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Prediction of energy balance and utilization for solar electric cars

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Abstract. Solar irradiation and ambient temperature are characterized by region, season and time-domain, which directly affects the performance of solar energy based car system. In this paper, the model of solar electric cars used was based in Xi'an. Firstly, the meteorological data are modelled to simulate the change of solar irradiation and ambient temperature, and then the temperature change of solar cell is calculated using the thermal equilibrium relation. The above work is based on the driving resistance and solar cell power generation model, which is simulated under the varying radiation conditions in a day. The daily power generation and solar electric car cruise mileage can be predicted by calculating solar cell efficiency and power. The above theoretical approach and research results can be used in the future for solar electric car program design and optimization for the future developments.

1. Introduction

Solar electric cars rely on the photovoltaic effect to produce electricity. In these types of cars, the controller and battery are used to drive the motor by overcoming the driving resistance. The solar energy characteristics are clean, pollution-free and inexhaustible. The application of solar energy in the renewable based cars has broad prospects and has emerged to be a hot topic [1,2]. In 1984, the solar electric car of Japan's Tokai University won the competition named as World Solar Challenge by using an average speed of 100 km/h [3]. Domestically, the research institutions of the universities including Tsinghua University, Shanghai Jiao Tong University and Jilin University have also carried out relevant research, and successfully produced a number of solar electric cars [4].

The core components of the solar electric car energy system are solar cells. The performance of the battery is affected by solar radiation and temperature, and the power generation capacity changes with time. Domestic scholars have done some research in proposing the corresponding solution to improve the matching of the power system and the energy efficiency [5-7]. The prediction of energy balance and utilization is still very complex because of many contributing factors such as change in solar irradiation, temperature and environmental factors. These above-mentioned factors change in the form of season, time domain, regional and domestic variations. Therefore, the theoretical based performance prediction of the solar electric car energy system is carried out by using driving resistance, solar cell power generation model, metrological data and thermal variations.

2. Running resistance and drive power

Solar electric cars rely on driving force to overcome the driving resistance to be able to drive. Driving resistance is the most important energy load of solar cars. Driving resistance mainly includes rolling resistance R_r (N), air resistance R_a (N), acceleration resistance R_{ac} (N) and slope resistance R_c (N), the formulae are given in preceding sections [8-10]:

2.1. Rolling resistance
The wheel in the car driving process continues to rotate and the resistance generated in the wheel is rolling resistance which is expressed as:

$$R_r = \mu_r \cdot W \tag{1}$$

In the above formula, μ_r - rolling resistance coefficient and W - total car weight (kg).

2.2. Air resistance
The car bears the resistance against the air while moving and it is named as the air resistance written as:

$$R_a = \frac{1}{2} C_d \rho A v^2 \tag{2}$$

In the above formula, C_d - air resistance coefficient; ρ - air density (kg/m^3); A - windward area (m^2); v - travel speed (m/s).

2.3. Slope resistance
When the car moves uphill, the car's gravity component along the slope is expressed as the slope of the car resistance, expressed as:

$$R_c = m \cdot g \cdot \sin\alpha \tag{3}$$

In the above formula, m - car mass (kg), g - acceleration due to gravity (m/s^2), α - slope angle (°).

2.4. Accelerate resistance
When the car accelerates, it is necessary to overcome the inertia force which is the same as to accelerate the resistance. The mass of the car is divided into two parts: translation mass and accelerated mass. Acceleration is not only the translation of the mass of inertial force, rotation mass also has inertial force. The acceleration resistance of the car can be expressed as:

$$R_{ac} = \delta \cdot m \cdot a \tag{4}$$

In the above formula, δ - car rotation mass conversion factor, m- car mass (kg), a -car acceleration (m/s^2).

2.5. Drive power
The air resistance is mainly determined by the design of the car. However, the acceleration resistance is determined by the way of running and slope resistance is determined by the driving the car on the road. Therefore, in the overall design, the car is considered runningon a flat road with the uniform speed but the impact of acceleration and slope resistance is not considered.

Knowing the rolling resistance and air resistance, the calculation of the drive power P_D (W) of the solar electric car power system can be done as follows:

$$P_D = (R_r + R_a) \cdot v \tag{5}$$

3. Solar cell power generation model

The principle of solar cell power generation is based on the semiconductor photovoltaic effect of solar radiation directly converted to electricity. The maximum power generation P_{mpp} of the solar cell is obtained under standard test conditions where the atmospheric thickness is AM 1.5, the temperature is 25°C, and the solar irradiance is 1000W/m^2. Since, the actual performance of the solar cell is affected by solar radiation and temperature, it is necessary to use the maximum power temperature coefficient to correct the power at the actual temperature and obtain the final actual power according to the approximate relationship with the solar irradiance [11].

3.1. Temperature correction

When the battery temperature is T (°C), the maximum power P_T (W) of the solar cell is:

$$P_T = [1 + (T - 25) \cdot \alpha^{'}] \cdot P_{mpp} \tag{6}$$

In the above formula, $\alpha^{'}$ - the maximum power temperature coefficient is generally around - 0.5% /°C.

3.2. Irradiation correction

In order to simplify the calculation, the solar cell power generation P is estimated to be proportional to the incident solar irradiance,

$$P = G_{on} \cdot P_T \cdot 1000^{-1} \tag{7}$$

In the above formula, G_{on} - the solar irradiance received by the solar cell (kWh/m^2), its value can be obtained according to the hourly meteorological data.

4. Hourly weather data

The location of the operation is located in Xi'an at 34.5° north latitude, 108.5° east longitude and 693 m above sea level. Since so far, China has not yet established a unified standard and national hourly weather data, especially solar radiation data. Therefore, the use of already known method of time based meteorological data generation is more appropriate at this stage. The weather data for solar and ambient temperatures is derived from NASA's historical data [12], as detailed in table 1:

Table 1. Solar energy and temperature.

month	daily total solar irradiation kWh/m^2/d	sunny total solar irradiation kWh/m^2/d	Daily average temperature ℃	daily range of temperature ℃
1	2.84	3.83	-5.49	7.44
2	3.34	4.86	-2.15	7.26
3	3.85	6.21	3.20	8.36
4	4.80	7.17	11.0	9.41
5	5.29	7.80	16.6	9.61
6	5.27	7.76	20.4	9.06
7	5.11	7.53	22.1	8.47
8	4.57	5.98	20.7	7.90
9	3.69	5.98	16.2	7.33
10	3.06	4.87	9.80	6.63
11	2.71	3.71	2.98	6.43
12	2.61	3.44	-3.18	5.80

The average daily sun irradiation is the daily average of the total radiation for the month, and the sunny day total solar irradiation is the amount of radiation in the sunny day, and the following formula is used [13]:

$$r_t = \pi/24 \cdot (a + b\cos\omega)(\cos\omega - \cos\omega_s)(\sin\omega_s - \omega\cdot\cos\omega_s)^{-1} \tag{8}$$

In the above formula, r_t - the ratio of total radiation in hour to total radiation, ω_s - sunset angle, ω – hour angle; the coefficient *a*, *b* are calculated as follows:

$$a = 0.409 + 0.5016 \cdot \sin(\omega_s - \pi/3) \tag{9}$$

$$b = 0.6609 - 0.4767\sin(\omega_s - \pi/3) \tag{10}$$

The solar irradiance at different time can be obtained by calculating r_t of different time and the daily total radiation.

In June and December, for example, the daily total solar irradiation and sunny total solar irradiation distribution with time is shown in figure 1:

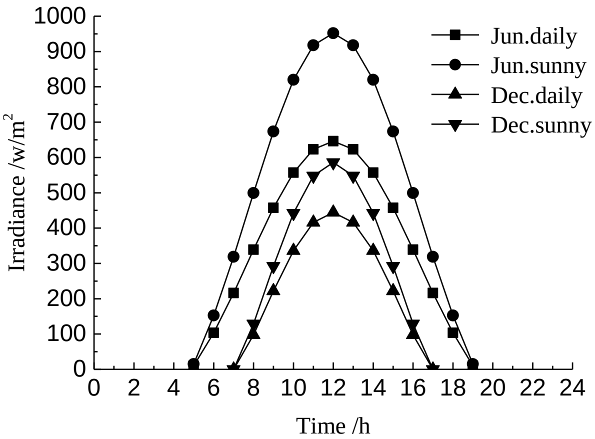

Figure 1. Hourly solar irradiance.

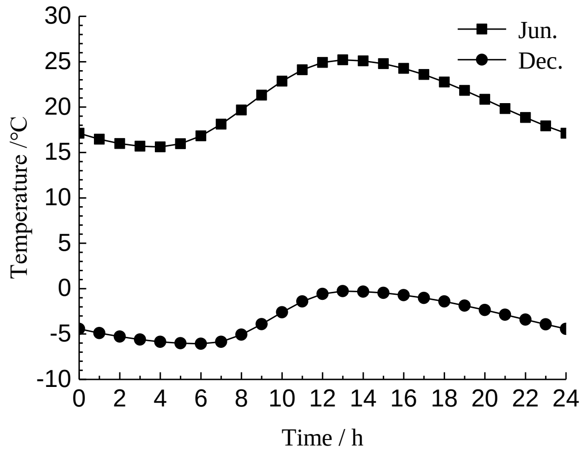

Figure 2. Hourly ambient temperature.

The data show that [14,15], the ambient temperature in the day can be approximated with a cosine function. Moreover, the maximum temperature generally occurs at 14:00, and the lowest temperature appears in the 1 hour before the sunrise. According to the daily average temperature, temperature differences and the change in sunrise time in the months of June and December are shown in figure 2.

5. Prediction of energy balance and utilization

5.1. Solar electric car conceptual model

The solar electric car model is shown in figure 3, which has length of 4 m, width of 1.7 m, height of 1 m, and weight of 350 kg. Solar electric cars rely on the photovoltaic effect to produce electricity. In these types of cars, the controller and battery are used to drive the motor by overcoming the driving resistance. For maximum power output, the system uses MPPT solar controller. When the intensity of light is large, the electric energy can drive the motor directly through the control system and drive the wheel. When the vehicle is at low speed or stagnant state, excess electricity can be stored in the battery. Otherwise, the battery through the control system discharge drives motor and then drives the car. The speed of the car is dependent on the control system which adjusts the current of the motor.

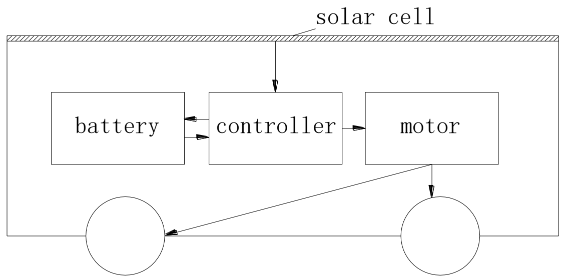

Figure 3. Solar electric car model.

The surface of solar electric car is equipped with 432 pieces of HH125M165-S2 monocrystalline silicon solar cells. In addition, 144 pieces of these cells constitute a PV module and a total of three PV modules are used. Under standard conditions, the power comes out to be 1223 Wp. Under the standard condition, the efficiency φ of HD125M165-S2 monocrystalline silicon solar cell is 18.2%, peak power P_{mpp} is 2.833Wp, and the maximum power temperature coefficient α is -0.46%/°C.

The four NCR18650A lithium ion battery stacks are used in series to form a power storage unit. In addition, sub string is made by joining 10 groups of these power storage units and 45 groups of sub-string are then connected in parallel. The total capacity of the battery pack is 2.09 kWh, the maximum discharge current is 1395 A and the total weight is 81.9 kg.

The information relevant to the solar electric model car include temporary cruise speed of 30 km/h (8.33 m/s), rolling resistance coefficient of 0.015, the wind area of 0.5 m^2, air resistance coefficient 0.35, and air density is 1.205 kg/m^3.

According to the formulas (1)-(6), the rolling resistance is 51.5 N and the air resistance is 7.3 N. Therefore, the total resistance is 58.8N and the required power is 489.8 W. The different efficiencies come out to be 95%, 90%, 95% and 75% for motor, mechanical transmission, MPPT solar controller and battery respectively. In addition, the required solar power supply is 804 W.

5.2. Solar cell temperature

Solar cell temperature is generally higher than the ambient temperature. However, sunshine makes the temperature rise but the wind blows the temperature down. The solar cell temperature T is simplified according to the thermal equilibrium relation [16].

$$\varepsilon \cdot G_{on} \cdot (1-\phi) = \varepsilon \cdot \sigma \cdot (T^4 - T_{sky}^4) + h(T - T_a) \quad (11)$$

The formula on the left side is the heat energy absorbed by the solar cell and the right side shows the release of heat which includes the radiant heat to the sky and the convective heat transferring with the environment. In the above formula, ε - solar cell heat radiation emissivity is set to 0.95; G_{on} - solar irradiance obtained by solar cells. According to meteorological data obtained by time; φ - solar cell photoelectric conversion efficiency and σ - Stephen-Boltzmann Constant, 5.76×10-8W/m^2·K^4. T_{sky} - Sky temperature, calculated as follows:

$$T_{sky} = 0.0552 T_a^{1.5} \quad (12)$$

T_a is the ambient temperature according to the meteorological data obtained by time. While, h - air convection heat transfer coefficient is calculated by the following formula:

$$h = 2.8 + 3.0 v_w \quad (13)$$

Where v_w is the surface wind speed which is approximately equal to the cruising speed of 8.33 m/s.

In June and December, for example, by using the formula (11) the changes in the solar cell temperature T with the time are shown in the results in figure 4.

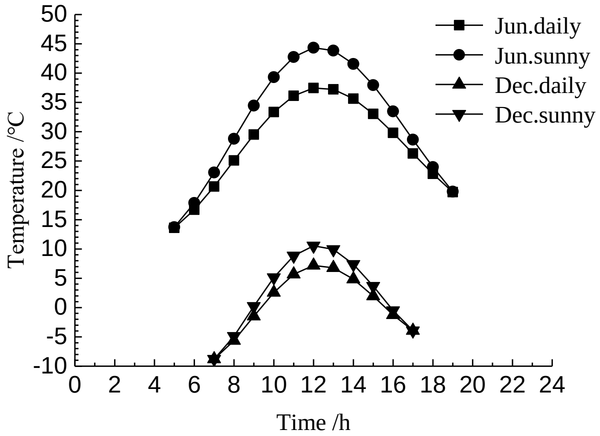

Figure 4. Hourly solar cell temperature.

5.3. Prediction results

The change in the solar cell temperature with the time will result in the change of efficiency which is shown in figure 5. Further, with the change of solar irradiance with time, the peak power changes are shown in figure 6.

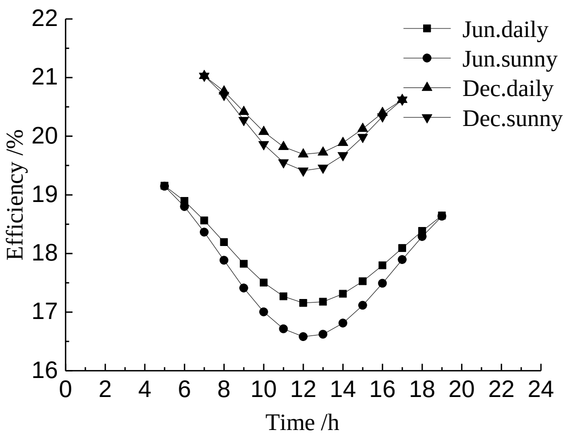

Figure 5. Hourly solar cell efficiency.

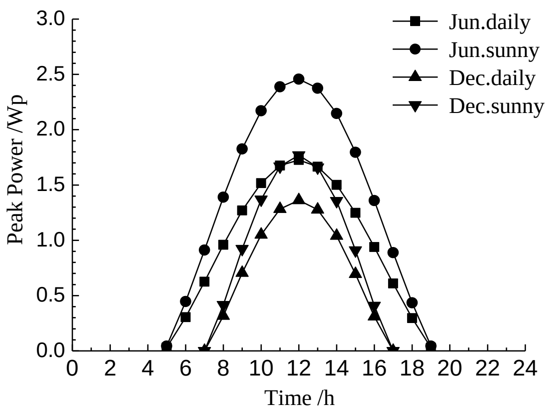

Figure 6. Hourly peak power of solar cell.

The time of 12 o'clock can be taken as symmetry for the solar power produced all around the day. By the impact of ambient temperature hysteresis, the power of the morning session is slightly higher than the afternoon. The average efficiency in June was 18.0% and 17.7% with average power of 0.960 W and 1.378 W respectively. On the other hand, the average efficiency in December was 20.1% and 19.9%, with the average power of 0.893 W and 1.164 W respectively.

The solar cell efficiency and power change with time from January to December. The total theoretical solar power generation from January to December is shown in figure 7. Further, according to the needs of the solar electric car photovoltaic power supply, from January to December, the solar electric car daily cruise stroke is shown in figure 8.

In the whole year, the maximum daily generation and cruise travel took place in May and the minimum occurred in December. In June, for example, the performance prediction results show that the average daily generating capacity of 432 solar modules is 6.33 KWh and 9.10 KWh under normal daily radiation and sunny day radiation respectively. According to the cruise speed of 30 km/h and the required solar power supply capacity of 804.0 W, the maximum theoretical travel is 232.0 km and

333.15 km with cruising time of 5.5 hours and 7.9 hours respectively. It should be noted that the actual cruise travel and time will be less than the above forecasted results due to acceleration and slope resistance.

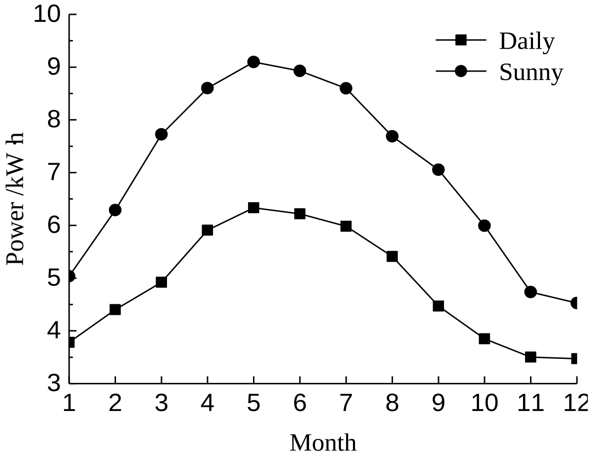

Figure 7. Theory daily power generation.

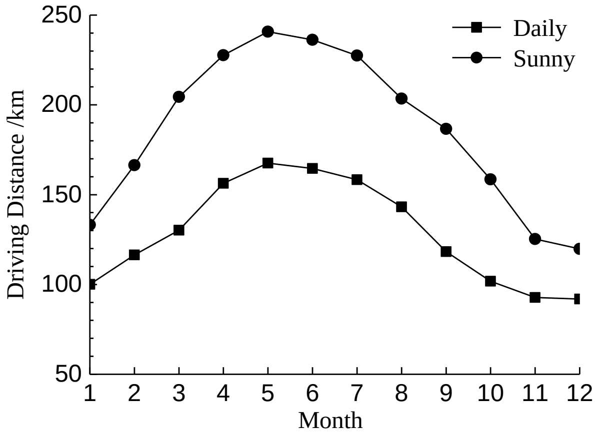

Figure 8. Daily driving distance.

6. Conclusion

Based on the concept model of solar electric car, this paper studies the performance prediction of energy system, and can get the following conclusions:

- The model and method established in this paper can be used to predict the performance of solar energy car energy system in different months. It can be used to verify and analyze the solar electric car in the developing stage. It can provide base for the selection and improvement of the scheme.
- The performance of the solar electric car energy system changes in a day with the time of 12 o'clock as the center. The 12 o'clock can be considered as symmetrical point. However, the lag of environmental temperature results into the morning value slightly greater than afternoon.
- Affected by changes in solar energy and ambient temperature in different months, the working capacity of solar energy vehicle energy system has nearly doubled the scope of the design. And the applications of the solar electric car system will have greater impact in the future.

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