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# Toward Self-Powered Solar-Battery Cars With Solar Array-Trailers: Implications Of Ultra-Efficient Solar-Arrays

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***Abstract*—The use of solar energy, in addition to battery power, in driving cars was attempted by several academic institutions and international competitions. To increase the solar energy acquired while driving the concept of solar-array trailers was introduced. The concept is based on connecting one/two solar array-trailers to the solar-battery cars. The ranges of application of these solar-battery cars with single and double solar-trailers were simulated with the efficiency of the solar arrays ranging from 13 to 20%. Significant savings on battery power were observed with the use of solar array-trailers. However, the size of cars tested above had a limiting mass of 500kg. Advancement in solar array manufacturing technology, such as multi-junction cells, is pushing the boundary of solar array efficiency close to 40% and beyond. This paper looks at the implications of such an achievement on the use of solar-battery cars with solar array-trailers. The paper starts by computing the changes to the operating boundaries of the system and compare them to previous publications. Second, the drive across the Australia continent is revisited for a solar-battery car and the new energy savings are computed. Third, since the ultimate goal is to be able to drive a full-size car with solar energy, a simulation of such a drive along the Australian continent is performed. A summary of the results is also presented.**

***Keywords—Self-Powered Solar Car; Solar Energy; Solar Array-Trailers; Multi-junction Solar Cells; World Solar Challenge; Super-size Solar Car***

## Introduction

Building cars that run on renewable energy resulted in the manufacturing of Solar-Battery-, Electric- and Hydrogen Fuel Cells vehicles [1-4].
The use of solar energy in the automotive sector was attempted by many academic institutions and tested by various world competitions [3-9]. The solar cars used were tailored toward a particular environment that accounts for the low specific surface energy of solar radiation. The low capacity of these cars limited their applicability beyond the academic circles. On the other hand, hydrogen fuel cells cars are still in the testing phase. In contrast, electric vehicles are gaining in market share due to increased battery capacity, however, they are still limited in use. Charging these cars requires external renewable energy sources which range from solar energy, solar arrays built on rooftops, solar/wind energy combined with the Micro/Public Grid, in addition to using fuel cells cars as dispatchable power plants [1-2, 10-11].
Common drawbacks of the above solutions are the need for an external source of energy to recharge the operating energy system with delays resulting from charging as well as the limited driving range. For example, battery charging time can range from half an hour to several hours depending on the charging mode. And, the driving range is limited by the battery capacity as well as the driving patterns [2].

One way of designing a self-powered solar-battery car, i.e., with an independent energy source on board, is through the use solar array-trailers. The possible use of solar array-trailers with solar-battery cars was discussed in Kasti [12-14]. Another advantage of solar array-trailers is the increase in the acquired solar energy.
In Kasti [12], an exploration of the concept was carried out for a 500kg car to determine the operating speed limits based on energy and stability requirements. The terrain was assumed to have low slopes. The solar array efficiency was assumed to be 13% and two wheels were used per trailer. Speeds around 70km/h and 80km/h were found to be upper bounds for energy and stability requirements, respectively.
In Kasti [13], the solar array efficiency was raised to 20% and four wheels were used per trailer. In this case, the operating limits were increased to 80km/h due to energy requirement and 90km/h due to stability.
In Kasti [14], three tasks were accomplished:

- First, the effects of variations in the drag area coefficient, rolling resistance, and road inclination on the applicability of the car-trailer system were determined. For a car with two solar array-trailers, battery power is not needed for any of the operating states till 40km/h.

- Second, an effective rolling resistance coefficient was calculated that accounts for manufacturing imperfections, components flexibilities, and misalignments of trailers.
- Third, the response of the car-trailer system was simulated in an environment similar to the World Solar Challenge with a drive along Stuart highway/Highway1 in Australia.
  A 500kg car with two trailers would use no battery power at 40km/h with 20% solar array efficiency.

In this paper, the responses of solar-battery cars with 40% solar array efficiency are calculated. A new category is added, namely, a car of 2100kg mass.
The increase in solar array efficiency is based on advances in multi-junction solar cells [15-16].

The paper is divided into three main sections:

- In the first section, the changes in the operating boundaries of the system, derived in Kasti [14] for 20% solar array efficiency, are recalculated for the various operating states and for 40% solar panel efficiency.
- Second, the drive across the Australia continent is revisited for a 500kg solar-battery car and the new energy savings are computed [14].
- Third, since the ultimate goal is to be able to drive a full-size car with solar energy, a simulation is performed with a super-size car and super-size solar arrays along Stuart Highway/Highway1 across the Australian continent.

The paper concludes with a summary of the results.

## I. ROAD DATA, CAR AND SOLAR ARRAY-TRAILER PROPERTIES

The proposed car and solar array-trailer configuration is depicted in Fig. (1).The solar car-trailer system is subjected to two environments with two types of cars studied. The details of the environments are listed in Table 1 and the types of cars used in the simulations are described in Table 2.

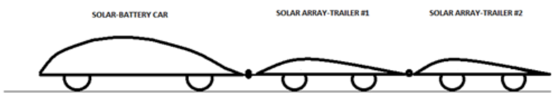



Fig. 1 Solar-battery car with solar array-trailers

Table 1. Environments of the drives

| | |
|---|---|
| I | Local Drive – Section II |
| II | Drive across Australia (3000km) – low gradient terrain |

The first drive is a local drive where the operating limits of the various parameters affecting the energy of the system are determined. The second is a global drive, through the continent of Australia, where the ground slope is mild but the drive is over 3000km long. In this case, the changes in latitude and longitude of the location are taken into consideration in the solar energy calculations.

Table 2. Types of cars and trailers

| | Car | | | Trailer | | | |
|---|---|---|---|---|---|---|---|
| Type no. | Mass (kg) | $C_dA_d$ ($m^2$) | $C_{rr}$ | Masst (kg) | $C_dA_{dt}$ ($m^2$) | $C_{rrt}$ | Solar Array size |
| I | 500. | 3*0.12 | 0.01 | 100. | 0.12 | 0.0055 | 2x4m$^2$ |
| II | 2100. | 6*0.12 | 0.02 | 180. | 1.8*0.12 | 0.0055 | 4x4m$^2$ |

The first type of car and trailers is the one used in previous publications except that the solar array efficiency is increased to 40% [12-14]. The second type is a super-size car with the width of the trailer increased to accommodate a 4x4m$^2$ solar array.
The nomenclature of the different terms is shown in Table 8.

## II. OPERATING LIMITS OF THE SYSTEM WITH LOCAL DRIVE

For the local drive, the track and the parameters considered are as follows:

- The car was driven during daylight hours, from 9:00am to 5:00pm, at the end of the month of March.
- The track latitude was 24.08$^o$N with a constant slope of 0.2%.
- The maximum solar power reaching the Earth surface was assumed to be 1000W/m$^2$.
- The energy calculations are based on the approach presented in [3] where the drive is assumed to be local and the changes in latitude and longitude are assumed negligible.
- The effects of drag, gravity, rolling resistance, and variable sunlight due to time changes were taken into account in the power calculations.
- The efficiency of power conversion from input power to output power was assumed to be 85%.

The total necessary power was obtained by adding the powers of drag, rolling resistance, and gravity, i.e., $P_{drag}+P_{rolling}+P_{gravity}$. And, the battery power required is equal to the power provided by the solar array(s) subtracted from the total necessary power:
$P_{battery} = (P_{drag}+P_{rolling}+P_{gravity}) - P_{array}$ .

As far as the variances to the reference configuration that test the operating limits, the following operating states were considered, as shown in Table 3 [14]:

Table 3. Operating States (RC=Reference Configuration)

| | | | | | |
|---|---|---|---|---|---|
| State no. | 1 | 2 | 3 | 4 | 5 |
| Entity varied | $C_dA_{d,t}$=100% of RC | $C_dA_{d,t}$=200% of RC | $C_dA_{d,t}$=300% of RC | 0.2% slope | 2% slope |
| State no. | 6 | 7 | 8 | 9 | |
| Entity varied | 4% slope | $C_{rr,t}$=100% of RC | $C_{rr,t}$=200% of RC | $C_{rr,t}$=300% of RC | |

Three of the nine operating states represent the baseline similar to the reference configuration.

The average battery power for the nine operating states was calculated for seven traveling speeds: 25, 40, 50, 60, 70, 80 and 90km/h [14]. The results are plotted in Fig. 2. Shaded regions represent states where battery power is needed.

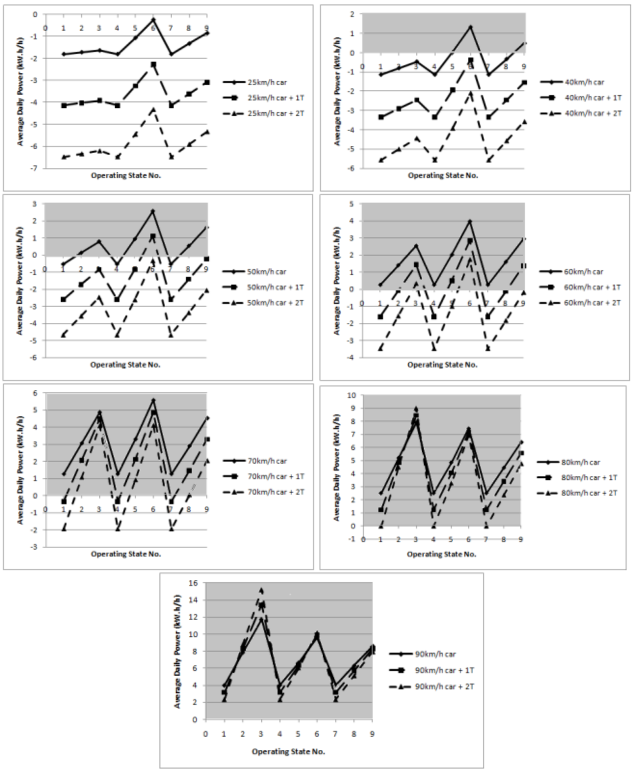



Fig. 2 Average battery power for a car, a car with one trailer and, a car with two trailers versus the nine operating states at the seven speeds of 25, 40, 50, 60, 70, 80 and 90km/h and 40% efficiency solar array-trailer

As shown in Fig. 2:

a) A **solar-battery car without trailers** needs no battery power at 25km/h for all states. With the speed reaching 60km/h, battery power is needed for all operating states.

b) For a **car with one solar-trailer**, battery power is needed at 50km/h for state 6 and all states at 80km/h.

c) On the other hand, for a **car with two solar-trailers**, it is not until 60km/h that battery power is needed for state 6 and all states at 90km/h.

## III. SIMULATING DRIVES ACROSS THE AUSTRALIAN CONTINENT AT CONSTANT SPEED

In this section, two drives across the continent of Australia are simulated [14]. Each drive is for 3000km from Darwin in the North to Adelaide in the South, along Stuart Highway/Highway 1. The results of the simulations are summarized for:

A. Drive of a Solar-Battery car of Type I.

B. Drive of a Super-size Solar-Battery car of type II.

### A. Drive of a Solar-Battery car of Type I.

The performance of a solar-battery car of type I was previously reported for a 20% solar-array efficiency [14]. In this section, the simulations are repeated for a solar array efficiency of 40% that account for:

- The monthly high/mean/low of daily solar energy based on meteorological data for all years. These were used to determine the factors to be applied to the extraterrestrial radiation to account for absorption, scattering and varying cloudy weather conditions [14,17].
- The changes in latitude and longitude of the location which are taken into consideration in the solar energy calculations.

The cumulative energies for the drive starting at the “typical” day of each month are plotted in figs. 3a-c for a car, and a car with two trailers. Three speeds were used: 40, 50 and 60 km/h.

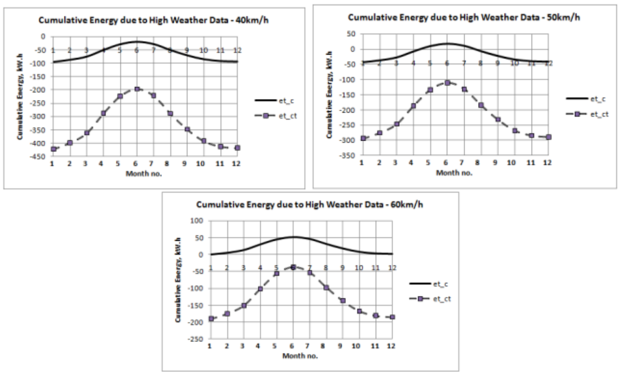



Fig. 3a Variation of the cumulative energy with the month of the year for a car and a car with two trailers for the speeds of: 40, 50, and 60km/h – High weather data – 40% solar efficiency

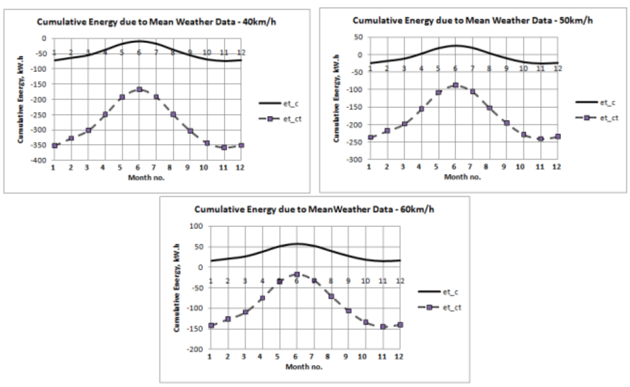


Fig. 3b Variation of the cumulative energy with the month of the year for a car and a car with two trailers for the speeds of: 40, 50, and 60km/h – Mean weather data – 40% solar efficiency

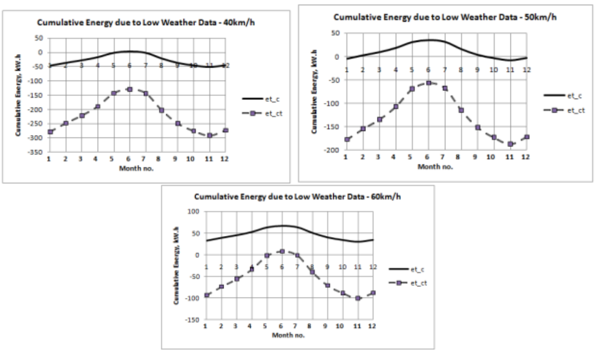


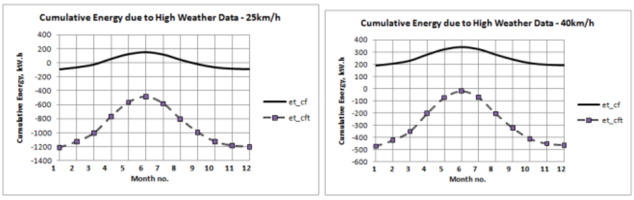

Fig. 3c Variation of the cumulative energy with the month of the year for a car and a car with two trailers for the speeds of: 40, 50, and 60km/h – Low weather data – 40% solar efficiency

At higher solar energy levels, a car would use no battery power at 40km/h, limited battery power at 50km/h, and, increased dependence on battery at 60km/h. For a car with two trailers, significant saving in energy is observed throughout the year.
At medium solar energy levels, a car has the same pattern of behavior as for high solar energy levels, with increased battery usage. For a car with two trailers, savings on energy are still seen.
At low solar energy levels, a car uses limited battery power at 40km/h and shifts to battery usage throughout the year at 60km/h. For a car with two-trailers, no battery power usage at 40km/h with limited battery usage at 60km/h for the month of June. Thus, at 40% solar array efficiency and medium solar energy levels, a car with trailers uses no battery power even at 60km/h.

## B. Drive of a Super-size Solar-Battery car

Since the ultimate goal is to be able to drive full-size cars with solar energy, the above calculations were performed for a super-size car of type II. The monthly high/mean/low of daily solar energy, for all years, were used to determine the factors to be applied to the extraterrestrial radiation to account for absorption, scattering and varying cloudy weather conditions.

The cumulative energies for the "typical" day of each month are plotted in figs. 4a-c for a car, and a car with two trailers at 40% solar array efficiency and in fig. 4d for 20% solar array efficiency. Four speeds were used: 25, 40, 50 and 60 km/h.



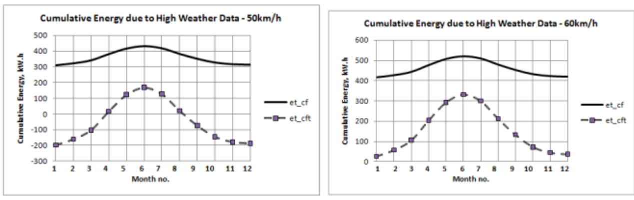



Fig. 4a Variation of the cumulative energy with the month of the year for a Super-size car and a Super-size car with two super-trailers for the speeds of: 25, 40, 50, and 60km/h – High weather data – **40% solar array efficiency**

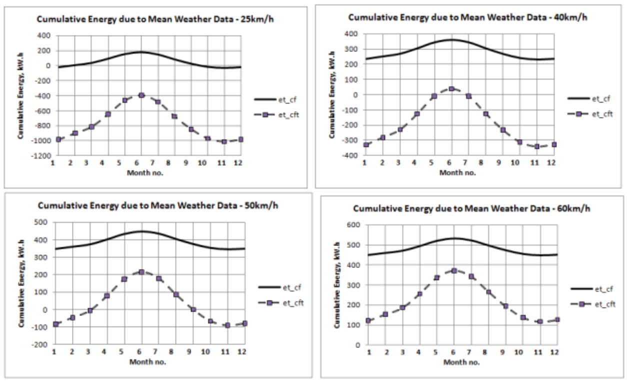



Fig. 4b Variation of the cumulative energy with the month of the year for a Super-size car and a Super-size car with two super-trailers for the speeds of: 25, 40, 50, and 60km/h – Mean weather data – **40% solar array efficiency**

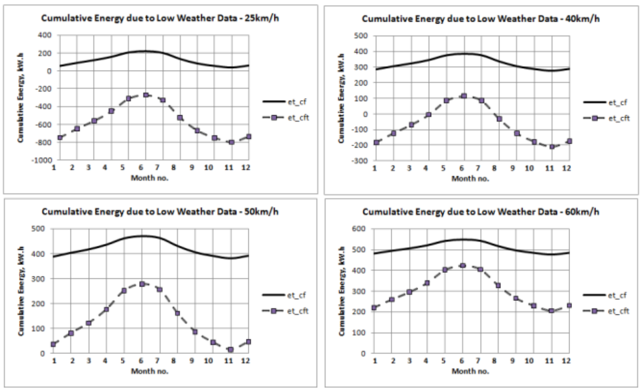



Fig. 4c Variation of the cumulative energy with the month of the year for a Super-size car and a Super-size car with two super-trailers for the speeds of: 25, 40, 50, and 60km/h – Low weather data – **40% solar array efficiency**

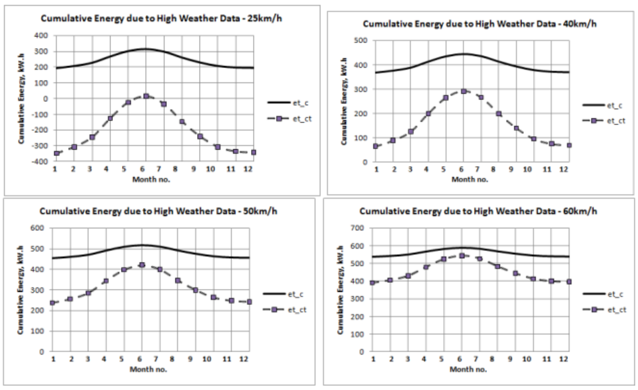



Fig. 4d Variation of the cumulative energy with the month of the year for a Super-size car and a Super-size car with two super-trailers for the speeds of: 25, 40, 50, and 60km/h – High weather data – **20% solar array efficiency**

The battery usage throughout the year is summarized in Tables 4-6.

Table 4 Battery usage during the year with high solar energy levels

| 40% cell efficiency | 25km/h | 40km/h | 50km/h | 60km/h |
|---|---|---|---|---|
| Car type II | Months 4-8 | All year | All year | All year |
| Car+2T TypeII | Large savings | No usage | Months 4-8 | All year |
| 20% cell efficiency | 25km/h | 40km/h | 50km/h | 60km/h |
| Car type II | All year | All year | All year | All year |
| Car+2T TypeII | June | All year | All year | All year |

Table 5 Battery usage during the year with medium solar energy levels

| 40% cell efficiency | 25km/h | 40km/h | 50km/h | 60km/h |
|---|---|---|---|---|
| Car type II | Months 2-9 | All year | All year | All year |
| Car+2T TypeII | Savings | June | Months 4-8 | All year |

Table 6 Battery usage during the year with low solar energy levels

| 40% cell efficiency | 25km/h | 40km/h | 50km/h | 60km/h |
|---|---|---|---|---|
| Car type II | All year | All year | All year | All year |
| Car+2T Type II | Savings | Months 5-7 | All year | All year |

As shown in Table 4, at high solar energy levels with 40% solar array efficiency, driving is possible all year at a speed of 40km/h with no battery usage when two trailers are used. The speed will have to be reduced to 25km/h for 20% efficiency solar arrays.

## IV. CONCLUSIONS

This paper looked at the implications of using ultra-efficient solar arrays (40% efficiency) in the design of self-powered solar-battery cars with/without solar array-trailers. First, the influencing parameters such as drag area coefficient, rolling resistance and ground slope, were varied to determine the operating boundaries of the system. A car with two solar array-trailers needs no battery power for any of the operating states till 60km/h at 40% solar array efficiency.

Second, a 3000km drive through the Australian continent was simulated for 500kg and 2100kg cars, types I and II, respectively. The battery power usage was determined for high/medium/low weather conditions throughout the year. A 500kg car with two solar trailers uses no battery power even at 60km/h with 40% solar array efficiency under mean solar energy conditions. A 2100kg car with two solar trailers driven at 40km/h under high solar energy levels and 40% solar array efficiency requires no battery usage compared to 25km/h at 20% solar array efficiency.

## APPENDIX

### I. Efficiencies of solar cells

A relevant partial list of efficiencies of solar cells is included in Table 7 as reported by the National Research Energy Laboratory [15] with discussions in [16].

Table 7 Efficiencies of Solar Cells

| Cell Type | Efficiency, % |
|---|---|
| Silicon Monocrystalline | 25 |
| Single-Junction GaAs: | |
| Single crystal | 27.5 |
| Thin-film crystal | 28.8 |
| Multi-junction Cells | |
| Three-junction (Sharp) | 37.9 |
| Four-junction (Boeing) | 38.8 |

Table 8 Nomenclature for the Car-Trailer system

| | |
|---|---|
| $AC_d$ | Drag Area coefficient ($m^2$). |
| $C_{rr}$ | Rolling resistance coefficient of the car. |
| $C_{rrt}$ | Rolling resistance coefficient of the Trailer. |
| $P_{battery}/P_{drag}/P_{rolling}/P_{gravity}/P_{array}$ | Power required by the battery; Power due to drag, rolling, gravity; Power produced by the solar array (W), respectively. |
| 1T, 2T | One and two trailers, respectively. |
| et_c, et_ct | Cumulative energies of a car, and a car with two trailers, respectively. |
| et_cf,et_cft | Cumulative energies of a Super-size car, and a Super-size car with two trailers, respectively |

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