Practical Efficiency of Photovoltaic Panel Used for Solar Vehicles

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Abstract. In this experimental investigation, practical efficiency of semi-flexible monocrystalline silicon solar panel used for a solar powered car called "Firat Force" and a solar powered minibus called "Commagene" was determined. Firat Force has 6 solar PV modules, a maintenance free long life gel battery pack, a regenerative brushless DC electric motor and Commagene has 12 solar PV modules, a maintenance free long life gel battery pack, a regenerative brushless DC electric motor. In addition, both solar vehicles have MPPT (Maximum power point tracker), ECU (Electronic control unit), differential, instrument panel, steering system, brake system, brake and gas pedals, mechanical equipments, chassis and frame. These two solar vehicles were used for people transportation in Adiyaman city, Turkey, during one year (June 2010-May 2011) of test. As a result, the practical efficiency of semi-flexible monocrystalline silicon solar panel used for Firat Force and Commagene was determined as 13 % in despite of efficiency value of 18% (at 1000 W/m^2 and 25 °C) given by the producer company. Besides, the total efficiency (from PV panels to vehicle wheel) of the system was also defined as 9%.

1. Introduction

Scarcity and cost of fossil fuels combined with their greenhouse gas emissions make the development of non-fossil fuel based methods of transportation a high-priority task. Therefore, academic studies regarding renewable and clean energy like solar energy are rapidly increasing in the last decade. This regenerative, clean and free energy could be harnessed in several ways. This energy can be converted to electric power by using solar photovoltaic (PV) modules. The produced electricity from solar panels can also be stored in the batteries to operate DC motors of solar powered vehicles [1]-[5]. We believe that solar powered vehicles are smart solution for transportation of people particularly for small and flat location cities that have relatively high solar radiation along the year.

Adiyaman City (Latitude= 37,45 °, Longitude= 38,17 °and Altitude= 672 m) is located in Southeast of Turkey. It has a university called "Adiyaman University". The university campus is about 5 km far from the city centre. City population is about 210000 and area of the city is 1700 km^2. Most of the city roads have the gradient (slope) less than 10%. In the city the solar radiation is relatively high enough to be efficiently used. The annual total solar energy is about 1600 kWh/m^2.year.

In this experimental investigation, practical efficiency of semi-flexible monocrystalline silicon solar panel used for a solar powered car called "Firat Force" and a solar powered minibus called "Commagene" was determined.

2. Materials and methods

Firat Force has 6 solar PV modules (4x30x0.125x0.125+2x10x0.125x0.125=2.19 m^2), a maintenance free long life gel battery pack (6 batteries: 8 V, 190 Ah, maximum 250 Ah for short period, 9120 Wh), a regenerative (can also be used as generator) brushless DC electric motor (4.5 kW, maximum power 6 kW) and Commagene has 12 solar PV modules (8x14x0.125x0.125+2x12x 0.125x0.125+2x72x0.125x0.125=4.38 m^2), a main-tenance free long life gel battery pack (12 batteries: 6 V, 190 Ah, maximum 250 Ah for short period, 13680 Wh), a regenerative (can also be used as generator) brushless DC electric motor (6.3 kW, maximum power 8 kW)). In addition, each vehicle has MPPT (Maximum power point tracker), ECU (Electronic control unit), differential and external automatic charge device. Each vehicle was also equipped with a mechanical steering system, a free front and rear mechanical suspension system, the chassis constructed from stainless steel pipe covered with special paint, the frame constructed from impact-resist fiber composite material, an instrument panel, a brake and a gas pedal, all standard systems such as signaling, lighting and warning systems.

Some needed technical specifications concerned with Firat Force and Commagene are given in Table 1. In addition, schematic presentation of PV module location, electrical system and power supply for the vehicles are also given in Figure 1, 2 3, 4 and 5.

The electric energy for charging battery pack is supplied by the PV modules. The energy is converted from the solar energy to electric power through the installation of solar photovoltaic modules located on top of the vehicles (Figure 6a, 6b) [6]-[9]. The supplied electric energy is stored in batteries that feed the DC motor.

**Table 1.** Technical specifications of solar vehicles.

| Specifications	Vehicle Type	
	Firat Force	**Commagene**
Class	Prototype	Prototype
Axle number	2	2
Wheel number	4	4
Powered axle	1 (rear)	1 (rear)
Unloaded mass	705 kg	1550 kg
Maximum loaded mas.	1025 kg	2600 kg
Motor type	Regenerative brushless DC	Regenerative brushless DC
Motor efficiency	88%	90%
Motor nominal power	4.5 kW	6.3 kW
Motor nominal rpm	3000 rpm $\pm\%10$	3000 rpm $\pm\%10$
Motor nominal torque	25 Nm	34 Nm
Suggested speed	40 km/h	40 km/h
PVmodule type	Semiflexible Monocrystal Si	Semiflexible Monocrystal Si
Module efficiency	18% @ 1000 W/m^2, 25 ^{o}C	18% @ 1000 W/m^2, 25 ^{o}C
Module area	[4(6x5) + 2(2x5)] x [0.125x0.125] = 2.19 m^2	[8(7x2) + 2(6x2) +2(6x12)]x [0.125 x 0.125] = 4.38 m^2
MPPT efficiency	95 %	95 %
Battery pack	6 batteries, 8 V, 190 Ah	12 batteries, 6 V, 190 Ah
Battery type	Maintenance free long life gel	Maintenance free long life gel
Battery energy	9120 Wh @ C20 discharge	13680 Wh @ C20 discharge
Battery voltage	Nominal 48V	Nominal 72 V
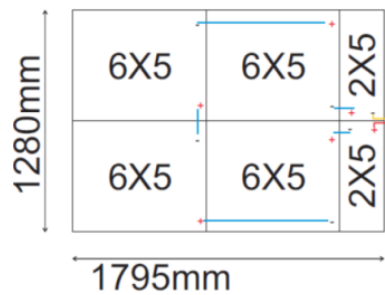
Figure 1. Schematic presentation of PV module location for Firat Force.
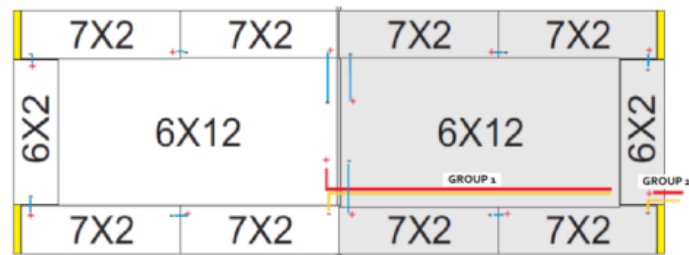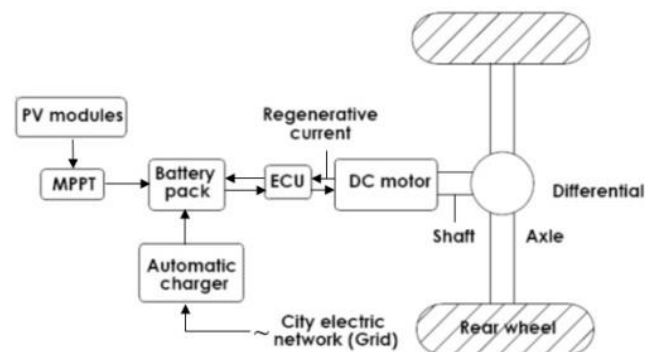

Figure 2. Schematic presentation of PV module location for Commagene.
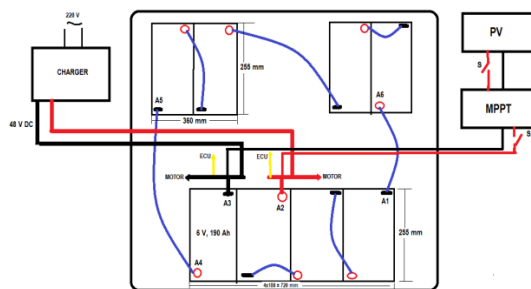
Figure 3. Schematic presentation of Firat Force electrical system.
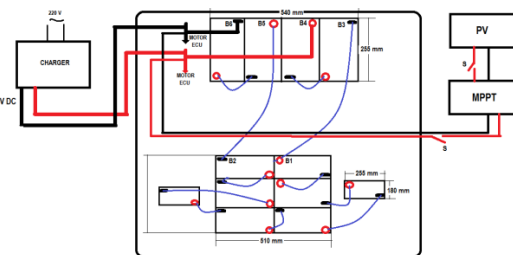
Figure 4. Schematic presentation of Commagene electrical system.

Figure 5. Schematic presentation of power supply for Firat Foce and Commagene.

Figure 6a. A view of Firat Force PV panel location.

Figure 6b. A view of Commagene PV panel location.

The needed total area of solar photovoltaic module was determined based on the DC motor power. In order to calculate the approximate power needed for any vehicle, the average incident solar radiation and daytime of the city (mean of about 40 years), vehicle speed, efficiency of the PV panels, road features and grade, carrying number of people, needed daily road distance for transportation and the efficiency of all equipments have been considered. To determine the total needed force and power for any vehicle to overcome all resistances, Equations 1, 2, 3, 4 and some coefficients were used.   In addition, the power supplied by PV panels, the efficiency of PV panels (from PV panel to ECU), the efficiency of total system (from PV panel to vehicle wheel) were calculated by using Equations 5, 6, 7 and 8 [10]-[16]. As seen from Equation 7 that basically, the efficiency of PV panel equals to electric power produced by PV panels divided by solar power that comes to the total surface of the PV panel. All symbols used in equations are described in the Nomenclature.

$$F_{TT} = F_{AC} + F_{GR} + F_{AE} + F_{RR} \dots\dots\dots\dots\dots\dots\dots(1)$$

$$F_{TT} = \lambda ma + mgp + 0.5\rho c_w A_C v^2 + mgf_R \dots\dots\dots\dots(2)$$

$$q_{TP} = F_{TT} v \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(3)$$

$$p = \sin\alpha \cong tg\alpha \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(4)$$

$$\lambda = 1.03...1.45; \quad a = 0.3...0.5m/s^2; \quad \rho \cong 1.226Ns^2/m^4 (@1.0133bar \& 15^0C); \quad c_w \cong 0.30; \quad A_C \cong 1.85m^2; \quad f_R = 0.01...0.02$$

$$q_{SR} = I_R A_{PV} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(5)$$

$$q_{PV} = VC \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(6)$$

$$\eta_{PV} = \frac{q_{PV}}{q_{SR}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(7)$$

$$\eta_{SY} = \eta_{PV}\eta_{MPPT}\eta_{BA}\eta_{ECU}\eta_{DC}\eta_{TR} \dots\dots\dots\dots\dots\dots(8)$$

$$\eta_{PV} \cong 0.18; \quad \eta_{MPPT} \cong 0.95; \quad \eta_{BA} = 0.80...0.90; \quad \eta_{ECU} = 0.90...0.95; \quad \eta_{DC} \cong 0.88; \quad \eta_{TR} \cong 0.98;$$

The solar vehicles were used for people transportation in the city to see the unexpected problems regarding design, manufacture and vehicle systems during one year (June 2010-May 2011) (Figure 7a, 7b). During this period we have made some preliminary tests. These preliminary experiments showed us that the best way to see the exact performance or efficiency of any solar powered vehicle under city normal traffic conditions is to use the solar vehicles nonstop with full charged batteries while PV panels off and PV panels on. Therefore, the vehicles were tested while PV panels off (battery pack was charged with electricity only), PV panels on (battery pack was charged with PV panels during use) on the standard road (asphalt-paved road with gradient of about 0%) and on the mixed road (asphalt-paved and unimproved roads with different gradients of 0%...20%) during 3 months (June, July and August 2011) under normal city traffic flow. All tests were made between the times of 10:00 (morning)-17:00 (afternoon). Firat Force was loaded with 2 and 5 persons (driver included) while Commagene loaded with 5 and 10 persons (driver included) during all tests for their total transportation distance. The difference of transportation distance between PV panels off and PV panels on positions was recorded as transportation distance supplied by solar energy. As known, this energy is renewable and clean energy. On this account, Firat Force and Commagene apparently can be called clean or green vehicles. However in many literatures, all electric vehicles are called green or clean vehicle. It should be noted that it completely depends on the energy sources that electric produced from. It is not possible to say that all electric vehicles are green or clean.

Figure7a. A view of Firat Force test activities.

Figure 7b. A view of Commagene test activities.

Besides, the term "efficiency" should be used instead of term "performance" for PV cell, module or panel, in despite of given by some literatures. Because, term "efficiency" is very appropriate to explain the amount of energy conversion from one form to another (form light or solar to electricity for PV cell). However, the term "performance" is particularly suitable to clarify the speed comparision of any activity, process or work.

3. Results and Observations

Firat Force and Commagene were tested on the standard road (asphalt-paved road with gradient of about 0%) and on the mixed road (asphalt-paved and unimproved roads with different gradients of 0%...20%) during 3 months (June, July and August 2011) under normal city traffic flow for practical efficiency of PV panels. All data regarding solar radiation intensity and PV panels were given in Table 2 and 3 for Firat Force and Commagene, respectively. Average values of these data can also be seen from these tables. The average practical PV panel efficiency was seen as approximately 13% from Table 2 and 3 for Firat Force and Commagene. The total system efficiency (from PV panel to vehicle wheel) was also seen as approximately 9% (calculated from Equation 8) for both solar vehicles. In addition, the average solar radiation and daily sunshine hours were determined as 525.22 W/m^2 and 8.11 h/day for Adiyaman city, Turkey (Figure 8). The average calculated transportation distance, amount of saved fuel, amount of saved money and percentage of full charged with PV panel for one year were also given for Firat Force and Commagene (Figure 9a,9b and 10a,10b) [9], [17].

Table 2. Data regarding Firat Force

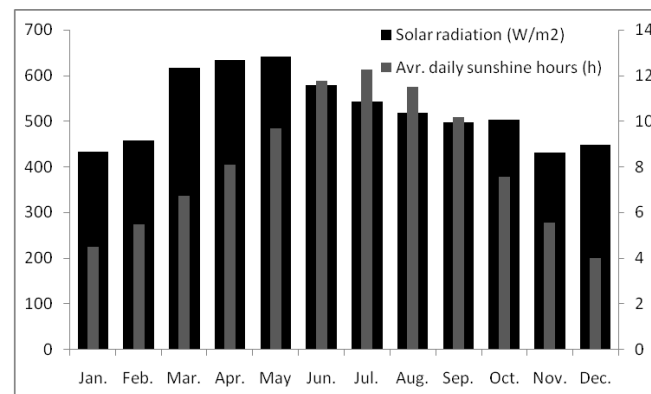| Road Fea.	P.No	S.I.(W/m^2)	A (m^2)	S.P. (W)	PV-P(W)	PV-E(%)
Stdrd. road	2	980	2.19	2146	245	11.4
Stdrd. road	5	975	2.19	2135	250	11.7
Average efficiency of PV + MPPT						*11.5*
Average efficiency of PV						*≈ 13*
System total efficiency (from PV to wheel)						*≈ 9*
PV module efficiency at 1000 W/m^2 and 25 ℃						*18*

Road Feat: Road feature; P. No. : Passsenger number; S.I. :Solar radiation intensity; A : PV panel surface area; S.P. : Solar power; PV-P : PV panel power; PV-E : PV panel efficiency.

Table 3. Data regarding Commagene

Road Fea.	P.No	S.I.(W/m^2)	A(m^2)	S.P.(W)	PV-P(W)	PV-E (%)
Stdrd. road	5	980	4.38	4292	510	11.8
Stdrd. road	10	980	4.38	4292	485	11.3
Average efficiency of PV + MPPT						*11.5*
Average efficiency of PV						*≈ 13*

| *System total efficiency (from PV to wheel)*	*≈ 9*
PV module efficiency at 1000 W/m² and 25 ℃	*18*

Road Feat: Road feature; P. No. : Passsenger number; S.I. Solar radiation intensity; A: PV panel surface area; S.P. : Solar power; PV-P : PV panel power; PV-E : PV panel efficiency.


Figure 8. Solar radiation (right axis: W/m²) and average daily sunshine duration (left axis: h) related to months.
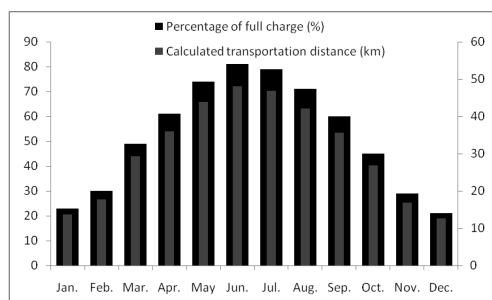
Figure 9a. Charge of solar PV panels as a percentage of full charged battery pack (right axis: %) and calculated transportation distance (left axis: km) related to months (for Firat Force).
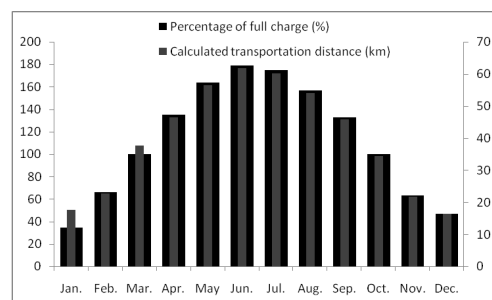

Figure 9b. Charge of solar PV panels as a percentage of full charged battery pack (right axis: %) and calculated transportation distance (left axis: km) related to months (for Commagene).
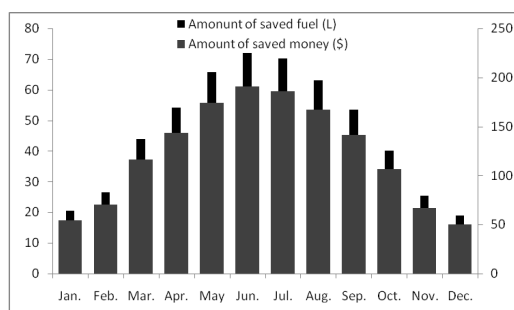
Figure 10a. Amount of saved fuel (right axis: L) and amount of saved money (left axis: $) related to months per year (The fuel consumption of an internal combustion engine (ICE) was accepted as 5L/100 km and Turkey fuel sale price (March 2013, 2.65 $/L) was considered for the calculation) (for Firat Force)
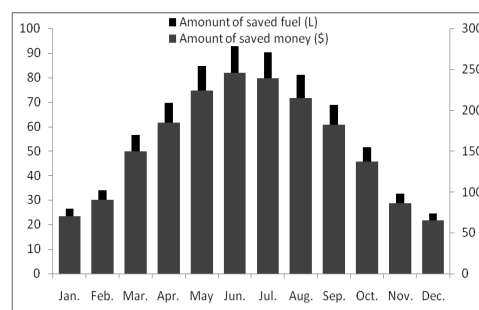
Figure 10b. Amount of saved fuel (right axis: L) and amount of saved money (left axis: $) related to months per year (The fuel consumption of an internal combustion engine (ICE) was accepted as 5L/100 km and Turkey fuel sale price (March 2013, 2.65 $/L) was considered for the calculation) (for Commagene).

4. Conclusions

The main conclusion of this experimental investigation is that solar power vehicles should be used with nonstop use under city normal traffic conditions to define the practical (most realistic) efficiency of solar panels. The results showed us that the average practical efficiency of semi-flexible monocrystalline silicon PV panel is approximately 13% in despite of 18% given by the manufacturer company for standard test conditions of 1000 W/m2 and 25 °C. The solar vehicle total system efficiency form PV panel to the vehicle wheel was also seen about 9%. Therefore, in order to design any solar vehicle with minimum mistake the practical losses of the PV panels and vehicle power supply system should be considered. Otherwise, theoretical approximation should not meet the practical needed.

5. Acknowledgement

6. Nomenclature

a : Acceleration, m/s^2

A_C : Frontal area of the vehicle, m^2

A_{PV} : Photovoltaic PV area, m^2

C : Average current, A

c_w : Coefficient of drag

F_{AC} : Needed force for acceleration, N

F_{AE} : Needed force for aerodynamic resistances, N

F_{GR} : Needed force for grade resistance, N

f_R : Coefficient of rolling friction

F_{RR} : Needed force for rolling resistance, N

F_{TT} : Needed total force to overcome all resistances, N

g : Gravitational acceleration, m/s^2

I_R : Incident solar radiation, W/m^2

m : Vehicle mass, kg

q_{PV} : Photovoltaic (PV) power, W

q_{SR} : Incident solar power, W

q_{TP} : Needed total power of the vehicle, W

v : Speed of the vehicle, m/s

V : Average voltage, V

Greek

α : Road grade

η_{BA} : Battery efficiency

η_{DC} : DC motor efficiency

η_{ECU} : Electronic control unit (ECU) efficiency

η_{MPPT} : Maximum power point tracker $(MPPT)$ efficiency

η_{PV} : Photovoltaic (PV) efficiency

η_{SY} : System efficiency

η_{TR} : Transmission efficiency

λ : Rotational inertia factor

ρ : Air density, kg/m^3

7. References

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