Reasons why modern steam engines make sense as a future drive train in future vehicles

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RANOTOR is founded by the former project leader of SAAB steam engine project during the 70's. The last years RANOTOR has carried out project together with automotive industry for WHR (Waste Heat Recovery) and Royal Technology University of Stockholm

There are several reasons why it should be well founded to claim that modern steam engine has a huge potential to offer attractive drivetrains for future vehicles.

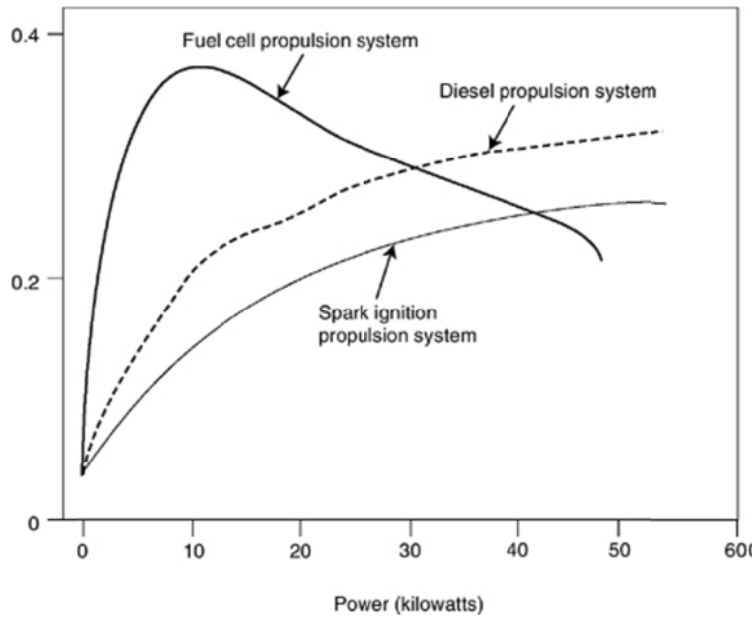
- Superior primary energy source flexibility (solar, electricity , biofuel)
- Can form hybrids with ICE, Electric propulsion and fuel cells
- Low tail pipe emissions when burning a fuel.
- Possibility to harness intermittent renewable with a thermal battery
- Regenerative engine braking
- High part load efficiency (high average energy efficiency)
- Low cost (no exotic expensive material and low mass of material normalized to power)
- Attractive torque characteristic (high low end torque, elastic torque = increased torque when lowering shaft speed)

Energy efficiency

Besides the upfront cost for the propulsion system and the cost for the energy carrier the energy conversion (Well To Wheel) is important both from economy point of view and mostly also from environmentally point of view. Most people think steam engine has to offer poor efficiency because old classic steam engine had low efficiency. However modern steam engine operate at much higher pressure, temperature and shaft-speed which gives both higher efficiency and high power density.

The power density of a 220 bar and 6000 rpm steam engine could give about ten times higher specific power (kW/liter) than an ICE. Even when adding the steam generator and a TES (Thermal Energy Storage) the total weight and volume normalized to maximum power is low.

One important thing when talking about efficiency for the propulsion system proper is the maximum and part load efficiency. In figure 1 the typical overall efficiency for different propulsion system as function of load (power) is shown, Diesel propulsion system has very high efficiency at full load but at low loads the efficiency drops considerably. Gasoline engine has even lower part load efficiency. However fuel cell and steam engine has the highest efficiency at part load. During typical driving cycles part load is most significant load and therefore steam engine has higher average efficiency during a typical driving cycle. In Figure 1 there are two steam engine illustrated. One steam engine operates with supercritical steam of 220 bar and 500 C and has a part load efficiency of 32 %. Such a steam engine has claimed to been build and tested and will have higher energy efficiency in most types of driving cycles. The other steam engine is the next generation high-tech steam engine system using ceramic steam generator etc. and operate at 300 bar and + 1000 C which should be able to an efficiency at part load that is higher than diesel engines at full load



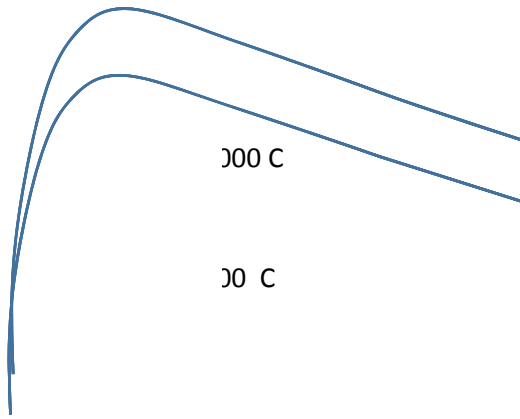


Figure 1. Overall efficiency as function of power from Web article

Superior primary energy source flexibility, True energy flexible machine

A steam engine with its external combustion can more or less burn any kind of fuel. The external combustion that is taking place at low temperature compared to an ICE don't generate NOX emissions and it can burn liquid, gaseous and even solid fuel and producing steam by cooling hot solid reactors.

Besides the possibilities to makes use of a wide range of fuel, the steam engine can harness waste heat (**WHR = Waste Heat Recovery**) from ICE (Internal Combustion Engine) or high temperature fuel cells and form hybrids with very high fuel efficiency. With a TES (Thermal Energy Storage, explained below) a WHR hybrid can get the same advantages as an electric hybrid , that is higher efficiency on the ICE and regenerative engine braking PLUS recovering the waste heat in the exhaust gas stream. Also, together with a high temperature solid fuel cell there is a potential to get over 50 % efficiency from fuel to the wheel at part load.

Liquid and gaseous fuel. The external combustion makes it possible to make use of a wide range of liquid and gaseous fuel with more or less the same type of burner and still offer low exhaust gas emissions. When Internal combustion engine and fuel cell requires very clean and well specified liquid and gaseous fuel the steam engine with the external combustion can make use of unrefined fuel that cost less than the clean fuel to ICE, With a novel catalytic burner it is possible to burn almost all kind of fuel with very low exhaust gas emissions,

Hydrogen Is touted as a future energy carrier for propulsions of vehicles. So far it seems that hydrogen in a fuel cell is very expensive solution. Some propose to use ICE instead of fuel cells because they are cheap to manufacture. However, using hydrogen in an ICE has some problems as lower power density and NOX formation whereas the steam engine with its external combustion makes it easier to burn hydrogen and get higher power density and no NOX emissions.

Solid biofuel is probably consider as out of questions for most people but it is not farfetched to use so called black pellets (torrefied biofuel). Indeed, energy content for black pellets normalized to weight and volume are about half of that of diesel fuel but it is superior electric batteries when it comes to energy density. A bio fuel burner gets very big if it has to provide peak power in vehicle applications, however, with a TES the burner and the steam generator has only to be sized for average power output which makes it possible to realize compact propulsion system using solid biofuel.

High Temperature fuel cell (SOFC) and steam engine hybrid. SOFC operate at high temperature and will together with a steam engine offer a perfect matched hybrid with extraordinary high efficiency at part load, high specific power and multi-fuel capability. SOFC doesn't like to change temperature up and down but the steam engine make it is possible to relief temperature changes.

Metal fuel. Not many people thinking of metal as a fuel. Actually, metal powder can be oxidized in the same way as other fuel and form iron oxide from iron powder. The iron oxide is stored onboard in a tank until refill of new iron power is taking place. That means no tail pipe emissions in the same way as for electric propulsion. Also, in the same way as the weight of the electric battery is always on board and has been transported around the weight of metal is always on board but energy density for iron powder is much better than electric batteries. Metal fuel is not a new idea and has been tested in ICE but the metal power clogging up the ICE. The steam engine with its external combustion and thermal storage has a much more favorable situation to make use of metal fuel which is an

abundant resource on our and other planets which is the reason why European Space Agency promote the concept with modern steam engine for metal fuel. In the same way as for solid bio fuel there is a need for a thermal storage that relieves the burner to follow the fluctuating power output of the engine.

LENR or cold fusion is on and off claimed to be a reality. If LENR would be a reality there is hardly any other propulsion system that can transfer heat from the solid hot reactor core to a working fluid in the same compact way as a steam generator. Furthermore, the reactor can probably not follow the heavy fluctuating power demand that is the case in a vehicle and a TES is needed (See below)

Hydrogen peroxide is mainly used in rocket as propellant. A steam engine with an open system, that is, no condensing closed loop can use hydro peroxide as fuel and working fluid. The only emission is water and oxygen. Hydrogen peroxide has been used in submarines before but some accident has caused a reputation to be dangers. That is also true if not handle in a proper way but some researcher said it can be handle in a safe way or at least as safe as other fuels. Hydrogen peroxide can be considered as hydrogen in liquid form and therefore easier to handle.

Table 1 Energy density for different energy carrier

Energy carrier	**Energy density (kWh/kg)**	**Energy density (kWh/liter**
Diesel	12	10
Methanol	6,4	5
Black pellets	5	5
Iron powder	1,9	5
Hydrogen (300 bar tank)	0,9	0,8
Hydrogen peroxide (70 %)	0,8	1.2
Lithium-Ion *	0,10	0,050
LENR (To be good to be true?)	?	?

As claimed above the modern steam engine has a great possibility to makes use of different fuels and converts the fuel in an efficient way to propulsion on the wheel. To harness intermittent renewable electricity from solar and wind and recovering engine braking and smoothing the burn rate when burning solid fuel as black pellets , metal fuel or LENR there is a need for a storage or rather than a storage we should called it a buffer or peak shaving device.

Thermal energy storage vs. electric battery

As mentioned above there are a need for some kind of energy storage that can store steam that is generated from a bio fuel burner, metal fuel burner or a LENR reactor that should operate at more or less constant load and that can supply steam much more rapidly to the steam engine that has to respond quickly on power demand. Furthermore, if steam engine is going to harness intermittent renewable there is a need for a storage of the intermittent energy.

In an electric hybrid drive train the electric batteries embodied the storage that makes it possible for the ICE to operate at more constant load and offering higher efficiency but electric batteries suffer from low energy density and power density but also degradation that adds additional operating cost besides the electric cost.

In large solar steam power plants thermal storage is used to store the thermal energy produced in the concentrating solar collectors before the electricity in the turbine is produced rather than

producing electricity first and then store the electricity in electric batteries. The reason is the high cost for the electric batteries compared to the thermal storage.

The modern steam engine for vehicles also employee a thermal storage or a Steam Buffer that is the counter part of the electric batteries.

Round trip efficiency and Exergy

One of the strongest argument for electric propulsion is the possibility to harness electricity from solar and wind energy. The round trip efficiency from charging of the electric battery and discharging the electric battery is high and is about 70 %. When charging the Steam Buffer with electricity that is converted into thermal energy and when the thermal energy in the steam buffer is converted to work on the steam engine outgoing shaft the round trip efficiency is about 30 %.

It can be considered as waste of exergy (energy quality) to use electricity that is converted into thermal energy. However, there is a lot of heat in the condenser that is useful both during winter and summer season. In an all electric propulsion system electricity from the battery has to be used to run a heat pump/AC to get heating during winter and AC during summer. In the steam engine system the condenser heat is used directly for heating during winter period and during summer the condenser heat is running a heat driven AC unit. Taking into account that the condenser heat is providing useful energy for compartment heating and AC which power amounts to about 10 kW the round trip efficiency is considerably better even if electricity is converted into thermal energy in the Steam Buffer.

The steam buffer can also be charged by thermal energy from concentrating solar collectors which, convert solar energy into steam with an efficiency of 65 % compared to solar energy to electricity with 15 % for a PV, meaning that Well To Wheel is better for a Solar Steam system than a Solar Electric system. The price for a concentrating solar collector and a PV is about the same which would mean lower cost for the Solar Steam system.

Electric steam power

In the above the steam engine has been mainly compared with electric propulsion because it is electric propulsion that most people believe will offer the greenest propulsion system. The bottle neck for electric propulsions seems however still be the electric batteries. .

Only Electric

EV or HEV is today on almost all vehicle manufacture agenda. As mentioned above using electricity to produce steam and store the thermal energy in a TES (Thermal Energy Storage) is also possible. However, a TES has lower energy density (kWh/kg) than a Li-Ion battery and a steam engine with TES that is only running on electricity is not a winner.

However in the same as ICE and electric propulsion system form electric hybrid a Steam engine can form an electric hybrid. There are several possible advantages with a steam electric hybrid compared to an ICE-Electric hybrid. First, the many different fuels that are described above can be used. Depending on market and available fuel, the burner is selected. Second the high part load efficiency for the steam engine means that a parallel hybrid with high peak power (kW/kg, kW/USD) but still low fuel consumption is possible to realize. Third the steam engine can also offer regenerative engine braking and complement the electric propulsion engine braking

Environment impact

Besides the above mentioned qualities as performance, energy conversion efficiency, round trip efficiency etc. there are important parameters as cost and environmental impact. The amount of material and its cost are the parameters that mostly determined the product cost in mass productions. Most people think steam engine has to be bulky and weight a lot. As mentioned above the modern steam engine is much more compact than old classic steam engine. Actually, the power density defined as weight per kW for the whole drive train can be less than for a conventional ICE. The material availability and the environmental aspect also influence long term cost. The steam engine proper and the steam generator is mainly built of steel , some graphite and in the 300 bar 1000 C version, ceramics material has to be used in some components. The material used in the Steam buffer is a ceramic material and is manufactured from waste material and is today mainly used as landfill and construction material and is claimed to have no environmental negative impact.

Electric batteries are a much more complex product that consists of many different materials. A Lithium –Ion battery consist only a small amount of Lithium and even if Lithium is considered as an environmental friendly component there are other components that is defined as hazardous. As an example, according to U.S. federal regulations, Li-ion batteries are classified hazardous due to their lead (Pb) content. However, according to California regulations, all lithium batteries tested are classified hazardous due to excessive levels of cobalt

Read more at: http://phys.org/news/2013-05-emphasis-recycling-reuse-li-ion-batteries.html#jCp