

PHOTOVOLTAIC APPLICATIONS FOR ELECTRIC VEHICLES

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ABSTRACT

This paper describes current solar car technology, rules and strategies for the major racing events, and plans for GM Sunrayce USA, a university competition of solar-powered cars scheduled for July, 1990. The paper also describes plans by the Department of Energy to investigate the technical requirements and economic viability of solar-assisted commuter cars.

1. INTRODUCTION

A solar race car is a lightweight, aerodynamically efficient electric vehicle that generates its own power from sunlight. Its reliance upon renewable energy results in a completely self-sufficient, non-polluting race car.

The electric propulsion system in a solar car is not new. The first electric car was built in 1838, and until the 1930's there were more electric cars on the road than gasoline cars. What is new is the use of photovoltaic solar cells to convert sunlight directly into electricity instead of depending solely on batteries. This enables the car to be driven continuously during daylight hours without having to refuel. Batteries are only used to accelerate and travel at higher speeds when necessary.

2. ENVIRONMENTAL IMPACT

It is becoming more and more evident that fuel consumption for transportation has an ever increasing effect on the environment and the economy. In the U.S., transportation sources are responsible for 69 percent of lead, 70 percent of carbon monoxide, 45 percent of nitrous oxides and 35 percent of the reactive hydrocarbons released into the air. Furthermore, cars and light trucks are the largest single contributing sector to CO₂ buildup, responsible for 33 percent of all emissions. This is caused by burning over eight million barrels of oil daily, which has also caused increases in U.S. oil imports and our nation's trade deficit.

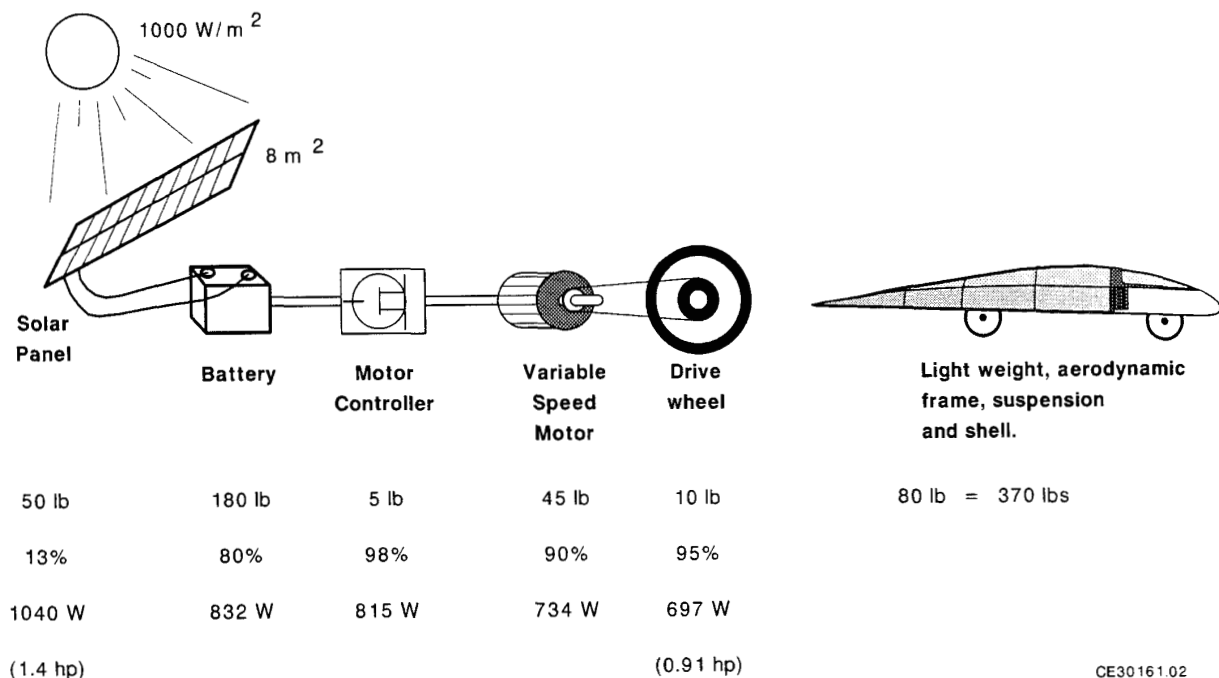
The statistics describing automobile use are staggering. Three hundred million cars in the world, consuming billions of barrels of oil, costing billions of dollars, travelling trillions of miles each year. Even more alarming is the fact that vehicle miles driven (VMD) in the United States is constantly on the rise. This is a trend seen throughout the world as well.

Solar energy and electric vehicle development are important components in the portfolio of energy and transportation technologies that can help achieve national environmental objectives. Solar energy is clean energy that can play a vital role in supplying energy for our homes, businesses and utilities. Electric vehicles are pollution-free during operation which, if used for urban commuting, have the potential to significantly reduce city smog. Replacing gasoline powered cars with electric cars would remove emissions from street level and, in most cases, from the urban area. That means the highest concentration of emissions would be removed from locations where most people breathe.

3. SOLAR RACE CAR TECHNOLOGY

A cross-country road rallye featuring photovoltaic-powered electric race cars is an exciting sporting event. Recent improvements in solar cell efficiency, light weight aerodynamic body design, and control electronics provide solar cars with surprising performance characteristics. They can maintain speeds of 40 mph using just solar energy and over 70 mph with battery auxiliary.

The propulsion system in a solar car is made up of four basic components. Solar cells convert sunlight directly into electricity. The electricity is used to power a variable-speed electric motor with direct drive to the wheels. Batteries allow the car to accelerate and travel at higher speeds when necessary. Electronics are used to maximize electrical power transfer between the solar cells, battery and motor.



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The best solar race cars today weigh between 350 and 400 pounds, and they are built from the ground up. Each component is selected for its lightweight strength, compactness, efficiency, reliability and speed. The figure above illustrates the approximate weights, conversion efficiencies, and energy consumption of the various components. Essentially, the amount of energy these cars have to work with is one horsepower.

4. SUNRAYCER

The most well-known solar car is the SUNRAYCER designed by AeroVironment, Inc. for General Motors Corporation (GM). It was entered in the Australian World Solar Challenge in 1987 and won easily. The World Solar Challenge is a 1900 mile north-to-south transcontinental race of solar vehicles from Darwin to Adelaide. The next race is scheduled to start November 11, 1990.

GM SUNRAYCER was donated to the Smithsonian Institution's National Museum of American History in Washington, D.C., on September 28, 1989. It is on display in the museum's Transportation Hall. The car leaves behind several solar-powered world-speed records that still stand: 48.7 mph with no batteries, 75.3 mph averaged over ten miles with solar plus batteries.

The SUNRAYCER used 8800 solar cells in its eight square meter panel. Twenty

percent of the panel area was comprised of 16.5% efficient single-crystal silicon cells. The remaining eighty percent of the area contained 20% efficient gallium arsenide cells. In the best sunny conditions in Australia, the array delivered 1,550 watts. The entire solar panel was separated into twelve smaller arrays that were connected to the battery by peak power trackers that maximize the output power. The battery powered the motor through an inverter that generated three-phase AC power. The inverter allowed control based on constant current, constant speed (rpm), or constant torque. Its efficiency was 97 percent.

Silver zinc batteries that weighed 60 pounds and could store three kilowatt hours were used. This is the electrical equivalent of a lead-acid battery weighing four times as much. The car's Magnequench electric motor weighed 11 pounds and could continuously deliver four horsepower.

SUNRAYCER weighed 390 pounds without a driver. The frame and chassis were constructed out of aluminum tubing. The body's exterior was made of a Kevlar-Nomex-Kevlar sandwich. The aerodynamic design resulted in a very low drag coefficient that was measured at .125 in the GM wind tunnel. SUNRAYCER expended 1.84 horsepower to overcome the drag. A conventional car expends 9.52 horsepower.

After winning the World Solar Challenge race, the SUNRAYCER began an international

tour and was featured at more than 160 events. Recognizing the tremendous public interest and excitement SUNRAYCER generated, GM created an educational program for elementary and secondary students based on SUNRAYCER's technology. Today, that educational program has expanded to involve college science and engineering students. Thirty-two universities are building solar cars to compete in a cross-country race called GM Sunrayce USA.

5. GM SUNRAYCE USA

The Department of Energy (DOE) and the Society of Automotive Engineers (SAE) have joined General Motors Corporation in creating GM Sunrayce USA. The Rayce is dedicated to the educational development of university science and engineering students throughout North America. GM Sunrayce USA will be a south-to-north, transcontinental race held in early July, 1990. It will run approximately 1800 miles from Orlando, Florida to Detroit, Michigan. Sunrayce will be staged over nine days with stops along the way in different towns and cities. All entrants are North American university teams. Two schools from Canada and one from Puerto Rico are included.

Invitations to submit solar race car proposals were sent to universities and colleges across North America in December, 1988. The proposal request required university teams to describe how they would: organize and raise funds; select the vehicle concept; undertake engineering tasks; obtain components; build the vehicle; perform evaluation, reliability, and durability testing; select and train drivers; and plan a strategy for the nine day race. Sixty-one proposals were received. In March, 1989, thirty-two were chosen. Each of the selected teams received \$7000 (\$5000 from GM and \$2000 from DOE) to help get their projects underway.

The list of universities, colleges, and two-year schools is impressive. Their participation promises to make an exciting event. GM has also offered a very desirable prize for the first, second, and third place finishers. It will send the top three teams to participate in the 1990 Australian World Solar Challenge, all expenses paid.

Basic race rules are similar to the Australian World Solar Challenge. Sunlight is the only source of power allowed for the race cars. Each vehicle's solar array may not exceed four meters long by two meters wide by 1.6 meters high. (essentially 8m²) Battery power is limited to 5 kWhr.

The race objective is to design and build a car from the ground up, with the capability to collect and convert more sunlight than the next cars, and then use that energy as effectively as possible to win the race. Efficiency plays an important role because sunlight availability can change rapidly. A winning strategy is often based on the successful prediction of the next day's weather which adds to the excitement and skill required in the race. A solar race is more an intellectual mastery of nature and technology than a race of raw horsepower.

GM Sunrayce USA is a two-year program for universities that actually culminates with the running of the race. Hours of classroom instruction and homework are spent before final designs and engineering trade-offs are completed. Courses are designed around the Sunrayce project, and many seniors who participate use some aspect of Sunrayce for their senior projects.

The competitive nature of building a solar race car and the motivation created by its relationship to national concerns, provides an exceptional learning experience. Sunrayce is providing hundreds of students the chance to challenge the future "hands-on" and to display their efforts to the world.

The creators of Sunrayce are an exceptional group of people brought together by the common desire to challenge and expand human knowledge. GM Sunrayce USA, and the Sunraycer that inspired its creation, will always stand as symbols that our nation is still in the forefront of innovative thinking.

6. 1989 SWISS TOUR DE SOL

The Swiss Tour de Sol is the oldest and largest solar racing event. It has been held in Switzerland each year since 1984. Its purpose is to promote the use of solar energy and solar-powered electric vehicles, with emphasis on the promotion of solar electric vehicles for "everyday use." In essence, the Tour de Sol is a moving car show. The event is staged over a seven day period, with stops along the way in different towns and cities. This allows the public time to view the race, get a closer look at the cars, and meet the drivers. People can also talk to company representatives to purchase cars that are available for sale. There are currently at least six companies that sell photovoltaic-assisted electric automobiles in Europe.

There were four race categories in the 1989 Tour de Sol:

1. Solar Race Cars
2. Electric Cars that Recharge on PV
3. Electric Cars that Recharge on Utility
4. Commercial Production Solar Cars

Number of Entrants:

Category

- | | |
|----|----------------|
| 1. | 13 cars |
| 2. | 19 cars |
| 3. | 30 cars |
| 4. | 15 cars |
| | <u>77 cars</u> |

Category 1: Solar Race Cars. These are very lightweight, aerodynamic, one-passenger vehicles (approximately 450-500 lbs with driver). Their only source of power is through solar photovoltaic (PV) electricity generation. The PV panels have to be mounted on the car and their peak power is limited to 480 watts. Maximum battery capacity is limited to 4.8 kWhr.

Category 2: PV Powered Commuter Cars. These are small, typically two-passenger prototype cars, but some could carry up to four passengers. This category also could only recharge on solar energy. Most had PV panels ranging from 100 to 250 watts mounted on their roofs and hood. In addition, they would recharge from a portable array before and at the end of each driving period. The total power of the array could not exceed 480 watts (same as category 1) for the driver, with an additional 240 watts allowed for each additional passenger up to 960 watts, or three people. Maximum battery capacity is 7.2 kWhr for one passenger, 10.8 kWhr for two passengers, and 14.4 kWhr for three passengers. The passengers had to ride in the cars if larger arrays and battery capacities were used.

Category 3: PV-Assisted Commuter Cars that could Utility Recharge. This category of vehicles is physically the same as Category 2. The difference is that instead of transporting a portable array to recharge they could use a utility outlet. However, the amount of power is rationed and measured. Each night a set amount of electricity could be used for recharging. That energy was the equivalent of the amount which a Category 2 solar vehicle was able to charge on that particular day of the race.

Category 4: Commercial Production Cars. This category is the same as category 3. It is a new category this year for commercial companies that have solar commuter cars for sale. The requirement is that each company have already produced at least 15 automobiles.

The objective of the Tour de Sol is to see who can drive the prescribed route in the shortest time using only solar energy. Each day an approximate 40-mile route had to be navigated. The rules state that a minimum time will be given for each day's specified route based on the speed limits over the course to discourage speeding. For example, if there are 20 miles of 60mph zones and 20 miles of 30mph zones, one hour would be the minimum time given. (20 times one minute per mile, plus 20 times two minutes per mile.) At the end of each segment there are optional "laps" that can be driven which, on some days, extend the total miles driven up to 70-80 miles. The extra laps provide a way to let the most efficient cars out-perform the less efficient cars by driving farther. It also provides more "race" for the public to watch. The extra laps typically are run around and through the final city in which that day's segment ends. Hundreds of people line the streets and watch as the solar cars drive extra laps, typically for about an hour.

The 1989 Tour de Sol was well organized. There were no accidents or major problems. The race made headline news all across Switzerland and enticed thousands of people to come and watch. As a vehicle demonstration, the event was impressive. The speeds and range attained by the vehicles adequately demonstrated their viability. The event was an exciting demonstration of the potential of solar energy and "clean car" technology.

7. FUTURE PV APPLICATIONS FOR ELECTRIC PASSENGER VEHICLES

Applying solar race car technology to electric passenger cars is a logical extension. The DOE has initiated a study to investigate the technical requirements and economic viability of this application.

The potential benefits of mounting photovoltaic panels on an electric vehicle include increased range, reduced recharge frequency, and reduced operating expense. The range benefit is variable in that it applies only to daytime driving and varies with weather and season. The two main components of operating expense impacted by PV are energy and battery replacement costs. It is anticipated that battery replacement cost may dominate because battery depreciation is generally more than three times the energy cost, and cycle life improves rapidly as depth of

discharge is diminished. Therefore, the impact of PV on energy cost and battery depreciation are key items of the study. In order to quantitatively assess the impact of PV on electric vehicle range, energy use, and battery depreciation, several models are mathematically coupled. These models include:

- Solar Insolation and Temperature Model. This model provides an average measure of solar insolation and ambient temperature versus time of day, time of year and geographical location.
- Solar Cell Model. This model provides a measure of solar cell efficiency versus insolation and temperature.
- Power Conversion Model. This model deals with the power conversion and control circuitry which interface between the PV array and the battery bus. The model provides efficiency versus power and includes power tracking losses.
- Vehicle Energy Use Model. This model provides two measures of vehicle energy use: one includes the battery cycle efficiency and one does not. Cost of electrical energy for different locations will also be provided here.
- Battery Life and Cost Model. This model provides an estimate of battery life and cost by modeling degradations in internal resistance and capacity as a function of: battery type, calendar age, and cycle number and cycle depth.
- Vehicle Use Pattern Model. This model describes expected use patterns such as average miles driven per day. Also included are expected parking patterns (i.e. times when the vehicle is expected to be in sunlight or shade).

Using the models as inputs, a computer algorithm will be generated which will provide vehicle range, required recharge frequency, and initial operating and net costs as outputs. This will be done on a worst-case/best-case basis. A first order sensitivity analysis will be included so that the impact of individual parameters may be assessed. From this, a set of necessary combinations of parameters and conditions which warrant PV additions to electric vehicles will be identified. The study is scheduled to be completed in July, 1990.

9. FURTHER INFORMATION

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