Engineering and Material Science Faculty
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Improve Design of Solar Transportation System for Long Distance

Bachelor Thesis

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Submission Date:	25 May, 2015

This is to certify that:

(i) the thesis comprises only my original work towards the Bachelor Degree

(ii) due acknowledgement has been made in the text to all other material used

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25 May, 2015

Acknowledgment

First of all, I would like to thank Prof. Yasser Fouad for providing me a wealth of information in every aspect of my thesis. Thank you for believing in me and I am forever grateful. I also would like to thank my family, and friends for their support to me and to my thoughts.

Abstract

This thesis deals with avoiding the reliance on the limited source of energy such as petroleum, also as the global warming increasingly threatening our planet earth. In an attempt to avoid these two main problems is to use renewable energy instead, which is limitless, free, and pollution free. Developing the car by using solar energy as their only source of energy for supporting the car with energy. Using solar panels, they collect it during the day for storing this energy into batteries to be used to operate the car. Its major advantage lies in the fact that it is simple and versatile, which makes it applicable to a large range of cars of different weight loads, and different speeds.

Key words: Solar powered cars, Solar Energy, PWM, Conceptual Design Methodology

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Chapter 1

Introduction

1.1 Motivations and Objectives

The ability for a renewable energy dependent transportation system for a long distance and a longer period of time has become a key issue and a research target, in both of the domains of civilian transportation and unmanned transportation vehicles. This domain is increasingly taking an important place in the whole world for civilian and unfortunately military applications. The required extended period of time and distances endurance are needed in public transportation, law enforcement, distant areas that can't be reached. In addition to the benefits of reducing carbon dioxide emission. According to United States The second largest producer of CO_2 in the world [1], transportation in USA is considered the second source of CO2 emission by 31% [2].

For the moment, it is only possible to reach such ambitious goals using electric solar powered platforms. Photovoltaics modules may be used to collect the energy of the sun during the day, one part being used directly to power the propulsion unit and onboard instruments, the other part being stored in batteries for the night usage.

In order to reach the target needed of endurance, the design of the solar vehicle has to be thought carefully and globally, as a system composed of many subsystems that are continuously exchanging energy. Due to these relationships, each part has to be sized accordingly to all the others. Here, the design, method is to engineering what the recipe is to cooking. A good chef can cook an exceptional meal with standard products, whereas his apprentice can miss it completely even using expensive high quality products. Simply because a crucial part lies in the combination of all the elements, and not only in their quality. This is especially true for multidisciplinary projects, the case of solar car being an ideal example as it requires knowledge in the fields of aerodynamics, actuators, sensors, electronics, energy storage, photovoltaic, etc.

The present thesis lies within the scope of this project. Its objective is not only to study a fixed design for a well determined mission, but rather to develop a versatile design methodology, that can be used for other projects, with different designs or mass of passengers, and rapidly adapted to new technology improvements. It is not intended to focus on car external design only, as this domain was already often covered, but aims rather at studying the sizing relationships between the elements. Laws of scaling make them clear, what becomes problematic or easier when decreasing or increasing the number of passengers.

1.2 History of Solar Powered Cars

1.2.1 Electric Vehicles

The harnessing of electrical energy is one of mankind's greatest achievements. English chemist John F. Daniell [3] was credited with developing the first "primary" cell, even though his work was a continuation of the research carried out in the late 1700's by Italian scientist Alessandro Volta.

Volta's battery (or galvanic cell), called the "Voltaic Pile," consisted of silver and zinc discs separated with cardboard and soaked in salt water. Daniell's primary cell was more efficient, but French physicist Gaston Plante took this discovery one step further in 1859 with the invention of the lead-acid storage battery. The modern "dry cell" battery was developed just a few years later by another Frenchman, Georges Leclanche.

Figure 1.1: A voltaic pile, the first chemical battery

By 1900, 38% of pleasure cars sold in the U.S. were electrically powered, 22% gasoline-driven, and 40% steam-driven. But steam had had its day, and the wealthy showed an overwhelming admiration for the quietness and simplicity of the electric cars.

The French BGS Electric Car held the world's distance record on a single charge - 290km in 1900. Electric-powered taxis plied the streets of New York, but country trips were a constant problem. With no power source at their country estates to recharge the batteries of their carriages, the wealthy found electric transport had its limitations. The development of the automobile starter motor by Charles Kettering in 1911 ended the electric vehicle's hold on the market place.

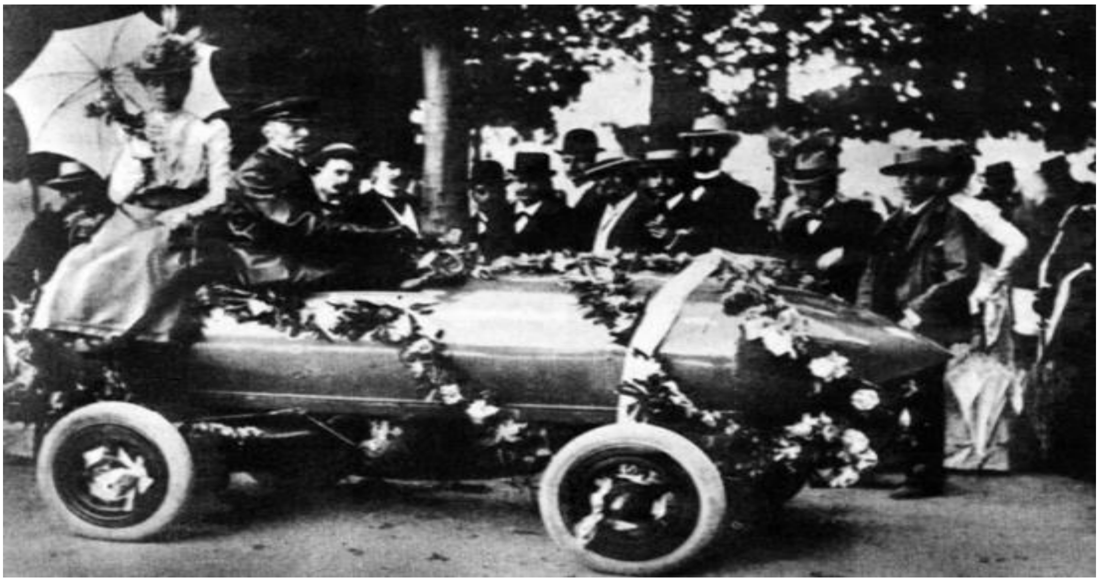


Figure 1.2: The first car which exceeded 100 km/h - was an electric car [4].

The year 1912 was the high point for electric vehicles in the U.S. with almost 34,000 cars, trucks and buses registered for road use. This trend for electric vehicles went downhill from here with only limited use in specialized commercial applications.

The 1967 GM Electro-van was one of the most famous examples of the fuel cell electric vehicle. Using NASA technology, GM engineers developed a means of using a non-liquid membrane and platinum electrodes which acted as a catalyst in the presence of hydrogen and oxygen. It was effective, but costly.

Electric vehicles even made it to the moon with the Apollo 15, 16 and 17 missions. Despite this success, the EV has continued to be plagued with problems that restrict its use, namely cost, range, weight and recharging time. Solutions to these problems are within our grasp, and are presently being implemented in the new electric vehicles rolling off the assembly line.

1.2.2 Storing the Sun's Energy

Photovoltaic cells are constructed of semiconductor materials which can absorb light and convert it to electricity. The term itself is derived from the Greek "photo" meaning light, and "voltaic" from Alessandro Volta.

The most commonly used semiconductor is silicon (sand), one of the most abundant materials on earth. The manufacture of an active silicon cell, at its simplest level, involves growing a crystal of silicon from reservoirs of molten silicon. Silicon in its pure form is somewhat poor in its ability to conduct electricity, therefore it is necessary to add small amounts of impurities. The type of impurity used in this "doping" operation is dependent on whether we want the semiconductor to conduct positive or negative charges.

As a rule, phosphorous will be added to produce a silicon that will conduct negative charge (electrons) and is referred to as an n-type silicon. The addition of boron to the silicon will produce the opposite effect, conducting positive charges (hole), and is referred to as a p-type silicon.

Once these two types of silicon have been produced and are layered into a single cell, a junction is formed called a p-n junction. It is at this junction that a voltage potential is developed, similar to that at the terminal of a storage battery.

When sunlight strikes the cell in the vicinity of the p-n junction, each photon generates an electron and a hole. The electron and the hole move apart; this movement of charge constitutes an electric current which can be made to do some external work.

Typically, the potential difference in a silicon solar cell is of the order of 0.5 volts, while the current produced depends on the amount of sunlight, area of the cell, etc. By connecting several cells, in series or parallel, the voltage or current output of the array can be increased. The energy is then stored in batteries.

Today's batteries are rated by their ampere-hour capacity. Generally, 5, 10, or 20 hour rates have been common measures. For example, if a battery is rated at 60 amp/hours at the 20 hour rate, it means that the battery can be discharged at 3 amps for 20 hours without the voltage falling below 1.75 volts per cell, or 10.5 volts in the case of a 12-volt battery.

1.2.3 Solar Car's Evolution

On August 3/ 1955, William G. Cobb of the General Motors Corp. (GM) demonstrates his 15-inch-long "Sunmobile," the world's first solar-powered automobile, at the General Motors Powerama auto show held in Chicago, Illinois [5].

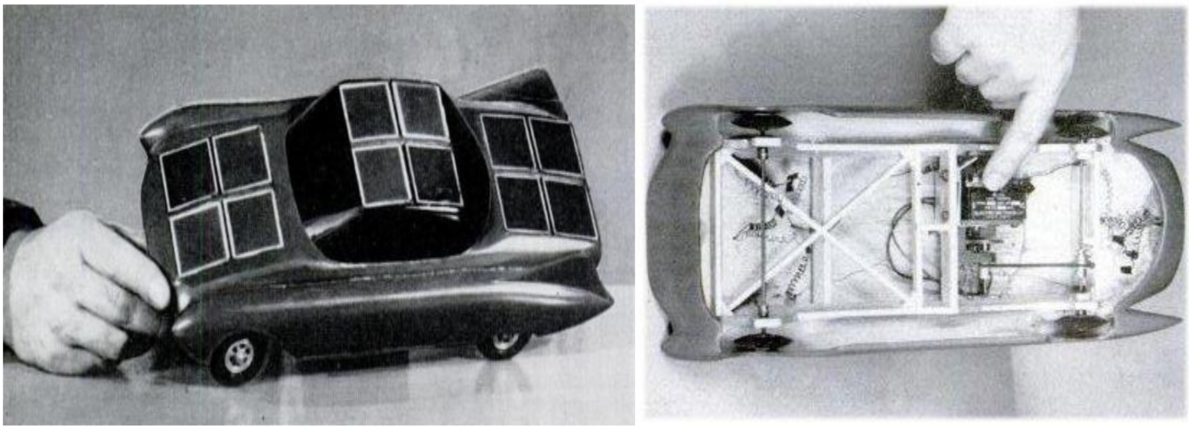


Figure 1.3: "Sunmobile" - 15 inch model of first solar car from outside (on the left) and from the inside (on the right).

Cobb's Sunmobile introduced, however briefly, the field of photovoltaics--the process by which the sun's rays are converted into electricity when exposed to certain surfaces--into the gasoline-drenched automotive industry. When sunlight hit 12 photoelectric cells made of selenium (a non-metal substance with conducting properties) built into the Sunmobile, an electric current was produced that in turn powered a tiny motor. The motor turned the vehicle's driveshaft, which was connected to its rear axle by a pulley. Visitors to the month-long, $7 million Powerama marvelled at some 250 free exhibits spread over 1 million square feet of space on the shores of Lake Michigan. In addition to Cobb's futuristic miniautomobile, Powerama visitors were treated to an impressive display of GM's diesel-fuelled empire, from oil wells and cotton gins to submarines and other military equipment.

The first solar car in history was obviously too small to drive. Now, let's jump to 1962 when the first solar car that a person could drive was demonstrated to the public. The

Figure 1.4: First electric car to run on Photovoltaic energy in 1958.

The first electric car to run on photovoltaic energy was made in 1958[6], but they didn't show it until 4 years later. Around 10,640 individual solar cells were mounted to the rooftop of the Baker to help propel it.

In 1977, Alabama University professor Ed Passereni built the Bluebird solar car, which was a prototype full scale vehicle. The Bluebird was supposed to move from power created by the photovoltaic cells only without the use of a battery. The Bluebird was exhibited in the Knoxville, TN 1982 World's Fair.

Between 1977 and 1980 (the exact dates are not known for sure), at Tokyo Denki University, Professor Masaharu Fujita first created a solar bicycle, then a 4-wheel solar car. The car was actually two solar bicycles put together.

Figure 1.5: In 1979 Englishman Alain Freeman invented a solar car (pictured right). His road registered the same vehicle in 1980. The Freeman solar car was a 3-wheeler with a solar panel on the roof.

At the engineering department at Tel Aviv University in Israel, Arye Braunstein and his colleagues created a solar car in 1980 (pictured below). The solar car had a solar panel on the hood and on the roof of the Citicar comprised of 432 cells creating 400 watts of peak power. The solar car used 8 batteries of 6 volts each to store the photovoltaic energy.

Figure 1.6: The 1,320 pound solar Citicar is said by the engineering department to have been able to reach up to 40 mph with a maximum range of 50 miles.

In 1981 Hans Tholstrup and Larry Perkins built a solar powered racecar. In 1982, the pair became the first to cross a continent in a solar car, from Perth to Sydney, Australia. Tholstrup is the creator of the World Solar Challenge in Australia.

Figure 1.7: The Sunrunner, piloted by Greg, set the first speed record for a solar car in the Guinness Book of World Records, reaching a top speed of 41mph.

In 1984, Greg Johanson and Joel Davidson invented the Sunrunner solar race car. The Sunrunner set the official Guinness world record in Bellflower, California of 24.7 mph. In the Mojave Desert of California and final top speed of 41 mph was officially recorded for a "Solely Solar Powered Vehicle" (did not use a battery). The 1986 Guinness Book of World Records publicized these official records.

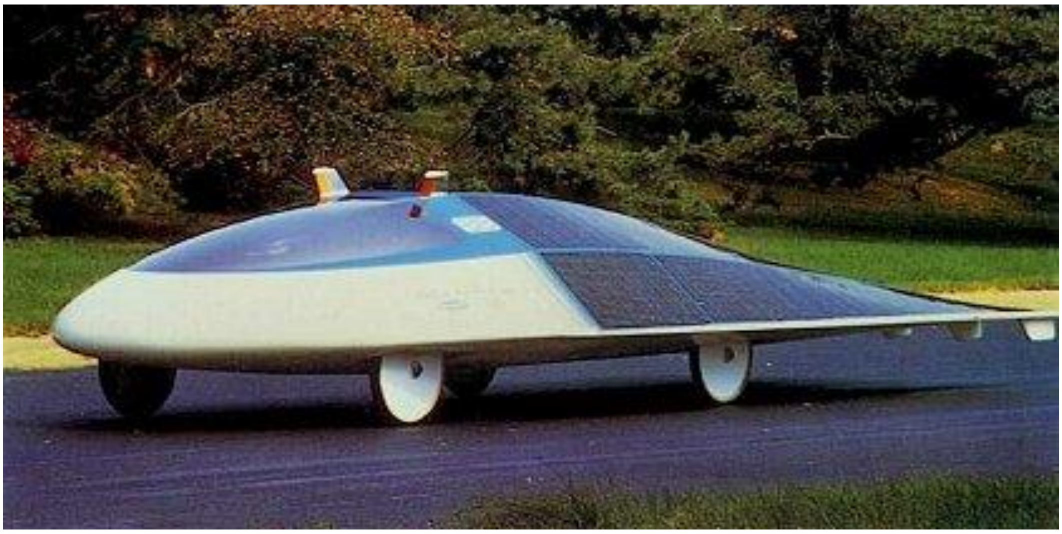


Figure 1.8: GM Sunraycer

The Sunraycer was a solar powered race car designed to compete in the world's first race featuring solar-powered cars. This race is now called the World Solar Challenge -will be discussed in details in **The History of Solar Car Racing** section**-** The GM Sunraycer in 1987 completed a 1,866 mile trip with an average speed of 42 mph. The race, in November 1987, was from Darwin in the north of Australia, to Adelaide in the south. The race course followed the Stuart Highway for nearly the entire trip, going past Alice in the middle of the continent.

The Sunraycer, with John Harvey driving won the pole position with the fastest speed of all the 24 contestants (109 km/h) and from the start of the race to the end, it was always in first place. It raced the 1,867 miles (3,005 km) with an average speed of 41.6 mph (66.9 km/h), finishing the race in just 5.2 days. This was 50% faster than the second place vehicle (which arrived in Adelaide two days after the Sunraycer). Roger Smith, the GM CEO, went to Adelaide to congratulate his winning team.

In June, of the following year (1988), the Sunraycer smashed the solar powered speed record with a top speed of 75.276 mph (121.145 km/h) (set in Mesa, Arizona). For comparison, the winning car in the 2005 World Solar Challenge was the Nuna 3 which had a top speed of 140 km/h (87 mph) and cruised with speeds of 110 to 120 km/h (av. speed 103 km/h for entire 3000 km). This record held until it was broken by UNSW Sunswift in January 2011.

Since this time there have been many solar cars invented at universities for competitions such as the Shell Eco Marathon. There is also a commercially available solar car called the Venturi Astrolab. Time will only tell how far the solar car makes it with today's and tomorrow's technology.

Today, more than a half-century after Cobb debuted the Sunmobile, a mass-produced solar car has yet to hit the market anywhere in the world. Solar-car competitions are held worldwide, however, in which design teams pit their sun-powered creations (also known as photovoltaic or PV cars) against each other in road races such as the 2008 North American Solar Challenge, a 2,400-mile drive from Dallas, Texas, to Calgary, Alberta, Canada.

In early 2009, The Nikkei [7], a Japanese business daily, reported that Toyota Motor Corp. was secretly developing a vehicle that would be powered totally by solar energy. Hurt by a growing global financial crisis and a surge in the Japanese yen relative to other currencies, Toyota had announced in late 2008 that it was expecting its first operating loss in 70 years.

Despite hard economic times, Toyota (which in 1997 launched the Prius, the world's first mass-produced hybrid vehicle) has no plans to relinquish its reputation as an automotive industry leader in green technology. The company uses solar panels to produce some of its own electricity at its Tsutsumi plant in central Japan, and in mid-2008 announced that it would install solar panels on the roof of the next generation of its ground-breaking electric-gasoline hybrid Prius cars. The panels would supply part of the 2 to 5 kilowatts needed to power the car's air conditioning system.

Figure 1.9: Toyota Prius with an aftermarket solar panel kit that could extend the car’s range in electric mode by 20 miles [9].

According to The Nikkei, Toyota's planned solar car is not expected to hit the market for years. The electric vehicle will get some of its power from solar cells on the vehicle, and will be recharged with electricity generated from solar panels on the roofs of car owners' homes.

Now a days overall major companies are trying to generate ventilating systems and electronics of the car with solar generated electric energy.

1.2.4 The History of Solar Car Racing

Like the electric automobiles of the early 20th century, a solar car is powered by electricity. Unlike its predecessor, a solar car uses only sunshine for fuel. Photovoltaic cells on the car collect and convert the energy from sunlight directly into electricity, making the vehicle completely self-sufficient. [See diagram]

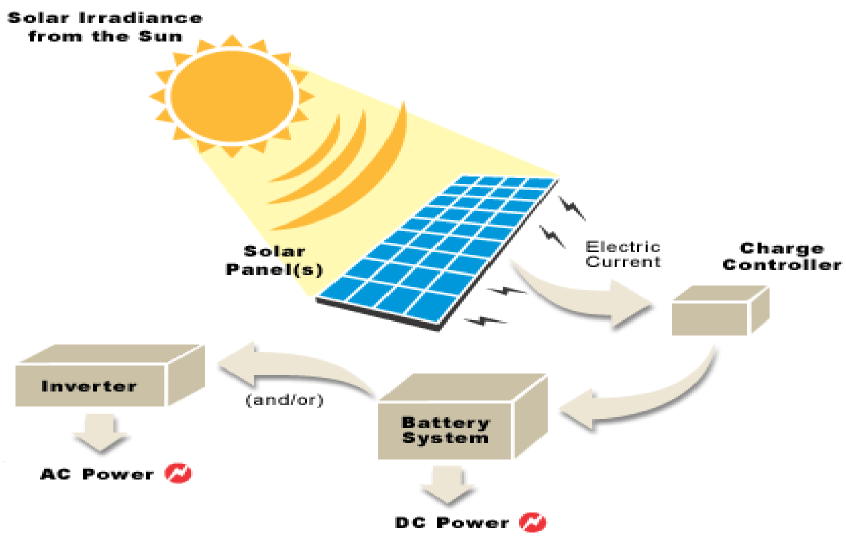


Figure 1.10: Diagram shows how solar panel works in car’s system.

The main objective of any solar car manufacturer is to build an efficient, "winning" vehicle. Design considerations included hundreds of trade-offs, but certain elements are essential.

Reliability is an important design factor. A vehicle which performed well without any major breakdowns would cover the race distance in less time.

The overall shape of a solar car is another important design factor. Teams had to determine how and where they would mount the solar cells for maximum energy grain. They also had to decide how to maintain low weight and minimize aerodynamic drag.

A typical solar car generates 700-1500 watts of power, or about 1-2 horsepower. This makes aerodynamic drag and rolling friction critical considerations.

The two most notable solar car distance (overland) races are the World Solar Challenge [8] and the North American Solar Challenge. They are contested by a variety of university and corporate teams. Corporate teams participate in the races to give their design teams experience of working with both alternative energy sources and advanced materials. University teams participate in order to give their students experience in designing high technology cars and working with environmental and advanced materials technology. These races are often sponsored by government or educational agencies and businesses such as Toyota keen to promote renewable energy sources.

World Solar Challenge

The 1987 Australian World Solar Challenge saw 23 participants inaugurate the first such race, followed by the European Tour de Sol, the American Tour de Sol, and the SUNRAYCE. Spectacular corporate and college vehicle adorned these early races and is pictured below.

Figure 1.11: Mana La, co-designed by James L. Amick, components built by Douglas J. Amick; sponsored by John Paul Mitchell Systems for the first ever World Solar Challenge cross-country race in Australia, 1987.

This race features a field of competitors from around the world who race to cross the Australian continent. In 2005, the DutchNuna 3 team won this challenge for a 3rd time in a record average speed of 102.75 km/h over a distance of 3000 km, followed by the

Australian Aurora (92.03 km/h) and the University of Michigan (90.03 km/h). The increasingly high speeds of the 2005 race participants has led to the rules being changed for future solar cars starting in the 2007 race.

The 20th Anniversary race of the World Solar Challenge ran in October 2007. Major regulation changes were released in June 2006 for this race to increase safety, to build a new generation of solar car, which with little modification could be the basis for a practical proposition for sustainable transport and intended to slow down cars in the main event, which could easily exceed the speed limit (110 km/h) in previous years. The winner again was the Nuna 4 team averaging 90.87 km/h. The winner in the Adventure Class (driving under old rules) was the Ashiya University Solar Car Project team averaging 93.57 km/h.

In 2013 the organisers of the event introduced the Cruiser Class to the World Solar Challenge, designed to encourage contestants to design a "practical" solar powered vehicle. This race requires that vehicles have four wheels and upright seating for passengers, and is judged on a number of factors including time, payload, passenger miles, and external energy use.[3] The University of new South Wales solar racing team, UNSW Sunswift, had the fastest car to finish in the 2013 Cruiser Class but was awarded third place overall.

North American Solar Challenge

The American Solar Challenge, previously known as the 'North American Solar Challenge' and 'Sunrayce USA', features mostly collegiate teams racing in timed intervals in the United States and Canada.

The American Solar Challenge was sponsored in part by several small sponsors. However, funding was cut near the end of 2005, and the NASC 2007 was cancelled. The North American solar racing community worked to find a solution, bringing in Toyota as a primary sponsor for a 2008 race. Toyota has since dropped the sponsorship. The last North American Solar Challenge was run from June 13–21, 2010, from Dallas, Broken Arrow, OK to Naperville, IL. The race was won by the University of Michigan Solar Car Team. Michigan has won the race the last three times it has been held, and six times out of the ten it has been held.

Speed Records

Fédération International de l'Automobile (FIA)

The FIA recognise a land speed record for vehicles powered only by solar panels. The current record was set by the Raedthuys Solar Team, of the University of Twente with their car SolUTra. The record of 37.757 km/h was set in 2005. The record takes place over a flying 1000m run, and is the average speed of 2 runs in opposite directions.

In July, 2014, a group of Australian students from the UNSW Sunswift solar racing team at the University of New South Wales broke a world record in their solar car, for the fastest electric car weighing less than 500 kilograms (1,100 lb) and capable of travelling 500 kilometres (310 mi) on a single battery charge. This particular record was overseen by the Confederation of Australian Motorsport on behalf of the FIA and is not exclusive to solar powered cars but to any electric car, and so during the attempt the solar panels were disconnected from the electrical systems. The previous record of 73 kilometres per hour (45 mph) - which had been set in 1988 - was broken by the team with an average speed of 107 kilometres per hour (66 mph) over the 500 kilometres (310 mi) distance.

Guinness World Records

Guinness World Records recognize a land speed record for vehicles powered only by solar panels. This record is currently held by the University of New South Wales with the car Sunswift IV. Its 25-kilogram (55 lb) battery was removed so the vehicle was powered only by its solar panels. The record of 88.8 kilometres per hour (55.2 mph) was set on 7 January 2011 at the naval air base HMAS *Albatross* in Nowra, breaking the record previously held by the General Motors car Sunraycer of 78.3 kilometres per hour (48.7 mph). The record takes place over a flying 500 metres (1,600 ft.) stretch, and is the average of two runs in opposite directions.

Chapter 2

Basic Concepts

2.1 Introduction

In this chapter, we briefly explain the basic principle that makes a solar car and especially the technologies that are involved. Only the theory that is needed to understand the design in the next chapter is discussed. References allow the reader who wants to dig deeper in a subject to do so.

Solar cars combine technology typically used in the aerospace, bicycle, alternative energy and automotive industries. The design of a solar vehicle is severely limited by the amount of energy input into the car. Most solar cars have been built for the purpose of solar car races.

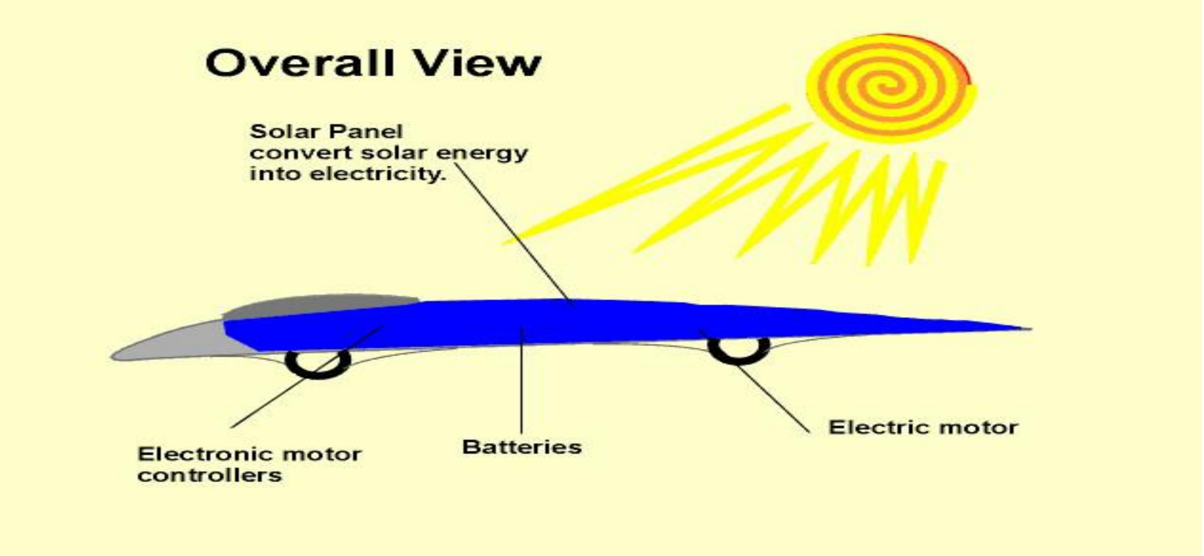


Figure 2.1: An overall view of solar cars.

The solar panels, composed by solar cells connected by solar cells connected in a defined configuration, cover a given surface of the car's body or potentially other parts connected to the car. During the day, depending on the sun irradiance and the weather conditions, the Solar panels convert light into electric energy. A converter ensures that the solar panel is working on charging the batteries. That is why a Pulse width modulation charger is used which is an effective mean to achieve constant voltage for battery charging. This power obtained is used firstly to charge the battery then it used to supply the motor and the electronics in the car.

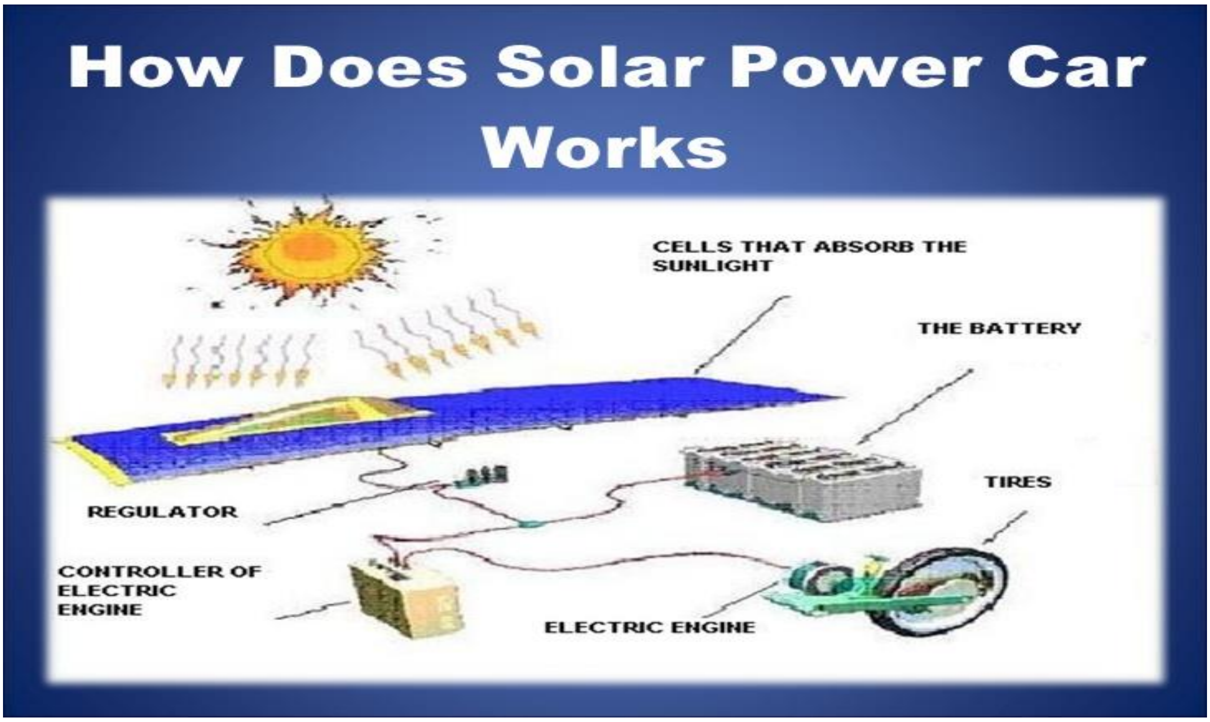


Figure 2.2: Solar car basic principle.

During the night, as no more power comes from the solar panels, the various elements consuming energy are supplied by the battery that last for the specified time which is limited by the batteries capacity, the load on the car, and the distance to be covered by the car. After the description of this general concept, we will approach the theory of the different parts separately in the next sections.

2.2 Mechanical Systems

The mechanical systems are designed to keep friction and weight to a minimum while maintaining strength and stiffness. Designers normally use aluminium, titanium and composites to provide a structure that meets strength and stiffness requirements whilst being fairly light. Steel is used for some suspension parts on many cars.

Solar cars usually have three wheels, but some have four. Three-wheelers usually have two front wheels and one rear wheel: the front wheels steer and the rear wheel follows. Four-wheel vehicles are set up like normal cars or similarly to three-wheeled vehicles with the two rear wheels close together.

Solar cars have a wide range of suspensions because of varying bodies and chassis. The most common front suspension is the double wishbone suspension. The rear suspension is often a trailing-arm suspension as found in motor cycles.

Solar cars are required to meet rigorous standards for brakes. Disc brakes are the most commonly used due to their good braking ability and ability to adjust. Mechanical and hydraulic brakes are both widely used. The brake pads or shoes are typically designed to retract to minimize brake drag, on leading cars.

Steering systems for solar cars also vary. The major design factors for steering systems are efficiency, reliability and precision alignment to minimize tire wear and power loss. The popularity of solar car racing has led to some tire manufacturers designing tires for solar vehicles. This has increased overall safety and performance.

All the top teams now use wheel motors, eliminating belt or chain drives.

Testing is essential to demonstrating vehicle reliability prior to a race. It is easy to spend a hundred thousand dollars to gain a two hour advantage, and equally easy to lose two hours due to reliability issues.

2.3 Solar Cell

A solar cell or photovoltaic cell is a device that converts solar energy into electricity by the photovoltaic effect. It is very widely used in space application because it allows a clean and long-duration source of energy requiring almost no maintenance. Solar cells are composed of various semiconducting materials, constituting one or more layers. Silicon is very often used as it is the second most abundant element in Earth‘s crust and thus inexpensive. For this reason, this material will be considered in the further explanations that are also valid for other types of semiconductors.

2.3.1 Working Principles

In figure 2.3, a simple silicon solar cell is represented with two doped semiconductors layers, p-type and n-type. When the sunlight strikes the solar cell surface the cell creates charge carriers as electrons and holes. The internal field produced by junction separates some of the positive charges (holes) from the negative charges (electrons). The holes are swept into the positive or player and the electrons are swept into the negative or n-layer. When a circuit is made, the free electrons have to pass through the load to recombine with the positive holes, current can be produced from the cells under illumination.

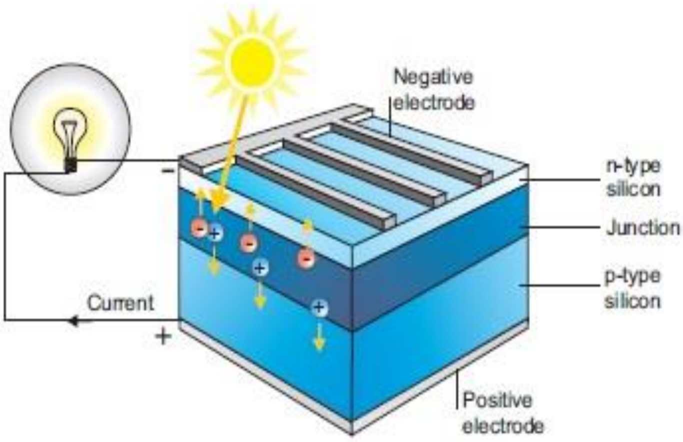


Figure 2.3: Working principle of a solar cell.

2.3.2 Characteristic equation

To understand the electronic behaviour of a solar cell, it is useful to create a model which is electrically equivalent, and is based on discrete electrical components whose behaviour is well known. An ideal solar cell may be modelled by a current source in parallel with a diode; in practice no solar cell is ideal, so a shunt resistance and a series resistance component are added to the model. The resulting equivalent circuit of a solar cell is shown on the left. Also shown, on the right, is the schematic representation of a solar cell for use in circuit di

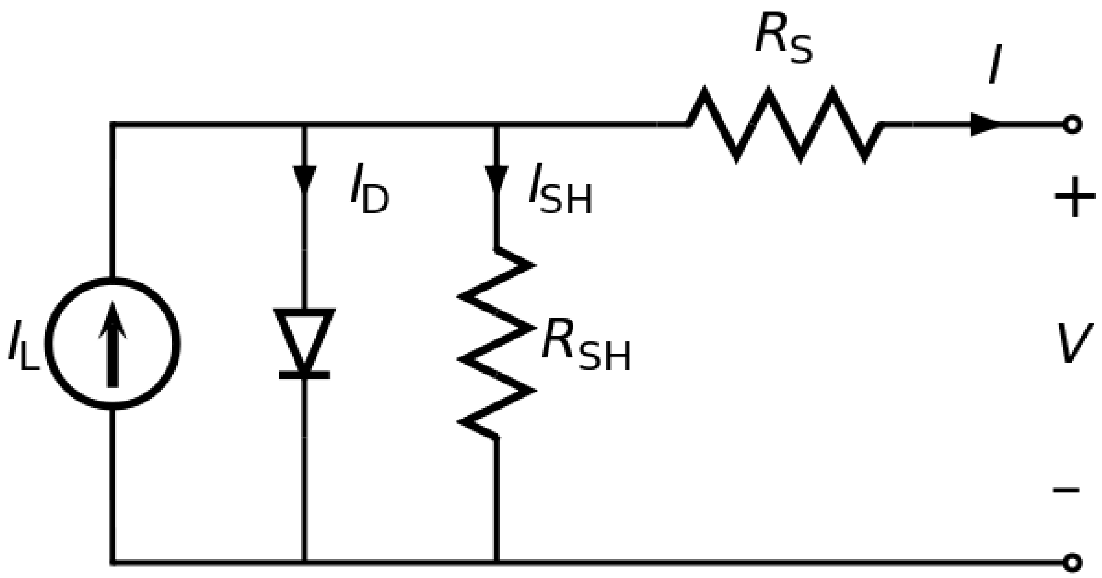


Figure 2.4: The equivalent circuit of solar cell.

Of course through the day the temperature of solar panel increases which in turn decreases the efficiency of the solar cells [11]. So in turn we have to study the effect of temperature on the solar cells.

$$I = I_L - I_D - I_{SH}$$

Where

- I = output current (ampere)

- I_L = photo generated current (ampere)
- I_D = diode current (ampere)
- I_{SH} = shunt current (ampere)

The current through these elements is governed by the voltage across them:

$$V_j = V + IR_S$$

Where

- V_j = voltage across both diode and resistor R_{SH} (volt)
- V = voltage across the output terminals (volt)
- I = output current (ampere)
- R_S = series resistance (Ω).

By the Shockley diode equation, the current diverted through the diode is:

$$I_D = I_0 \left\{ \exp\left[\frac{qV_j}{nkT}\right] - 1 \right\}$$ [6]

Where

- I_0 = reverse saturation current (ampere)
- n = diode ideal factor (1 for an ideal diode)
- q = elementary charge
- k = Boltzmann's constant
- T = absolute temperature
- At 25°C, $kT/q \approx 0.0259$ volt.

By Ohm's law, the current diverted through the shunt resistor is:

$$I_{SH} = \frac{V_j}{R_{SH}}$$

Where

- R_{SH} = shunt resistance (Ω).

Substituting these into the first equation produces the characteristic equation of a solar cell, which relates solar cell parameters to the output current and voltage:

$$I = I_L - I_0 \left\{ \exp\left[\frac{q(V + IR_S)}{nkT}\right] - 1 \right\} - \frac{V + IR_S}{R_{SH}}.$$

An alternative derivation produces an equation similar in appearance, but with *V* on the left-hand side. The two alternatives are identities; that is, they yield precisely the same results.

In principle, given a particular operating voltage *V* the equation may be solved to determine the operating current *I* at that voltage. However, because the equation involves *I* on both sides in a transcendental function the equation has no general analytical solution. However, even without a solution it is physically instructive. Furthermore, it is easily solved using numerical methods. (A general analytical solution to the equation is possible using Lambert's W function, but since Lambert's W generally itself must be solved numerically this is a technicality.)

Since the parameters I_0, n, R_S, and R_{SH} cannot be measured directly, the most common application of the characteristic equation is nonlinear regression to extract the values of these parameters on the basis of their combined effect on solar cell behaviour.

2.3.3 Effect of Temperature on Solar Cell

Temperature affects the characteristic equation in two ways: directly, via *T* in the exponential term, and indirectly via its effect on I_0 (strictly speaking, temperature affects all of the terms, but these two far more significantly than the others). While increasing *T* reduces the magnitude of the exponent in the characteristic equation, the value of I_0 increases exponentially with *T*. The net effect is to reduce V_{OC} (the open-circuit voltage) linearly with increasing temperature. The magnitude of this reduction is inversely proportional to V_{OC}; that is, cells with higher values of V_{OC} suffer smaller reductions in voltage with increasing temperature. For most crystalline silicon solar cells the change in V_{OC} with temperature is about -0.50%/°C, though the rate for the highest-efficiency crystalline silicon cells is around -0.35%/°C. By way of comparison, the rate for amorphous silicon solar cells is -0.20%/°C to -0.30%/°C, depending on how the cell is made.

The amount of photogenerated current I_L increases slightly with increasing temperature because of an increase in the number of thermally generated carriers in the cell. This effect is slight, however: about 0.065%/°C for crystalline silicon cells and 0.09% for amorphous silicon cells.

The overall effect of temperature on cell efficiency can be computed using these factors in combination with the characteristic equation. However, since the change in voltage is much stronger than the change in current, the overall effect on efficiency tends to be similar to that on voltage. Most crystalline silicon solar cells decline in efficiency by 0.50%/°C and most amorphous cells decline by 0.15-0.25%/°C. The figure above shows I-V curves that might typically be seen for a crystalline silicon solar cell at various temperatures.

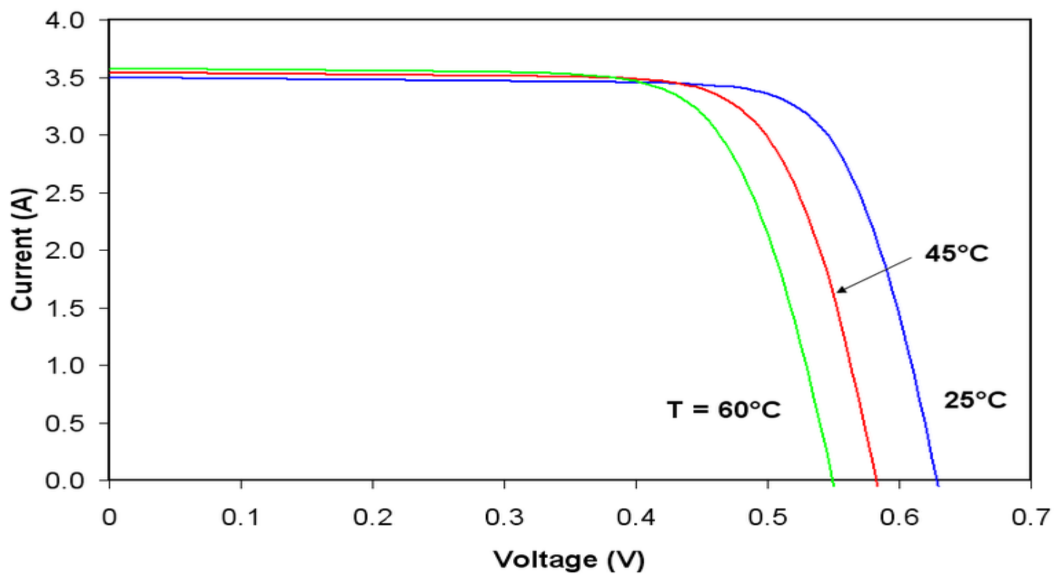


Figure 2.5: Effect of temperature on the current-voltage characteristics of a solar cell.

2.3.4 Types of Solar Cells

There exist various types of photovoltaic cells that can be sorted according to the type of material, the fabrication process, substrate, etc. The objective here is only to give a short and non-exhaustive overview of the existing types. The reader can refer to [13] for deeper information.

The most widely used type of material is silicon, because of its abundance and low cost. We can distinguish three types of ***silicon solar cells*** according to the type of crystal:

• Monocrystalline, for which absolutely pure semiconducting material is used which gives a high level of efficiency but at a high cost.

• Polycrystalline, composed of crystal structures of varying sizes. The manufacturing process is more cost efficient but leads to less efficient solar cells.

• Amorphous, or thin-layer cell, where a silicon film is deposited on glass or another substrate material, even flexible. The thickness of this layer is less than 1 μm, thus the production costs are very low, but the efficiency is poor as well.

However, other materials can be used as well like elements from group's three to five of the periodic table of the elements to produce ***compound solar cells***. These include gallium arsenide, copper indium diselenide, cadmium telluride, etc. These cells are more expensive to produce, but lead to higher efficiency.

We can also mention the ***polymer solar cells*** made of organic material and the ***dye sensitized solar cells*** that are very promising technologies because they are inexpensive to fabricate. However, these technologies suffer from unstable efficiency problems that still must be solved and are not yet viable for industry.

In fact, the most efficient solar cells are of a stack of individual single junction cells in descending order of bandgap. The top cell captures high energy photons and passes the rest on to lower-bandgap cells. These multi junction cells can then convert a wider part of the solar spectrum of figure 2.6 leading to a high efficiency that goes up to 40 %. Figure 2.7 shows then best efficiencies obtained for various solar cell technologies.

An ideal and perfect solar cell that would cover the entire spectrum and convert all this energy into electricity would have an efficiency of 100 %. In reality, depending on the semiconductors used, only a part of this spectrum is covered.

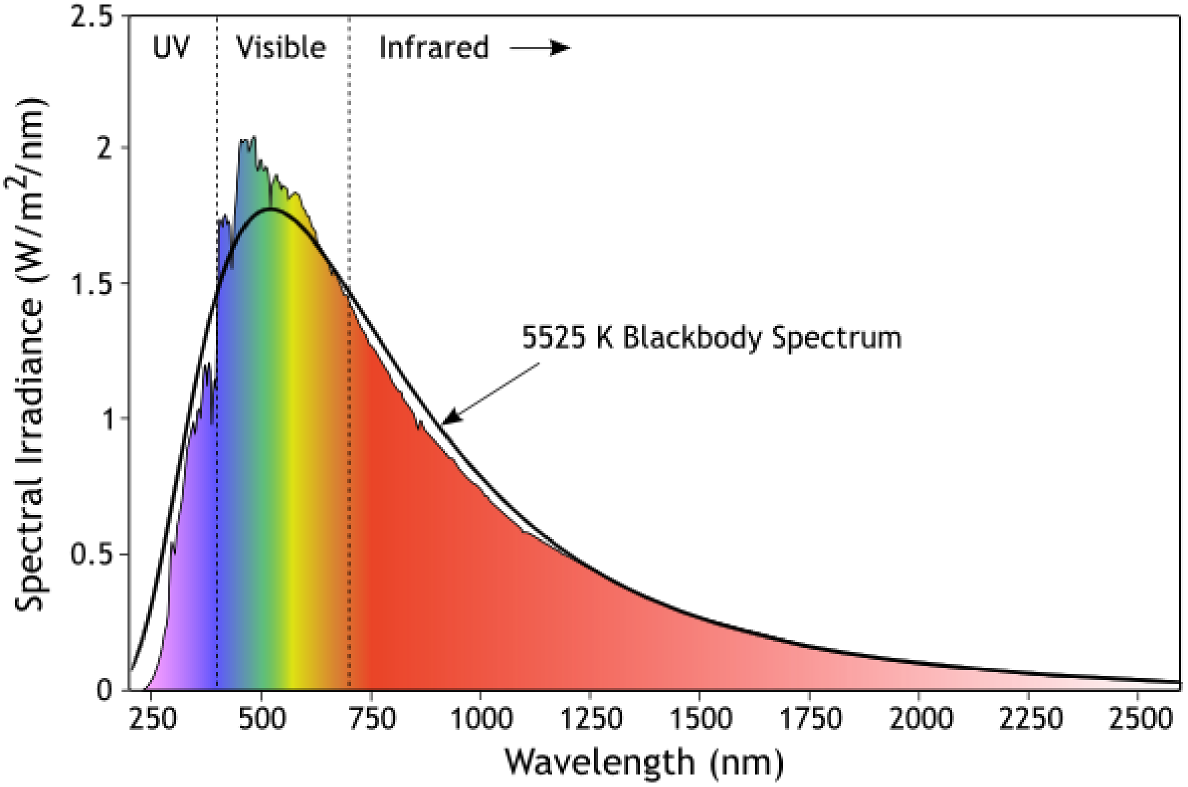


Figure 2.6: Solar radiation spectrum.

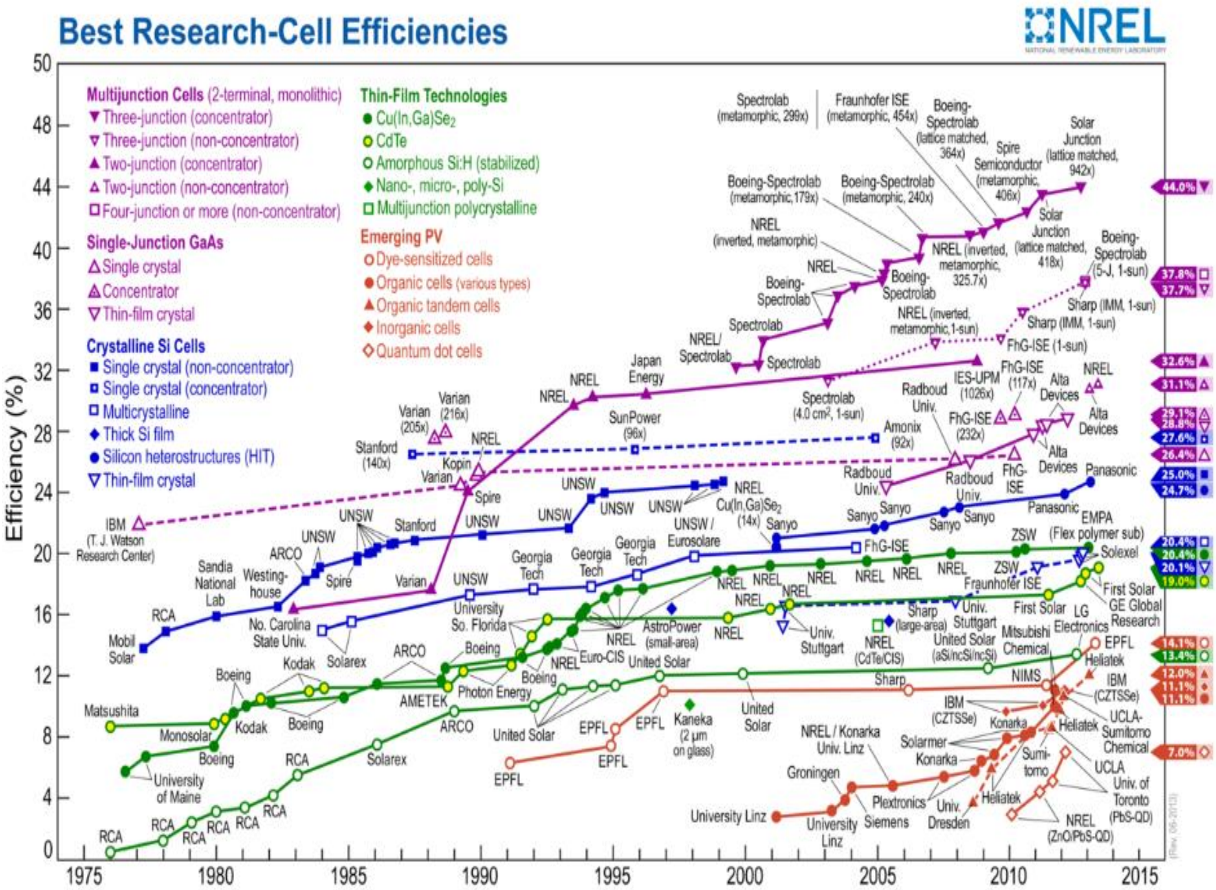


Figure 2.7: Best Research-Cell Efficiencies.

2.3.5 Current and Voltage of a Solar Cell

1. The current to voltage curve of a solar cell has a very characteristic shape and can be described by the mathematical models of an ideal or real photovoltaic generator that will not be developed here but can be found in [14]. As depicted in figure 2.6, when the cell pads are not connected, no current is produced and the voltage equals *VOC*, the open circuit voltage. When it is short circuited, the voltage is zero but the current equals *ISC*. In between these two points where in both cases the power retrieved is zero, there is a working point,

called the maximum power point, where the power one can retrieve is the highest and equals *Pmax* = *VMPP IMPP* . It is precisely at this point that the cells should be used and the ratio between *Pmax* and the light intensity represents precisely the efficiency of the solar cell. However, the curve, and thus this point, is not fixed and varies depending on many parameters.

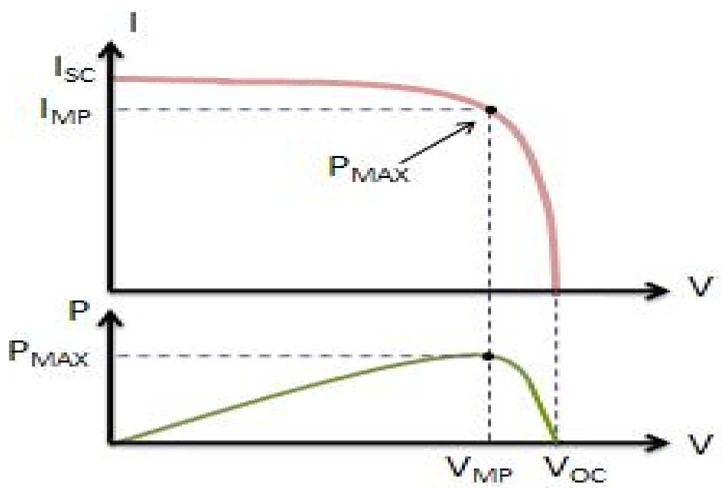


Figure 2.8: Current to voltage curve of a solar cell.

The current of a solar cell is proportional to its area and varies almost linearly with the light intensity (Figure 2.7). The voltage varies only a little bit when the light intensity changes and is independent of the cell surface, but depends on the semiconductor material. For a single layer silicon cell, *VMPP* is around 0.5 V, but for a triple junction gallium arsenide cell, it increases up to 2.27 V. The important values of *VOC*, *ISC*, *VMPP* , and *IMPP* are given in solar cells datasheets under standard spectrum conditions, either AM0 or AM1.5, that were presented previously. Temperature also affects the characteristics of solar cells. When it increases, the voltage decreases slightly whereas the current increases insignificantly. Globally, the power that a solar cell can give is higher for lower temperature, considering the same irradiance conditions (Figure 2.7 & Figure 2.3). An assembly of solar cells connected electrically in parallel, which increases the current, or in series, increasing then the voltage, is referred to as a solar module or solar panel. The I-V curve of a solar module has a scaled but similar shape to that of the single cell curve.

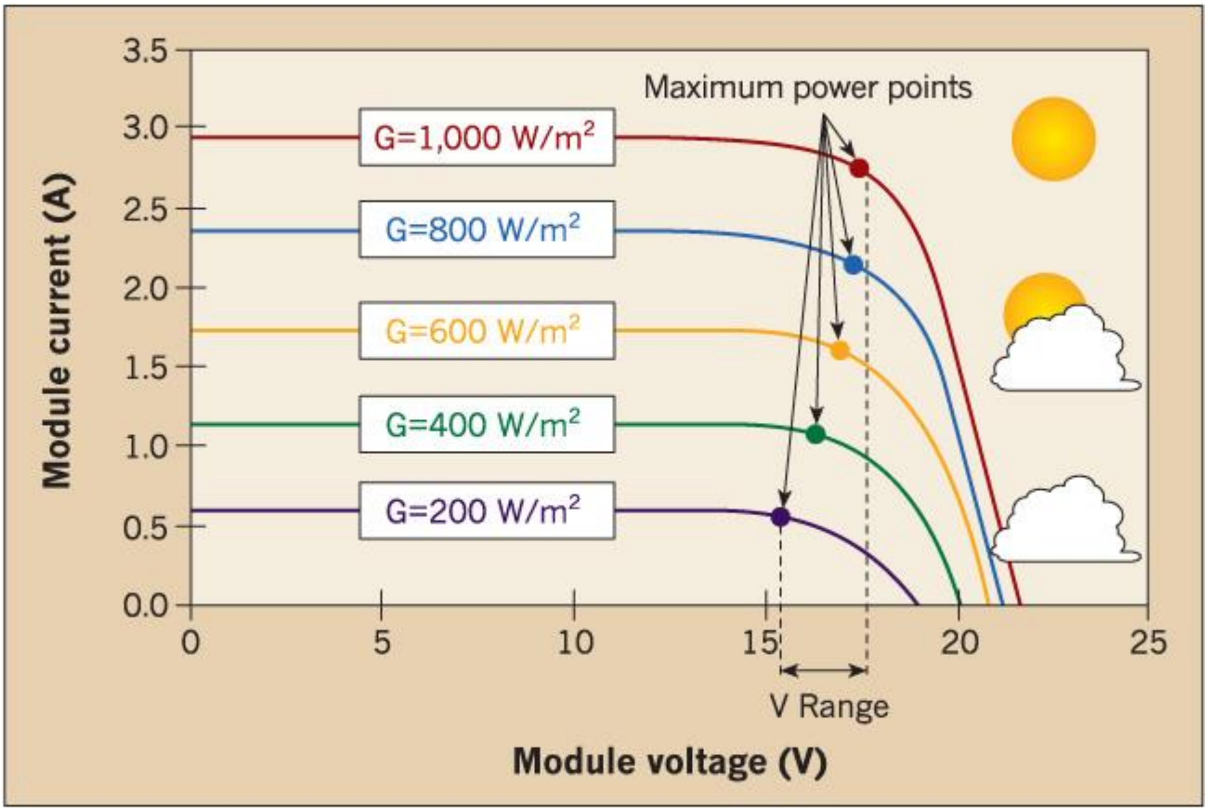


Figure 2.9: Variation of the current to voltage curve of a solar cell with irradiance [12]

2.3.6 Solar Arrays

The solar array consists of hundreds of photovoltaic solar cells converting sunlight into electricity. In order to construct an array, PV cells are placed together to form modules which are placed together to form an array [22].The larger arrays in use can produce over 2 kilowatts (2.6 hp).

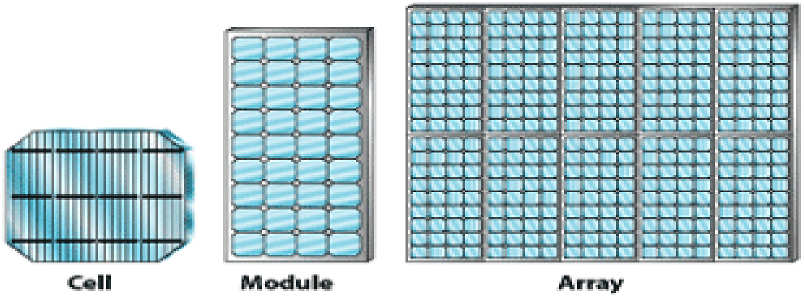


Figure 2.10: cell, module, and array

The solar array can be mounted in several ways:

- **Horizontal**: This most common arrangement gives most overall power during most of the day in low latitudes or higher latitude summers and offers little interaction with the wind. Horizontal arrays can be integrated or be in the form of a free canopy.
- **Vertical**: This arrangement is sometimes found in free standing or integrated sails to harness wind energy [23].Useful solar power is limited to mornings, evenings, or winters and when the vehicle is pointing in the right direction.
- **Adjustable**: Free solar arrays can often be tilted around the axis of travel in order to increase power when the sun is low and well to the side. An alternative is to tilt the whole vehicle when parked. Two-axis adjustment is only found on marine vehicles, where the aerodynamic resistance is of less importance than with road vehicles.
- **Integrated**: Some vehicles cover every available surface with solar cells. Some of the cells will be at an optimal angle whereas others will be shaded.
- **Trailer**: Solar trailers are especially useful for retrofitting existing vehicles with little stability, e.g. bicycles. Some trailers also include the batteries and others also the drive motor.
- **Remote**: By mounting the solar array at a stationary location instead of the vehicle, power can be maximised and resistance minimized. The virtual grid-connection however involves more electrical losses than with true solar vehicles and the battery must be larger.

The choice of solar array geometry involves an optimization between power output, aerodynamic resistance and vehicle mass, as well as practical considerations. For example, a free horizontal canopy gives 2-3 times the surface area of a vehicle with integrated cells but offers better cooling of the cells and shading of the riders. There are also thin flexible solar arrays in development.

Solar arrays on solar cars are mounted and encapsulated very differently from stationary solar arrays. Solar arrays on solar cars are usually mounted using industrial grade double-sided adhesive tape right onto the car's body. The arrays are encapsulated using thin layers of Tedlar.

Some solar cars use gallium arsenide solar cells, with efficiencies around thirty percent. Other solar cars use silicon solar cells, with efficiencies around twenty percent.

2.4 Energy Storage

When the energy production is not constant and continuous, a good energy storage method is necessary. We can list many different ways to store energy [16]:

• Chemical (hydrogen, biofuels)
• Electrochemical (batteries, fuel cells)
• Electrical (capacitor, super capacitor, superconducting magnetic energy storage or SMES)
• Mechanical (compressed air, flywheel)
• Thermal

These different technologies coexist because their characteristics make them attractive to different applications. From a user point of view, the main selection criteria are the energy and power density, the response time, the lifetime, the efficiency and of course the costs.

In the case of a solar car, the gravimetric energy density in Wh/kg, also called specific energy, and the peak power are the most crucial parameters that determine the choice of the energy storage method. The volumetric energy density will of course also have an influence on the fuselage size, but this volume plays a minor role on the power required compared to the weight. A look at figure 2.9 shows that in the present case, electrochemical batteries and fuel cells are the two best candidates. In fact, they have the highest energy density from all the solutions that are reversible.

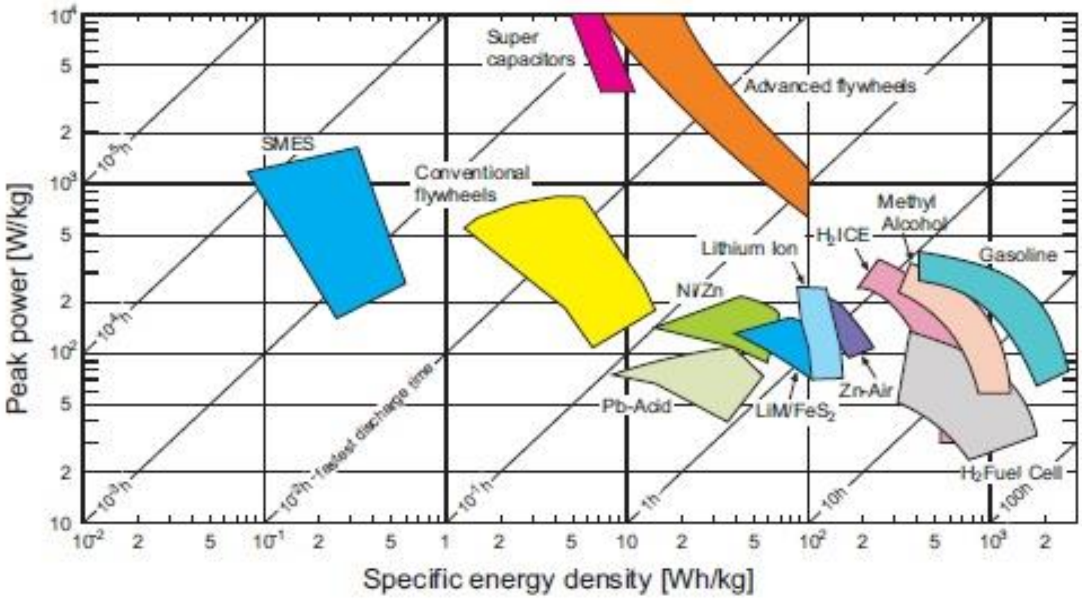


Figure 2.11: The Ragone Plot - Peak power and specific energy density of various energy storage methods [15]

2.4.1 Electrochemical Batteries

Working Principle

Electrochemical batteries are energy storage devices, which are able to convert chemically stored energy into electrical energy during discharging. They are composed of a cathode and an anode, made of two dissimilar metals, which are in contact with an electrolyte. When all elements are in contact with each other, a flow of electron is produced. If the process is reversible so that they can be recharged, they are referred to as secondary batteries, in the other case they are primary batteries [17]. Concerning a solar car, rechargeable batteries will of course be used.

Several technologies are available and currently, the lithium-ion (or lithium ion-polymer where the electrolyte is a gel and not a liquid) technology is the best concerning gravimetric energy density, compared to lead-acid, nickel cadmium (NiCad) or nickel-metalhydride (NiMH). The nominal voltage of a lithium-ion cell is 3.7V compared to 1.2V for NiCad and NiMH and its capacity, in Ah depends on its size. Due to cost and limited budget I had to use lead acid batteries. Which is a poor choice, but it works. So let’s study its properties in more details.

2.4.2 Lead–acid battery History

The French scientist Gautherot observed in 1801 that wires that had been used for electrolysis experiments would themselves provide a small amount of "secondary" current after the main battery had been disconnected [19] .In 1859, Gaston Planté's lead-acid battery was the first battery that could be recharged by passing a reverse current through it. Planté's first model consisted of two lead sheets separated by rubber strips and rolled into a spiral [20]. His batteries were first used to power the lights in train carriages while stopped at a station. In 1881, Camille Alphonse Faure invented an improved version that consisted of a lead grid lattice, into which a lead oxide paste was pressed, forming a plate. This design was easier to mass-produce. An early manufacturer (from 1886) of lead–acid batteries was Henri Tudor.

Using a gel electrolyte instead of a liquid allows the battery to be used in different positions without leakage. Gel electrolyte batteries for any position date from 1930s and even in late 1920s portable suitcase radio sets allowed the cell vertical or horizontal (but not inverted) due to valve design (see third Edition of Wireless Constructor's Encyclopaedia byFrederick James Camm). In the 1970s, the valve-regulated lead acid battery (often called "sealed") was developed, including modern absorbed glass mat types, allowing operation in any position.

Discharge

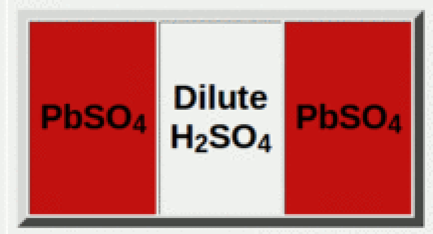


Figure 2.12: Fully discharged: two identical lead sulphate plates

In the discharged state both the positive and negative plates become lead (II) sulphate (PbSO4), and the electrolyte loses much of its dissolved sulphuric acid and becomes primarily water. The discharge process is driven by the conduction of electrons from the negative plate back into the cell at the positive plate in the external circuit.

Negative plate reaction:

$$Pb\ (s) + HSO^-_4\ (aq) \rightarrow PbSO_4(s) + H^+\ (aq) + 2e^-$$

Positive plate reaction:

$$PbO_2(s) + HSO^-_4\ (aq) + 3H^+\ (aq) + 2e^- \rightarrow PbSO_4\ (s) + 2H_2O\ (l)$$

The total reaction can be written as

$$Pb(s) + PbO_2\ (s) + 2H_2SO_4\ (aq) \rightarrow 2PbSO_4(s) + 2H_2O\ (l)$$

The sum of the molecular masses of the reactants is 642.6 g/mol, so theoretically a cell can produce two faradays of charge (192,971 coulombs) from 642.6 g of reactants, or 83.4 ampere-hours per kilogram (or 13.9 ampere-hours per kilogram for a 12-volt battery). For a 2 volts cell, this comes to 167 watt-hours per kilogram of reactants, but a lead-acid cell in practice gives only 30–40 watt-hours per kilogram of battery, due to the mass of the water and other constituent parts.

Charging

Overcharging with high charging voltages generates oxygen and hydrogen gas by electrolysis of water, which is lost to the cell. Periodic maintenance of lead-acid batteries requires inspection of the electrolyte level and replacement of any water that has been lost.

Due to the freezing-point depression of the electrolyte, as the battery discharges and the concentration of sulphuric acid decreases, the electrolyte is more likely to freeze during winter weather when discharged.

Ion Motion

During discharge, H^+ produced at the negative plates moves into the electrolyte solution and then is consumed into the positive plates [21], while HSO^-_4 is consumed at both plates. The reverse occurs during charge. This motion can be by electrically driven proton flow or Grotthuss mechanism, or by diffusion through the medium, or by flow of a liquid electrolyte medium. Since the density is greater when the sulphuric acid concentration is higher, the liquid will tend to circulate by convection. Therefore a liquid-medium cell tends to rapidly discharge and rapidly charge more efficiently than an otherwise similar gel cell.

2.4.3 Lead-acid Batteries Cycles

Starting Batteries

Lead-acid batteries designed for starting automotive engines are not designed for deep discharge. They have a large number of thin plates designed for maximum surface area, and therefore maximum current output, but which can easily be damaged by deep discharge. Repeated deep discharges will result in capacity loss and ultimately in premature failure, as the electrodes disintegrate due to mechanical stresses that arise from cycling. Starting batteries kept on continuous float charge will have corrosion in the electrodes which will result in premature failure. Starting batteries should be kept open circuit but charged regularly (at least once every two weeks) to prevent sulphating to occur.

Starting batteries are lighter weight than deep cycle batteries of the same battery dimensions, because the cell plates do not extend all the way to the bottom of the battery case. This allows loose disintegrated lead to fall off the plates and collect under the cells, to prolong the service life of the battery. If this loose debris rises high enough it can touch the plates and lead to failure of a cell, resulting in loss of battery voltage and capacity.

Deep Cycle Batteries

Specially designed deep-cycle cells are much less susceptible to degradation due to cycling, and are required for applications where the batteries are regularly discharged, such as photovoltaic systems, electric vehicles (forklift, golf cart, electric cars and other) and uninterruptible power supplies. These batteries have thicker plates that can deliver less *peak current*, but can withstand frequent discharging.

Some batteries are designed as a compromise between starter (high-current) and deep cycle batteries. They are able to be discharged to a greater degree than automotive batteries, but less so than deep cycle batteries. They may be referred to as "Marine/Motorhome" batteries, or "leisure batteries".

Fast and slow charge and discharge

The capacity of a lead–acid battery is not a fixed quantity but varies according to how quickly it is discharged. An empirical relationship between discharge rate and capacity is known as Peukert's law.

When a battery is charged or discharged, only the reacting chemicals, which are at the interface between the electrodes and the electrolyte, are initially affected. With time, the charge stored in the chemicals at the interface, often called "interface charge" or "surface charge", spreads by diffusion of these chemicals throughout the volume of the active material.

Consider a battery that has been completely discharged (such as occurs when leaving the car lights on overnight, a current draw of about 6 amps). If it then is given a fast charge for only a few minutes, the battery plates charge only near the interface between the plates and the electrolyte. In this case the battery voltage might rise to a value near that of the charger voltage; this causes the charging current to decrease significantly. After a few hours this interface charge will spread to the volume of the electrode and electrolyte; this leads to an interface charge so low that it may be insufficient to start the car. As long as the charging voltage stays below the gassing voltage (about 14.4 volts in a normal lead-acid battery), battery damage is unlikely, and in time the battery should return to a nominally charged state.

2.5 Solar Charger Types

There is 2 major types of solar chargers MPPT and PWM, and I believe the best way to understand both and to know the difference between them is to compare between them.

1. What do they do?

The PWM controller is in essence a switch that connects a solar array to a battery. The result is that the voltage of the array will be pulled down to near that of the battery.

The MPPT controller is more sophisticated (and more expensive): it will adjust its input voltage to harvest the maximum power from the solar array and then transform this power to supply the varying voltage requirement, of the battery plus load. Thus, it essentially decouples the array and battery voltages so that there can be, for example, a 12 volt battery on one side of the MPPT charge controller and a large number of cells wired in series to produce 36 volts on the other.

2. The resultant twin strengths of an MPPT controller

a) Maximum Power Point Tracking

The MPPT controller will harvest more power from the solar array. The performance advantage is substantial (10% to 40%) when the solar cell temperature is low (below 45°C), or very high (above 75°C), or when irradiance is very low.

At high temperature or low irradiance the output voltage of the array will drop dramatically. More cells must then be connected in series to make sure that the output voltage of the array exceeds battery voltage by a comfortable margin.

b) Lower cabling cost and/or lower cabling losse

Ohm's law tells us that losses due to cable resistance are Pc (Watt) = R_c x I^2, where R_c is the resistance of the cable. What this formula shows is that for a given cable loss, cable cross sectional area can be reduced by a factor of four when doubling the array voltage.

In the case of a given nominal power, more cells in series will increase the output voltage and reduce the output current of the array (P = V x I, thus, if P doesn't change, then I must decrease when V increases).

As array size increases, cable length will increase. The option to wire more panels in series and thereby decrease the cable cross sectional area with a resultant drop in cost, is a compelling reason to install an MPPT controller as soon as the array power exceeds a few hundred Watts (12 V battery), or several 100 Watts (24 V or 48 V battery).

3. Conclusion [25]

PWM

The PWM charge controller is a good low cost solution for small systems only, when solar cell temperature is moderate to high (between 45°C and 75°C).

MPPT

To fully exploit the potential of the MPPT controller, the array voltage should be substantially higher than the battery voltage. The MPPT controller is the solution of choice for higher power systems (because of the lowest overall system cost due to smaller cable cross sectional areas). The MPPT controller will also harvest substantially more power when the solar cell temperature is low (below 45°C), or very high (above 75°C), or when irradiance is very low.

SUMMARY OF COMPARISON

	PWM Charge Controller	MPPT Charge Controller
Array Voltage	PV array & battery voltages should match	PV array voltage can be higher than battery voltage
Battery Voltage	Operates at battery voltage so it performs well in warm temperatures and when the battery is almost full	Operates above battery voltage so it is can provide “boost” in cold temperatures and when the battery is low.
System Size	Typically recommended for use in smaller systems where MPPT benefits are minimal	≈ 150W – 200W or higher to take advantage of MPPT benefits
Off-Grid or Grid-Tie	Must use off-grid PV modules typically with Vmp ≈ 17 to 18 Volts for every 12V nominal battery voltage	Enables the use of lower cost/grid-tie PV Modules helping bring down the overall PV system cost
Array Sizing Method	PV array sized in Amps (based on current produced when PV array is operating at battery voltage)	PV array sized in Watts (based on the Controller Max. Charging Current x Battery Voltage)

For more information refer to [24].

2.6 Dc Motors

A **DC motor** is any of a class of electrical machines that converts direct current electrical power into mechanical power. The most common types rely on the forces produced by magnetic fields. Nearly all types of DC motors have some internal mechanism, either electromechanical or electronic, to periodically change the direction of current flow in part of the motor. Most types produce rotary motion; a linear motor directly produces force and motion in a straight line.

DC motors were the first type widely used, since they could be powered from existing direct-current lighting power distribution systems. A DC motor's speed can be controlled over a wide range, using either a variable supply voltage or by changing the strength of current in its field windings. Small DC motors are used in tools, toys, and appliances. The universal motor can operate on direct current but is a lightweight motor used for portable power tools and appliances. Larger DC motors are used in propulsion of electric vehicles, elevator and hoists, or in drives for steel rolling mills. The advent of power electronics has made replacement of DC motors with AC motors possible in many applications.

Brushed

The brushed DC electric motor generates torque directly from DC power supplied to the motor by using internal commutation, stationary magnets (permanent or electromagnets), and rotating electrical magnets.

Advantages of a brushed DC motor include low initial cost, high reliability, and simple control of motor speed. Disadvantages are high maintenance and low life-span for high intensity uses. Maintenance involves regularly replacing the carbon brushes and springs which carry the electric current, as well as cleaning or replacing the commutator. These components are necessary for transferring electrical power from outside the motor to the spinning wire windings of the rotor inside the motor. Brushes consist of conductors.

Brushless

Typical brushless DC motors use a rotating permanent magnet in the rotor, and stationary electrical current/coil magnets on the motor housing for the stator. A motor controller converts DC to AC. This design is mechanically simpler than that of brushed motors because it eliminates the complication of transferring power from outside the motor to the spinning rotor. The motor controller can sense the rotor's position via Hall effect sensors or similar and precisely control the timing, phase, etc., of the current in the rotor coils to optimize torque, conserve power, regulate speed, and even apply some braking. Advantages of brushless motors include long life span, little or no maintenance, and high efficiency. Disadvantages include high initial cost, and more complicated motor speed controllers. Some such brushless motors are sometimes referred to as "synchronous motors" although they have no external power supply to be synchronized with, as would be the case with normal AC synchronous motors.

Uncommutated

Other types of DC motors require no commutation.

- Homopolar motor – A homopolar motor has a magnetic field along the axis of rotation and an electric current that at some point is not parallel to the magnetic field. The name homopolar refers to the absence of polarity change.

Homopolar motors necessarily have a single-turn coil, which limits them to very low voltages. This has restricted the practical application of this type of motor.

- Ball bearing motor – A ball bearing motor is an unusual electric motor that consists of two ball bearing-type bearings, with the inner races mounted on a common conductive shaft, and the outer races connected to a high current, low voltage power supply. An alternative construction fits the outer races inside a metal tube, while the inner races are mounted on a shaft with a non-conductive section (e.g. two sleeves on an insulating rod). This method has the advantage that the tube will act as a flywheel. The direction of rotation is determined by the initial spin which is usually required to get it going.

Permanent Magnet Stator

- A PM motor does not have a field winding on the stator frame, instead relying on PMs to provide the magnetic field against which the rotor field interacts to produce torque. Compensating windings in series with the armature may be used on large motors to improve commutation under load. Because this field is fixed, it cannot be adjusted for speed control. PM Fields (stators) are convenient in miniature motors to eliminate the power consumption of the field winding. Larger DC motors are of the "dynamo" type, which have stator windings. Historically, PMs could not be made to retain high flux if they were disassembled; field windings were more practical to obtain the needed amount of flux. However, large PMs are costly, as well as dangerous and difficult to assemble; this favors wound fields for large machines.
- To minimize overall weight and size, miniature PM motors may use high energy magnets made with neodymium or other strategic elements; most such are neodymium-iron-boron alloy. With their higher flux density, electric machines with high-energy PMs are at least competitive with all optimally designed singly fed synchronous and induction electric machines. Miniature motors resemble the structure in the illustration, except that they have at least three rotor poles (to ensure starting, regardless of rotor position) and their outer housing is a steel tube that magnetically links the exteriors of the curved field magnets.

Chapter 3

Design Methodology

3.1 Chassis & Gearbox

In this chapter I will put every part into application, with the concrete example of the design of my solar car prototype. First step I was lucky enough to find a chassis that wasn't used by anyone and it was also made for 2 people.

So I bought the chassis have a differential gearbox with a transmission ratio of 3:1. By that transmission ratio will increase the torque the motor 3 times and decrease the speed by 3 times. The Chassis Dimensions are 105 cm width, 170 cm length, and 182 cm height. I changed the outer shape of car chassis by fiberglass, to make its shape more appealing and acceptable. Of course a lot of the Chassis parts was not welded well and some were broken so I fixed them also. After that I designed a roof for the solar panels with dimensions of (132 × 66).

$$\boxed{i=\frac{\omega_1}{\omega_2}=\frac{n_1}{n_2}=\frac{d_2}{d_1}=\frac{N_2}{N_1}}$$

(Transmission ratio Equation.)

The input torque T_A applied to the input gear G_A and the output torque T_B on the output gear G_B are related by the ratio

$$R=\frac{T_B}{T_A},$$

Where R is the gear ratio of the gear train.

Figure 3.1: Car before, when bought (front view).

Figure 3.2: Car after major modifications (front view).

Figure 3.3: Car before, when bought (back view).

Figure 3.4: Car after major modifications (back view).

3.2 Brushed DC Motor

Table 3.1: Weight distribution of the car.

Chassis	**≈ 110 Kg**
Batteries	**≈ 20 Kg**
Solar Panels	**≈ 12 Kg**
Cables, and electronics	**≈ 8 Kg**
2 People each 90 Kg	**≈ 180 Kg**
Total	**≈ 330 Newton**

Torque = Newton*Tyre radius

Torque = 330 Newton * 0.175 Meter = 57.75 N.m.

The Speed at the beginning is needed to range between 20 – 30 Km / H

$$\mathbf{v = r \times RPM \times 2\pi}$$

Where:

v: Linear velocity, in m/s

r: Radius, in meter

RPM: Angular velocity, in RPM (Rounds per Minute)

The RPM to Linear Velocity formula is:

$$\mathbf{v = r \times RPM \times (2\pi/60)}$$

24 km / h ≈ 6.67 m / s

6.67 m / s = 0.175 m × RPM × (2π / 60)

So RPM = 363.7827 round / min

Before Gearbox the RPM is 3 times the value = 1091.34 ≈ **1100 RPM**

The Speed at the beginning needed range between 20 – 30 Km / H

So by equation we need 366.6 RPM output from Gearbox, so Motors Rpm must be 1100 RPM.

Output Torque from gearbox (57.75 N.m.) = Input Torque of motor x Gear Ratio (3)

Input Torque of motor = 57.75/3 = 19.25 N.m.

Power = (Ti × 2π × rpm) / 60

Power = (19.25×2π×1100)/ (60) ≈ 2217.440815 Watts

Because 246 watts = 1 Hp

So we need 2.97244 ≈ **3 Hp**

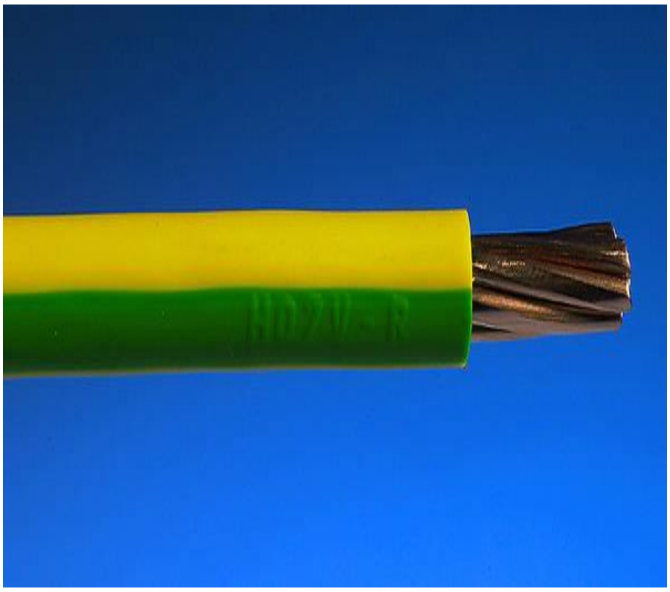
I need a 3 Hp brushed DC motor 24 V, 1100 RPM.

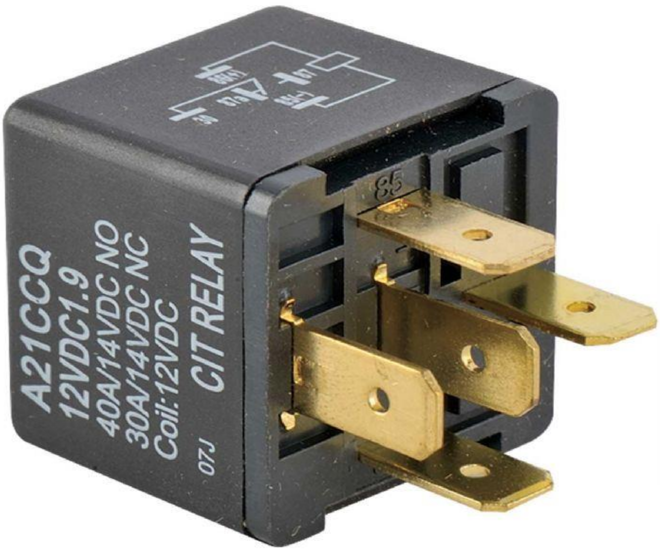
3.3 Electronic Circuits

In Egypt the main problem is the lack of components. I wanted to control my car by using PWM method but the obstacle was that the components would not be able to tolerate the high ampere and high temperature as the transistor, regulator etc. So I used the main idea behind PWM, which is using the voltage difference to make 2 different speed levels for my car. I have 2 lead-acid battery, the first stage's source will be 12V-36AH lead-acid battery, and the second stage's source will be the 2 batteries in series forming 24V-36AH lead-acid battery.

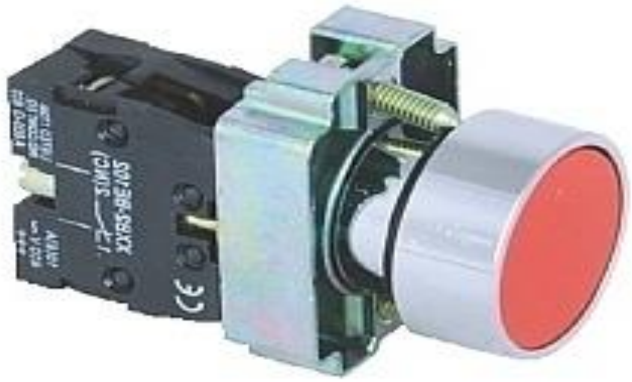
This transformation from the no start engine stage to the first stage and finally to the second stage, will be done by 4 relays, 3 of them 150A-24V relays, and the fourth one is a 3A-24V relay. The wiring of high ampere consumption is 35mm wires and the others is 2mm wires.

Table 3.2: Electronic Components

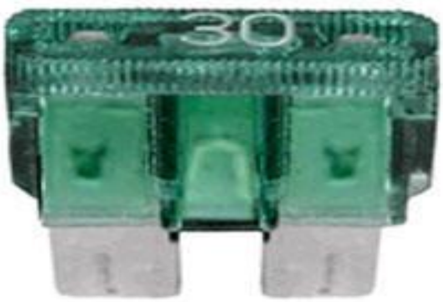
Component Name		Quantity
2 mm wire		100 meters of wire
35 mm wire		12 meters of wire

Relay Coil: 24VDC Contact: DPDT 150 Ampere		3 Relays
12VDC Automotive Relay		1 Relay

12V-36AH Lead-Acid Battery		2 Batteries
24V-3A Relay		1 Relay
85 watt Solar Panel		2 Solar Panels

Push Button		2 Push Buttons
Switch		3 Switches

Key Switch		1 Key Switch
Electronic Flasher		1 Electronic Flasher

30 Ampere Fuse		1 Fuse
Solar Charger Controller 12V/24V,10A		2 PWM Solar Chargers

First speed the motor is connected to 2 relays 150A-24V in series to divide the high ampere which may reach to 180 amperes - on 2 relays, so they can tolerate it.

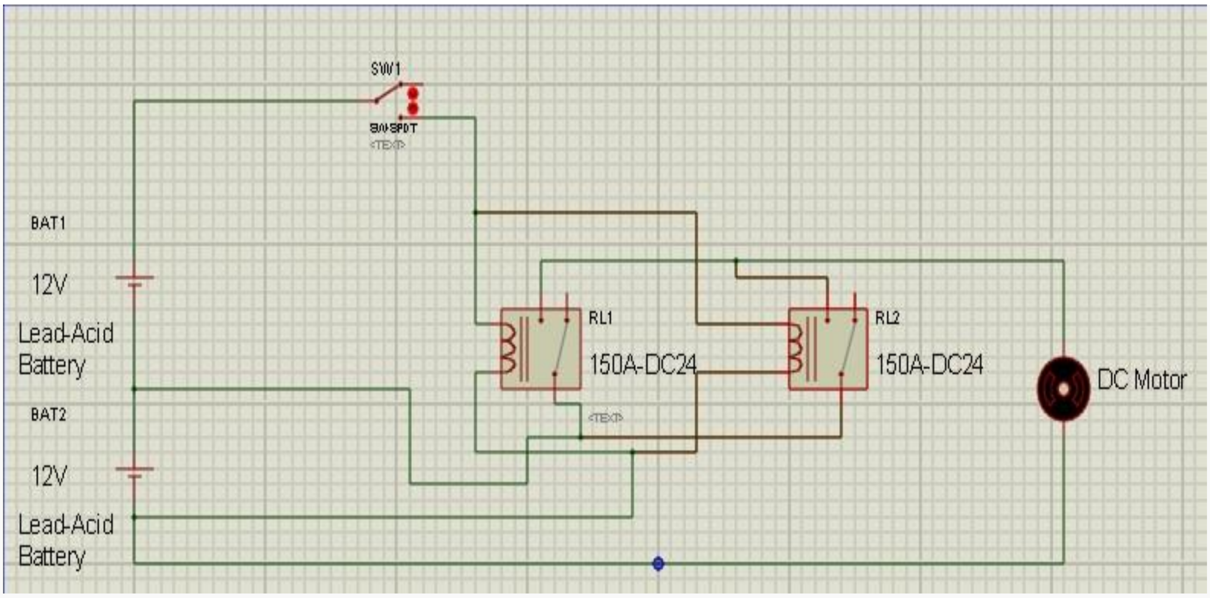


Figure 3.5: First Speed motor is supplied with 12V/171A at the start.

Second stage the motor is connected to 1 relay 150A-24V because the 180 volts will be divided by 2 because of increasing the volt 2 times:

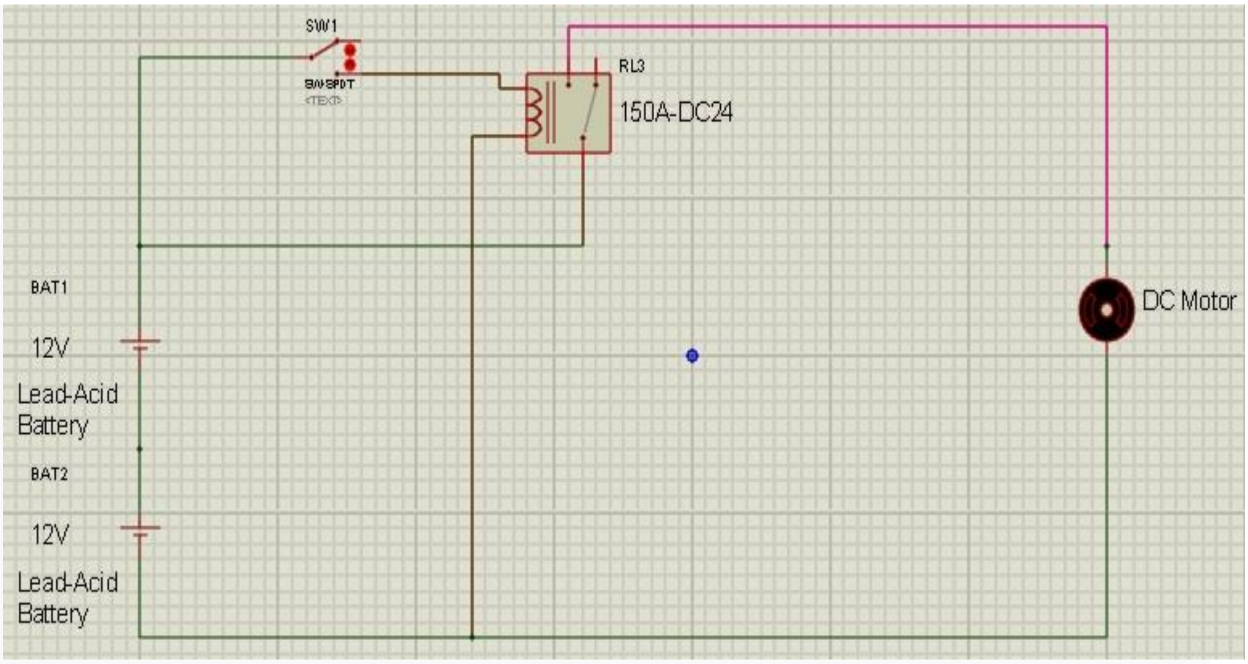


Figure 3.6: Second Speed motor is supplied with 24V/86A at the start.

An **overall view** of the Controlling Systems

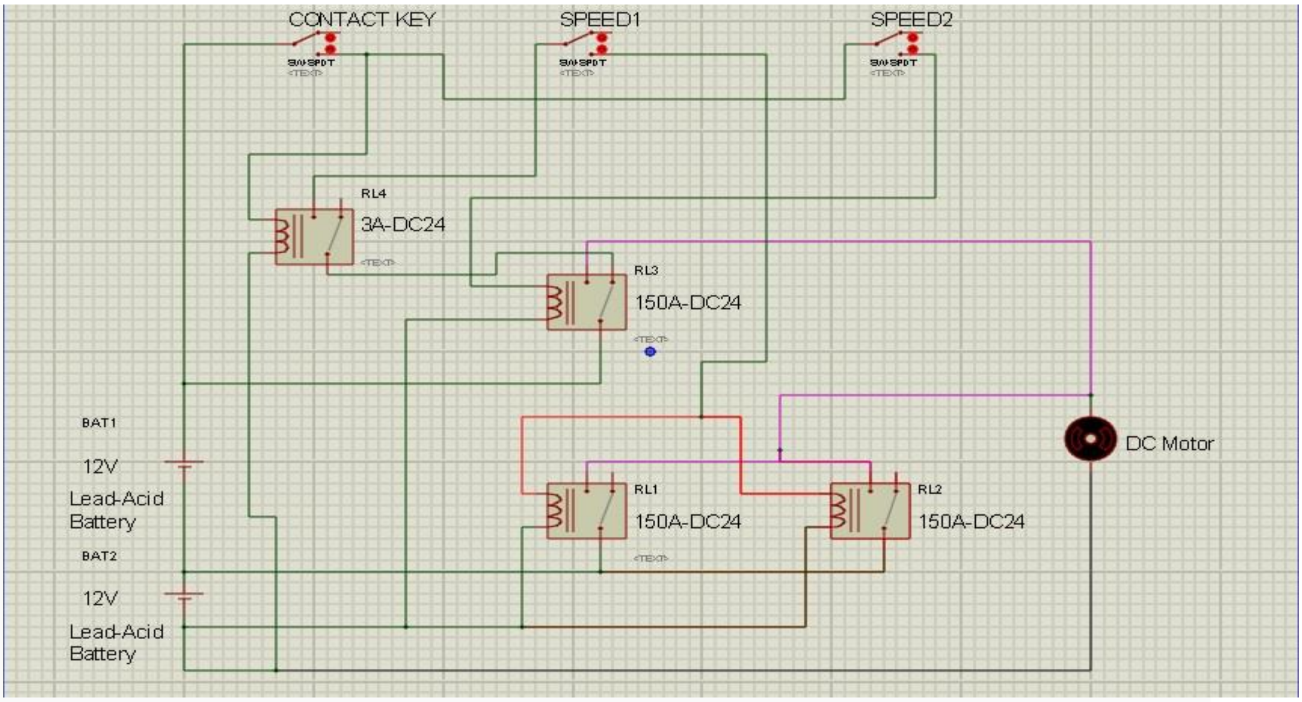


Figure 3.7: The whole Controlling system.

Car Light & horn Electronics

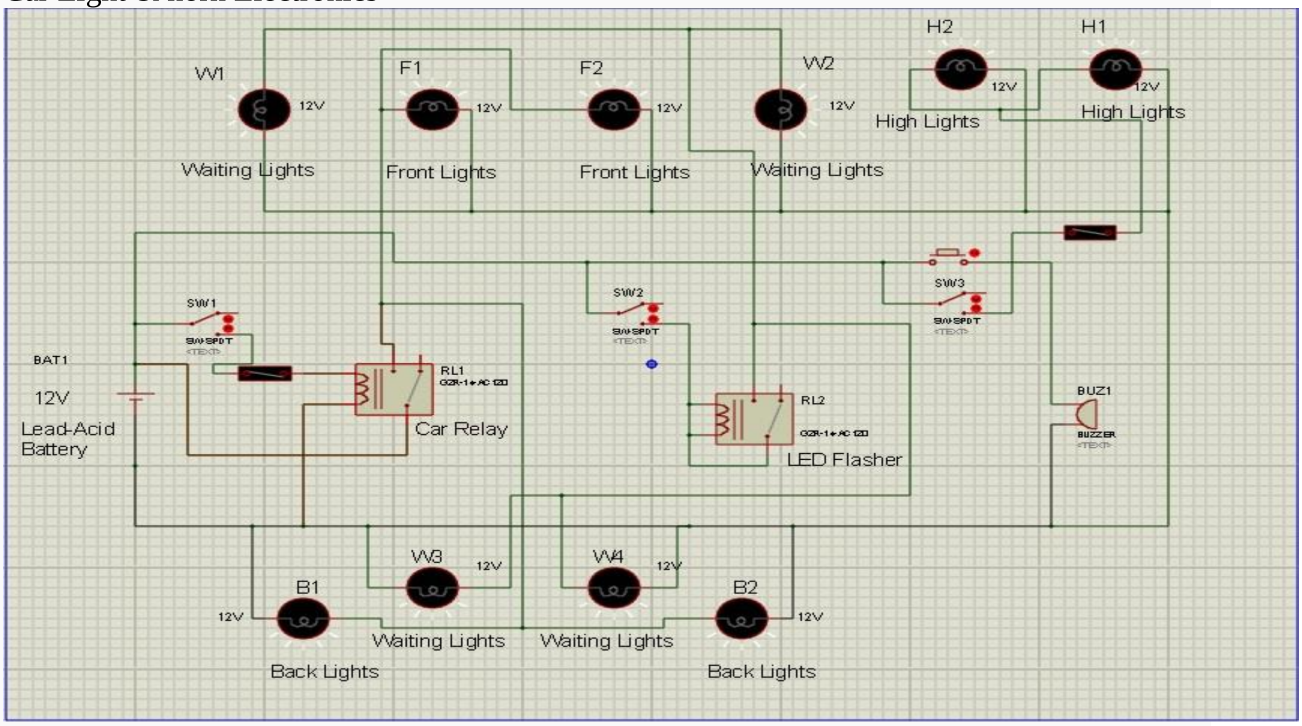


Figure 3.8: Front, back, waiting Lights, and the horn Circuits.

3.4 Daily Solar Energy Obtained

3.4.1 Irradiance Model

The irradiance depends on a lot of variables such as geographic location, time, plane orientation, and weather conditions. Here we will use a simple trigonometric model with only two parameters, the maximum irradiance I_{max} and the duration of the day T_{day}, that can be easily interpreted. The daily solar energy per square meter is the surface below the curve and can be easily calculated in equation (3.1). In order to take into account cloudy days, a constant w_{thr} is added with a value between 1 (clear sky) and 0 (dark). This constitutes a margin for the calculation.

$$E_{day\ density} = (I_{max} * T_{day}) * (\eta_{wthr}) / (\pi/2) \qquad \text{equation (3.1)}$$

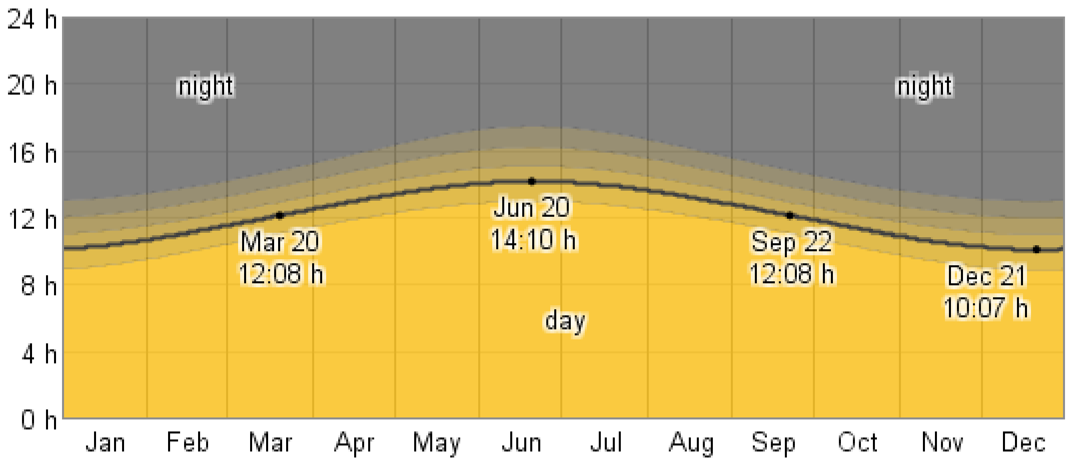


Figure 3.9: Relation between day duration & day through the year in Egypt.

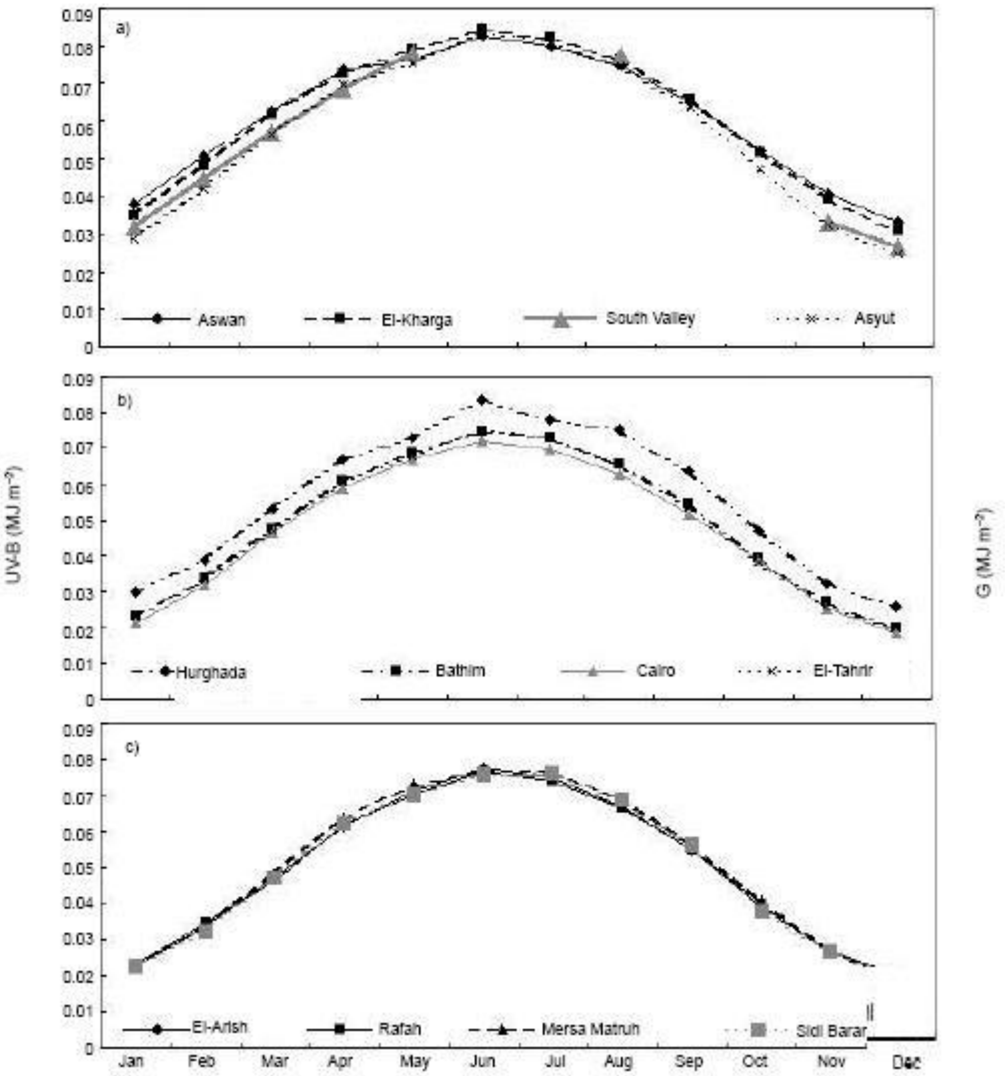


Figure 3.10: The annual variation of monthly values of UV-B at a) Aswan, El-Kharga, South Valley and Asyut. b) Hurghada, Bathim, Cairo and Tahrir. c) El-Arish, Rafah, Mersa Matruh and Sidi Barani.

We can observe that in winter, the duration of the day but also the maximum irradiance decrease due to the very low sun elevation.

3.4.2 Solar Cells

17% efficient Polycrystalline Solar Panels

Maximum Power (Pmax): 85W (+10% / -5%)

Maximum Power Voltage (Vmpp): 18.1V

Maximum Power Current (Impp): 4.7A

Open Circuit Voltage (Voc): 21.3V

Short Circuit Current (Isc): 4.9A

Of area 132 × 66 = 8,712 cm^2

3.5 PWM Controller

- Rated Charge Current: 10A
- Rated Discharge Current: 10A
- Rated Charge Power for 12V : 120W
- Rated Charge Power for 24V : 240W
- System Voltage: 12V/24V Auto
- Maximum Solar Panel Voltage: 40V

3.6 Batteries Calculations

The car runs on 36 AH-12Volt-Lead Acid Battery *2

Theoretically the motor on 12v should consume:

- First Speed 2238 W / 12 V = 186.5 A

- Second Speed 2238 W / 24 V = 93.25 A

- Woking on the first speed (H) 36 AH / 186.5 A ≈ 0.193 H ≈ 11.58 Min

- Working on the second speed (H) 36 AH / 93.25 A ≈ 0.386 H ≈ 23.16 Min

Bec. : (velocity = Distance / Time)

- Woking on the first speed (Km)

» 13 Km = d / 0.193 » d ≈ 2.509 Km » d ≈ 2.5 Km

- Woking on the second speed (Km)

» 27 Km = d / 0.386 » d ≈ 10.422 Km » d ≈ 10.4 Km

Estimating Battery Charge Time from Solar Jeff May 14, 2010 All, DIY 18 research. This means an 85 Watt, 18 Volt panel and a 36 AH, 12V battery, how long does it take to completely charge? The quick and very wrong answer would be to figure out the ampere hours of the battery (36 AH / (85 W / 18 V) = 7.62 hours). The reality is about 2.5 times longer.

There are four main reasons for the difference, even in ideal conditions. First, the Wattage rating on the panel is the open circuit Voltage multiplied by the peak current. When you connect a panel to a battery, the Voltage drops down to that of the load, about 4.5V. All the power that enters the battery does not get converted into storage energy. Some percentage is lost as heat as the process to convert the incoming power into stored power takes energy. Finally, the efficiency of the solar panel decreases because of heat.

In field tests, it has been seen that the combined loss factor is about 2.5. So Divide the Watt hours of the battery by the Wattage of the panel and multiply by 2.5.

So the reality calculations are $2.5 \times 7.62 = 19.05$ hours

For 7 hours daily in summer »19.05 hours / 7 hours per day = 2.72 days

Chapter 4

Results

The car's approximate maximum speed reached at second speed in reality was 32 Km/h: The car starts at 25 Km / h, and then accelerates till it reaches 32 Km / h. The ampere supplied by the battery to the motor was 162.4 A at the beginning of movement then decreases to reach 143 A. The duration at max speed was approximately 30 min which means by the equation.

» (velocity=distance/Time)   » 32 Km / h = d / 0.5 h

» distance ≈ 16 Km

The time taken to charge the batteries was approximately close to the calculated time which was 19.5 hours in reality, which equals to 2.78 days of charging.

Discussion

First of all as we notice that the ampere supplied to the motor was lower than calculated, also the ampere decreases as the motor accelerates. Which gave the car more running time, and in addition to that the speed achieved in reality was more than expected in calculations. Of course as the running time and speed increased the distance covered by the car increased. The charging time of the batteries was approximately equal to the calculations, due to the high loss factor multiplied to the ideal case calculation.

Chapter 5

Conclusions

- **Overcoming the obstacle of depending on limited energy source type such as petroleum, coal, and gas.**
- **Presented a simple application methodology for the design of solar cars.**
- **The car has the advantage of being very cheap.**
- **The solar car can be produced by local components in Egypt.**
- **The solar car helps in reducing the global warming effect, eco-friendly car.**
- **The thesis presents the methodology to calculate required components for different required weight load, and needed speed.**
- **The car is economical for short distances.**

Chapter 6

Scope of Future Studies

1. **Further improvement in decreasing the charging time will be achieved by exchanging the polymorphic solar panels by higher efficiency multi junctional solar panels that reached now to high efficiency reaching more than 40 %, and gradually plummeting in prices.**
2. **Improvements in decreasing the charging time can also be achieved by exchanging the PWM solar charger with an MPPT solar charger.**
3. **In an attempt to increase the time of running of motor is to use Ion-lithium batteries instead of Lead-acid batteries, because of high-energy density and lightweight speciality.**
4. **Besides the last improvement we can increase the ampere-hour of the batteries to increase the working time, of course in result the distance covered will increase.**
5. **As for the controlling system we can improve it by searching the best way to control the car without consuming that much amperes taken.**
6. **Use a regenerative braking motor.**
7. **The design of Chassis in a more efficient way, and lighter material.**
8. **Finally, the design of outer body by putting in consideration decreasing the air drag force, to minimize the power losses.**
9. **Make the outer body out of carbon fiber, because it gives more stiffness and strength to the car’s outer body.**

10. **We can increase solar panel's efficiency, by studying effect of coating solar panels to prevent the decrease that occurs due to dust accumulation.**

Self-Cleaning and Antimicrobial Actions using the secrets of Nature can be described in three simple ways:

1. Hydrophobic (water repelling, drops form beads washing away sand or dust).

2.Hydrophilic (water attracting , drops flatten out washing away dirt and dust).

3. Photo catalytic (UV-induced reactions that cause decomposition of dirt molecules).

11. **Design the car with a 3 wheel mechanism to decrease rolling resistance, and aerodynamics drag.**
12. **Finally, develop a tilting roof which tilts 45 degrees to North,when car is parked.**

Bibliography

[1] Statista

http://www.statista.com/statistics/271748/the-largest-emitters-of-co2-in-the-world/

[2] EPA

http://www.epa.gov/climatechange/ghgemissions/gases/co2.html

[3] Solar Car Challenge

http://www.solarcarchallenge.org/challenge/history.shtml

[4] PrestigeElectricCar

http://www.prestigeelectriccar.com/history-8-_The_first_car_which_exceeded_100_kmh

[5] Popular Science, October 1955, Vol. 167, No. 4, ISSN 0161-7370, Published by Bonnier Corporation

[6] Lynch, J., Power from sunlight: photovoltaics

[7] Popular Mechanics, September 1955, Vol. 104, No. 3, ISSN 0032-4558, Published by Hearst Magazines

[8] The Leading Edge, Tamai, Goro, Robert Bently, Inc., 1999

[9] The New York Times

http://wheels.blogs.nytimes.com/2009/01/07/solar-cars-not-likely-anytime-soon/?_r=0

[10] Solar Vehicle Performance, Dr. Eric Slimko, December 1, 1991

[11] Antonio Luque and Steven Hegedus (2003). *Handbook of Photovoltaic Science and Engineering*. John Wiley and Sons.

[12] Rob Andrews, Andrew Pollard, Joshua M. Pearce, "Improved parametric empirical determination of module short circuit current for modelling and optimization of solar photovoltaic systems", *Solar Energy* (2012).

[13] R. W. Miles, K. M. Hynes, and I. Forbes. Photovoltaic Solar Cells: An Overview of State-of-the-Art Cell Development and Environmental Issues. *Progress in Crystal Growth and Characterization of Materials*, 51(1-3):1–42, January 2005.

[14] T. Markvart and L. Castañer. *Practical Handbook of Photovoltaics: Fundamentals and Applications*. Elsevier, Oxford, UK, 2003.

[15] Forschungsverbund energie niedersachsen with data from Lawrence Livermore Labs.

[16] Mora Associates (Overview of Energy Storage Methods)

http://www.moraassociates.com/reports/0712%20Energy%20storage.pdf

[17] P. H. L. Notten. Rechargeable Batteries : Efficient Energy Storage Devices for Wireless Electronics. In S. Mukherjee and et al., editors, *AmIware Hardware Technology Drivers of Ambient Intelligence*, Philips Research, part 5, pages 315–345. Springer Netherlands, 2006.

[18] Mora Associates (Overview of Energy Storage Methods)

http://www.moraassociates.com/reports/0712%20Energy%20storage.pdf

[19] Crompton, Thomas Roy (2000), *Battery Reference Book*, Newnes.

[20] Corrosion Doctors

http://www.corrosion-doctors.org/Biographies/PlantelBio.htm

[21] Linden, David; Reddy, Thomas B., ed. (2002). *Handbook of Batteries* (3rd ed.). New York: McGraw-Hill.

[22] Lynch, J., Power from sunlight: photovoltaics.

[23] The Leading Edge, Tamai, Goro, Robert Bentley, Inc., 1999, p. 137.

[24] Victro Energy

http://www.victronenergy.com/upload/documents/White-paper-Which-solar-charge-controller-PWM-or-MPPT.pdf

[25] Solar Craft

http://solarcraft.net/articles/comparing-pwm-and-mppt-charge-controllers/