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ENERGY PARAMETERS OF A SOLAR CAR FOR JORDAN

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Abstract—All parameters related to car energy were investigated in this work, and the power basics of a car design powered by solar energy are laid down. Year-round weather conditions, car weight, road roughness and road inclination were taken as variable parameters used to calculate the car speed and working hours (year round). Fixed parameters taken for the design were: a photovoltaic generator area of 6 m^2, car length of 5 m, car width of 1.8 m and maximum power output of 480 W/person with a maximum of two persons. These parameters depended on the regulations of "Tour de Sol '91". Calculations depended on Amman weather conditions. Sixteen ASI 16-200 ARCO SOLAR INC. model photovoltaic modules were used, with three DELCO 1150 lead acid batteries connected to a permanent magnet DC motor of 0.8 hp. This car can run at different speeds 3–6 hours/day on 200 days/year. Copyright © 1996 Elsevier Science Ltd

Solar car   Solar energy   Transport energy   Jordan

INTRODUCTION

About 99% of transport uses fossil fuel energy. Attempts to use other sources of energy in this sector are facing difficulties, some of them are still in the experimental phase today. Solar energy, as a renewable source of energy, succeeds in areas such as water heating and low capacity (less than 10 kW) electrical generation, but is still facing major difficulties in other practices and uses. The storage problem and the high initial costs are examples of the many problems facing solar energy use. In the transportation sector, the use of solar energy faces, besides these problems, the problems of electrical cars, such as the batteries and transmission problems. Many in the world attempted to carry out the idea of a solar car, jointly forming an association and establishing a yearly race for solar powered cars, in a different country each year. This work shows the design power parameters for a solar car intended to participate in one of these races. The specifications are according to "Tour de Sol '91" regulations [1, 2]. The weather data of the Amman area were taken as basic for this study.

Local weather data was extracted from the publications of the Meteorological Department and the Royal Scientific Society (RSS) [3, 4].

Concentration was focused on the university area northwest of Amman, where the monthly mean ambient temperature reaches a maximum value of 30°C in summer and a minimum of 5°C in winter. The wind speed ranges from 5.82 m/s, as monthly average in October, to 3.18 m/s in April. The sunshine duration also ranges from 12.2 hours in summer to 7.9 hours in winter. The maximum hourly solar global irradiation received by a horizontal surface was 1034 Wh/m^2 in June 1987. The average diffuse to global ratio ranged between 0.127 in July and 0.421 in December [4].

Different car weights, speeds, and road inclinations were investigated for a car with the following specifications.

CAR SPECIFICATIONS

The specifications adopted in this work follow the international "Tour de Sol '91" race regulations, which was held in Switzerland in May 1991:

Vehicle length	5 m
Vehicle width	1.8 m

Solar generator area	6 m^2
Maximum output at maximum peak point (MPP)	480 W/person
Maximum persons	2
Minimum output at MPP	120 W/person
Operating voltage	no restrictions.

Other regulations of more detailed items were not used by this work but can be found in Ref. [2]. The following are the specifications chosen by this work, which were used as complementary to the regulations used.

Generator orientation	horizontal
Operating voltage	32 V
Car weight	200 or 300 kg
Road inclination angle	0, 10, 20, 30 deg
Road rolling resistance coefficient, f	0.01 or 0.02
Wind drag coefficient c_w	0.1 or 0.2
Maximum speed	40 km/h.

The storage system was designed to store sufficient energy to drive the car for 2 hours in no direct solar radiation conditions, or after sunset.

THE SOLAR GENERATOR

Different kinds of photovoltaic modules can be found nowadays, monocrystalline, polycrystalline, or amorphous, in different makes and models. Choosing a suitable module for a job must depend on its efficiency and availability.

Sixteen ASI 16-200 ARCO SOLAR INC. modules of 0.43 m^2 each were used to form the 6 m^2 generator area of 8% maximum efficiency. They are electrically connected in the pattern shown in Fig. 1 to give an output voltage of 32 V. The following are the manufacturer's published specifications of the module:

Maximum power	36 W at 1000 W/m^2 and 28°C ambient temperature
Current (I)	2.05 Amperes at maximum power output
Voltage (V)	16 volts at maximum power output
Size	30.5 × 121.9 × 3.8 cm
Weight	4.99 kg.

A specimen panel was tested in the weather conditions of Amman and the I-V curve was constructed and is shown in Fig. 2, which shows approximately similar results to those published by the manufacturer. The point of maximum power was identified and its values were used in the calculations.

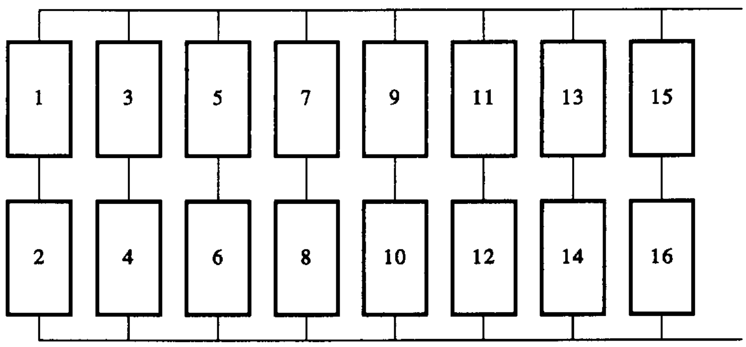

Fig. 1. Module connection diagram.

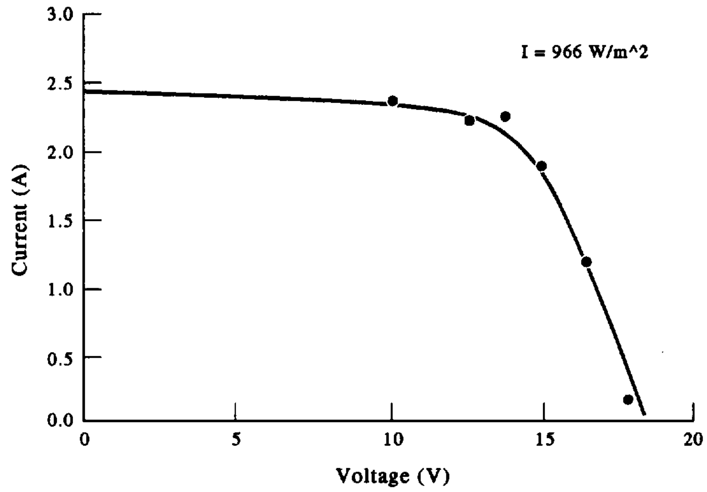

Fig. 2. Actual module current–voltage curve.

ENERGY STORAGE

Two main functions are required by any successful energy storage system; extra power shaving, which means the capability to smooth the electrical input to the motor, and supply of power when it is needed during conditions of low or no solar irradiation. Because of the large storage capacity of lead acid batteries, they were seen to be the most suitable for this job, in spite of the high competition from newly developed batteries, such as zinc-chlorine or sodium-sulfur batteries, in prices and weights.

The lead-acid batteries power-weight ratio is 25 Wh/kg and their specific price is 8.5 $/kWh (5.7 Jordanian Dinars). The following are the specifications of the proposed batteries:

Type	Delco 1150
Capacity	105 Ampere. hour (AH)
Depth of discharge	80%
Voltage	12 V (DC)
Weight	26.8 kg
Size	17.8 × 33 × 13.8 cm
Number of batteries	3

The circuit connecting the generator to the batteries and the load must keep the current output (I) around the value of the maximum power point. Figure 3 shows such an arrangement which suits both the generator and the motor. A control signal switch is used to control the circuit [5].

THE ELECTRICAL MOTOR

The DC output of the generator will be degraded if it is passed through an inverte to produce AC output, besides the difficulties of weight, space and cost of any new equipment to be added. DC motors possess some advantages of better efficiency and lower losses compared with AC

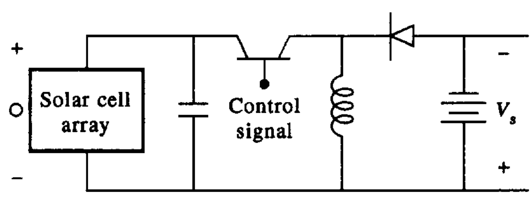

Fig. 3. Maximum power point tracking circuit.

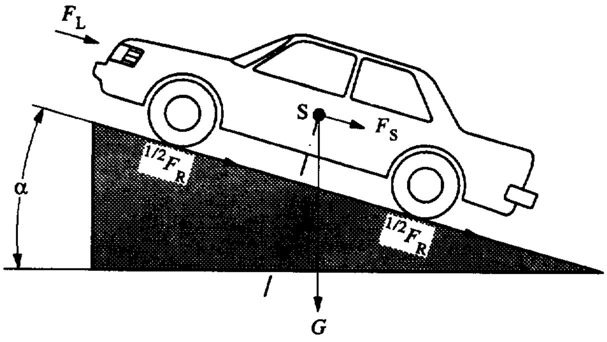

Fig. 4. Components of driving resistance.

motors. The linear torque-speed characteristics, high stall torque and light weight were the main considerations behind the choice of using a permanent magnet (PM) DC motor for this work.

The temperature of the motor is a vital parameter and needs to be watched carefully against the speed-torque relation to keep within the practical continuous working conditions, either without cooling air or with cooling air [6]. The following are the specifications of the chosen motor:

Type	PMDC, non ferrous core
Power	0.8 hp
Voltage input	32 V.

The power of the motor was calculated using the optimum root mean square method explained in Ref. [7].

VEHICLE DYNAMICS

The driving resistance F_w has three components known as: rolling force F_r, aerodynamic drag force F_l and climbing force F_s. These forces can be related by the following equation, see Fig. 4.

$$F_w = F_r + F_l + F_s. \tag{1}$$

The rolling force and the aerodynamic drag are dependent on the rolling resistance coefficient f and drag coefficient C_w, respectively [8]. When the forces are multiplied by the vehicle speed, corresponding powers are produced, and the powers are related according to the following equation:

$$P_w = P_r + P_l + P_s. \tag{2}$$

Tables 1–4 show samples of the results of the calculated powers for different car weights, speeds, road inclinations, and different coefficients.

It is evident that the designed car possesses a maximum power of 0.574 kW and can run at 40 km/h if its weight is 300 kg and rolling factor f is 0.01 for a horizontal road. It runs at 35 km/h if the rolling factor is changed to 0.02, even if its weight is reduced to 200 kg. At an inclination angle of about 20° no more than 5 km/h can be attained by the car at any combination of conditions. Good examples of different combinations of weight, speed, road angle and other factors can be extracted from the tables.

Table 1. Vehicle dynamics performance

V (Km/h)	10	20	30	40	50	60
P_{st} (kW)	0.0	0.0	0.0	0.0	0.0	0.0
P_{ro} (kW)	0.109	0.218	0.327	0.436	0.545	0.654
P_l (kW)	0.004	0.031	0.104	0.247	0.482	0.833
P_2 (kW)	0.113	0.249	0.431	0.683	1.027	1.487
P_w (hp)	0.151	0.334	0.578	0.915	1.376	1.993

Car mass: 200 kg, road inclination: 0°, rolling coefficient: 0.02, drag coefficient: 0.2.

Table 2. Vehicle dynamics performance

V (Km/h)	10	20	30	40	50	60
P_{st} (kW)	0.0	0.0	0.0	0.0	0.0	0.0
P_{ro} (kW)	0.082	0.164	0.245	0.327	0.409	0.491
P_l (kW)	0.004	0.031	0.104	0.247	0.482	0.833
P_w (kW)	0.086	0.194	0.349	0.574	0.891	1.323
P_w (hp)	0.115	0.261	0.468	0.769	1.194	1.774

Car mass: 300 kg, road inclination: 0°, rolling coefficient: 0.01, drag coefficient: 0.2.

Table 3. Vehicle dynamics performance

V (Km/h)	10	20	30	40	50	60
P_{st} (kW)	1.864	3.728	5.592	7.456	9.320	11.184
P_{ro} (kW)	0.055	0.109	0.164	0.218	0.273	0.327
P_l (kW)	0.002	0.015	0.052	0.123	0.241	0.416
P_w (kW)	1.920	3.852	5.808	7.797	9.833	11.927
P_w (hp)	2.574	5.164	7.785	1.452	13.182	15.988

Car mass: 200 kg, road inclination: 20°, rolling coefficient: 0.01, drag coefficient: 0.1.

Table 4. Vehicle dynamics performance

V (Km/h)	10	20	30	40	50	60
P_{st} (kW)	2.796	5.592	8.388	11.184	13.980	16.776
P_{ro} (kW)	0.082	0.164	0.245	0.327	0.409	0.491
P_l (kW)	0.004	0.031	0.104	0.217	0.482	0.833
P_w (kW)	2.882	5.786	8.737	11.758	14.871	18.099
P_w (hp)	3.863	7.756	11.712	15.761	19.934	24.262

Car mass: 300 kg, road inclination: 20°, rolling coefficient: 0.01, drag coefficient: 0.2.

CAR BRAKES SYSTEM

A team of investigators conducted a separate investigation [9] of braking systems for a 300 kg car running at 40 km/h. Disk type brakes were found to have better performance for effectiveness and heat dissipation than drum brakes. A local market survey unveiled three different pad makes, company A of German make, company B of Turkish make and company C of Jordanian make. A comparative experimental study was performed to check the suitability for use. A grinding machine with about 1 hp motor was modified by a cast iron disc of 32 cm diameter replacing the grinder disk, with an arm fitted to the moving head against an adjustable spring. The pads were fitted at the end of the arm with the centre at a distance of about 30 cm. Experiments were carried out at different speeds and different spring loads. Time registration for both wear and surface temperature of the pads were tabulated. The wear was measured using a highly sensitive weight scale, while the temperature was measured using a digital microprocessor connected to three thermocouples embedded in the pad surface. A sample of the results is shown in Figs 5 and 6. The best performance for wear resistance is demonstrated by the B sample, while the best for heat

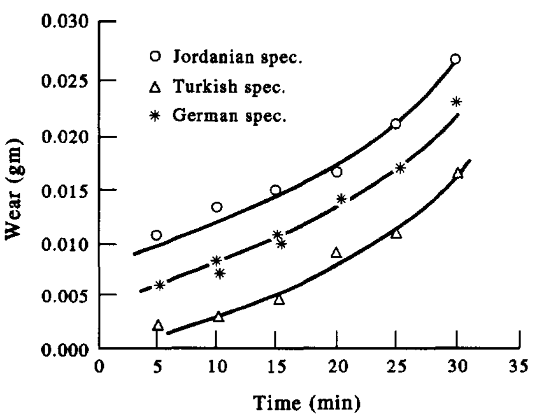

Fig. 5. Wear vs time at 40 km/h.

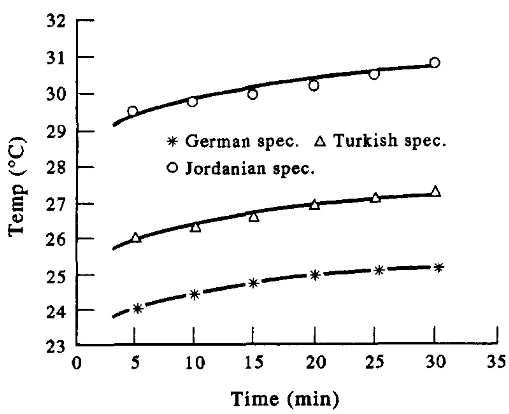

Fig. 6. Pad temperature vs time at 40 km/h.

dissipation and lower temperature obtained was for the A sample. It was decided to use the A sample because of low temperature causing little damage to other parts of the wheel.

SOLAR RADIATION CRITERIA

The full power generation period is taken as a measure of conditions suitable for car driving. This period is the time during which the power generated by the car is enough, or more than enough, to run it at 40 km/h when its weight is 300 kg with a horizontal road. At any other time, the car may move either by using stored energy or at lower speeds. These are not full power generation times. It was found by calculation that the full power generation time requires solar irradiation of 800 W/m^2 received by a horizontal surface. Tables of 1987 solar radiation [4] were used to indicate year round full power generation times. The results are shown in Fig. 7. The 3–6

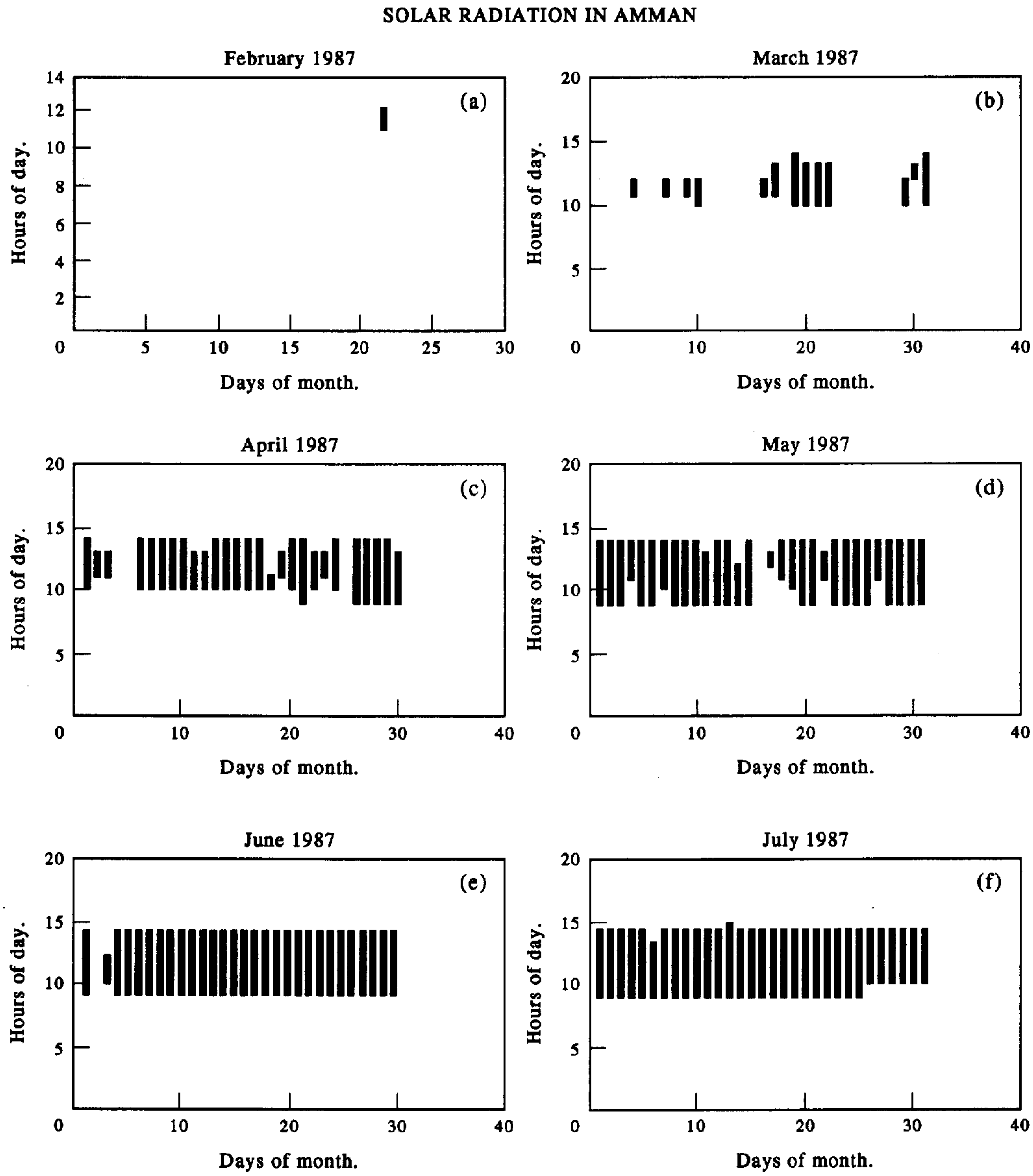

Fig. 7 (a–f) *See caption opposite*

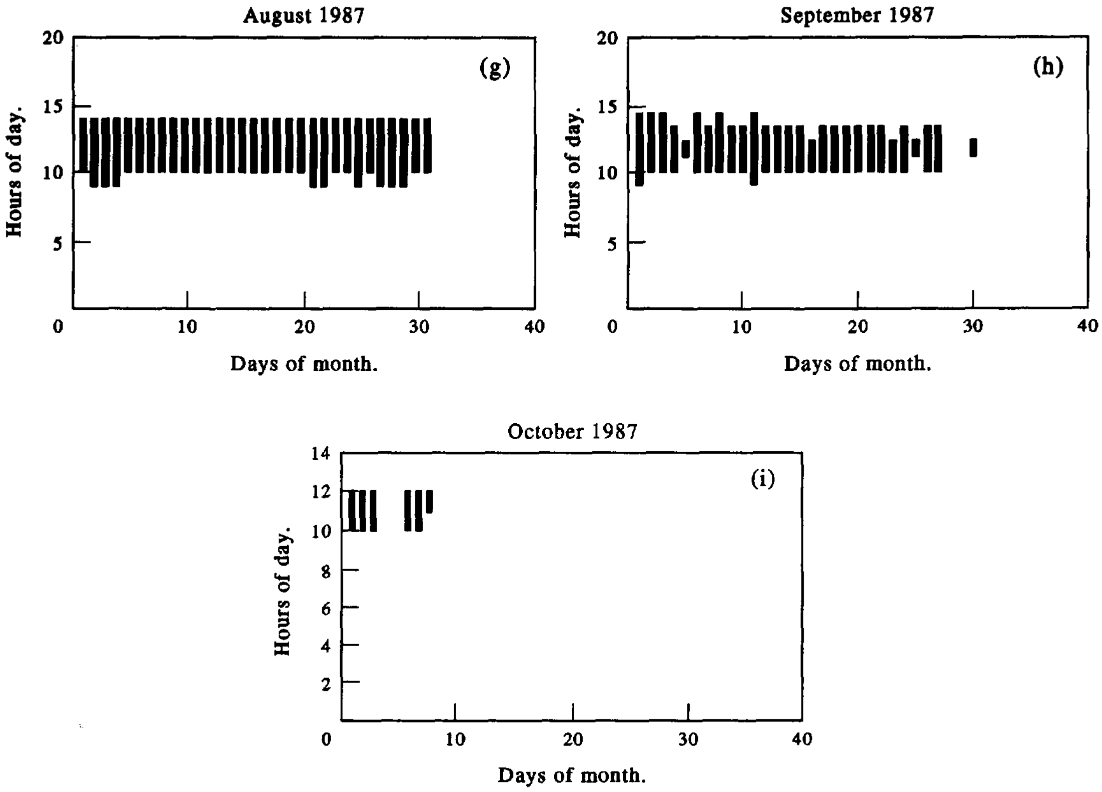

Fig. 7 (g–i)

Fig. 7. Full power generation hours for 1987.

hour daily periods for 200 days/year are the only periods that can be labelled as full power generation times, with no times found in November, December or January. All hours of full power generation occurred between 9 o'clock in the mornings and 3 o'clock in the afternoon, common before noon hours in cold months and afternoon hours for hot months. This is caused by the sun declination angle and by the afternoon clouds on autumn and spring days.

ENERGY SAVINGS AND ECONOMICS

Jordan is granted an abundance of solar energy but is lacking any trace of oil reserves. In a country like this, any use of renewable sources of energy will reflect a very appreciable economical move. Forty percent of imported fossil fuels are used for transport means, so this work is presented within a desirable direction in an attempt to save and reduce the country's yearly fuel bill.

At the individual level for car users or owners, a simple economical analysis shows that this car would be uneconomical. The price difference from an ordinary car would amount to about 5300 Jordan dinars (JD), assuming an annual interest rate of 8% and annual savings, which are the annual cost of operation of a similar traditional car of 320 JD (fuel and extra services), then the pay back period will be 11 years. If more powerful cars are designed, savings will be less, and the pay back period will be longer. Adding this to the limited speed of the car will deem the car unsaleable.

CONCLUSION

The design of a solar car is not an easy job, and it does not end with putting down some calculated parameters or even producing the first prototype. It is a continuous job with changes and modifications even after producing the commercial type. This work is the first step on a long track, and it concerns the energy parameters of the car.

The main features of this design are a 6 m^2 solar generator fitted with three lead-acid storage batteries, and all feed a 32 volt 0.8 hp PMDC motor. This car, of 300 kg weight, is expected to run at 40 km/h on a horizontal road in the Amman, Jordan, area 3–6 hours/day on 200 days/year. More working hours may be obtained at lower speeds.

The car does not seem economical for individual use, but for the country yearly energy bill, it is very beneficial. A prototype of such a car is expected to be manufactured locally.

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