EVS27
Barcelona, Spain, November 17-20, 2013

Energy chain and efficiency in urban traffic for ICE and EV

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Abstract

Well to Wheel (WTW) efficiency is divided into Well to Tank (WTT) and Tank to Wheel (TTW). For ICE, WTT is much more efficient than TTW. For EV the opposite is the case. Over the whole WTW energy chain, only the best case for ICE is slightly more efficient than the worst case for EV. Although the TTW-efficiency for ICE will still increase, due to Peak Oil, WTT-efficiency for ICE will decrease. If sustainable electricity supply grows, WTT- efficiency of EV will increase. Moreover, the TTW-efficiency for EV in urban traffic is still increasing, among others through more effective regenerative braking.

Keywords: efficiency, energy recovery, energy chain

1 Introduction

A lot of discussions concern the efficiency of Electric Vehicles (EV) compared with Internal Combustion Engines (ICE). The persistent belief in the inefficiency of Power Plants has led to the widespread assumption that EV is less efficient than ICE for the entire energy chain. In this paper the efficiency of some relevant energy chains for electricity is compared with that of crude oil to petrol and diesel. The variety in comparisons to the efficiency between EV and ICE complicates the discussion. Moreover the location of the energy source also influences the results. Not only because of the energy required for transportation, but also because the quality of the energy source is relevant. In this paper oil, natural gas, coal, wind and water form the bases of the energy chains for operational vehicles which are used in Rotterdam, the Netherlands. This energy chain study is executed as part of the eMobility-lab research of the Rotterdam University of Applied Sience.

2 Methods

The energy chain is divided in Well-to-Tank (WTT) {fig 1} and Tank-to-Wheel (TTW). Both parts contain different possibilities and their specific energy losses. Therefore it is chosen to provide an optimistic and a pessimistic result. The realistic result is defined asthe mean between optimistic and pessimistic results except when several (>2) sources indicate the same value; then this value is taken.
The data and findings from the Tank-To-Wheel report [1], the Well-To-Tank report [2] and the Well-To-Wheel report [3] from the EU are used for the WTT for ICE.
The Green Power for Electric Cars from Kampman et al. [4] support these figures.

The oral information from the president of Shell Netherlands BV [5] that the current energy costs are 0.2 barrel for the production of 1-barrel oil, is not found on paper yet, but should be kept in mind and adds to the credibility of the estimations for the Energy Return on Energy of Investment (EROI) from Nathan Gagnon et al [6]. This is used for the outlook to the future.

In the TTW analysis the brakefactor (BF) as proposed by Van Sterkenburg et al. [7] is used. The BF indicates the possible regenerative brake energy (W_{brake}) of the vehicle in a certain trip based on a measured drive cycle. In “Using regenerative braking a must for the environment!” [8], the potential profit is discussed.
The figures used for the estimations were based on middle class cars (1050 – 1350 kg exclusive batteries) in urban traffic of Rotterdam. Because of usability in other energy pathways or drive cycles the efficiency is expressed in terms of percentage rather than in energy per unit distance. The energy losses by evaporation of petrol and the self-discharging of batteries were left out. They are small and depend on the conditions of use.

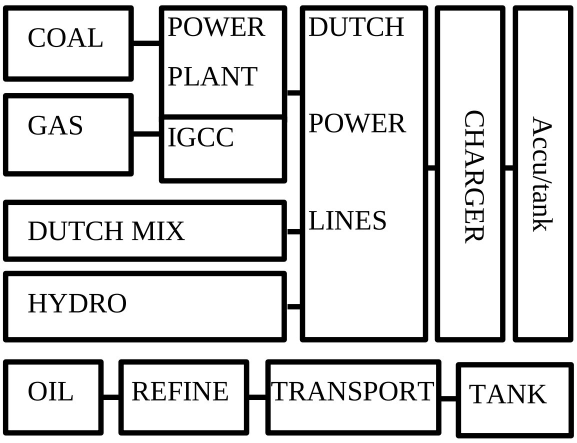


Figure 1: Overview of the considered energy pathways for EV and ICE. IGCC represent the integrated gasification combined-cycle. Hydro represent the Green Certificate used by the Rotterdam public transport provider RET.

3 Results

The research and development of tyre manufacturers has resulted in a generic increase in overall efficiency. The European Commission made targets for the efficiency of the tyres [9]. Both ICE and EV share the same benefits of this development.

3.1 ICE

3.1.1 Well-to-Tank ICE

Crude Oil has an efficiency of 0,025 MJ/MJ with a variation in the range from 0,01 – 0,04 MJ/MJ [3]. Even though the Proved Reserves are still growing [10], in time this probably does not compensate the growth in energy consumption and the trend that the energy needed for exploration and production is rising as well [6]. Oil transportation has a loss of 1 % including the empty return of the tanker. Refining in Europe has a loss of about 6 %. This is a conservative figure because the EU-report [3] gives 0,08 MJ/MJ for gasoline and 0,10 MJ/MJ for diesel. However, the side-products of the refining are disturbing a clear view on the energy needed. Distribution of petrol and diesel takes about 20 kJ/MJ [3]. The energy needs for the filling station (lighting etc.) is only of interest when the turnover is very low.
For the US the story about Peak Oil [11] seems to be history with the exploration of shale oil. However the EROI of shale oil according to Cleveland’s study [12] varies in the range from 1 barrel needed for the production of 1 to 2 barrels for the whole process and in another more optimistic case 1 for 2 to 16. For the time being shale oil is a negligible factor in Europe. In the USA shale oil and shale gas are currently booming [13] and as side effect export of coal to Europe is increased. These instabilities in the fossil energy market will influence the efficiency for the Power Stations and consequently the EV.

3.1.2 Tank-to-Wheel ICE

For the TTW-efficiency the engine losses are the most dominant. Van Mierlo [14] and the CE-report [4] mention for urban traffic an efficiency range from 13 % to 20 %. The introduction of start-stop systems will increase the efficiency. Mazda claims 14 % efficiency increase [15]. Bosch claims 8%. The practical profits and use of this system are not known yet. Less than 5% of the fleet of cars in the Netherlands is equipped with this system (2012), but its share is fast growing. In the Netherlands 35 % of the new cars are equipped with this system and 40% in Belgium [16].
City cars with a lower mass are also more efficient. Nissan has co-developed Advanced High Tensile Strength Steel and claims that extensive use of this material can reduce mass by 15% for all its models in 2017 [17].

3.1.3 Well-to-Tank ICE

Figure 2 represents the relative energy losses. In urban traffic the useful energy for middleclass cars is 11% to 18% of the energy of the raw material. From the energy of the raw materials 83% to 88 % reaches the tank. The biggest energy loss of 80% to 85% is due to the poor mechanical efficiency of the ICE engine [4] when unfavourable Urban traffic conditions are taken into account.

Figure 2 Mean relative energy-loss for ICE

3.2 EV

3.2.1 Well-to-Tank EV

The WTT for EV highly depends on the choice of the type of Fossil Energy Power Station or Green Energy source. In the different literature sources [2], [4], [14] the results hardly differ.
The coal power plant has an efficiency of 39%. With integrated gasification combined-cycle (IGCC) an efficiency of 44% to 55% is possible. In case of CO2 Capture and Storage (CCS) a loss of efficiency of 8% is expected. In the Netherlands CCS is not yet deployed since the safety is publicly disputed and cost efficiency is low.
A gas power plant has an efficiency of 43%, with a combined cycle this can increase to 55%. The typical energy mix in the Netherlands includes coal, gas and some nuclear and renewables has an efficiency of 42% [4].

Despite the fact that the Green Certificate is based on renewable Hydro, in reality also this energy chain is not free of efficiency losses. The transportation of hydro energy from Norway causes extra losses of minimum 4% [18][19]. In detail the efficiency is 96,0 % if the power transportation through the NorNed High Voltage Direct Curent (HDVC)-cable is 600 MW and 94,5 % if the power is 700 MW.
Most Norwegian hydropower plants are equipped with Francis turbines. The efficiency of a Francis turbine is 90 % or higher [20]. The generator has an efficiency of 97%.
Most power plants feed in the extra high voltage line. In the Netherlands the total grid losses are the last years stable 5 % [21]. In table 1 is insight in the details.

Table 1: Loss of Energy due to transportation and transformation in the Dutch Power Lines [21]

Cause:	Loss [%]
Extra high voltage line 380/250k	0,9
High voltage line 150/110 kV	0,6
Medium voltage line 10/50 kV	0,1 .. 2,7
Transformer high/medium voltage	0,5
Transformer medium/low voltage	1,1 .. 2,6
Low voltage line 230/400 V	1,4

By local circumstances the efficiency of the power line will vary from 92% to 96%.
The battery charger can, depending on the Electric Vehicle application, be part of the grid or of the vehicle and is available in different qualities [22]. The efficiency varies from 76 to 98%. In this study it was chosen to consider it to be part of the grid, because this makes the battery more comparable with the tank.

3.2.2 Tank-to-Wheel EV

For EV the TTW-efficiency is much better than for ICE. Overall driving efficiency of the Tesla Roadster is 88% [23]. In practice the driving efficiency of EV’s will strongly depend on the amount of regenerative braking [8] and the efficiency and mass of the battery. The efficiency of the motor depends more on the costs rather than on the physical possibilities. Regenerative braking has a direct positive effect on the WTW-efficiency. In urban traffic the use of regenerative braking will offset the mass effect (table 2). In that condition BF can be 0,5. In figure 3 the potential profit in raw material use at the energy source as a function of BF with different internal losses is given.

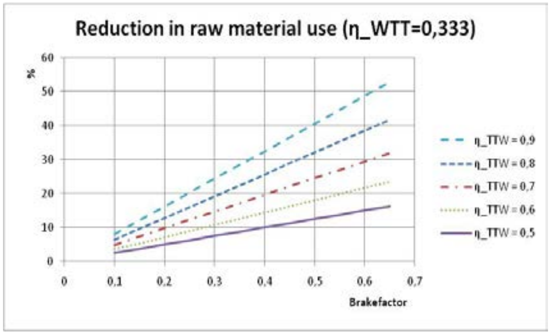


Figure 3: Reduction in raw material use

Figure 5 shows an example of the measured regenerative energy (negative current) in e-Busz at Rotterdam.

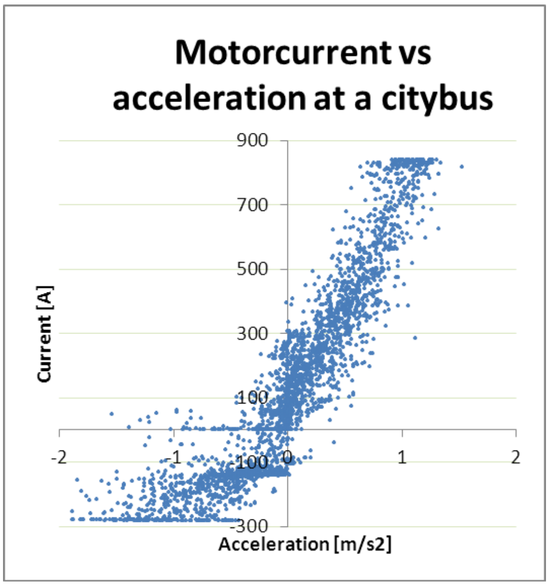


Figure 5: Regenerative braking measurements in a city cycle of a city bus [8]

The built-in safety limitations in the converter still give significant possibilities to optimize the regeneration process if you compare the relative low negative current for deceleration with to the higher positive current for acceleration.

For reason of simplicity for the mass effect it is pessimistically assumed that the energy consumption is proportional to the mass. Furthermore because of the low urban speeds the air resistance is left out of the equation. The mass of the battery pack is highly dependent on the target range. A battery pack of 200 kg with the mass of the vehicle of 1100 kg leads to a pessimistic efficiency of 0.82.

The advantage of regenerative braking by Sterkenburg [7] measured at the Binkie (5500 kg) respectively Parkshuttle (4650 kg) 1.3 MJ to 6.7 MJ and 1.5 MJ to 6.6 MJ. That results in an efficiency factor of 1.24 respectively 1.29.

For a middle class vehicle a conservative estimate of a BF is 0.4 which at 60% TTW-efficiency gives an efficiency factor of 1.15 (see Figure 3, 15% reduction in raw material).

At high speed the power delivery of the generator is limited. Therefore, usually in addition to regenerative braking, also the mechanical brake is used. Regeneration with low speeds indicates a impedance problem between the generator and the battery. Therefore the Lexus uses only the mechanical brakes with speeds lower than 7 km/h and also uses mechanical brakes with higher speeds.

For most models it is not known to what portion mechanical brakes are used.

The 1.15 efficiency factor is applied to the pessimistic mass effect to get the optimistic mass effect which than includes the positive effect of regenerative braking. It goes without saying that if the brake factor and TTW efficiency increases the negative effect of the mass effect could be overcompensated by the positive effect of regenerative braking..

Table 2 reproduce the optimistic and pessimistic values for different EV parts.

Table 2: Borders in efficiency of parts of TTW by EV

part	Energy efficiency TTW	
	pessimistic	optimistic
Battery	0,80	0,99
Inverter	0,94	0,96
Motor	0,85	0,92
Transmission	0,94	0,96
Mass effect/ regenerative braking	0,82	0,94
Total	0.49	0.83

3.2.3 Well-to-Tank EV

Figure 6 shows the mean relative energy loss of EV. The losses are as explained above mainly in the electricity production, while the electric vehicle is very efficient. This is in contrast to opposite distribution of losses as shown in Figure 2 for the ICE.

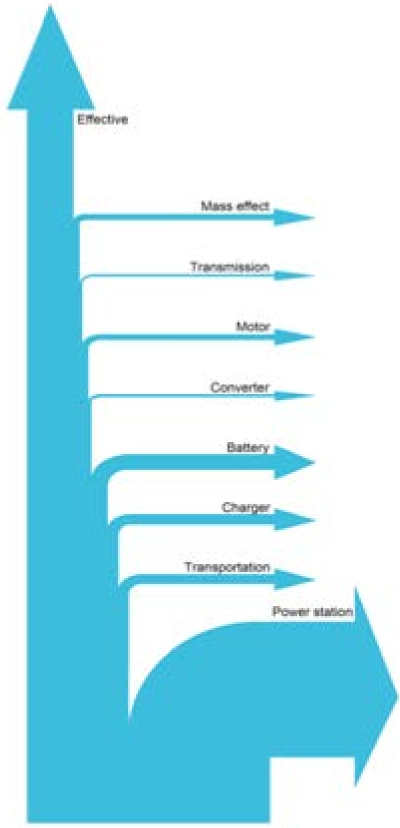


Figure 6 Mean relative energy-loss for EV (mix)

3.3 Final result

In figure 7 the results are totalised.

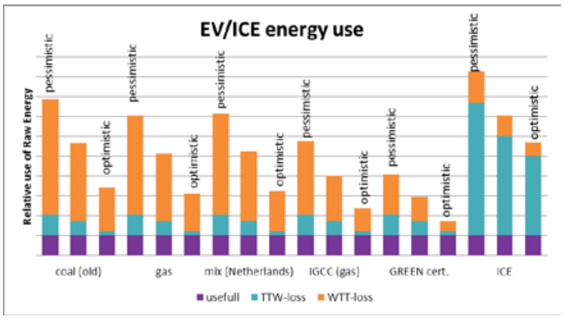
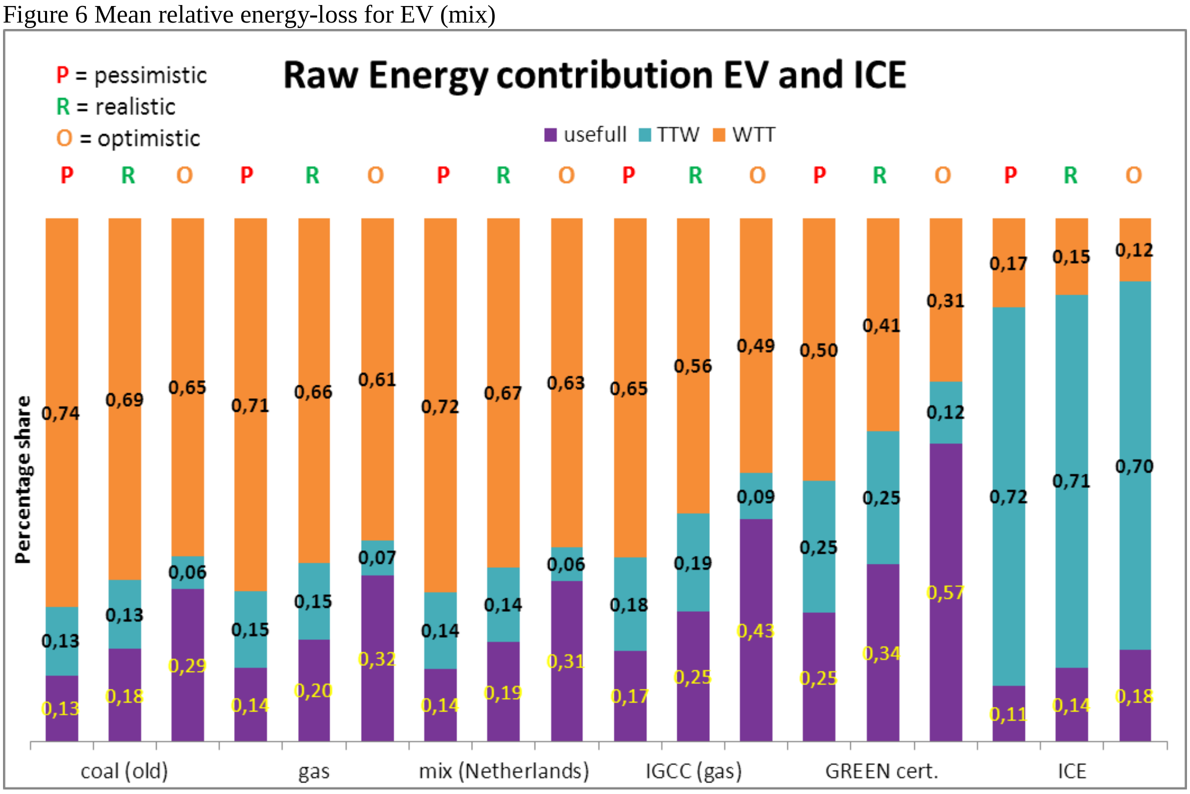


Figure 7 Relative energy use with different sources for electricity for EV and energy use for ICE in urban traffic.

In figure 8 are the same results presented as part of the raw energy-use.



Figuur 8 Distribution of Raw Energy Use

4 Discussion

Even though it might be argued that some of the values used were estimated instead of actually measured the main findings will not change because it concerns little contributions. Only the best case for ICE is only just more efficient than the worst case for EV. This is mainly due to the positive TTW of EVs in urban traffic. Especially EV's that are dedicated to Urban use will benefit from maximum regenerative braking and do not need high driving ranges. For highway use the efficiency for ICE is not studied, but will be probably better. For long distance traffic the advantage of generative braking is less and the need for more battery energy storage will increase the mass and therefore decrease the efficiency of EV.
The spread between optimistic and pessimistic is not only due to variations in definitions in the references but also due to the generalizations of the pathways of the energy chain as well as the vehicles.
Because of expected future developments the results are very time-dependent.

4.1 Future

In future the efficiency of oil wells will decrease. Tar sands and shale oil will exacerbate this decline. J. David Hughes [24] claims the lifetime of a production well is three years at the most. That will lower the EROI and will bring us more close to what is called the energy cliff (figure 9).

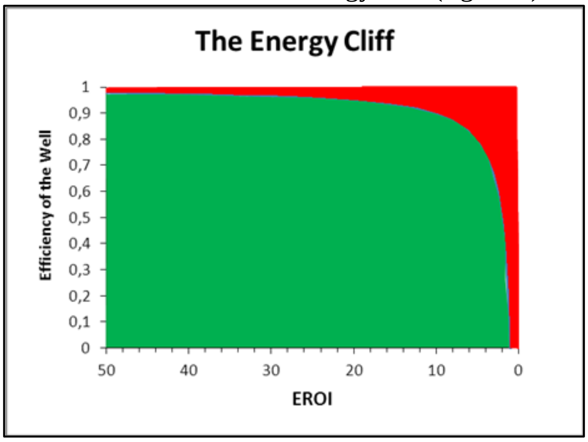


Figure 9 Efficiency of the well versus EROI

The introduction of electro-mechanical energy storage during braking could increase the efficiency of ICE. Self-steering cars and build-in intelligence and traffic regulation may give some relief on the congestions in the city. On the other hand the trend toward renewable energy for the electricity production will proceed. This makes that the EROI gap between fossil and renewable energy will get more and more a significant argument. It's even questionable if renewable energy will be accountable with losses of energy. In principle they do the not use raw material other than for the materials for the construction. Regarding the EV technology the effect of regenerative braking will be further optimized by the introduction of one pedal driving [Tesla] and the weight penalty of energy loss will be reduced thanks to more advanced and faster chargeable batteries. Permanent magnets with rare earth metals are becoming more expensive. That's why the induction motor or the switched reluctance motor will be used more and more.
The loss in Power Lines can be reduced to a third when gas insulated lines are used [25]. Then the transport of electricity will be more efficient.

5 Conclusion

In urban traffic the use of energy for EV is more efficient than then for ICE. The type of the power plant largely determines the benefits. The EV fed by old coal power plant hardly differs from ICE. The green certificate source is superior.
The results strongly depend on the country of application. Future developments may change these findings over time. But in general one can conclude that from a perspective of saving raw materials for energy production the trend will be strongly in favour for EV. And current urban EVs will only be the frontrunners for the electrification of road transport.

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