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REGULAR ARTICLE

Design method and theoretical analysis for wheel-hub driving solar tractor

Chao Zhang[1,2], Huisong Gao[1], Xiaoting Deng[1], Zhixiong Lu[1,2]*, Yi Lei[1], Huadong Zhou[1]

[1]College of Engineering, Nanjing Agricultural University, Nanjing, China, [2]Jiangsu Key Laboratory for Intelligent Agricultural Equipment, Nanjing, China

ABSTRACT

Burning fossil fuels to produce greenhouse gases, leading to global climate change. The sustainable development requires to design a environmentally benign tractor, which have no or little air pollution during operation. Considering these constraints, Presents a wheel-hub driving solar tractor design method, includes the integral structure design and the main components choose,such as hub moter, battery, gearbox, etc.,and put forward cumulative operation time throughout the day (COTTD) as solar tractor working ability evaluation index. Combined with the local meteorological, predicted the generation capacity of photovoltaic (PV) array in different time of the year, 1.19 kWh/d in winter and 3 kWh/d in summer. Analysis the COTTD relationship with speed of tractor, mass of tractor, slope of road under different work conditions. When the operating speed increases, the trend of COTTD is shortened. Under the same conditions, the COTTD in winter is significantly shorter than the summer. When the speed is 6 km/h on flat road, the COTTD will decrease with the total mass increase. The slope of the road has great influence on COTTD. This research provides valuable technology reference for solar tractor system design and optimize control.

Keywords: Design method; Renewable energy; Solar tractor; Wheel-hub driving

INTRODUCTION

Carbon dioxide and other greenhouse gases produced by burning of fossil fuels cause ecosystems and global warming, and the transportation industry has been one of the main industries of global greenhouse gases emission (Tie and Tan, 2013). Thus, the problem of replacing fossil fuel-based energy systems are worthy of attention. Solar energy is a kind of green energy, which can provides an additional energy resources and benefits to the environment. It has wide application prospect in agricultural engineering and gradually becoming a hot research topic (Redpath et al., 2011; Cakmak and Yildiz, 2012; Hafiz and Warren, 2015). Therefore, it is necessity to utilize solar energy in agricultural mechanization. Compared with the solar vehicle, solar tractor can be driving the tractor on field road, but also can be used for a variety of crops transportation, spraying pesticides, field irrigation and driving other ancillary equipment (Mousazadeh et al., 2009).

Mousazadeh evaluated the life cycle analysis of Solar Assist Plug-in Hybrid electric Tractor (SAPHT) project and compared the results with that of an internal combustion engine tractor, reporting that replaced each internal combustion engine tractor by SAPHT can reduce approximately 14 ton CO_{2equ} emission every year. Meanwhile it prevents large amount of other emissions such as SO_2, HC and PM entering to air, water and soil in the life-time. The life-cycle costs (LCC) of SAPHT is lower than internal combustion engine tractor at any diesel fuel unit price (Mousazadeh et al., 2011).

The product of Sun Horse of Free Power Systems company which can continue working for hours on a fully charged whether the energy from on board 200 W solar panel or from 110 VA.C. outlet. The tractor also can supply 2.5 kW of 110V A.C. at anywhere to drive all portable corded electric tools, even a 3HP water pump or a small home (Zhang et al., 2015).

In China, Zhang present a solar radiations model for a sample day to design a solar garden tractor, but this method are based on local meteorological station history data, needed more atmospheric information, it couldn't

***Corresponding author:**
Zhixiong Lu, College of Engineering, Nanjing Agricultural University, Nanjing 210031, China. E-mail: luzx@njau.edu.cn

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calculate the solar radiation on photovoltaic panel of any orientation, any latitude and any time of the year, then limited the application of that method (Zhang et al., 2015). Tsinghua University, Shanghai Jiao Tong University, Jilin University and other scientific research institutions have successfully developed some solar vehicle (Li, 2011), but about solar tractor papers are few published. Up to now, no detailed driving system analysis is carried out on solar tractor. The emphasis of this paper is study of the solar tractor drive system design method and theory, and put forward cumulative operation time throughout the day (COTTD) as solar tractor working ability evaluation index. Then combined with an example to verify the proposed design method and analyze the relationship between the speed of the tractor and COTTD under different work conditions.

MATERIALS AND METHODS

Overall system design

At present, solar tractor mainly adopt the following three kinds of drive scheme: 1) the traditional drive mode; 2) the deceleration drive mode; 3) wheel drive mode. Among them, the traditional drive mode retains original traditional tractor clutch and gearbox structure, its features are high starting torque, simple operation and control, but the large space occupation, high energy loss, high noise, total mass heavy, lower speed, mileage is short. Compared with the traditional drive mode the deceleration drive mode have no clutch and gearbox, motor power through the reducer directly to driving axle, this kind of drive mode is simple structure, light weight, low noise, but control is relatively complicated, and there is a certain energy loss. Wheel drive mode using hub motor direct drive tractor, this drive mode have little power train components, simple structure, low noise, lightweight, good controllability advantage, but the cost is high.

Due to the wheel drive mode can be controlled and optimized by the energy management system, and have short transmission chain. It is beneficial to improve the efficiency of transmission system, increase operation time, reduce noise and expand mileage, therefore, this study drive system use the wheel drive mode, the overall scheme show in Fig. 1. This system is mainly composed of 1 PV array, 2 controller, 3 DC/AC outlet, 4 storage battery, 5 hub motor, 6 wheel-side reducer.The PV array collect the solar energy and then convert it to usable electrical energy, part of the energy used to drive hub motor and through DC/AC outlet to drive other working implements, the controller will store other energy to battery. The controller prevents the battery from over charging and discharging, to make battery life last longer. DC/AC outlet also has the function of charging the battery in the normal way,in the condition of low sunshine, due to the cloudy, foggy sky or in the rain season, this can expanse the battery life span.

Theoretical design computation

Hub motor power calculation

The hub motor is used to drive the tractor. Its power is decided by the tractor road load force and speed. Among them, the driving resistance is mainly composed of rolling resistance, aerodynamic drag, acceleration resistance and gradient resistance. Consider solar tractor drive speed is low and change slowly, so when determine hub motor power, we can neglect aerodynamic drag and acceleration resistance power, only consider the horizontal and slope road driving power required (Hilliard and Jamieson, 2007; Wang et al., 2014; Kolator and Białobrzewski, 2011).

The frictional force, made by the tires and the road, needs a force to overcome which called 'Rolling Resistance' and is calculated as following:

$$F_f = \mathrm{mg}f \tag{1}$$

where F_f is the rolling resistance of tractor (N), m is the using mass of tractor (kg), taking 400 kg, g is the gravitational acceleration (N/kg), taking 9.8 N/kg, f is the coefficient of rolling resistant, which is a non linearly dependence of tractor speed, tires type and pressure. Solar tractor tire used dry farmland tires on the rural road, taking 0.1.

On horizontal road, generally the tractor can reach the maximum velocity, so use the maximum velocity to determine the horizontal driving power, the corresponding formula is:

$$\mathrm{P}_f = \mathrm{mg}fv_{\mathrm{max}} \tag{2}$$

Where P_f is the flat road driving power (W), v_{max} is the maximum velocity of tractor (m/s), taking 2.78 m/s.

When the tractor driving on the slope road, $mg\sin\lambda$ is the component force of the tractor gravity, $mgf\cos\lambda$ is the rolling resistance, then the grade resistance force is:

$$F_\lambda = mg\sin\lambda + mgf\cos\lambda \tag{3}$$

Where F_λ is the grade resistance (N), λ is the slope angle, taking 15°.

Generally, on slope road tractor velocity is lowest, so use minimum velocity to determine the slope driving power, the corresponding formula is:

$$P_\lambda = (mg\sin\lambda + mgf\cos\lambda)v_{\mathrm{min}} \tag{4}$$

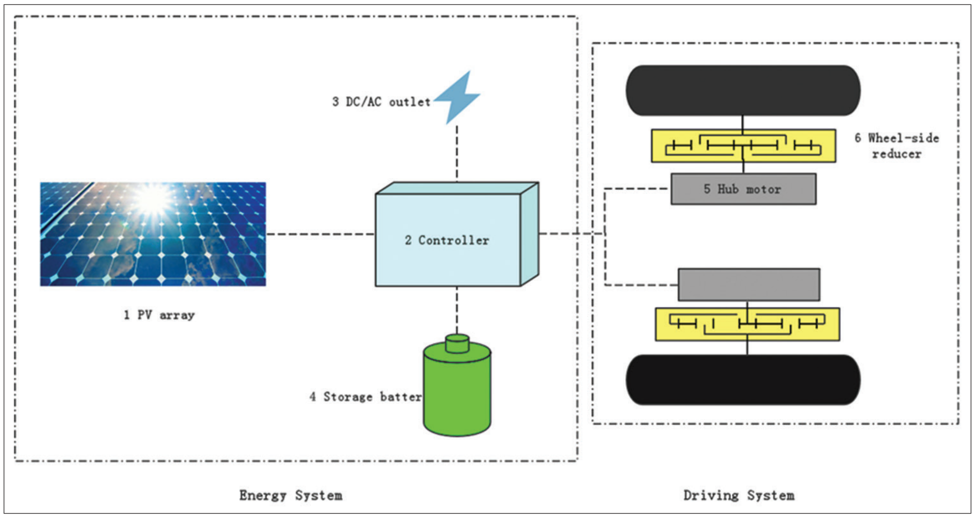

Fig 1. The overall structure diagram of solar tractor.

Where P_λ is the slope road driving power (W), v_{min} is the velocity of a sloping road (m/s), taking 0.83m/s.

Taking into account the working conditions and the various grade roads, when select the motor should set aside reserve supply power, so choose the maximum of P_f and P_λ then multiplied by the reserve supply power coefficient,so tractor required maximum driving power is:

$$P_{max} = \beta \max(P_f, P_\lambda) \tag{5}$$

Where P_{max} is the maximum driving power (W). Calculated that P_{max} is 978 W, due to use wheel drive mode, so use two hub motor, power 700 W, rated speed 800 r/min.

Electric farm implements power calculation

The solar garden tractor is mainly used for light load garden jobs such as grass cutting, pesticide spray and field irrigation (Xu et al., 2012). According to the experience of the operator, grass cutting operation is the largest load, so use the power of grass cutting to determine the electric farm implements power:

$$P_g = \frac{v_g B L_0}{1000} \tag{6}$$

Where P_g is the grass cutting required power (W), v_g is the grass cutting operation velocity (m/s), taking 1m/s, B is the cutting width (mm), taking 1000mm, L_0 is cutting per square meter of grass required power (N·m/m^2). Reference grass cutting measured experimental data, cutting the lawn unit area required for power taken L_0=200~300n•m/m^2. Calculated that P_g is 200~300 W, selective mowing motor power is 300 W (Shan et al., 2010).

Transmission ratio calculation

Solar garden tractor wheel side reducer use NGW type single row planetary gear train, which has advantages of compact structure, small size, lightweight and high transmission efficiency characteristics.

According to the motor rated speed and the tractor normal speed in the field to determine the transmission ratio of planetary gear reducer, the calculation formula is:

$$i \oplus 0.1\frac{n_d r_q}{v} \tag{7}$$

Where i is the given ratio; n_d is the motor rated speed (r/min), r_q is the radius of the drive wheels (m), taking 0.2 m, v is the tractor normal velocity in the field (m/s).

Matching the tooth number in NGW single-row planetary gear is:

$$z_a : z_c : z_b : C = z_a : \frac{i^b_{aX} - 2}{2} z_a : (i^b_{aX} - 1) z_a : \frac{i^b_{aX}}{n_P} z_a \tag{8}$$

Where z_a is the teeth number of sun gear; z_c is the teeth number of planet gear; z_b is the teeth number of annular gear; C is integer; i^b_{ax} is the transmission ratio of planetary gear; n_p is the number of planet gear. Calculated that single row planetary gear transmission ratio is 5.0526, planetary characteristic parameter is 4.0526.

Battery parameter determination

Battery parameters determination should be satisfied the demand of working conditions without solar panel. After the battery type selected, then need to calculate the number of batteries. This paper according to the tractor maximum using power and the rated operating time to calculate the number of batteries.

Number of batteries is determined by the tractor maximum using power

Battery terminal voltage at time x is(Deng et al., 2012):

$$U_x = E_x - I_x R_x \tag{9}$$

Where U_x is the battery terminal voltage at time x (V), E_x is the electromotive force at time x (V), I_x is the discharge current at time x (A), R_x is the internal resistance of battery at time x (Ω).

Set the battery initial electromotive force as E_0, and constant power output, then the battery maximum output power is:

$$P_{B\max} = \frac{E_0^2}{4R_0} \tag{10}$$

Where $P_{B\max}$ is the battery maximum output power (W), R_0 is the battery internal resistance at initial time (Ω).

In practical terms, in order to prevent excessive discharge current have an impact on battery life, usually require the battery operating voltage is not less than 2/3 of E_0. Therefore, in practical application the battery maximum output power is given by:

$$P_{B\max} = \frac{2E_0^2}{9R_0} \tag{11}$$

The maximum output power of the battery must satisfy the maximum power demand of the tractor when solar garden tractor working, namely the power should satisfy the maximum driving power when mowing operation, so the number of the batteries is determined:

$$n_1 \geq \frac{P_{\max} + P_g}{P_{B\max}\eta_m} \tag{12}$$

Where n_1 is the number of batteries; η_m is the efficiency of motor and motor controller.

Number of batteries is determined by the rated operation time

Rated operation time refers to after the battery fully charged, the tractor continuous working time under the rated operation condition, denoted by T_N. In order to ensure solar tractor can work properly without solar energy, battery rated output energy should higher than tractor maximum energy demand in the rated operation time, namely under maximum driving power to mow in the rated operation time.

Battery rated output energy W_B is given by:

$$W_B = n_2 C_B E_0 D_B \tag{13}$$

Where W_B is the battery rated output energy (Wh), n_2 is the number of batteries; C_B is the battery rated capacity (Ah), D_B is the maximum depth of discharge.

Grass cutting operation energy under maximum driving power is given by:

$$W_g = T_N(P_{\max} + P_g) \tag{14}$$

So that:

$$n_2 C_B E_0 D_B \geq T_N(P_{\max} + P_g) \tag{15}$$

Finally:

$$n_2 \geq \frac{T_N(P_{\max} + P_g)}{C_B E_0 D_B} \tag{16}$$

Determine the number of batteries

Battery number n take the maximum of n_1 and n_2:

$$n \geq \max(n_1,\ n_2) \tag{17}$$

Finally, the number of batteries n should be based on the motor voltage requirement to make appropriate adjustments. Calculated battery number is 4, battery rated voltage is 48V, rated capacity is 35 Ah.

PV array power determination

The η_{ch} is the efficiency of battery charging, and the η_{cc} is the efficiency of charge controller, so the energy of PV array E_p is given by:

$$E_p = \frac{C_B \times V_B}{\eta_{ch} \times \eta_{cc}} \tag{18}$$

Where, V_B is the battery rated voltage (V).

Determination PV array power should be consider the local solar radiation intensity change throughout the day, the PV array power is:

$$P_{pv} = \frac{E_P}{t_h \times k_d \times k_{ap} \times k_w} \tag{19}$$

Where P_{pv} is the PV array power (W), t_h is the solar radiation intensity time throughout the day (h), k_d is the solar radiation intensity factor, k_{ap} is the aging factor, k_w is the temperature factor. By calculation, select 4 PV panels, which rated power are 110 W. The PV array total efficiency is 11%, approximately 4 m^2.

Cloudless solar radiations

PV array generated energy throughout the day is determined by the solar radiation throughout the day and PV array itself, the solar radiation throughout the day related to the location of the sun, the air mass factor, atmospheric layer state and light incident angle. The total solar radiation on a tilted PV panel includes direct beam radiation, diffuse radiation and reflected radiation.

The form of the solar radiation model is given as follows:

$$G_{TP} = G_{BP} + G_{DP} + G_{RP} \tag{20}$$

Where G_{TP} is the total solar radiation on the surface of PV, G_{BP} is the direct beam radiation on the surface of PV, G_{DP} is the diffuse radiation on PV surface, G_{RP} is the ground reflected radiation on PV surface.

Direct solar beam radiation

The direct solar beam radiation G_{BP} is expressed as follows(McIntyre, 2012):

$$G_{BP} = G_B \cos\theta \tag{21}$$

Where G_B is the direct solar beam radiation on earth surface, θ is the angle of incidence between the normal to the surface of PV and the incoming direct beam.

Direct solar beam radiation on the earth surface G_B, calculated as the distance of the beam goes through atmosphere, is not difficult to account the factors such as clouds and turbidity, air pollution, dust and atmospheric water vapor (Gueymard, 1993). and the direct solar beam radiation model treats attenuation as an exponential decay function, which is calculated as following:

$$G_B = G_0 e^{-km} \tag{22}$$

Where G_0 is the extraterrestrial radiation, k is the optical depth that is a dimensionless factor, m is the air mass ratio.

The extraterrestrial radiation G_0 is relevant to the day number of the year, it is expressed as follows:

$$G_0 = 1160 + 75\sin[360(n - 275)/365] \tag{23}$$

Where n is the day number of the year, in common year, set n to 1 at the first day of the year, and at the last day of the year n is 365. But in leap year n need to add 1 before March, and since March 1 the calculation method is like in a common year. such as in leap year, January 1 as day 2, February 29 as day 61, March 1 as day 60 and December 31 as day 365. The n is given in Table 1.

The optical depth k is given by:

$$k = 0.174 + 0.035\sin[360(n - 100)/365] \tag{24}$$

The mass ratio of air m, given by:

$$m = \frac{1}{\sin\beta} \tag{25}$$

Where β is the sun altitude angle.

The incident angle θ is expressed by the equation:

$$\cos\theta = \cos\beta\cos(\phi_S - \phi_P)\sin\varphi + \sin\beta\cos\varphi \tag{26}$$

Where ϕ_s is the sun azimuth angle, which is positive in the morning where the sun is in the east, and when the sun is in the west, it becomes negative in the afternoon. ϕ_p is azimuth angle of PV panel, which is positive in the southeast and negative in the southwest. φ is panel tilt angle, as shown in Fig. 2.

The sun azimuth angle ϕ_s can be described as follows:

$$\sin\phi_S = (\cos\delta\sin H)/\cos\beta \tag{27}$$

Table 1: The day numberof the year *n*

Month	The *i* day of each month	Comment
January	*i* (leap year add 1)	*i* is 1~31
February	31+*i* (leap year add 1)	*i* is 1~28 (29)
March	59+*i*	*i* is 1~31
April	90+*i*	*i* is 1~30
May	120+*i*	*i* is 1~31
June	151+*i*	*i* is 1~30
July	181+*i*	*i* is 1~31
August	212+*i*	*i* is 1~31
September	243+*i*	*i* is 1~30
October	273+*i*	*i* is 1~31
November	304+*i*	*i* is 1~30
December	334+*i*	*i* is 1~31

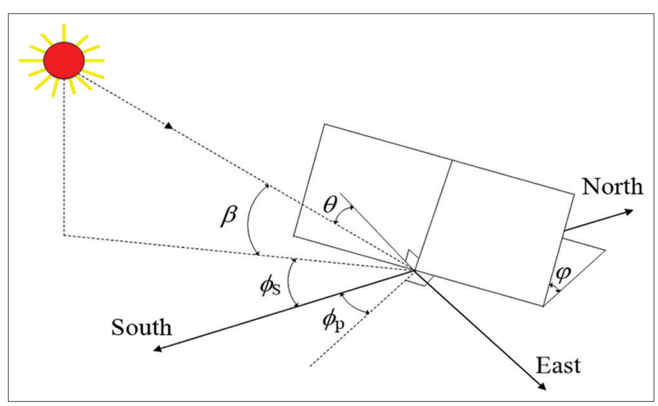

Fig 2. The position of the sun and PV panel.

Where δ is the declination angle,which is between the Earth's equator plane and a line drawn from the Earth's centre. It varies between the extremes of ±23.45°. H is the hour angle. β is the sun altitude angle. Due to the movement of the earth around the sun are extremely complex, if want to get the real values of solar declination, need for high accuracy real-time astronomical survey or look-up table in the almanac. This is very inconvenient for solar energy utilization. So in the field of solar energy utilization extrapolation method is commonly used and generalize a simple algorithm to calculate. The declination angle can be approximated from the equation of Cooper using the day number of the year(Al-Mohamad, 2004):

$$\delta = 23.45\sin[\frac{360}{365}(n-81)] \quad (28)$$

The hour angle H, which value increases by 15° per hour of solar time, and is calculated as following:

$$H = 15°(12-h) \quad (29)$$

Where h is different hours in a given day from 01:00 a.m. to 24:00 p.m.

The sun altitude angle β, which is between the sun's position and the horizontal plane of the Earth's surface, which relative to local latitude, time of the day and the hour angle.

$$\sin\beta = \cos L\cos\delta\cos H + \sin L\sin\delta \quad (30)$$

Where L is the local latitude.

The magnitude of the sun azimuth lays up to 90°away from south in the early morning and late afternoon during spring and summer. Because the inverse of the sine is ambiguous, so the azimuth may be greater than or less than 90°, The following formula could determine the sun azimuth:

$$\text{If} \quad \cos H \geq (\tan\delta/\tan L), \quad \text{then} |\phi_S| \leq 90°; \quad \text{otherwise} |\phi_S| > 90° \quad (31)$$

Diffuse radiation model

The diffuse radiation G_{DH} is proportional to the direct solar beam radiation on horizontal plane, which can be described as follows:

$$G_{DH} = C\ G_B \quad (32)$$

Where C is the sky diffuse factor, and is computed as following:

$$C = 0.095 + 0.04\sin[\frac{360}{365}(n-100)] \quad (33)$$

When φ is zero, the panel lays flatly to the ground and fully reflects to the sky and also completely receives the horizontal radiation. When the panel is perpendicular to the ground, half of the sky can't be seen, and the panel can only accept half of the diffuse radiation, so the PV panel diffuse radiation can be expressed as:

$$G_{DP} = G_{DH}(\frac{1+\cos\varphi}{2}) = C\ G_B(\frac{1+\cos\varphi}{2}) \quad (34)$$

Reflected radiation model

The reflected radiation is the product of the total horizontal radiation times the ground reflectance, and also related to the slope of PV panel, so the expression for PV panel reflected radiation is given by:

$$G_{RP} = \rho G_B(\sin\beta + C)(\frac{1-\cos\varphi}{2}) \quad (35)$$

Where ϱ is ground reflectance, and the default value is 0.2.

Combining the Relations (21), (34) and (35) gives the following expression for total radiation on PV panel in a cloudless day:

$$G_{TP} = G_0\exp(-k/\sin\beta)[\cos\beta\cos(\phi_S-\phi_P)\sin\varphi + C((1+\cos\varphi)/2) + \rho(\sin\beta + C)((1-\cos\varphi)/2) + \sin\beta\cos\varphi] \quad (36)$$

Performance evaluation method

To evaluate the working ability of solar tractor, proposed COTTD T_C as the evaluation index. COTTD refers to the sum of solar tractor working time in a day on a full charged. In order to calculate the COTTD, assume the total energy equal to the tractor consumes energy. Solar tractor obtain total energy composed of PV array daily total output energy and the rated energy of the battery.

$$W_O = W_S + W_B \quad (37)$$

Where, W_O is the solar tractor obtain total energy (Wh), W_S is the PV array output total energy throughout the day (Wh).

Therefore, COTTD under tractor maximum power is given by:

$$T_C = \frac{W_O}{P_{max} + P_g} \quad (38)$$

RESULTS AND DISCUSSION

Through relation (36), the solar radiation could be calculated at any time and location. Make the PV array installation azimuth angle is 0 degree, at the same time, calculated the average insolation at different slope angle each month, then obtain the each month daily average solar energy at different slope angle. As shown in Fig. 3, in different months, solar energy has a peak, the peak slope angle is the best angle in that month.

Commonly the PV array on solar tractor is horizontal, then the monthly daily average solar energy on horizontal can be calculated as shown in Fig. 4. In January is about 3 $kWh/m^2/d$, and in June is about 7.6 $kWh/m^2/d$. So can use these two months represent winter and summer.

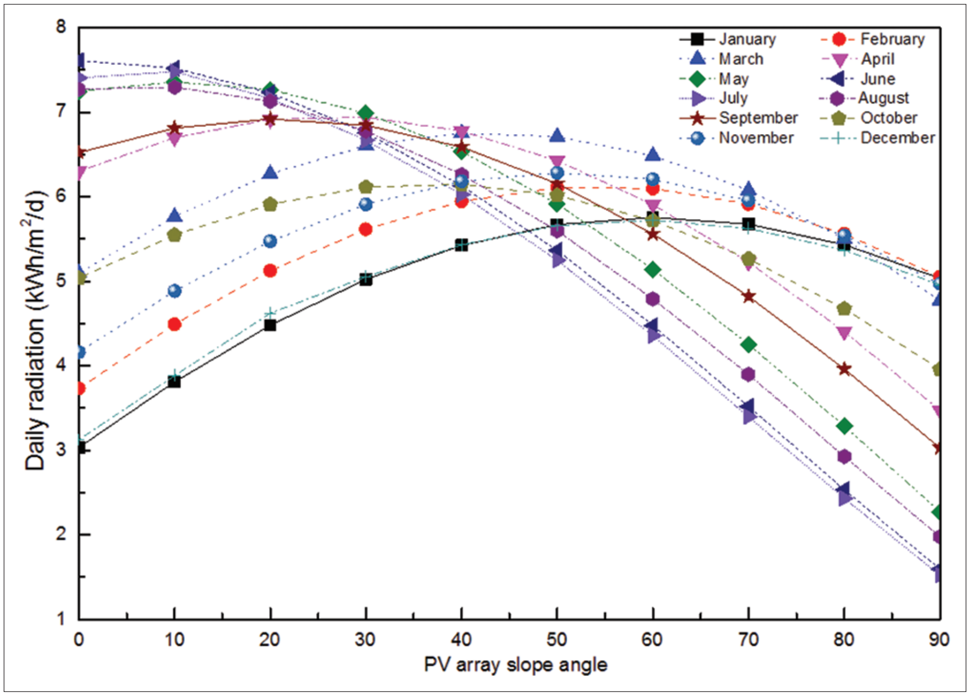

Fig 3. Different monthly daily radiation at different slope angle.

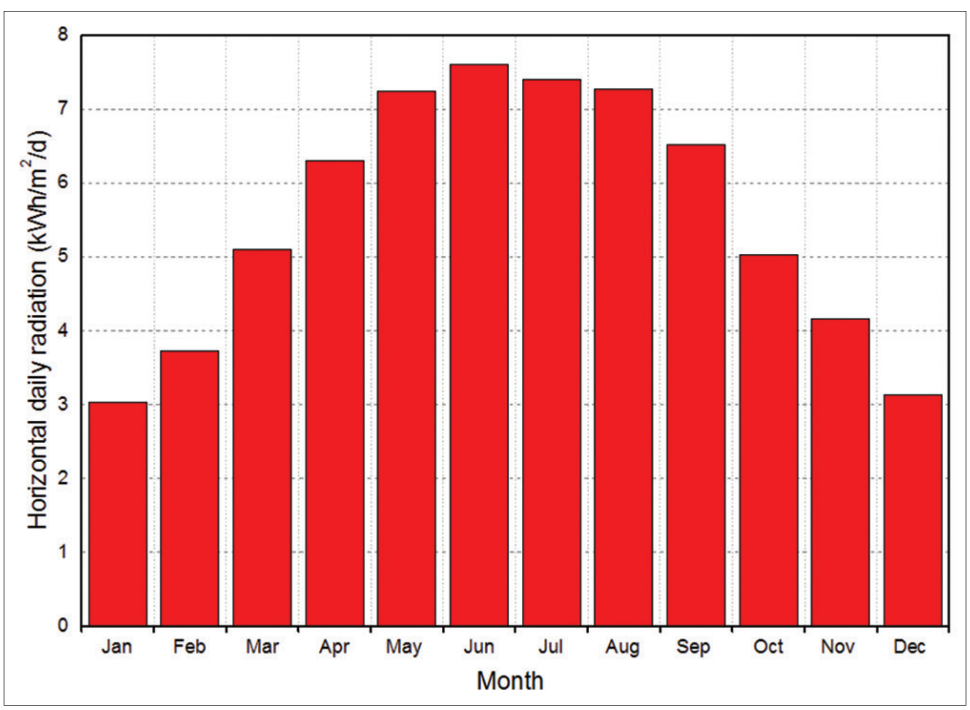

Fig 4. Horizontal daily radiation in Nanjing, China.

Consider the efficiency and panel area of PV array, the available energy of a day at winter and summer is 1.32 kWh/d and 3.34 kWh/d, respectively. Efficiency of most modern MPPT (maximum power point tracker) devices is around 92% to 97%. Using this 90% factor, daily available energy becomes 1.19 kWh/d in winter and 3 kWh/d in summer.

A case study of solar garden tractor, combine with all day's electricity energy of PV array, according to Equation (38), then calculated the COTTD under different working conditions as shown in Figs. 5 and 6, then analyze the COTTD under the different solar tractor mass as showed in Fig. 7. In Fig. 8 shows the relationship between COTTD and the slope of the road.

Fig. 5 shows the COTTD in summer. As can be seen, with the operating speed increase, the COTTD is shortened, this is due to the discharge current increased with increasing operation speed, thus resulting in the actual discharge capacity of the battery drop. The COTTD of ramp operation is significantly shorter than the horizontal operation. This is because the tractor has to overcome the ramp resistance.

Fig. 6 shows the COTTD in winter. Compared with Fig. 5, under the same conditions, the COTTD in winter is significantly shorter than in summer. At the speed of 8 km/h, tractor working at ramp operation the COTTD is about 2 hours.

Fig. 7 shows that the capability of solar tractor carrying different loads, and it is assumed the speed is 6 km/h, and the road is horizontal. According to Fig. 7, one can conclude that, the COTTD is highest at the condition of transportation in summer and lowest at the condition of grass cutting in winter. In addition, when the total mass is 1100 kg, for transportation in winter and grass cutting in summer conditions, the COTTD are the same.

Fig. 8 shows the COTTD at different slope road, it is assumed the tractor speed is 3 km/h, as can be seen, slope

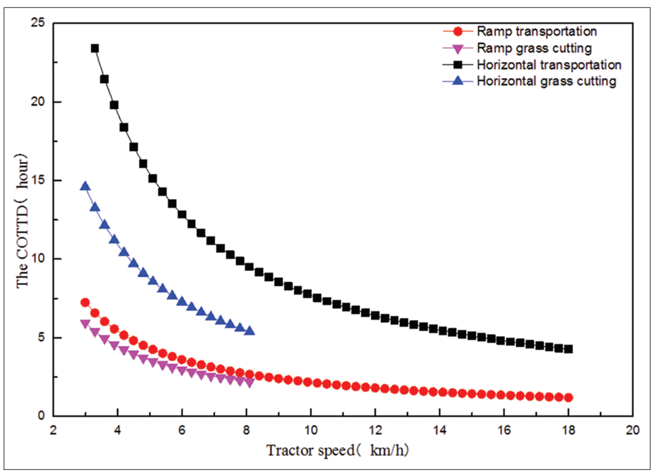

Fig 5. Solar tractor COTTD in summer.

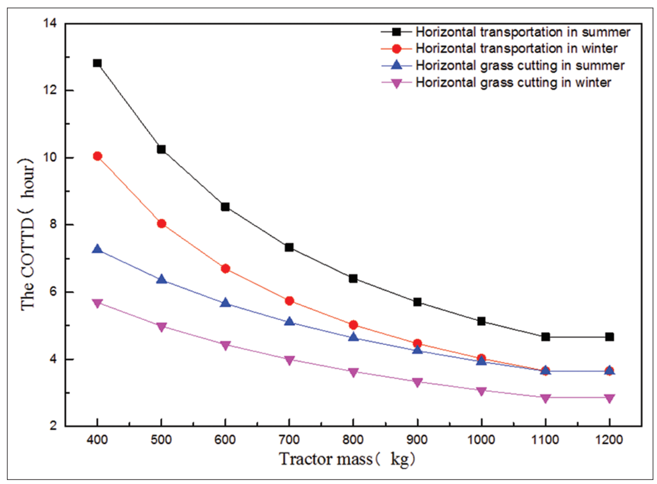

Fig 7. The COTTD for different mass.

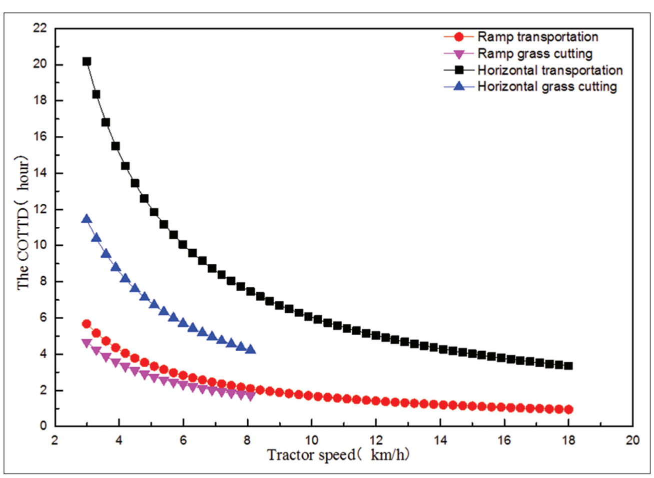

Fig 6. Solar tractor COTTD in winter.

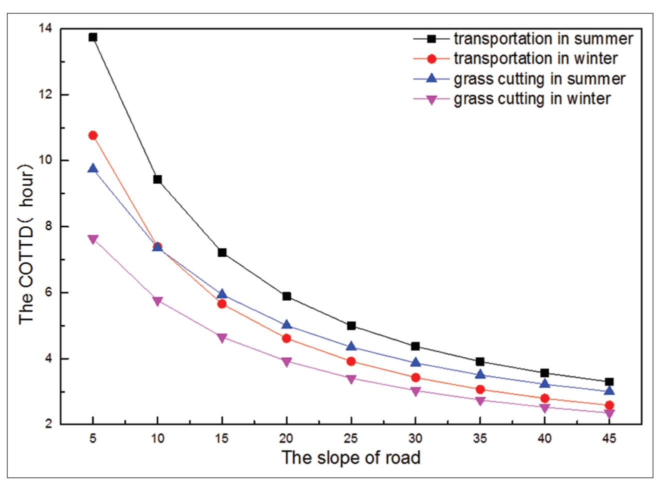

Fig 8. The COTTD for different slope of road.

of road have great influence on COTTD, at grass cutting in winter on 20% slope the solar tractor can be able to support 4 h, 25% slope at transportation in winter, 30% slope at grass cutting in summer,35% slope at transportation in summer.

CONCLUSION

An onboard PV array provides approximately 1.19 kWh/d in winter and 3 kWh/d in summer. Consider the energy is provided by the PV arrays and battery pack, at 8 km/h the solar tractor operated at horizontal transportation in summer for 9.5 h, 7.5 h at horizontal transportation in winter, 5.38 h at horizontal grass cutting in summer, 4.2 h at horizontal grass cutting in winter, 2.6 h at ramp transportation in summer, 2.2 h at ramp grass cutting in summer, 2.1 h ramp transportation in winter and 1.7 h at ramp grass cutting in winter. At the same time, solar tractor on a flat road at 6 km/h, transportation operation in summer for 5.1 h, transportation in winter for 4 h, grass cutting in summer for 3.9 h, grass cutting in winter for 3 h. At the speed of 3 km/h, 20% slope for grass cutting in winter, 25% slope at transportation in winter, 30% slope for grass cutting in summer and 35% slope at transportation in summer could support 4 h.

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Author's contributions

C. Z. wrote the article and corrected it. Z. L. the corresponding author designed the research plan, organized the study. H. G. and X. D. coordinated the data analysis, and contributed to the writing of the manuscript. Y. L. and H. Z. participated in the experimental design and coordinated the data analysis.

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