Analysis of Hybrid Solar Vehicle Systems: Advances and Remaining Barriers to Consumer Adoption

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***Abstract*— Although solar-powered vehicles have often served as student and university technical showpieces, few have made the leap into real consumer products. The current project investigates the conceptualization and engineering of a solar-hybrid car optimized using established best practices from contemporary EV and hybrid models. By analyzing the most advanced electrical and mechanical subsystems—selected for maximal efficiency and economic viability—our prototype incorporates the latest available market technologies, while explicitly addressing the limitations inherent to daily urban automotive use. Our comprehensive review provides a systems overview, evaluates component efficiency, and offers a detailed financial breakdown with pathways for further optimization. The resulting synthesis demonstrates that the solar-hybrid mobility concept, using refinements from proven vehicle technologies, can be both economically competitive and operationally practical for widespread daily transportation.**

Keywords-Solar car; automobile; financial study; photovoltaic; solar panels.

I. INTRODUCTION

Until nowadays, most solar cars were built especially for racing because they include only one passenger which reduces significantly the weight of the car thus reducing its efficiency and speed. Besides, even if the public opinion become more aware and pushing toward renewable energy, not a lot of budget and advertisements were allocated to encourage consumers to buy and use solar case making them hard to customize and difficult to sell in the market for profit. There are many solar car races where several universities and corporate teams compete to win the race; four of them are the most notable:

- World Solar Challenge: is a race for solar car that covers 3,021 km from Darwin to Adelaide in Australia. The winner car of 2009 and 2011 challenge was Tokai Challenger a Japanese car made in the Japanese Tokai University. This car covered 2998 km in 29 hours 49 minutes and with an average speed of 100.54 km/h. Concerning its solar cells, they have used a total of 2176 of powering satellites solar cells covering an area of 6 m². their performance was 1.8 kW with an energy conversion efficiency of 30 % which is the higher in the world since conventional crystalline silicon solar cells typically have a little more than 15 % efficiency. In addition, its motor also attained a high efficiency that was 97 % [1].
- American Solar Challenge: is a race for solar car organized across the United States and Canada. The 2010 race was won by the University of Michigan. The race started in Tulsa and ended in Naperville, Illinois. The car covered a speed of 168.98 km/h and had a battery of type lithium Ion and a solar cells made of silicon. Furthermore, the car's weight was 320 lbs without a driver with a chasis and body of type Carbon Fiber Monocoque [2] and performes using a brushless electric DC motor with an efficiency of 98 %.
- Solar Car Challenge: is an annual race for solar car for high school students. The race is a track race around the Texas Motor Speedway. The winner car of the 2011 classic division was Sundancer II made in Houstan High School. The car had an average speed of 56.33 km/h. The car was not precisely fast because the strategy followed to build it was based more on reliability and consistency rather than high speed. Sundancer II had 708 solar cells with an overall efficiency of 14.5 % and 2 Concorde batteries that have 108 Ampere hour each [3]. The car's weight was 317.5 kg without the driver and it used two hydraulic disc breaking systems one in the front and the other in the rear.
- South African Solar Challenge*:* is an alternative fuel vehicle auto racing challenge in Africa. The race distance is over 4,100 km and it starts at Johannesburg to Cape Town to Durban and finishes in Pretoria. The Tokai Challenger (presented earlier) has also won the 2010 South African Solar Challenge. The car covered 4061.8 km in 45 hours 5 minutes with an average speed of 90.1 km/h. It was equipped with Sharp solar cells developed for outer space applications.

The above built solar cars are all made for racing which:

- The consumer considers the solar car as a futuristic dream rather than a vehicle that can be used in the real life for daily activities because of minimal discussions about their feasibility.
- The technology concerning solar cars had rapidly saturated and did not evolve as it should which shows an opposite progress between the evolution of the gasoline car technology and the solar car technology.
- Solar car innovators failed to target the right consumers market in order to make their cars sellable.

The aim of this project is to build a car that includes some of the best features of the designs discussed previously and still be able to merchandize it as a consumer car in an automobile company. Those features are mainly the speed that is directly related to the weight, the efficiency of the solar panels specifically and overall mechanical and electrical system generally. Then, we will try to look to some new technologies either existing in the market or in the research progress that are cheap and feasible to improve the technical characteristics of Ralos car.

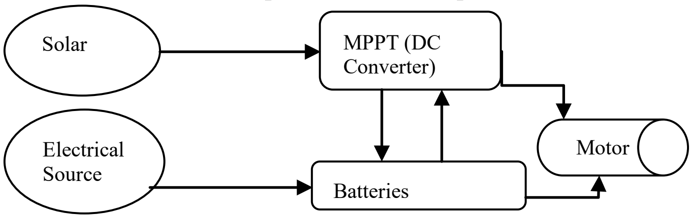
Besides, based on an economical study of the Moroccan market, failure of solar cars customization will be avoided by targeting the right customers and thus designing a car with the most compatible characteristics to everyday life needs. This paper is divided into four main sections. We will first start by discussing the electrical and mechanical system to attain the desired performance of our car. In addition to our added contribution to the design based on new possible technologies. Then a financial study is conducted to avoid penetrating the wrong industrial market. Finally, a small conclusion will be given to summarize our findings and present future works.

II. THE ELECTRICAL SYSTEM

After, many researches and decisions based on some of the most known and best solar cars' electric system, we were able to design a better system including the best features for an optimal consumer car. The electrical system in our solar car is the main source of energy. This later has two major parts, the first one deals with the fundamental source of energy, which is solar energy, the second one is a backup that we'll be implemented, to assure that we can always use the car no matter the situation, even if we do not have sun.

A. Solar System

Taking a look to the solar system, it has five essential components. The first one is solar panels that get photons from sun radiation and convert it to an electrical energy. Directly connected to a converter, the electrical voltage created is then converted to a Direct Current (DC). The current then goes to the motor so that the car can move. Solar panels are also connected to some batteries that stock energy using an electrochemical method that we will discuss later on the paper. Fig. 1 and Fig. 2 present the described general circuit of solar system. We will then have a brief description of each component.



Panels Figure 1: The general electrical system of the solar car.

1) Solar panels

The main components of solar panels are solar cells. The purpose of a solar cell or photovoltaic cell is to convert solar energy to electrical. This is done by using semiconductors where we have is a P-N junction of a diode, which is when in contact with photons creates an important movement of electrons. This movement is the source of our electrical current. In our case the type of cells that we will be using are Crystalline Silicon Solar Cells. The reason behind this choice is the high efficiency that it offers. In fact there efficiency can attain up to 20-30 % of efficiency at 25 °C. The compound materials enable these cells to absorb more of the available light spectrum than silicon but are more expensive to make. Each compound cell is composed of three main layers: germanium at the bottom, indium gallium arsenide (InGaAs) or gallium arsenide (GaAs) in the middle, and indium gallium phosphide (InGaP) on top. Sharp corp. announced the development of a new compound solar cell with a 35.8 % conversion efficiency, the world's highest, according to the company. Using panels with this type of cells, we will need a total of four panels, since each one produces a voltage of 12 V. Put together in series we get a total voltage of 48 V, which is the exactly the voltage needed for our motor [6], [7].

2) Power Trackers

An important component of the general circuit of our solar system is the power trackers, also called MPPT (maximum power point tracking). The aim of this device is to keep track of the current following through the system. Since solar panels depends of the sunlight, this might goes up and down, which will result in the creation of an unstable circuit, which cannot be used directly for our motor. So the device that we are using is a DC converter, will produce a direct voltage of 48 V, reading to be used by our motor [10].

3) Batteries

As the sun is not a source that we have 24 hours per day, installation of batteries is important to maintain the work of our car. The principle of batteries is purely chemical: it consists of two electrodes (plates) that are put one in front of the other, separated by a mixture called electrolyte. This later, with the presence of a current creates a chemical reaction (exchange of electrons) that produces a voltage. Batteries are also made to store electrical current thanks to the pressure that it has between its plates. There exist many types of batteries, the one that are most used, and which we will use are lead acid batteries. The choice of this type was made because of the price of these accumulators compared to the nickel-cadmium accumulators that are more expensive [8], [10].

4) Motor

After the source of energy this is the most important device which enables the car to move. In a solar car, the adequate type is a brushless DC motor, since we have a direct current that is produced by our power trackers are explained before. BLDC motors offer several advantages over brushed DC motors, including more torque per weight, more torque per watt (increased efficiency), increased reliability, reduced noise, longer lifetime (no brush and commutator erosion), elimination of ionizing sparks from the commutator, and overall reduction of electromagnetic interference (EMI). With no windings on the rotor, they are not subjected to centrifugal forces, and because the windings are supported by the housing, they can be cooled by conduction, requiring no airflow inside the motor for cooling.

This in turn means that the motor's internals can be entirely enclosed and protected from dirt or other foreign matter. The way how DC motors work is simple when we see it as a magnetic field that produces a force thanks to the flow of current. In fact, the electrical motor is based a loop that creates forces in the opposite direction, which will produce a rotation after pairing the two forces [10].

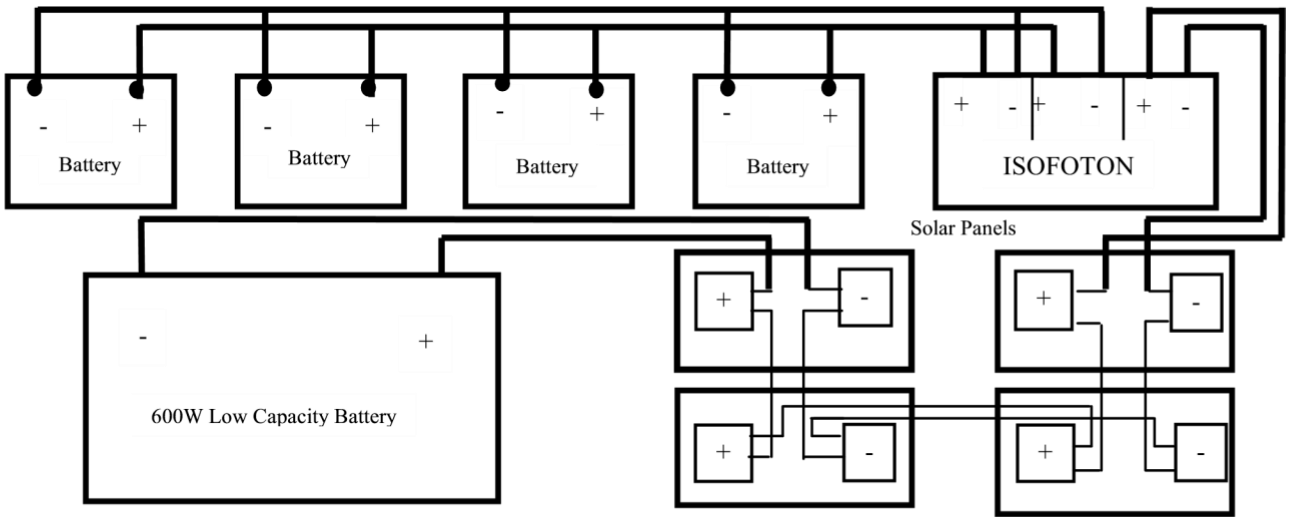


Figure 2: RALOS energy storage system's circuit.

B. Hybrid System

The hybrid system is a second source using electricity as a backup system. In fact, if our batteries are empty, and there is no sun, the car can be connected to a 220 V which will transform it to a 48 V, since this is the voltage that our motor needs to work. In order to do that, the car will need a converter that will reduce the obtained voltage from the electrical source so that we can charge our batteries (Fig. 1).

III. The Mechanical System

An optimal electric system to increase the efficiency is not enough. We should also take into consideration the existing technologies to design an optimal mechanical system as well. This system is considered to be the structural foundation of the solar car. By looking to the existing state of art related to the various designs of solar cars we came up with a mechanical system that is easy in the concept, but designed to minimize friction and weight while maintaining the strength needed to handle the various road conditions. The quest for a light, yet reliable vehicle is essentially related to the choice of materials used in the design. Lightweight metals such as aluminum, titanium and composites are widely used by designers to optimize the strength to weight ratio needed to build efficient components. The largest and central component of our mechanical design is the frame of the car, which is the structure that encloses and protects the driver and to which all the other components will be attached. The remaining mechanical components are the moving parts: wheels, suspension, steering, braking and tires. In the following sections, we will discuss the different components of the mechanical system and the criteria related to each choice we made in our design.

A. The car Chassis

The car chassis holds all the main parts together and it should be designed to be as minimal as possible yet able to protect the driver in an accident and support the different components by providing a strong and stable platform. One thing we discovered while looking to the different designs available is that there is no ideal design. Designing and building a solar car will always involve many tradeoffs. Our car should be light since to be easier for the motor to push; however, a light car can also be easily for the wind to push making it harder to follow a straight line: therefore, the choice of material used in the design is critical. There are basically two types of frame styles available: the tubular metal space frame and the carbon fiber composite monocoque chassis. In the space frame design each element is selected based on the strength, the weight and the tube size and shape. Instead of the metal tubes in the space frame design, the monocoque is made from composite material formed into a round cornered box. The material in this type of design supports itself by creating a strong but light compartment for the car. In order to make a final decision on which frame will be suitable for our design, research was completed on carbon fiber and aluminum used in the monocoque design, including the manufacturing time, the materials properties and drawbacks and its previous usage on existing solar cars. The monocoque design has not only shown an overall structure integrity, but also an efficient and cost effective mean for production. In addition, stress calculations from previous works were compared to see the frame based on the monocoque model's withstanding loading on the car.

B. Wheels Configuration

Probably the most critical mechanical decision was related to the wheels configuration. While most of the solar cars have the traditional four wheels system, some cars pursue the three wheels design which usually has two wheels in the front (that steer) and one rear wheel (that follows). Eliminating a wheel reduces the rolling resistance; however, with only three wheels the stability problems rise especially during an accident or tire blow out since having a single wheel in the front reduces the braking performance to the half. In that sense, three wheels solar car system is considered as an engineering challenge associated with very few cases of success. In addition to the number of wheels used, the choice of material is important due to the interface between the car and the road. A wheel is usually composed of a rubber tire and a rim that supports the tire. The combination of materials should be of light weight but at the same time be able to withstand the loading of driving and should have the lowest rolling resistance possible.

C. Suspension

Once the layout of the wheels is determined, suspension should be designed to hold the wheels in the right position while isolating the car from the road's defects and perturbations and allowing the wheels to spin freely. Many suspension designs have been used on solar cars based on traditional automobiles, motorcycles or even bicycles. The task was researching the different suspension designs, selecting the appropriate one for the solar car and then comparing the different characteristics of a solar car in contrast with a passenger car. Solar car suspension system tends to be more rigid compared to the traditional car suspension system simply to avoid waste of energy on a more comfortable car. We have chosen the most common configuration which is the parallel aarms .This design is composed of different joints that allow the whole structure to pivot with the road contact. Using computer modeling, we will be able to adjust the length of the a-arms and its angles which will decrease any side to side movement and by that eliminating energy waste.

D. Steering

The steering system main goal is to assure that the driver of the vehicle is able to steer it precisely in the desired direction. It is also particularly important to look at this subsystem since its one of the few inputs that driver has control over. Again, different steering designs are present for solar cars but based on our four wheels chosen design, it is advisable to work out the geometry so that the two front wheels run parallel when the car is going in a straight direction, but when the car is turning than the wheels should turn at a different radius to avoid unnecessary drag force. Those principles are based on Ackerman steering geometry used on most car production [11], [12].

E. Brakes

The goal of the breaking system is to slow down or stop the car in motion by applying a sort of a frictional force against the surface in which the vehicle is driven on. Actually, the braking mechanism is based on the energy conservation mechanism we saw in thermodynamics class which states that the energy cannot be created nor destroyed, only converted from one form to another. The braking system converts the energy stored in the vehicle due to the motion to thermal energy. This energy is directly related to the car's mass and velocity. Ideally, all the energy should be absorbed by the components of the braking system and this transfer in energy is what causes the car to slow down. Several braking system designs exist; however, regarding our project we found that the hydraulic disk brakes will be the most suitable. The mechanism consists of transferring the braking force applied by the driver to a master cylinder through the principle of pressurized hydraulic fluid. The cylinder pushes the fluid into the hydraulic lines which will apply a pressure against the calipers piston. As the force increases, the pressure on the caliper increases causing more friction between the pads and the rotor. The friction caused is what will make the car slow down [13].While choosing the adequate braking system; safety was one of our major criteria. The solar car will have two independent braking systems, in accordance with the standard dual braking system in the traditional cars.

F. Tires

In order to improve the efficiency of our design, tires with very low rolling resistance will be used. The rolling resistance is the resistance that occurs when a round object rolls on a surface. Looking at the different type of tires available we found a design that attracted our attention called the Ecopia EP80 tires with ultra-low rolling resistance that combines the energy efficient tire technologies with an ecological oriented strategy [14].

IV. New Technologies to Optimize the Energy Losses

Now that we have a clear prototype design of our RALOS car, we thought about possible ways to increase our car's efficiency in addition to what was mentioned all along the paper by investigating some of the feasible technologies that are already existing in the market or still under research. Those technologies can be thought about as possible and future added value to Ralos car that should be examined to maintain the car development and improvement. The three primary areas of energy loss consist of aerodynamic drag, braking, and rolling resistance [10]. While designing the car, it is critical to minimize the aerodynamic drag (air resistance) which increases exponentially with speed by making the solar cells as smooth as possible. It is also important to give a special attention to the braking area especially with the possibility of recycling energy by using the process of regenerative braking. Regenerative braking consists of capturing the vehicle's momentum (kinetic energy) and turning it into electricity that recharges the battery as the vehicle is slowing down and/or stopping. During this process, the electric motor is reversed when braking so that it becomes a generator producing electricity. In addition, solar cars have to be very light and for reducing the rolling resistance which is proportional to weight [20].

Other additional technologies such as solar painting can target the solar cells limitations which are able to convert only 12.5 % of the small amount of sunlight that reaches the car directly from the sun. This involves the development of a completely printable organic solar cell based on semiconducting polymer nanoparticles dispersed in water. Essentially these tiny particles in suspension are a water-based paint, which produce coating containing cells capable of capturing solar energy and generating electricity. These coating are now put onto plastic sheets that can be placed on the roof, but more research is conducted so it will be possible to directly paint a roof or building surface. Organic solar cells can be applied at extremely low cost to a vast array of vehicles and in any desired color. This technology will also decrease the weight of our solar cars for a higher speed and will enhance the design of the car to make it more appealing to consumers who are not attracted by a car covered by solar panels [21].

Another critical problem is the functioning of the car at night or at rainy and cloudy day. Here's where a battery or small electrical engine would come in. As a result, we opted for a practical and consumer solar car that rely on additional power sources to ensure that the car gets going any time it is needed.

Solar cells are also an optimal device to invest toward their development. So for increasing the car's efficiency, we can use multi-junction cells which use two or more layers of different materials with different band gaps and thus to absorb highenergy photons (while allowing lower-energy photons to be absorbed by the lower band gap material beneath) and can have more than one electric field.

V. BUSINESS PLAN

The first step for a successful business plan is developing very good marketing strategies by examining the technology as well as the targeted market to avoid failures by penetrating the wrong market. We should look at the technology's weaknesses that should be improved to satisfy the proposed market; in addition, to the social events that may lead this market to become optimal. The success of our project depends on targeting the right market by targeting customers that will value the technology's strengths despite its weaknesses.

A. Financial Crisis and Global Warming

The world is suffering from a disastrous and global financial crisis that doesn't stop spreading and worsening. The world economy is definitely suffering from a slowing growth, from a shortage of fuel and a dramatic increase of its price and the price of its derivatives (2 euros/ litter on the 14 of March in Paris). In fact scientists estimate that this energy essential to the world's economy will disappear by about fifty years. Another important issue is the impact of the energy sources on the environment. To reduce the global warming development, it is essential to cut down on our dependency on fossil fuels by developing the renewable energy sector such as hydropower, nuclear power, wind energy, solar energy and biogas. In fact, solar energy as a source for generating electricity is considered as the possible solution to overcome both the economical and the pollution crisis.

B. Market Analysis

To first penetrate the market, it is important to adapt the new technology to the existing market to gain the needed performance and successfully present the product to the customers [5].

1) Solar Panels Market

The global solar energy market is huge and generates billions of dollars each year with a percentage located to researches funding and projects investment. The solar industry is based on generating clean and endless supply of energy from the sun. Solar energy is clearly considered as a solution to fulfill the population's increasing needs of energy. In fact, the most targeted form of energy that people will actually pay for is electricity (sometimes thermal energy for few applications). To generate this energy, industry use solar panels that uses the photo-electric effect to generate electrical current from photons. This technology has been thoroughly researched for many years leading to the development of cheaper types such as silicone-base solar panels due the decrease of silicone price thanks to its oversupply [17].

2) Automobile Industry

The automobile industry is suffering from slow sales, poor financial performance, overpriced workforce and lack of investment because of the collapse of the world economy. Actually, comparing 2010 sales of gas-electric vehicles with its equivalent in 2011, it is clear that they fell by 2.2%. Considering problems caused by fuel based cars such as global warming, shortage and conflicts related to oil, the solarelectrical car industry is expected to expand quickly. Because electrical cars involve a significantly polluting process while generating the electricity needed to power the cars, we will use the electrical system as a backup system and predicate on a solar system [16], [20].

Thanks to this market analysis, we were able to collect valuable information about the solar car industry to be able to commercialize our car at affordable prices. Moreover, we think that this car is a viable solution for us to save gas and the environment especially that Morocco is characterized by its abundance of sunlight.

C. Project Description 1) Mission Statement

The project's mission consists of building a working, an environmental friendly, and a competitive solar car in terms of innovative technologies and cost to spread the use of solar energy for transportation purposes [18].

2) Product Description

RALOS car is an effective solar car that is charged using solar cells affixed to the shell of the vehicle or thanks to the backup electrical system in case of an insufficient solar power. The rotation of the wheels on the ground transforms solar energy into kinetic energy, which also powers the car. RALOS car is considered to be the first car in Morocco that uses both solar and kinetic energy. This product is mainly used to reduce the carbon emission from fuels, help preserve environment and reduce the global warming effects. It will help people save money because of its low consumption of fuel which is considered as the best criteria of our solar car. The project is developed carefully taking into consideration the reduction of the emissions and the cost and ensuring the most efficient use of the power generated [18]. As a result, this car is not too expensive especially that they are cheaper to maintain and can be presented to the consumer market because of its price affordability.

D. Targeted Companies

Another important step for a successful marketing strategy for our solar car is the choice of the appropriate customers. We are soliciting companies in the larger engineering and manufacturing community who may be interested in our project especially those who went green and aim to protect the environment from further damages such as Toyota. Our solar car might also be of interest to NASA as a terrestrial application of the rovers they use in space. Data collection in a hot, sun rich area where manual labor is difficult would be an ideal application. The vehicles would recharge autonomously, and the driver's discomfort would not be an issue because there would not be a driver. In addition, these vehicles could be kept lightweight and simple without a need for too many amenities. We also want to attract individual customers that are worried about rising fuel prices and greenhouse gas emissions along with the advantages of a silent motor and an automatic recharge[19], [5].

E. Project Budget

We established a rough estimate for our budget taking in consideration the components used to build the solar (Table I). We decided to compare the estimated budget of the RALOS car with the cheapest car available in Morocco. According to a Wandaloo, the least expensive car we were able to find is *Changhe* (65900 MAD) [22]. Because this brand name is not that known, we decided to choose the second less expensive car in Morocco which is Suzuki Alto 0.8 GA (69900 MAD) [19]. So we can see that the capital investment in the ordinary car is already higher than the one allocated for our solar car. This car uses gasoline with consumption in the combined cycle fuel of 6.8 l/100 km. It is true that this car can reach a speed of 133 km while the solar one around 70 km, but if we take into consideration the increase in the price of gasoline we will notice that we pay a lot more for a small difference in speed that we can't even reach according to the Moroccan road laws. We also have to compute the monthly fees for the gasoline consumption. If we estimate that a normal person drive an average of 40Km/day which result on 1200 Km/month and that the price of gasoline is 10 MAD/l , we will end up with a consumption in the combined cycle fuel of 81.6 l/1200 km, a monthly cost of 816 MAD and a yearly cost of 9792 MAD. In comparison with a 0 MAD yearly cost in the RALOS car (except some minor maintenance costs), the normal car gasoline cost can be huge and get even larger because of the inflation rates and the increase of the fuel prices.

TABLE I. SUMMARY OF STARTUP COSTS

System	Component	Quantity	Price
Chassis			
	Wheels	4	$1,005
	Suspension (a-arms)	1	$392
	Brakes (hydraulic disk)	2	$ 240*2= $480
	Tires (ecopia EP80)	4	$100*4=$400
	Foot Throttle (FSC010 Goldenmotor)	1	$30
Solar Array			
	Solar Cells	36*4	$560*4= 2240
	MPPT	1	$521
Battery Pack			
	Batteries	6	$24*6= 144
Motor			
	Motor	1	$260
Miscellaneous			
	Frame Monocoque (Seats, Seat Belt, Horn, Steering wheel)	1	$16+ 2 + 20 + 400= $438
Tools			
	Starter tools	1	$18
Total			**$5928≈ MAD 50000**

VI. CONCLUSION

The solar car can be considered as the planet hope taking into consideration the situation of the environment in term of pollution and financial crisis. It solves many problems related to environment and it's definitely the best pollution free method. RALOS project is a theoretical design of a solar car that has a hybrid system as a back-up source. After going through the electrical and mechanical requirements for the design technologies, we performed a financial analysis of the targeted Moroccan market specifically, but can be generalized internationally to estimate the solar cars' budget and thus the whole project. We can see that the initial cost (fifty thousand MAD) of the components is low in contrast with the long term benefit that the solar car provides to the consumer (efficiency that doesn't exceed 20 %). Therefore, we proposed new technologies that can be investigated in other researches for a better conversion of solar energy. A future research can explore more, with simulation and exact scientific data, the study developed by scientists at Rensselaer Polytechnic Institute who by using an antireflective coating allowed solar panels to absorb 96.21 % of sunlight from nearly any angle thus allowing the power generation to significantly increase. This solution can be seen as a way to improve our design in the future in addition to many others as stated before.

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