LENR Powered Electric Vehicles

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Abstract – *Current electric vehicles (EV) and fuel cell vehicles (FCEV) suffer from several limitations that prevent them from becoming a true commercial success.*
When available, kilowatt class LENR generators combined with modern thermoelectric conversion technology could enable designing new type of automobiles, being low cost, maintenance free and zero emission at the same time.
In the present talk, we will discuss what are to current limitations of electric vehicles and battery technology, how LENR technology can propose an alternative to large battery storage on EV, what are the available compact solutions for energy harvesting and thermoelectric conversion from LENR thermal energy, what are the longer term design alternatives and finally what is the expected timeline to develop prototypes and commercial products.

Key words: LENR generator, autonomous, self-powered, electric vehicles, electric cars, battery, thermoelectric conversion, Stirling engine, Rankine engine, Rankine turbine**.**

I. INTRODUCTION

In order to find a solution to both pollution increase and global warming directly attributable to the transportation industry, more and more car manufacturers are proposing zero emission vehicles (ZEV) in their product line. However if hybrid vehicles are now proving to be a true commercial success and financially sustainable for the industry, electric vehicles (EV) or fuel cell vehicles (FCEV) are still lacking to propose a valid alternative to thermal engine automotives, either due to cost of manufacturing, cost of ownership, range anxiety, battery reliability or lack of charging or refueling infrastructure. Most car manufacturers believe that several decades will be necessary to really switch away from fossil fuel vehicles.

Pike Research forecasts cumulative sales of plug-in electric vehicles to reach 5.2 million worldwide by 2017, up from only 114,000 vehicles in 2011. At that time, a total of nearly 7.7 million fast charging station locations will be required worldwide. Companies like ABB entered the charging station market and values it at about $1 billion.

However, a disruptive technology like LENR generator could potentially change this paradigm completely.

II. ELECTRIC VEHICLES

While electric vehicles (EV) include electric trains, electric buses, electric aircrafts, electric boats, electric motorcycles or even electric spacecrafts, we will focus in this paper on electric cars.

Even if electric cars look to be attractive on paper, they suffer from a major pain points: batteries.

Whatever the battery technology used – lead acid, NiMH, Li-ion –, battery are not efficient in comparison to internal combustion engines (ICE).

With Li-ion technology, the cost per kWh of storage capacity is typically between $250 and $350. A small 20kWh battery pack represents at least $5000 cost adder in comparison to a regular ICE car.

Batteries add a lot of weight to the car which reduces the safety of the vehicle and increases its electric power consumption. The specific energy of a full Li-ion battery pack is typical 140 Wh/kg where lead acid batteries offer only 40 Wh/kg. A small Li-ion pack of 20 kWh adds at least 140 kg to the car and the 85 kWh battery module used on the Tesla Model S Performance weights about 600 kg.

Reliability is another major pain point of batteries. Lead acid batteries have very low charging cycle lifespan of about 600 full cycles. In a car application, the user has to replace the lead acid battery every 5 to 6 years. With Li-ion or more advanced chemistry like lithium iron phosphate ($LiFePO_4$) or nanophosphate batteries, the cycle life can be extended to over 1000 full cycles with little loss of performance which gives a lifetime of about 10 years. But after 10 years, the battery performance is clearly affected and might need to be replaced at high cost. Moreover, battery modules are built by stacking battery cells in series and parallel combinations. Some controlling electronics is embedded inside the battery module to monitor the performance of each cell individually and bypass the bad ones that might affect the overall performance of the module. This ends up by adding cost to the module and potentially reducing the capacity and the voltage of the battery after several years of daily usage.

Even if Li-ion batteries are getting safer every year, there are still some safety concerns with such batteries. Some electric cars have been reported to catch fire.

Lithium production comes mainly from Bolivia and Chile, which can trigger geopolitical concerns for resource, is the need for lithium is increased by 2 or 3 order of magnitudes.

Finally, one of the biggest concerns about electric vehicles is the range anxiety. Currently, an electric car requires a charging station infrastructure for non urban trip. The range of current electric cars goes from 100 to 450 km per charge. And even with high power fast charge station, only 1.70 km of range can be obtained per minute of charge, thus 25 km in 15 minutes.

The power consumption of electric cars is mainly affected by the speed of the vehicle and its weight as showed in Fig. 1 and Fig. 2. Even thought the Tesla Model S has a better aerodynamics, the battery consumption is higher compared to the Tesla Roadster due to a higher weight.

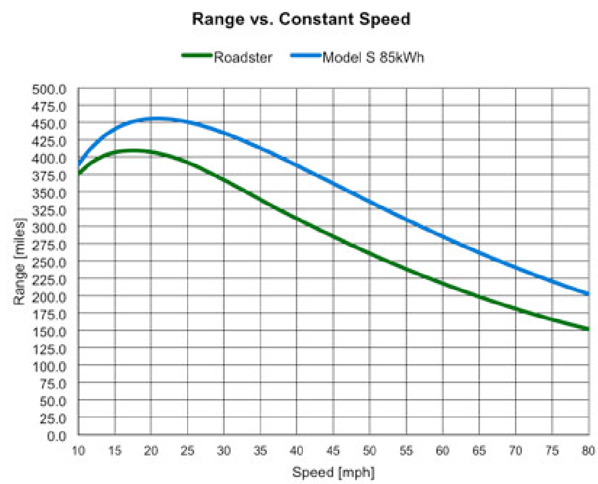

Fig. 1 Range versus speed of electric car
Tesla Roadster battery: 53 kWh
Tesla Model S battery: 85 kWh
(source: Tesla Motors)

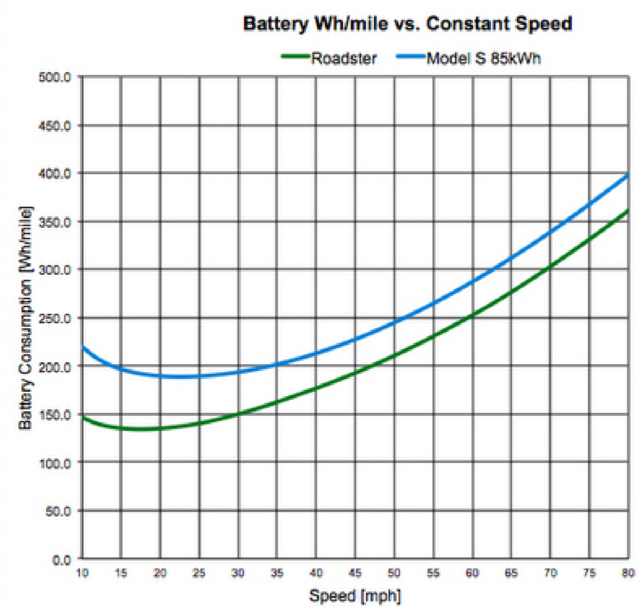

Fig. 2 Battery consumption versus speed of electric car (source: Tesla Motors)

III. POWER REQUIREMENT OF ELECTRIC CARS

While the peak power for a standard car is typically in the order of 100 hp or 75kW and is required to accelerate the car decently, the average power consumption is much lower. For typical electric car, the average power consumption is between 10 kWh to 20 kWh for every 100 km at a constant speed of 100 km/h which corresponds to 10 to 20 kW of constant electric consumption. The average power consumption is typically 5 to 10 times smaller than the peak power. Table 1 lists the different specifications of three common electric cars.

TABLE I

Specifications of typical electric cars

	Renault Zoé	Nissan Leaf	Tesla Model S Perf.
Battery Capacity	22 kWh (Li-ion)	24 kWh (Li-ion)	85kWh (Li-ion)
Typical Range	200 km	175 km	480 km
Motor Peak Power	65 kW	80 kW	325 kW
Avg. Power Cons.	13.0 kWh / 100 km	14.0 kWh / 100 km	19.0 kWh / 100 km
Fast Charge	80% in 30min (42kW - 63A)	80% in 30min (44kW / 400V / 110A)	55% in 30min
Bat. Spec. Power		525 W/kg	
Bat. Spec. Energy		140 Wh/kg	
Battery Weight		171 kg / 218 kg	
Estim Bat. Cost		US$ 18'000.-	US$ 42'000.-

However, it is important to notice that the instantaneous power requirement can highly vary during a trip especially in case of uphill and downhill on the path. Fig. 3 shows the speed of an electric car (in blue) and the corresponding power consumption or breaking power generation (in yellow) along the track on top of the figure.

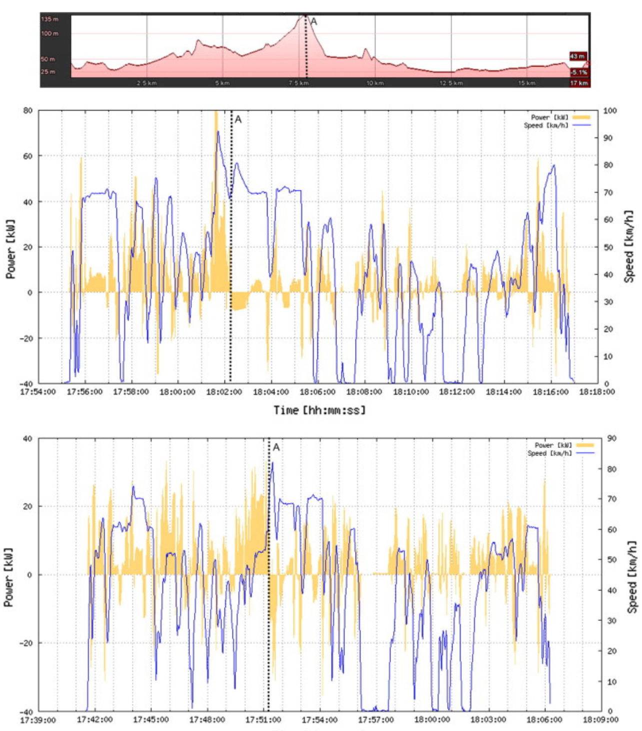

Fig. 3 Power consumption and speed versus time
In yellow: Power consumption/generation
In blue: Vehicle speed

As it can be seen on Fig. 3, the power needs can vary a lot over time. If a constant electric power generator of 10 to 20 kWh would be enough to power the car in average, an energy buffer is definitely needed to absorb the large amount of power peaks. This energy buffer can be an electric battery, a super capacitor, a mechanical flywheel or a combination of these.

IV. LENR POWER SOURCE FOR EV

Companies like Defkalion Green Technology or Leonardo Corp. are starting to advertise LENR generators delivering thermal power ranging from 5 to 45 kW in a controlled and stable way with a COP between 6 and over 30. These reactors, based on pressurized hydrogen loaded nickel reactions, are claimed to work continuously for 6 months with one charge of nickel and hydrogen fuel.

Combined with a thermoelectric conversion system, such thermal power generator would produce enough heat for a long enough period to be able to charge the battery of an electric car. If the COP is high enough, the electrical output power from the thermoelectric converter can be sufficient to power the LENR generator input and charge the EV batteries at the same time.

Defkalion Hyperion preliminary prototype has dimensions (55cm x 45cm x 42cm) compatible with the storage and cargo space volume available in an electric car. It also weights about 50 kg which makes it also compatible with maximum allowable load weight.

In terms of manufacturing cost, such generator would cost less than $1000 to produce in high volume, thus making it competitive compared to gasoline or diesel combustion engine and to Li-ion battery storage and the cost of refueling is expected to be lower than $200 for a 45 kW generator.

It is important to notice that powering a car with such generator would not improve a lot the power density and the specific power of the energy source compared to Li-ion battery module for example. However it would drastically improve the energy density and the specific energy by 2 to 3 orders of magnitude, thus making the vehicle autonomous in terms of power supply for 6 months if the LENR generator needs to run 24 by 7, but much more if it can be turned on and off on demand.

V. SELF POWERED ELECTRIC CARS

In order to build a self powered electric vehicle using LENR as source of energy, four main technical bricks are required:

1. LENR thermal generator
2. Thermoelectric conversion system

3. Electrical storage system
4. Electric vehicle

Except from kilowatt range LENR generators that still need to be validated by third party tests, all the other technology bricks – thermoelectric converter and electric cars including battery storage – are all available on the market with a large variety of solutions.

Such self powered electric would be really an ideal car as it has the potential to cost less to manufacture than a regular ICE car, to require less maintenance, to reduce considerably the fuel costs, to be driven anywhere and anytime without requiring an infrastructure – gas stations or electrical charging stations – and, cherry on the cake, to be sustainable for the planet and green as it would be true zero emission. It would only require to refuel the nickel and hydrogen fuel every 6 months or every year for a cost of \$100 to \$200.

At LENR Cars, we call this ideal car: the iCar.

The first generation of iCar was planned to use thermoelectric generators or TEG which convert heat or more precisely temperature differences directly into electrical energy, using the Seebeck effect. Modern TEG use bismuth telluride (Bi2Te3) semiconductor p-n junctions to convert temperature delta into electricity. Their typical efficiency is around 4.5-5% for standard modules and up to 8-10% for more advanced generations. The maximum temperature these TEG can endure sits between 250°C and 320°C. They typically require a ΔT of over 250°C to achieve efficiency over 5%.

Assuming a 45 kW_T LENR thermal generator combined with five 500W TEG modules (Fig. 4 and 5) working at a ΔT of 250°C with an efficiency of 5%, we can expect an electrical output of 2.25 kW_e. This solution would increase the weight of the car by 125 kg in addition to the 50 kg of the LENR generator without counting for the cooling system.

Part Number	TEG500
Matched Load Output Power	500 W
Open Circuit Voltage	420VDC
Matched Load Output Voltage	200 VDC
Internal Resistance	58Ohm
Matched Load Current	3.5 A
Number of TEG Modules	48Pcs TEP1-12656-0.6
Hot Oil Flow Rate	＞0.25m3 /h
Hot Oil Input Temperature	＞250°C
Water Input Rate	＞0.5m3 /h
Input Water Temperature	＜30°C
Oil Pipe connector	Fillet DN15
Water inlet and outlet	Inlet and outlet 1/2
Dimension(long x Height x width)	560mm×500mm×120 mm
Weight	25（Kgs）

Fig. 4 TEG500 module specification from Thermonamic

Then assuming roughly 500 W_e consumed by pumps and electric fans for the heat exchanger and cooling system, about 1.75 kW_e remains available. From this power, nearly 1.25 kW_e – assuming a COP of 36 – would be needed to power the input of the LENR generator. Finally a power of only 500 W_e is left to charge the battery of the car out of the initial 45 kW_T. Moreover, we have to consider a maximum efficiency of 90% for the charging system of the battery module. Thus in the full cycle, somewhere closer to 450 W_e would be used to really charge the battery continuously, corresponding to an overall efficiency of only 1%.

Such implementation would require an important radiator or other type of water cooling system to evacuate the remaining 42.75 kW_T of heat not converted into electricity. If we compare such cooling requirement to the one used in a sport car like the Corvette ZR1 during racing a track. The engine such race car works at 75% of time in full charge with a peak power of 638 hp or 476 kW of mechanical power and with an efficiency of the combustion engine under 30%, thus corresponding to a power of 1190 kW from burning fuel and 833 kW of heat not converted into mechanical work. Half of this heat is evacuated through the exhaust gas and the other half through the radiator. So when a car is moving, evacuating 50 kW of heat or more is not an issue. However, it can become problematic when the car is parked in a garage, as the generator might be supposed to work 24 by 7 until the battery of the car is fully charged.

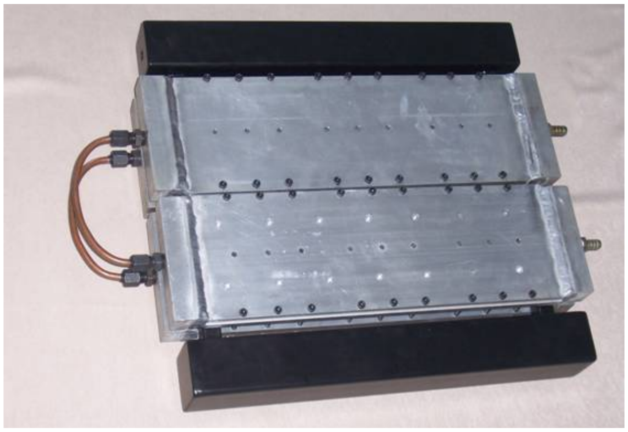

Fig. 5 Picture of TEG500 module from Thermonamic

Anyway, even with only 1% of overall efficiency, having an on-board generator of 450 W would be interesting for an electric car. The average power consumption for a large electric sedan like the Tesla Model S is 180 Wh/km at an average highway speed of 100 km/h. An energy generation of 450 Wh/h will produce 10.8 kWh peer day corresponding to 60 km of self powered range available per day or 420 km per week which is above the average distance travelled by car driver in Europe.

The EV platform planned for this generation was a Tesla Model S Performance, as it offers the largest battery storage currently available on market with 85 kWh with a decent electric motor delivering 325 kW. A single trip of 500 km would be possible with an average of 420 km per week in fully autonomous power mode.

We will most probably never prototype this first generation based on TEG mainly for cost reasons and due to a total additional weight estimated at over 250 kg. More interesting thermoelectric solutions, initially planned for the second generation of iCar, are already commercially available and would make more sense even for a first prototype.

VI. ADVANCED THERMOELECTRIC CONVERTER

By using thermoelectric conversion system with higher efficiency, it becomes possible to reduce the size of the energy storage, of the batteries. A 20 kWh battery is enough to run a relatively large electric car for 1 hour at 100 km/h. This would be enough to cover the starting time of the LENR generator. Thus it would be possible to stop the LENR generator when the battery is fully charged and to start it only when the car is being driven or even shortly before. This can simplify a lot the heat extraction system and clearly increase the time between two refills.

Among all thermoelectric conversion solutions available, we looked particularly at systems working in close cycle to guarantee a true zero emission solution. We also looked only at solutions with high conversion efficiency rate and which are compatible in terms of power, temperature range, size, weight and cost with both LENR generators and with commercial applications in electric cars. Three technologies seem to emerge:

1. Free piston Stirling engine
2. Modern steam engine (closed Rankine cycle)
3. Super CO_2 Rankine turbine

VI.A. Free Piston Stirling Engine

Small Stirling engine of 1 kWe output power range are available on the market, like for example the EG-1000 from Sunpower (Fig. 6). Such Stirling engine requires a temperature ratio (T_{hot} / T_{cold} in °K) of above 2.7 to reach a conversion efficiency above 30%. With a T_{hot} temperature estimated at 700°K (~ 430°C) and a Tcold temperature of 320°K (~ 50°C), the temperature ratio is 2.2. The conversion efficiency in that case is estimated at 27%.

One of the main advantages of Stirling engines and especially free piston Stirling engine configuration is the very low level of friction involved and an extremely low wear of moving parts. The lifecycle of such Stirling engine is typically above 15 years without any maintenance. However, Stirling engines including the alternator can represent a relatively large and heavy solution. For larger scale version, the CSSE study (Conceptual Stirling Space Engine) from NASA estimates a specific power of 200W/kg including the alternator for a 25 kWe output power version. This would give a weight for the thermoelectric conversion of 125 kg, not including the cooling system maintaining the low temperature side at 50°C. Larger scale Stirling engines do exist like the 75 kWe Kawasaki Kockums V4-275R used on Soryu Class Japanese submarines, however the specifications of these engines are unknown to us.

For an electric car application a range between 8 kWe to 15 kWe would make most sense. It is reasonable to imagine that such Stirling engine could be designed with a weight kept under 100 kg including linear alternator and a water cooling radiator. Then with the LENR generator, the total weight would be less than 150 kg making this solution suitable as on-board power source for an electric car.

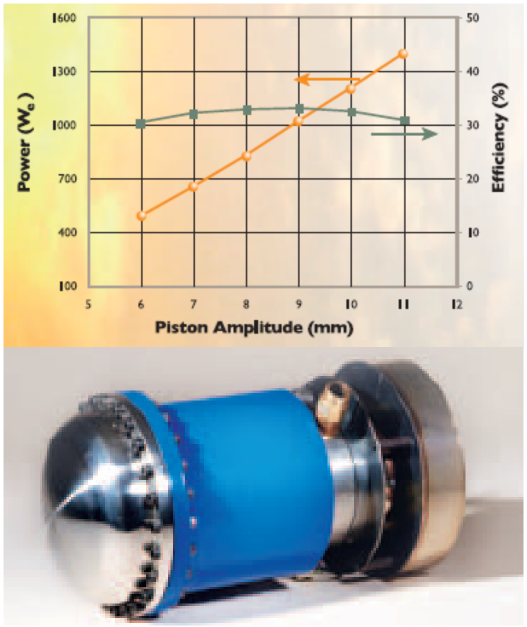

Fig. 6 Sunpower EG-1000 including propane burner

VI.B. Modern Steam Engine

Modern generation of steam piston engines working in closed Rankine cycle have been designed and developed in Germany by IAV GmbH and Enginion AG in the early 2000. Initially designed to work with a fuel burning heat source, the design can be adapted to LENR generator.

While the conversion efficiency is lower than with Stirling engine, typically 20% to 23%, the specific power is higher. Enginion developed a 6 kWe steam engine weighting 32 kg and working in closed cycle (Fig. 7). Once again, with this steam solution, the thermoelectric converter could be scale from 6 kWe to 18 kWe while keeping the weight controlled between 32 kg and 100 kg respectively.

Fig. 7 Enginion steam engine prototype

Cyclone Power Technology is Florida based company also developing modern steam engines used a modified version of the Rankine cycle, called the Schoell cycle. They currently have a relatively compact 100 hp (70 kW_{mech}) steam engine working with fuel burner with an efficiency of about 30% (Fig. 8), but requiring a high temperature heat source. Cyclone Power Technology has also developed a smaller engine working in closed cycle designed for waste heat recovery applications. This Waste Heat Engine (WHE) has a power output of 10 kWe (Fig. 9) and can work with a temperature input of 315°C which makes it directly compatible with Hyperion LENR generators. This solution is very light with only 9 kg, not including the alternator and the condenser. However the conversion efficiency is lower and rated at about 12%.

Fig. 8 Cyclone Power Mark V steam engine

Fig. 9 Cyclone Power WHE-25 generator

VI.C. Super CO_2 Rankine Turbine

Another very interesting thermoelectric conversion solution is Super CO_2 Rankine turbine. About 90% of the electricity produced in the world is used large scale steam

Rankine turbines. These big turbines have usually a high conversion efficiency of 42% to 47%. However, they require a steam temperature of 600 °C to avoid damaging the blades of the turbine with water droplets. For smaller scale application, several companies have developed Organic Rankine Cycle turbines or ORC turbines using an organic gas (CFC or HC gas like isobutene or propane) in closed cycle instead of water as the working fluid. Such ORC turbines can then work at much lower temperature, typically between 80°C to 140°C depending on the organic fluid used. However OCR turbines offer a much lower efficiency compared to steam turbine with typically only 18%.

To combine low working temperature with high conversion efficiency, supercritical CO_2 turbines have been designed. Supercritical phase for CO_2 can be reached at relatively low pressure (100 bars) and low temperature (100°C). Sandia National Labs is currently working on a large scale Super-CO_2 turbine design where there researchers are expecting a conversion efficiency improvement of 50% compared to standard steam turbines resulting in a net efficiency estimated around 60% while working at lower temperature between 300°C and 500°C. Infinite Turbine LLC, a company based in Wisconsin specialized in small scale ORC turbines, has recently modified one of their ORC turbine design to make it work with supercritical CO_2 fluid (Fig. 10). This 10 to 20 kWe turbine generator prototype can work between 100°C and 500°C with an efficiency of 40% to 50%. The turbine itself, as well as both the evaporator and condenser heat exchanger, is very compact and light. The CO_2 bottle is also compact enough to fit inside an electric car.

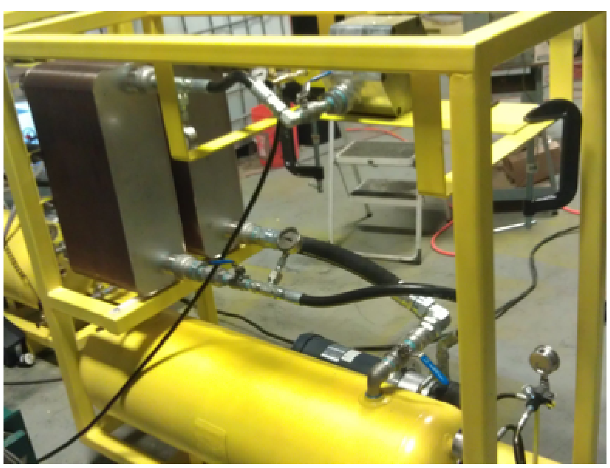

Fig. 9 R744 Supercritical CO_2 turbine from Infinite Turbine

VII. LENR EV PERFORMANCE

Considering that a solution producing 8 kWe available to charge the EV batteries might be feasible with a 40 kW_T LENR generator – if such generator becomes demonstrated and commercially available – and with an advanced thermoelectric conversion (Stirling, Rankine pistons or S-CO_2 Rankine turbine) allowing an overall net efficiency of nearly 20%, it is then possible to estimate the performance of this range extender for a small electric city car and for a larger 5 seats sedan.

VII.A. Renault Zoé

A hybrid version of the Renault Zoé city car with an on-board LENR electric generator producing 8 kW of electricity to recharge the battery, the range would be extended to 440 km when driving the car at 100 km/h. Then it becomes very interesting to notice that this range becomes unlimited when the car is driven at an average speed under 70km/h which is generally the case for such cars. The detailed estimations of the range performance are listed in Table II.

VII.B. Tesla Model S 40kWh

A similar calculation can be done for a bigger sedan EV like the 40 kWh version of the Tesla Model S. The on-board 8 kW LENR electric generator would increase the range to about 400 km when driving the car at 100 km/h, a value very close to the range available on a standard 85 kWh version of the Model S which costs $20’000 more than the 40 kWh one. Thus, the LENR hybrid version offers similar range at high speed but for a lower cost of manufacturing and ownership. Then at a lower speed, this range becomes very important with about 1500 km or 22 hours of driving when the car is running at an average speed of 70km/h. Moreover, it seems difficult to imagine driving 22 hours without rest breaks. And at this average speed of 70km/h, a 20 min break would add another 100 km (or 1½ hours) to the range.

Finally, the range becomes also unlimited for the Tesla Model S with an average speed of 60 km/h or lower. The detailed estimations of the range performance are listed in Table II.

TABLE II

LENR Powered Electric Vehicles Estimated Specifications

	Renault Zoé	Tesla Model S
Battery capacity	22 kWh	40 kWh
LENR generated power	8 kW	8 kW
Avg. motor consumption at 100 km/h	130 Wh/km or 13.0 kW	180 Wh/km or 18.0 kW
Avg. motor consumption at 70 km/h	110 Wh/km or 7.7 kW	140 Wh/km or 9.8 kW
Avg. motor consumption at 50 km/h	100 Wh/km or 5.0 kW	115 Wh/km or 5.8 kW
Net power consumption at 100 km/h	5.0 kW	10.0 kW
Net power consumption at 70 km/h	0.3 kW	1.8 kW
Net power consumption at 50 km/h	- 3.0 kW	- 2.2 kW
Range at 100 km/h	440 km	400 km
Range at70 km/h	> 5000 km	1500 km
Range at 50 km/h	unlimited	unlimited

VIII. CONCLUSIONS

With the present paper, we showed that if kW scale LENR thermal generators become available, several technologies to convert the heat into electricity are already available. We demonstrate that these thermoelectric conversion solutions are compatible in terms of size, weight to be embedded on board of an electric car. Moreover these solutions are cost effective at least compared to Li-ion battery storage, thus making such LENR powered electric vehicles commercially interesting with a lower manufacturing cost. The usage cost – fuel cost and maintenance cost – would be a lot lower compared to both regular combustion engine cars and standard electric cars. Finally, as the thermoelectric conversion solutions presented in this paper are all working in closed cycle, such LENR hybrid car would be truly zero emission vehicle.

Therefore, it is possible to imagine that commercial version of such LENR powered cars, clean, affordable and simple to use could become available about 4 to 5 years after the validation and certification of kW scale LENR thermal generators. The value proposition for a customer would be far better than what is proposed with current electric cars and could drastically accelerate the adoption rate of zero emission vehicles. We also believe that a first prototype can be built by end of 2013.

In conclusion, the application of LENR generators for cars makes sense even if it is probably the most complicated application within the transportation industry. Similar solutions would obviously be also very interesting for other electric vehicles like trains, electric boats and electric planes.

NOMENCLATURE

COP	Coefficient of performance (Pout/Pin ratio)
EV	Electric vehicle
FCEV	Fuel cell electric vehicle
ICE	Internal combustion engine
ORC	Organic Rankine Cycle
TEG	Thermoelectric generator
WHE	Waste heat engine
ZEV	Zero emission vehicle

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