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HOW ENERGY EFFICIENT IS ELECTRIFIED TRANSPORT?

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WHY ENERGY EFFICIENCY?

This chapter examines the energy efficiency of electromobility. The transport sector accounts for a considerable share of overall energy use in modern societies. More efficient vehicles can help to reduce our use of scarce and costly energy resources such as fossil oil, which is currently the main energy source for transportation.

The total cost of ownership (TCO) is important for many vehicle owners (see Chapter 12 for a discussion on cost versus value and alternatives to vehicle ownership). The TCO can be separated into capital costs (the cost of purchasing vehicles) and operational costs (the cost of using vehicles). Fuel costs typically comprise a significant part of overall operational costs. This is especially true for countries where fuel taxes are high. Increased energy efficiency can thus reduce the TCO.

It is important to note that many other factors influence the attractiveness of different propulsion alternatives. From a climate perspective, CO_2 emissions may be more important than energy efficiency, for instance. Using different renewable energy sources for electromobility brings additional factors into play, such as the area of land required to produce a unit of energy. However, these aspects are related to energy efficiency (see Chapter 6 on environmental issues).

Systems Perspectives on Electromobility 2013, ISBN 978-91-980973-1-3

For any given vehicle there may be a conflict between energy efficiency, cost and performance. Efficient components are expensive, and performance demands such as better acceleration typically result in higher energy use. At present, there are several types of alternative fuels and drivetrains to select from. Technologies with higher energy efficiencies will not necessarily deliver in terms of performance and cost. Notwithstanding, there appears to be a need for energy efficient vehicles due to increased global energy demands and related policy developments (See, for instance, the discussion on land use for bioenergy in Chapter 3 in Systems perspectives on Biorefineries.)

Electric drivetrains are more efficient than the ICE because of their high-energy conversion efficiency. The latter is evaluated from 'tank to wheel' (TTW) or from the electricity outlet to the wheel for electric drivetrains. The way in which electricity is produced and distributed from "well to tank" (WTT) can also be important for the overall energy efficiency of the transport system. (See Chapter 6, and Figure 6.1 for definitions of WTT and TTW.)

This chapter examines the energy efficiency of electric cars. The rationale for this limitation is that cars currently dominate both passenger transport and transport energy use. We examine the efficiency of both components within the vehicle and the energy supply system – including upstream energy conversion.

ENERGY EFFICIENCY IN ELECTRIC VEHICLES

We begin by examining the processes and components that determine TTW efficiency. Energy is used for different purposes within vehicles. Most energy is used to propel vehicles (propulsion energy) and is thus supplied to the drivetrain (B_{DL} – see Figure 5.1). A considerable amount of energy is also supplied to auxiliary equipment (B_{Aux}). Some of this equipment is necessary to ensure that the drivetrain functions properly. The cooling system, for instance, requires energy for circulating cooling liquids. Interior heating of the passenger compartment also requires large amounts of energy.

The concept of TTW efficiency was developed for vehicles utilising liquid fuels, in which the process of refuelling vehicles does not involve considerable losses. For electric drivetrains, non-negligible losses occur when charging vehicles. Placing the system boundary at 'the tank' (i.e. the battery) is thus unsuitable. It is important to include energy losses related to charging and restate TTW as *from electric grid to wheel* (GTW). This is broader than considering only energy conversions *from battery to wheel* (BTW).

The ultimate losses in power delivered to the wheels (P_{W+}) are due to air drag resistance and rolling resistance (P_{Res}) (see Figure 5.1). The power needed for acceleration and travelling uphill (P_{St}) is stored as kinetic and potential energy. This stored energy can be utilised when the car is slowing down or travelling downhill. In an ordinary combustion engine car, kinetic and potential energy are converted into heat by braking or by rolling and air resistance losses. Electric vehicles can recover all or part of the energy delivered back from the road to the wheels (P_{W-}). This is because the motor can operate as a generator that is driven by the wheels to deliver energy back to the battery (B_{Rec}). Electric vehicles also avoid idling losses during stops, although some conventional cars are equipped with stop-start or hybrid systems. The amount of energy recovered depends on the recovery efficiency of the car and driving patterns. Driving patterns are determined by road profiles, traffic situations and users' driving styles. It is also convenient to distinguish between gross and net energy efficiency (TTW_{gross} and TTW_{net}). The ultimate necessary net supply of propulsion energy is equal to the resistance losses (P_{Res}), that is, the gross energy supply requirement at the wheels (P_{W+}), minus the option for recovery of energy (P_{W-}).

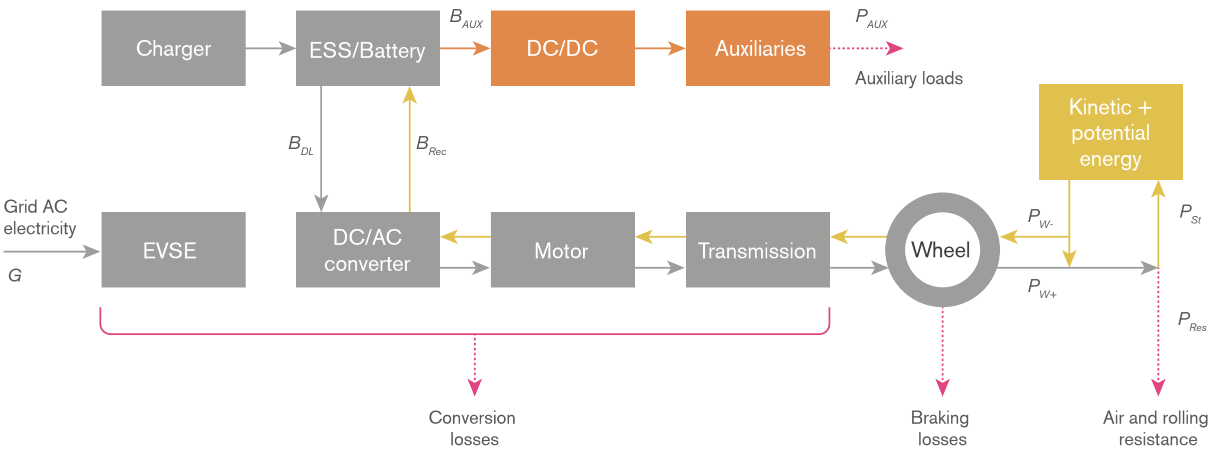


Figure 5.1 The conversion chain in electric vehicles. Energy is transferred from grid electricity (G), via the battery (B_{DL} and B_{Aux}), to energy at the wheels (P_{W+}) and auxiliary equipment (P_{Aux}). Part of stored potential and kinetic energy is recovered through the wheels (P_{W-}) to the battery (B_{Rec}).

ENERGY EFFICIENCY OF THE ELECTRIC COMPONENTS

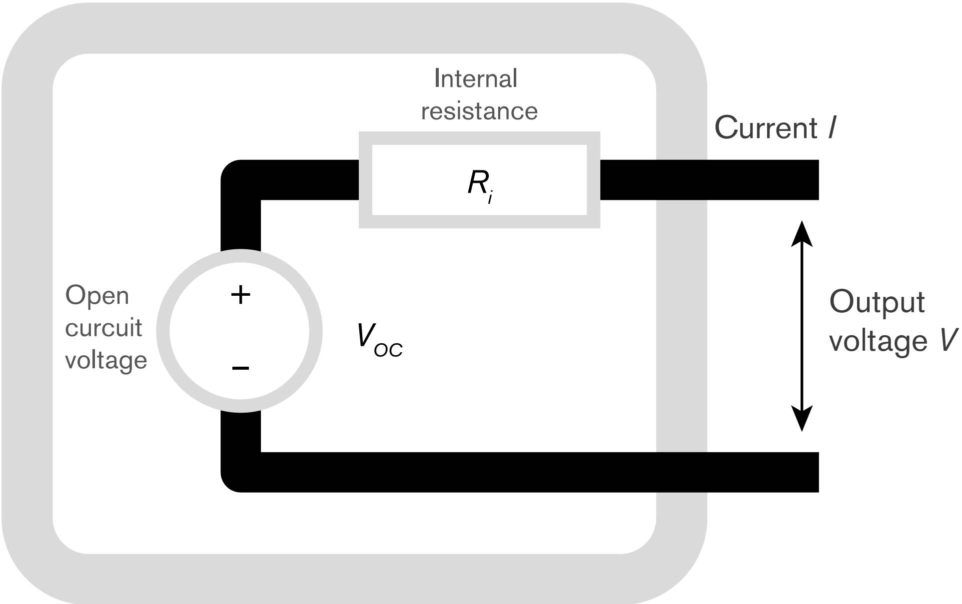
Charging equipment can be placed inside or outside vehicles (see also Chapter 3). Charging from an ordinary low-voltage household outlet commonly makes use of a charger placed in the car, which then converts the outlet AC current into DC. A typical 230 V and 10 A outlet provides about 2 kW of charging power. However, there are several on-board available chargers which can be connected to a three-phase outlet to deliver 10-20 kW. High-power charging (fast charging) can be achieved using an external charger to supply DC current to the car.

Household outlets are not to be used directly but should be complemented with *Electric Vehicle Supply Equipment* (EVSE) with inbuilt safety and control features. Losses in the EVSE are roughly 1-2% of the energy throughput (Table 5.1). The EVSE may also use energy in standby mode. Around 5 W standby power has been measured for commercial equipment. Over a year this can add up to around 40 kWh, which equates to two full charges of an EV.

Although *chargers* can operate with a peak efficiency of 92-95%, most commercially available chargers have much lower peak efficiencies. Lithium-ion batteries are sensitive to overvoltage when charged. Charging empty batteries thus starts at constant current. When a predefined voltage level is reached, the charging is switched to constant voltage with a gradually decrease in current and power. Charger efficiency in this low-power top-up phase may gradually decrease.

The overall efficiency of the Nissan Leaf on-board charger including an EVSE, for instance is 85%. The charger for a GM Volt, also including EVSE, has an efficiency of 89-91%. For the Peugeot Ion the overall efficiency from grid AC to battery DC has been measured to 82%. Commercial fast chargers (50 kW) have an overall efficiency of 89%.[1]

Inductive/resonance charging (see Chapter 2 and 3) incurs energy losses from the contactless transfer of power to the vehicle. Transfer efficiency is 90% under optimal conditions.



Output voltage $V = V_{OC} - R_i I$

Power output $P = V_{OC} I - R_i I^2$

Figure 5.2 A simple model of a battery. Losses increase faster (~ I^2) than the power output (≈ ~ I).

Losses in the *battery* are due to internal resistance, which transforms some of the stored chemical energy into internal heat instead of externally supplied power. A battery can be modelled as a voltage source in series with a resistor (Figure 5.2). With increased charging or output power, a larger share of the energy turns into internal heat losses, lowering the energy efficiency. Increasing the ratio between electrode area and volume can lower the specific resistance and raise the maximum power output. However, for the same energy capacity, this will lead to a more costly battery.

1 Fast charging is restricted to the constant current phase and stops at approximately 80-85% of the battery capacity.

Table 5.1 Conversion efficiency of different components in the electric drivetrain.

Component/ mode	Conversion efficiency	Efficiency characteristics	Possible future development
EVSE	98-99%	Standby losses in EVSE	Standby losses may be considerably lowered
Charger	Peak 85-95% Fast charging around 90%	Charger efficiency decreases for power considerably below rated power	Potential for higher efficiency over a broader power range
Battery	Losses in charging and discharging around 1%/C	Relative losses increase with power both in charging and discharging. Trade-off between losses and cost. (High power batteries have lower losses but at a cost) Different battery chemistries have different characteristics. Losses increase with use and calendar time (ageing).	New electrodes and electrolytes with higher power capabilities can reduce losses
Power electronics, boost converter	96-99%	Lower conversion efficiency for higher voltage steps	
Power electronics, DC/AC converter	Peak 95-99%	Higher voltage and lower switching frequency give higher efficiency.	SiC power electronics (Ch. 3) with very high conversion efficiency > 99%
Electric motor/ generator	Peak 90-96%	Lower conversion efficiency at either low torque or low speed. Higher voltage and motor speed give higher efficiency.	Considerable loss reduction unlikely. Trade-off with cost, size and materials' availability.
Transmission	92-98%	Avoiding gearbox increases efficiency. High motor speed may require reduction gear. Differential necessary if not in wheel motors.	Elimination of transmission by in-wheel motors possible development
Total driveline	Peak eff. ≈ 73-88%. Instant efficiency is the product of driveline component efficiencies, which vary with working point	Depends on the technology as well as the driving pattern. Avoidance of high speeds and frequent and strong accelerations/decelerations will increase efficiency.	The driveline involves many conversions between components, each with high efficiency, which need to be, and can be, even more efficient
Energy recovery in deceleration	Peak efficiency ≈ 100% of forward battery to wheel efficiency	Efficiency roughly same as for forward directed power in the driveline. The power of recovery is limited by motor/power electronics and by the vehicle stability and safety requirements when braking only the driving wheels.	Separate high power recovery system with low losses, such as supercapacitors. In-wheel motors can make recovery more efficient.

BEV-sized batteries have little problem achieving high efficiencies in driving or regeneration. With slow charging and efficient driving during operation and testing, the turnaround battery efficiency in the Nissan Leaf BEV has been measured at up to 97%. Smaller PHEV batteries are more strained, while small HEV batteries suffer from considerable losses at high power. The relationship between power output and energy storage capacity, or the speed at which a battery is emptied, is measured in cycles per hour (C).[2] Existing batteries typically have energy losses of around one percentage of efficiency per C during charging and discharging. Fast charging and low temperature increase the losses considerably. Battery efficiency may also decrease with time because battery ageing leads to a successive increase in the internal resistance and lower capacity.

Existing commercial *power electronics* (converters) are based on silicon-based semiconductors and transistors (see Chapter 3), and have over 95% efficiency through a large part of their operating range (Figure 5.3). Major losses are due to switching and increase with the duration and frequency of switching. While duration is technology dependent, a high switching frequency is desirable for low volume and noise. Power electronics based on silicon carbide (SiC) technology, with considerably faster switching and thus lower losses, are now becoming available. Lower losses and lower temperature sensitivities of SiC components eliminates the need for cooling systems, which provides additional energy savings.

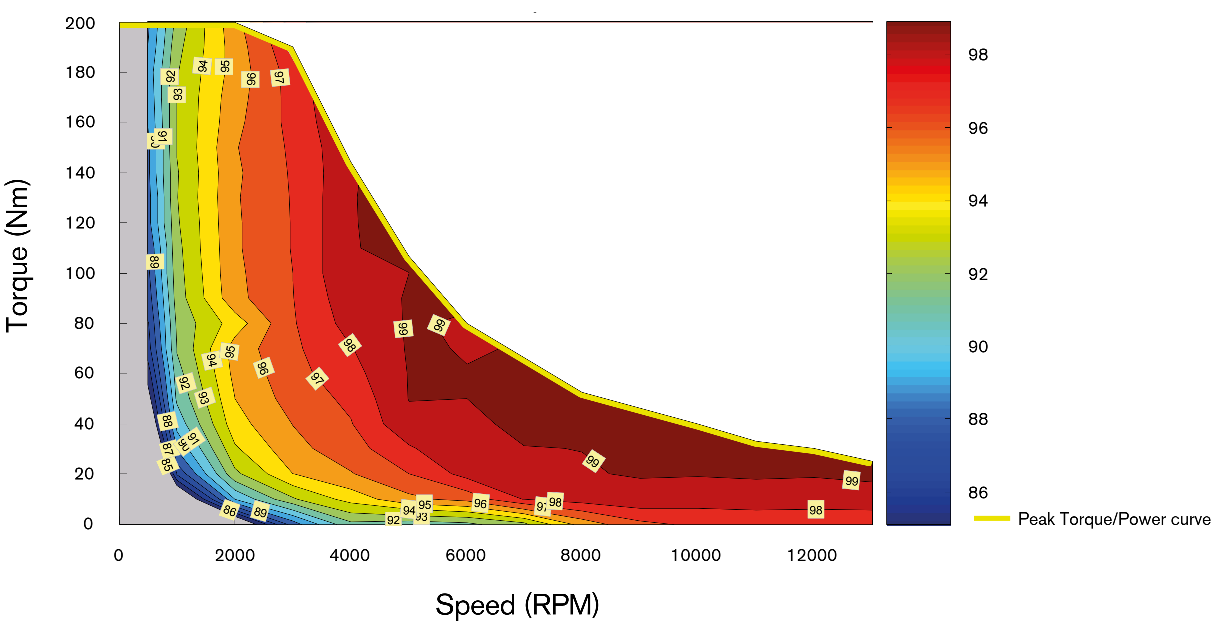


Figure 5.3 2010 Toyota Prius inverter (DC/AC converter) efficiency contours.[3]

If the motor requires a voltage higher than the battery voltage (at high speed, for example), battery power must be raised to a higher voltage before conversion to AC power. This is performed in a DC/DC converter called a 'boost converter'.

2 'C' values refer to an output rate normalized to battery capacity. 1 C is defined as the power at which the battery would be discharged in one hour. Thus 1 C will equal 24 kW and 1.2 kW for a 24 kWh BEV battery and a 1.2 kWh HEV battery, respectively, which can be compared to the average power need for driving of around 10 kW.

3 Efficiences for 650 V_{dc}. T.A. Burress et al, 2011, "Evaluation of the 2010 Toyota Prius Hybrid Synergy Drive System." Oak Ridge Nat Lab report ORNL/TM-2010/253.

The energy efficiency of such a converter is between 96-99%, with higher voltage steps resulting in lower efficiency.

The losses in the *motor* (also *generator*) are mainly due to internal resistive losses in the windings, currents induced by magnetisation and mechanical friction. Different types of motors have different efficiencies (Chapter 3, Table 3.1). Permanent magnet synchronous motors (PMSM) are already magnetised and thus incur lower losses.

Electric motors have high efficiencies for particular torque and speed intervals (see Figure 5.4). Efficiency decreases considerably at very low torque and speed, which relates to driving conditions such as vehicle queues. The specific efficiency characteristics versus torque and speed vary with the type and design of the motor and influence the gains or losses achieved with a gearbox. However, due to the high motor efficiency at very different operating points, electric vehicle transmissions are simpler than for ICE vehicles, and may not require a gearbox at all. The transmission losses between the power source and the wheels are therefore normally lower than in conventional cars. A possible (future) option is to mount the electric motors directly to the wheels (in-wheel motors). This can help in reducing transmission losses to a minimum.

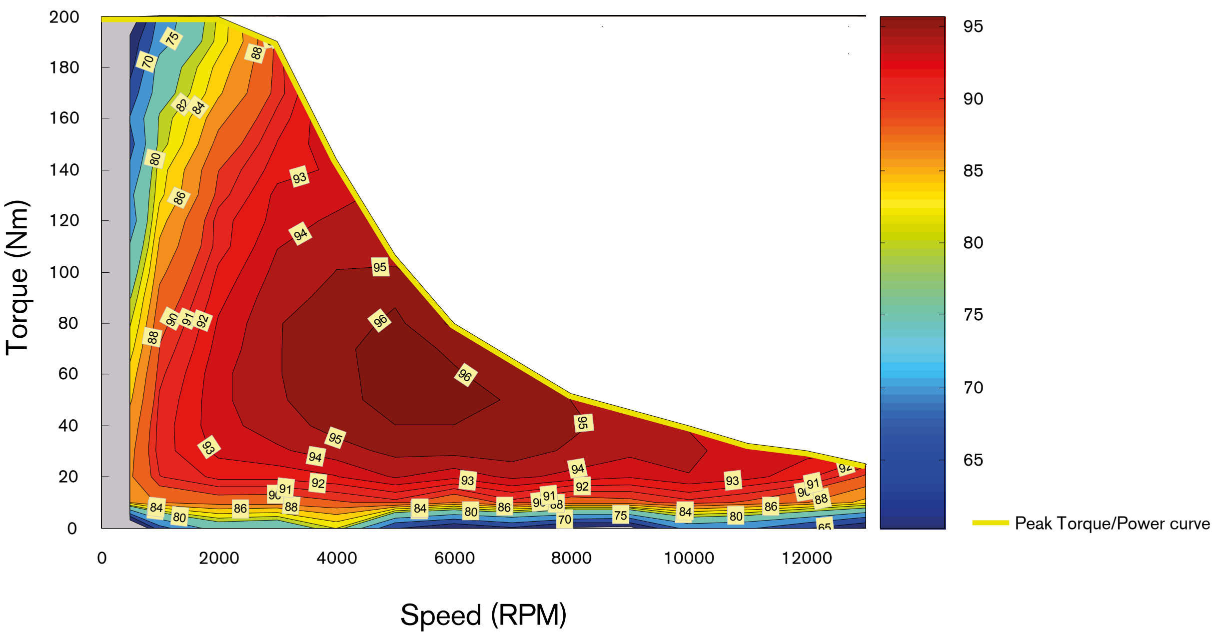


Figure 5.4 2010 Toyota Prius motor efficiency contours.[3]

As mentioned above, recovering kinetic and potential energy is an important feature of electrified vehicles. Recovery by operating the drivetrain ‘backwards’ means that the conversion efficiency is potentially equal to the forward direction. However, fully charged batteries cannot recover any energy. The drivetrain also limits recovery power. The power involved in braking can occasionally be very high since cars can stop much faster than they can accelerate. Recovery occurs through the driving wheels only. Road and weather conditions combined with vehicle control and safety consideration can thus further limit recovery efficiency.

The actual energy recovered in real driving is also strongly dependent on traffic and driving style. Hard braking can restrict energy recovery. Eco-driving techniques that save on propulsion energy in conventional cars will have a similar effect for electric cars, but may produce a smaller benefit when energy recovery is available.

Several kilowatts of *auxiliary power* are required in modern cars. Electric cars require a considerable amount of auxiliary power in addition to that required for the powertrain. The basic electronic functioning does not require that much auxiliary power. Starting a Nissan Leaf, for instance, requires around 0.2 kW, which corresponds to 2–4% of the battery energy used during driving. However, power steering and braking, lighting, wipers, adjustable seats and mirrors, and infotainment require considerable amounts of auxiliary power (see Chapter 7 for consequences in terms of materials requirements of increasing demand for auxiliary components). Battery conditioning is specific for electric vehicles. Because today's lithium-ion batteries are temperature sensitive, auxiliary power for battery temperature conditioning is often necessary. High temperatures, which result from internal heat generation or a warm climate will lower the battery lifetime. Cold ambient temperatures reduce the power and energy capacity of the battery. During driving, the battery must provide this auxiliary energy.

The power requirements for interior heating and cooling require most auxiliary power. Compared to conventional vehicles, electric vehicles generate little or no surplus from the cooling system and interior heating thus requires extra power. The need to supply auxiliary power for interior heating means that cold ambient temperatures can halve electric vehicle ranges.

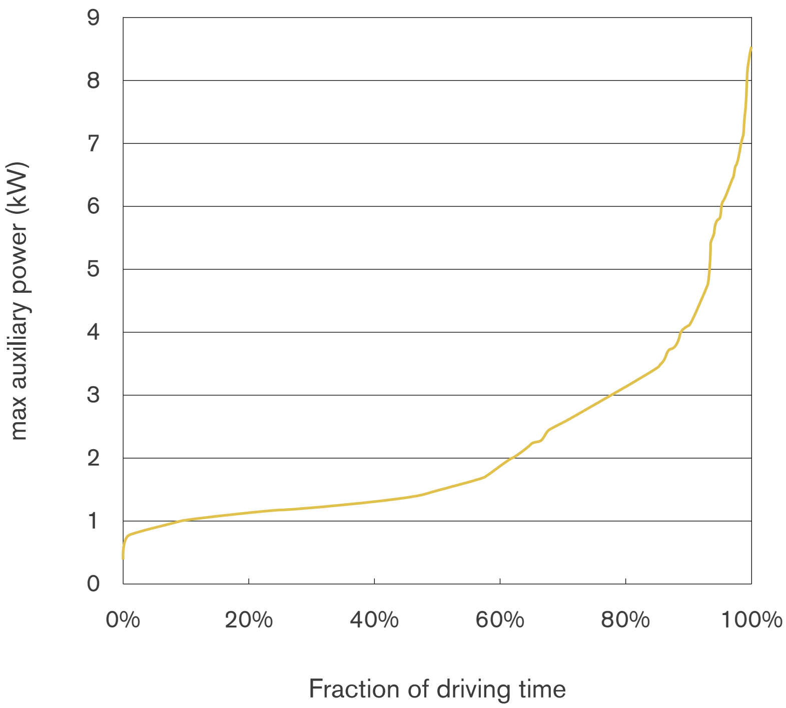


Figure 5.5 Measured auxiliary power use in six Peugeot Ions during real driving. The driving occurred at all seasons of the year in Belgium.[4]

4 Laurent De Vroey, One year behind the wheel of an electric car. Presentation at EEVC-2012, Nov 20-22, 2012 Brussels.

The energy use of auxiliaries has been measured for real driving conditions. For the Peugeot Ion, auxiliaries consumed 37% of the battery energy in average Belgium driving conditions. Auxiliaries required over 2 kW on average, but varied between 0.8 and 8.5 kW (Figure 5.5). Auxiliary power requirements increased considerably in cold temperatures. The average energy consumption (including propulsion) almost doubled for a temperature drop between +25 °C and -10 °C.

It is thus important that car producers consider ways to mitigate auxiliary power requirements by, for instance, insulating the passenger compartment and improving heat recovery. Since air conditioning is supplied via heat pumps in existing vehicles, electric vehicles can use heat pumps for heating and to recover low temperature heat from different sources in the vehicle. Alternatively, heat can be supplied by a fuel burner to alleviate burdens on the battery.

VEHICLE ENERGY USE AND EFFICIENCY

We now return to the efficiency of the full vehicle. Table 5.2 gives some efficiency measures at the vehicle level. The numbers are for a Nissan Leaf electric vehicle driving on two US test drive cycles. The ultimate losses are due to air and rolling resistance, which is the net energy supplied to the road. With this as a basis, the overall propulsion efficiency is around 45-70% for electric vehicles. As an example, the Nissan Leaf on the US UDDS test cycle requires 0.121 kWh/km electric energy from the grid for propulsion, while the air and rolling resistance losses are 0.56 kWh/km. This gives an overall BTW_{net} energy efficiency of 46%. For a conventional vehicle with no energy recovery, the braking energy is often included in the ‘needed’ energy. This corresponds to the gross energy delivered to the wheel. For a Nissan Leaf on the UDDS this gross energy is 0.117 kWh/km, which gives a BTW_{gross} energy efficiency of 97%.[5]

The table illustrates that any figure for the overall energy conversion efficiency in the vehicle will depend heavily on how it is defined. It is reasonable to compare energy input to the energy delivered to the road – but does this figure also include the energy recovered to the wheels and lost in braking? There are other ambiguities, including how one should handle the energy going to auxiliaries and at which point one should start to account for the input – at the battery or at the grid outlet.

Figure 5.6 illustrates the overall energy efficiency of an electric vehicle. It shows various measurements for Peugeot Ion electric vehicles operating in real driving conditions in Belgium. The energy delivered to the wheels was measured using a dynamometer.[6] Auxiliaries’ energy use accounts for a very large share of the net energy delivered to the battery. GTW_{gross} is estimated at only 35-43%. Without any auxiliary energy use the energy delivered from the grid would have been 42% less. The GTW_{gross} efficiency would have been equal to the drivetrain conversion efficiency from the battery to the wheels (= P_{W+}/B_{DL}), estimated at 61-75%.

5 When energy recovery is allowed, this number does not really measure conversion efficiency since it could reach levels above unity if a large share of the battery output energy is recovered.

6 The higher figure is a maximum value achieved in the dynamometer measurement under optimal conditions. The lower figure is an estimated value for year-round real world driving.

Table 5.2 Various energy efficiency measures for Nissan Leaf on the US city test cycle (UDDS) and highway test cycle (HWFET). For comparison the corresponding efficiency for a conventional vehicle is added. Formulas refer to the designation in Figure 5.1.

Efficiency measure	**Formula (Fig 5.1)**	**Energy in**	**Energy out**	**En. eff. on UDDS**	**En. eff. on HWFET**
ELECTRIC VEHICLE					
Powertrain efficiency	P_{W+}/B_{DL}	Gross battery output to powertrain only	Supplied wheel work (gross energy supplied from wheel to road)	73%	68%
Recovery train efficiency	B_{Rec}/P_{W-}	Energy supplied from road to wheel	Energy recovered to battery	73%	67%
Battery to wheel net, BTW_{net}	$P_{Res}/(B_{DL}+B_{Aux}-B_{Rec})$	Net battery output	Road load (air and rolling resistance = net energy supplied from wheel to road)	46%	63%
Battery to wheel gross, BTW_{gross}	$P_{W+}/(B_{DL}+B_{Aux}-B_{Rec})$	Net battery output	Supplied wheel work	97%	72%
Grid to wheel net, GTW_{net}	P_{Res}/G	AC grid	Road load	38%	52%
Grid to wheel gross, GTW_{gross}	P_{W+}/G	AC grid	Supplied wheel work	79%	59%
CONV. VEHICLE[a]					
Tank to wheel net, TTW_{net}	P_{Res}/F	Fuel energy	Road load	8.5%	21%
Tank to wheel gross, TTW_{gross}	P_{W+}/F	Fuel energy	Supplied wheel work	18%	24%

[a] The conventional vehicle is a 2012 Ford Focus 2.0 litre with 6-speed automatic transmission. Its fuel consumption on the European drive cycle NEDC is 6.1 litres/100 km.

The efficiency of the charging process is relatively low – only 82%. This could be justified by the fact that these losses imply greater use of grid electricity. In contrast, conversion losses in the drivetrain reduce range and performance and are thus more critical to engineering efforts.

We can compare the conversion efficiency figures discussed here with the corresponding figures for conventional cars. Table 5.2 compares the efficiency of a Nissan Leaf with a similarly sized vehicle – a Ford Focus with a 2 litre gasoline engine. The TTW_{gross} and TTW_{net} values are 4.5 and 2.5 times smaller for US city and highway cycles, respectively. For cases with a cold climate the differences will decrease – especially for urban driving where electric vehicles produce less surplus energy for interior heating.

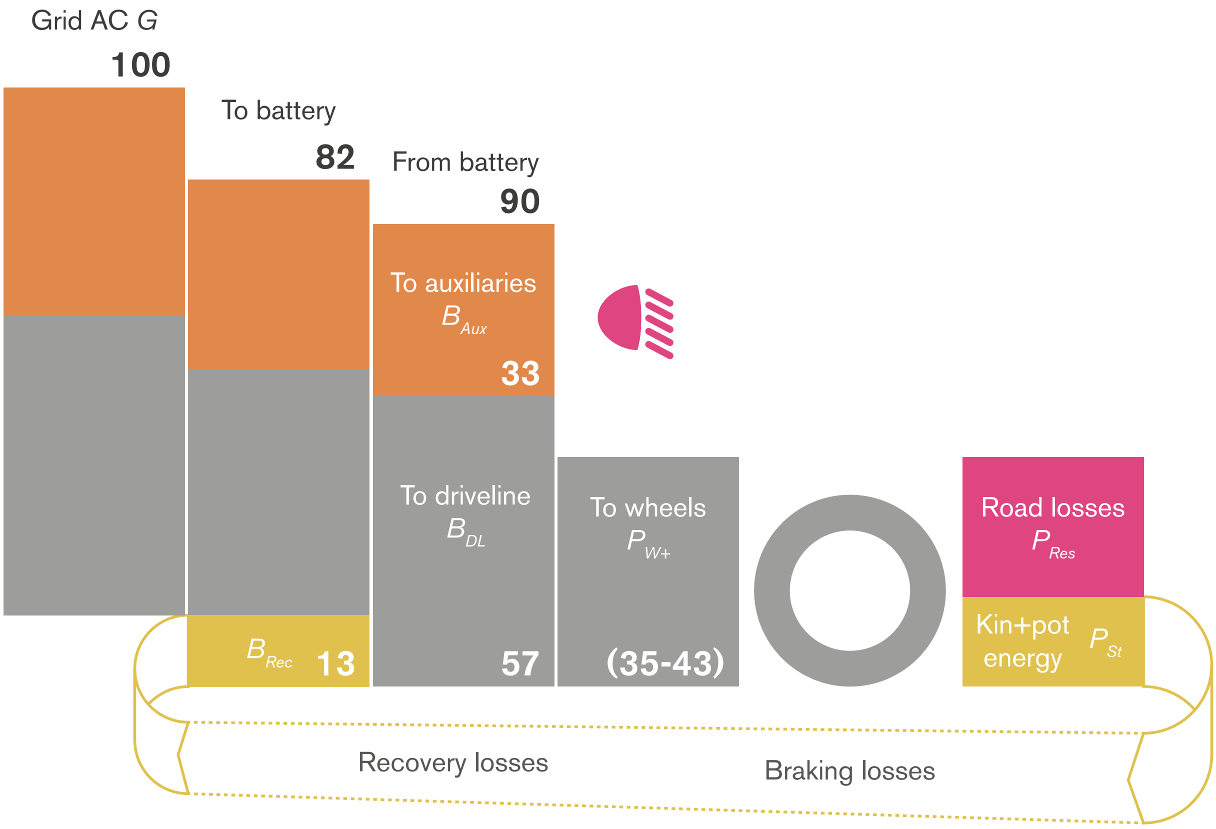


Figure 5.6 Energy fluxes for a Peugeot Ion electric vehicle during real driving conditions in Belgium. Figures in parenthesis are estimates based on dynamometer measurement. The figures are given in percentages of the energy delivered from the grid = 100. Orange denotes the share required by auxiliaries.[7]

The current push for lower fuel consumption, driven mainly by the European Union legislation on CO_2 emissions, has decreased the energy use gap between ordinary cars and electric vehicles. New vehicles have bodies with lower air resistance and are equipped with low rolling resistance tires, which decreases fuel consumption. Combustion engines have become more sophisticated and have lower specific fuel use because of techniques such as direct injection, stratified charging, downsizing, turbocharging, and by lowering auxiliary power requirements. Drivetrains have been gradually or wholly hybridised by introducing start-stop systems, for instance. Moreover, over 50% of newly sold cars in the EU are equipped with the more efficient diesel engines.

Battery weight affects energy efficiency. Many commercially available electric cars have ranges in the order of 150 km under 'light conditions' (low acceleration, speed and auxiliary power requirements). Ranges are typically halved by more severe driving conditions. These cars have a battery pack that weighs around 300 kg, which thus corresponds to 2-4 kg of battery for every km of range.[8] Further extension of the range will increase the battery weight, implying higher specific energy use. Technological developments leading to higher specific capacity will not only lower energy storage costs but also increase the energy efficiency of the vehicle for a given range. The construction of an extensive charging infrastructure

7 Laurent De Vroey, One year behind the wheel of an electric car. Presentation at EEVC-2012, Nov 20-22, 2012, Brussels.
8 This corresponds to, for instance, a specific energy use for these conditions of around 14 kWh/100 km for 'light conditions'; a battery capacity utilisation of 90%; and a specific battery pack capacity of 80 Wh/kg.

may assist in increasing energy efficiency by allowing for smaller batteries and lower weight.

Finally, in Table 5.3, the energy characteristics for electric and conventional vehicles in different situations are compared qualitatively. The electric vehicle is not superior in all situations, concerning refuelling, for instance. However, the superior average efficiency of the propulsion driveline makes electric vehicles a more efficient option in general terms, as shown in Table 5.2.

Table 5.3 Comparison of the electric drivetrain with a conventional drivetrain.

Situation	Electric driveline	Conventional driveline
Supplying energy to the vehicle	Charging involves losses	Negligible losses
Vehicle stops	No energy use	Energy wasting due to idling
City traffic with many stops and acceleration	Energy recovery possible in deceleration/downhill driving	Much energy lost in braking. No energy recovery
Low speed/low power need	High conversion efficiency	Engine works with low conversion efficiency
High speed/high power need	Conversion efficiency goes down somewhat with power	Engine works in more efficient mode
Cold climate	Extra energy for cabin heating needed, possibly also for battery conditioning, possibly also when parked	Heat for cabin heating available for free from engine waste heat
Warm climate	ACC energy efficiently delivered from battery	ACC energy from fuel via less efficient engine
Requirement for long range, large auxiliary or comfort energy use	The extra weight due to larger battery will increase the power and energy need for propulsion	Negligible influence

SYSTEMS ENERGY USE AND EFFICIENCY

We have so far discussed the energy efficiency of electric vehicles. Electric vehicles will be part of a larger energy and electricity system and the way in which electricity is produced and delivered to the vehicle will play an important role in the total efficiency of that larger system (see also Chapters 8 and 9). The efficiency of the entire fuel chain (the WTW efficiency) can be calculated by combining information on how the fuel or electricity for vehicles is produced with the previously discussed numbers on vehicle efficiency.

Table 5.4 and Figure 5.7 show some examples of supply chain efficiencies and the corresponding total fuel chain energy use. We can conclude that the supply chain is very important for the total efficiency. The chains O-CV and O-EV in Table 5.4 illustrate the case for using crude oil for either conventional or electric vehicle fuels. Despite the higher vehicle efficiency for the EV, the difference in WTW efficiency between the electric and the conventional car almost disappears because the crude oil WTT process is much more efficient for conventional vehicles, as illustrated in Figure 5.7. There are substantial losses in the production of electrical or mechanical energy from fuels and any chains using fuels will contain one such conversion. With electric cars this conversion step is just moved to the system for electricity production.

Table 5.4 Well to Tank (WTT) efficiencies for crude oil and solar energy transport fuel chains.

		Efficiency				
WTT energy supply chain		**Solar energy conversion**[a]	**Conversion to fuel**[b]	**Distribution to fuelling point**	**WTT' (=conv. + distr.)**	**Solar energy to tank**
O-CV	*Crude oil*–Refinery–*Gasoline* (–CV)		0.8-0.9	0.99	0.79-0.89	
O-EV	*Crude oil*–Refinery–*Fuel oil*–Power plant–*Electricity* (–EV)		0.30-0.45	0.90-0.95	0.27-0.43	
Sc-CV	*Solar energy*–Farming–*Corn*–Biorefinery–*Ethanol* (–CV)	0.003	0.25	0.99	0.25	0.00075
Sc-EV	*Solar energy*–Farming–*Willow*–Power plant–*Electricity* (–EV)	0.005	0.30-0.40	0.90-0.95	0.27-0.38	0.0014-0.0019
Se-EV	*Solar energy*–Solar cell–*Electricity* (–EV)	0.05-0.10	1	0.90-0.95	0.90-0.95	0.045-0.095

[a]Starting from solar energy flux onto utilised surface area. Solar to corn production efficiency: average US values. Solar to willow: Swedish values. Solar energy to electricity: assumed at 0.10-0.20 for the solar cell panels, with a ground cover ratio (panel to ground area) of 0.5.

[b]US data for corn to ethanol: 1 MJ of ethanol requires 2.14 MJ of corn and 0.72 MJ of fossil fuels, of which half is assumed to be substituted by ethanol and half directly with biomass. Source: Geyer et al, 2013. Spatially explicit life cycle assessment of sun-to-wheels transportation pathways in the US. Env Sci & Techn 47, 1170-1176. The indirect energy required for the energy investment in the technical artefacts used for energy conversion, e.g. oil refinery plants or solar cells, is not included. Adding this number would, however, not change the result substantially since in most systems it would amount to less than 10% of the energy turnover. See e.g. Kushnir, D., Sandén, B.A., 2011. Multi-level energy analysis of emerging technologies: A case study in new materials for lithium ion batteries. Journal of Cleaner Production 19, 1405-1416.

When starting from a renewable crop (see chains Sc-CV and Sc-EV) the difference once again increases. The production of liquid fuels such as ethanol from energy crops is typically less energy efficient than direct production of gasoline from crude oil. This is true even when disregarding the solar energy input, due to large energy inputs in biomass growth with intensive crop production and large conversion losses and energy inputs in the production of the high-quality liquid fuel. Any liquid fuel production from solid fossil coal will suffer similar conversion losses. Directly converting solar energy into electricity (chain Se-EV) avoids all of these losses and results in an efficient WTT process for EVs.

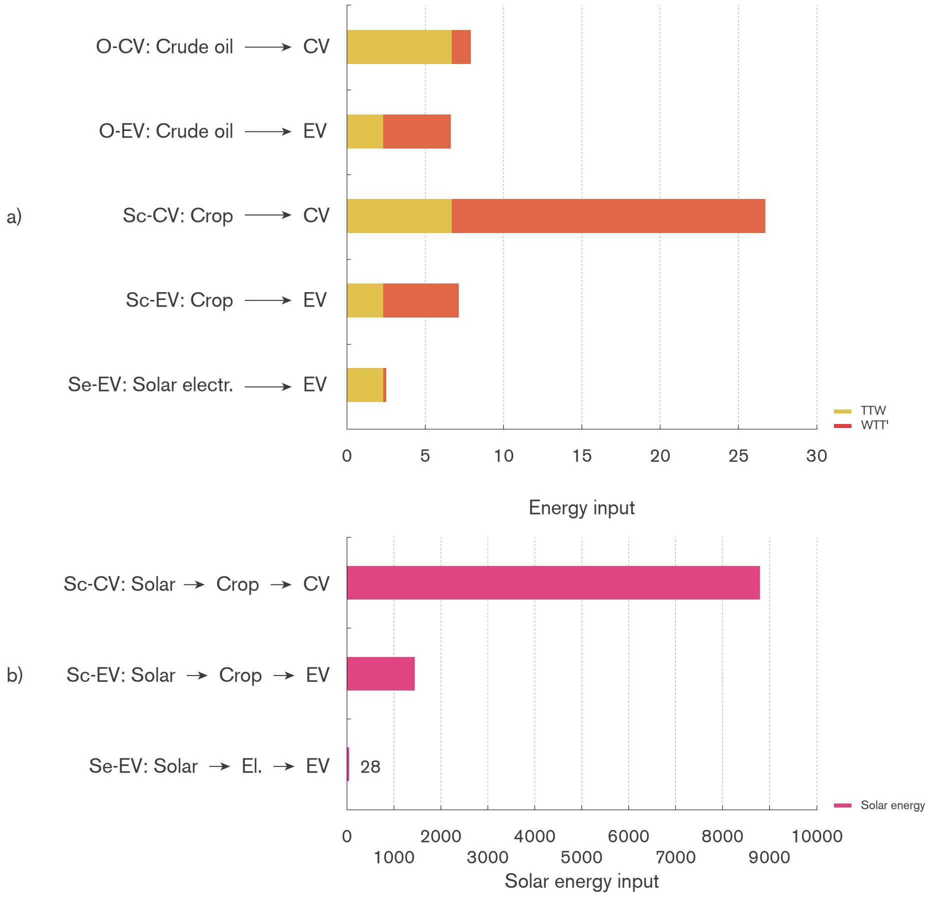


Figure 5.7 Well to wheel (WTW) energy input requirements along the different vehicle energy chains normalised to 1 at the wheels. Figure a) includes the energy input required to compensate for losses in the vehicle, TTW (from Table 5.2), and the fuel/electricity chain (excluding conversion from solar energy), WTT' (from Table 5.4). TTW is here defined as GTW_{net} and TTW_{net} for the EV and CV drivetrains, respectively. The mean value of the two drive cycles is used. Taking the efficiency of solar energy conversion into account (Table 5.4) as in Figure b), the losses in the bioenergy systems exceed those of direct solar energy conversion by two orders of magnitude. This indicates that electromobility opens up a pathway to radically more energy efficient transport systems based on renewable energy compared to those dependent on liquid biofuels, independently of the efficiency of the electric drive train *per se*.

The utilised solar energy (taken as the influx of the solar energy on the area utilised for energy capture) for the renewable energy chains is very large – see Figure 5.7b. This is especially the case for the two chains that utilise biological crop production, which has very low efficiency in terms of solar energy capture. The solar energy input is a factor 50-300 times larger for bio-production paths compared to the chain utilising solar cells. Although this energy is 'free', the solar energy input is directly proportional to the land area needed for the capture and land area may be limited. Furthermore land for growing crops must be fertile, whereas the solar cells have no such requirements and can be placed on marginal land or buildings.

Comparing the energy efficiency of different energy chains is a complex issue (discussed further in Chapter 6). When energy is coproduced, for instance, the allocation of the energy inputs will be arbitrary to some extent. When renewable resources such as wind and solar energy are utilised, various factors influence the ultimate renewable energy input. A factor omitted here (but which is further discussed in Chapter 6) is the energy cost for production (and recycling) of the vehicle itself, which is non-negligible and must be considered in an overall assessment.

SUMMARY

We can conclude that the energy efficiencies of the various components within the electric cars are generally very high. However, the many components in electric cars incur their own losses, lowering the total chain conversion efficiency. Non-propulsion energy use may also be considerable in comparison, especially for compartment heating and cooling. Notwithstanding, electric cars are more energy efficient than cars with internal combustion engines.

Besides the conversion efficiency within the vehicle, the efficiency of the energy supply (WTT efficiency) is a very important factor for the efficiency of the total energy chain (WTW) of the electric vehicle. Furthermore, electric vehicles are potentially important components in energy systems of the future. For such systems it is important to consider the energy and cost efficiency of the energy system as a whole. With limited fossil fuel resources, bio-productive land areas and greenhouse gas sinks, the single energy chain must be balanced against its influence on the total system. It is thus important to examine the role of electric vehicles in future energy systems in terms of energy efficiency alongside environmental, economic and other societal parameters.