ppm)	O2 (%)	NOx (ppm)	λ	AFR	Opacity (%)
Idle	1,35	0,030	23,0	18,4	192	3	25	5,80
	1,41	0,030	57,0	18,5	151	3	25	5,70
	2,02	0,040	33,0	17,6	169	3	25	4.9
Average	1,59	0,03	37,7	18,2	171	3	25	5,75
1000 Watt	2,92	0,030	54,0	16,1	585	3	25	3,60
	2,89	0,020	36,0	16,2	584	3	25	3,60
	2,97	0,030	27,0	16,2	612	3	25	3,90
Average	2,93	0,027	39,0	16,2	594	3	25	3,70
1500 Watt	3,65	0,030	57,0	15,4	736	3	25	3,30
	3,55	0,040	46,0	15,3	756	3	25	2,20
	3,77	0,020	26,0	14,7	802	3	25	2,90
Average	3,71	0,025	41,5	15,0	769	3	25	3,10
2000 Watt	4,28	0,030	75,0	14,5	794	3	25	2,50
	4,13	0,030	55,0	14,5	807	3	25	2,40
	4,12	0,030	45,0	14,5	841	3	25	2,10
Average	4,18	0,03	58,3	14,5	814	3	25	2,33
2500 Watt	6,61	0,050	53,0	11,2	921	3	25	10,20
	4,02	0,040	35,0	14,8	557	3	25	10,10
	4,43	0,040	47,0	14,3	581	3	25	10,40
Average	5,02	0,04	45,0	13,4	686	3	25	10,23

Figure 41: Data from gas analyzer

2 Palm oil

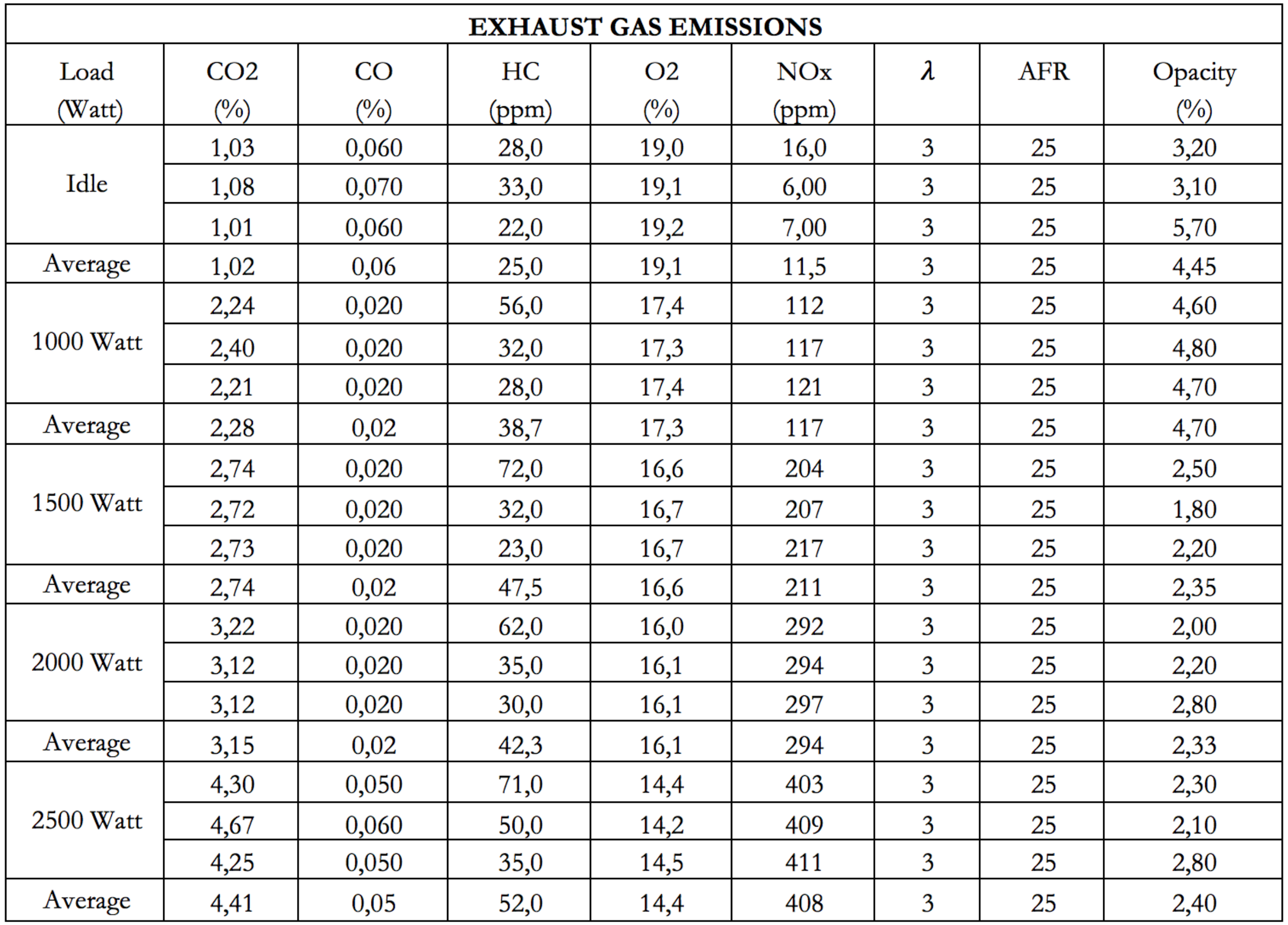
Load (Watt)	Volt (V)	Current (A)	Power (W)	Fuel Time (sec / 50ml)
Idle	0	0	0	419
1000 Watt	229	4,79	1070	302
1500 Watt	228	6,90	1560	251
2000 Watt	225	9,19	2070	210
2500 Watt	225	11,4	2570	175

Figure 42: Data used in calculations



ENGINE TEMPERATURE					
Load (Watt)	Fuel Tank (°C)	Fuel Line (°C)	Intake (°C)	Exhaust (°C)	Water (°C)
Idle	95,0	45,0	35,0	59,0	48,0
	90,0	49,0	27,0	66,0	43,0
	92,0	58,0	27,0	63,0	54,0
Average	92,3	50,7	29,7	62,7	48,3
1000 Watt	96,0	68,0	32,0	86,0	64,0
	90,0	72,0	32,0	90,0	67,0
	88,0	73,0	32,0	92,0	69,0
Average	91,3	71,0	32,0	89,3	66,7
1500 Watt	89,0	75,0	33,0	97,0	71,0
	98,0	79,0	34,0	105	75,0
	114	70,0	35,0	113	73,0
Average	102	72,5	34,0	105	72,0
2000 Watt	108	68,0	35,0	116	78,0
	97,0	71,0	37,0	127	81,0
	101	75,0	38,0	131	84,0
	102	71,3	36,7	125	81,0
2500 Watt	95,0	79,0	40,0	143	88,0
	96,0	85,0	43,0	153	94,0
	90,0	89,0	45,0	158	97,0
Average	93,7	84,3	42,7	151	93,0

Figure 43: Data from thermocoils



EXHAUST GAS EMISSIONS

Load (Watt)	CO2 (%)	CO (%)	HC (ppm)	O2 (%)	NOx (ppm)	λ	AFR	Opacity (%)
Idle	1,03	0,060	28,0	19,0	16,0	3	25	3,20
	1,08	0,070	33,0	19,1	6,00	3	25	3,10
	1,01	0,060	22,0	19,2	7,00	3	25	5,70
Average	1,02	0,06	25,0	19,1	11,5	3	25	4,45
1000 Watt	2,24	0,020	56,0	17,4	112	3	25	4,60
	2,40	0,020	32,0	17,3	117	3	25	4,80
	2,21	0,020	28,0	17,4	121	3	25	4,70
Average	2,28	0,02	38,7	17,3	117	3	25	4,70
1500 Watt	2,74	0,020	72,0	16,6	204	3	25	2,50
	2,72	0,020	32,0	16,7	207	3	25	1,80
	2,73	0,020	23,0	16,7	217	3	25	2,20
Average	2,74	0,02	47,5	16,6	211	3	25	2,35
2000 Watt	3,22	0,020	62,0	16,0	292	3	25	2,00
	3,12	0,020	35,0	16,1	294	3	25	2,20
	3,12	0,020	30,0	16,1	297	3	25	2,80
Average	3,15	0,02	42,3	16,1	294	3	25	2,33
2500 Watt	4,30	0,050	71,0	14,4	403	3	25	2,30
	4,67	0,060	50,0	14,2	409	3	25	2,10
	4,25	0,050	35,0	14,5	411	3	25	2,80
Average	4,41	0,05	52,0	14,4	408	3	25	2,40

Figure 44: Data from gas analyzer

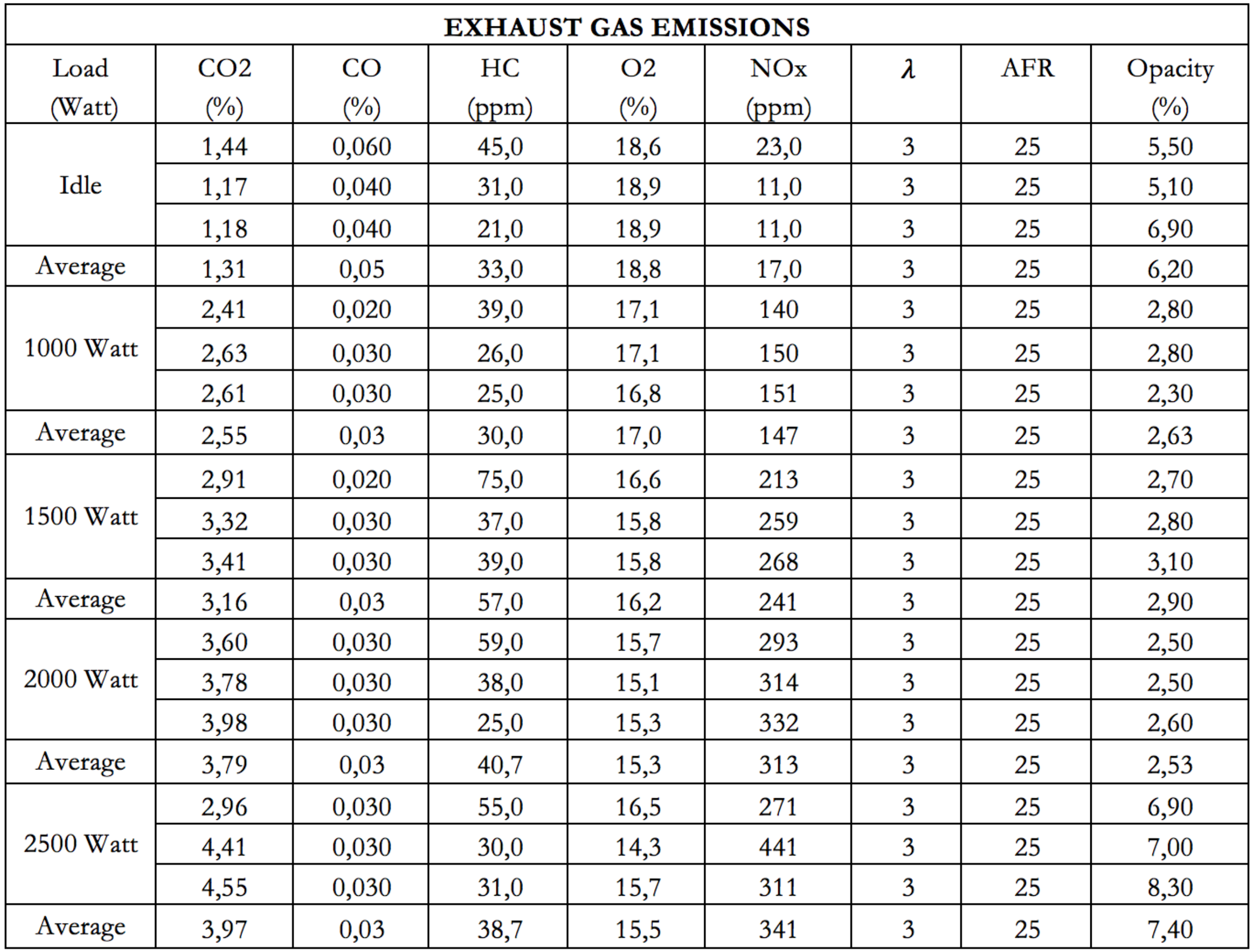
3 Coconut oil

Load (Watt)	Volt (V)	Current (A)	Power (W)	Fuel Time (sec / 50ml)
Idle	0	0,00	0	420
1000 Watt	229	4,71	1050	290
1500 Watt	228	6,91	1560	240
2000 Watt	226	9,21	2070	200
2500 Watt	224	11,4	2570	170

Figure 45: Data used in calculations

ENGINE TEMPERATURE					
Load (Watt)	Fuel Tank (°C)	Fuel Line (°C)	Intake (°C)	Exhaust (°C)	Water (°C)
Idle	90,0	47,0	26,0	53,0	45,0
	89,0	44,0	27,0	59,0	40,0
	92,0	46,0	27,0	62,0	41,0
Average	91,0	46,5	26,5	57,5	43,0
1000 Watt	90,0	57,0	29,0	66,0	53,0
	90,0	63,0	29,0	74,0	55,0
	90,0	62,0	30,0	69,0	58,0
Average	90,0	60,7	29,3	69,7	55,3
1500 Watt	90,0	63,0	32,0	72,0	59,0
	90,0	63,0	31,0	68,0	58,0
	90,0	63,0	33,0	99,0	63,0
Average	90,0	63,0	32,5	85,5	61,0
2000 Watt	90,0	71,0	33,0	102	68,0
	89,0	75,0	35,0	106	71,0
	90,0	77,0	37,0	108	73,0
	89,7	74,3	35,0	105	70,7
2500 Watt	90,0	80,0	37,0	116	75,0
	91,0	82,0	38,0	122	78,0
	89,0	85,0	27,0	130	79,0
Average	90,0	82,3	34,0	123	77,3

Figure 46: Data from thermocoils



EXHAUST GAS EMISSIONS

Load (Watt)	CO2 (%)	CO (%)	HC (ppm)	O2 (%)	NOx (ppm)	λ	AFR	Opacity (%)
Idle	1,44	0,060	45,0	18,6	23,0	3	25	5,50
	1,17	0,040	31,0	18,9	11,0	3	25	5,10
	1,18	0,040	21,0	18,9	11,0	3	25	6,90
Average	1,31	0,05	33,0	18,8	17,0	3	25	6,20
1000 Watt	2,41	0,020	39,0	17,1	140	3	25	2,80
	2,63	0,030	26,0	17,1	150	3	25	2,80
	2,61	0,030	25,0	16,8	151	3	25	2,30
Average	2,55	0,03	30,0	17,0	147	3	25	2,63
1500 Watt	2,91	0,020	75,0	16,6	213	3	25	2,70
	3,32	0,030	37,0	15,8	259	3	25	2,80
	3,41	0,030	39,0	15,8	268	3	25	3,10
Average	3,16	0,03	57,0	16,2	241	3	25	2,90
2000 Watt	3,60	0,030	59,0	15,7	293	3	25	2,50
	3,78	0,030	38,0	15,1	314	3	25	2,50
	3,98	0,030	25,0	15,3	332	3	25	2,60
Average	3,79	0,03	40,7	15,3	313	3	25	2,53
2500 Watt	2,96	0,030	55,0	16,5	271	3	25	6,90
	4,41	0,030	30,0	14,3	441	3	25	7,00
	4,55	0,030	31,0	15,7	311	3	25	8,30
Average	3,97	0,03	38,7	15,5	341	3	25	7,40

Figure 47: Data from gas analyzer

Appendix: Calculations

$$\dot{m}_f = \frac{50}{t}\rho * 3,6 \tag{14}$$

$$BSFC = \frac{\dot{m}_f}{P} = \frac{\frac{50}{t}\rho * 3,6}{P} * 1000 \tag{15}$$

$$BSEC = \frac{BSFC * LHV}{1000} \tag{16}$$

$$BTE = \frac{P * 10^5}{\frac{50}{t}\rho * LHV} \tag{17}$$

$$BMEP = \frac{P * 60 * n_R}{V_d * n_c * N} \tag{18}$$

Where:
t - time in seconds for 50ml of fuel to be consumed (s/50ml)
ρ - density (kg/m^3)
$\dot{m}_f$ - mass flow (g/h)
BSFC - Brake specific fuel consumption (g/kWh)
LHV - Lower heating value (kJ/kg)
P - Power (W)
BSEC - Brake specific energy consumption (kJ/kWh)
BTE - Brake thermal efficiency (%)
V_d - displacement volume (l)
n_c - number of cylinders
N - rotational speed (rpm)
n_R- number of crank revolutions
BMEP - Brake mean effective pressure (kPa)

Appendix: Solar module properties

Table 8: PV panel properties - PERLIGHT

Solar Module Type	PLM-050M/12
Out peak power (Pm)	50W
Open Circuit Voltage (Voc)	22.6V
Short Circuit Current (Isc)	3.08A
No. of Cells	36
Power Tolerane	0/+3%
Max. Power Voltage(Vmp)	17.4V
Max. Power Current (Imp)	2.87A
Size of Module (Length*Width*Thickness)	571*676*35mm