SOLAR-HYDROGEN-POWERED VEHICLE

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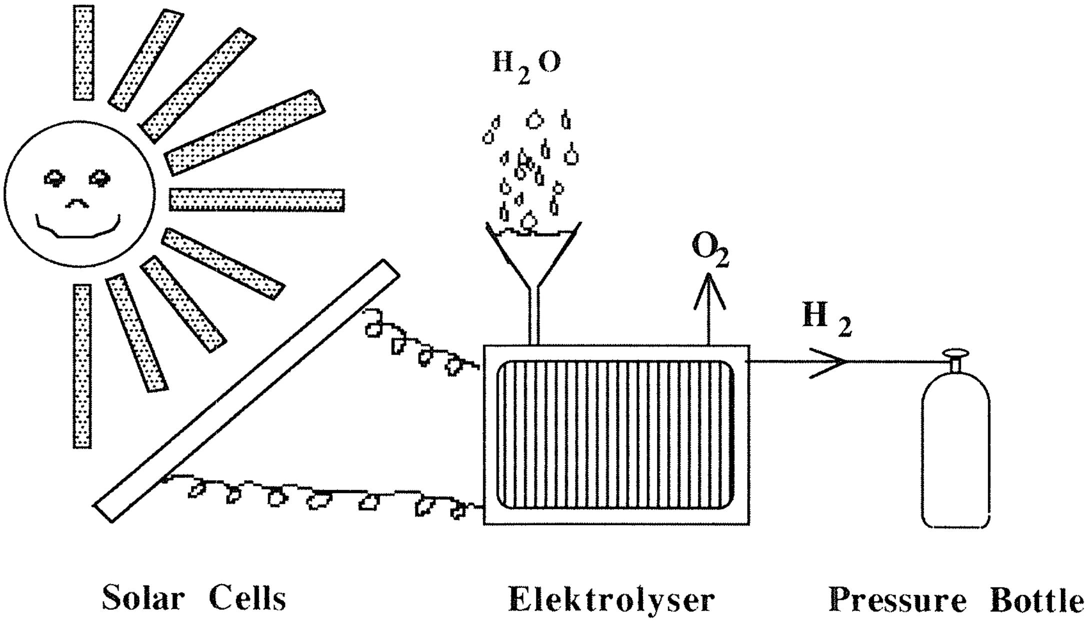
ABSTRACT

The aim of this project was to operate a small vehicle exclusively with solar-produced hydrogen, to make comparisons with similar but purely electrically driven solar vehicles, and to demonstrate the whole system publicly. The chosen procedure was:

Solar cells ⇒ electrolysis under pressure ⇒ storage in pressure vessel ⇒ internal combustion engine ⇒ continuously variable transmission ⇒ wheels. The driving performance turned out to be rather modest compared to that of similar electrical solar-powered vehicles using lead-acid batteries and the efficiency much poorer. In spite of this, the range can be up to twice longer. It is shown that the range could increased by a further factor of 4 if optimised composite pressure vessels are used. It is described how the total efficiency of the system could be improved if a hybrid drive concept is used. The project continues with the development of such a system using a Stirling generator, which will be practically silent and realise very low levels of pollution even if other fuels than hydrogen are used.



INTRODUCTION

Many hydrogen vehicle projects exist and several solar-powered hydrogen-producing plants have by now been completed. Our goal was however to operate a small experimental vehicle exclusively with hydrogen made by a dedicated solar "filling station". This two-year research project was a cooperation between Metkon SA and Ing. Büro Schmidt and was principally supported by the Swiss Department of Energy.

The vehicle used was not a conventional car but a light, efficient one-person three-wheeler for the following reasons:

1) Conventional cars require so much energy that the required amount of hydrogen would have meant a large, costly solar-hydrogen installation quite outside the timescale and possible finances of this project.

2) Hydrogen-powering conventional cars solves only one of many problems: that of immediate exhaust pollution. Noise, energy wastage, the deaths and injuries of countless people and animals and the destruction of landscapes and towns remain problems that can only be solved by new concepts in traffic. Small, lightweight vehicles are not a complete solution, but at least a step in the right direction.

3) It is possible to race experimental solar-powered and electric vehicles in several countries. In particular the Swiss Tour de Sol, which was responsible for triggering most of the recent developments in this field, offers an experimental forum for such vehicles "on the road", as the authorities offer special simplified licencing arrangements for this event.

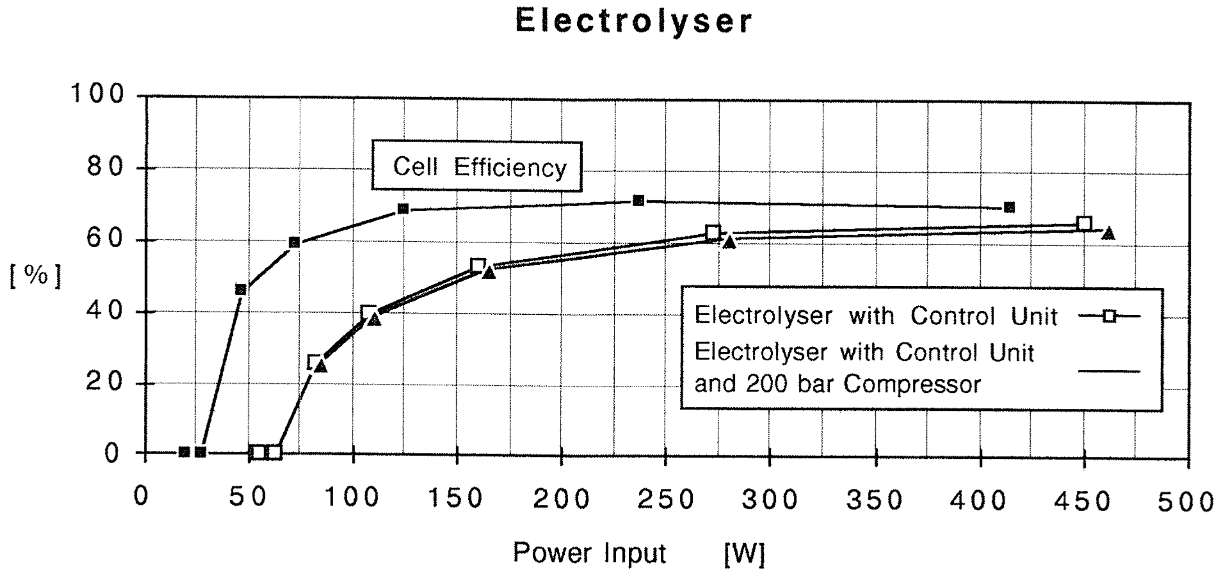
4) The vehicle chosen had been in use previously with a solar-electric drive, allowing direct comparisons between the electric and hydrogen energy storage modes.

In contrast to the toxic exhausts of hydrocarbon-powered vehicles, hydrogen vehicles emit only steam with small traces of nitrogen oxides. In particular there is of course no CO_2. Although hydrogen can at present be derived from fossil fuels more cheaply than from renewable sources, it is the latter which are of interest in the long run. In this context, hydrogen is regarded as an energy storage medium rather than a fuel.

HYDROGEN PRODUCTION

The easiest and best-known way of producing hydrogen from renewable sources is via the electrolysis of water. The electricity required can come from water, wind, solar, or biomass-derived power. Various different types of electrolysers are available in many sizes. Our electrolyser works with a liquid electrolyte (potassium hydroxid solution) and advanced electrode and diaphragm materials. In contrast to most other electrolysers, this one is designed for a working pressure of up to 3o bar. This electrolytic compression is not only highly efficient, in this case it actually turns out to be more than completely free, energywise, as slightly less energy is required to produce a given amount of hydrogen at maximum pressure than at a low pressure.

The efficiency of electrolysers can be quite high, approaching 100% in some cases. Ours can achieve about 65% as is seen below. These values were measured near STP. They improve slightly with higher temperatures and pressures.



The electrolyser is normally powered by a rooftop panel array of 1250 W nominal power. The panels are connected to the electrolyser through a Maximum Power Tracker (MPT), an electronic device which always loads the solar cells in such a way that they can operate at maximum efficiency.

A second method of connecting the solar array and the electrolyser is with the rooftop array feeding a mains inverter and a mains power supply feeding the electrolyser. This can thus be used at any location with a mains connection. In this way, the mains act not only as a transmission medium but also as a virtual storage medium.

Although the peak efficieny of the mains connection is only 50-80% of that of the direct connection (depending on the power supply used), the average effciency is higher as all power produced by the solar array is fed into the mains throughout the year, whenever there is any light, and whether the electrolyser is operating or not. In our case, the surplus energy is used to supply all the electricity needed in a 3-person household from spring to autumn. The electrolyser can now be operated continuously at the most favourable power level and without the corrosion which is associated with the intermittent operation caused by clouds and nightfall.

HYDROGEN STORAGE

Direct storage of hydrogen gas (GH_2) in pressure vessels was chosen as the only method practical for a small vehicle at the present time. Storage in metal hydrides is perhaps the safest method, but such systems are not necessarily lighter and they are very costly, with little potential for cost or weight reduction. The production and storage of liquid hydrogen

(LH_2) at -252°C involves too many losses to be practical for a small vehicle.

Materials

Steel bottles are widely used for hydrogen storage. Design, manufacture, and testing of vessels are straightforward and follow established procedures. The behaviour of steel is well understood and documented, resulting in relatively narrow safety factors (e.g. Bursting pressure/Test pressure/Working pressure = 5/3/2 from Swiss regulations). Hydrogen embrittlement restricts the use of high tensile alloys (they may not exceed 950 MPa with present regulations). 200 bar bottles are an easily available, relatively cheap product which store approximately 1% of their weight as H_2 (if this sounds like very little, consider that, because of the extremely high energy density of hydrogen (≈33 kWh/kg), the steel bottle with H_2 stores about *ten times more energy* than a lead-acid accumulator of the same weight).

Several materials are available as fibers which exceed the specific tensile strength of steel by over an order of magnitude. **Composite** bottles can be formed of a filament winding on a separate gas-tight liner. As the required safety factor for such vessels in current regulations is currently twice that of steel and a composite vessel also requires a liner and some resin to hold together and protect the fibers, the full potential of these bottles is not yet realised and the ones available certified for use store 2-4.5% GH_2 by weight. With careful quality control and cycle history monitoring it might be possible to raise this value to over 10%, providing over 3 kWh/kg energy density, of which10-50% can appear at the wheels as motive power.

Storage Pressure

The amount of material required to fabricate a vessel for the storage of a given amount of gas is in principle less for small pressures, as ambient atmospheric pressure reduces the vessel's required back-pressure by 1 bar and because the gas becomes less compressible at higher pressures.

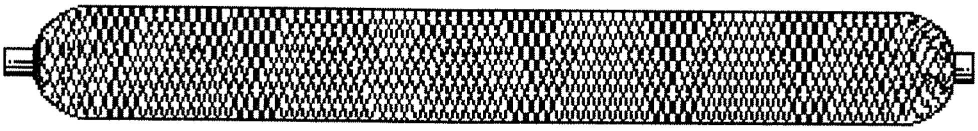
Low storage pressures are only however only practical in very few cases because of the extremely low density (≈0.09 kg/m^3 at NTP).

Higher pressures waste less interior vehicle space and vessels use material more effciently and in practice are thus lighter as well. Only at extremely high pressures would they become heavier again, due to the increasing incompressibility.

The energy required for the isothermal compression of an ideal gas is $nRT \ln(P_1/P_2)$. n is the number of moles, R the molar gas constant and T the temperature in K, so that this works out to about 101 $\ln(P_1/P_2)$ kJ/Nm^3 at 0°C or 110 $\ln(P_1/P_2)$ kJ/Nm^3 at 24°C. For example, to store hydrogen at 200 bar, about 5% of its energy equivalent is required for compression. In practice, this figure is less for electrolytic compression and more for mechanical compression. In contrast, the figure is at least 30% for making liquid hydrogen. Some of the energy used for compression or liquefaction is in principle recoverable.

30 bar composite vessels

With 30 bar available from the electrolyser, the original intention was to buy or make lightweight vessels for this pressure. No suitable commercially made bottles could be located. Therefore a new technique was devised which is especially suited for hand-laminating low to medium pressure bottles. One bottle was made for a working pressure of 30 bar and a bursting pressure of 150 bar. This was tested at the Swiss safety authority EMPA, where it burst at 150 bar, exactly as calculated, in spite of problems with premature leakage. Further bottles were not made, as about another ten would have been required just for destructive testing and this procedure would taken more time than available. This bottle could store only 1.3% H_2 by weight at 30 bar, due to excess resin in the lay-up.



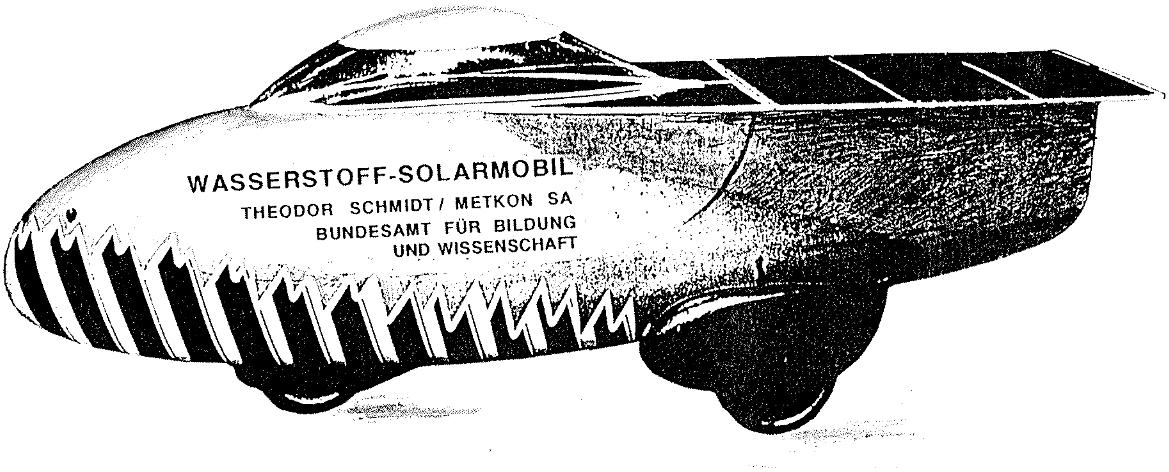
200 bar Steel Bottles with Compressor

In order to allow the proper use of easily available 200 bar steel bottles, a compressor was constructed for an input of 30 bar and an output of up to 200 bar.

With 30 bar available, the required 6-7 fold compression can be done in a single stage with a modest energy requirement. The compressor is driven intermittently by a 150 W electric motor and less than 2% of the electrolyser's total electric input is needed to run the compressor to 200 bar. Two opposing pistons are balanced and work rather slowly, so that compression is nearly isothermal. High-quality valves and piston seals ensure practically zero leakage.

The total measured efficiency of producing 200 bar, electrically derived hydrogen was 30% with the mains connection and an ordinary power supply, 50% with an advanced power supply, and 60% with a direct connection, using 500 W DC as the input. At this power level, 2 Nm^3 H_2 can be produced per day, which can be stored in one 10 l steel bottle weighing 14 kg. With a stronger power supply, the electrolyser itself could work at twice this rate.

THE VEHICLE



The test vehicle is a modified racing solarmobile with reasonably low mass ($\approx$125 kg) and rolling resistance ($C_R \approx 1\%$) and very low aerodynamic resistance ($C_D \cdot A \approx 0.15\ m^2$). Only 500W mechanical power is required to propel this vehicle at 50 km/h on the level. Some of the onboard solar cells were retained in order to power the engine's starting motor and the vehicle's lights and ancillary equipment.

Motor Conversion

A small internal-combustion otto-cycle 4-stroke engine was chosen as the only presently available practical heat-engine usable in this size, in spite of the many disadvantages. A suitable engine was supplied by Romeo Gridelli, who had used this to win the 1982 World Mileage Marathon (0.15 l Petrol/100 km).

The initial conversion to GH_2 proved easy and straightforward. External mixture formation in the intake manifold is the classic method of operating such small engines with low-pressure GH_2:

— replacement of carburetor with long intake manifold in order to store the continually formed H_2/air mixture until the next intake stroke. Supply of H_2 near the intake valve.

— removal of the crankcase ventilation connection from the intake manifold in order to prevent explosive mixtures forming in the crankcase. ([1] stresses this as important and goes to great lengths to provide forced crankcase ventilation.)

Although it was easy to get the engine to run on H_2 in some manner, it proved much more difficult to avoid frequent flashbacks of the mixture into the intake manifold, resulting in very loud bangs and sometimes flames.

— As most of the initial problems occurred during starting, the greatest improvement was achieved by fitting an electric starter and cranking the engine for a second or so before admitting any H_2.

— A flowmeter was essential, in order to be able to admit exactly the right amount of H_2, especially for starting.

— The air intake was adjusted with a variable restriction in the intake manifold. This was an initial setting and subsequent control of the engine was by amount of H_2 admitted only.

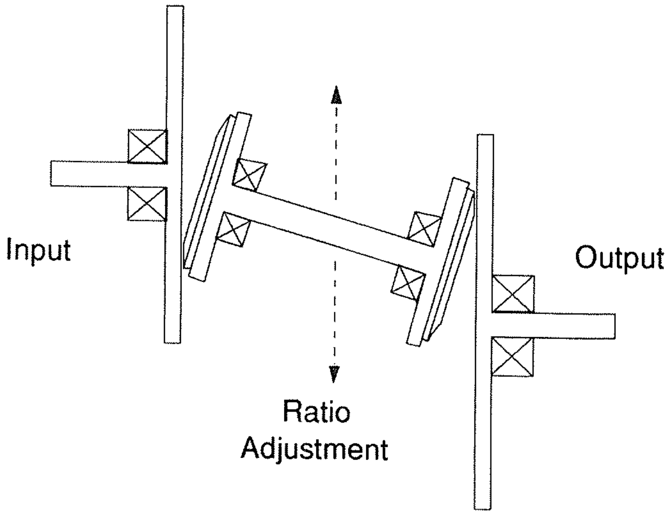
Eventually the engine behaved and measurements could be made using a simple dynamometer. The best efficiency recorded was 21% at 3000 rpm, a power of 520 W and a λ of 2.5. (λ is the air-to-fuel ratio, being defined as 1 when exactly as much air as theoretically required for complete combustion is present)

Because of several mechanical problems and the rather low power of this motor, a nearly identical new one was purchased, but with 107 cm^3 rather than 67 cm^3 cubic capacity. Used with petrol, the manufacturer gives 2.6 kW at 3600 min^{-1} and a maximum efficiency of 25%. The compression ratio is given as 8.7. The new motor was converted in a similar manner to the old one. It was possible to use the original electronic magneto ignition in spite of its fixed timing angle of 25° before TDC, which is rather early for H_2.

The engine was then installed in the vehicle and first driving tests done. It was quickly apparent that this motor was very prone to sudden stalling when loaded too much. In contrast to petrol operation, where more torque is generally available by introducing more fuel, injecting more GH^2 displaces the same volume of air, limiting maximum power more quickly than with a liquid fuel. At the stochiometric ratio, where λ, the air/fuel ratio, is defined to be 1, the mixture contains about 30% H_2 by volume, limiting the maximum power to some 70% of that with liquid fuels or even other heavier gaseous fuels, e.g. propane, where only 4% is required for a stochiometric mixture. A simply modified engine like this one won't run near $\lambda=1$ in any case, as the combustion temperature becomes so high that preignitions and flashbacks become uncontrollable without special measures, e.g. water induction. It runs well on very lean mixtures ($\lambda \approx 4$-5 idling, ≈ 2-3 working), but stops well before $\lambda=1$, again limiting the maximum power to a value well below that available with heavier fuels.

Gearing

With such a relatively weak engine, a very wide range of gearing is required if the vehicle is to be capable of both climbing an incline and running on the level at a reasonable speed. Such a gear was developed and constructed from two "Deltamats" in tandem, a continuously variable transmission (CVT), developed by Willi Lanker and manufactured by Delta AG, which was used with great sucess in the early Tours de Sol. The ratio is adjustable from 0.33 to 4.5, giving a total adjustment range of over 13. The vehicle is geared from 6 km/h to 80 km/h at maximum motor revolutions.



This shows the principle of the CVT. Not shown are cams which set the pressure of the rubbing surfaces proportional to the torque and the spring-loaded carriage which sets the gear ratio automatically to the desired input torque.

The efficiency of this device is a pretty constant 70-75% over all powers and ratios.

RESULTS

A datalogger was installed in the vehicle to measure speed and distance, hydrogen consumption, and road inclination and acceleration. This data was transferred to a computer after a run and evaluated. A typical run is shown below.

Consumption on straight, level stretches was 24 Nl/km (72 Wh/km, corresponds to 0.82 l petrol/100 km)) at 25 km/h and 31 Nl/km (93 Wh/km, 1.05 l /100 km) at 45 km/h. Climbing a gradient of ≈7% gave 175 Nl/km. These are the optimum values and consumption over stretches including varying gradients and stops was several times higher. With such values and the amount of hydrogen available from the electrolyser, it would have been possible to compete in the easier stages of the Tour de Sol, but not to complete the whole Tour with its over 3400 m of altitude to be climbed and 560 km distance in sometimes heavy traffic. Therefore we did not compete in the Tour but only gave a few demonstrations on a closed circuit.

The average mechanical efficiency of the total drive train from motor to wheel (including gearing) was measured to be about 60%.

Comparison to Electric Drive

As the same vehicle was previously raced while fitted out with an electric motor, both quantitave and qualitative comparisons could be made:

— At speeds on the level of 40-50 km/h, the electric version required 650-900 W electric power, the hydrogen version 3600 W (using 1 Nl/min H_2 ≈ 180 W). At about 25 km/h, the electric version 250-300 W, the hydrogen version 3100 W. The vehicle is thus about 4 times less efficient in the hydrogen mode than in the electric mode and roughly 10 times less efficient during partial load. These values are for steady-state driving; in real traffic conditions with inclines and stop-and-go conditions, both modes suffer.

— The range with 30 kg of lead-acid batteries is 50-90 km, the range with 30 kg of steel hydrogen bottles would be 165 km (at even 45 km/h). The range with hydrogen is thus about twice the range with lead batteries under ideal conditions. In real traffic the ranges would probably be about about equal, but the hydrogen system has the advantage that it does not deteriorate so quickly with age and that it provides heating in winter. Lead-acid batteries perform poorly in cold weather and have to be replaced every few years and much sooner if abused.

— A 500-1000 W electric motor is sufficient to give the vehicle a perfectly acceptable driving performance, as the motor can be overloaded for accereration and hill-climbing. The 1000-1500 W hydrogen motor is adequate for constant driving on the level but unsatisfactory for accelerating and hill-climbing. It would have to be larger, giving even worse partial-load efficiency.

FUTURE IMPROVEMENTS

The poor overall efficiency is in part due to the inherent poor effciency of this type and size of engine (max. 25-30%), in part due to the not completely satisfactory conversion (giving10-20%), but also because it is difficult to operate any such engine at its best operating point. With the required power output varying considerably, the engine is often running at less than peak efficiency. Because of its poor overload capability, an engine correctly sized for steady-state driving on the level (as in our case), is underpowered for acceleration and hill-climbing. If a large engine is chosen, as is the case with most motor vehicles, efficiency is poor during the frequent partial-load conditions. The larger engine also requires a heavier chassis and drive components, further increasing fuel consumption.

Viewed in this perspective, the internal combustion engine is a poor motor for driving road vehicles, especially if the fuel is precious solar hydrogen. Although engine manufacturers can build very good hydrogen engines, the problem of poor efficiency at partial load remains and additional fuel is wasted by vehicles which are standing still or even going downhill! One solution could be a hybrid concept as described below.

The Hybrid SolarMobile

A hybrid vehicle usually has several motors connected in parallel which can be used together or separately. Mostly these consist of an electric drive used for low-speed driving in town and a more powerful engine using a chemical fuel for driving uphill, for accelerating quickly, and for driving longer distances at higher speeds. Another concept has the motors connected in series: A relatively weaker chemically-fuelled engine continually charges up the battery supply for a powerful electric drive. The chemical engine can thus be rather small, needing to supply only the vehicle's average power or less, and be operated at a single operating point where its effciency is highest. The main electric drive can consist of a motor powerful enough for good acceleration and braking and a relatively small battery of a type chosen to offer the best compromise between high charging efficiency and high power density. The parallel concept mentioned first is best when mostly out-of-town, long-distance driving is done, with some driving in towns where internal combustion engines are prohibited; the series concept is best for frequent short-distance urban stop-and go driving with occasional longer trips required, which is indeed the pattern most prevalent in Europe. We will therefore concentrate on the series system, which also allows short trips to be powered by direct charging of the battery from the mains when available, while the hybrid charger is used if the battery's range is likely to be exceeded and always if heating is required. Short trips may thus need less primary energy than long trips, provided that this is originally produced by solar means, as is frequently done in Switzerland, or by water or wind power.

The best hybrid charger would be a fuel cell battery with conversion efficiencies of over 50% obtainable, but this is likely to remain extremely expensive for quite some time. The short-term solution is an internal combustion engine generator suitably silenced and detoxified. A better engine to use is the Stirling engine with external combustion, which is not only much quieter and cleaner, but can utilise any heat source. One type of this engine works without any rotating parts, driving a linear electric generator directly by vibration. Our project will continue with the evaluation of such a free-piston-stirling-engine-generator for vehicles. If possible, a modular approach will be adopted, allowing existing electric vehicles to be fitted with such a range extender. It is hoped that such a solution would remove one psychological barrier against electric vehicles: that of getting stuck with empty batteries.

Advantages of a Hybrid over a pure EV:

Long-distance driving possible
Rapid "filling-up" possible
Extension of battery life or
reduction of battery weight
Removal of the fear of getting stuck
Operation with just about any renewable or fossil fuel possible,
in addition to direct mains or solar charging
Less emissions and noise than conventional motor vehicles
Higher efficiency than conventional motor vehicles
Free heating as with conventional motor vehicles

Disadvantages:

Higher complexity, making it more difficult to reach cost and weight targets

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