

Comparing fuel cells and other power trains for different vehicle applications.

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Summary

This paper compares the total cost of ownership (TCO) for fuel cell, battery electric, range extender and biofuel combustion engine power trains. The TCO difference shows that the power trains are suitable for very different vehicle niches. Battery electric vehicles can reach the lowest cost per kilometer, but only if the battery is utilized very much. Fuel cell range extender vehicles are cost effective for vehicles requiring long driving range but typically driving shorter distances. Internal combustion engine power trains will have the lowest TCO for vehicles with short driving distance during their life, even if the biofuel is rather expensive.

Keywords: Cost, Powertrain, Fuel cell vehicle, Battery electric vehicle, Range.

1 Introduction

This paper presents results from a project analyzing the state of the art in fuel cell vehicles and the total cost of ownership for fuel cell power trains and some competing power train types. The project aim is to determine for which vehicles fuel cells are likely to be the most cost effective power train. As a first step in the study, a database was compiled consisting of 109 fuel cell vehicles presented between 2006 and 2016. The database was analyzed to find indications of which fuel cell power train that dominates for different types of vehicles. Also, it was investigated if there are trends in the technological choices.

Figure 1 shows all the fuel cell vehicle in the database, divided according to vehicle type and power train configuration. The figure indicates that hybrid power trains dominate for cars and buses. Here, a hybrid uses a power battery to support the fuel cell and increase the efficiency. If considering the numbers of vehicles on the roads, such hybrids dominate completely. However, data does not indicate any clear trend over time. It could also be noted that there is a large variety of different power trains in the data set. Partly this is because the database includes some concept vehicles, which typically test the extremes. Another reason is that fuel cell vehicle technology still is developing rapidly and there are many possible combinations of fuel cells, batteries and or combustion engines. More results from the database are found in the project report [1].

Given this background, the purpose of this paper is to present the other part of the project, in which a selection of sustainable power trains are compared with a focus on one very important aspect, the cost of ownership. Note that the aim of this study is not to get the perfect and exact costs for the investigate power trains, but rather to describe the mechanisms which make them more or less cost effective for different market niches.

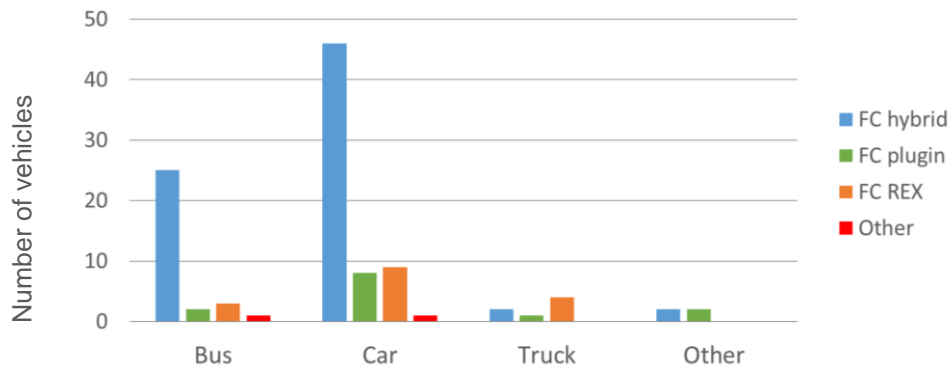


Figure 1: Mix of power trains per vehicle type for the 109 fuel cell vehicles in the database.

2 How the different power train types are compared

There are many factors which can influence what powertrain is preferred in a vehicle. These are for example the *cost*, *functionality differences* and *sustainability* of the different power trains. This study focuses on comparing differences in total cost of ownership (TCO) and only for power trains which have the potential to be sustainable in the long term. Since the TCO shows significant difference between the different powertrains it is believed that this will be an important factor for which power train type to use in vehicles for different niches, but notice that other factors may influence this decision significantly.

TCO is made up of many different parts, of which some of the major are:

- **Investment in the power train**
- **Investment in on-board energy storage**
- **Cost for fuel/energy**
- Cost for infrastructure to supply fuel or energy (may be included in fuel cost)
- Cost for maintenance
- Cost for driver's time to charge/refuel the vehicle

The focus in this paper is on the three first costs. Supply infrastructure is assumed to be included in the fuel or energy price, the cost for maintenance is in this study assumed to be the same for all the power trains. Both these assumptions are rather coarse, and they should be analysed further to get a more complete picture of the differences between different power train options. Driver's time may be an important factor if the charging or refuelling of the vehicle require different time for the driver depending on which powertrain technology is used, however that factor has not been included in this comparison.

2.1 Assumptions for the cost analysis

Instead of first defining the vehicle niches and analysing all different ways in which a vehicle can be used, this study starts in the other end by using the TCO equation and from that determining which parameters we need to describe for the different vehicle niches in order to determine the TCO. This is a way to minimize the number of parameters needed to describe the vehicle niches, as any difference in how the vehicle is used which does not directly or indirectly influence the TCO will not be important to include when comparing TCO. To minimize the number of parameters has one other important advantage, and that is that it can show that two types of vehicles which are used in very different ways, despite their apparent differences, may be very similar when it comes to which powertrain is most cost effective.

The TCO equations used here only describe the main costs which we expect to be different between the different power trains. Costs which are the same irrespective of powertrain are not included.

In these TCO calculations interest rate has been neglected, because it allows eliminating one parameter describing the vehicle niches. If interest rate is not included it does not matter how many years a vehicle lives, as long as we describe how much energy it uses during its life length. Without the influence of interest rate, two vehicles will have the same TCO as long as it has the same energy consumption during their life, no matter how long life length the vehicle has. If the interest rate is only a few percent and the life length of

the vehicles does not differ hugely the influence of interest rate on the TCO variations between different power trains will be a second order effect. This simplification of course introduces an error, but it is justifiable when making a general comparison like in this study as the simplification instead allows us to show a simpler pattern of roughly when a certain powertrain is most cost effective.

Another factor which has been excluded from this analysis is taxes. Taxes play a major role in determining the user's cost for different power trains. However, taxes are often not only a way of generating income to the government but they are also often used to encourage users to select the power trains which the society prefers. Thus they are sometimes used to deliberately shift the cost balance between different power trains. Since we want to analyse the economy from a societal perspective we therefore exclude the taxes, and assumes that in the long run the government will need to tax vehicles equally much irrespective of what technology is selected. The fact that we exclude tax may make our cost comparisons deviate from what the user experiences today, but that deviation is in itself interesting to find as it will be an indication that taxes does not favour the most cost-effective solutions.

2.2 Some parameters describing vehicle niches

The cost of the power train will depend mainly on the performance requirements for its components. The higher performance needed, the more expensive the components will be. For combustion engines and electric motors there are several performance requirements which will influence the cost. In this basic study we just use the power of the engine/motor as the only performance measure, well aware that there are other factors which influence as well. We also include the necessary gears and transmission in the cost of the combustion engine or the electric propulsion motor.

The cost of all the investigated types of on-board storage will change with how much energy they are required to store. Fuel tanks and gas tanks can easily supply energy at a high rate, at no or little extra cost and therefore their cost is not significantly influenced by the power they need to deliver. Batteries, however, have clear limits in how high power they can deliver, and if they are required to deliver high power they will become more expensive either because they need to be made bigger than what is required from an energy perspective, or because more expensive types of battery cells are required. Thus, the power required from the energy storage is also an important cost parameter for batteries.

For a range extender we assume that the power required from it will be the main performance parameter, just like for the engines or motors. The required number of running hours of the range extender may also influence the cost of it, but that has not been included in this cost model.

The specific cost for the energy used by the vehicle will be a large part of the TCO, and therefore the total energy consumption of the vehicle is another important parameter. There are some cases when we may need to describe more details of the energy consumption than just the total energy required, and that is for power trains which can deliver the energy from two different sources with different specific cost of the energy, like for a battery electric vehicle with a range extender. When analysing such power trains we also need to add parameters necessary to determine how much of the energy comes from the different sources.

Summary of key parameters we need to describe for the vehicle niches thus are

- Required power of the power train (P_{PT}).
Note that this power can be delivered by different components in parallel, like for example a fuel cell with a parallel battery which are sharing the power demand during acceleration.
- Maximum energy required to be stored on board (E_{PT}).
This parameter corresponds to the maximum driving range between charges/fuelling.
- Total energy consumption during vehicle life (E_{Life}), measured at the wheels.
This parameter, combined with the average energy consumption per kilometre, correspond to the total life time driving distance of the vehicle.
- For range extender vehicles there is also a fourth vehicle niche parameter:
Fraction of the energy from the grid ($k_{REXgrid}$). This parameter can be evaluated from a distribution of driving range between charging occasions but it also depends on battery size. Therefore it is not only a measure of the vehicle niche, but influenced by how the power train is designed.

3 Power train cost models

In order to determine the power train cost we need a model of how required component size depend on the power train related parameters from the vehicle niches. From the component sizes the cost of the components can be calculated. In the coming section the cost parameters used are presented, and then the sizing of the components are discussed in one section per type of power train.

3.1 Component cost models

The component cost models can have any mathematical form, and in this investigation a simple affine cost model is used for all the components. Thus each component has a starting cost, plus a cost which increase linearly with the size of the component. So for each component there is a start cost parameter and a marginal cost parameter. An affine cost model is mostly accurate enough as long as the size of the components stay within the same order of magnitude. If sizes vary very much a more detailed cost model may be required. For some components, like batteries, affine cost models work well also with big variation in size. In this study the cost parameters in Table 1 are used. The cost for the petrol combustion engine power trains are modelled as

$$Cost_{ICEPetrol}(P_{ICE}) = K_{ICEPetrol} + k_{ICEPetrol} P_{ICE} \quad (1)$$

and similarly for diesel power train

$$Cost_{ICEDiesel}(P_{ICE}) = K_{ICEDiesel} + k_{ICEDiesel} P_{ICE} \quad (2)$$

The fuel tank size depends on the required energy to be stored on-board. Note that the stored energy is calculated at the wheels, and therefore the efficiency of the power train and the specific energy content of the fuel will influence the required tank size and thereby its cost

$$Cost_{TankX}(E_{PT}) = K_{Tank} + k_{Tank} \frac{E_{PT}}{e_{fuelX} \eta_{PTX}} \quad (3)$$

where e_{fuelX} is the specific energy of fuel X and η_{PTX} is the average efficiency of the power train of type X.

Hydrogen tanks have a similar cost model, just that the parameter values are different, and that the tank size of a hydrogen tank is expressed in kg of hydrogen and not in litres as the tanks for liquid fuels are.

$$Cost_{H2Tank}(E_{PT}) = K_{H2Tank} + k_{H2Tank} \frac{E_{PT}}{e_{H2} \eta_{FuelCell}} \quad (4)$$

The cost of a fuel cell is modelled as

$$Cost_{FuelCell}(P_{FuelCell}) = K_{FuelCell} + k_{FuelCell} P_{FuelCell} \quad (5)$$

and the cost of and electric machine with power electronics and a mechanical transmission are

$$Cost_{Emotor}(P_{Emotor}) = K_{Emotor} + k_{Emotor} P_{Emotor} \quad (6)$$

The cost model for batteries are based on the same affine cost models, but since batteries need to be sized to meet both energy and power requirements, and that there are different types of batteries to select from, the model becomes a little more complex. In this cost model it is assumed that there are only two types of battery cells to select from. Either power optimized batteries designed to deliver high power rather than high energy content or energy optimized batteries with the opposite priority. From the required power it is calculated what minimum size, in kWh, the battery can have and still meet the power requirements. The highest of the required storage size and the minimum size to meet the power demand will be the selected and determines the battery cost. This sizing is carried out twice, for both the energy optimized and the power optimized battery cells. The type of cell which leads to the lowest cost will be selected for the investigated power train. Thus the battery cost can be expressed as

$$Cost_{batt}(P_{batt}, E_{batt}) = \min(Cost_{Ebatt}(P_{batt}, E_{batt}), Cost_{Pbatt}(P_{batt}, E_{batt})) \quad (7)$$

where

$$Cost_{Ebatt}(P_{batt}, E_{batt}) = K_{Ebatt} + k_{Ebatt} \max\left(E_{batt}, \frac{P_{batt}}{C_{Ebatt}}\right) \quad (8)$$

$$Cost_{Pbatt}(P_{batt}, E_{batt}) = K_{Pbatt} + k_{Pbatt} \max\left(E_{batt}, \frac{P_{batt}}{C_{Pbatt}}\right) \quad (9)$$

The petrol engine range extender is basically a petrol engine plus a generator and thus the cost model is

$$Cost_{ICEREX}(P_{REX}) = K_{ICEREX} + k_{ICEREX} P_{REX} \quad (10)$$

where

$$K_{ICEREX} = K_{ICEPetrol} + K_{Emotor} \quad (11)$$

$$k_{ICEREX} = k_{ICEPetrol} + k_{Emotor} \quad (12)$$

As a fuel cell already delivers its energy in form of electricity it can be used as range extender with no important modification and therefore the cost of a fuel cell range extender is the same as the cost of a fuel cell of the same power.

Basic data for determining the cost parameters has been taken from many sources, and they are then analysed by the experts involved in the project to find what we think is the most realistic values for our purpose. Therefore there is no single reference for the parameter values, but they are for example based on reports like [2]. Note also that the aim of the study is not to get the best absolute cost values, but the find what are the main cost differences which influence which is the most cost effective power train technology. Thus, some errors in parameter values are acceptable as long as they do not radically change the cost balance between the different power trains. It can be noted that the found differences in investment and operating costs between the different powertrains are rather big, and therefore it seems that the conclusions are not very sensitive to errors in the cost parameters. As the new power train technologies becomes more mature it is recommended to repeat this type of analysis, with more accurate cost models.

Table 1: Component cost model parameters

Component	Start cost parameter	Value	Marginal cost parameter	Value	Additional parameters	Value
Petrol engine w. transmission	$K_{ICEPetrol}$	600 \$	$k_{ICEPetrol}$	9 \$/kW		
Diesel engine w. transmission	$K_{ICEDiesel}$	1000 \$	$k_{ICEDiesel}$	15 \$/kW		
Electric motor with inverter & transm.	K_{Emotor}	200 \$	k_{Emotor}	35 \$/kW		
Fuel cell	$K_{Fuelcell}$	1000 \$	$k_{Fuelcell}$	40 \$/kW		
Petrol engine REX	K_{ICEREX}	800 \$	k_{ICEREX}	44 \$/kW		
Fuel cell REX	$K_{Fuelcell}^1$	1000 \$	$k_{Fuelcell}$	40 \$/kW		
Energy optimized Battery	K_{Ebatt}	200 \$	k_{Ebatt}	250 \$/kWh	Max discharge rate	4 C
Power optimized Battery	K_{Pbatt}	200 \$	k_{Pbatt}	500 \$/kWh	Max discharge rate	15 C
Fuel tank	K_{Tank}	50 \$	k_{Tank}	1 \$/litre		
Hydrogen tank	K_{H2Tank}	300 \$	k_{H2Tank}	360 \$/kg		

3.2 Combustion engine power train (ICEV)

For power trains with only one source of power, like a conventional combustion engine power train, sizing is easy since the engine power will need to be the same as the total required power for that vehicle niche, P_{PT} , and the tank will need to be sized according to the energy required between refuelling, E_{PT} . Thus the cost for a petrol power train can be modelled as

$$Cost_{ICEPetrolPT}(P_{PT}, E_{PT}) = Cost_{ICEPetrol}(P_{PT}) + Cost_{TankPetrol}(E_{PT}) \quad (13)$$

and the diesel power train cost is modelled in the same way

$$Cost_{ICEDieselPT}(P_{PT}, E_{PT}) = Cost_{ICEDiesel}(P_{PT}) + Cost_{TankDiesel}(E_{PT}) \quad (14)$$

3.3 Fuel cell power train (FCEV)

A fuel cell power train will always use a battery in parallel with the fuel cell to handle transients in power demand which the fuel cell is not quick enough to follow and to store regenerated brake energy. Therefore we need to determine how high power the fuel cell needs to deliver and how much the battery shall be required to deliver. There is a minimum size of the battery which allow good enough transient response of the power train, and we have set this to $P_{FCbattMin} = 30$ kW for a typical car. There is also a minimum size of the fuel cell which is determined by the highest average power demand the power train is required to deliver for about 10 minutes or more. For such long time the battery cannot contribute much as it will soon be emptied. For cars the highest long term average power demand seem to be high speed motorway driving or perhaps climbing high mountains. For driving a car on a motorway with power for climate conditioning the power required in average will be about $P_{FCMin} = 30$ kW for many cars. This will be the lowest power the fuel cell can be sized for, and equally the minimum size of a range extender.

The sum of the battery power and fuel cell power must be equal to, or bigger than, the required power train power. To minimize the cost it has been assumed that the battery power plus fuel cell power shall equal the required power train power. This is not in itself sufficient information to size the components since there are many possible combinations of battery power and fuel cell power which meet the power requirement for the vehicle niche. We have assumed that the vehicle manufacturer will select the minimum battery size of $P_{FCbattMin} = 30$ kW and the rest of the power train power from the fuel cell. Thus the fuel cell power train cost will include cost for the fuel cell, a battery, a hydrogen tank and an electric propulsion motor

$$\begin{aligned} Cost_{FuelCellPT}(P_{PT}, E_{PT}) = & Cost_{FuelCell}(P_{PT} - P_{FCbattMin}) + Cost_{Battery}(P_{FCbattMin}, 0 \text{ kWh}) + \dots \\ & \dots + Cost_{H2Tank}(E_{PT}) + Cost_{Emotor}(P_{PT}) \end{aligned} \quad (15)$$

3.4 Battery electric power train (BEV)

The sizing of the components in a battery electric power train is very simple since the propulsion motor and the battery simply will need to meet the requirement for whole power train

$$Cost_{BEVPT}(P_{PT}, E_{PT}) = Cost_{Battery}(P_{PT}, E_{PT}) + Cost_{Emotor}(P_{PT}) \quad (16)$$

3.5 Range Extender power train (FCREX and ICEREX)

A range extender vehicle, either with fuel cell range extender or combustion engine range extender will be most economic to size the range extender only for the highest average power demand, which in this study is assumed to be $P_{REX} = 30$ kW, as described in the section on fuel cell sizing above. A range extender power train is not fully defined by the power train requirements from the vehicle niche, as the range requirement can be met in different ways. Either the battery can be small, and then the fuel tank need to be bigger, or the battery can be bigger and then the tank can be smaller. The concept of range extender only makes economic sense for vehicles which have a typical driving range which is much smaller than the longest driving range they are required to handle, which is the case for most private cars. The concept also is developed since the cost for a big battery is very high compared to the cost of a big tank. Thus a range extender vehicle typically is designed with a rather small battery. In this study the battery size has been set to $E_{REXbatt} = 10$ kWh, as a reasonable size which can handle a large part of the driving on the battery and also meet reasonable power requirements when run only on the battery. In a more thorough study the battery size should be varied depending on how different vehicles are used, but that is not done in this study. The variation in driving range have not been defined in detail, but instead it has been assumed that 67% of the total energy consumption comes from charging and the remaining 33% from fuel.

In this study only series hybrid range extenders are analysed and it is assumed that the vehicle shall have full performance when driving only on the battery, without support from the range extender. The cost for a fuel cell range extender power train will thus include cost for propulsion motor, a battery and fuel cell

$$\begin{aligned} Cost_{FCREXPT}(P_{PT}, E_{PT}) = & Cost_{Battery}(P_{PT}, E_{REXbatt}) + Cost_{Emotor}(P_{PT}) + Cost_{FuelCell}(P_{REX}) + \\ & \dots + Cost_{H2Tank}(E_{PT} - E_{REXbatt}) \end{aligned} \quad (17)$$

Similarly, the petrol engine range extender power train will cost

$$Cost_{ICEREXPT}(P_{PT}, E_{PT}) = Cost_{Battery}(P_{PT}, E_{REXbatt}) + Cost_{Emotor}(P_{PT}) + Cost_{ICEREX}(P_{REX}) + \dots + Cost_{TankPetrol}(E_{PT} - E_{REXbatt}) \quad (18)$$

4 Power train cost for different vehicle niches

The investment part of the TCO will depend on the requirement on the power train and the required on-board energy storage. In Figure 2 the cost of 100 kW power trains are plotted as functions of required on-board energy storage. Note that the cost for a battery electric power train has two plateaus in the cost curve. This is because the battery will need a minimum size in order to meet the power demand, and a smaller battery cannot be used even if the energy requirement allows it. The first plateau in the diagram, between 0 and 6 kWh, is when the energy requirement is so low that power optimized batteries are the cheapest but they are sized by the power requirement. Above 6 kWh the cost increase as bigger and bigger power optimized batteries are required. At 12 kWh there is a second plateau, and that is because energy optimized batteries are cheaper than power optimized, even though they need to be oversized to meet the power demand. Above 25 kWh energy optimized batteries are cheapest and they are sized by the energy requirement, leading to a cost increasing linearly with energy requirement. The same phenomena can be seen in the cost for the two range extender power trains. However, in contrast to the battery power train the batteries are not increased above 10 kWh and any energy requirement higher than that is met by increasing the fuel tank size instead.

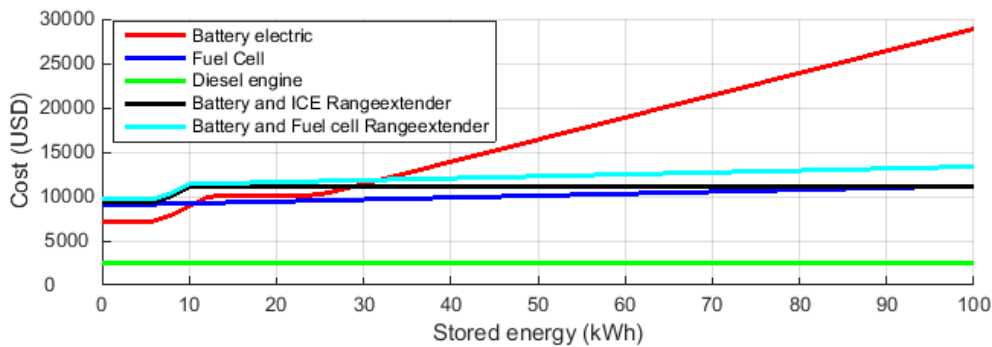


Figure 2: The investment cost in 100 kW power trains as function of on-board energy storage

It can be seen that combustion engine power trains are by far the cheapest, with almost no additional cost for increased on-board storage, the battery power train is cheaper than fuel cell power train, but only if the required on-board storage is lower than about 10 kWh, which would give a very low range of about 65 km per charge. The fuel cell based power trains have a small but noticeable cost increase as the stored energy is increased, due to the rather high cost of hydrogen tanks.

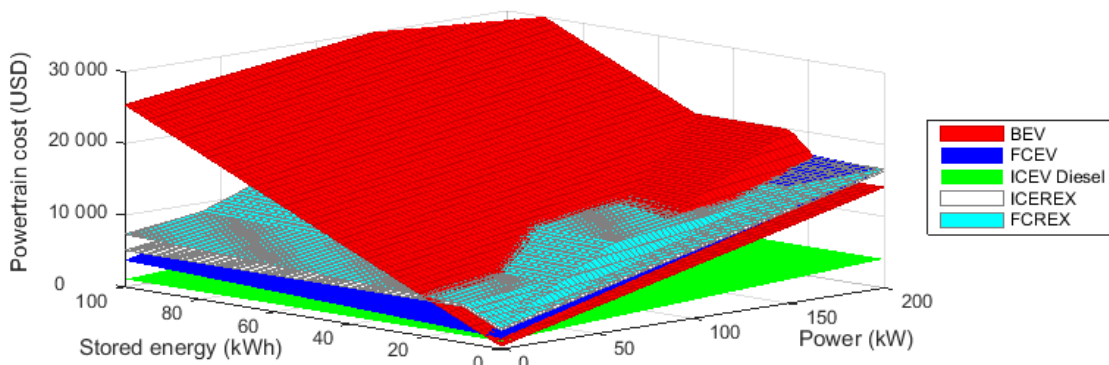


Figure 3: The power train cost for different vehicle specifications.

If we also vary the required power train power the cost curves in the 2D plot in Figure 2 will become a 3D plot as shown in Figure 3. Notice that the cost of the battery power train varies in a completely different way than the cost of other power trains, which is a main reason why it is very important to define which vehicle niche is analysed before answering which power train is the most cost effective. The combustion engine is still the cheapest power train for all realistic vehicle specifications. However, there are very important

differences in fuel/energy cost between the different power trains, which needs to be included before it is possible to draw conclusion on which power train is most cost effective.

5 Fuel and energy cost

In this chapter the operating cost of the different power train types is analysed. The energy cost at the wheels for different power train types can be determined from the specific fuel cost and the specific energy of the fuel together with the average efficiency of the power train type as

$$Cost_{EnergyWheel} = \frac{k_{fuel}}{e_{fuel} \eta_{PTtype}} \quad (19)$$

The parameter values and cost of the energy at the wheels for the different power train types are given in Table 2. It can be seen that the cost for the energy varies by a factor of 536% between the cheapest and most expensive power train type. The order of increasing cost for energy is BEV, FCREX, ICEREX, FCEV, ICE biodiesel, ICE biopetrol.

Table 2: Parameters for specific fuel/energy consumption and cost.
Conventional petrol and diesel only included as references, as they are not sustainable.

	Specific “fuel” cost without tax, k_{fuel}	Specific energy e_{fuel}	Average efficiency “Tank”-to-wheel η_{PTtype}	Energy cost at the wheels
<i>Petrol (unsustainable)</i>	0.71 \$/l	9.7 kWh/l	25 % (mild hybrid)	0.29 \$/kWh
<i>Diesel (unsustainable)</i>	0.71 \$/l	10.7 kWh/l	30% (mild hybrid)	0.22 \$/kWh
Bio-Petrol	1.41 \$/l	9.7 kWh/l	25 % (mild hybrid)	0.59 \$/kWh
Bio-Diesel	1.41 \$/l	10.7 kWh/l	30% (mild hybrid)	0.44 \$/kWh
Hydrogen	5 \$/kg	33 kWh/kg	50%	0.30 \$/kWh
Electricity from grid	0.1 \$/kWh	n.a.	90%	0.11 \$/kWh
FC Range extender 33% on Hydrogen	5 \$/kg and 0.1 \$/kWh	-	50% and 90%	0.17 \$/kWh
ICE Range extender 33% on Bio-Petrol	1.41 \$/l and 0.1 \$/kWh	-	25% and 90%	0.27 \$/kWh

5.1 How energy consumption during vehicle life influence the TCO

The relative importance of low cost for the power train and low cost for the fuel/energy depends on how much energy the vehicle will use during its life. For a vehicle which is driven very little it will be sound to select the power train with the lowest cost of the power train itself. For a vehicle driving extremely long it will in principle be best to select the power train type with the lowest cost for the fuel, almost regardless of the cost for the power train itself. An example of how the TCO can be compared for a fixed power train specification is shown in Figure 4. There we can see a comparison between 100 kW power trains for cars, with on-board storage capacity capable of delivering 75 kWh (to the wheels). To make it easier to interpret the results the x-axis has been rescaled from total energy during the vehicle life into driving distance, using an energy consumption of 0.15 kWh/km.

The cost of a power train can be read at the y-axis, since the cost of the energy consumption is zero there. It can be seen that the cheapest power train is the petrol engine power train, followed by the diesel engine power train. The fuel cell powertrain is significantly more expensive than the combustion engine powertrains, and the most expensive powertrain is the battery electric power train. However, the specific cost for the wheel energy, or in this case the cost per driven km, is also very different between the different powertrains. This can be seen as the varying slope of the TCO curves in the diagram. The cost per km to run a petrol engine on bio petrol is the highest and therefore the investment cost advantage of that powertrain is quickly lost once the vehicle runs longer distances. At about 50'000 km driving the higher investment in the diesel powertrain has been paid back by its lower running costs. The fuel cell powertrain is far more expensive than the diesel powertrain, but if it runs more than 380'000 km the lower operating cost will compensate for its higher cost than the diesel engine. The battery electric vehicle has the lowest running cost of all these powertrains, but due to its very high powertrain cost it takes very long driving distances for it to have lower TCO than the fuel

cell powertrain. In this example it takes 430,000 km until the low running cost compensates for the high powertrain cost, almost no private car will drive that long. Note, that this is only one of many possible examples, and changes in battery size, the investment cost or energy cost will significantly change the total driving ranges at which the different powertrains are most cost effective. Another important observation is that for traditional combustion engine powertrains the fuel cost during the vehicle life exceed the total cost of the power train, while for battery electric powertrains, and perhaps also for fuel cell powertrains, the investment in the powertrain may be bigger than the total cost of fuel/energy during the whole life of the vehicle.

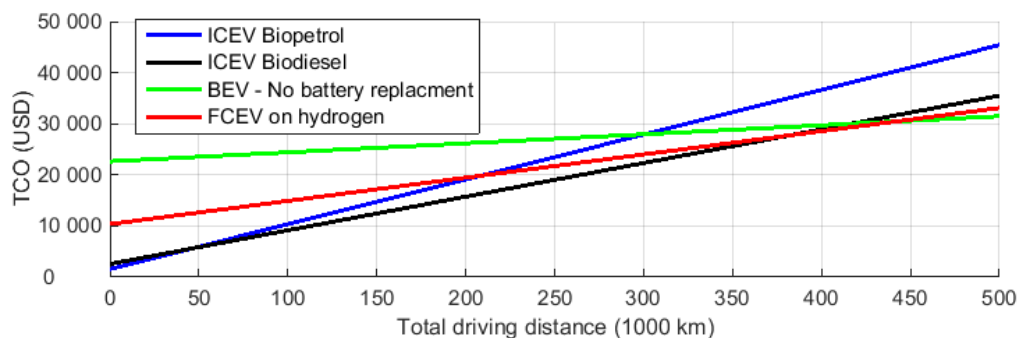


Figure 4: Example of TCO for some power trains to show the effect of total driving distance during the vehicle life, without fuel taxes.

5.2 Cost for battery replacement

For the battery electric car there may also be an additional operating cost, if the battery has to be replaced during the vehicle life. As the battery is a very expensive component, it will radically change the operating cost. Batteries life length can be described in number of cycles, but the number of cycles a battery lasts depends strongly on how much energy is charged in each cycle, and to complicate it even more, very few vehicles are used such that they are charged equally much each time. Instead of defining exactly how the battery is used, the TCO equation help us determine how to describe the life length in a way which describe the influence on TCO in the simplest way. Defining a battery utilization factor, as how much energy the battery has cycled during its life length expressed in units of the capacity of the battery (C) is a very good measure as it can tell how much energy the vehicle can use during its life length before the battery has to be replaced. A battery which is charged fully in each cycle and lasts 2000 cycles, will have a battery utilization of 2000C. A more typical BEV battery will during its life often not cycle more than 667C since it has to be sized for rather long driving range, which is rarely used. A private car with a battery very well sized for a fixed commute distance will perhaps reach a battery utilization factor of 1,800C. Higher battery utilization than that is difficult to achieve for a privately used BEV, unless the battery is charged more than once per day. A vehicle which can have a very high battery utilization is city buses with charging at each end stop. Their batteries typically are sized for much more energy than what is charged at each end stop, but since they charge something like 10-20 times per day they can reach battery utilizations of about 13,000C. This high battery utilization is possible since batteries which are only charged about 25% of their full capacity in each charge can live more than 100,000 cycles.

In Figure 5 the cost for the energy is plotted as a function of the total energy consumption during the vehicle life. The cost for the BEV powertrain is also plotted for a powertrain in which battery utilization is 13,000C, 1,800C and 667C. In the diagram it can be seen that the operating cost of the vehicle takes a step upward each time the battery needs to be replaced. It can be seen that a battery which reach 13,000C utilization does not significantly add to the operating cost, while the cost to replace a battery after 1,800C will increase the cost for running a BEV so much that it is a little higher than the operating cost of the fuel cell vehicle. Should the battery need to be replaced after a utilization of only 667C the operating cost for a BEV becomes higher than for a biodiesel powertrain and almost as high as the cost to operate a biopetrol engine powertrain.

Of course very few private cars will replace their batteries many times during the life length, or even once, so the yellow curve should not be interpreted that vehicles will be designed such that they require many battery replacements during their life. It will typically be cheaper to oversize the battery and thus allow it to

last many more cycles. Still the curves in Figure 5 show that in order for battery electric powertrains to be much cheaper to operate than the other alternatives, the battery utilization must be high, preferably much higher than what is possible in many private cars due to their typical usage profiles. Really low operating cost is possible for BEV's but only if battery utilization is several thousand times the capacity, which is only realistic if the battery is rather small and instead is charged more than once per day during its whole life.

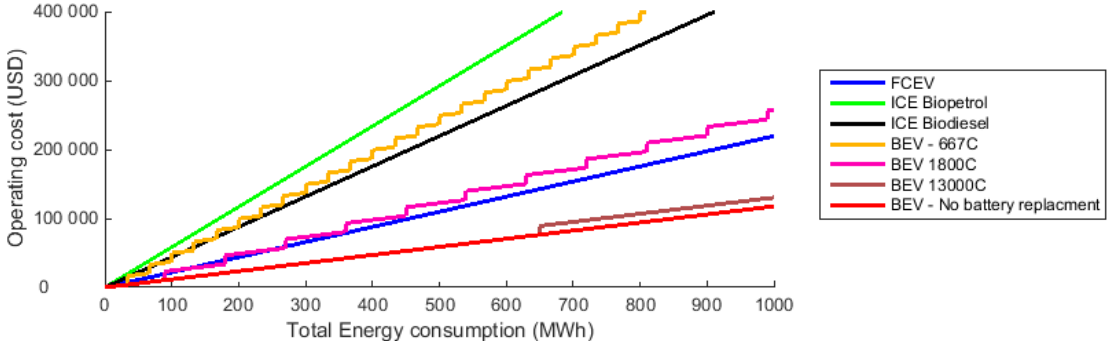


Figure 5: Operating cost as a function of total energy use during vehicle life, including battery replacement cost.

6 TCO comparison for different vehicle niches

In this chapter the TCO is compared for vehicle niches with different combinations of *stored on-board energy* and *total energy used during the vehicle life*, for 100 kW powertrains. To make it easier to interpret the values of stored energy and the energy consumption during the life, they have both been translated into distances assuming an energy consumption of 150 Wh/km which is a value relevant for cars. The powertrain with the lowest TCO has been selected for each vehicle niche. First this comparison is made only for battery electric vehicle and a fuel cell vehicle with no plug-in battery. The results are shown in Figure 6 in which the colour represent which of the power train has lowest TCO for a certain vehicle niche. To make it easier to interpret the diagram, some different types of car types are shown in the diagram. Note that variations in how a car is used can be very large, so the different cars types shall only be seen as very rough examples of where in the diagram that type of car can be found. It can be seen that the battery electric car is cheapest in a large segment of vehicle usage, however, the fuel cell wins for general purpose private cars, while BEV is better for example for long distance commuting cars with rather small range.

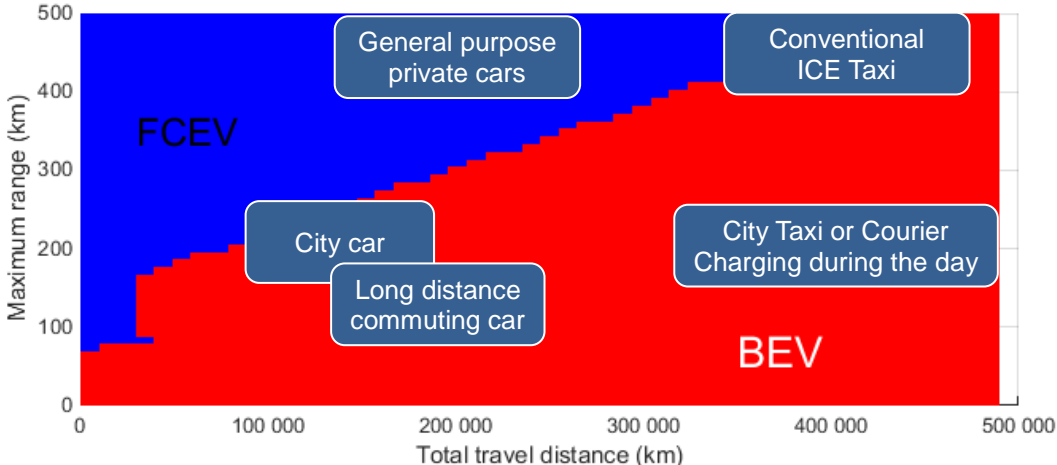


Figure 6: The cheapest power train solution, of FCEV and BEV, for different vehicle usage profiles.

The same analysis is repeated but now including also biodiesel combustion engine powertrains and battery electric vehicles with different range extender solutions. The results of that is presented in Figure 7. There, it can be seen that the biodiesel combustion engine takes over a large segment from the FCEV and the BEV. The segment in which biodiesel powertrain is most cost effective is vehicles driving short to medium long distance during their life length, except for some niches in which low driving range is sufficient. The pure

fuel cell powertrain is no longer a winner, but instead a battery electric vehicle with fuel cell range extender is a winner for vehicles with long driving range per tank and also long total range during its life. The BEV still is a winner in the lower right corner, but compared to the earlier case its part of the possible market has been reduced rather much by both the other powertrains. Note that the Fuel cell range extender wins under the assumption that it can be driven 67% on energy from the electric grid. For vehicles which can only have a small part of the energy from the grid a traditional fuel cell power train will be more cost effective than the fuel cell range extender power train.

Another result of this investigation is that even though it seems like the battery electric vehicles can take a large part of all possible vehicle usage segments, it is a segment in which very few of today's BEV vehicles are found. The main limitation is that the vehicle must be charged several times per day in order for a BEV to reach the really low TCO. It is mainly some commercial vehicles and car sharing vehicles and perhaps long distance commuting vehicles which are likely to be used in that way. More typical private cars seems have lower TCO if they use combustion engine on biodiesel or a fuel cell range extender powertrain. It shall however be repeated, that the selection of power train is not only determined by the lowest TCO, so this shall not by itself be seen as a final answer to what powertrain will be a winner in what segment.

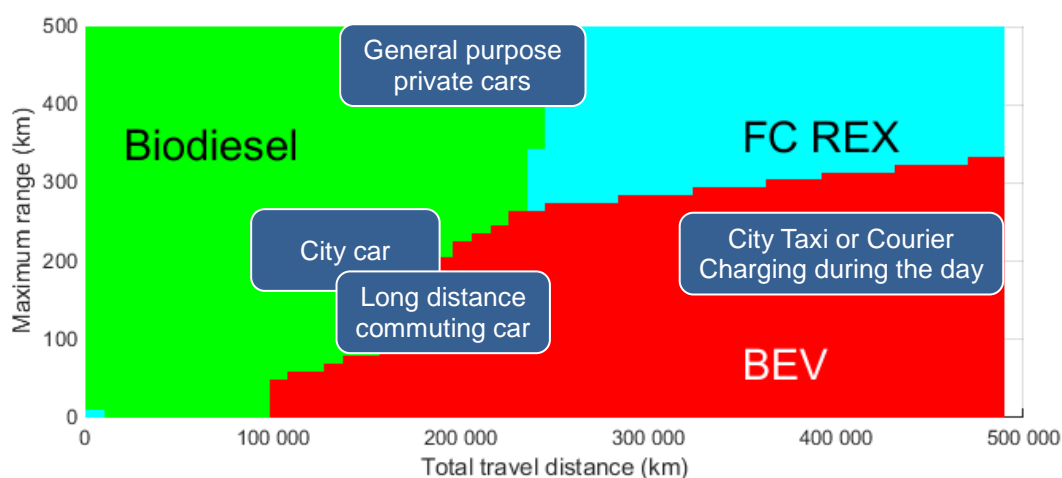


Figure 7: The cheapest power train solution for different vehicle usage profiles

7 Summary

This study makes a qualitative comparison of TCO for different sustainable powertrains, for different vehicle niches. It is found that key parameters for determining which power train is most cost effective are the *power of the power train*, the size of the *on-board energy storage*, and the *total energy consumption* during the vehicle life. For range extender power trains the *fraction of energy which can be charged from the grid* is also a key parameter for the TCO. The battery utilization factor is also found to be a key indicator for if a BEV will be cost effective, and utilization of 2000C or higher is required for really low TCO for a BEV.

The TCO analysis shows that the cost parameters for the different power train types are so different that it is unlikely that one power train type will be suitable for most types of road vehicles. BEV's have a potential to have very low TCO, but only if they drive very long distance during their life and the required driving range per charge is not too long. If longer driving range is required battery electric cars with fuel cell range extender are more cost effective. For vehicles with a short to medium long driving distance during their life biofuel combustion engine seems to be most cost effective, due to the very low cost for the power train.

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