Energy Efficiency Analysis of Electric Vehicle System Components

Aarniovuori Lassi, Pyrhönen Juha, Liu Dong, Kauranen Pertti, Korhonen Juhamatti, Tikka Ville

This is a Author's accepted manuscript (AAM) version of a publication

published by IEEE

in 2023 IEEE Transportation Electrification Conference and Expo, Asia-Pacific (ITEC Asia-Pacific)

DOI: 10.1109/ITECAsia-Pacific59272.2023.10372377

Please cite the publication as follows:

L. Aarniovuori, J. Pyrhönen, D. Liu, P. Kauranen, J. Korhonen and V. Tikka, "Energy Efficiency Analysis of Electric Vehicle System Components," 2023 IEEE Transportation Electrification Conference and Expo, Asia-Pacific (ITEC Asia-Pacific), Chiang Mai, Thailand, 2023, pp. 1-6, doi: 10.1109/ITECAsia-Pacific59272.2023.10372377.

Energy Efficiency Analysis of Electric Vehicle System Components

Lassi Aarniovuori
School of Energy Systems
LUT University
Lahti, Finland
lassi.aarniovuori@lut.fi

Dong Liu
School of Energy Systems
LUT University
Lahti, Finland
dong.liu@lut.fi

Juhamatti Korhonen
School of Energy Systems
LUT University
Lappeenranta, Finland
juhamatti.korhonen@lut.fi

Juha Pyrhönen
School of Energy Systems
LUT University
Lappeenranta, Finland
juha.pyrhonen@lut.fi

Pertti Kauranen
School of Energy Systems
LUT University
Kotka, Finland
pertti.kauranen@lut.fi

Ville Tikka
School of Energy Systems
LUT University
Lappeenranta, Finland
ville.tikka@lut.fi

***Abstract*—There are several figures used to promote the energy efficiency of battery electric vehicles (BEVs). A critical analysis of the energy consumption of BEV systems is presented here. A typical approach to estimate the efficiency of BEVs is to use fixed values for each component. Often the best possible value is taken in use. In practice, the efficiencies vary as a function of the operation point of the device and ambient conditions where the EV is used. It is also important to remember that propulsion is just part of the energy consumption in a modern EV and other consumers like air conditioning may use a high share of energy. The range of efficiency of each stage of an EV system is presented and the influential factors are discussed.**

Keywords—battery electric vehicle, charging, energy efficiency, power conversion, tank to wheel, well to tank

I. INTRODUCTION (*HEADING 1*)

Building an electric vehicle, especially its battery, is a highly CO_2-intensive process and using them can be regarded as green as the electricity source that is used to power them. The literature has shown different kinds of figures that are used to evaluate the efficiency of EV systems [1]-[3].

The main components of a typical EV are an on-board charger, a battery as electric energy storage, power electronic converter, electrical machine, step-down gear and a transmission system. An EV also has a set of auxiliary systems the most important energy consumers of which are heating, ventilation and air-conditioning (HVAC) systems. Typical EVs also have a high-power charging port to be used with an external fast charger.

An electrical machine can work as a motor, or a generator and it converts electrical energy to mechanical energy or vice versa. The electric power control unit is based on power electronic circuits, and it controls the power flow between the main components. Typically, the power electronic converter is a two-level voltage-source three-phase converter, nowadays realized with Silicon semiconductors in typical models and wide band gap (WBG) power switches like SiC switches in premium electric vehicles.

The transmission system is typically a reducer or step-down gear with a high gear ratio to enable higher and higher rated rotational speed of the propulsion electrical machine. The rotational speeds of an electrical machine used in EVs are typically much higher than what is used in the industry. Depending on the design and resources used an electrical machine can be manufactured to deliver a very high efficiency in a wide operation range.

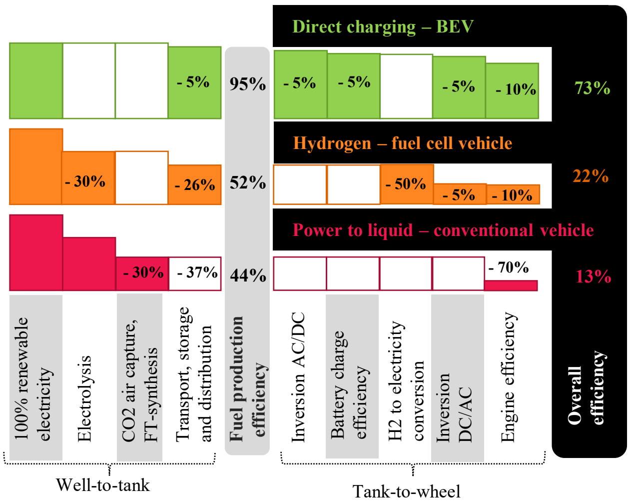

Fig. 1. Breakdown of the energy efficiency of the different fuel systems.

The efficiency of industrial electrical machines has been pushed to higher and higher levels during the latest decades and the loss modelling and loss minimization have become popular research topics. Traditional electric motor loss components are resistive losses (I^2R) in the conductors, iron losses in the magnetic parts, mechanical losses including ventilation and friction and these loss components can be determined well experimentally. The modelling accuracy of these losses is at a high level. One of loss components in converter-fed electrical machines is the additional high frequency losses induced by the PWM supply. The behaviour of this loss component is well understood [4], but it cannot be yet modelled with high accuracy. However, it can be determined from experimental results with frequency domain harmonic power method as explained in [5]. When direct-on-line supply is in focus the research interest has been aimed on determining the machine efficiency at a single operation point and maybe additionally in a few partial load points. In frequency converter driven machines, a wider operation area is used and efficiency maps instead of efficiency points are preferred.

However, as EVs are getting more and more popular, demands for material efficiency are given by different regulatory officials. Both US and EU are demanding highly resource-efficient low-cost electrical motors with minimum usage of scarce materials for EV propulsion [6],[7]. Avoiding e.g. rare-earth materials and trying to reach as high material efficiency as possible increases the electromagnetic stresses in a machine and as a result efficiency may start suffering. In fact, the benefit of using permanent magnet excitation cannot be mitigated with any other known design feature and therefore the PM-machine efficiency is superior compared with other electrical machine technologies.

Besides the drivetrain of a BEV, the so-called well-to-tank and tank-to-wheel efficiencies are also important indicators for evaluating different vehicle technologies as shown in Fig. 1. Figure 1. studies three alternative paths from totally renewable electricity to the wheels of a vehicle in case of a BEV, a fuel-cell EV or a traditional internal combustion engine vehicle. The figure shows optimistic values for the BEV and results in 73% efficiency from well to wheel. This can be regarded to be close to the maximum possible efficiency for a BEV ecosystem.

In case of a BEV the efficiency of power generation and transmission to a charger and the efficiency of the charger and battery need, however, more careful assessment. The paper presents the numbers of efficiency from the well to wheel including all the stages to illustrate and discuss how efficient a modern BEV ecosystem can be.

II. Power Conversion and Losses in an EV System

Electrical power is generated in a power station, transmitted through the power grid, delivered to the charging station and used for charging the battery of an EV. According to IEA Coal supplies over a third of global electricity generation even though it is the most carbon-intensive fossil fuel [8]. In 2022 the CO_2 emission from coal power plant even increased by 2%. After generation, transmission, distributing and charging an electric car battery the electrical power is converted into mechanical power driving the wheels via a transmission of the EV. The section from power generation to the battery is also called well to tank for an EV system. The section from the battery to the wheels is also called tank to wheel. The term tank is used for internal combustion engine (ICE) vehicles but can also be used for EVs for comparison of energy conversion. In this section we break down the process and analyze the efficiency of each component or stage

A. *Electricity transmission and distribution system*

After a generator has converted mechanical energy into electricity its power is supplied via a block transformer to the transmission grid. The transformer energy efficiency is in the range of 99% and therefore does not contribute to a large energy loss. According to Fingrid the share of losses in the Finnish main grid is 1.2 – 1.4 TWh per year, which corresponds to approximately 1.5 percent of the electricity consumption in Finland as a whole. Transmission line efficiency, therefore, is in the range of 98.5%. The distribution losses in Finland are about 2.5 – 3% and the distribution system efficiency therefore about 97%. As a result, the EV battery charger can reach 95% of the generated electricity. In many countries, however, the transmission and distribution losses can be very much higher. According to statistics of IEA [9], it is shown that the electric network efficiency e.g. in Germany is 96%, United Kingdom 92%. The OECD average is 94% and the World average is 92%. The low average efficiency value of the world is largely explained by the non-technical losses i.e. the electricity consumption that is not billed.

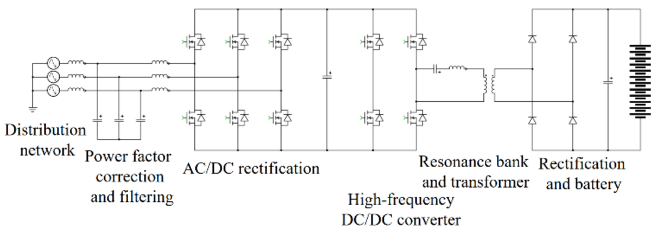

Fig. 2. A typical EV charger topology.

B. *Charger*

The batteries of EVs can be charged using an AC or a DC charger and typically both charger types are utilized from time to time depending on the location and usage of the vehicle. One of the problems related to charger efficiency is that a galvanic isolation is demanded. Therefore, a charger must always have a transformer. Fig. 2 illustrates a typical charger topology. Conventionally the charger is divided into two conversion stages: AC/DC rectifying the grid AC voltage and an isolating DC/DC converter to control the power flow and voltage level. There are numerous different topologies to implement both conversion states, and these depend mainly on the nominal power of the charging system [10].

Regardless of the topology or the peak power of the system, the converter will generate losses while it converts the electrical power to the different from. In practice, all power electronics components have conduction and switching losses. For example, if the charger has first an AC/DC rectifying converter realized with PN diodes and is supplied from 400 V AC grid the diode-bridge forward threshold voltage is typically 1.55 V (SEMIPAC 1200 V, 85 A). This corresponds to 0.6% loss, i.e. 99.4% efficiency. If the rectification demands for improved power quality, a power factor correction (PFC) method is required. Again, this feature can be implemented with various topologies, yet each of these use active semiconductor switches, for example using a three-phase two-level inverter as illustrated in Fig. 2. The cost of improving the power quality drawn from the AC grid comes with increased power losses in the conversion, mainly due to the switching losses of the converter. Soft-switching isolating DC/DC converters have become the most viable solution for implementing the isolation. A comprehensive list of converter topologies and their power and peak efficiencies can be found in [10].

The distribution of the losses through a cost-effective charging-system can be as follows: high-frequency (HF) SiC-FET inverter efficiency can be 99%. The resonance bank HF inductor easily creates 1% losses and therefore offers 99% efficiency. The best efficiency of the HF transformer is 98% and the rectifier and the filter combined efficiency can be 99%. The total efficiency of the charger at best is therefore, 95%. However, this peak efficiency value can be obtained only in optimum operation point. Typically, the charger must be able to charge the EV batteries with different DC – voltage levels e.g. 400 V and 800 V and therefore it can only operate in the optimum point with specific vehicles. Both the desired output voltage and current flowing through the system have an effect on the charger efficiency. The rated current can only be applied for a limited time period during the charging period and therefore the charger is typically operating with partial load and not at its best efficiency point.

There is evidence that in many cases, especially, the on-board chargers have a very poor efficiency. In some cases, the low-power charger can have an efficiency of just 60% but typical efficiency values vary between 75% and 95% [11]. A charger can have significant no-load losses and therefore it is clever to use a high charging current from the charger point of view [12]. Regardless of the topology or nominal power, the efficiency of the charger is conventionally at its lowest at the low end of the operational power [13],[14].

C. Battery

All batteries have losses [15]. Electrical energy from the charger is converted into chemical energy in a lithium-ion battery. The travelling of lithium ions in the battery causes heat and results in power losses. Batteries typically built of small cells also include lots of wiring that creates its own Joule losses. In modern cars there is a thermal management system to reduce energy loss while trying to keep the battery temperature at an acceptable level. When simplified, it is possible to say that the power loss takes place in an internal resistance of the battery. As a result, the battery charging and discharging takes place more effectively when a low charging or discharging power is used. Battery temperature, however, has a big impact on the charging capability. At low temperature batteries do not accept charge and have to be heated to be charged in a proper way.

Charging an electric car battery at a low power is beneficial if we just observe the battery but please remember that the charger efficiency may be low at the same time deteriorating the energy efficiency of the system. It seems to be that the charger and the battery build up the most vulnerable components of the whole system from the energy efficiency point of view.

We measured the efficiency of an NMC cell as an example. The following values were measured for the discharge efficiency of a 18650 NMC cells at room temperature compared to 24 h discharge (0.04 C): The results were the following: At 0.5 C current the battery discharge efficiency was 95%; at 1.0 C, 90%; at 2.0 C, 80%. Roughly speaking, these can also be used for charging, although the charging losses may be slightly higher.

These numbers coincide well with the idea that the cell has a per-unit internal resistance of $R = 0.1$. With this it is easy to calculate the energy loss at 2C current: Per-unit time to total discharge is theoretically 0.5 and the per-unit $\int I^2 R dt$ energy loss W is now

$$W = 0.5 \times 2^2 \times 0.1 = 0.2$$

This matches with the 80% discharging efficiency of the battery at 2C current. Let us now use the same value for charging the battery, i.e. 80% charging efficiency.

Present day cars do not constantly need 2 C current for driving conditions but with e.g. a 100 kWh battery 0.2 C discharging is acceptable. This would result in 98% discharging efficiency during driving at 20 kW input power to motor. Let us now assume that the battery is fast charged at 2C current and discharged at 0.2 C current, its best possible energy efficiency is 78%.

D. Motor converter

The task of the motor converter is to correctly control the electric motor of the EV. If the converter is equipped with a modern WBG power bridge it can have 99% rated point

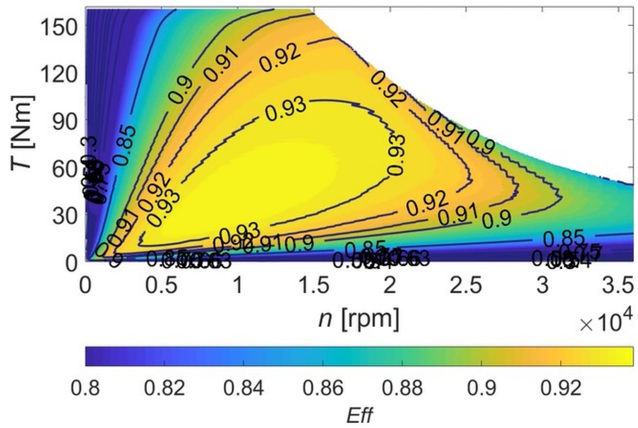

Fig. 3. Efficiency map of a PM motor for EVs. (Figure produced by Dr. Ilya Petrov, LUT University)

efficiency. The efficiency also remains high at a wide operating range. However, at the lowest power levels the efficiency rapidly drops down [16]. The motor converter is a four-quadrant device enabling accelerating and regenerative braking in both directions. Kinetic energy regeneration is extremely beneficial in city driving with frequent starts and stops.

E. Motor

When observing the development of commercial vehicle electric propulsion motors, it is easy to see that generation after generation the motor rotational speeds have increased. Present-day electric vehicle motors spin close to 20 000 rpm maximally.

The electric motor can be built very efficient. However, at least EU and US officials want that the EV electric motors should be as material efficient and as cheap as possible. To achieve such targets a high-speed motor is needed and no or very limited mass of rare-earth materials can be used.

For example: EU is presently running research projects where the targets set for an EV motor are: Specific power 7 kW/kg, power density 23 kW/litre, cost less than 6 €/kW, usage of permanent magnet material 60% lower than in state-of-the-art car propulsion motors. LUT researchers are designing a PMaSynRM for this purpose. In case of a 120 kW constant power motor the mass can be 17.2 kg and the volume 5.2 litres. The mass of NdFeB magnets allowed is 300 g per motor. With such limitations the cost target can be reached but the efficiency of the motor will be lower than in the best state of the art EV motors that can reach 97 – 97% efficiency at their best operating point. The motor developed can now reach almost 94% efficiency at its best operating point, but the high-efficiency area of the motor is wide offering at least 93% efficiency on the practical operating points of the motor, as illustrated in Fig. 3.

F. Reduction gear

The above-mentioned motor is spinning at 12000 rpm at its rated point and maximally close to 30 000 rpm. If the top speed of the car is about 200 km/h its 225/60R17 wheels have to spin about 1500 rpm maximally. Such numbers result in a need of a step-down gear that has a gear ratio of 30000/1500 = 20:1. Such a gear ratio typically needs at least three shafts to reduce the speed down to a suitable level. We can estimate that the gearbox efficiency is $0.985^3 = 0.956$ as there typically is 1.5% per cogwheel contact.

G. Final drive

The final drive includes constant-velocity joints, protection rubber seals, drive shafts, wheel bearing hubs and finally wheels. The mechanical efficiency before wheels is 99%. Therefore, the efficiency of the final drive without wheels is 99%. In principle, the efficiency of the wheels should be the same in an ICE car as in an and EV. However, electric vehicles are typically 500 kg heavier than their ICE-car counterparts because of the large battery packs. Therefore, the tire friction in an electric car is higher than in an ICE car.

A tire's rolling resistance refers to the energy consumed in the tire's deformation during road contact. This covers about a fifth of the car's energy consumption, making it a significant part of the costs and environmental impact of driving as well [17]. A premium electric vehicle consumes 20 kWh energy when driving 100 km. If 20% of this is coming from the friction, it means 4 kWh/100 km. As said above, the electrical vehicles are typically 500 kg heavier than ICE counterparts. Let us assume that a traditional ICE car has mass of 1535 kg (VW Passat) while its EV counterpart has mass of 2000 kg (VW ID7). That is 30% more. This also transfers to 30% more rolling friction in case of an EV increasing the rolling friction from 4 kWh to 5.2 kWh per 100 km. If we convert these into efficiency numbers, we could say that ICE-car wheel efficiency is 0.8 while the EV tire efficiency is around 0.74.

Table I presents the breakdown of the estimated efficiency of well-to-wheel EV system. Here we see that the charger and the battery have a very large effect on the efficiency of the electric vehicle. If a high-efficiency charger and low charging power are used to avoid high battery losses the propulsion efficiency of an EV can reach 70%. If, however, fast charging is applied the well to tank efficiency remains at 71.4 %. The electric drive-train efficiency from tank to wheel hub is 87%. The efficiency from well to wheel hub is 62%. If we take the higher EV tire friction into account, we can give as a kind of comparing number a 58.4% efficiency for the EV from well to wheel. This number can of course be criticized.

However, propulsion alone is not enough as often an EV needs to be heated or air-conditioned during driving.

III. Factors that Influence the System Efficiency

There are multiple factors that influence the system efficiency, these factors are shortly discussed here.

A. Ambient temperature – Heating

As the location changes to cities where more hot or cold extremes might be observed, a wider spread of vehicle range throughout the year is expected. According to the study in the US, on the worst day of the year the average drive range of a fleet can be from as low as 27 km up to 45 km across the US due to climate differences [18]. This result implies that countries like Finland are significantly different from countries like e.g. Brazil regarding the EV efficiency, especially, in winter. In an EV, heating consumes a lot of energy from the battery as there is not enough waste heat on board. The most difficult situation is if a car is parked in a cold temperature and the battery needs to be heated first with its own energy. In Finland a popular magazine Tekniikan Maailma measured that 8% of the battery capacity of Porsche Taycan was needed for its own heating before the vehicle could be started after having stayed overnight in −30°C. The battery had been charged full in the previous day and the car was started next morning without any extra help form network.

TABLE II. Breakdown of Efficiency Estimation of Well-To-Wheel of EV Systems

SYSTEM COMPONENT	VALUE
OECD Network	94%
Battery charger	75 – 95%
Battery	78 – 96% (so far 55% - 85.7%)
Motor converter	99%
Motor	93%
Reduction gear	95.6%
Final drive	99%
EV tire efficiency/ICE tire efficiency	94%*
EV total	45 – 70%

*Because of the heavier vehicle mass the tire friction in an EV is higher than in an ICE vehicle

During normal winter driving lots of energy is consumed in the heating of the vehicle passenger compartment. Present-day passenger vehicles typically have a 6…9 kW heating resistor that is used in temperatures below −10°C. In addition, many EVs have a heat pump that makes the cabin heating more energy efficient at temperatures higher than −10°C. The following table lists some examples of the reduction of the range in case of heating the car [19].

If we take the average value derived from Table II, the result is that when heating is needed the car range is reduced to 71% compared to the case where no heating or air-conditioning is needed. This shows that if the typical value for propulsion is 20 kWh/100 km the total consumption during heating is 28 kWh. i.e. 8 kWh extra is needed to keep the car warm enough to make travelling comfortable.

In case of an ICE car no extra fuel is needed for heating as the ICE efficiency is poor enough to deliver enough heat in most cases. However, TDI Diesel engines may have difficulties in delivering enough heat when operating at temperatures below −20°C. When driving at −30°C extra fuel-operated heater is often needed to keep a TDI-engine vehicle warm. With Otto-engines there seems to be always enough heat available for heating the cabin. If and ICE car is regarded as a CHP power plant its efficiency increases clearly when operating in cold environment while the efficiency of EVs goes down as no waste heat is available for heating purposes.

B. Ambient temperature – Air conditioning

Air conditioning is one task that can easily be seen in the energy consumption of an EV. An electric motor needs to run a compressor that needs even 7 kW shaft power in case of the hottest environment. Therefore, driving in either −20°C with heating or +30°C in sunshine the car energy demand is increased from 20 kWh/100 km – needed for propulsion – to 27~28 kWh/100 km to cover all the needs of motoring.

This additional energy consumption can directly be seen in case of an EV while in case of an ICE the engine load is naturally increased let us say from 20 kW to 27 kW, Fig. 4.

In this map adding 7 kW to the motor load at 100 km/h results in a small increase in the effective middle pressure of the engine and a corresponding increase in the efficiency will take place. Therefore, in case of an ICE the fuel consumption is not affecting as directly in the consumption as in case of an EV. If the car is running on its highest gear ratio at 100 km/h

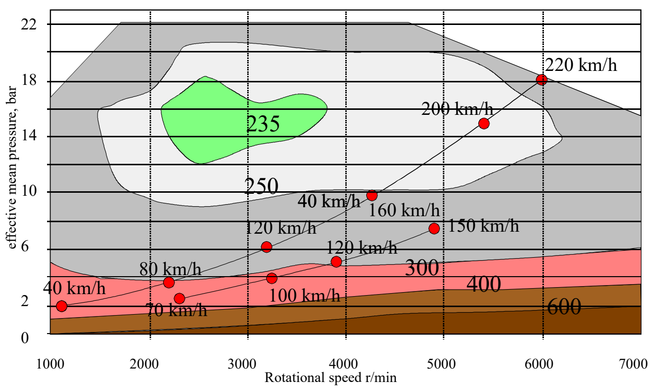

Fig. 4. Map of specific fuel consumption as a function of internal combustion engine's rotational speed and engine pressure.

TABLE III. COMPARISON OF REDUCTION OF DRIVING RANGE FROM HEATING (RANGE WITH HEATING OFF: 100%)

Model	Reduction (%)	Remaining (%)
Hyundai Kona Electric	10	90
Kia Niro EV	10	90
Tesla Model S	18	82
Chevrolet Bolt EV	31	69
Jaguar I-PACE	32	68
Nissan Leaf	33	67
Tesla Model 3	40	60
BMW i3 94Ah	42	58
Renault Samsung SM3 Z.E	43	57

its effective mean pressure is 5 bar. To increase the power from 16 kW to 23 kW the mean pressure needs to increase close to 7 bar. The corresponding specific consumption lowers from about 290 to 270 g/kWh partly compensating for the increased power demand. The fuel consumption would increase from 5.8 L/100 km to 7 L/100 km. This corresponds to a 20% increase while in an EV there is a need for 40% increase in electric power consumption.

A typical EV, therefore, needs 27 kWh net energy per 100 km when driving in a hot environment at 100 km/h. In the worst case the energy taken from the network supplying generator is using the worst or the best efficiencies found in table 3 20 kWh/0.45 + 7 kWh/0.55 = 57 kWh or in the best case 20 kWh/0.7 + 7 kWh/0.857 = 37 kWh. 5.7 kWh corresponds to 5.7 litres of gasoline and 37 kWh 3.7 litres. Therefore, a VW Golf with a TSI engine at its best with 5.8 L/100 km is very close to the consumption of the EV.

The generating emissions vary strongly depending on a country's electric energy generating system. The estimates of the carbon intensity of electricity show that in the EU27, the emissions associated with gross electricity production reached 296 g CO_2eq/kWh electricity in 2022. Using this value for the previous 37 kWh or 57 kWh/100 km results in 110 g or 170 g CO_2eq/km for the electric vehicle.

A VW Golf with a TSI engine runs 100 km with 5.8 L of petrol resulting in 5.8 L × 2.34 kg CO_2/L = 13.6 kg CO_2/100 km corresponding to 136 g CO_2/km. If there is a significant share of biofuel blended in petrol the fossil emission of the vehicle will drop down from this figure.

Obviously, in EU an electric vehicle emits about the same amount of CO_2 per km as a modern ICE-vehicle. Therefore, there is a strong need to get the electricity emission down before the EVs can improve the environment from their CO_2 emissions point of view.

In Finland, the average electricity generation emissions are low. Statistics Finland publishes coefficients for the CO_2 emissions of Finland's average electricity generation. The average calculated from these for the last three statistical years (2019-2021), where cogeneration is divided by energy method, is 77 g CO_2/kWh. So, in Finland using the EV emits between 29 and 44 g CO_2eq/km. To reach similar values, our example ICE vehicle would need 70 … 80 % biofuel in the tank. The most efficient way of achieving this would be using biomethane. Its promotion, however, has ended in the EU in practice.

Manufacturing so-called liquid e-fuels is technically possible but has not so far been done in a wide scope and many regard this route so energy-inefficient that it is not regarded feasible for passenger vehicles. One of the easiest possible liquid e-fuels is synthetic methanol. The problem related to e-fuels is that the efficiency from generator to tank is low, in the range of 50% [20]. Therefore, an ICE car consuming liquid fuels needs about double amount of electricity compared to a battery electric vehicle.

C. *Load*

Load of the drivetrain or engine of a vehicle affects the efficiency. Based on a large dataset including many different vehicles, it is estimated in [21] that an EV's efficiency drops with increasing loading. For example, the efficiency can be 85% at 10% load and 68% at full load. In [22], analysis based on a simulation tool provide calculation results for one specific vehicle. The highest efficiency of 82% occurs at 55% load while the full load gives an efficiency of 75% and 10% load gives an efficiency of 65%.

D. *Regenerative braking*

EVs offer regenerative braking, which increases the energy efficiency, especially in city driving. The US Department of Energy estimated the equivalent increase of efficiency to be 22% combining city and highway driving (34% for city and 6% for highway) [4]. This number was estimated to be 10% in [14]. The regenerative braking is, however, taken directly into account in the energy-consumption measurement results of electric cars. Despite regenerative braking they normally consume 20 … 25 kWh of electricity in normal use per 100 km.

E. *Car manufacturing*

On average, around 5.6 tonnes of CO_2 are released during a petrol or diesel car's manufacture, around three quarters of which are released during production of the steel body. We might assume that manufacturing an electric vehicle without battery also emits about the same amount of CO_2.

However, battery manufacturing is environmentally very costly. Estimates about the CO_2 emissions vary strongly but on average we can take 100 kg of CO_2/kWh of battery capacity. Therefore, a typical 80 kWh battery emits 8000 kg/ of CO_2 during battery manufacturing. Therefore, a new EV has emitted about 14 tonnes of CO_2 before it has moved a meter on road.

CONCLUSIONS

The energy consumption and CO_2 intensity of EVs are a function of many parameters. The paper presents the possible efficiency range of each stage of a BEV system. One of the most critical parts of efficiency is the battery charging. High-power charging strongly reduces the system efficiency and sacrifices also the lifetime of the battery. From generator to battery energy the efficiency can vary between 55% - 85.7% depending on the charger efficiency and the power of charging. This step can be regarded as the Achilles heel of the whole system. From tank to wheel the drive train efficiency is high. The only problem is the heavy tare of the EV which increases the energy consumption as a result of high rolling friction. Auxiliary systems burden the energy efficiency of EVs strongly. Heating and air-conditioning become very costly in EVs. There are not enough heat losses available in an EV contrary to ICE cars. Running an air-conditioning compressor also directly consumes energy from a battery. If an electric car is operated with average EU electricity its energy efficiency is on the same range as with an ICE car operating with fossil fuel. To win in emissions, the electricity supplied to an EV needs to be fossil free. A big remaining problem is the high emissions of battery manufacturing. This makes the carbon intensity of an EV a difficult issue at the moment. The worst case of well-to-wheel efficiency is about 45%. One weak point of EVs obviously is the on-board charger. Regulation should remove low-efficiency chargers from EVs.

A comparison between the BEV system and ICE vehicle systems was also presented. The study shows that an EV is not a silver bullet solving all the environmental issues in motoring. To get overall help from EVs the electricity generation must be carbon neutral. Otherwise EVs can either just maintain or even increase the system carbon emissions. With the present-day emissions in EU an EV system is not better than an ICE car with fossil fuels. In Finland the EV is clearly better from its operating emissions point of view. If we let the ICE car emit 136 g and the EV system average 35 gCO_2/km to cover the 8000 kg battery manufacturing burden, there is a need to drive about 80 Mm before the EV becomes more environmentally friendly than its ICE counterpart on Finnish roads.

References

[1] E. Roshandel, A. Mahmoudi, S. Kahourzade, A. Yazdani, and G. Shafiullah, “Losses in Efficiency Maps of Electric Vehicles: An Overview,” Energies, vol. 14, no. 22, p. 7805, Nov. 2021, doi: 10.3390/en14227805.

[2] S. Kosai, M, Nakanishi and E. Yamasue. “Vehicle energy efficiency evaluation from well-to-wheel lifecycle,” Transportation Research Part D, vol. 65, 2018, pp. 355-36, ISSN 1361-9209. https://doi.org/10.1016/j.trd.2018.09.011

[3] S. Ramachandran and U. Stimming, “Well to wheel analysis of low cardon alternatives for road traffic,” Energy & Environmental Science, 2015, no. 8, pp. 3313.

[4] H. Kärkkäinen, L. Aarniovuori, M. Niemelä and J. Pyrhönen, "Converter-fed induction motor losses in different operating points," *2016 18th European Conference on Power Electronics and Applications (EPE'16 ECCE Europe)*, Karlsruhe, Germany, 2016, pp. 1-8, doi: 10.1109/EPE.2016.7695508.

[5] H. Kärkkäinen, L. Aarniovuori, S. Makkonen, M. Niemelä and J. Pyrhönen, "Determination of High-Frequency Harmonic Power in Converter-Fed Motors," *2022 International Conference on Electrical Machines (ICEM)*, Valencia, Spain, 2022, pp. 394-400, doi: 10.1109/ICEM51905.2022.9910715.

[6] U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy. Where the Energy Goes: Electric Cars. Available: https://www.fueleconomy.gov/feg/atv-ev.shtml#data-source.

[7] R. Edwards, J-F. Larive, D. Rickeard and W. Weindorf, Well-to-Tank Report Version 4.a JEC well-to-wheels analysis: well-to-wheels analysis of future automotive fuels and powertrains in the European context, Joint Research Centre, Institute for Energy and Transport, 2014.

[8] IEA, “Coal in Net Zero Transitions”, World Energy Outlook Special Report. IEA Publications, November, 2022.

[9] IEA Statistics © OECD/IEA 2018, “Electric power transmission and distribution losses (% of output) – Finland.” Available: https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS?end=2014&locations=FI&start=1960.

[10] M. Safayatullah, M. T. Elrais, S. Ghosh, R. Rezaii and I. Batarseh, "A Comprehensive Review of Power Converter Topologies and Control Methods for Electric Vehicle Fast Charging Applications," IEEE Access, vol. 10, pp. 40753-40793, 2022.

[11] Kieldsen, A., Thingvad, A., Martinenas, S., & Sørensen, T. M. (2016). Efficiency Test Method for Electric Vehicle Chargers. In Proceedings of EVS29 - International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium

[12] Go-e, “EV Charging Losses: Where Does The Energy Go?”, Oct 2022. Available: https://go-e.com/en/magazine/ev-charging-losses.

[13] Y. Jiang, L. Wang, Y. Wang, J. Liu, M. Wu and G. Ning, "Analysis, Design, and Implementation of WPT System for EV's Battery Charging Based on Optimal Operation Frequency Range," IEEE Trans. Power Electron., vol. 34, no. 7, pp. 6890-6905, July 2019.

[14] Z. Zhang, C. Liu, M. Wang, Y. Si, Y. Liu and Q. Lei, "High-Efficiency High-Power-Density CLLC Resonant Converter With Low-Stray-Capacitance and Well-Heat-Dissipated Planar Transformer for EV On-Board Charger," IEEE Trans. Power Electron., vol. 35, no. 10, pp. 10831-10851, Oct. 2020.

[15] M. Armand & J.M. Tarascon, Building better batteries. Nature 451, 652–657 (2008).

[16] X. Ding, M. Du, C. Duan, H. Guo, R. Xiong, J. Xu, J. Cheng, P. C. K. Luk, "Analytical and Experimental Evaluation of SiC-Inverter Nonlinearities for Traction Drives Used in Electric Vehicles," IEEE Trans. Vehic. Tech., vol. 67, no. 1, pp. 146-159, Jan. 2018.

[17] Michelin, What is rolling resistance? Available: https://www.michelin.co.uk/auto/advice/tyre-basics/rolling-resistance

[18] T. Yuksel and J. Michalek, “Effects of regional temperature on electric vehicle efficiency, range, and emissions in the United States,” Environ. Sci. Technol., vol. 49, no. 6, pp. 3974-3980, 2015.

[19] B. Krivevski, Hyundai and Kia Turn Up EV Efficiency with New Heat Pump Technology, Available: https://electriccarsreport.com/2020/06/hyundai-and-kia-turn-up-ev-efficiency-with-new-heat-pump-technology.

[20] Fasihi, M., Bogdanov, D., Breyer, C., Long-Term Hydrocarbon Trade Options for the Maghreb Region and Europe—Renewable Energy Based Synthetic Fuels for a Net Zero Emissions World, MDPI Sustainability, Published: 19 February.0

[21] O. Hjelkrem, P. Arnesen, T. Bø and R. Sondell, “Estimation of tank-to-wheel efficiency functions based on type approval data,” Applied Energy, vol. 276, 2020, 115463.

[22] M. Li, X. Zhang and G. Li, “A comprehensive assessment of battery and fuel cell electric vehicles using a well-to-wheel analysis,” Energy, vol. 94, pp. 693-704, 2016.