TECHNICAL UNIVERSITY OF CRETE

School of
Electrical and Computer Engineering

THESIS

Dimensioning Electrical Power Supply System for Motorhome with Photovoltaics and Alternator

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ΠΟΛΥΤΕΧΝΕΙΟ ΚΡΗΤΗΣ

ΣΧΟΛΗ ΗΛΕΚΤΡΟΛΟΓΩΝ ΜΗΧΑΝΙΚΩΝ ΚΑΙ ΜΗΧΑΝΙΚΩΝ ΥΠΟΛΟΓΙΣΤΩΝ

ΔΙΠΛΩΜΑΤΙΚΗ ΕΡΓΑΣΙΑ

Διαστασιολόγηση Συστήματος Τροφοδοσίας με Ηλεκτρική Ενέργεια για Τροχόσπιτο με Φωτοβολταϊκά και Εναλλακτήρα

ΕΞΕΤΑΣΤΙΚΗ ΕΠΙΤΡΟΠΗ
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Eucharist

I am deeply grateful for the unwavering support and guidance provided by my family, whose nurturing environment has been instrumental in my personal and academic development. My sincere appreciation extends to my dedicated colleagues and friends, with whom I have navigated through rigorous academic endeavors and exchanged invaluable insights and perspectives. I would also like to express my profound gratitude to the scholarly mentors who have generously imparted their wisdom and understanding, offering empathetic support during challenging times. Lastly, I extend my thanks to all individuals whose contributions have enriched the content of this thesis, shaping it into its final form.

Abstract

The thesis focuses on the development and evaluation of a hybrid power system for a motorhome. It encompasses the integration of an additional alternator attached to the vehicle's engine and a photovoltaic system installed on the roof. The primary objective is to assess the system's capability to provide electrical power independently, regardless of weather conditions, during weekly travel. Additionally, the system accommodates an extra load and separate battery, which activation is dedicated once a week for special occasions. The study delves into a comprehensive literature review, conducts the sizing of each component to align with consumer needs, and outlines the simulations of various trip scenarios in diverse geographical locations to analyze the photovoltaic system's energy performance. Ultimately, the research evaluates the system's reliability by simulating different parameters and drawing conclusions.

Περίληψη

Η διατριβή επικεντρώνεται στην ανάπτυξη και αξιολόγηση ενός υβριδικού συστήματος ισχύος για ένα αυτοκινούμενο. Περιλαμβάνει την ενσωμάτωση ενός πρόσθετου εναλλάκτηρα συνδεδεμένου στον κινητήρα του οχήματος και ενός φωτοβολταϊκού συστήματος εγκατεστημένο στην οροφή. Ο πρωταρχικός στόχος είναι να αξιολογηθεί η ενεργειακή αυτονομία του συστήματος, ανεξάρτητα από τις καιρικές συνθήκες, κατά τη διάρκεια εβδομαδιαίων ταξιδιών. Επιπλέον, το σύστημα διαθέτη ένα επιπλέον φορτίο με ξεχωριστή μπαταρία, η ενεργοποίηση της οποίας αφιερώνεται μία φορά την εβδομάδα για ειδικό σκοπό. Η μελέτη εμβαθύνει σε μια ολοκληρωμένη βιβλιογραφική ανασκόπηση, διαστασιολογείται το κάθε στοιχείο ώστε να ικανοποιεί τις ανάγκες των καταναλωτών και περιγράφει τις προσομοιώσεις διαφόρων σεναρίων ταξιδιού σε διάφορες γεωγραφικές τοποθεσίες για την ανάλυση της ενεργειακής απόδοσης του φωτοβολταϊκού συστήματος. Τελικά, η έρευνα αξιολογεί την αξιοπιστία του συστήματος μέσω της προσομοίωσης διαφορετικών παραμέτρων και εξάγονται συμπεράσματα.

TABLE OF TEXT CONTENT

CHAPTER 0 — Introduction

CHAPTER 1 — Literature Review

CHAPTER 2 — Dimensioning

TABLE OF VISUAL CONTENT

TABLES

FIGURES

EQUATIONS

CHAPTER 0 | Introduction

This thesis is based on the efficacy of mobile renewable energy. Although the automobile industry predeveloped the engine and all of the systems that make up a car in the 21st century long ago, renewable energy is a newer industrialized branch exploring different applications.[21] There is an ever-growing need for renewable energy in every aspect of life.

- **Socioeconomic**

People want to find a simple and cheap solution, so it is easy to save money and detach from the grid.[20]

- **Political**

Governments sponsor these sectors to boost their political campaigns in the name of combating global warming.[19]

- **Geothermal**

This problem is valid if global warming is an actual concern which is the outage of fossil fuel[22]. This affects mostly "green" wise the currently combustion engine motor-based devices and the replacement of new ones[23].

0.1 Motivation

The need for expression on the street level is a rarity rather than a privilege. COVID-19 was an attack on humanity that distorted human reality forever. It made people go deeper into their egocentric reality, and very much through the cell phone. For instance, during the latest pandemic, many Greeks had to send an SMS request to the government through their phone.[24] This caused a reactive wave of people searching for alternative ways to break through the conditioned appeal. This, combined with more intelligent systems dictating and replacing our daily cognitive knowledge with technological advancements such as AI, is a practical solution. The counter battle to all this is street-level self-expression.

0.2 Scope

This thesis harnesses the photovoltaic energy from photovoltaic arrays and the movement from the automotive engine. Depending on these two parameters, mathematically modeled scenarios are created, drawing the corresponding solutions as to whether an autonomous power system is feasible. This way, a person could build a mobile power system based on the investor's needs.

0.3 Outline

The outline of each chapter is described below.

• Chapter 1 — Literature Review

In this chapter, all components consisting of a hybrid power system are analyzed.

• Chapter 2 — Dimensioning

Each component is sized based on the user's needs.

• Chapter 3 — Modeling

Each component is mathematically modeled so a simulation program can run it.

• Chapter 4 — Simulation: Evaluation, Scenarios & Results

In this chapter, different parameters are considered when designing the scenarios run by the simulation program, and the engine is evaluated based on the modeling.

• Chapter 5 — Conclusions, Future Work & Discussions

The conclusions are drawn, and future work and discussions are reviewed.

1.1 Photovoltaic Cells

Photovoltaics, also known as solar arrays or solar panels, consist of solar cells. Solar cells are semiconductors that can absorb light and deliver a portion of energy to the carrier of electrical current. An ideal solar cell can be represented by a current source connected in parallel with a rectifying diode. A solar cell in the dark is simply a diode.

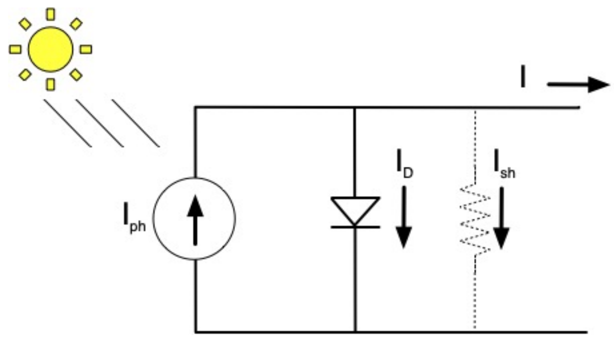


Figure 1–1. Equivalent circuit of an ideal solar cell (complete lines).
Non-ideal components as shown here, such as the shunt current Ish (dotted lines)

1.1.1 Characteristic Curves

■ I-V Solar Cell Curve

The current (I) – volt (V) curve is a graph that depicts the correlation and possible combinations of a typical solar cell based on equation (1.1). The power production of the cell is equal to the area size of the rectangle that fits under the line of the Shockley equation. The maximum point of the amperage (I_{mp}) and voltage (V_{mp}) is the maximum area, thus maximum power production (P_{mp}).

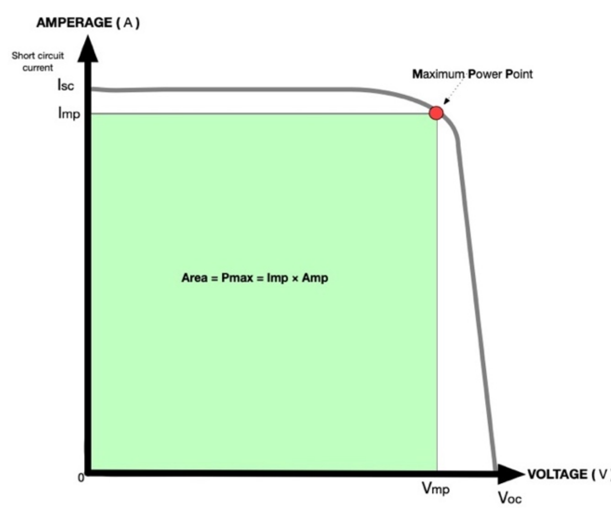


Figure 1–2. I-V curve of a typical silicon solar cell

Shockley solar cell equation:

$$I = I_{ph} - I_D\left(e^{\frac{qV}{k_b T}} - 1\right) \tag{1.1}$$

Where:

I_{ph} photogenerated current
I_D Diode current
k_b Boltzmann's constant: 1.38×10^{-23}
T cell temperature in Kelvin
q charge of an electron: 1.602×10^{-9} C
V Maximum power point voltage

■ Power Voltage Curve

The power (P) – voltage (V) curve of a solar cell or P-V curve is based on the I-V above graph, coming from the relation of P = V × I derived from Ohms law. Instead of the amperage on the y-axis, there is the power output.

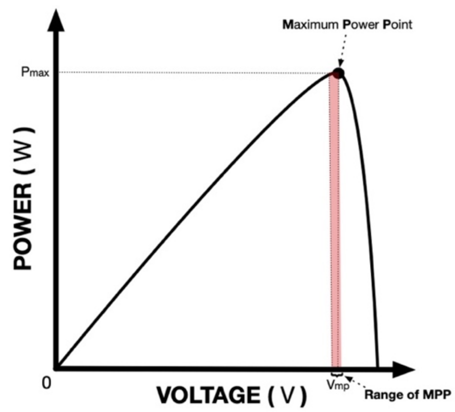


Figure 1–3. Characteristic curve expressed as Power and Voltage.

1.1.2 Specifications

Most manufacturers provide a series of data that characterize an array's electrical and physical attributes. Below is the common data provided by photovoltaic panel manufacturers' datasheets.

■ Electrical Specifications

— **V_{oc}: Open Circuit Voltage**
Maximum voltage, which is measured when there is a break in the circuit.

— **I_{sc}: Short Circuit Amperage**
The maximum current when the output terminals are shorted.

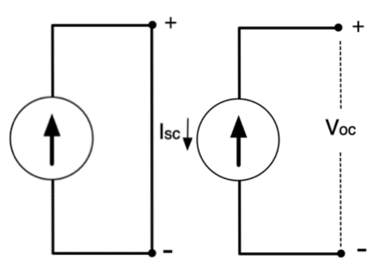


Figure 1–4. Short circuit (left), Open circuit (right)

— **Fill Factor** (FF)
The fill factor is the product of current and voltage at maximum power point (Vmp, Imp) to the product of open circuit voltage and short circuit current.

$$Fill\ Factor = \frac{P_m}{I_{sc} \times V_{oc}} \tag{1.2}$$

This value gives an estimate about the quality of the array. The closer to 1, the more power can be produced. Typical values are 0.7 to 0.8. The FF affects the squareness of the I-V Curve. The lower the FF, the less square the I-V gets.

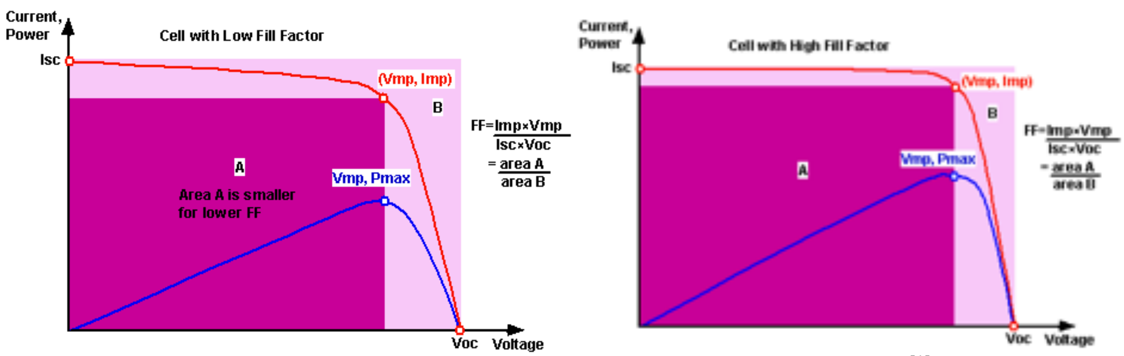


Figure 1–5. Effect of the Fill Factor on the curvature of the IV graph[1]

— **Efficiency** (%)
The ratio between the maximum electrical power output the array can produce, and the amount of solar radiation exposed on the panel is called efficiency.

$$efficiency = \frac{P_{out}}{P_{in}} \tag{1.3}$$

— **Temperature Coefficient**
The temperature coefficient describes the relative change of a physical property associated with a given change in temperature. For a property R that changes when the temperature changes by dT. Practically, the equation describes how much power will decrease every one degree Celsius above twenty-five degrees Celsius. The temperature coefficient mathematically α is defined by the following equation below:

$$\frac{dR}{R} = a\ dT \tag{1.4}$$

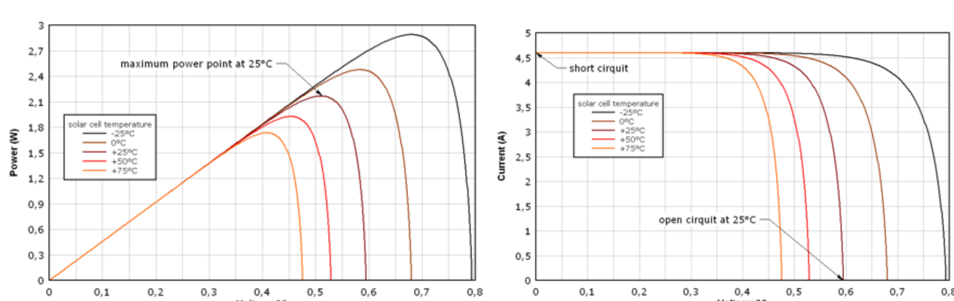


Figure 1–6. Temperature Effect on characteristic curves P-V (left) I-V (right)

■ Physical Characteristics

The solar panel industry has standardized most solar panels' dimensions based on the solar cells' chemical attributes and the consumers' daily energy consumption.

Table 1–1 | Common Physical Characteristics		
	Residential	**Commercial**
Length (m)	1.65	1.98
Width (m)	1	1
Weight (kg)	15-25	30-45
Number of Solar cells	60	72-98

1.1.3 Types

Throughout the history of solar cells, there have been many ways to create these devices, with different materials and creation methods. The abovementioned aspects create different photovoltaic solutions based on the intended usage.

— **Monocrystalline**
Monocrystalline solar arrays are the most common. The solar cells contain a pure square-edge cut silicon wafer made of a single crystal of silicon using the Czochralski method. The efficiency of these solar cells can exceed 20%.

— **Polycrystalline**
Polycrystalline solar arrays were developed after monocrystalline technology and are cheaper and less efficient. They usually have a bluish color. Unlike monocrystalline, polycrystalline is composed of fragments of silicon crystals that are melted together in a mold before being cut into wafers. The efficiency of these panels is approximately 18% lower than that of monocrystalline panels.

— **Thin Film**
Thin film solar arrays, also called second-generation solar cells, are made of various materials, such as Amorphous silicon (a-Si), which is used in packet size calculator copper, indium gallium selenide (CIGS), cadmium telluride (CdTe), and the most prevalent calcium arsenide (CaAs). In this thin and flexible panel, the semiconductive material is placed between transparent conducting layers, which contribute to capturing sunlight. The efficiency of this technology reaches 11-15%.

Monocrystalline Polycrystalline Thin Film

Figure 1–7. Common types of solar panels

TABLE 1–2 | Solar Panel Type Attributes				
TYPE	**MATERIAL**	**EFFICIENCY**	**COST**	**APPEARANCE**
Monocrystalline	Pure silicon crystal	18−20% >	highest	Black or dark blue with rounded corners
Polycrystalline	Silicon fragments	15−17%	high	Blue rectangular
Thin film	various	11−15%	lowest	Black/blue uniform surface

1.2 Alternators

Alternators are mechanical devices that convert mechanical energy into electrical energy inputted through an external circular motion. In vehicles, they are placed near the engine, connected with a drive belt and the engine's crank pulley, as displayed in the photo below.

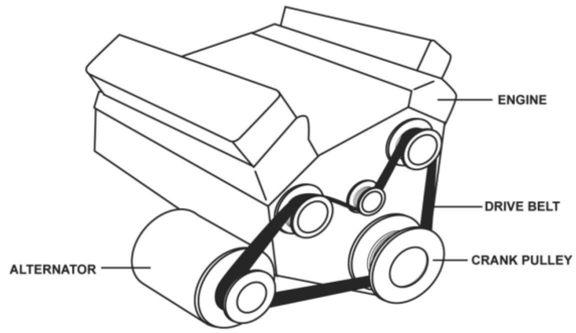


Figure 2–1. Standard topology of engine and alternator

■ Pulley ratio

When the engine is turned on, the crank pulley rotates, and so does the alternator at a relative speed. The pulley ratio is the comparative diameter size of the two pulleys, which also proportionally affects the speeds. Most vehicles have a 2:1 ratio, with the greater number referring to the engine's pulley. For instance, if the crank pulley speed is 1000 rounds per minute (RPM) and the alternator's RPM is 2000 RPM, that is a 2:1 pulley ratio, and 3000 RPM is a 3:1 pulley ratio. The pulley ratio is a division of the crank pulley by the alternator pulley.

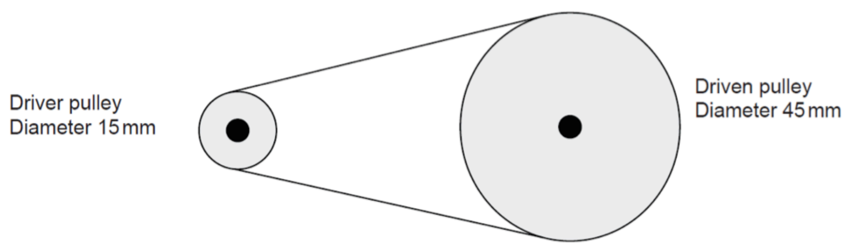


Figure 2–2. Pulley ratio of 3:1

■ Mechanical Energy to Electrical Energy

The main parts of an alternator that create electricity are the rotor and the stator. The rotor produces a magnetic field spinning inside the stator. Due to the effect of electromagnetic conduction, the flow of electrons is induced into the stator's coils, producing alternating current.

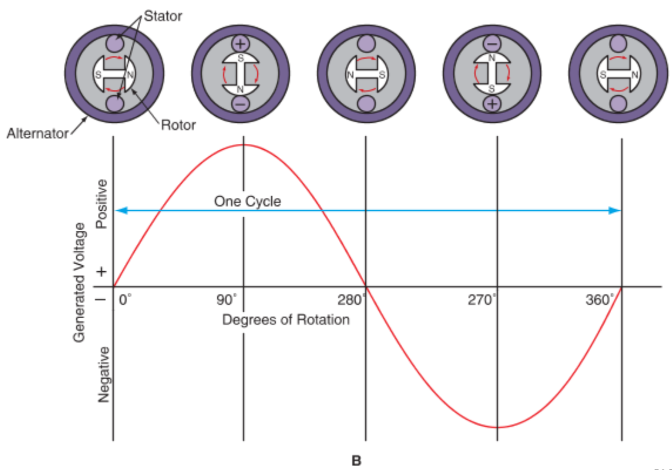


Figure 2–3. Simplified graph of a single-phase alternator[2]

The voltage and current vary depending on the engine's speed, thus the alternator. The alternating current (AC) is converted to direct current (DC) through a rectifier, and afterward, the voltage is controlled through a regulator, resulting in a DC source with a relatively steady voltage. After the two steps of processing the alternators' output, the electrical energy is distributed to the vehicle's operative electrical loads (lights, dashboard, wipers, et cetera), and the excess energy for automotive use is stored in the battery.

1.2.1 Output Curve

The alternator's output, specified through its characteristic curve, is directly influenced by the speed of the rotor, measured in RPM. The faster the rotor turns, the higher the amperage, producing more energy. The temperature affects the alternator's output energy in an inverse proportion. In some datasheets, more than one curve represents the temperature effect.

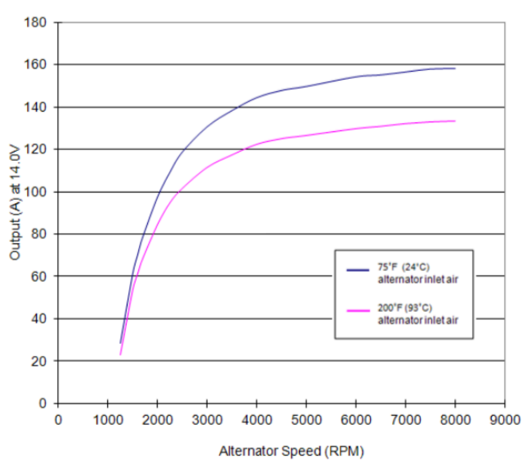


Figure 2–4. Output curve of a RAM alternator brand displaying the temperature effect

1.2.2 Consisting Parts

Alternators for automotive use commonly consist of a pulley, bearing, rotor, stator, rectifier, and voltage regulator. All aforementioned parts are housed in an aluminum frame, which is nonmagnetic and also provides heat dissipation.

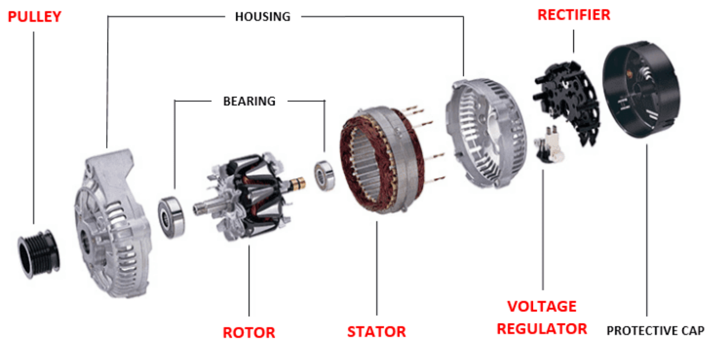


Figure 2–5. Alternator main parts

▪ **Pulley**
A pulley is a wheel that contacts a drive belt. The pulley could have grooved rims, also called sheaves, or grooves placed around the cylinder parallel to the spinning axis that help prevent the drive belt from slipping off. The number and type of grooves must match all pulleys to ensure optimal mechanical movement with the proper drive belt.

▪ **Bearing**
The bearing consists of cylindrical metal rings that encase spherical or cylindrical metals. They are two bearings holding the rotor in place, allowing it to rotate smoothly. Alternator failure is susceptible to alternator bearings failure due to long exposure to high temperature and/or dirt accumulation, which may result in grinding noise.

▪ **Rotor**
The rotor is the part that spins based on the pulley movement. There are two types of rotors for alternators˙ salient pole and cylindrical pole.

— **Salient pole**
A salient pole rotor is a large magnet with poles made of steel lamination projecting out of the rotor's core. Direct current is supplied to the poles, or the poles consist of permanent magnets that result in a spinning magnetic field. This type of rotor has a large diameter and a short axial length. The air gap between the rotor and the stator is non-uniform.

Figure 2–6. Salient pole rotor

– **Cylindrical pole (non-salient)**

The cylindrical-shaped rotor is made of solid steel with slots running along the outside length of the cylinder, holding the field windings of the rotor, which are laminated copper bars inserted into the slots and secured by wedges. The slots are insulated from the windings and held at the rotor's end by slip rings. An external direct current source is connected to the concentrically mounted slip rings with brushes running along the rings. The brushes make electrical contact with the rotating slip rings. DC is also supplied through brushless excitation from a rectifier mounted on the machine shaft that converts alternating to direct current.

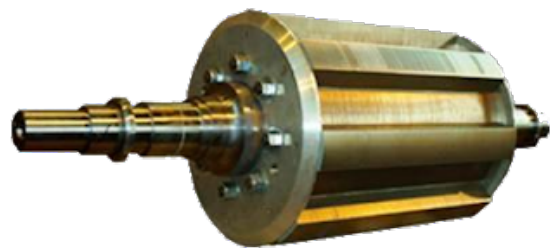


Figure 2–7. Cylindrical pole rotor

▪ **Stator**

The stator is an immobile part that consists of several windings and converts the rotating magnetic field to an electric current. The windings are wound around the stator core with high-status alloy steel so that eddy current losses will be reduced. The windings are usually connected as a star connection, but many alternators are also linked in a triangle.

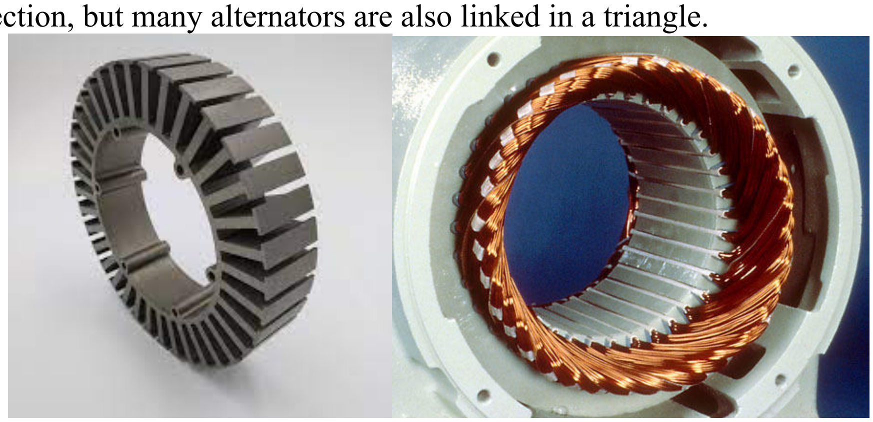


Figure 2–8. Stator Core (left) and Stator windings (right)

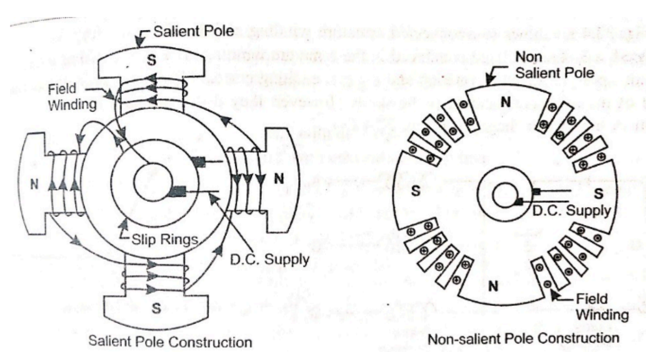


Figure 2–9. Salient (Left) and non-salient (Right) pole construction

▪ **Rectifier**
The bridge rectifier converts the AC produced by the alternator to DC to supply the battery and vehicle load. It usually consists of 6 diodes in a circuit rectifier topology.

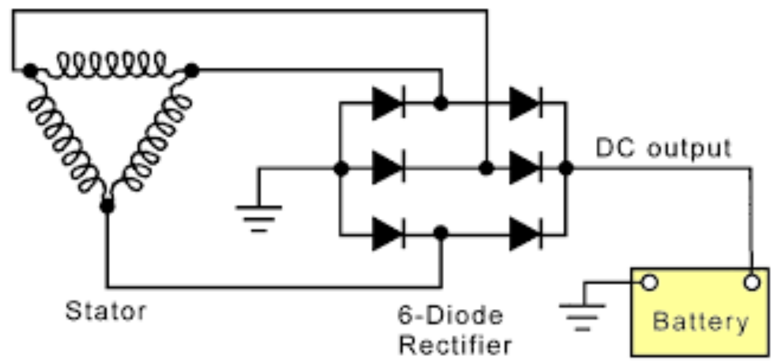


Figure 2–10. Rectifier circuit. Stator could be a triangle or star connection

.

▪ **Voltage Regulator**
The voltage regulator outputs the converted DC and keeps a relatively steady output voltage for the battery and other devices. It monitors the battery and stator voltages, and depending on the measured voltages, the regulator adjusts the field current.When the charging system voltage rises above a pre-determined voltage level the regulator decreases the field current, and vice versa.

1.3 Batteries

A battery is a device that contains chemicals. When short-circuited, it allows electrons to flow through chemical reactions that convert the stored chemical energy to electrical energy.

■ Category

There are two major categories of batteries based on their use[25]:

— **Primary**
  Used once and then discarded intended for single use due to the irreversible change affecting the electrode.

— **Secondary**
  Batteries that can be recharged and have their chemistry reverted to the original state with relatively small wear are also commonly known as rechargeable batteries and are made for multiple uses.

■ Layout

Inside a battery, smaller divisions are not visible from the outer packaging.

— **Cell**
  The core mechanism and the smallest division is the battery cell.

— **Module**
  Cells connected in series or parallel form a battery module.

— **Pack**
  Many battery modules make up a battery pack.

■ Structure

A step lower to the analysis is the basic internal structure of a battery. There are two terminals, positive and negative, the anode and cathode, respectively, connected through a liquid or solid electrolyte chemical compound.

— **Positive** (+) **Terminal** (cathode)
— **Negative** (–) **Terminal** (anode)
— **Electrolyte,**
  is made out of liquid or solid material and connects the two terminals.

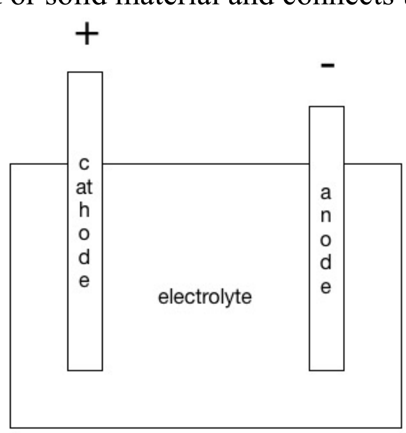


Figure 3–1. Basic structure of a battery

1.3.1 Types

Depending on the chemicals used inside a battery cell, there are 5 types of batteries used in PV systems to date:

- **Lead-acid**
- **Nickel-cadmium** (Ni-Cd)
- **Nickel-iron** (NiFe)
- **Nickel-metal hydride** (NiHM)
- **Lithium-ion**

The most commonly used for automotive use are lead-acid and, in some cases, nickel-cadmium. Lithium-ion batteries are a more reliable option in many aspects with the development of electric cars.

■ Lead-Acid

Lead-acid batteries are the earliest rechargeable type of battery discovered by French physicist Gaston Planté in 1859. A lead-acid battery can be made out of a bucket filled with an electrolyte, sulfuric acid (H_2SO_4), and two plates, one negative with finely divided lead (Pb) and positive with lead dioxide (PbO_2).

Overall:

$$\underset{charged}{PbO_2 + Pb + 2H_2SO_4} \Leftrightarrow \underset{discharged}{2PbSO_4 + 2H_2O}$$

At the positive plate:

$$\underset{charged}{PbO_2 + 3H^+ + HSO_4^+ + 2e^-} \Leftrightarrow \underset{discharged}{PBSO_4 + 2H_2O}$$

At the negative plate:

$$\underset{charged}{Pb + HSO_4^-} \Leftrightarrow \underset{discharged}{PbSO_4 + H^+ + 2e^-}$$

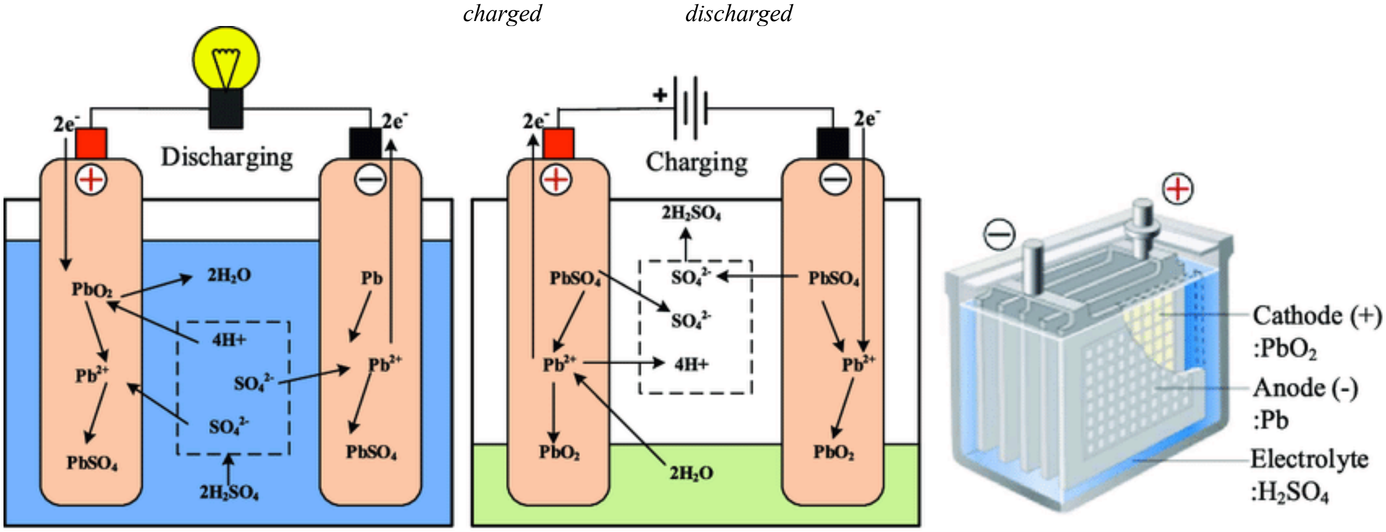


Figure 3–2. Lead acid battery chemical reactions[3]

Two main categories define lead-acid batteries depending on the overcharge results and construction and are open or vented. The last is split into valve-regulated or sealed.

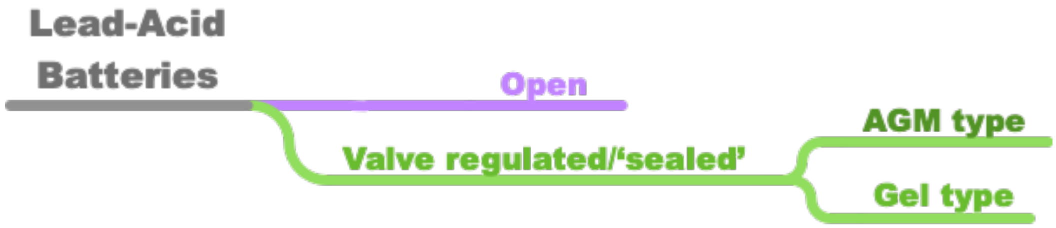


Figure 3–3. Lead acid batteries types

– **Vented Acid Batteries** (Open)

These batteries are also known as flooded or 'wet cell' batteries. When this type of battery is overcharged, it releases hydrogen (H) and oxygen (O_2), so the electrolyte liquid in the cell periodically reduces. For this reason, the user has to check them periodically and fill the batteries with distilled water to compensate for the loss. That is why storing these batteries in a separate room is preferable.

– **Valve-regulated Acid Batteries** (Sealed)

This type of battery is constructed sealed, and when overcharged, oxygen gas is produced at the positive plate within the partially filled space with lead acid, reaching the negative plate where it can be converted back to water. This conversion can only happen at a certain rate. In the case of a fault condition, which means when internal gas of oxygen can build up faster than it could be recombined (i.e., high charging current), there is a possibility for a release of the surplus oxygen and some acid spray into the atmosphere, which is irreversible.
Now, there are two types of valve-regulated batteries depending on the content and construction of the battery.

- **Absorbent Glass Mat** (AGM)

  This type of battery uses an absorbent glass mat between tightly packed flat plates. The acid is absorbed in the glass mat separator except for the pores, leaving a pathway for the converted oxygen in the positive plate to make its way to the negative plate. AGM batteries can produce a good, high-current performance. They are susceptible to water losses because they contain very little acid.

- **Gel Type**

  "The electrolytes in these types of batteries are mixed with finely-divided silica which forms a thick plate or gel. The freshly mixed gel is poured into the cell container before it sets. As the gel dries, microscopic cracks form which allow the passage of gas between the positive and negative plates required for the recombination process. This formation of cracks may occur during the early part of a gel battery through the safety valve. The gel provides a better means of heat conduction from the plates to the cell walls than in AGM batteries, so heat produced on overcharge is lost more efficiently. The sustained high current capability is not as good for gel batteries as for AGM batteries. At high operating temperatures, they will suffer to some extent from water loss, but since there is more acid that in an equivalent AGM battery, the lifetime reduction will not be so severe."[4]

■ **Nickel-Cadmium** (Ni-Cd)

Nickel-Cadmium (Ni-Cd) could also be used in photovoltaic systems when the batteries are extremely high above 40°C or very low below freezing point temperatures. The infrastructure is the same as the aforementioned battery type with different chemistry. In particular, Ni-Cd batteries in the charged state have positive plates with nickel oxy-hydroxide (NiOOH) as active material, negative plates with finely divided cadmium metal as active material, and an electrolyte of potassium hydroxide (KOH) in water at 20–35% by weight. On discharge, the NiOOH of the positive plate is converted to Ni(OH), and the cadmium metal of the negative plate is converted to $Cd(OH)_2$.

At the positive plate:

$$\underset{charged}{NiOOH + H_2O + e^-} \Leftrightarrow \underset{discharged}{Ni(OH)_2 + OH^-}$$

At the negative plate:

$$\underset{charged}{Cd + 2OH^-} \Leftrightarrow \underset{discharged}{Cd(OH)_2 + 2e^-}$$

Overall:

$$\underset{charged}{2NiOOH + Cd + 2H_2O} \Leftrightarrow \underset{discharged}{2NI(OH)_2 + Cd(OH)_2}$$

It is worth mentioning that in the nickel-cadmium battery, there is no potassium hydroxide electrolyte involved in any of the reactions (charged/discharged). Therefore, the chemical consistency of the electrolyte remains constant, and the discharge reaction needs to have an adequate supply of ions from the electrolyte to ensure that total capacity is reached. These two reasons are in contrast to the behavior of lead-acid batteries. Although the Ni-Cd batteries can be discharged at 0% without no damage, a DOD of 90% is recommended. The reason for this minimum is that some cells will inevitably have less capacity than others, and if the battery discharge exceeds their capacity limit, the low-capacity cells can be driven into reverse polarity, which can shorten their life. Industrial nickel-cadmium batteries used in renewable power systems are generally of an open type and designed for stand-by use.

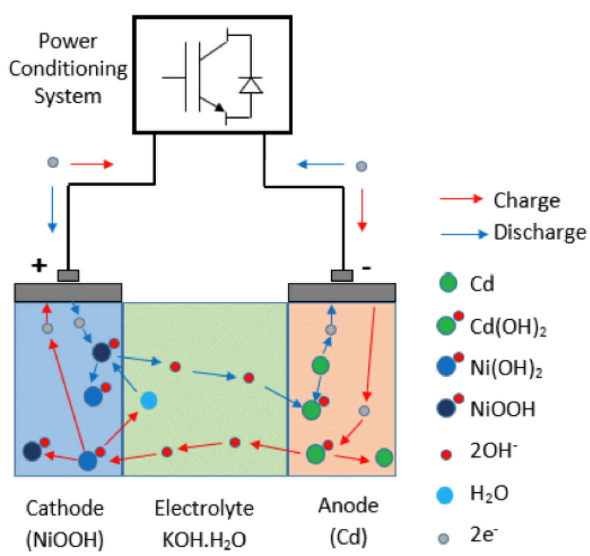


Figure 3–4. Ni-Cd battery at charge and discharge[5]

■ Nickel Metal Hydride (NiHM)

Nickel metal hydride (NiMH) batteries, like Ni-Cd batteries, use nickel oxide hydroxide (NiOOH) for the negative pole. The positive terminal is made of a hydrogen-absorbing alloy.

Negative electrode:

$$\underset{\text{charged}}{H_2O + M + e^-} \Leftrightarrow \underset{\text{discharged}}{OH^- + MH}$$

Positive electrode:

$$\underset{\text{charged}}{Ni(OH)_2 + OH^-} \Leftrightarrow \underset{\text{discharged}}{NiO(OH) + H_2O + e^-}$$

Figure 3–5. Commercial NiMH battery

■ Nickel-Iron (NiFe)

A nickel-iron (NiFe) battery, invented by Thomas Edison in 1901, has an iron (Fe) negative terminal and nickel oxide-hydroxide NiO(OH) positive terminal with potassium hydroxide (KOH) for the electrolyte. These types of batteries are tolerant to overcharging, discharging, and short-circuiting. Being robust, they could last for years when continually charged and are preferred as a backup energy source.

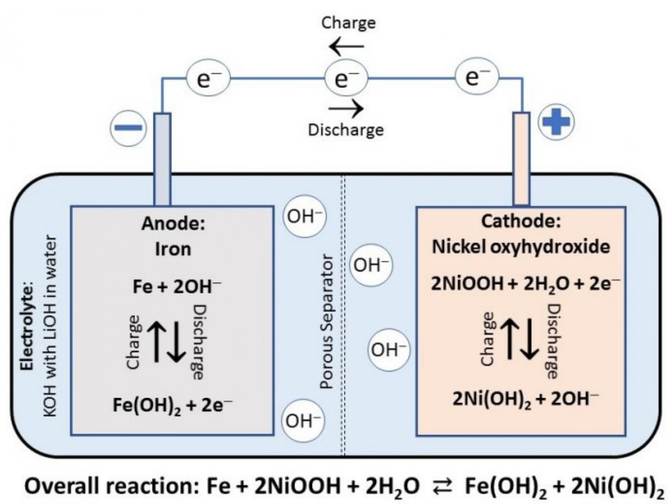


Figure 3–6. Nickel Iron battery chemical reaction[6]

1.3.2 Condition Parameters

Two parameters describe the capacity status of the battery.

— **State of Charge** (SOC)
SOC is the current capacity available in the battery.

$$SOC = \frac{capacity\ discharged}{nominal\ capacity} \times 100\ \% \qquad (1.5)$$

— **Depth of Discharge** (DOD)
DOD is the lowest allowable point at which the battery can discharge and can be used as an alternative method to find the battery's SOC. For instance, a DOD of 80% for lead acid batteries is considered a deep discharge.

TABLE 2–1 | SOC & DOD	
SOC	**DOD**
100 %	0 %
75 %	25 %
50 %	50 %
25 %	75 %
0 %	100 %

1.3.3 Technical Specifications

The most common technical specifications found in many datasheets are mentioned below.

— **Charge / Discharge Rate**
Discharge and charge rates are scales that compare currents and time that are charged, independent of the battery capacity. The value can be seen as C-Rate or plane Rate and is expressed in hours. The formula below equates to the C-Rate:

$$Rate = \frac{Capacity\ (Ah)}{Time\ (h)} \qquad (1.6)$$

A 1C rate means the entire battery can discharge in 1 hour, a 2C rate in half an hour, C / 2=0.5C in 2 hours, etc. The standard is 1C, except if the battery manufacturer specifies something different. For example, a battery with a written capacity of 100Ah can discharge 100A of current in 1 hour. A 2C rate for this battery is a discharge of 200A in half an hour and C/2 50A for 2 hours.

TABLE 2–2 | C-rate Example		
Time (h)	**Rate**	**Amps**
20	0.05C	20.8
10	0.10C	37.4
8	0.13C	45.1
5	0.20C	68
3	0.33C	93.9
2	0.50C	123
1	1C	232
1/2	2C	116

Figure 3–7. 300A Car Jumper SCDSCI-IE, 5.4 Ah
with jumpstart current of 150–300 A, a rate of 30–35 C

— **Voltage** could be:

- **Nominal**
  The voltage reference by the manufacturer.
- **Terminal**
  The voltage between the battery terminals when a load is connected. Terminal voltage also depends on the battery's SOC.
- **Open circuit**
  The voltage between the battery terminals when no load is connected. The open circuit voltage increases with the SOC.
- **Cut-off**
  Is the minimum voltage value a battery can have. This also defines when the battery is completely discharged.
- **End Voltage**
  The lower the end voltage, the more the available capacity. The end voltage of two different batteries must match.

— **Internal Resistance**
The resistance inside the battery. There is a different internal resistance for charging and discharging, and it is dependent on the battery SOC. Higher internal resistance is translated to increased heat and decreased battery efficiency.

— **Temperature Coefficient**
It is also seen as temperature compensation (TC) or temperature compensation coefficient and is valued in mV/°C per cell.

— **Specific energy** (Wh/kg)
The maximum energy per mass unit is also known as the gravimetric energy density of a battery. Battery chemistry and packaging determine this value. Considering the energy load, this information could be useful in determining the battery weight needed to satisfy the load.

— **Energy Density** (Wh/L)
The nominal rating of battery energy per unit volume is also called the volumetric energy density. Battery chemistry and packaging also determine this value. Knowing the user's energy consumption, battery size can be determined.

— **Specific Power** (W/kg)
The rated power per mass unit of a battery. This value is determined by battery chemistry and packaging.

— **Power Density** (W/L)
The maximum available power per unit volume.

— **Cycle Life**
Cycling is the repetition of the discharge and recharge process. One cycle is the discharge to a certain DOD followed by one full recharge. The number of cycles measures how often this process can be repeated throughout a battery's lifetime. The smaller the DOD, the more cycles throughout the battery's lifetime.

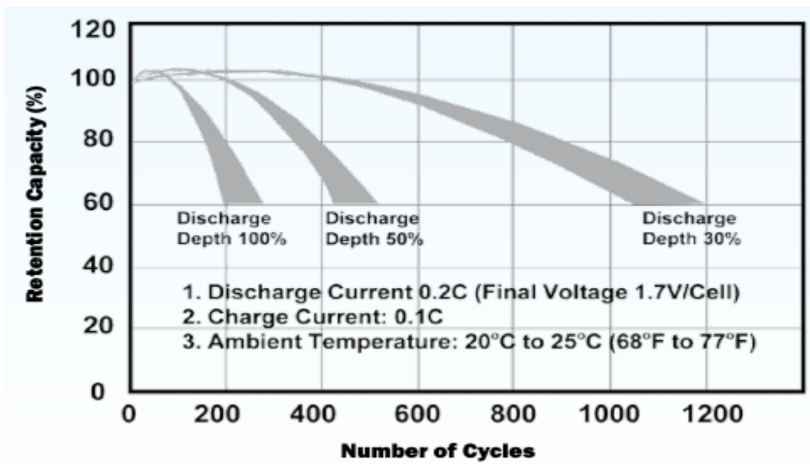


Figure 3–8. Cycle use of a rechargeable battery[7]

1.3.4 Capacity Variation

The most common unit to measure battery capacity is ampere-hour (Ah). Many parameters affect this value. For this reason, the Nominal or Rated capacity assigned to a battery should not be taken for granted since other factors affect it, which are:

— **Discharge rate**
The lower the discharge rate, the more adequately acid can be supplied to the plates during discharge reactions.

— **Temperature**
One of the key challenges in lead-acid battery technology is the decrease in capacity at lower temperatures. This is influenced by several factors, including increased resistance and reduced diffusion rates in the electrolyte. Lead-acid batteries with a large acid reserve tend to lose more capacity at low temperatures than those with a smaller acid volume. While the capacity of batteries does increase slightly above the typically stated 20ºC operating temperature, it is not a significant enough change to consider.

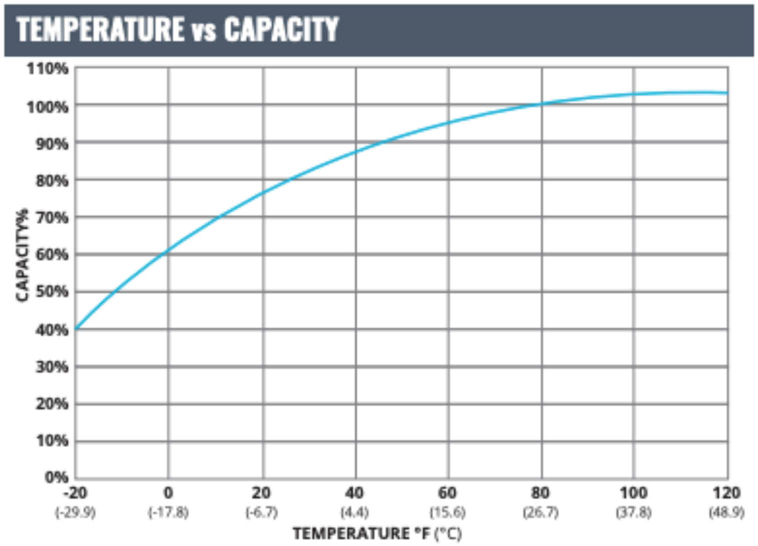


Figure 3–9. Capacity dependence on temperature. Battery FullRiver DC400

1.4 Power Converters

Power converters are devices that convert a power system's input amperage or voltage to a greater, lesser, or the same amount using transistors as switches forming the desired output.

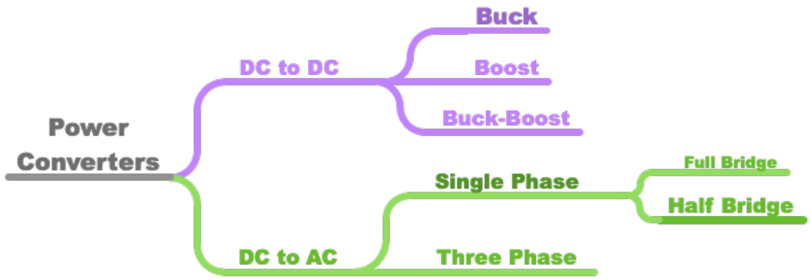


Figure 4–1. Types of power converters

1.4.1 Direct Current (DC) to DC

■ **Parts**

DC to DC converters consist of particular key components, and different circuit topologies are made depending on their arrangement. The key components are:

- — **L** **Inductor**
- — **D** **Diode**
- — **S** **Switch**
- — **C** **Capacitor**,
  stores charge and maintain a smooth output voltage as the switch is cycled on and off.

The switch (S), which is a transistor, is either a type of Metal Oxide Field Effect Transistor (MOSFET) commonly used for relatively low power or an Insulated-Gate Bipolar Transistor (IGBT) at higher powers. A switching frequency greater than 100 kHz is common for MOSFET switches. IGBT switches need more time to switch OFF, and the frequency is around 25 kHz. In any of these cases, the load voltage (V_l) can be controlled through the duty cycle ratio (D), which is the percentage of the signal that is active (ON) to when it is inactive (OFF). For example, D=40% means that the signal is on 40 percent of the time and 60 percent off. Also, the source voltage (V_s) is always greater than the load voltage (V_l).

■ **Functionality**

Terminologies about some of the functionalities of converters are listed below.

— **Active State (ON)**

While the switch is on, the current that passes through the inductor increases at a rate:

$$\frac{dI}{dt} = \frac{V_S - V_l}{L} \tag{1.7}$$

— **Inactive State (OFF)**

When the switch is turned off, the current in the inductor will flow, and it will be commuted from the switch to the diode. The rate of change of the current without taking into consideration the voltage drop across the diode is given by the rate:

$$\frac{dI}{dt} = -\frac{V_l}{L} \tag{1.8}$$

— **Cycle**

The switch is turned ON and OFF in a cycle with a period of T, and the current builds up and decays, respectively. If the current in the inductor does not zero before the switch turns on again, then the converter is said to be operating in continuous or discontinuous mode. The continuous mode is preferable because it is more efficient.

— **Filter**
A filter is considered a converter that maintains the input at the same level. For practical reasons, a suitable converter is required between the junction of the solar array and the converter. This is necessary to make the current drawn from the array constant.

■ Types

These three types of converters mentioned below and are the basis for DC-to-DC converter circuit topology.

— **Buck Converter**
The buck or forward converter reduces the voltage input through the formula:

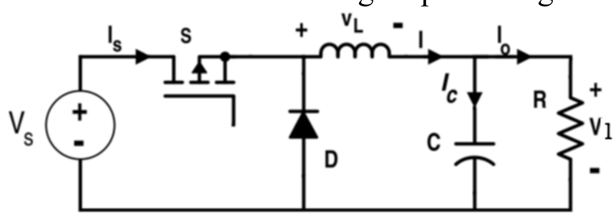


Figure 4–2. Circuit topology of a buck converter

$$V_l = D \cdot V_s \quad (1.9)$$

— **Boost Converter**
The boost converter increases the voltage in continuous current operation; the formula is given:

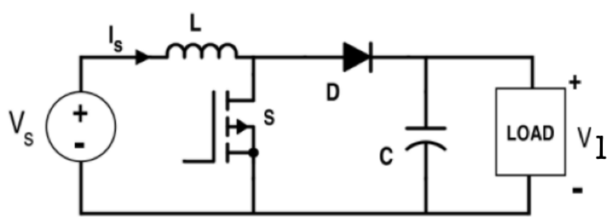


Figure 4–3. Circuit topology of the boost converter

$$V_I = \frac{I}{1-D} \cdot V_s \quad (1.10)$$

— **Buck–Boost Converter**

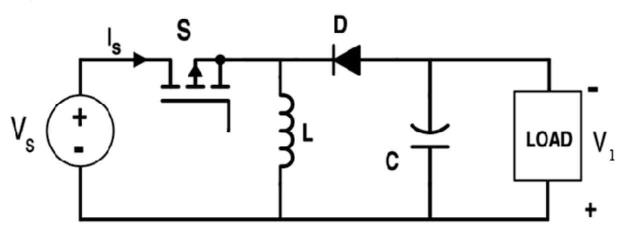


Figure 4–4. Circuit topology of a buck-boost converter

The buck–boost or flyback converter has the feature that the voltage could rise or lower depending on the user's needs; for continuous inductor current, the load voltage is:

$$V_l = \frac{-D}{1-D} \quad (1.11)$$

1.4.2 DC to Alternating Current (AC)

A DC-to-AC converter is also called an inverter, a circuit that converts direct current to alternating current. Inverters consist of MOSFETs, IGBTs, bipolar transistors, or thyristors and function as switches to create an alternating positive and negative current proposition. The switches of the inverter switch alternately to form a square wave.

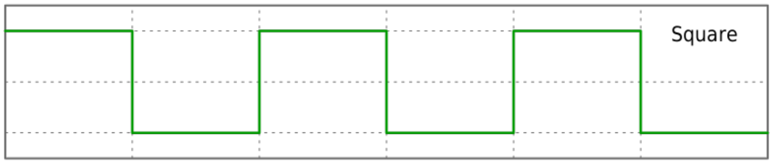


Figure 4–5. Square wave graph, THD=45%

The production of the square wave is very simple, but the load voltage cannot be controlled, and the harmonic content is very high. Modified square wave inverters adjust the switching scheme so that the two pairs of switches do not operate simultaneously, but there is a phase shift between them, leading to intervals where both pairs of switches are open and closed, resulting in the graphs below. This way, the control of load voltage is possible, and the more levels the waveform can reach, the less harmonic content.

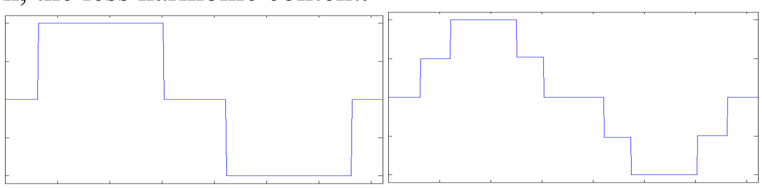


Figure 4–6. 3-level modified square wave, THD≈ >23.8% (left)
5-level modified square wave, THD ≈ 6.5% (right)

The smoothest and gradually increasing and decreasing is the pure sine wave. In practice, an inverter can never reproduce a pure sine wave, and the decline from the actual sine wave is measured by the percentage of total harmonic distortion (THD).

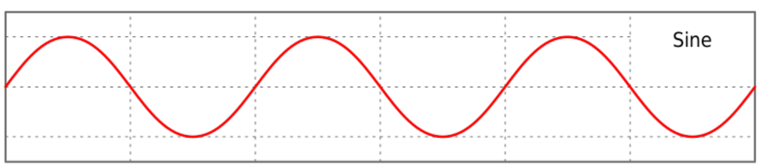


Figure 4–7. Pure sine wave

■ Inverter Specifications

Many manufacturers share common specifications in the datasheets they provide.

— **Total Harmonic Distortion** (THD)

A common value used to evaluate the quality of the sine wave is the Total Harmonic Distortion (THD), also called the Distortion Factor (DF). This parameter indicates the declination to the true sine wave.

This is a crucial decision when choosing an inverter to power loads sensitive to the power input and output, such as speakers, which could make buzzing sounds.

— **Input**

The system's input is characterized by voltage and current. These values can be expressed either as the maximum value of each or within a range.

— **Surge Power**
Inverters can handle sudden peaks of energy lasting a few seconds, called power surges. The aforementioned form of energy can occur during the ignition of an electrical device consisting of a motor or compressor. Other reasons could be a lightning strike, the interference of the power supply system with wildlife, or anything that interrupts or sends electricity back to the system[8]. Surges can range from a couple of volts to thousands. Not all inverters support this case and could be found in a different datasheet section.

— **Frequency**
The voltage's frequency output is between 50 and 60 hertz, and most countries support 50 Hz for powering their devices.

— **Voltage output**
The globe runs on two voltage ranges: 110–127V and 220–240V as a standard[9]. Special types of devices may require different voltages. For example, in the US, the standard is 120V, although there could be heating devices that require 240V.

— **Efficiency**
Efficiency is also important before choosing a suitable one for a standalone power system. Efficiency is expressed as the power output of the AC inverter to the power DC input.

$$n_{inveter} = \frac{P_{AC}}{P_{DC}} \tag{1.12}$$

High-quality sine wave inverters are rated at 90–95% efficiency. Lower-quality modified sine wave inverters are less efficient, an estimated 75–85%. High-frequency inverters are usually more efficient than low-frequency.
Many manuals, more descriptive of their product, provide an efficiency curve graph that states efficiency is a function of power output. Rarer cases provide temperature derating, which is imperceptible at normal living temperatures.

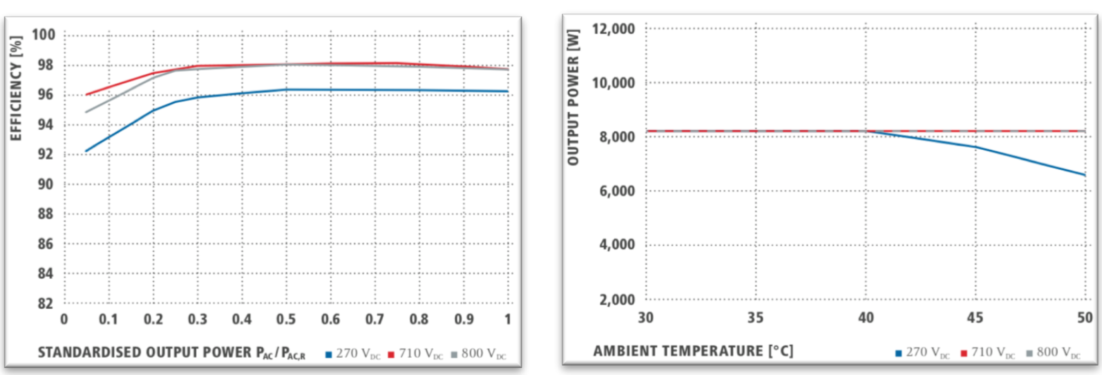


Figure 4–8. Efficiency curve (left) Temperature Dependace (Right), Fronius Primo 8.2

■ Types

— **Single-phase inverter**

A single–phase inverter is a switching device that cyclically reverses the polarity of the input supply. It has two basic configurations: half bridge and full bridge.

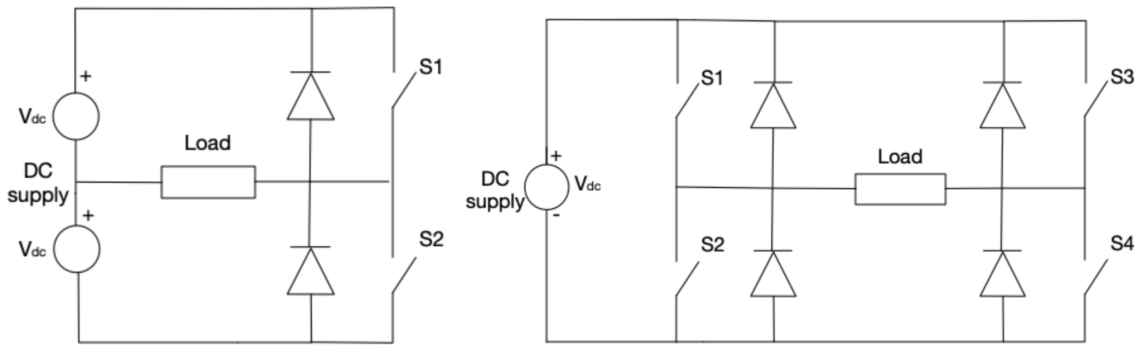


Figure 4–9. Half Bridge (left) and Full Bridge (right) configuration

■ = closed ○ = open	S1	S2
$< t \leq T/2$	■	○
$T/2 < t \leq T$	○	■

■ = closed ○ = open	S1	S2	S3	S4
$0 < t \leq T/2$	■	■	○	○
$T/2 < t \leq T$	○	○	■	■

Figure 4–10. Half Bridge (left) and Full Bridge (right),
Square wave generator switch sequence.

— **Three-phase inverter**

At higher power levels a three-phase inverter is used more often. The three pairs of switches are switched in a cyclic manner with a 120° phase shift between each pair.

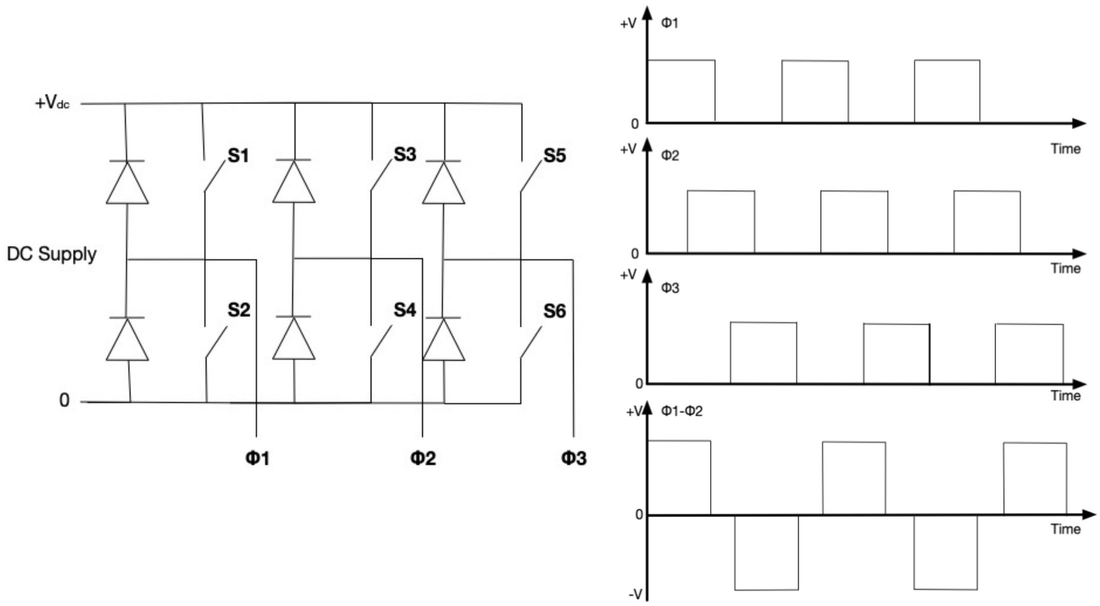


Figure 4-11. Basic circuit of the three-phase inverter (Left)
& voltage waveforms at φ1, φ2, φ3 for simple square wave switching, inter-phase voltages φ1-φ2 (Right)

1.5 Cables

Wiring is essential for connecting all electrical devices in an electrical system. For that reason, it is crucial to choose the proper cable to transfer the energy from one component to another.

1.5.1 Wire Conductor

The inside of a cable is a wire with electrical conductance properties.

■ Materials

There are two main types of conductor material used in a cable:

— **Aluminum** (Al)
— **Copper** (Cu)

Other metals can be combined with those above, creating alloys or coated metals such as gold (Au), silver (Ag), Tin (Sn), Nickel (Ni), Tungsten (T), Magnesium (Mg), Zinc (Zn) and any other depending on the attributes of the element and the purpose it could be used for.

■ Comparison

Copper has higher electrical conductivity than aluminum by approximately 1.6 times. To attribute to an aluminum conductor, the cross-sectional size area of aluminum must become larger to compensate for its higher electrical resistivity and requires an estimate of a 56% larger cross-sectional area than copper[10].
Aluminum costs approximately four times less than copper[11], which makes it preferable for large products requiring extensive wiring and for long distances, such as distributing power from power plants to a faraway village.
Another important factor to consider is the expansion coefficient, which is 1.8 times higher than aluminum. This means aluminum can expand and contract much more in higher evolving temperatures, causing to loosen connections overtime, leading to a possible fire risk from arching.

TABLE 3–1 | Copper vs Aluminum				
Attribute	**Unit of measurement**	**Copper**	**Aluminum**	**Cu / Al**
Electrical conductivity	ρ (Ω•m) at 20 °C	1.68×10^{-8}	2.82×10^{-8}	0.6 %
Expansion coefficient	Fractional expansion per degree ° C x10^{-6}	13	24	0.54
Tensile strength	N/mm^2(annealed)	200-250	50-60	× 4
Density	g/cm^3	8.91	2.70	× 3.3
Melting Point	°C	1083	660	× 1.64
Specific Weight	Kg/dm^3	8.93	2.64	× 3.38
Price	USD per ton	8,767.80	2,225.65	× 3.93

■ Construction

A wire can be found in two forms: solid or stranded.

— **Solid**

A single wire or single-strand wire consists of one piece. It is often used in breadboards, offers lower resistance, and is best for higher frequencies.

— **Stranded**

A stranded wire comprises several wires bundled together to form a single conductor. This type of construction gives the wire more flexibility and is thus preferred when higher electrical and mechanical resistance to metal fatigue is required.

Figure 5–1. Solid & stranded wire

◆ **Skin Effect**

At high frequencies, current travels around the surface of a solid core due to the skin effect. In a stranded wire, the strands are short-circuited, creating gaps within the theoretically single-core wire. Therefore, stranded wires are affected less than solid core wires.

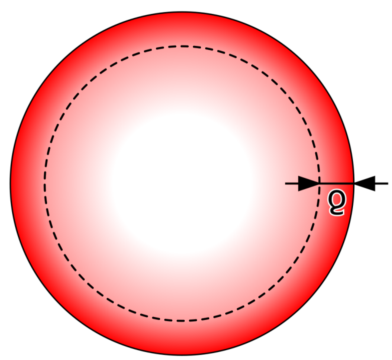
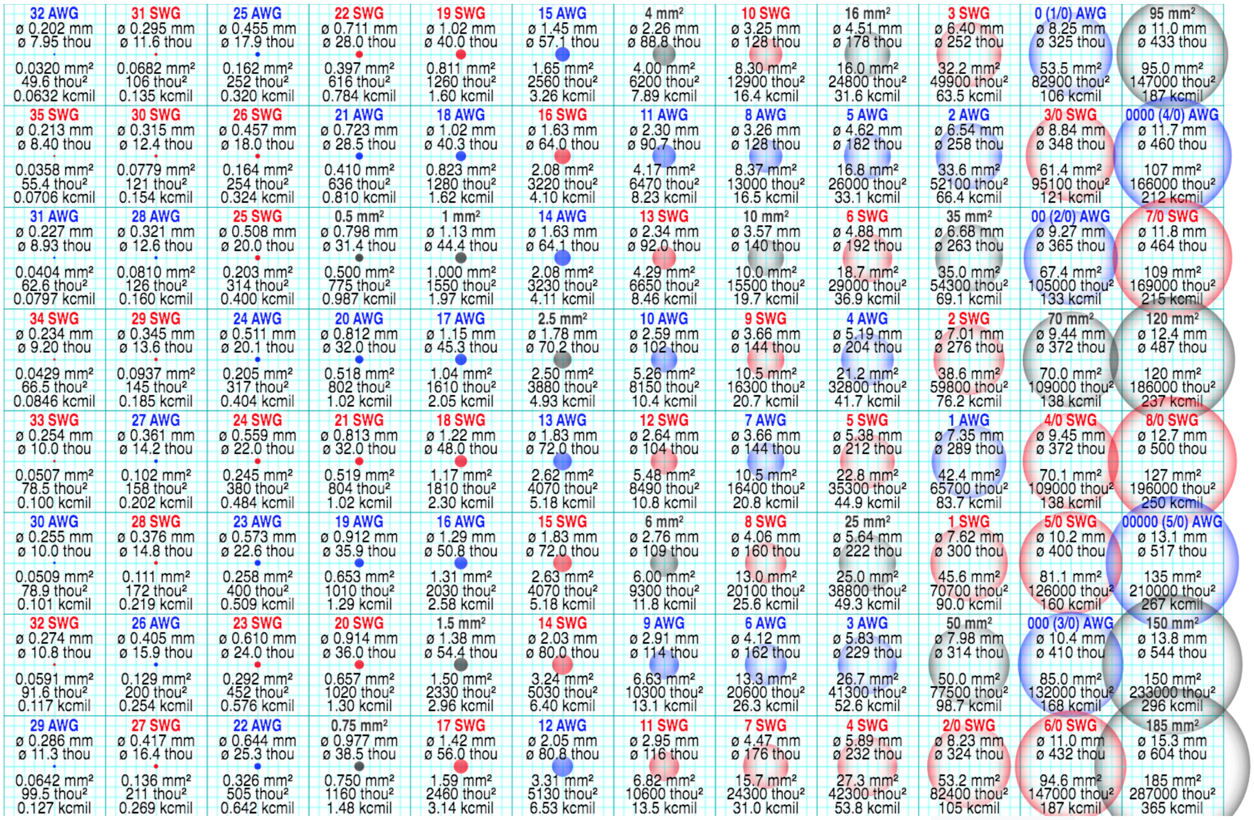


Figure 5–2. Areas affected by the skin effect

■ Sizes

Wires come in different thicknesses depending on the amount of energy needed to be transferred and primarily on the ampacity. Secondary, in consideration is the voltage drop which correlates directly with the length and the size of the wire. Other factors may also be taken into consideration.

The description of the wire thickness is expressed through different systems around the globe. The most widely used standards are Standard Wire Gauge (SWG), and American Wire Gauge (AWG) which are very similar, although different; the global standardization is from the International Electrotechnical Commission IEC 60228.



• red SWG
• blue AWG
• black IEC 60228

Figure 5-3. Wire thickness standards[12]

1.5.2 Insulation

The insulation covering of a wire is used to protect the conductor material inside from heat, moisture, ultraviolet light, chemicals, or anything that will disturb the flow of electrical energy.

■ Materials

Depending on the mix of polymers and other materials, three main categories of insulation exist. The types of insulation are:

- **Plastic**
- **Rubber**
- **Fluoropolymer**,
  for applications demanding heat resistance.

■ Labelling

On the cable, there is a high possibility to have letters indicating the value of resistance to different conditions. There are different standards in different countries that indicate the materials and the properties of the insulation used.

TABLE 3–2 | Insulation type Initials by the NEC					
Plastic	**Code**	**Rubber**	**Code**	**Fluoropolymer**	**Code**
Polyvinyl chloride	PVC	Thermoplastic rubber	TPR	Perfluoroalkoxy	PFA
Semi-Rigid PVC	SR-PVC	Ethylene propylene rubber	EPR	Polytetrafluoroethylene	PTFE
Plenum PVC	Plenum PVC	Ethylene propylene diene monomer	EPDM	Fluorinated Ethylene Propylene	FEP
Polyethylene	PE	Silicon		Polyvinylidene Fluoride	PVDF
Polypropylene	PP	Fiber glass		Thermoplastic Elastomers	TPE
Polyurethane	PUR	Styrene-butadiene rubber	SBR	ethylene tetrafluoroethylene	ETFE
Chlorinated Polyethylene	CPE	Chlorosulfonated Polyethylene	CSPE	Ethylene ChloroTriFluoroEthylene	ECTFE
		Ethylene Propylene Diene Monomer	EPDM		

TABLE 3–3 | Comparative Properties of Fluoropolymer Insulations						
	FEP	**ETFE**	**PTFE**	**PVDF**	**ECTFE**	**TPE**
Oxidation Resistance	O	E	O	O	O	E
Heat Resistance	O	E	O	O	O	E
Oil Resistance	O	E	E-O	E	O	G
Low-Temperature Flexibility	O	E	O	F	O	E
Ozone Resistance	E	E	O	E	E	E
Weather (Sun Resistance)	O	E	O	E-O	O	E
Abrasion Resistance	E	E	O	E	E	F-G
Electrical Properties	E	E	E	G-E	E	E
Flame Resistance	O	G	E	E	E-O	F-G
Nuclear Radiation Resistance	P-G	E	P	E	E	G
Water Resistance	E	E	E	E	E	G-E

Acid Resistance	E	E	E	G-E	E	G
Alkali Resistance	E	E	E	E	E	G-E
Alcohol Resistance	E	E	E	E	E	G
Aliphatic Hydrocarbons Resistance	E	E	E	E	E	P
Aromatic Hydrocarbons Resistance	E	E	E	G-E	E	P
Halogenated Hydrocarbonic Resistance	E	E	E	G	E	-
Underground Burial	E	E	E	E	E	P

TABLE 3–4 | Comparative Properties of Rubber Insulations

	Rubber	**Neoprene**	**CSPE**	**EPDM**	**Silicone**
Oxidation Resistance	F	G	E	E	E
Heat Resistance	F	G	E	E	O
Oil Resistance	P	G	G	P	F-G
Low-Temperature Flexibility	G	F-G	F	G-E	O
Ozone Resistance	P	G	E	E	O
Weather (Sun Resistance)	F	G	E	E	O
Abrasion Resistance	E	G-E	G	G	P
Electrical Properties	G	P	G	E	G
Flame Resistance	P	G	G	P	F-G
Nuclear Radiation Resistance	F	F-G	E	G	E
Water Resistance	G	E	E	G-E	E
Acid Resistance	F-G	G	E	G-E	F-G

Alkali Resistance	F-G	G	E	G-E	F-G
Alcohol Resistance	G	F	G	P	G
Aliphatic Hydrocarbons Resistance	P	G	F	P	P-F
Aromatic Hydrocarbons Resistance	P	P-F	F	F	P
Halogenated Hydrocarbons Resistance	P	P	P-F	P	P-G
Oxidation Resistance	F	G	E	E	E

TABLE 3–5 | Comparative Properties of Plastic Insulations

	PVC	**PE**	**LDPE**	**Cellular PE**	**HDPE**	**PP**	**CELLULAR PUR**	**PVC**	**Plenum Nylon**	**CPE**
Oxidation Resistance	E	E	E	E	E	E	E	E	E	E
Heat Resistance	G-E	G	G	E	E	E	G	G-E	E	E
Oil Resistance	F	G-E	G	G-E	F	F	E	F	E	E
Low-Temperature Flexibility	P-G	E	E	E	P	P	G	P-G	G	E
Ozone Resistance	E	E	E	E	E	E	E	E	E	E
Weather (Sun Resistance)	G-E	E	E	E	E	E	G	G	E	E
Abrasion Resistance	F-G	G	F	E	F-G	F-G	O	F-G	E	E-O
Electrical Properties	F-G	E	E	E	E	E	P	G	P	E
Flame Resistance	E	P	P	P	P	P	P	E	P	E
Nuclear Radiation Resistance	F	G-E	G	G-E	F	F	G	F	F-G	O
Water Resistance	F-G	E	E	E	E	E	P-G	F	P-F	O
Acid Resistance	G-E	G-E	G-E	E	E	E	F	G	P-F	E
Alkali Resistance	G-E	G-E	G-E	E	E	E	F	G	E	E

Alcohol Resistance	P-E	E	E	E	E	E	P-G	G	P	E
Aliphatic Hydrocarbons Resistance	P	G-E	G	G-E	P-F	P	P-G	P	G	E
Aromatic Hydrocarbons Resistance	P-F	P	P	P	P-F	P	P-G	P-F	G	G-E
Halogenated Hydrocarbon Resistance	P-F	G	G	G	P	P	P-G	P-F	G	E
Underground Burial	F-G	G	-	G	-	-	G	P	-	P
Oxidation Resistance	E	E	E	E	E	E	E	E	E	E
Heat Resistance	G-E	G	G	E	E	E	G	G-E	E	E

TABLE 3–6 | Letter indication of insulation based on attributes National Electric Code (NEC)

Indication	**Resistance**
H	Heat
W	Moisture
T	Thermoplastic
USE	Branch Circuit Cable- Single Conductor
UF	Underground feeder
2	Permitted to be used at a continuous 90°C (194°F) operating temperature, wet or dry
USE	Branch Circuit Cable- Single Conductor

TABLE 3–7 | Example of possible cable labels

Type Letter	**Name**	**Maximum Provisions**	**Application Provisions**	**Insulation**	**Outer covering**
THHN	Heat Resistant Thermoplastic	90˚C, 194˚F	Dry or Damp Locations	Flame retardant, heatresistant thermoplastic	Nylon jacket or equivalent
THW	Moisture & Heat Resistant Thermoplastic	75-90˚C, 167-194˚F	Dry or Wet Locations	Flame retardant, moisture and heat resistant thermoplastic	None
THWN	Moisture& Heat Resistant Thermoplastic	75˚C, 167˚F	Dry or Wet Locations	Flame retardant, moisture and heat resistant thermoplastic	Nylon jacket or equivalent

TW	Moisture resistant thermoplastic	60˚C, 140˚F	Dry or Wet Locations	Flame retardant, moisture resistant thermoplastic	None
UF and USE	Underground Feeder & Branch Circuit Cable- Single Conductor	60-75˚C, 140-167˚F	See Article 338 and 339: Service Entrance	Moisture and heat resistant	Integral with insulation and Moisture resistant
USE-2* and RHW-2*	Moisture resistant thermoplastic and Branch Circuit Cable- Single Conductor	90˚C, 194˚F	Dry or Wet and Service Entrance	Moisture and heat resistant	Moisture resistant with insulation
PV Wire**	Thicker insulation or jacket to provide additional protection against the abuse that USE-2 wire may receive.	90˚C (194˚F) wet, 150˚C (302˚F) dry	Dry or Wet and Service Entrance	Moisture and heat resistant	Moisture resistant with insulation

TABLE 3–8 | European Standard Insulation labelling (CENELEC)

Type Letter	Meaning
B	EPR rubber T. 90°C
E	Polyethylene (PE)
G	EVA Rubber T. 110°C
M	Mineral
N	Polychloroprene or equivalent
N2	Polychloroprene or equivalent for welding cable
N4	Chlorosulphonated Polyethylene (CSP) or equivalent
Q	PUR
R	Standard EPR rubber T.60 °C
S	Silicone Rubber
T	Textile yarn braid
J	Glass yarn braid
V	Polyvinylchloride (PVC) T.70°C
V2	Polyvinylchloride (PVC) T.90°C
V3	Low temperature Polyvinylchloride (PVC)
V4	Cross-linked Polyvinylchloride (XLPE)
V5	Oil resisting PVC compound
X	Cross-linked Polyethylene (XLPE)
Z	Low smoke and zero halogen elastomeric compound
Z1	Tape, wire or flat wire (copper) screen

1.5.3 Color code

Every wire inside a cable has a different color to indicate its polarity. In different countries, they are different color coding for the wire coatings, such as the National Electrical Code (NEC) in the United States, Canadian Electric Code (CEC), BS 7671 for Britain, and the International Electrotechnical Commission (IEC) which include most international countries.

TABLES 3–9 | AC Power circuit wiring color codes[18]			
International Electric Code (IEC)			
Function	**Label**	**Color**	**Color, old IEC**
Protective earth	PE	Green-yellow	Green-yellow
Neutral	N	Blue	Blue
Line, single phase	L	Brown	Brown or black
Line, 3-phase	L1	Brown	Brown or black
Line, 3-phase	L2	Black	Brown or black
Line, 3-phase	L3	Grey	Brown or black
United Kingdom (UK)			
Function	**Label**	**Color, IEC**	**Color, old IEC**
Protective earth	PE	Green-yellow	Green-yellow
Neutral	N	Blue	Black
Line, single phase	L	Brown	Red
Line, 3-phase	L1	Brown	Red
Line, 3-phase	L2	Black	Yellow
Line, 3-phase	L3	Grey	Blue
United States (US)			
Function	**Label**	**Color, IEC**	**Color, old IEC**
Protective earth	PG	Green-yellow, green, bare	Green
Neutral	N	White	Grey
Line, single phase	L	Black	Red
Line, 3-phase	L1	Black	Brown
Line, 3-phase	L2	Red	Orange
Line, 3-phase	L3	Blue	Yellow

1.6 Loads

An electrical load is anything that consumes electrical energy. In other words, it is a device that converts electrical energy into a different form, such as heat, light, or motion.
There are three main types of loads: resistive, inductive, and capacitive. A more complex device could also include more than one type of load, such as a single–phase motor that contains all kinds of loads.

1.6.1 Types

Depending on the electrical components inside the electrical devices can be categorized:

— **Resistive**

Loads that consist of any heating element are considered a resistive load and obstruct the flow of electrical energy. The resistive load intakes electrical energy so that the current and voltage remain in the same phase. Conclusively, the power factor of this type of load remains in unity.

— **Inductive**

An inductive or reactive load is any device that has coils in it. Reactive loads include motors, compressors, speakers, transformers, vacuum cleaners, and air conditioners. In an inductive load, the current peaks after the voltage. Such loads consume reactive power, so power flows from the load to the source.

— **Capacitive**

In a capacitive load, current leads the voltage by 90 degrees. Capacitive loads do not exist in a stand-alone format. They are used at electrical substations to improve the overall power factor of the system and lessen the amount of power transformed to another form than electric energy.

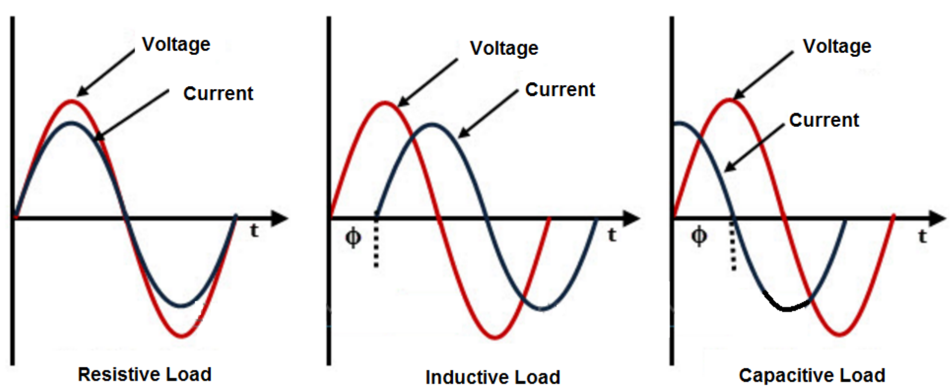


Figure 6–1. Flow of current and the corresponding voltage in each type of load

CHAPTER 2 | Dimensioning

Dimensioning is the process of examining the physical attribute of the world and search for the appropriate mechanical and electrical specifications of components of the electrical power system.
To start with the base, the automobile from the Italian company IVECO Daily 2000 is the domain. All dimensioning is based on the physical characteristics of this vehicle with pre-existing electrical power supply appliances from the market.

2.1 Photovoltaic Arrays

Solar panels are placed on the vehicle's roof, which limits the quantity depending on the size of the chosen solar array. The size of the solar panel depends on the manufacturer and model. Theoretically, covering the entire roof area with photovoltaic arrays of the highest efficiency is optimum for maximum electrical energy production.

2.1.1 Sizing and Placement

An area of 9 m^2 must be covered, with dimensions of 4,235 m length by 2,13 m width. The typical size for residential use can fit 4 panels and a maximum of 5 placed horizontally with a supportive roof extension.

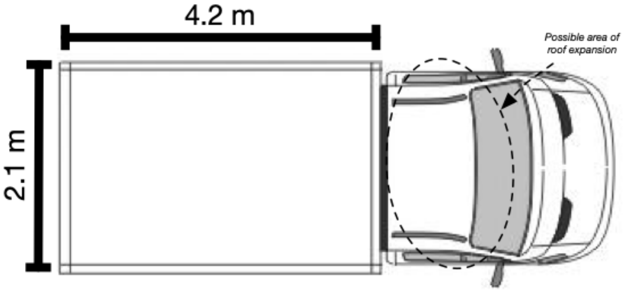


Figure 7–1. Top view of the automobile

Most commercial solar panels have a surface area of 1.65 m^2. Although a custom-sized solar panel is an option, the commercial size was chosen for this application for practical and cost reasons.

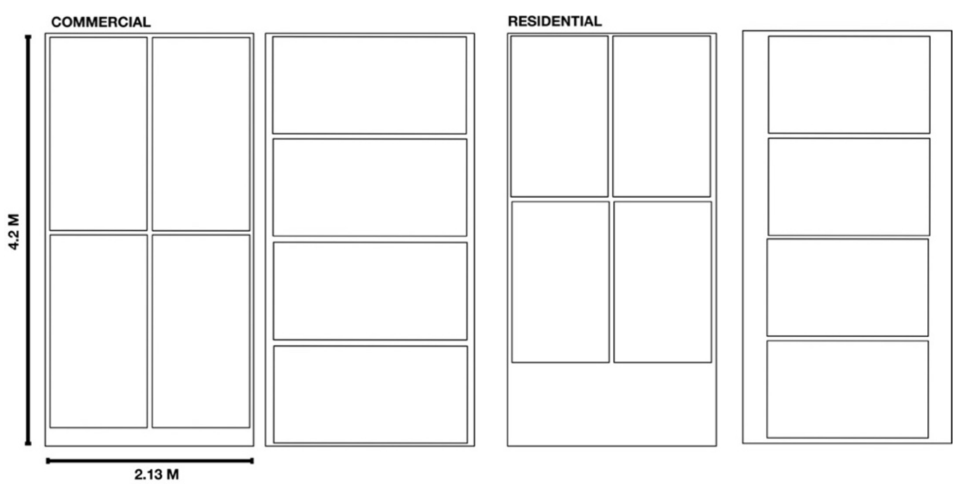


Figure 7-2. Solar array standard sizing commercial (left) and residential (right) Placement, either horizontally or vertically

2.1.2 Data Sheet Specifications

Studying each photovoltaic array manufacturer’s data sheet is crucial to choose the proper one for the autonomous energy system’s use.
After extensive research, the photovoltaic array chosen for simulation is the MAXEON 5 450 W, manufactured by SunPower.

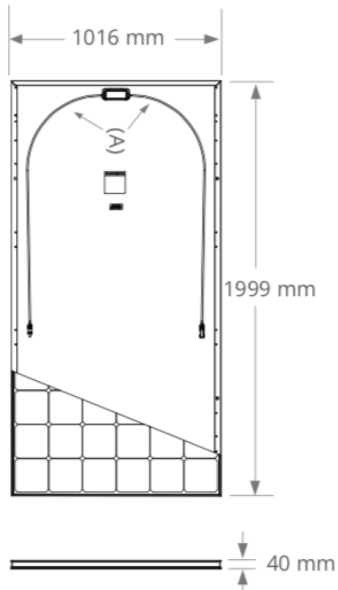


Figure 7-3. Solar array Maxeon 5 450 W by SunPower dimensions.

TABLE 4–1 | Photovoltaic Electrical Data			
	SPR-MAX5-450-COM	**SPR-MAX5-440-COM**	**SPR-MAX5-430-COM**
Nominal Power	450 W	440 W	430 W
Power Tolerance	+5/0%	+5/0%	+5/0%
Power Efficiency	22.2%	21.7%	21.2%
Rated Voltage (Vmpp)	44V	43.4V	42.7V
Rated Current	10.2A	10.2A	10.1A
Open-Circuit Voltage	51.9V	51.6V	51.2V
Short-Circuit Current (+/- 3%)	11.0A	10.9A	10.9A
Max. System Voltage	1000 V IEC		
Maximum Series Fuse	20A		
Power Temp Coefficient	-0.29% / °C		
Voltage Temp. Coefficient	-136 mV / °C		
Current Temp. Coefficient	5.7 mA / °C		

TABLE 4–2 | Operating Condition and Mechanical Data	
Temperature	-40° C to +85° C
Impact Resistance	25 mm diameter Hail at 23 m/s
Solar Cells	72 Monocrystalline Maxeon Gen 5
Glass	High transmission tempered anti-reflective
Junction Box	IP-68, Stäubli (MC4), 3 bypass diodes
Weight	21.6 kg
Max. Load	Wind: 2400 Pa, 244 kg/m2 front & back Snow: 5400 Pa, 550 kg/m front
Frame	Class 2 silver anodized

2.1.3 Circuit Configuration

The solar array's circuit connection configuration can be connected in parallel, in series, or in combination. The main parameter that determines the circuit topology is the maximum voltage input of the inverter. Most inverter inputs have a smaller limit to the amperage than the voltage input, making it more likely that the solar panels will be connected in series, where the ampere remains constant, whereas the voltage increases linearly per panel. For the above reasons, connecting the solar panels in series is preferable.

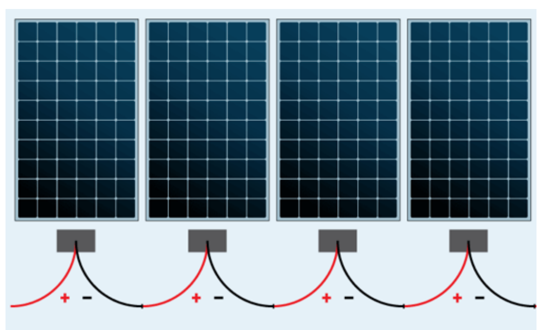


Figure 7–4 Circuit connection configuration

2.1.4 Orientation

A couple of assumptions were made based on the solar panel placement.

— The solar panels are placed at a 0-degree slope, meaning flat, to avoid aerodynamic drag.
— Azimuth = 0°, meaning that the vehicle is always parked facing north, with halal parking.
— The driver has in mind to park in an open area to avoid shade from the surroundings.

TABLE 4–3 | Solar Farm Characteristics	
Electrical Data	
Voltage	176 V
Amperage	11 A
Physical Data	
Surface area	8,123936 m2
Weight	86,4 kg

2.2 Alternator
The alternator can be the existing one in the automobile or replaced with a more efficient one from the automobile's electrical circuitry. However, this method is not efficient because it separates the electrical energy. Instead, an additional alternator can be installed near the engine and connected with a longer drive belt for improved electrical production efficiency. Alternators designated for automobiles commonly come in 12V or 24V and an amperage range from 100A to 125A.

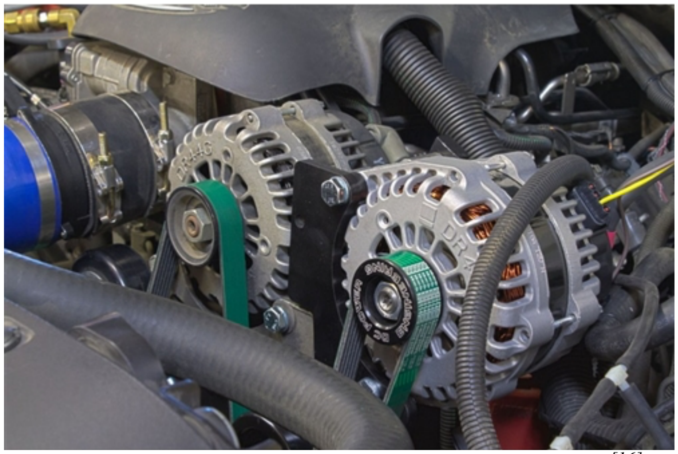


Figure 8–1. Dual Alternator installation on engine[16]

2.2.1 Sizing
As a rule of thumb, the alternator size must be 20% – 25% of the battery capacity.[15] The current produced should not exceed the charging current the battery can handle. For this reason, when we have a hybrid power system with two sources, the current sources must add up to the maximum battery charge current and then apply the same rule with the appropriate battery capacity.
A practical way to estimate the size of the alternator needed is to take an average RPM run speed, check the look-up table for the corresponding ampere production, and multiply it by the alternator voltage and the travel time.

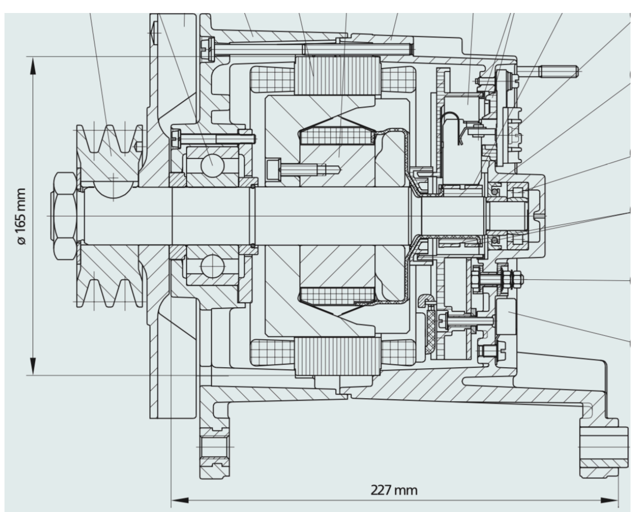


Figure 8–2. Alternator dimensions

2.2.2 Data Sheet Specifications

Including all the calculations from the study, the additional alternator chosen to be used in the simulation for the power system is a high-output alternator model AAT, 28V 140A, manufactured by the Czech company ISKRA Avtoelectrika d.d.

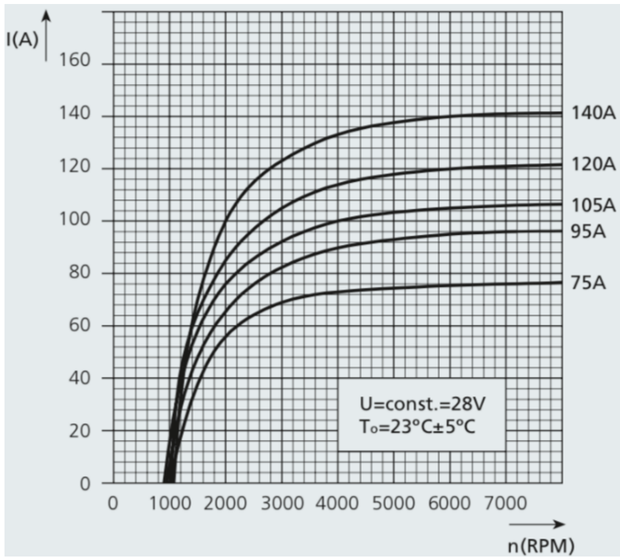


Figure 8–3. Alternator AAT Ampere output by ISKRA

Figure 8–4. Alternator AAT by ISKRA

2.3 Load

There are two loads connected to this electrical power system. One is for the user's everyday use, covering basic needs, the so-called household load (L_1), and the other is specially designated for outdoor events or the event load (L_2). To estimate the total load of each, a calculation had to be made with the rated power consumption multiplied by the amount of time in hours, the widely called kilowatt hours.

2.3.1 Household Load

The household load (L_1) comprises electrical appliances covering the user’s basic needs. These devices are activated based on a daily routine. Energy consumption is calculated in kilowatt-hours, multiplying the device's energy consumption by the hours it is activated. A 15% margin has been added to the overall load for safety reasons. The appliances that consist of household load are activated at different times depending mainly on the use on the daily routine.

◆ **Refrigerator**

Special attention is given to the refrigerator because it is the device that consumes more energy during the day. Based on different parameters such as the ambient temperature of the room, amount of food, and many other factors depending on the complexity of the device, the refrigerator could work in different modes of refrigeration˙ activating for a finite amount of time, typically spanning from 50% –70% in a 24-hour period. The cycle can be visualized as a square wave, on and off hour by hour, or activated more at peak usage hours and less during the nighttime, for example. In this application, a 50% cycle has been chosen.

		Environment (room)			W O R K				Charging Mobile devices					WC & Kitchen				
		Lights	FAN	WifiRouter	PC	Screen	speakers	mobile #1	mobile #2	Camera	Laptop	Tablet	water heater	FRIDGE	EXHAUST	Water Pump	
	HOURS\WATTS	50	30	10	180	40	200	10	10	10	50	10	200	200	20	60	Total Wh/hour
SLEEP	12:00 - 01:00	☐	☐	☐	☐	☐	☐	☑	☑	☑	☑	☐	☐	☑	☐	☐	280
	01:00 - 02:00	☐	☐	☐	☐	☐	☐	☑	☑	☑	☑	☑	☐	☐	☐	☐	90
	02:00 - 03:00	☐	☐	☐	☐	☐	☐	☑	☑	☑	☑	☑	☐	☑	☐	☐	290
	03:00 - 04:00	☐	☐	☐	☐	☐	☐	☑	☑	☑	☑	☑	☐	☐	☐	☐	90
	04:00 - 05:00	☐	☐	☐	☐	☐	☐	☑	☑	☑	☑	☑	☐	☑	☐	☐	290
	05:00 - 06:00	☐	☐	☐	☐	☐	☐	☑	☑	☑	☑	☑	☐	☐	☐	☐	90
	06:00 - 07:00	☐	☐	☐	☐	☐	☐	☑	☑	☑	☑	☑	☐	☑	☐	☐	290
	07:00 - 08:00	☑	☑	☑	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☑	350
	08:00 - 09:00	☑	☐	☑	☐	☐	☑	☐	☐	☐	☐	☐	☐	☑	☐	☐	460
WORK	09:00 - 10:00	☐	☐	☑	☑	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	230
	10:00 - 11:00	☐	☐	☑	☑	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	230
	11:00 - 12:00	☐	☐	☑	☑	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	230
	12:00 - 13:00	☐	☐	☑	☑	☑	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	430
	13:00 - 14:00	☐	☐	☑	☑	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	230
COOK	14:00 - 15:00	☑	☐	☑	☐	☐	☑	☐	☐	☐	☑	☐	☐	☑	☑	☑	590
	15:00 - 16:00	☐	☐	☑	☐	☐	☐	☐	☐	☐	☑	☐	☐	☑	☑	☐	280
	16:00 - 17:00	☐	☐	☑	☐	☐	☐	☐	☐	☐	☑	☐	☐	☑	☑	☐	280
	17:00 - 18:00	☐	☐	☑	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐	☑	270
	18:00 - 19:00	☑	☐	☑	☑	☑	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	480
	19:00 - 20:00	☑	☐	☑	☑	☑	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	480
CHILL	20:00 - 21:00	☑	☐	☑	☑	☑	☑	☐	☐	☐	☐	☐	☐	☑	☐	☐	680
	21:00 - 22:00	☑	☐	☑	☑	☑	☐	☐	☐	☐	☐	☐	☐	☑	☐	☑	540
	22:00 - 23:00	☑	☐	☑	☑	☐	☑	☐	☐	☐	☐	☐	☐	☑	☐	☐	640
	23:00 - 00:00	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	10
	HOURS	8	1	17	10	9	7	7	7	7	10	6	1	12	3	4	TOTAL Wh
	WATTHOURS	400	30	170	1800	360	1400	70	70	70	500	60	200	2400	60	240	7830

Figure 9–1. Appliance Schedule Activation

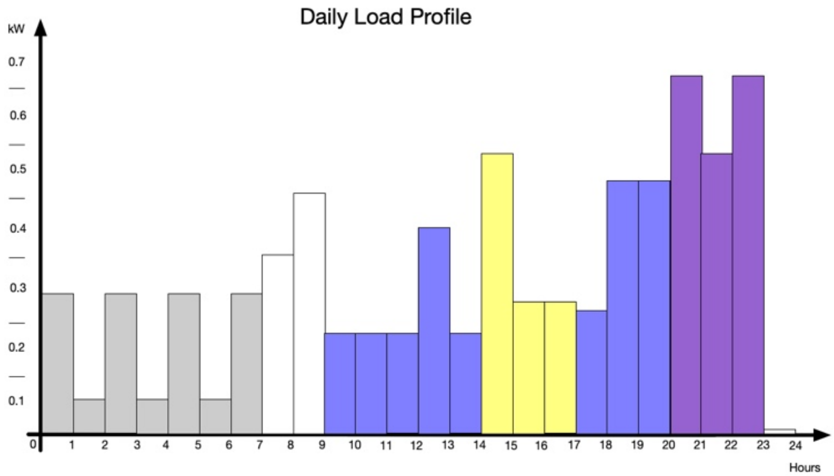


Figure 9–2. Daily load profile

2.3.2 Event Load

The event load (L_2) is dedicated to live events and consists mainly of a sound system and stage lighting. The equipment chosen is based on the execution of a live music event and is a high-voltage device with a range of power consumption depending on the application. Different power is consumed when frequencies are played through. Bass frequencies consume more energy than higher frequencies, so different genres have different consumption levels[29]. The events are designated to last for a maximum of three hours.

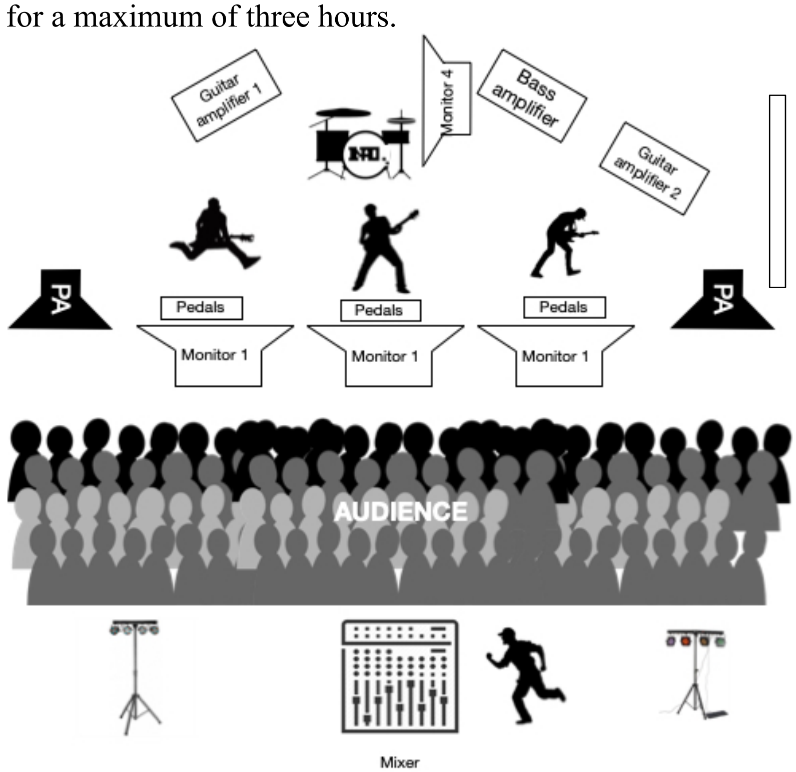


Figure 9–3. Common setup for the live music venue

◆ **Amplifier Current Draw**

The nominal power of a device is the rated power from the manufacturer. In the case of an audio amplifier, the actual energy consumed is not the nominal. In the world of audio, there is a rule of thumb that audio amplifiers use 1/8th of the nominal energy. Rarely reach a ¼ RMS power consumption of the nominal. Even at an energy consumption level of 1/3, the audio signal begins to clip due to excessive amplification.

The formula for the total consumption of live event devices:

$$\left[\left(\frac{1}{4}\right) \times \sum amplifier\ components\right] + other\ devices + stage\ light \tag{2.1}$$

TABLE 5–1 | Event Load					
Device	Wattage	Quantity	Total	¼ Nominal Wattage	1/8 Nominal Wattage
Sound					
Bass amplifier	400	1	400	100	50
Guitar amplifier	150	2	300	75	37.5
Microphone preamplifier	40	1	40	10	5
Speaker Monitors	200	4	800	200	100
Public Address System	5000	1	5000	1250	625
Mixer	100	1	100		
Effect Pedals	10	4	40		
Synth	20	2	40		
Laptop	50	1	50		
CD player	15	1	15		
other	20	-	20		
Lightning					
Device	Wattage	Quantity	Total W		
LED Stage Par 12×3	36	5	180		
	TOTAL	23	6985 2080	1262.5	

**Yellow color: power reduction is applied*
Green color: might be used optional

2.3.3 Total Load

The total household load, based on Figure 9-1, is 7830 watts. To remain safe and avoid power failure if a device is turned on for longer than computed or the power system supports guest users, an extra 15% safety margin has been added to the overall load, making up a rounded 9000 watt-hours per day.

The event load (L_2) after applying formula 2.1 is 2060 watts-hours. This is an amount of energy consumption already deducted due to the 1/8th rule of thumb. This load is planned to be used for 3 hours making the total event load (L_2) 6180Wh rounding it up to 6200Wh.

2.4 Inverter

Two main specifications must be considered to choose the proper inverter size, which has to do mainly with the output power which works in two states:

- **Continuous**
  The inverter's continuous power output, is a consistent maximum amount of amperage and a standard voltage of 120/240 VAC. This is similar to the output of a typical household outlet.
- **Peak power**
  In peak power, also known as surge power, voltage spike, transient voltage, the inverter can outburst for a relatively short time (a maximum ¼ hours), a high output of energy, usually twice the continuous power. Surge power is usually found in devices with motors or compressors that need a boost to kickstart, such as refrigerators or any device that includes motors.

The power system uses one inverter, so the maximum output of the two loads will be considered: the live load L_2 satisfying the sound amplifier loads. Other factors to be considered are:

- **Pure sine wave output**
- **Low THD**

Both of the parameters mentioned above are considered for powering the sensitive circuits of the sound system, which may affect the sound quality and the overall lifetime of the devices.

2.4.1 Sizing

Inverters usually come in 12V, 24V and 48V. The higher the voltage, the more efficient and pricier the inverters and thinner wiring needed, offsetting the cost. In order to size an inverter, all loads must be summed up to cover the case of all devices being active at once. This way, the continuous power is calculated. In most datasheets, the surge power is 1.5 to 2 times the nominal continuous power output of the inverter and is used to kick start devices that have motors.
All the devices for household load (L_1) are 1080 Wh and for event load (L_2) are 2080 Wh. That is why we will take the greater load to cover both cases.
After calculating the continuous power output, the apparent power is calculated multiply the numbers above to the power factor. In most cases it is 0.8.
Another aspect to take in consideration is the DC amps per hour and is the division of the continuous power output by the direct current voltage (24V) plus a 5% for the power loss of conversion[28].

<table>
<tr><th>TABLE 5–2 | Expected Inverter Electrical Specifications</th></tr>
<tr><td>Continuous Power Output ¼ / 1/8</td></tr>
<tr><td>2080 / 1262.5 Wh</td></tr>
<tr><td>Continuous Power Output × 2</td></tr>
<tr><td>4160 / 2525Wh</td></tr>
<tr><td>Apparent Power Output</td></tr>
<tr><td>2600 VA</td></tr>
</table>

Amp Output
86.66/52.6 A

.

2.4.2 Data Sheet Specifications

Taking into account the surge power, which, by rule, is twice the nominal rating, and the aforementioned parameters, the inverter chosen for this application is the Huawei SUN2000-4KTL-L1.

Technical Specification

Technical Specification	SUN2000 -2KTL-L1	SUN2000 -3KTL-L1	SUN2000 -4KTL-L1	SUN2000 -5KTL-L1
Efficiency				
Max. efficiency	98.2 %	98.3 %	98.4 %	98.4 %
European weighted efficiency	96.7 %	97.3 %	97.5 %	97.8 %
Input (PV)				
Recommended max. PV power [2]	3,000 Wp	4,500 Wp	6,000 Wp	7,500 Wp
Max. input voltage	600 V [3]			
Start-up voltage	100 V			
MPPT operating voltage range	90 V – 560 V [3]			
Rated input voltage	360 V			
Max. input current per MPPT	12.5 A			
Max. short-circuit current	18 A			
Number of MPP trackers	2			
Max. number of inputs	2			
Input (DC Battery)				
Compatible Battery	LG Chem RESU 7H_R / 10H_R			
Operating voltage range	350 ~ 450 Vdc			
Max operating current	10 A @7H_R / 15 A @10H_R			
Max charge power	3,500 W @7H_R / 5,000 W @10H_R			
Max discharge Power @7H_R	2,200 W	3,300 W	3,500 W	3,500 W
Max discharge Power @10H_R	2,200 W	3,300 W	4,400 W	5,000 W
Compatible Battery	HUAWEI Smart ESS Battery 5kWh – 30kWh [1]			
Operating voltage range	350 ~ 560 Vdc			
Max operating current	15 A			
Max charge Power	5,000 W [4]			
Max discharge Power	2,200 W	3,300 W	4,400 W	5,000 W
Output				
Grid connection	Single phase			
Rated output power	2,000 W	3,000 W	4,000 W	5,000 W [5]
Max. apparent power	2,200 VA	3,300 VA	4,400 VA	5,500 VA [7]
Rated output voltage	220 Vac / 230 Vac / 240 Vac			
Rated AC grid frequency	50 Hz / 60 Hz			
Max. output current	10 A	15 A	20 A	25 A [8]
Adjustable power factor	0.8 leading ... 0.8 lagging			
Max. total harmonic distortion	≤ 3 %			
Backup power output	Yes (via Backup Box-B0 [7])			

Figure 10–1. Inverter Technical specification

Figure 10–2. Huawei SUN2000-4KTL-L1

2.5 Battery
Batteries contain chemical contents that in many countries restrict the amount carried on a vehicle and usually occupy a relatively large space.

2.5.1 Sizing
The sizing of the battery depends on many parameters. A sufficient amount of battery capacity is calculated by considering many parameters. The more factors considered, the more accurate the estimation of ampere-hours required. The basic parameters are:

- **Days of autonomy**
- **Daily energy consumption**
- **Depth of discharge** (DOD)
- **DC power system voltage** (V_{dc})

For an even more accurate calculation on the battery sizing, these parameters could also be taken into account:

- **Inverter efficiency** (Eff_{inv})
- **Battery to load cable efficiency** (Eff_{cable})
- **Temperature Exposure**

Based on all of the above, the formula that calculates the capacity of the battery is[13]:

$$C = \frac{Daily\ kW\ consumed\ \times\ Days\ of\ autonomy}{V_{dc} \times\ DOD\ \times\ Eff_{inv}\ \times\ Eff_{cable}} \tag{2.2}$$

◆ **Case Study**
With a day of autonomy of one day, the battery that satisfies the household load (L_1) is 7830Wh (B_1), and for the event load (L_2) 6200Wh (B_2), DOD at 95%, inverter efficiency 95%, cable efficiency 95% and DC power system voltage of 24 V.

TABLE 6–1 | Battery Capacity Calculation			
LOAD	**DEMAND**	**BATTERY**	**CAPACITY**
Household Load (L1)	9000 Wh	Household (B_1)	437.66205 Ah
Event Load (L2)	6200Wh	Event (B2)	318.046578 Ah

Figure 11–1. Lithium Battery

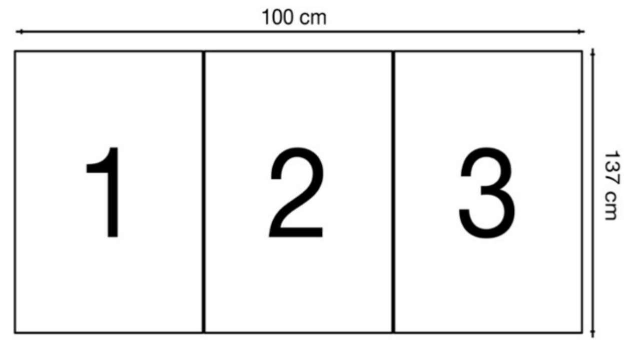


Figure 11–2. Battery Bank Size

2.5.2 Data sheet specifications

There are many types of batteries to install, but the most suitable for this type of use is lithium-ion batteries. Lithium-ion batteries are the safest option due to their low weight and lack hazardous spillable liquids compared to the previously widely used lead-acid batteries.
The chosen battery is from the company RENOGY, a lithium-ion phosphate battery.

TABLE 6–2 | BATTERY BANK RENOGY REGO 12V 400Ah	
Quantity	3
PHYSICAL CHARACTERISTICS	
Length (L)	1 m
Width (W)	1.37 m
Height (H)	0.8 m
Weight	153 kg
ELECTRICAL CHARACTERISTICS	
Nominal Voltage	12.8V
Rated Capacity	400Ah
Boost Voltage	14.4V
Maximum Charge Current	300A
Maximum Discharge Current	350A

2.5.3 Circuit Configuration

The batteries must be connected in a particular manner to match the system's capacity and voltage. In this case, there are three packs of 12.8 V, 400 Ah, two connected in series for L_1, and one separate for the special load L_2.

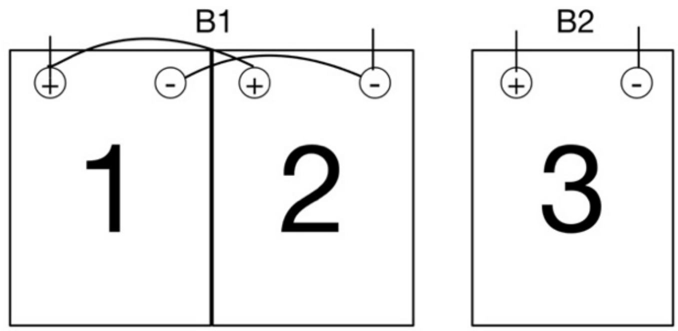


Figure 11–3. Battery configuration

CHAPTER 3 | Modeling

Modeling is the process of expressing the information of the world through mathematical equations. The system is considered an additional power system from the preexisting automotive power system plus photovoltaics. There are 2 batteries and 2 loads, each for a separate kind of use, channeled by one charge controller.

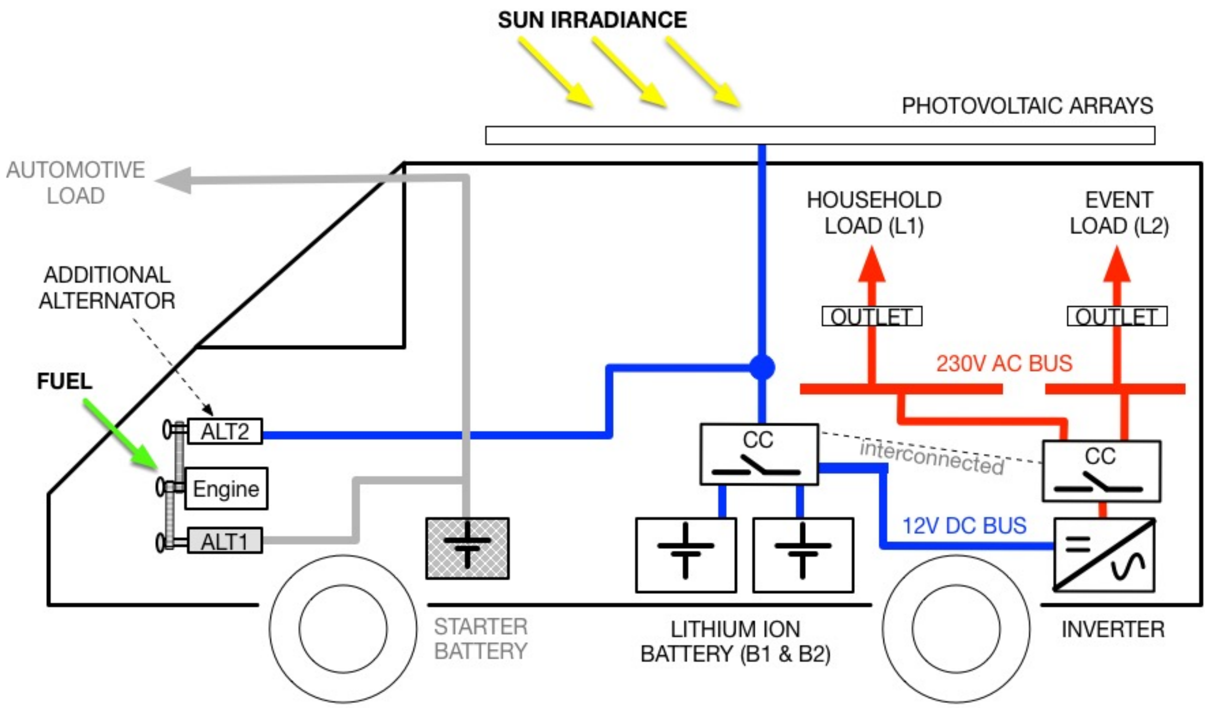


Figure 12–1. Power System Circuit Diagram

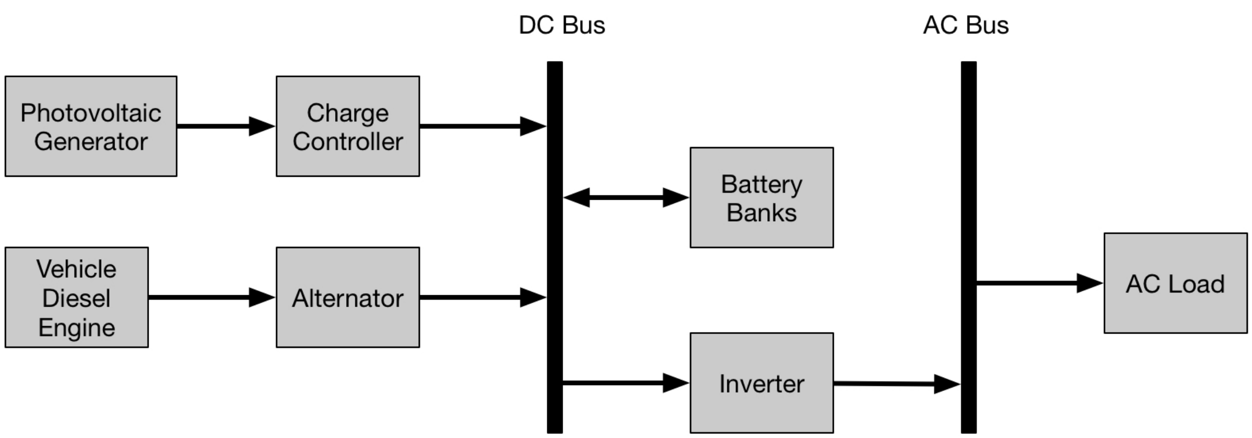


Figure 12–2. Power System Flow Diagram

3.1 Powertrain

Stripping down the vehicle to its vital parts is the powertrain and consists of all the parts that make the vehicle move. Those parts include:

- **Engine**
- **Transmission**
- **Rear Axle**

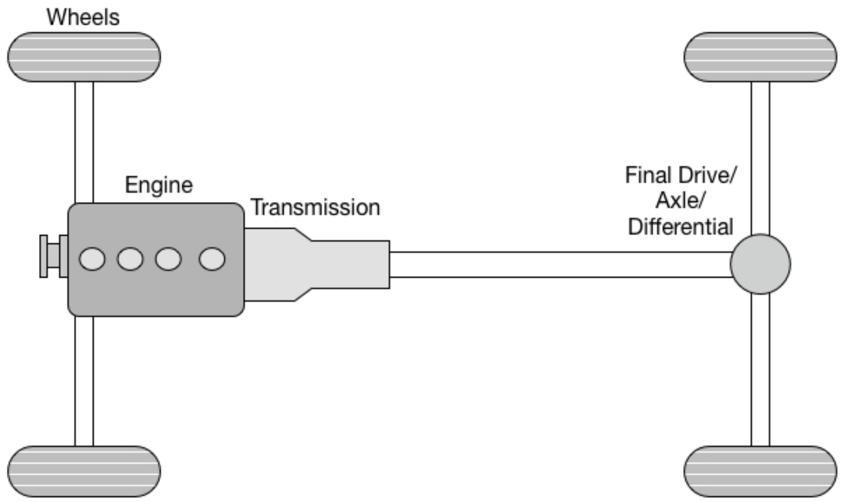


Figure 12–3. Powertrain outline

3.1.1 Engine

The engine's performance characteristics taken into consideration are the power production and fuel consumption. In this case, the automobile has the diesel engine SOFIM 8140.43S chosen because of itsnnbbbb wide span of values. According to the manufacturers manual, the engine idles at 800 RPM, and runs at a maximum speed of 3600 RPM; However, the graph depicts starting from 1200 RPM so the rest of the gap of [800,1200) is calculated via an interpolation method used with MATLAB's predefined functions [17]. All information is then structured in a look up table.

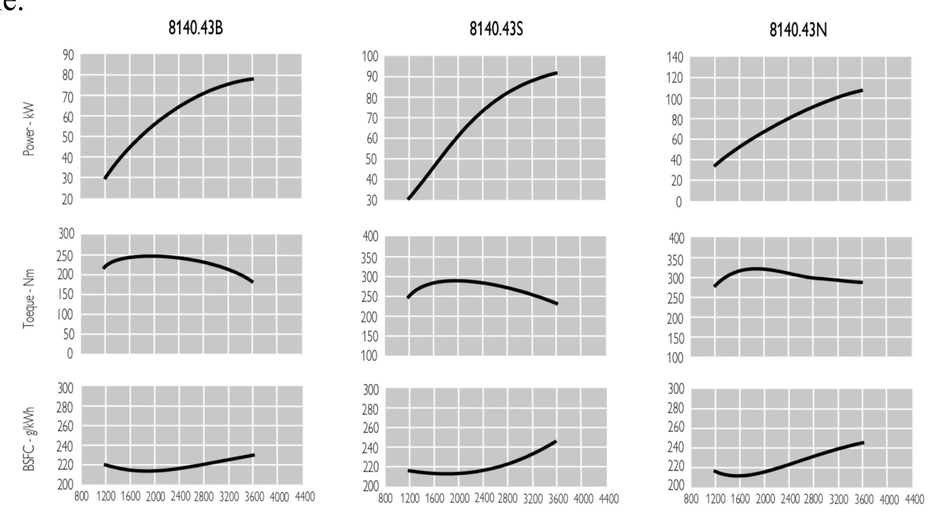


Figure 12-4. Engine datasheet information

- **Compressor input temperature 25 °C**
- **Intercooler outlet temperature 45 °C**
- **atmospheric pressure 100kPa**
- **Loss of load in engine input: 3.5 kPa**
- **Cetane number > 52**
- **Diesel Density: 835 g/dm³**

3.1.2 Rear Axle

An automotive rear axle is a rod that links mechanically the transmission to the driving wheels also known as final drive or differential.
This gear contributes to the system's overall gear ratio.
The powertrain's rear axle ratio is 3.1615. Other standard values indicatively are 4.44 and 3.91.

3.1.3 Transmission

The transmission used in this simulation is a 6-speed synchromesh named 2840.6 OD. The gear ratios for this particular model are listed below from the datasheet.

TABLE 7–1 | Gear ratios

Gear	Ratio
1st	5.375
2nd	3.154
3rd	2.041
4th	1.365
5th	1
6th	0.791
Reverse	4.838

◆ **Gear shift strategy**

The gear shift strategy modeled is a combination of fixed vehicle speed and imposed engine speed strategy.[14]
The speed intervals have been divided by the maximum rounds per minute which is 3600 and is constant for each gear. By adding the maximum allowed RPM of the engine in each transmission gear to formula 3.1, speed pockets are established. These intervals are directly correlated to each gear number, providing a threshold for when the gear should shift.

$$Top\ Speed = \frac{0.06 \times maxRPM \times \ [\pi \ \times Diameter_{tire}]}{gear\_ratio_{gear} \times Rear\_Axle\_ratio} \tag{3.1}$$

TABLE 7-2 Gear to corresponding threshold speed	
Top Velocity (km/h)	**Gear Shift**
22.52	1^{st}
38.39	2^{nd}
59.32	3^{rd}
88.7	4^{th}
121.08	5^{th}
153.07	6^{th}

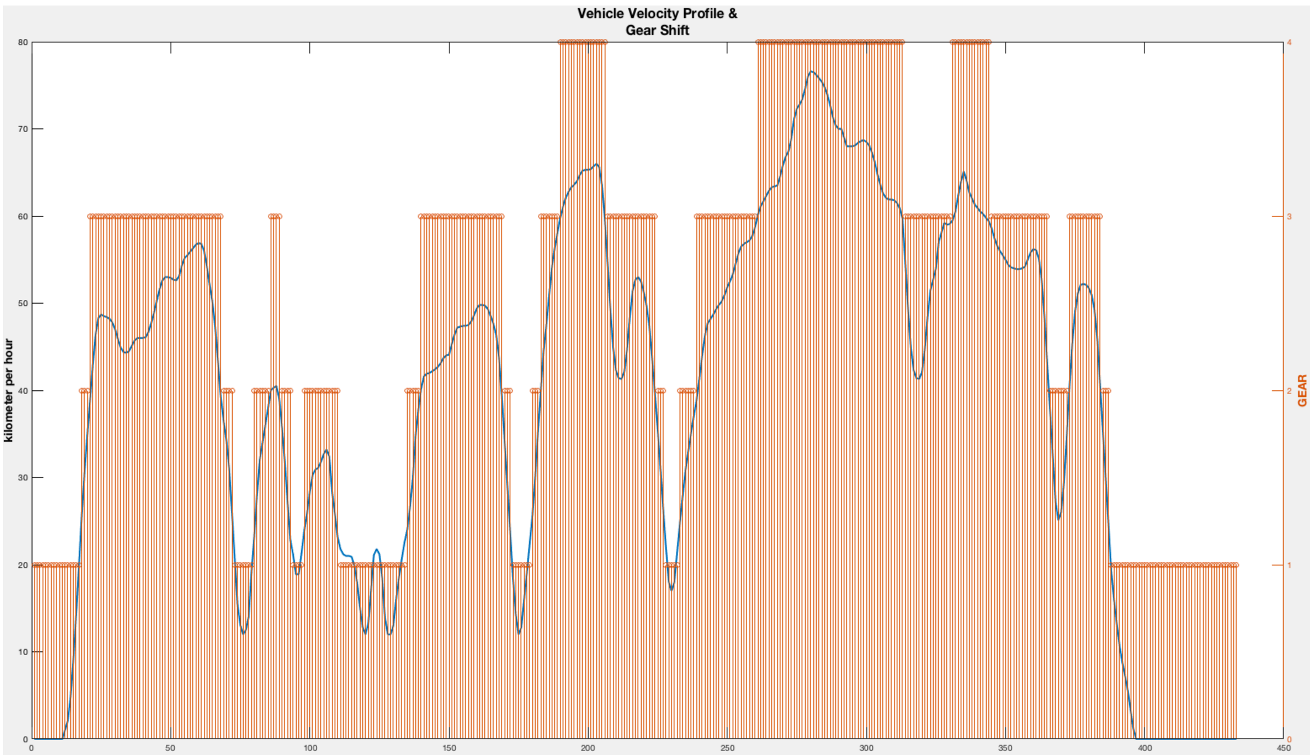


Figure 12–5. Gear Shift strategy applied

3.2 Photovoltaics

The formula to calculate the estimated energy production in watts of the photovoltaic array is calculated below:

$$E = A \times r \times H \times PR \quad (3.2)$$

Where:

- $\boldsymbol{A}$ Area size in m^2
- r Efficiency
- $\boldsymbol{H}$ Solar Irradiance in W/m^2
- $\boldsymbol{PR}$ Power Ratio

3.3 Alternator

The alternator can be modeled as a separate entity combining the alternator and engine as one. This can also be described as the alternator-engine system due to the fact that the alternator is interdependent on the engines' RPM. Abstractly, it can be viewed as a support engine genset or backup generator used in an ordinary photovoltaic system design but with a variable rotor speed based on the car engine's RPM or can be seen as a wind turbine being affected by the speed limits of the road.

As with the engine, the alternators datasheet RPM–Ampere output is also modeled to a lookup table.

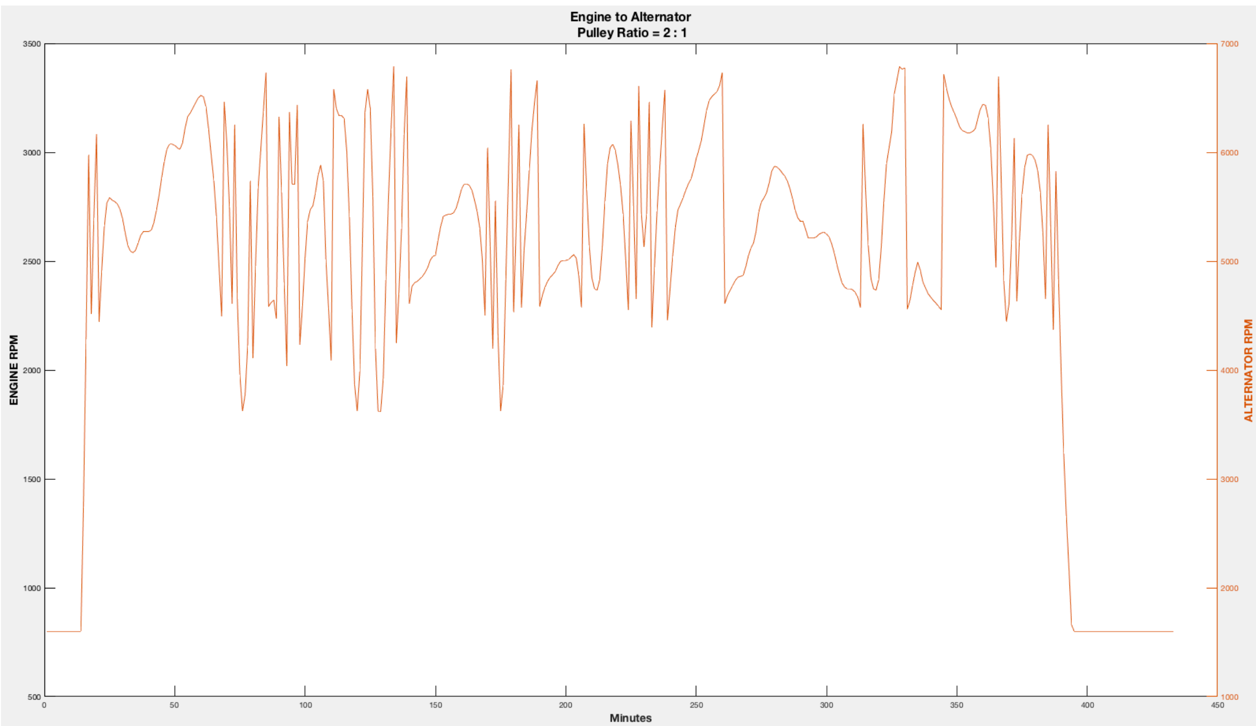


Figure 12–6. Engine vs Alternator RPM (MATLAB graph)

3.4 Battery

The battery is modeled as a bank of energy measured in kWh. Energy is drawn from the battery without an additional parameter of loss, such as cable heat loss or battery internal resistance, because of the imperceptible effect. The draw of energy is a subtraction of the energy reservoir and the load demand. Addition is done when excess energy is produced and saved in the batteries, adding to the reservoir.

3.5 Charge Controller

The charge controller operates with a clear priority, always ensuring that the household load (L_1) battery (B_1) is charged before the live venue battery (B_2).
This system is made possible by the charge controller's inbuilt programmable microcontroller and relay switch, which monitors the SOC of B_1 and channels the power source switch to B_2 only when B_1 is fully charged.
When the user takes the initiative to switch manually the relay on, the channel opens to battery B2 for discharging also. After B2 discharges at the predefined DOD the channel closes to its not previous, but first state with the ability to charge and discharge B1, prioritizing and activating the household use channel.

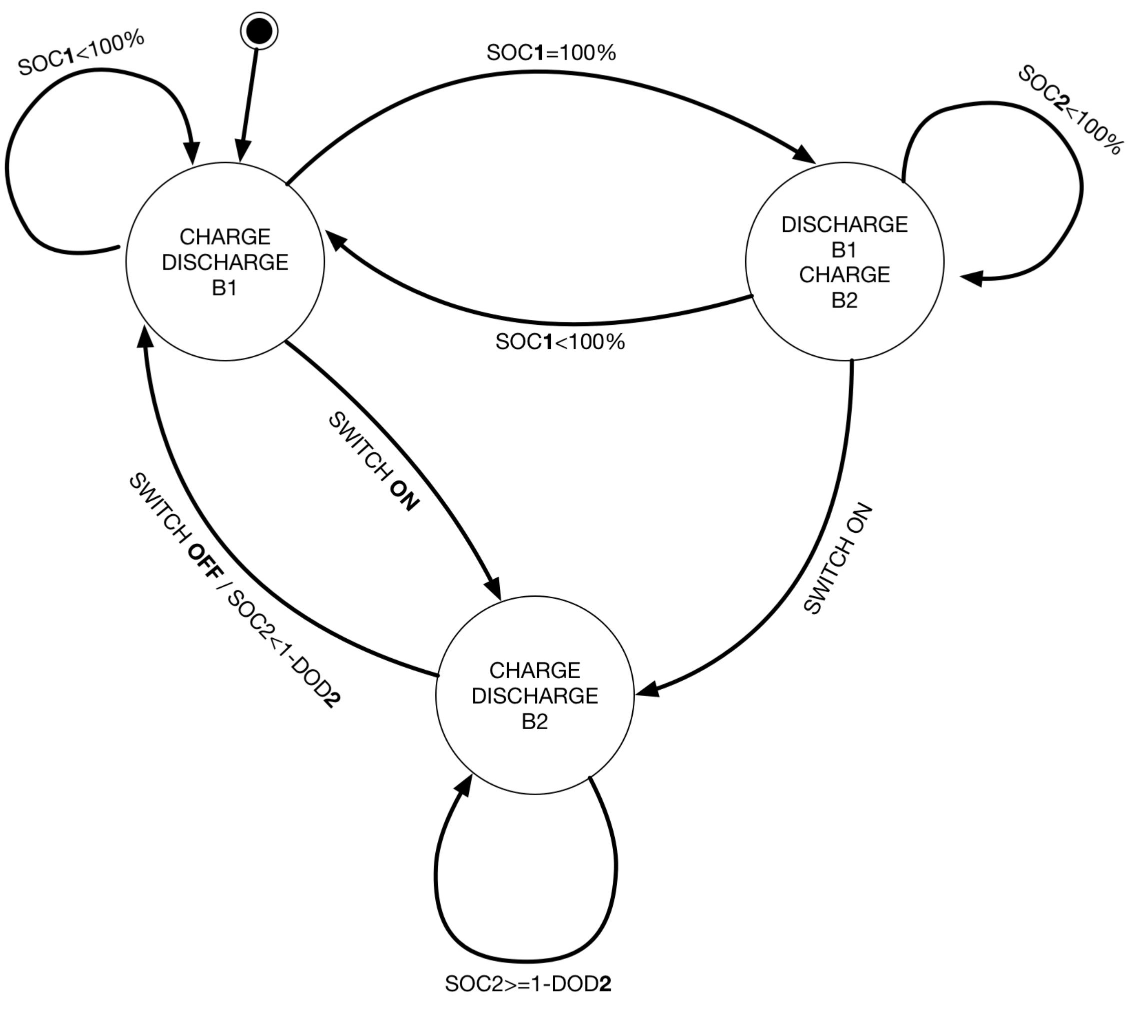


Figure 12–7. Finite State Machine (FSM) of Charge Controller

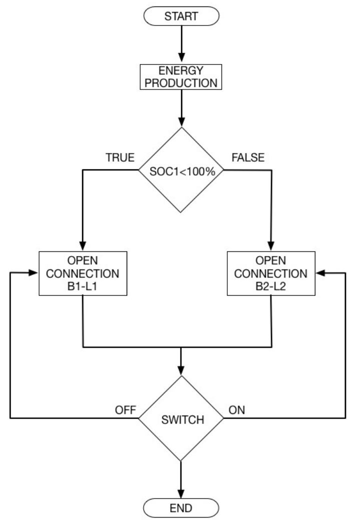


Figure 12–8. Power switching logic Flow Diagram

◆ Controller Operation

The user can choose one of the 2 channels: batteries (B_1, B_2) and loads (L_1, L_2). In the scenario when the day of the live event comes, the user activates the switch manually to channel 2. When B_2 state of charge falls below the assigned DOD (i.e. 5%) the charge controller triggers a signal to channel back to the default channel 1, L_1-B_1; also known as the household channel.

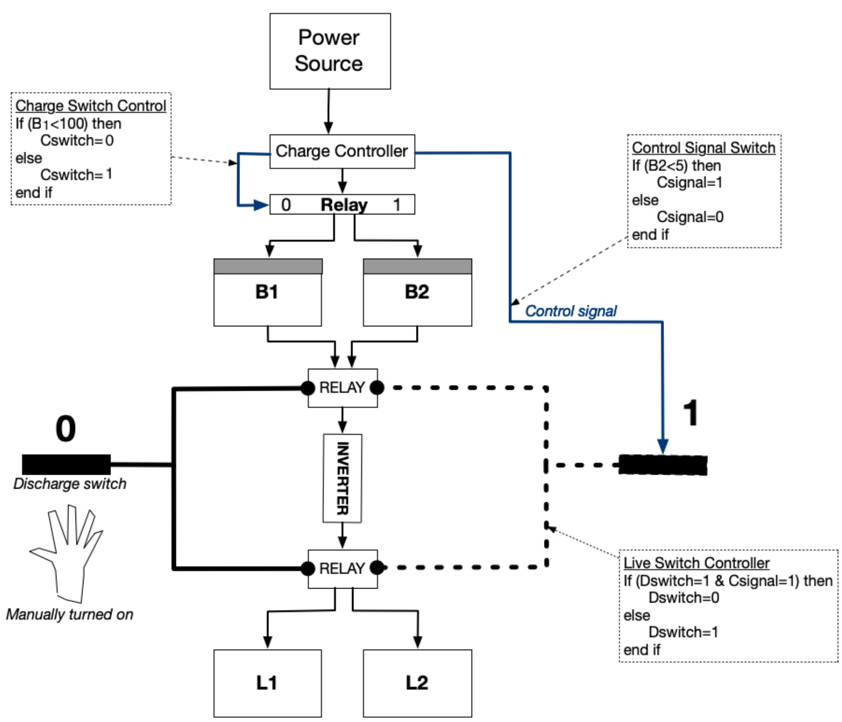


Figure 12–9. Power switching logic Physical Implementation

3.6 Input / Output System

The input and output of the system at an hourly rate are listed below.

■ **Input**:
- Solar Irradiance
- Road

■ **Output**:
- Consumption Curve
- Cost Function

The input is convolved to the output via formulas.

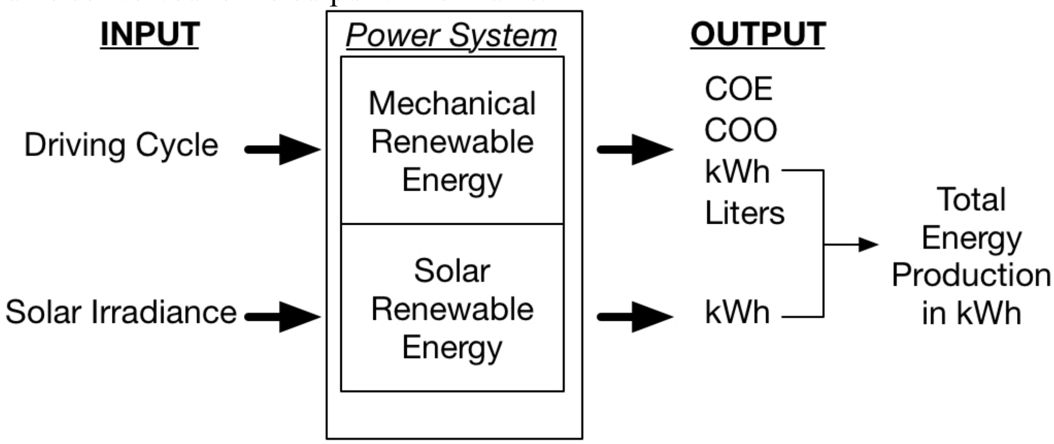


Figure 12–10. I/O Power System

3.6.1 Input

— 3.6.1.i Solar Irradiance

The information to simulate the photovoltaic energy production was acquired from the National Solar Radiation Database (NSRDB) and can extract information on an hourly or half-hourly basis on climatic measurements. The information about the three variable that describe solar irradiance were extracted and are: global horizontal irradiance (GHI), direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI) all measured in watts per square meter (W/m^2).

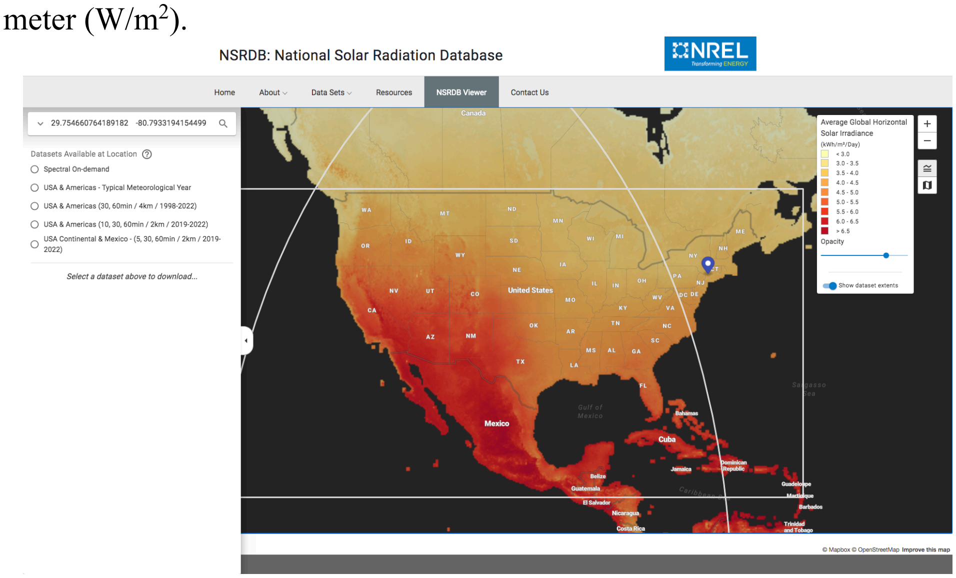


Figure 12–11. National Solar Radiation Database interface

— 3.6.1.ii Road

The road is a function of two parameters:

- **Velocity**
  The velocity is limited by the federal speed limit postings
- **Time**
  The time duration of the travel is limited by the maximum allowable continuous driving time according to the law.

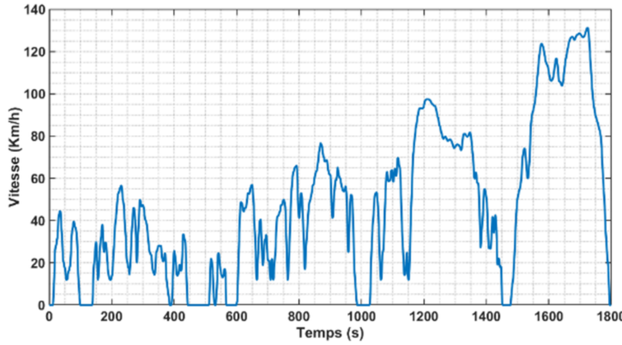


Figure 12–12. WLTP graph

The driving cycle used is the World Harmonized Light vehicles Test Procedure (WLTP) and is considered a global standard when it comes to testing vehicles and their energy consumption. In addition, it is worth mentioning that other standards like the NEDC, Sords, and FTP-75 are not used. Also, a 1-hour drive steady velocity at different speeds has been used.

3.6.2 Output

—3.6.2.i Consumption Curve

The diesel engine consumption curve in liter per hour is calculated through formula (.4) using the information from engine's datasheet and knowing the fuel density.
The conversion of the engines break specific fuel consumption (BSFC) graph from g/kWh to liter per hour, can be done by multiplying the product of engine power (kW) and consumption (BSFC) at a particular round per minute (RPM) by the constant of the reverse density (lt/g) of the fuel:

$$\left(\frac{g}{kWh} \times kW\right) @\, RPM \times \frac{lt}{g} = {}^{lt}/_{h}\ @RPM \qquad (3.3)$$

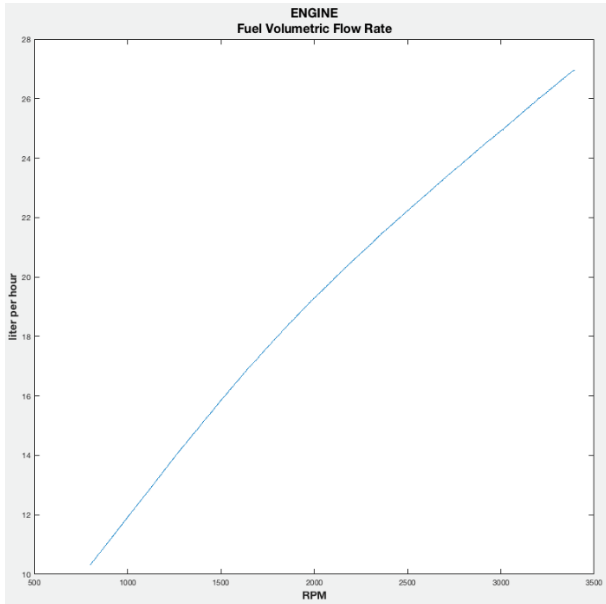


Figure 12–13. Fuel consumption (graph)

— 3.6.2.ii Cost Functions

The variables that make up the cost function are mainly economic, depending on the cost of energy produced, the energy produced, and the hourly rate of that quantity.

– **Cost Of Operation (COO)**
  The product of the total fuel consumed in liters and fuel cost calculated in dollars or commonly known as the how many dollars spent to complete the road trip.

$$\text{Cost } \mathbf{Of}\ \mathbf{O}\text{peration} = \text{Fuel Consumption} \times \text{Cost of Fuel} = \$ \quad (3.3)$$

– **Cost Of Energy (COE)**
  This value is the currency per kWh.
  The instant of engine fuel consumed is divided by the alternator power output.

$$\textbf{Cost Of Energy} = \frac{\textbf{Engine Fuel consumption} \times \textbf{Price}}{\textbf{Alternator Power Production}} = \$/\text{kWh} \quad (3.4)$$

— 3.6.2.iii Solar power

The solar power is calculated using equation 3.2

CHAPTER 4 | Simulation: Evaluation, Scenarios & Results

In this chapter, the conditions under which the system will operate are simulated through computer programs. First, the model is tested by running the system through some case tests, and the results are evaluated. Then, real-life scenarios are written to examine the system's energy autonomy under different circumstances.

4.1 Application Programs

Data was acquired and processed through several programs. Below are all the computer programs used to realize the simulation of the renewable power system. After running the heavy computational code on MATLAB and importing all the image graphs through WebPlotDigitizer, all the data is added to Microsoft Excel to run an hour-by-hour simulation of the scenarios written. All programs are mentioned in the order that they have been used.

4.1.1 WebPlotDigitizer

All datasheet graphs are inserted into the program WebPlotDigitizer, which recognizes the graph and samples it at a chosen rate.

The graphs screenshotted from the engines and alternators' data are inserted into the program. The values are sampled at a sample rate of 1 RPM and exported to a comma-separated value (CSV) file, where the engines' break specific fuel consumption (BSFC), power production, and alternator's ampere output graph are recorded.

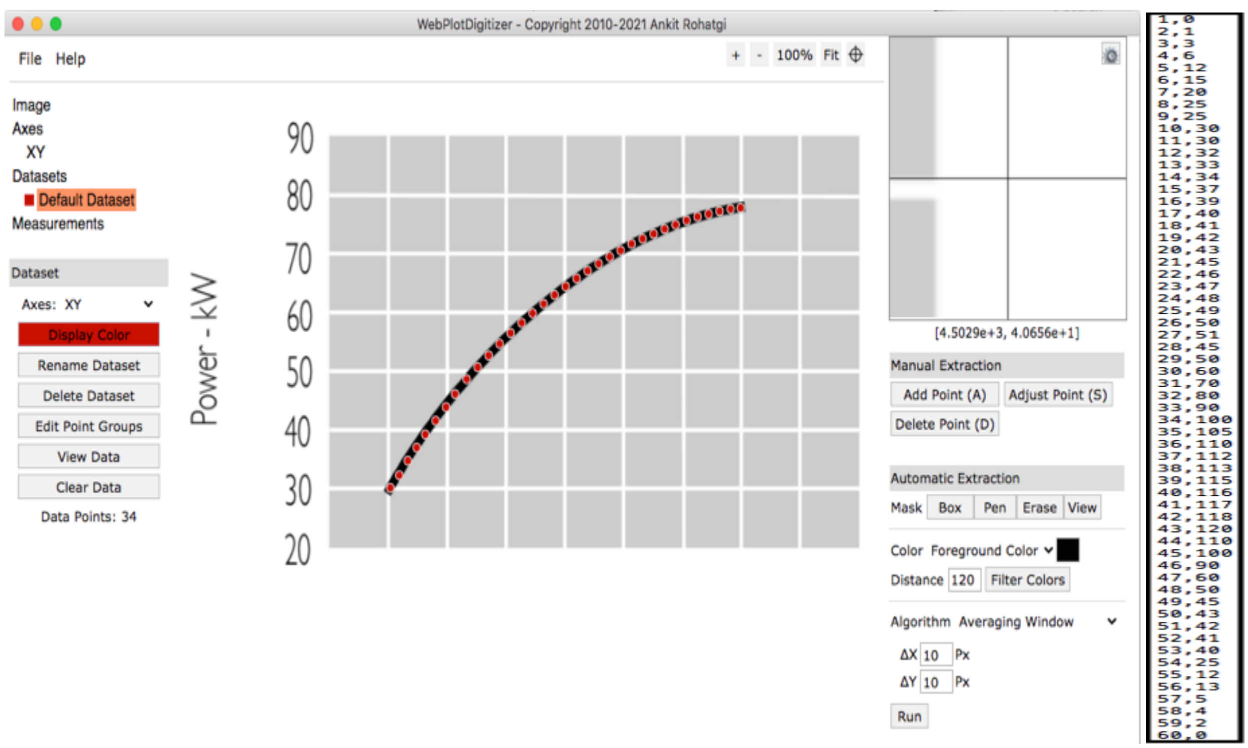


Figure 13–1. WebPlotDigitizer (left), Opened CSV file (right)

4.1.2 MATLAB

MATLAB is a programming language developed by the American company MathWorks and calculates heavy computational tasks such as vector multiplications and function plotting.
A series of algorithms process the data from the engine and the alternator and compute the desired outputs.
Below is the visual modeling of the code structure utilizing the flow chart diagram.

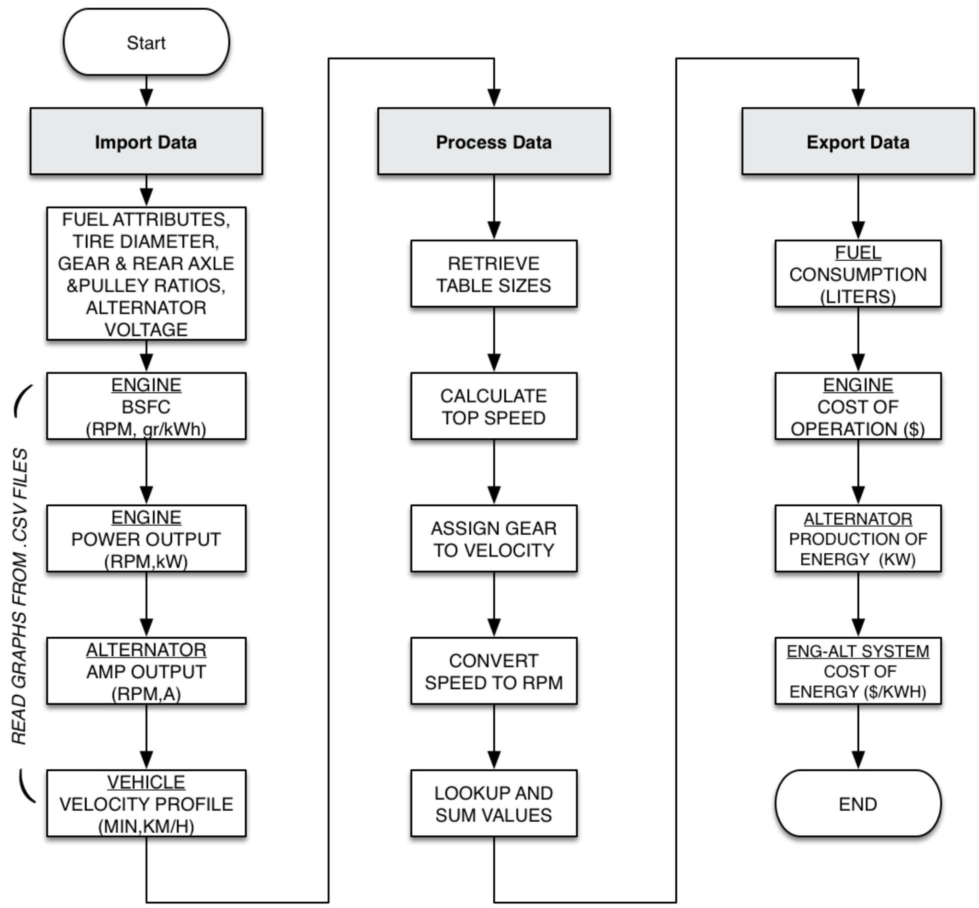


Figure 13–2. Flow chart diagram of code structure

Below are the algorithms that define the conversion of the velocity of the vehicle to rounds per minute and the calculation of the alternator-engine output; both variables registered in arrays.

■ **Algorithm 1: Velocity to RPM**

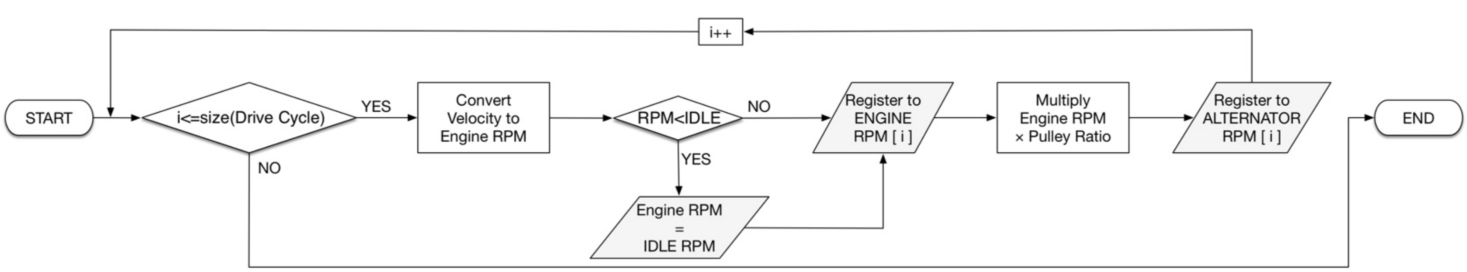


Figure 13–3. Flow chart: Velocity to engine RPM conversion

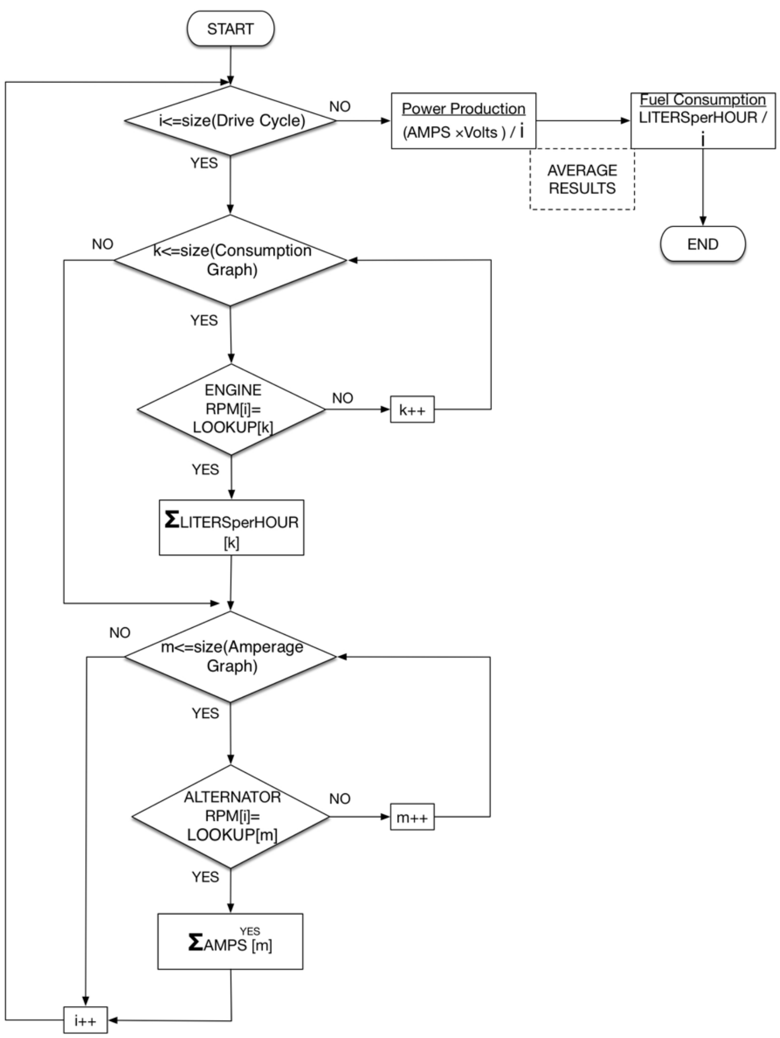
```
for i=1:r3

RPM=round(((DriveCycle(i,2)*GEAR_RATIO(GEAR(i))*REAR_AXLE_RATIO)/(0.06*pi*
TIRE_DMT))); %Equation 3.2
%%round it up so it could match to an RPM

    if RPM < 800
       RPM_ENG(i)=IDLE;
       RPM_ALT(i)=IDLE*PULLEY_RATIO;
    else
       RPM_ENG(i)=RPM;
       RPM_ALT(i)=RPM*PULLEY_RATIO;
    end

end
```

■ **Algorithm 2: Sum values**




```
for j=1:r3 %% master loop


%% nested loop 1: ENGINE
for k=1:r1
    if RPM_ENG(j) == x1(k)%__ADD UP___
      sum1=sum1+y3(k)%Fuel Consumption
      sum2=sum2+y2(k)%Energy Production
      break
    end
end


%% nested loop 2: ALTERNATOR
for l=m:r4
    if RPM_ALT(j) == x4(l)
      sum3=sum3+y4(l);%Total Amperage
      RPM_ALT_ENEG(j)=y4(l)*
VOLTAGE_ALT;%Total Alternator Energy Production
       break
    end
end

end

%% RESULTS
TOTAL_LITERS=sum1/60/60;
TOTAL_FUEL_COST=TOTAL_LITERS*DIESEL_PRC;
TOTAL_ALT_POWER=(sum3*VOLTAGE_ALT)/60/60;
TOTAL_ENG_POWER=sum2/60/60;

TOTAL_ENG_COE=TOTAL_FUEL_COST/TOTAL_ENG_P
OWER;
```

Figure 13–4. Flow chart: Alternator-Engine performance output

4.1.3 Excel

Excel is a computer program developed by the well-known American company Microsoft and is a spreadsheet editor. It uses Visual Basic for Applications (VBA) as its programming language and can be layered into many spreadsheets via so called worksheet tabs.
The spreadsheet file contains all the specifications and formulas of each component in separate worksheet tabs and process all the information in a day, at an hourly rate for a week.

	INPUT POWER RESOURCES			OUTPUT POWER (Wh)			ENERGY COMPENSATION (Wh)				ENERGY STORAGE SYSTEM				EXPENSES	
HOUR	SUN (W/m²)	GENSET (IDLE)	VEHICLE(km/s	PV	ALT	TOTAL	LOAD1	LOAD2	TOTAL	(OUT-IN)PUT	SOC1 (%)	SOC2(%)	B1(Wh)	B2(Wh)	LITERS	COO
0	0	0	0	0.00	0	0.00	280	0	280	-280.00	47.10	100.00	4539.94	7633.12	0	0
1	0	0	0	0.00	0	0.00	90	0	90	-90.00	46.16	100.00	4449.94	7633.12	0	0
2	0	0	0	0.00	0	0.00	290	0	290	-290.00	43.15	100.00	4159.94	7633.12	0	0
3	0	0	0	0.00	0	0.00	90	0	90	-90.00	42.22	100.00	4069.94	7633.12	0	0
4	0	0	0	0.00	0	0.00	290	0	290	-290.00	39.21	100.00	3779.94	7633.12	0	0
5	42	0	0	41.67	0	41.67	90	0	90	-48.33	38.71	100.00	3731.62	7633.12	0	0
6	199	0	0	197.46	0	197.46	290	0	290	-92.54	37.75	100.00	3639.08	7633.12	0	0
7	389	0	0	385.99	0	385.99	350	0	350	35.99	38.12	100.00	3675.06	7633.12	0	0
8	578	0	0	573.52	0	573.52	460	0	460	113.52	39.30	100.00	3788.58	7633.12	0	0
9	745	0	0	739.23	0	739.23	230	0	230	509.23	44.58	100.00	4297.81	7633.12	0	0
10	877	0	0	870.20	0	870.20	430	0	430	440.20	49.15	100.00	4738.01	7633.12	0	0
11	966	0	0	958.51	0	958.51	230	0	230	728.51	56.71	100.00	5466.53	7633.12	0	0
12	1001	0	0	993.24	0	993.24	430	0	430	563.24	62.55	100.00	6029.77	7633.12	0	0
13	985	0	0	977.37	0	977.37	230	0	230	747.37	70.30	100.00	6777.13	7633.12	0	0
14	915	0	0	907.91	0	907.91	590	0	590	317.91	73.60	100.00	7095.04	7633.12	0	0
15	785	0	0	778.92	0	778.92	80	0	80	698.92	80.85	100.00	7793.96	7633.12	0	0
16	553	0	0	548.71	0	548.71	280	0	280	268.71	83.64	100.00	8062.67	7633.12	0	0
17	301	0	0	298.67	0	298.67	270	0	270	28.67	83.94	100.00	8091.34	7633.12	0	0
18	266	0	0	263.94	0	263.94	680	0	680	-416.06	79.62	100.00	7675.28	7633.12	0	0
19	93	0	0	92.28	0	92.28	480	0	480	-387.72	75.60	100.00	7287.56	7633.12	0	0
20	0	0	0	0.00	0	0.00	680	0	680	-680.00	68.54	100.00	6607.56	7633.12	0	0
21	0	0	0	0.00	0	0.00	340	0	340	-340.00	65.02	100.00	6267.56	7633.12	0	0
22	0	0	0	0.00	0	0.00	640	0	640	-640.00	58.38	100.00	5627.56	7633.12	0	0
23	0	0	0	0.00	0	0.00	10	0	10	-10.00	58.27	100.00	5617.56	7633.12	0	0
TOTAL	W/m ² /Day	GENSET HOUR	DRIVE HOURS	WATT/DAY		WATTH/DAY			LOAD/DAY		OVERLOAD		LOSS		LITERS/DAY	$/DAY
	8710	0	0	8627.61	0.00	8627.61	7830	0	7830		0	0	0	0	0	0

DAY1 | DAY2 | DAY3 | DAY4 | DAY5 | DAY6 | DAY7 | OVERALL | SOLAR IRRADIANCE | FUEL | SOLAR PANEL | ALTERNATOR-ENGINE | BATTERY & OTHER | LOAD1 | LOAD2 | +

Figure 13–5. Microsoft Excel spreadsheet (above)

◆ Breakdown

■ Worksheet tabs

They are 7 identical and interconnected consecutively spreadsheets that represent a week, DAY1 being the first day of the week, DAY2 being the second day etc. These aforementioned spreadsheets retrieve the information from the other worksheet tabs from the same file and constitute the main place of calculations for the simulation.

DAY1 | DAY2 | DAY3 | DAY4 | DAY5 | DAY6 | DAY7

Figure 13–6. Microsoft Excel worksheet tabs: Simulation day by day

SOLAR IRRADIANCE | FUEL | SOLAR PANEL | ALTERNATOR-ENGINE | BATTERY & OTHER | LOAD1 | LOAD2

Figure 13–7. Microsoft Excel worksheet tabs: Power System Components

The day-by-day spreadsheets are divided into 5 sections: Input Power Resources, Output Power (Wh), Energy Compensation (Wh), Energy Storage System, Expenses.

INPUT POWER RESOURCES | OUTPUT POWER (Wh) | ENERGY COMPENSATION (Wh) | ENERGY STORAGE SYSTEM | EXPENSES

Figure 13–8. Microsoft Excel spreadsheet sections

■ **Cell modification**

The only cells that are writeable on the "DAY" spreadsheets to intervene with the simulation other than the weather conditions and load of the users daily routine are below the cells that state:

- **GENSET (IDLE)**
  Adding 1 to the cell means the vehicle is idling for that hour and zero means engine off for same amount of time.

- **Vehicle (km/h)**
  Inserting the hourly average speed of the automobile.

- **LOAD2**
  Adding the load amount in kWh for the hour of event consumption. For instance, according to equation 2.1 the total amount of the event load is 2000 watthours, and that value could be added to cell.

■ **Conditional Structures**

To regulate the values of each cell and format the values to real-world characteristics, conditions where applied using the IF function:

- **Battery**
  A battery has a specific amount of capacityrf. , meaning a subtraction and addition without no limits will make the battery overcharge or undercharge. Excel subtracts and adds variables without limit. To simulate the two batteries (B_1 & B_2) characteristics.

- **Overcharge / Undercharge**
  In order to make sure that the battery does not go beyond its maximum capacity, the left condition has been applied; and on the right the battery is secured to not fall below the preassigned DOD, each having the source code below.

```
If (capacity@hour > capacitymax) then
        B1=capacitymax ;
Else
        B1=capacity@hour;
End if
```

```
IF(N3-H4+G4>'BATTERY & OTHER'!B$9,
'BATTERY & OTHER'!B$9)
```

```
If (capacity@hour < capacitymin) then
        B1=capacitymin ;
Else
        B1=capacity@hour;
End if
```

```
IF(N3-H4+G4<='BATTERY &
OTHER'!B$11, 'BATTERY & OTHER'!B$11)
```

- **Finite State Machine**
  The implementation of the charge controller's behavior logic as in section 3.4 and FSM of figure 11 is when there is an overflow of energy at a particular hour for B_1, the excess energy goes to battery B_2.

```
=IF(N3-H4+G4>'BATTERY & OTHER'!B$9,'BATTERY & OTHER'!B$9, IF(N3-
H4+G4<='BATTERY & OTHER'!B$11, 'BATTERY & OTHER'!B$11,IF('BATTERY
& OTHER'!B$11<N3-H4+G4<'BATTERY & OTHER'!B$9,N3-H4+G4,N3-H4+G4)))
```

A more verbalized analysis is:
[(Battery capacity at previous hour – household load at current hour) = current SOC + overall power production] is greater than (>) the maximum battery capacity B_1 then the [overflow – the maximum battery capacity] = excess energy, is stored to battery B_2. Note that when the batteries reach the DOD, the SOC is considered 0.

– **Alternator**
Power production of the alternator is matched from the ALTERNATOR-ENGINE tab (TABLE 8-2) to the interval of speed via embedded if statements that check at what speed range it is.

```
=IF(C4=0,0,'ALTERNATOR-ENGINE'!$M$15)+IF(D4<=0,0,IF(D4<=20,'ALTERNATOR-ENGINE'!$C$8,IF(D4<=30,'ALTERNATOR-ENGINE'!$D$8,IF(D4<=40,'ALTERNATOR-ENGINE'!$E$8,IF(D4<=50,'ALTERNATOR-ENGINE'!$F$8,IF(D4<=60,'ALTERNATOR-ENGINE'!$G$8,IF(D4<=70,'ALTERNATOR-ENGINE'!$H$8,IF(D4<=80,'ALTERNATOR-ENGINE'!$I$8,IF(D4<=90,'ALTERNATOR-ENGINE'!$J$8,IF(D4<=100,'ALTERNATOR-ENGINE'!$K$8))))))))))
```

■ **Output Graph**
Using Microsoft's Excel tools and inserting a combination of charts into one graph we have a detailed graph of each day.

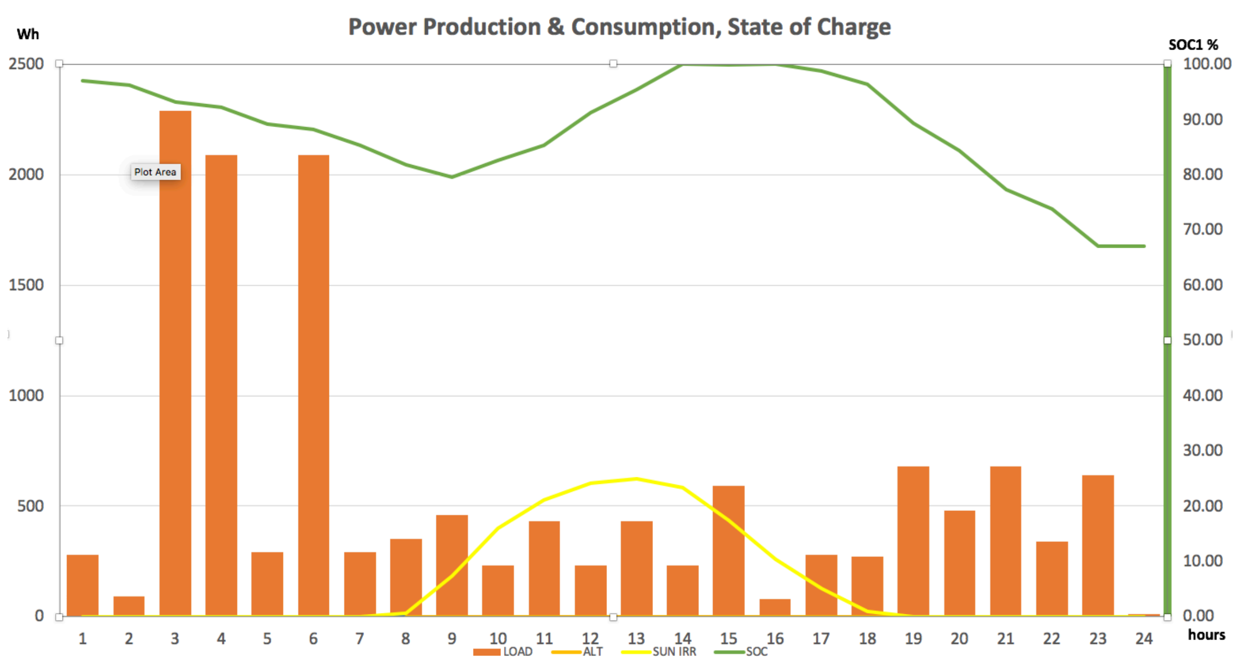


Figure 13–9. Output graph Microsoft Excel

4.2 Evaluation

The engine, alternator, and engine-alternator performance are studied by running them through a series of speed conditions. The significance of the variable condition and the span of the economic values it produces are evaluated giving an emphasis on the overload hours which are the hours that the load is not satisfied. The main goal is energy autonomy, followed by the economic aspect.

4.2.1 Case #1 – Constant speed

The alternator-engine model is tested by running the vehicle for an hour at different constant speeds.

TABLE 8–1 | Steady speed Output										
Km/h	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
Wh	1162	1619	1571	1498	1600	1480	1576	1624	1549	1595
Liters*	15.9	25	23.09	21.03	24.2	20.89	23.22	25.25	22.37	23.91
COO	27.84	43.26	40.41	36.8	42.36	36.57	40.64	44.19	39.14	41.84
COE	0.024	0.027	0.0257	0.0245	0.0264	0.0247	0.0257	0.0272	0.0252	0.0262

	TABLE 8–2 | Steady speed Statistics							
	AVERAGE	**MAX**	**MIN**	**RANGE**	**QUARTILE 1**	**QUARTILE 2**	**INTERQUARTILE RANGE**	**STANDARD DEVIATION**
Km/h	55	100	10	90	1	3		26.583202
Wh	1527.4	1624	1162	462	1510.75	1598.75	88	136.99975
Liters*	22.486	25.25	15.9	9.35	21.365	24.1275	2.7625	2.7464126
COO	39.355	44.19	27.84	16.35	37.385	42.23	4.845	4.8036612
COE	0.02566	0.0272	0.024	0.0032	0.024825	0.02635	0.001525	0.0010668

◆ **10 km/h Exclusion**

The 10 km/h output statistic is excluded from the statistical output due to its relatively lower values compared to the others, contributing to the overall statistic and affecting it.
The fuel consumption average comes out to 23.22 liters and with the 10 km/h added to the average comes out to 22.486 liters; a difference of 0.734 liter which costs approximately 3.625$ per gallon, that is 0.95 dollars per liter.
The energy production at the minimum and maximum range is 462W which is more than enough to cover an hour for a typical day. Excluding the 10 km/h, the range of energy produced is 144 watts which amount can cover half an hour of a daily routine.

4.2.2 Case #2 – Real world variable speed

The engine-alternator runs through the Worldwide Harmonized Light Vehicle Test Procedure (WLTP) to monitor its performance in real-world scenarios. The WLTP has a smaller duration, tests lasting from 9.5 minutes up to 30 minutes resulting in smaller statistical numbers.

**Fuel price 1.75$ per liter*

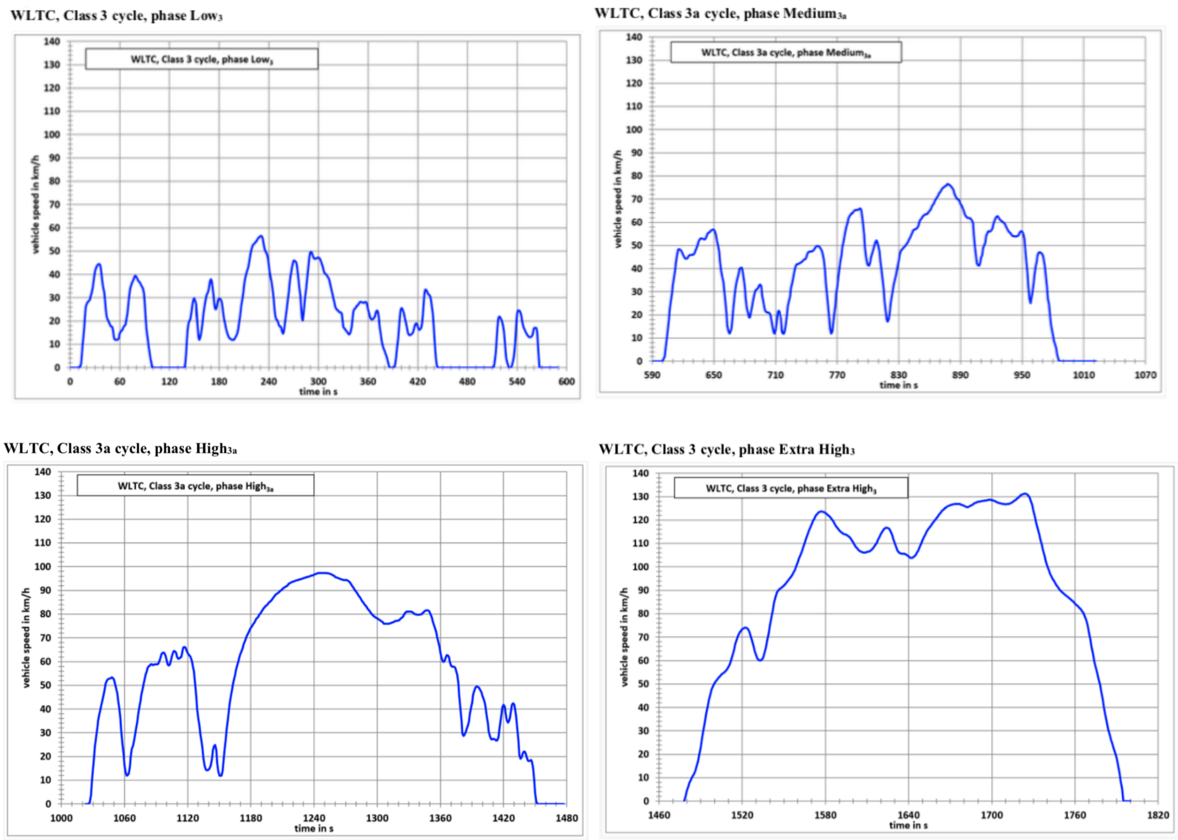


Figure 13–10. WLTP Class 3a and different phases

TABLE 8–3 | WLTP Class 3a output				
	LOW	**MID**	**HIGH**	**EXTREME HIGH**
W	183	167	186	138
Liters*	3	2.59	2.86	2.12
COO	5.34	4.54	5.01	3.72
COE	0.029	0.0271	0.0269	0.0269

	TABLE 8–4 | WLTP output statistics							
	AVERAGE	**MAX**	**MIN**	**RANGE**	**QUARTILE 1**	**QUARTILE 2**	**INTERQUARTLE**	**STANDARD DEVIATION**
W	168.5	186	138	48	159.75	183.75	24	21.97726098
Liters*	2.6425	3	2.12	0.88	2.4725	2.895	0.4225	0.387674692
COO	4.6525	5.34	3.72	1.62	4.335	5.0925	0.7575	0.70301138
COE	0.0275	0.03	0.027	0.002	0.0269	0.0276	0.0007	0.001070825

4.2.3 Case #3 – Empty to Full Charge

The field of interest discussed is related to the charging time of battery systems in emergency situations. Using a trial-and-error method, it was found that battery B1 takes 14 hours to fully charge in idle mode and 7 hours when driving. On the other hand, battery B2 takes 5 hours to charge when driving and doubles the time to 10 hours in idle mode. It is preferable to drive and

Fuel price 1.75$ per liter

charge and have 2 purposes in one rather to idle which is illegal in most countries and takes twice the time and energy.

4.2.4 Case #4 – Idling

The engine is tested under the circumstance of idling for an hour.

TABLE 8-5 | IDLE mode	
IDLE	**800 RPM**
Wh	789
Liters*	41.26
COO	72.12
COE	0.0915

This is the costliest way to charge batteries and it is twice the price and time compared to the constant speeds (section 4.2.1) and half the energy output. This high price is not an efficient method to charge the batteries.

4.2.5 Output Values

The COE has an incline of 0.001 throughout the different speeds; therefore, the variable values round up to the highest price of 0.03$/kWh when driving. Idling is a different engine operating mode, and it is priced at 0.09$/kWh.

Figure 13–11. *Proportionality of output values*

**Fuel price 1.75$ per liter*

4.3 Scenario Design

In this simulation stage, creating possible real-life scenarios and comparing the results of each diverse situation, conclusions can be drawn on the effect the weather has on the power system and the contribution of the alternator as a complimentary power source. Scenarios based on the weather; cloudiness and sun irradiation levels and activation of the engine (idling or driving) in case of non-satisfaction of the load.

The dimensioning of the system to maintain its energy autonomy, practically meaning the least overload hours accumulated possible. Although the engine itself is not considered a renewable source, its by-product while burning fossil fuel to travel, is exploited to its maximum.

First, the system's power sustainability is monitored solely with its renewable energy power sources. If every load is satisfied throughout a particular time frame, then the traveling of the vehicle or the alternator's power production could add as an addition to the replenished energy, which is the ideal scenario.

Then, if the system is not self-sustainable, the user must turn on the engine and charge the batteries for the household load, either traveling or remaining stationary with the engine on (idling).

In the previous section the performance of the alternator, engine and alternator-engine components are tested.

In this section the main goal is to test the autonomy of the motorhome when stationary for a week and travelling to change location or in the case of battery energy capacity depletion.

4.3.1 Scenario #1 - Seasonal

The effects of the different solar-powered energy outputs based on each month's average sun solace of each season representation excluding the use of the alternator have been examined.

The highest yield of solar power is in the summer season, the month of July.

February is the lowest-yielding month and is also considered the most critical month. If the system remains sustainable throughout this winter period, it should satisfy all other periods.

The sample was taken from this place because of its low irradiance levels, which means that if the power system could be reliable in these conditions, it could withstand any.

This first sample is taken during the summertime. The period chosen is July 4^{th} 2019 – July 10 2019 and peak solar irradiance reaches 1008 W/m^2.

The second sample is taken during the critical point month, which is the lowest yield of the sun irradiance period. This sample can show how autonomous and cost-effective the system is in the worst-case scenario, at a peak of 162 W/m^2 and time January 6^{th}, 2019 – January 12^{th}, 2019, which is ten times less solace than summertime.

To monitor the seasonal effect, two more samples were drawn in the milder temperatures of Fall and Spring; April 15^{th} 2019 – April 22^{nd} 2019, and October 21^{st} 2019 – October 28^{th} 2019.

The mildest sun yield is in the season of Fall and April, during which weather very often seems alike, with a peak high of 622 W/m^2 and 952 W/m^2.

TABLE 8–6 | Seasonal Weekly Energy Production

	Summer	Spring	Fall	Winter
Energy Production (Wh)	54997	41936	25938	10241
Energy reduction to maximum		24%	53%	88%

The results above are based on the number of overloads, meaning the sum of hours within the weekly timeframe tested at initial $SOC_{B1,B2}$=100% that the load is not satisfied.

TABLE 8–7 | Seasonal Overload Hours	
Season	**Overload Hours**
Summer	0
Spring	54
Fall	120
Winter	136

4.3.2 Scenario #2 – Cloud Effect

Two aspects where taken into account to study the effect the clouds have on the solar power production of the power system; the number of days and the day of occurrence of a cloudy sky, examined on a weekly basis. The clouds cut about 20% on average of the solar power.

– **Number of Days**
  To estimate the effect the cloudy days have on the weekly energy production, the following formula has been created and applied a summer period.

$$Weekly\ Energy\ Production(1-\frac{days\ of\ cloudiness}{7}\times cloudiness\ factor) \tag{4.1}$$

TABLE 8–8 | Cloud effect on weekly energy production		
Number of Days	**Energy Production** (Wh)	**Reduction**
1	53347	4%
2	51697	7%
3	50047	10%
4	48397	13%
5	46747	16%
6	45097	19%
7	43997	21%

A daily 3–4% energy reduction is recorded with the addition of a cloudy day.

– **Day of Occurrence**
  The day that the clouds occur affects the number of overload hours. The behavior of the power system is simulated in a clear and cloudy sky for seven days. Then, the simulation takes place at 1 to 7 days of continuous cloudiness at the beginning of the week and then the next day of a series of cloudy days, making up a total of 29 cases. First, at SOC=100% and then SOC=75%.

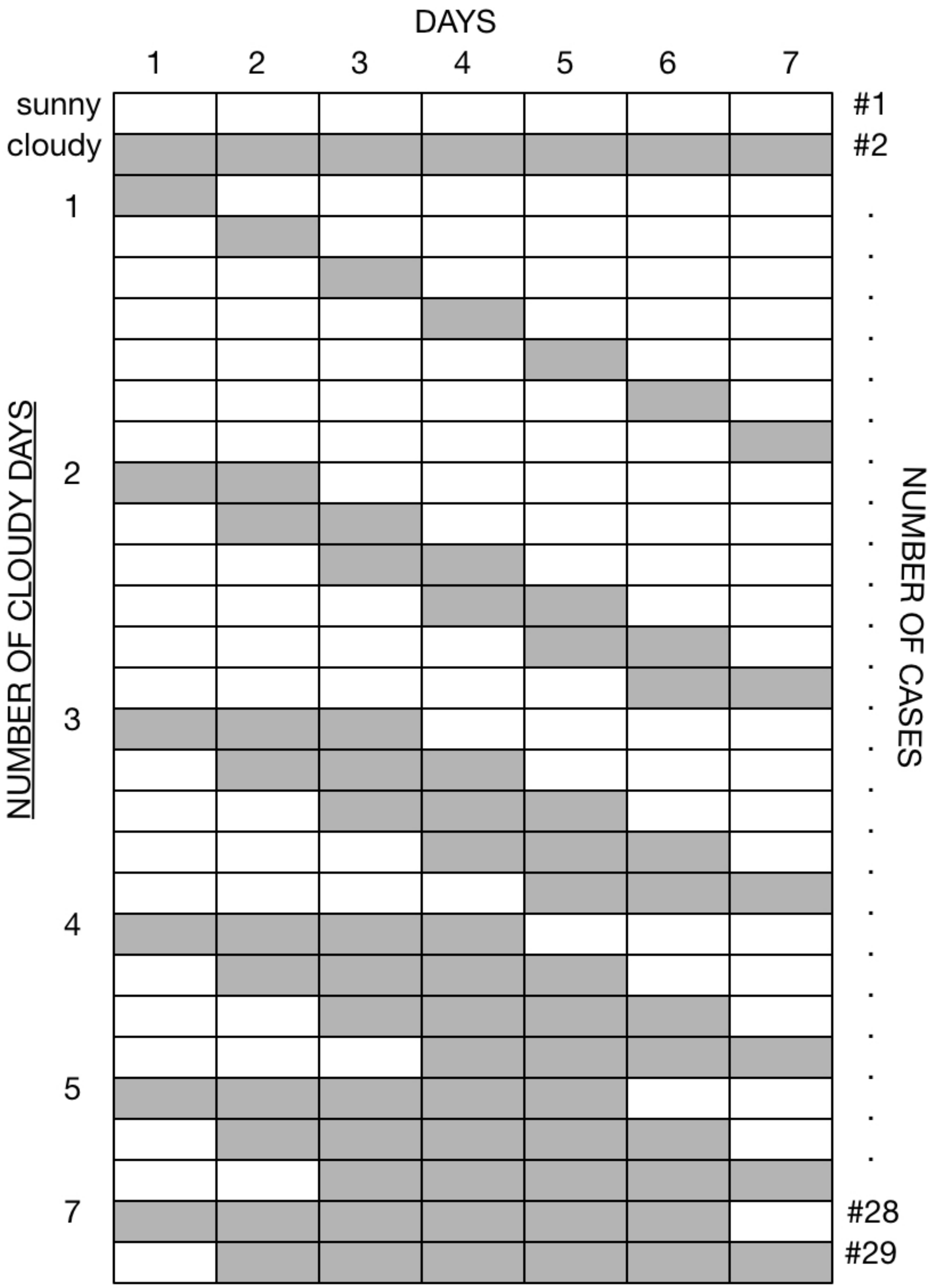


Figure 13–12. *Number of cloudy days cases*

TABLE 8–9 | Cloud Effect on overload hours (initial SOC=100%)				
	Overload hours			
Cloudy days	**Summer**	**Spring**	**Fall**	**Winter**
0	0	54	120	136
1	0	64	122	137
2	0	87	124	137
3	0	100	124	137
4	0	104	124	137
5	2	104	124	137
6	4	104	124	137
7	4	104	124	137

TABLE 8–10 | Cloud Effect on overload hours (initial SOC=75%)				
	Overload hours			
Cloudy days	**Summer**	**Summer**	**Summer**	**Summer**
0	0	97	126	146
1	0	109	132	147
2	0	125	136	147
3	0	128	136	147
4	2	128	136	147
5	4	128	136	147
6	6	128	136	147
7	6	128	136	147

At initial SOC=75%, the overload hours increase at a maximum of 43 hours and a minimum of 10 hours. That is a 25% decrease on initial SOC impact and a 44% increase in overload hours. Major effect takes place between the 1st and 2nd day since there is excess energy, which is not stored, and therefore more overload hours. If cloudy skies happen at the end of the week and the battery energy levels are drained, there are much fewer overload hours.

◆ **Cloudiness and Autonomy**

The autonomy is examined solely on solar power, and then the use of the alternator-engine to compensate the unsatisfied load hours.
In wintertime, when the weather is coldest, the energy autonomy lasts up to a day. To maintain it, the user must travel every other day to recharge the household load.
In the Fall, the autonomy lasts for two days, and in case of cloudy weather, the autonomy is reduced to 1,3 days, which is a 35% reduction of autonomy.
In spring, the average autonomy time is five days. If all seven days are cloudy, the power system autonomy is reduced by two days, which is a 40% reduction.
In the summer, the power system is completely autonomous even when there are clouds all week.

4.3.3 Scenario 3 – Geographical Effect

To examine the possible sun irradiance conditions, the power system is exposed to; the geographical placement of the power system was tested based on the range of GHI levels of the map. The sun irradiance levels have been divided into three groups: 7.5–6.9, 6.0–5.4 and 4.5–4.0 kWh/m^2/Day and simulate a continuum for a tour. Each group corresponds to a trip designed to navigate those energy levels. Those trips are named:

- **West Coast**
- **East Coast**
- **Canadian**

As for the engine-alternator entity, a consideration taken into account is to have the maximum amount of energy produced and safe for the driver within the legal driving limits, so the traveling period lasts up to 4 hours covering the driving law regulations in countries of the EU [27].

The driver travels from one area to another and is parked for a week. A total of 10 stops per trip.

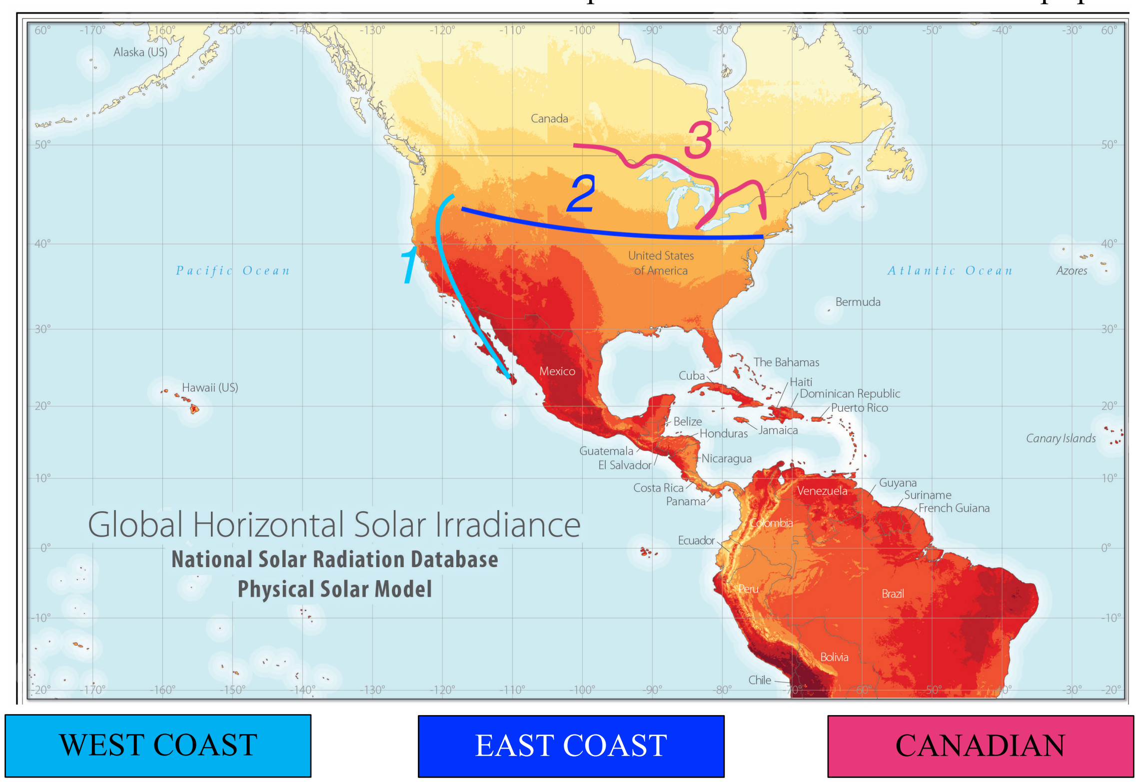


Figure 13–13. Global Horizontal Solar Irradiance Map (year-round) & approximate trips based on solar irradiance levels

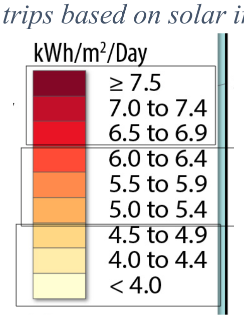


Figure 13–14. Global Horizontal Solar Irradiance levels grouped

– **Trip 1: West Coast**

A sample was taken from the west coast trip from January 1st to March 11th. A total of 3015 km was traveled from south to north, coast to coast, of the Pacific Ocean.

TABLE 8–11 | West Coast Tour					
# STOP	**PLACE**	**COORDINATES**	**TIME hours**	**DISTANCE Km**	**VELOCITY km/h**
1	La Paz, BS, MS	24°08'42.6"N 110°19'14.9"W			
2	Loreto, BS, MX	26°00'58.8"N 111°21'01.1"W	4:15 = 4.25	356	83.76
3	San Ignacio, BS, MX	27°18'13.4"N 112°54'02.5"W	4:06 4.1	272	66.34
4	Loncheria Ramirez* BC, MX (*restaurant)	29°02'38.8"N 114°09'06.3"W	3:42 3.7	276	74.59
5	San Felipe, BC, MX	31°01'58.4"N 114°49'58.6"W	4:30 4.5	266	59.1
6	San Diego, CA, USA	32°43'09.5"N 117°09'02.6"W	4:09 4.15	391	94.21
7	Buttonwillow, CA, USA	35°24'04.9"N 119°23'57.9"W	3:34 4.56	389	85.3
8	San Jose, CA, USA	37°19'52.7"N 121°51'18.6"W	3:20 3.33	351	105.4
9	Redding, CA, USA	40°33'42.6"N 122°23'31.9"W	3:40 3.66	400	109.28
10	Lakeview, OR, USA	42°12'06.3"N 120°22'04.9"W	3:30 3.5	320	91.42

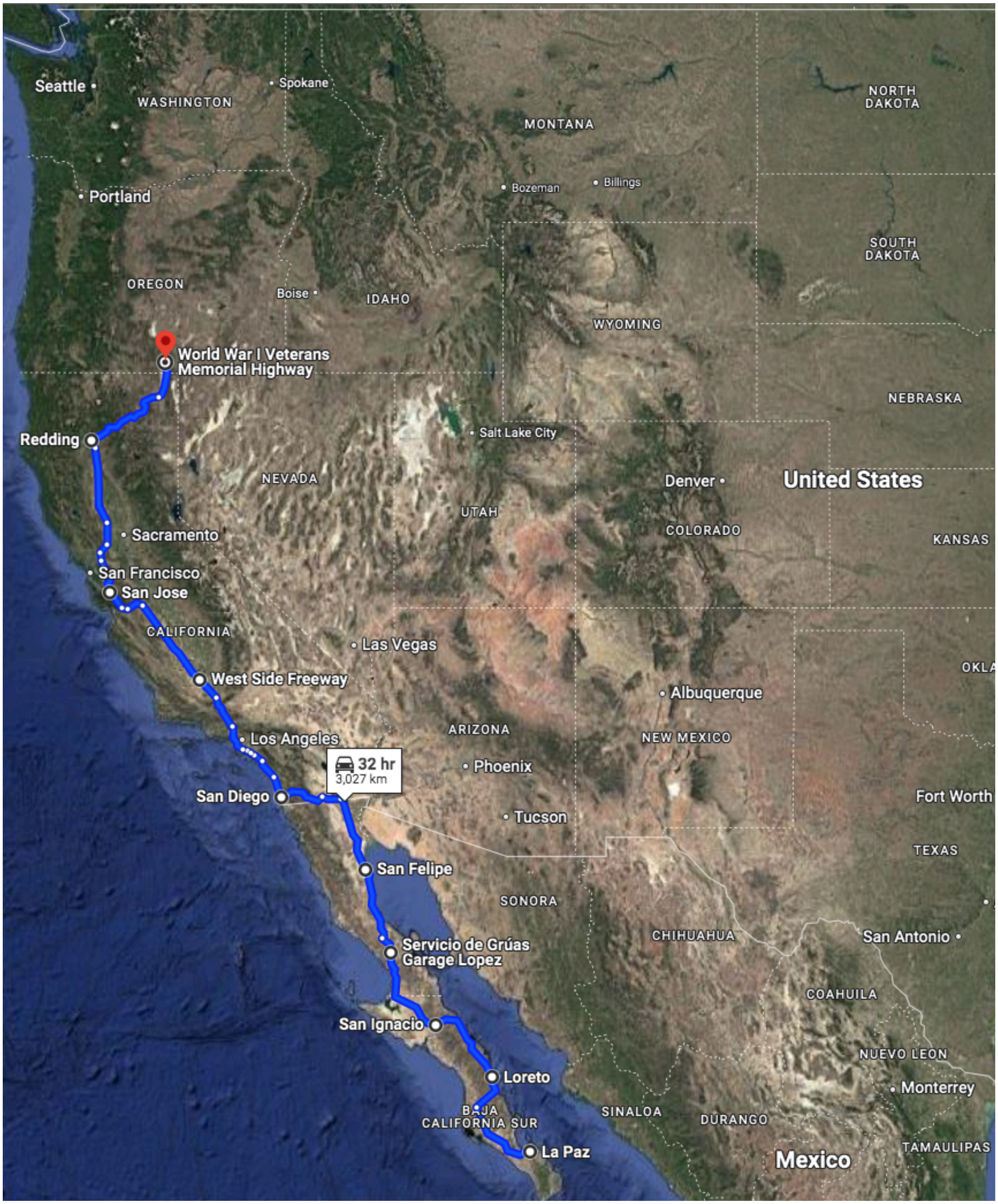


Figure 13–15. West Coast Tour

– **Trip 2: East Coast**

Another sample was taken from the East Coast Tour, which starts from the west and finishes at the east, going horizontally between 44°– 40°N.

TABLE 8–12 | East Coast Tour					
# STOP	PLACE	COORDINATES	DISTANCE Kilometers	TIME Hours	AVERAGE VELOCITY km/h
1	Ontario, OR	44°01'35.6"N 116°57'47.9"W			
2	Snowville, UT, USA	41°57'53.8"N 112°42'41.0"W	458	4:05 = 4.08	112.25
3	Rock Springs, WY, USA	41°35'17.4"N 109°11'59.9"W	404	3:43 3.72	108.6
4	Cheyenne, WY, USA	41°08'23.6"N 104°48'49.6"W	413	3:46 3.76	109.84
5	Kearney, NE, USA	40°41'02.9"N 99°06'22.1"W	510	4:36 4.6	110.86
6	West Des Moines, IA,US	41°35'08.2"N 93°46'11.4"W	494	4:27 4.45	111.01
7	Ladd, IL,USA	41°22'14.5"N 89°12'47.1"W	410	3:44 3.73	109.91
8	Fremont, IN, USA	41°43'40.9"N 84°55'50.2"W	383	3:42 4.7	81.4
9	Pittsburgh, PA, USA	40°25'33.4"N 79°59'23.0"W	485	4:38 4.63	104.75
10	Lanchester, PA,USA	40°03'54.8"N 76°18'46.6"W	380	3:37 3.61	105.26

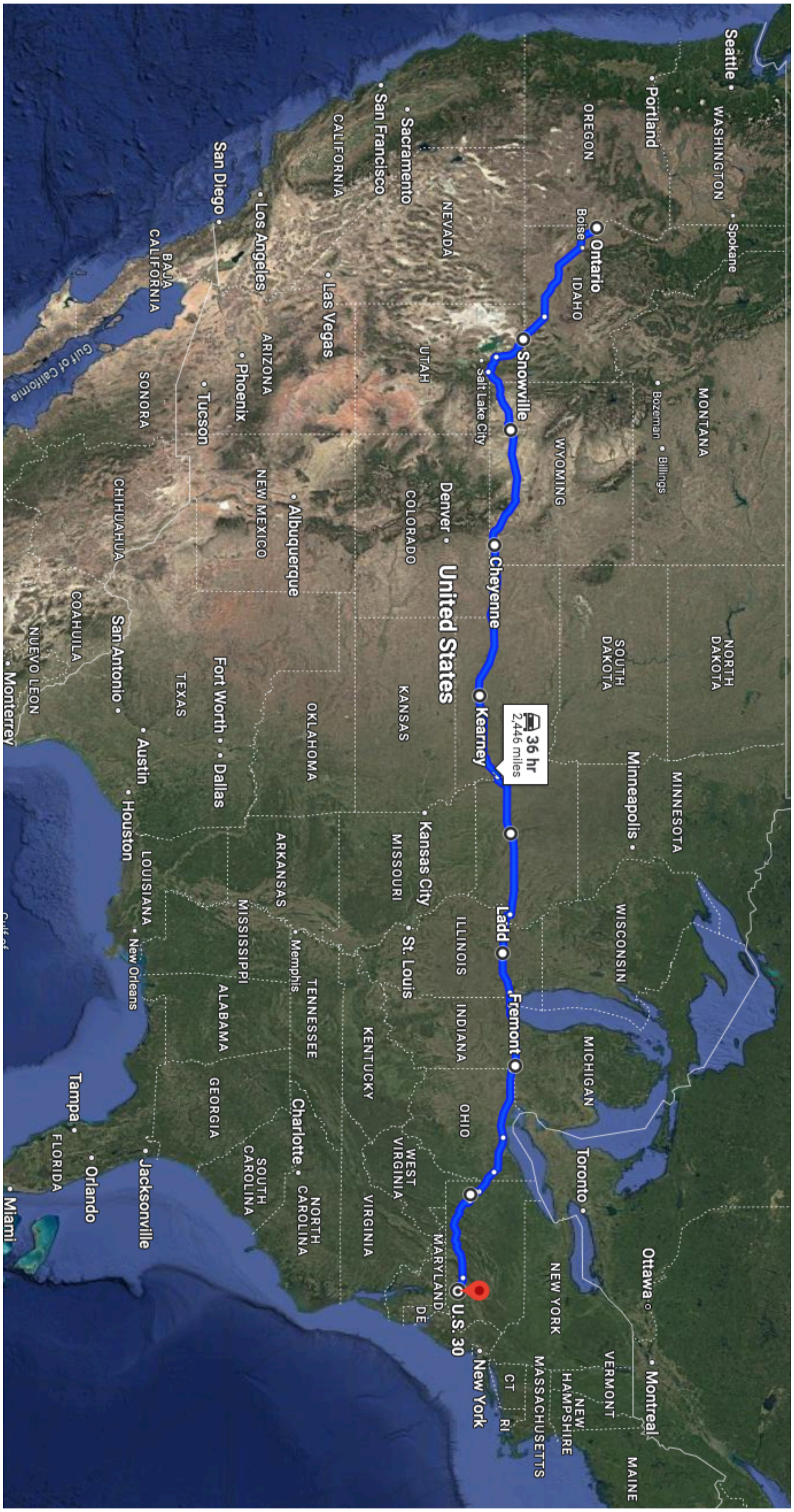


Figure 13–16. East Coast Tour

– **Trip 3: Canadian**
Taking measurements from the coldest part of America.

TABLE 8–13 | Canadian tour					
# STOP	**PLACE**	**COORDINATES**	**DISTANCE kilometers**	**TIME hours**	**AVERAGE VELOCITY km/h**
1	Kingston, NY, US	41°55'30.8"N 74°00'04.4"W			
2	Montreal, QC, CA	44°12'59.8"N 73°35'26.0"W	444	4:18 = 4.3	103.25
3	Bowmanville, ON, CA	43°54'21.1"N 78°41'05.0"W	496	4:34 4.56	108.77
4	Windsor, ON, CA	42°18'21.8"N 83°02'29.0"W	431	4:10 4.16	103.6
5	North York, ON, CA	43°43'17.0"N 79°31'15.6"W	356	3:26 3.43	103.79
6	Latchford, ON, CA	47°19'45.9"N 79°48'38.7"W	456	4:26 4.43	102.93
7	Chapleau, ON, CA	47°50'32.1"N 83°24'06.5"W	430	4:47 4.78	89.95
8	Terrace Bay, ON, CA	48°47'03.3"N 87°05'50.8"W	398	4:22 4.36	91.28
9	English River, ON, CA	49°13'39.2"N 90°57'53.4"W	387	4:04 4.06	95.3
10	Winnepeg, MB, CA	49°53'27.2"N 97°07'59.3"W	514	5:35 5.58	92.11

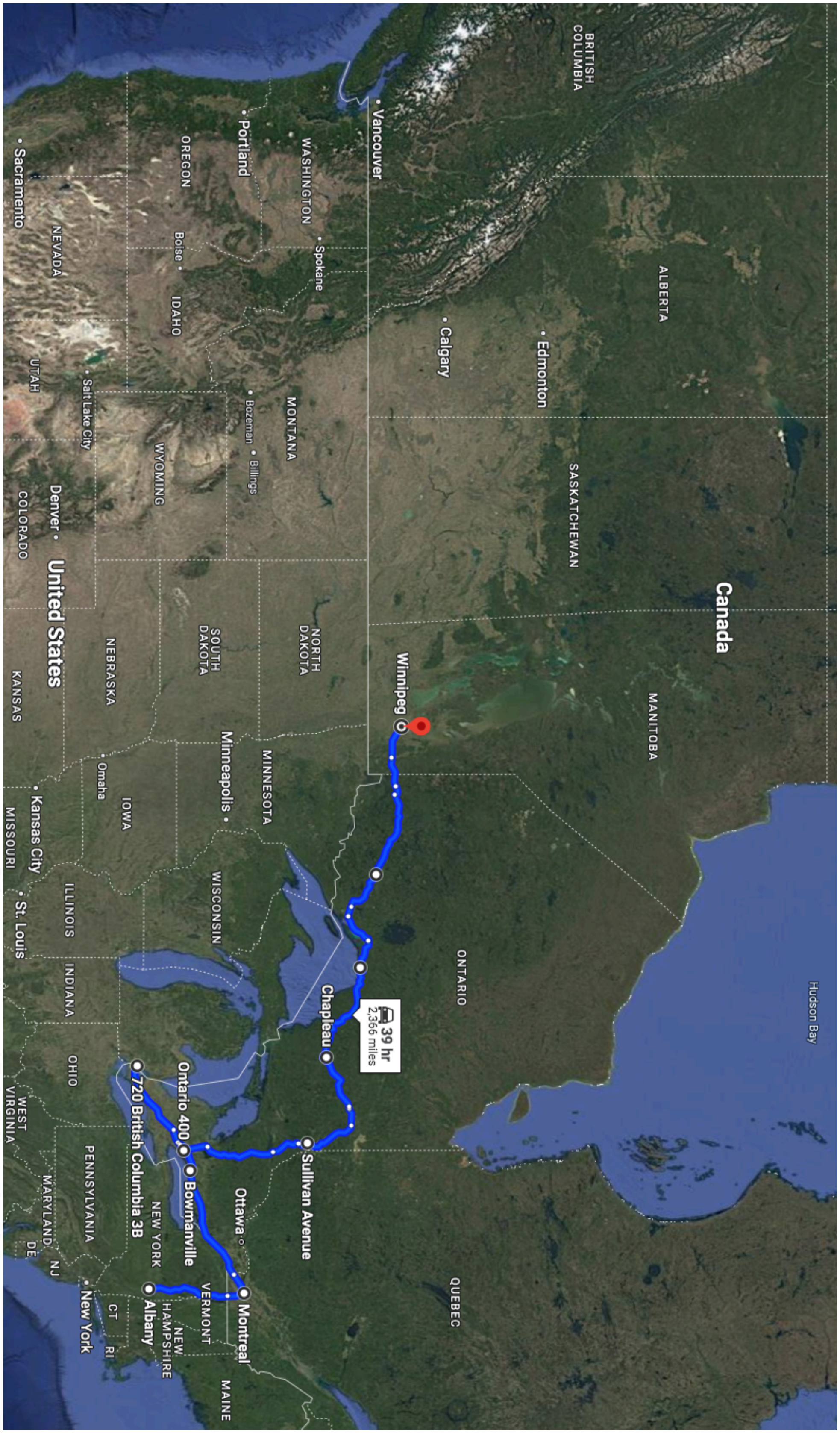


Figure 13–17. *Canadian Tour*

◆ **Results**

All results from the trips are gathered and are compared in the tables below.

Every week the car is parked. In order to maintain the power systems energy autonomy for the household load (L_1), the weather conditions and or sun irradiance is not enough for the solar system to satisfy all the loads. To cover the energy debt, the user has to either turn on the engine idling or travel, with the last being preferable.

The East and West coast trip have very similar results as for the effort put in for energy autonomy compensation and differ only 0.1 hours.

The Canadian tour has the biggest difference of 1.7–1.8 in genset hours and 5.1–5.2 in drive hours.

TABLE 8─14 | Solar irradiance statistics

	MINIMUM	MAXIMUM	AVERAGE	DISPERSION
West coast	0	1085	145.344779	155.479147
East coast	0	1071	178.99354	80.7323262
Canadian	0	998	152.03	3.84897372

TABLE 8–15 | West Coast tour engine activation

	WEEK 1	WEEK 2	WEEK 3	WEEK 4	WEEK 5	WEEK 6	WEEK 7	WEEK 8	WEEK 9	WEEK 10	AVERAGE
Genset Hours	12	9	10	3	16	12	8	15	12	17	11.4
Drive Hours	8	11	4	6	17	5	15	7	10	7	9
Total	20	20	14	9	33	17	23	22	22	24	20.4

TABLE 8–16 | East Coast tour engine activation

	WEEK 1	WEEK 2	WEEK 3	WEEK 4	WEEK 5	WEEK 6	WEEK 7	WEEK 8	WEEK 9	WEEK 10	AVERAGE
Genset Hours	10	9	10	7	16	14	10	11	12	16	11.5
Drive Hours	9	11	4	4	17	4	14	9	10	7	8.9
Total	19	20	14	11	33	18	24	20	22	23	20.4

TABLE 8–17 | Canadian tour engine activation

	WEEK 1	WEEK 2	WEEK 3	WEEK 4	WEEK 5	WEEK 6	WEEK 7	WEEK 8	WEEK 9	WEEK 10	AVERAGE
Genset Hours	12	16	15	12	15	14	12	13	6	16	13.1
Drive Hours	21	15	19	18	12	16	17	13	4	6	14.1
Total	33	31	34	30	27	30	29	26	10	22	27.2

CHAPTER 5 | Conclusions, Future Work & Discussions

5.1 Conclusions

By examining the power system, putting it to the test, and analyzing the results, conclusions can be drawn for the power-economic economy.

- All the values are mathematically proportional to the speed of the vehicle, which determines the gear clutch and, therefore, the engine rpm of the alternator rpm ratio and the energy production.
- There is no constant round up the energy production of the alternator. Every velocity the automobile reaches has a significant impact on the energy production.
- The alternator charges approximately twice the energy when the car is moving than when idling.
- A 20% reduction in solar irradiance due to clouds decreases energy autonomy by approximately 40%.
- The cloudy days of the week do affect the number of overall overloads. The first and second days of occurrence are cloudy. Happening later in the day will reduce the number of overloads.
- The increase in photovoltaic efficiency does not greatly impact the overload hours.
- There is no significant difference between the East and West Coast Tour. Sampling further geographically above where temperatures are lower shows a 33% increase in total average drive engine-alternator time and, therefore, overall cost.
- The colder the weather, the more the user has to travel to maintain energy autonomy and the higher the cost of operation.
- The proposed system is self-reliable for household use. However, the event load system must be charged from an external source.

5.2 Future work

Many factors could be added to this research to have a more spherical and accurate view of the simulation and also a better performance; these are:

- The addition of a wind turbine is a practical solution to increase energy production, thus making the power system more reliable.
- Taking more samples so there could be a better understanding of the power system.
- Considering more parameters, such as temperature, road incline, and engine torque, heat loss from cables could increase the number of conclusions although some might have an imperceptible effect on the power system of this study.
- Take into account the Torque (Nm) of the engine and model the incline of the road to calculate the resistance from the graph that is a parameter that affects the engine's performance.
- The effect of adding an additional alternator and the contribution to the fuel consumption.
- Calculation of the capital cost of solar power system and estimate the payback period and the COE of solar power.

5.3 Discussions

Since cost is not a limitation, it is worth investing in a higher-output alternator that will pay off in the long run. This would also be ideal for year-round use to satisfy the household load live system use.

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APPENDIX

■ Decoding Wheel Specifications

The vehicle's wheels must be in good condition to operate at full performance, which includes proper pressure on the wheels. The wheels and tire type play an important role in the vehicle's speed, analogous to the rounds per minute of the engine and, therefore, the alternator.

.1 Character Depiction

The dimensions of the wheels can be found encoded and engraved on the side of the tire, which is a standard format for all tires on the market. Below is a demonstration on a typical car wheel. This is a standard format for all automobile tires on the market.

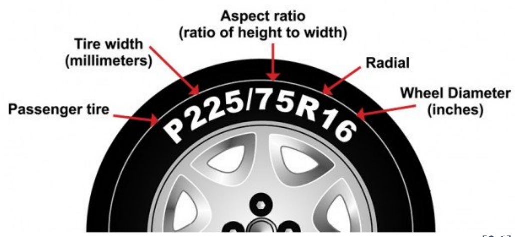

Figure -1. Encoded wheel characteristics [26]

◉ Example:

As seen on Figure -1 above, the wheel depicts the characters:

P225/75R16

— **1st Number: 225**

The width of the tire in millimeters.

225mm = 0.225m = **A**

The tire width affects the contact path to the ground. A bigger width has a tighter grip, thus increasing traction and, therefore, slightly increasing the fuel consumption.

Figure -2. Width of tire

— **2nd Number: 75**

The sidewall aspect ratio in millimeters. 75mm=0.75m. This determines the height of the sidewall from rim to tread. This is also called section height. The second number indicates the size ratio between tire width and height, meaning the percentage of the tire width. Or else the first number A is multiplied by the second number B. In this case,

$$0.75 \times \mathbf{A} = 0.75 \times 0.225 = 0.16875 \text{ m} = \mathbf{B}$$

Figure -3. Section height of the tire. Percentage of tire width.

— **3rd Number: 16**

The last number R16, represents the diameter of the rim in inches on which the tire is mounted.

16 inches = 0.4064 m = **C**

Figure -4. Diameter of rim

.2 Calculating the diameter of the wheel

The diameter (D) of the wheel is equal to the diameter of the rim (C) and twice the sidewall tire height (B):

$$D = 2 \times A \times B + C \tag{.1}$$

Figure -5. Diameter of rim (black line) and height of tire (white line)

The abovementioned formula, application to the exemplified tire:

$$2 \times 0.225 \times 0.75 + 0.4064 = 0.7439\ m = \mathbf{D}$$

■ Velocity to RPM

The velocity of the vehicle is calculated in km/h and is calculated through the formula:

$$\boldsymbol{u} = \frac{\boldsymbol{RPH} \times \boldsymbol{C}}{\boldsymbol{R}}$$

(.2)

Where:

$\boldsymbol{RPH}$ Rounds Per Hour.

The product of 60 rounds per minute of the engine converts the minutes to hours.

$$RPM \times 60 = RPH$$

$\boldsymbol{C}$ Circumference.

The diameter D is calculated by decoding the tire label of the vehicle as mentioned in the appendix sector.

$$C = \pi \times D$$

$\boldsymbol{R}$ Ratio.

The overall gear ratio of the gears' crankshaft, the transmissions, and the rear axle multiplied.

$$R = crankshaft \times transmission\ gear \times rear\ axle$$

After breaking down into smaller calculations the maximum velocity is

$$\frac{60 \times maxRPM \times \pi \times C}{R} = u_{max_n}$$

(.

■ Grams per liter to Liters per gram

The mass flow rate or the break specific fuel consumption graph is given in the engines datasheet and is measured in grams per kilowatt hours. To convert that value into a practical economic variable to study the economic aspect of the system, the mass flow rate must be converted to the volumetric flow rate. That way the calculation of the fuel consumption in volume is possible, calculating the economic variables based on standard measurements which is the liter.

The conversion from kilograms per cubic meter (kg/m^3) to grams per liter (g/lt) takes place when each volume is broken down to its equals:

$$kg/m^3 = {}^{1000\,g}/_{1000\,lt} = g\,/\,lt$$
$$\Leftrightarrow$$
$$kg/m^3 = g/lt$$

Knowing the density of the fuel and using the rule of three, liters per gram can be calculated. Diesel, in this case, has a density of 820 kg/m^3, which makes its inverse the specific volume.

$$\frac{820g}{1\ lt} = \frac{1g}{x} \Leftrightarrow x = \frac{g \cdot lt}{820\ g} \Rightarrow x = 0.001219512\ lt/g$$

TABLE -1 Density and specific volume		
FUEL	**g / lt**	**lt / g**
Diesel	820	0.001219512
Gasoline	740	0.001351351
Natural Gas	0.79	1.265822785
Ethanol	785	0.001273885
Methanol	792	0.001262626

■ Daily Routine

The driver wakes up at 7:00 and the lights of the cabin turn on (LIGHTS, FAN). Waking up is a process that takes two hours of existential time for himself. This includes eating breakfast(FRIDGE), defecation, cleaning his teeth and taking a shower(WATER PUMP) for his biological needs. Then he may connect to the internet (WIFI) to listen to the news or music(SPEAKERS) to cover his civil needs. Depending on the mood, he might go for a walk in between.

At 9:00 he is ready for work where he sits on the computer (PC, SCREEN) until 14:00 and then takes a break and uses the water closet to reset (WC) (WATER PUMP).

Cooks himself a meal (FRIDGE, EXHAUST, WATER HEATER, WATER PUMP) making her something to eat. The production, consumption and digestion of the food is a process that takes up 3 hours (14:00-17:00). After that he uses the WC to reset (WATER PUMP).

At 17:00 he continues working on his projects (PC, SCREEN) until 20:00 or the sunset in the summertime. At 20:00 the driver stops his works and uses the WC to reset.

After 20:00 the user is free to do anything which includes listening to music, watching a movie and making popcorn or just shutting everything off and going outside until 00:00.