# STEV1: Solar Thermal Electric Vehicle – A new vehicle concept based on Ideal Final Result

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## Abstract

This paper gives an overview of a new concept for using solar thermal energy in vehicles following the concept of Ideal Final Result for overcoming existing mental inertia. The concept is based on very high temperatures reached by concentration of solar energy, Stirling engines, which convert thermal energy into mechanical energy and, finally, energy storage using phase changing materials.

First, a short review of past research is given and the new vehicle structure is described: Solar energy is gathered by Fresnel lens and stored in a thermal tank. Once charged, the tank is placed in the car and connected to a heat exchanger, which transfers thermal energy to the hot side of the Stirling engine. A generator converts the mechanical output of the Stirling engine into electric energy for being used in hybrid vehicles.

This way 100% renewable energy is used, which may be obtained everywhere solar radiation, is available. This concept releases the vehicles from dependency on oil. Vehicles work without contaminating exhausts and make less noise than conventional cars with internal combustion engines. Using a serial hybrid configuration, the Stirling engine can always work on its best operation point and a smaller engine charge the batteries while the car is driven by more potent electric motors.

This technology can be applied to all types of vehicles, from small cars to trucks or trains. First simulations are used to forecast the power of the engine and sizes of the energy storages.

## 1. Introduction

Year by year people all around the globe spend 340*1018J with an upward trend [1]. The energy generation based on finite resources may be replaced by renewable energy. The strongest alternative, with a theoretical potential of 2.500.000*1018J per year, is solar energy. The technical potential, which means the amount of energy that can be obtained with the current technology is 600*1018J per year, more than the world’s total demand [1].

Research and development efforts with the aim of diminishing pollution and meeting environmental standards are creating new technologies and products, like photovoltaic cells, solar furnaces and solar water-heating systems. However, there is still potential in new application areas, such as acclimatization of buildings, electric energy generation and transportation.

In this paper a new concept for using solar energy in vehicles is presented that has been created based on TRIZ, especially following the Ideal Final Result concept for breaking mental inertia. It is based on Stirling engines which convert thermal energy into mechanical energy, Fresnel lens with passive tracking for gathering solar thermal energy, and thermal energy storage, based on phase change materials (PCM) that can accumulate large quantities of thermal energy. These basic components and concepts will be described in this paper and, a case study will also be presented.

In 1971, the Department of Energy (DOE) started a research program on the use of Stirling engines in vehicles. Together with other institutions and enterprises, such as NASA, General Motors and Stirling Thermal Motors Inc., to mention the most important, it achieved construction of several prototypes with gasoline fuel tanks, Stirling engines and direct power transmission between the engine and the wheels. Technical reports [2, 3] show that these cars had properties similar to those of conventional cars of that time. However, the concepts displayed important disadvantages, as Stirling engines are not appropriate for use in the same way as internal combustion engines (ICE) to directly drive mechanical energy to the wheels.

The last prototype built was a ’95 Chevrolet Lumina, which was a hybrid vehicle with a Stirling Thermal Motors Inc. (STM) Stirling engine, driving a generator in a serial hybrid configuration. The prototype did achieve its emission target, demonstrating ultralow-emission. However, it failed to meet several key requirements: specific shortcomings included lower-than-expected thermal efficiency, high heat rejection requirements, poor specific power, and excessive hydrogen leakage [4]. For these reasons and, additionally, the falling oil prices at the end of the Near-East crisis, there was no further development of this concept. To this day, the DOE has not continued the research.

Today, more than a decade later, things have changed. Fuel prices have continued to rise. New technology allows the use of new materials with better characteristics, at lower prices. Technical solutions, not feasible ten or twenty years ago, are becoming viable today.

There are several electric and hybrid vehicles available on the market, many of their components have entered into mass production and especially in electric energy storage systems enormous improvements have been made. Batteries have become cheaper, smaller and lighter. There are several electric and hybrid vehicles available on the market. Many of their components are being mass produced, especially electric energy storage systems, in which great strides have been made.

An additional important factor that drives the development of new concept vehicles using alternative energy is that societies are becoming more conscious of the need to protect the environment, and people are willing to spend extra money when they can buy a product that does not contaminate. Governments have recognized the need for renewable energy technology and offer special programs to support acquisition of nonpolluting technology.

## 2. Fundamentals

There are three basic types of hybrid vehicles: parallel, serial and mixed engine configurations. For the proposed vehicle concept, the serial hybrid configuration has been chosen (Fig. 1):

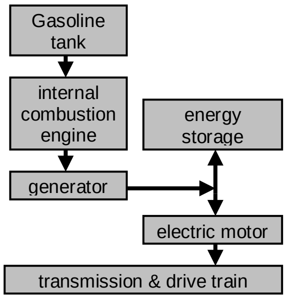

**Figure 1. Serial hybrid configuration**

In serial hybrids, the drive wheels are driven entirely by electric motors, with electrical energy supplied by another, different engine that is connected to an electric generator. The battery, as an energy buffer, permits the complete decoupling of the engine/generator combination from the drive. In this way, the electricity generation is set independently of the actual momentary driving demands and can be optimized for maximum efficiency or lowest contamination possible. Brake energy can be re-used [5].

Thus, the engine/generator-combination must be powerful enough to satisfy at least the vehicle's average energy consumption. Electric motors must meet all the requirements for maximum acceleration and hill climbing with a fully loaded car.

In the present paper, the use of Stirling engines and thermal energy storage in hybrid vehicles is proposed, as serial hybrid configuration. The Stirling engine has no direct connection to the driven wheels, so that Stirling engine disadvantages, such as long warm up phase and the retarded change of revolution speed, are eliminated. Other benefits of serial hybrid configuration can be adopted. One of them is a concept called Vehicle to Grid [6]; the hybrid vehicles are connected to the grid and sell their energy.

The emphasis in approach is to replace the ICE and the gasoline tank with a Stirling engine and thermal energy storage. The focus is energy supply, storage and transformation, as well as vehicle concepts for different types of use.

Fundamental for the new energy concept in this serial hybrid are four components that replace the ICE gasoline tank and infrastructure. They are described in the next paragraphs.

As shown in Figure 2, gasoline, the current energy source in vehicles, has very high specific energy and energy density; it allows lightweight vehicles with ranges above 1000km. Figure 2 presents values of gasoline and phase change materials without a storage device; hydrogen and batteries include the storage device.

Alternatives to gasoline must be competitive not just in price, size and weight, but also in handling and security. Current electric batteries are too heavy, expensive and do not last long enough and must be replaced before the calculated lifetime of a car expires. Hydrogen is quite acceptable in size and weight, but it uses too much energy to generate hydrogen, its storage is complicated and its productions costs are excessive.

- Thermal Storage Tank

This suggests a new approach, solar thermal energy storage: PCMs are heated by solar radiation and stored in an isolated device. Tecnológico de Monterrey is working on several technologies (see example [11]) to reach a small, light, low-cost isolation, using a combination of different insulation materials and vacuum. The amount of stored energy depends on temperature and materials. First prototypes will use molten salt, sodium chloride (NaCl) or a material mix based on silicon dioxide (Si02) in a temperature range between of 800°C to 1300°C.

Future work will be focused on tanks at very high temperatures, based on W. Foppe´s patent [10] that describes a thermal energy storage device using boron nitride at 2400°C. As can be observed in Figure 2, this material can store more energy per liter than gasoline.

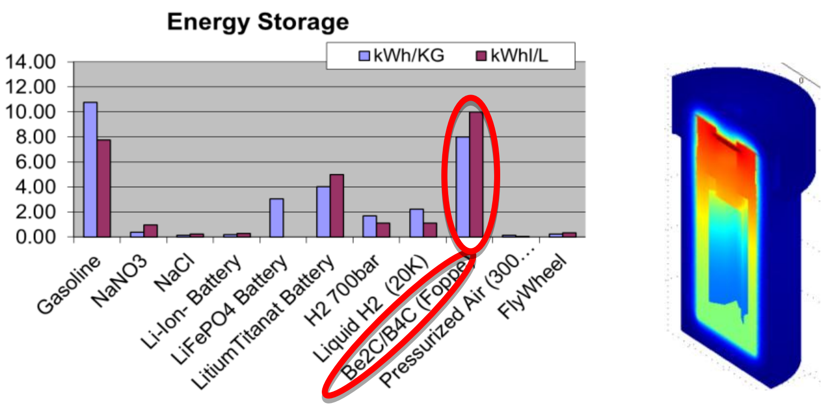


**Figure 2. Thermal Energy Storage: specific energy, energy density [7-10] and thermal tank**

- Passive Tracking Enhanced Solar Concentrator Device, Performed by Fresnel Lens

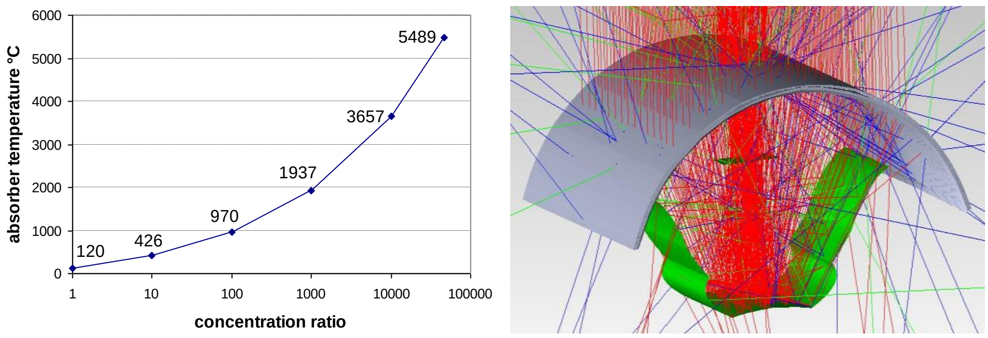


**Figure 3. Concentration of solar radiation [1] using Fresnel lens with passive tracking [12]**

To achieve the required high temperatures for solar energy, it is necessary to concentrate the radiation (Figure 3). Current technology uses active tracking to follow the sun's trajectory. Our Ideal Final Result approach is to eliminate the need for moving parts by creating a Fresnel lens that projects and concentrates solar radiation always to a defined point, independent of solar altitude [12]. Figure 3 demonstrates one of the possible designs. One benefit of this design is a lightweight structure without any moving parts that can be easily positioned where required.

- Heat exchanger

To connect the thermal energy storage to a Stirling engine a heat exchanger is used. Besides heat transfer and isolation to surrounding parts, it also has a valve to regulate the amount of transferred energy [13]. At Tecnológico de Monterrey variants of heat exchangers are being researched, based on solid materials that transmit the thermal energy by conduction. Another alternative that is being analyzed is the use of high temperature heat pipes.

- Stirling engine or any other device to convert heat energy into mechanical energy

In the STEV1 a Stirling engine replaces the ICE in the serial hybrid configuration. Depending on the vehicle's size and operation, there are several possible engines on the market.

At the same time, mainly for reasons of product availability and cost, Tecnológico de Monterrey is also doing research in other concepts that convert heat into electricity. In the patent application [14] an engine is presented which contains the advantages of Stirling and Brayton cycles. A Brayton engine is basically composed of a compressor, a combustor and a turbine. Well-known applications of the Brayton technology are turbines in jet airplanes. They consist of an open cycle, and the gas used in the engine, typically air, is renewed at the beginning of every new cycle.

Like the Stirling engine, an engine based on the Brayton cycle can be driven by many heat sources, such as waste heat and solar thermal energy, among others.

Moreno in [15] describes the invention process using TRIZ for a new design. The Brayton engine is changed into a closed cycle, and the proposed cycle follows the same phase diagram pattern that the Brayton cycle does, but the heat is applied externally just the way it is applied to a Stirling engine ( see Figure 4).

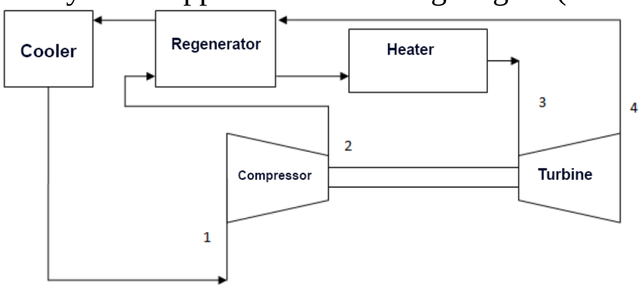


**Figure 4. Closed Brayton Cycle Engine**

In contrast to a Stirling engine, in the closed Brayton cycle the gas flows only in one direction, a steady-state process, which means that the temperature, pressure and volume in each section remain constant. This engine works with temperature difference between heater and cooler. It has a continuous movement and with solar energy it is possible to obtain electric energy not only without producing any contamination, but also without fresh air consumption.

- Vehicle concept and possible prototypes

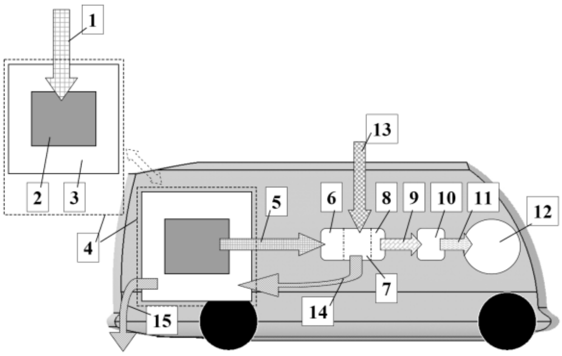


**Figure 5. Vehicle with Stirling Engine and Thermal Energy Storage [16]**

Figure 5 shows the conceptual assembly of STEV1. Concentrated solar energy (1) heats thermal energy storage (2). After being charged with high temperature thermal energy, the thermal storage tank is put in the vehicle and connected by a heat exchanger (5) to a Stirling engine (6-8). With the mechanical energy (9) a generator (10) is driven and creates electric energy (11) for the electric propulsion system (12). (13-15) demonstrate possible waste-heat recovery.

There are two fundamental concepts for new product development: proof of concept and poof of business. The first should demonstrate the function of the proposed concept; it shows the technical feasibility. The second concept goes one step further because it must also prove economic practicality. In this case it should demonstrate that the proposed technology can compete with hybrid vehicles with ICE, and that all the required parts and materials are available at reasonable costs.

The proof of concept being developed is following: an electric golf cart is equipped with a free piston Stirling engine of approximately 1kWe and a thermal energy storage tank. Conventional vehicles of this size have electric engines of about 2 or 3 kW and can transport two to six people. The Stirling engine of Microgen [17] is being acquired for this application.

A proof of business under analysis is following: a conventional car or bus is converted into a prototype, preferably a serial hybrid vehicle, so that only the ICE and the fuel tank must be replaced by the Stirling engine and a thermal tank. One possibility is Stirling Biopower‘s Stirling engine [18].

In these two concepts, there are clear differences not only in the price of the prototypes, but also in the technical expenditure and in the final value of the vehicle. In this case, the value is not so much the amount of money for which the vehicle could be sold, but rather, the impression it makes on the public and the press.

Other proof of business possibilities include:

- A minibus for school transportation, with base stations, in which the solar power is collected
- Vehicles used in a closed system, such as ferries, vehicles on company premises, nature parks, etc., with the background to create with just a few points the infrastructure needed for their operation.

These vehicles must meet higher quality and function standards; they must provide functions similar to those of series vehicles, since they are not only used by trained persons, but also by potential customers.

## 3. Virtual Case Study: Expreso Tec

Tecnológico de Monterrey has a number of shuttles called Expreso Tec and Circuito Tec. There are 12 different routes and the mission is to offer students and employees safe, reliable transportation in a territory covering the most important areas of the city of Monterrey. Two different vehicle types are mainly used: city buses with about 35 seats for routes that cross the city and microbuses for routes covering the area near the campus (Circuito Tec).

The Circuito Tec has been preselected for a first proof of business analysis, in one complete route of about 8.5km and returns to the campus in less than 30 minutes. It does not operate at a steady speed so brake energy recovery applies. Average speed is about 17km/h, and high velocities are not needed. A maximum speed of 80 km/h is fast enough for any situation.

The infrastructure for local solar thermal energy collection can be built on the base, so that the microbus can exchange its tank at the time when it is needed.

A market analysis shows that the Toyota Coaster Hybrid EV [19] is one of the vehicles which can be adapted to the thermal energy storage with comparatively little work. In 1997 this serial hybrid vehicle, designed for 21 to 25 passengers, entered the

Japanese market; it was also sold in a few other countries. The benefits of this vehicle are that it already has the complete electric system, including 5,28kWh electric energy storage and a 70kW electric propulsion motor. The 36kW internal combustion engine, the 25kW generator and the gasoline tank have to be replaced to adapt it to the new proposed concept.

Several interactions with possible suppliers showed that there are realistic possibilities to obtain 25kW Stirling engines.

- Simulation

AVL ADVISOR [20] is a Matlab-based program for simulating all kinds of vehicles. As input, all vehicle properties are defined, as well as velocity profile, road properties and environmental conditions.

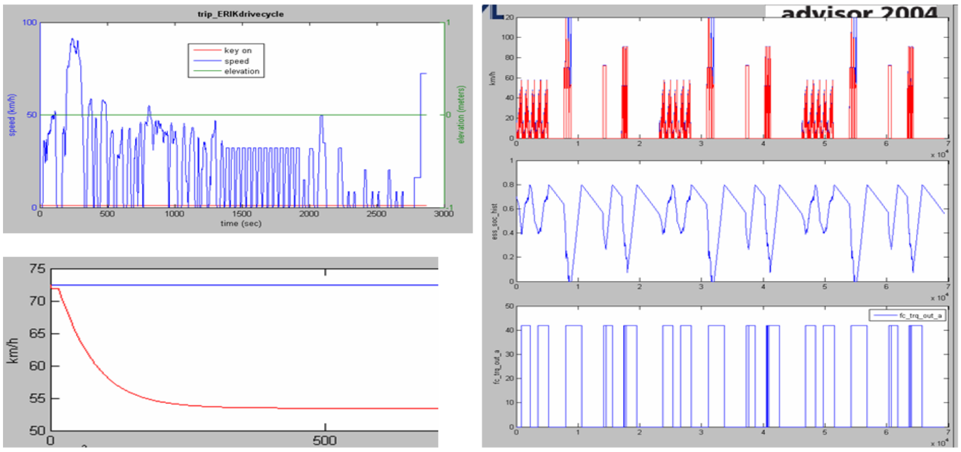


**Figure 6. Simulation of a serial hybrid Microbus: 4t, 25kW ICE engine, 90kW electric motor**

Figure 6 shows the results of a simulation with a serial hybrid microbus similar to the Toyota Coaster Hybrid without brake energy recovery. The aim is to discover the capacity of several component configurations, especially in sizing the Stirling engine and the electric energy storage system for optimizing size and weight. Figure 6 shows on the lower left hand side the vehicle’s behavior when set to a steady velocity. First, when the batteries are charged 80%, it runs at up to 72km/h, but the generator does not provide sufficient energy to maintain this speed. Later, when the batteries are completely discharged, the maximum speed is less than 55 km/h. On the right hand side of Figure 6, a simulation of various velocities is shown; low speed stop-and-go, peaks of high speed and steady speed are calculated. The first graph (red lines) is the velocity profile. It should be mentioned that the vehicle meets the expectations in nearly all points; it runs out of energy only at high speed, as can be seen in the second graph, which shows the state of charge of the electric batteries. The last graph indicates when the ICE is turned on.

The next step in these simulations will be to replace the ICE with a Stirling engine [21] and to add a regenerative braking model [22]. When this is done, basic configuration of the hybrid vehicle, such as engine sizes and amount of energy stored, can be determined in the simulation. Velocity and elevation profiles have been measured in Expreso Tec by GPS and later were converted into a table for ADVISOR.

## Conclusion

The research to date shows that the Ideal Final Result concept of TRIZ combined with updated research leads to new concepts worth developing, since this approach guides us to new, better products. A new kind of vehicle, using renewable, non-polluting energy, on a competitive basis with gasoline powered cars, is conceivable. Nevertheless, there are still many challenges, of which one of the biggest is safety. Especially in a mobile application, all components, including the thermal energy storage, must be failure-proof, even in the case of accidents.

Future work will involve developing improvements and adaptations of existing technology to the energy concept presented and its components. Plans call for the construction of several prototypes, beginning with a first thermal tank that works at temperatures of up to 1200°C. In this device PCM will be heated by solar radiation concentrated by Fresnel lens and later connected to a small Stirling engine (output: 1W). This combination will be used for first testing of a serial hybrid configuration.

Looking into the future, we anticipate two general research emphases: on the one hand, low-cost thermal energy collection and storage at a temperature between 800°C and 1200°C, and conversion into electricity. A later challenge is to develop lightweight thermal storage for high temperatures above 2400°C. The first focus will be used for proof of concept, while the second promises a technology able to replace gasoline powered vehicles in various circumstances.

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