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Are global CO_2 emission reductions possible by driving electric?[1]

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Abstract

In this study, a well to wheel CO_2 analysis of the usage phase of an EV compared with internal combustion engine (ICE) based vehicles (including hybrid) is conducted. This study uses type approval data of the vehicles, which is governmentally verified and official fuel consumption data for comparison. The study found that in Europe, the EV has lower CO_2 emissions compared with any fossil fuelled car regardless of the country's electricity mix. Widespread use of TH!NK city and other EVs will - due to increased energy efficiency - create a significant reduction of global CO_2 emissions compared with combustion engine vehicles. For urban driving this reduction amounts to about 95% in Norway, 90% in Switzerland, 40-60% in the UK and 30-50% in the Netherlands, depending on the fuel efficiency of the combustion engine car. The reduction varies depending on the driving pattern and the traffic conditions, but will reduce the overall global emissions considerably. Moving from a combustion engine to an electric engine will be necessary to reduce the impacts of transport on climate change.

Keywords: climate change, ICE, BEV, well-to-wheel, life cycle analysis

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1 Introduction

Among the many human activities producing greenhouse gases, the use of energy represents by far the largest source of emissions. Energy usage accounts for over 80% of the global anthropogenic greenhouse gases. Since 1870, the annual CO2 emissions from fuel combustion dramatically increased from near zero to 27.1 Gt CO2 in 2005 [1]. Between 1971 and 2005, the combined share of electricity and heat generation and transport shifted from one-half to two-thirds of global emissions and in 2005 was over 70% of the world’s electricity and heat generated from fossil fuels [1]. While electricity and heat generation draws from various energy sources, the transport sector relies almost entirely on oil (95% of the energy used for transport came from oil in 2005). Since 1971, the CO2 emissions from oil consumption in most sectors remained nearly steady in absolute terms whereas the emissions in the transport sector were more than doubled. Dominated by road traffic is this end-use sector the strongest driver of world dependence on oil. Fossil fuel combustion is the single largest human influence on climate change and world leaders have recognized the need to address and reduce CO2 emissions from fuel combustion.

In light of the global challenges of increasing demands for energy and the impacts of climate change, there has been an increasing focus on alternative vehicles such as electric vehicles (EVs). Many skeptics argue that driving EVs only moves the emissions (including CO2) from the sector of transport to the sector of electricity generation. Proponents argue that the global CO2 balance will be drastically reduced due to the winning energy efficiency of the electrical engine compared with the internal combustion engine (ICE). As a rule of thumb, an electrical engine often achieves 85-90% energy conversion efficiency, while an ICE achieves about 15-20% [2].

Different studies utilizing varying methodologies have been conducted on this topic. Finkbeiner [3] and Schweimer [4] conducted life cycle assessment of internal combustion engine vehicles, Samaras [5] utilized an economic input – output model for life cycle analysis focusing on plug-in hybrid drives and Widmer et al. [6] conducted a well to wheel study of different drive trains but utilizing the same reference vehicle. This study uses vehicle type approval data based on the European driving cycle which is the only officially verified way of comparing fuel efficiency in Europe. The advantage is that environmental impacts of vehicle construction, such as the vehicle weight on CO2 emissions or engine efficiencies, are fully counted for in real life measurements. To the best of my knowledge, no other study has yet made use of this information for comparing drive trains. The objective of this analysis is to compare the CO2 well-to-wheel emissions of EV with ICE based vehicles (including hybrid) combining life-cycle inventory data with official type approval data of vehicle fuel consumption.

2 Methodology

2.1 Electricity emission data

The production of electricity generates different amount of CO2 depending on the fuel. For example, the electricity in Norway originates mostly from hydropower whereas Germany has an overweight of fossil fuel based production. In addition, the emissions per kilowatt hour (kWh) may vary significantly from one year to the next depending on the generation mix of the given year. For example, Norway imported 15334 Gwh from other countries (mostly Sweden and Denmark) whereas it exported 3842 Gwh in 2004, but was a net exporter of about 12 Gwh in 2005 [7]. This makes it difficult to estimate an average of the electricity generation mix of a given country for a given year.

Electrical power is also lost by transmission. This applies to short distances as well as to cross country high voltage lines. In this study the Ecoinvent database v2.0 is used which contains international industrial life cycle inventory data on energy supply, resource extraction, material supply, chemicals, metals, agriculture, waste management services, and transport services [8]. The database takes into account the international electricity market and consequently the sources of its imports, the life cycle inventory data of electricity production such as construction or fuel transportation as well as power losses for the year 2004 [8]. The electricity mix of a given country is calculated by adding the domestic production with import.

2.2 Fossil Fuel Emission Data

Petrol and diesel are mixtures of liquid hydrocarbons refined from crude petroleum. The production of these fuels involves extraction, separation of crude oil from other fluids, transport to refineries, processing (fractional distillation), transport to regional storage locations and distribution to fuel stations. Different estimations of CO2 emissions from fuel production exist [4, 9, 10]. However, it is necessary to apply the same collection and estimation method for comparing alternatives. Thus, the same database as for calculating the CO2 emissions from electricity production is applied (EcoInvent 2.0) [8, 9]. A part of these emissions is allocated to the electricity consumed at refineries. Because Western Europe has an open electricity market, Ecoinvent assumes the refineries to be supplied by the Western European grid mix. At the gas station the associated well-to-tank emissions for supply of one liter fuel were 478.5 grams for petroleum and 420 grams for diesel [9]. The CO2 emissions per liter fuel combusted were 2.40 and 2.66 kilograms (kg) for petroleum and diesel respectively. The total emissions associated with consuming one liter (l) of fuel were 2.99 kg for gasoline (0.48 kg/l + 2.40 kg/l) and 3.08 kg for diesel (0.42 kg/l + 2.66 kg/l).

2.3 Driving Cycles

All cars sold in the European Union after 1 January 2001 are required to conduct drive cycle tests for type approval. In this study we use the European driving cycle, defined in EU Directive 80/1268/EEC [11], in order to compare the fuel and electricity consumption of the vehicles. The driving cycle consist of two parts: an urban (UDC) and an extra-urban (EUDC) driving cycle. The fuel test cycle is the same as the one used to determine the official exhaust emission classification for the vehicle in question. As a prerequisite are the cars run-in and driven for at least 3000 kilometres before testing. The UDC starts by taking the vehicle into the test area where the ambient temperature is between 20 ° and 30 °C on a rolling road where the emissions are to be collected from key-on (cold start). The UDC consists of a series of accelerations, steady speeds, decelerations and idling. Maximum speed is 50 kph, average speed is 19 kph, and the distance is 4 km. Immediately after the UDC starts the extra-urban driving cycle (EUDC). The EUDC consists of driving at roughly half-steady speed with some accelerations, decelerations, and engine idling towards the end of the cycle. The maximum speed is 120 kph, average speed is 63 kph, and the distance is 7km. The mixed driving cycle (MUDC) is the average of the two tests, weighted by the distances covered in each part. Note that the EV has a limitation to its maximum speed of 100 kph. Consequently, the driving cycle did not exceed 100 kph for the EV, TH!NK city.

2.4 Vehicles

2.4.1 Electric Vehicle

The electric vehicle used in this study is the TH!NK city. It has two seats and an optional choice of two rear children seats and weighs 1038 kg. The range of the UDC is 203 km and 180 km for the MUDC. The driving efficiency per kilometre is 0.153 kWh per kilometre (km) for UDC and 0.172 kWh/km for MUDC. This includes a 10% charging loss of the battery which has a capacity of 28.2 kWh. Although an EV has no cold start implications, using the heater requires electricity and decreases range. However, the use of the heater is a function of climatic conditions and time. Table 1 shows estimated heater usage as a function of climatic conditions to achieve high visibility and a comfortable temperature in the coupe (20-22 degrees Celsius) for the average user. However, an option of electric demist and deice front window exists which would reduce the load on the heater. This is not taken into account in this study.

Engine idling of an EV does not require electricity. The electricity used will be for powering other systems, e.g., lights. EVs also have regenerative brakes which charge the battery. This is an advantage in stop-and-go situations. Generally driving at low speed is also advantageous for the range, because the air resistance grows proportionately to the square of the velocity.

Table 1: Average heater usage at different temperatures

Outside temp	Start up time	Start up effect	Maintenance effect	Heater usage 30 min	Heater usage 60 min
5˚C	5 min	4 kw	1 kw	0,75 kwh	1,25 kwh
0˚C	15 min	4 kw	1 kw	1,25 kwh	1,75 kwh
-5˚C	15 min	4 kw	2 kw	1,5 kwh	2,5 kwh
-10˚C	15 min	4 kw	4 kw	2,0 kwh	4,0 kwh

2.4.2 ICE vehicle

In this study, one petrol (p) – Nissan Micra (1240 cc), one diesel (d) – Citroen C1 (1395 cc), and one hybrid (h) – Toyota Prius, ICE vehicle were analyzed. The UDC fuel consumption for the vehicles were 7.4 l/100 km for petrol, 5.3 l/100 km for diesel and 5.0 for hybrid. For MUDC the fuel consumption were 5.9 l/100 km for petrol, 4.1 l/100 km for diesel and 4.3 l /100 km for hybrid. The fuel consumption was collected from the designated UK Vehicle Type Approval authority database [12]. The well-to-wheel emissions are then calculated by multiplying the fuel consumption per kilometer of a selected driving cycle with the CO2 emissions associated with one litre fuel consumed.

For cold conditions, the engine combustion surfaces and engine oil must be warmed up. The sometimes competing requirements to provide timely heat to the heater and heat to the engine increases fuel consumption. Some factors such as coolant flow rate affect heater warm-up positively while affecting engine warm-up negatively. Fuel consumption increases almost linearly as a function of decreasing temperature, although at very low temperature the amount partially and non-combusted fuel increases disproportionately while the CO2 emissions stagnate or even decrease [13]. The UDC test is conducted in a room which holds a temperature of about 23˚Celsius, bit which does not reflect cold winter conditions. For a category Euro-4 petrol or diesel engine, the cold start phase lasts for about 7 km, or 22 minutes and 15 seconds at 19 km/h [13]. 19 km/h is the same average speed as in the UDC. In Table 2, a linear increase of the extra fuel consumption is assumed and which is based on [13]. Measurements conducted at temperatures 23˚C, -7˚C and -20˚C found 0.04, 0.13 and 0.18 litre extra combusted per start for petrol and 0.05, 0.14 and 0.20 for diesel.

Table 2: extra fuel consumption at cold start as a function of temperature.

Temperature	Litre/Start Petrol	Litre/Start Diesel
5˚C	0,0960	0,1061
0˚C	0,1120	0,1205
-5˚C	0,1279	0,1350
-10˚C	0,1449	0,1583

2.4.3 Rush Hour

A field study from the city of Brussels of relatively low-mileage cars found that fuel consumption was 20-45% higher during rush hours compared to Sundays and that compared to driving constant at 50 kph, driving during rush hours (13.5 kph average speed) doubled CO2 emissions [14]. Similarly, a traffic simulation of rush hour with 5000 vehicles/hour in a heavy congested urban motorway, reflecting the traffic situation of many large cities was performed by Knutsen & Bang [15]. Knutsen & Bang simulated the effect of expanding the motorway with one extra lane and thus improving the traffic flow conditions. The lack of sufficient capacity resulted in very low traffic speed (stop-and-go conditions), whereas adding the extra lane, increased the average speed from 32.4 kph to 54.7 kph. In total, adding the extra lane decreased the CO2 emissions for new cars (1-5 years) by 32% for petrol cars and 30% for diesel cars. The reduction in CO2 emissions was 38% including all types of vehicles. The authors noted that the real average speed would be lower because cars would be queuing also to get into and exit the highway. The findings of Knudsen and Bang of 32% and 30% for newer petrol cars and diesel cars respectively are applied in this scenario. For a hybrid vehicle, the performance in rush hour depends on several external factors such as engine temperature, size and charging status of the battery, and time queuing [16], but no study of hybrid vehicle performance in rush hour was found. In this study, given the limited battery capacity of the Toyota Prius, it is assumed that the hybrid vehicle uses 20% more fuel during rush hour. The fuel consumption associated with rush hour was added to the well-to-wheel fuel consumption for the UDC.

3 Results

The first part of the results section is dedicated to the UDC and MUDC which is the basic fundament for the second part containing the more advanced scenarios Nordic Winter and Rush Hour.

3.1 Urban Driving Cycle

The EV related emissions vary from 5 grams (g) per kilometre (km) for Norway to 99 g/km in the Netherlands as can be seen in Figure 1. Nevertheless, the EV saves about 97% of emissions per km driven in Norway irrespectively of ICE drive train, whereas in the Netherlands the savings range from 31.3% for the hybrid to 53.5% for the petrol vehicle. This is a considerable saving considering the vehicle’s lifetime. For example, in the Netherlands, a country which has an overweight of fossil fuelled electricity generation, the EV saves about 7.2 metric tons of CO2 emissions over 160 000km

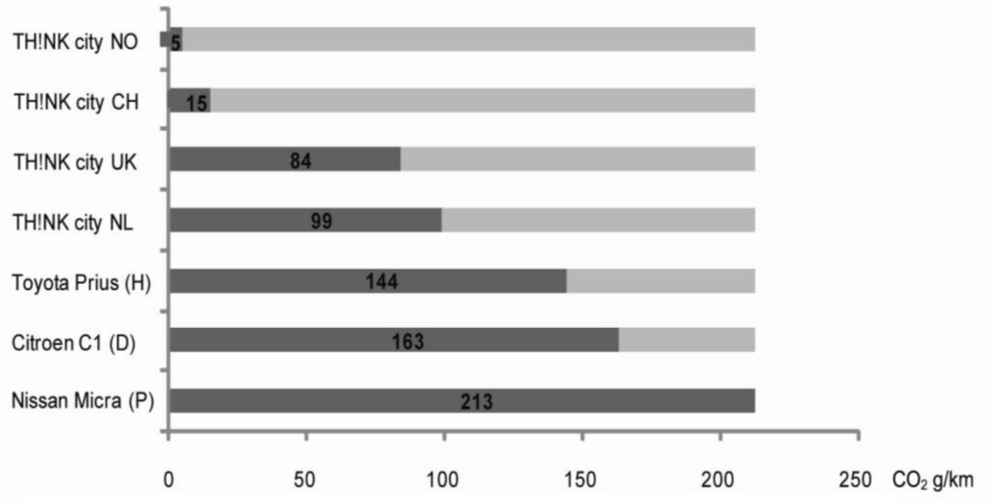

Figure 1: Well-to-wheel CO2 emissions of urban driving cycle.

compared to the hybrid, in Norway the saving would amount to 22.2 tons. In Europe, the EV has lower CO2 emissions compared with any fossil fuelled car regardless of the country's electricity mix.

3.2 Mixed Urban Driving Cycle

Similar trends as with the UDC can be observed for the MUDC. However, the ICE vehicles perform slightly better in MUDC due to more optimized utilization of the ICE engine. The EV has lower well to wheel CO2 emissions regardless of country and ICE drivetrain. The high share of hydropower in Norway reduces EV 97.0% or 162 grams of CO2 emissions per driven kilometre comparing the EV with the petrol vehicle, but drops to 32.9% or 55 grams of reduced emissions for the fossil fuel loaded electricity mix of the Netherlands. Other ICE drivetrains and electricity mixes can be seen in Figure 2.

3.3

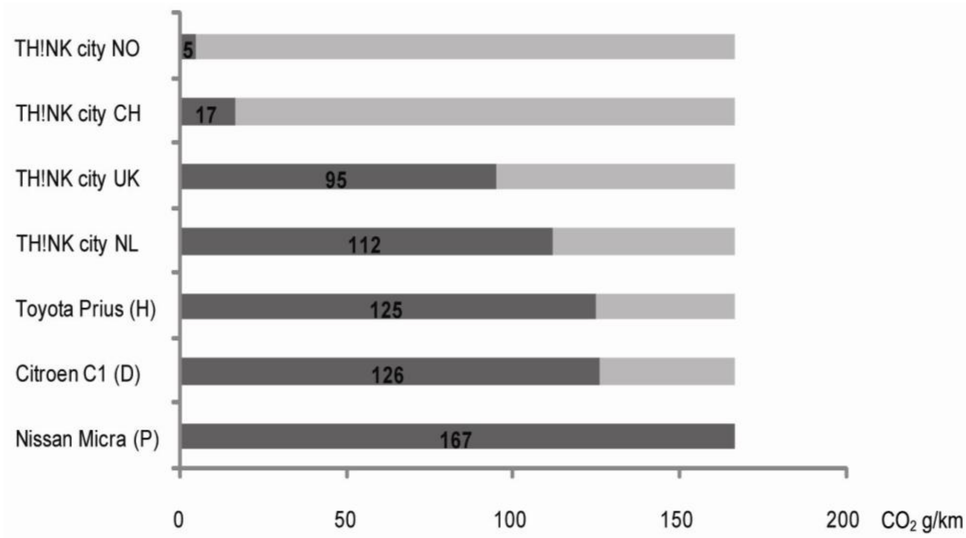

Figure 2: Well-to-wheel CO2 Emissions of mixed urban driving cycle

Scenario 1: Nordic Winter

The Nordic winter can be cold and may provide challenges for both driver and vehicle. In this scenario, we compare various climatic conditions and related use of heater for the UDC driving 30 minutes and a longer drive of 60 minutes composed of 30 minutes UDC and 30 minutes MUDC.

Table 3 compares the EV with the ICE cars from cold start, driving for 30 minutes at various temperatures. At temperature -10˚C the EV saves 5-31% of CO2 emissions per driven kilometre in Western Europe, 67-76% with the Nordic Grid and 94-96% in Norway. The EV also performs better at lower temperature. For a 60 minute drive and typical winter conditions in Western Europe (-5˚C to 5˚C), the EV has 12-47% lower emissions than the ICE vehicles as can be seen in Table 4. At -10˚C in Western Europe, the most fuel efficient fossil fuelled car, the hybrid vehicle, performs marginally better at low temperature, whereas a petrol vehicle does not. However, the average temperatures in January for various cities are typically Oslo -7˚C, London 3˚C, Paris 4˚C, Amsterdam 2˚C, Berlin -1˚C, Stockholm -3˚C, and Zurich -1˚C. With other words, cold Nordic conditions occur rarely in other cities of Western Europe. The EV's performance will of course also depend on the country in question, e.g. France has considerably lower CO2 emissions than Germany. Temperature is important because the relatively low energy efficiency of the combustion engines creates spill heat that can be used for the heater while for an electric vehicle this heat has to be created. However, the EV still performs better at cold temperature than ICE vehicles.

Table 3: Percentage reduction in CO2 emissions, comparing the EV with ICE cars in cold climate and driving 30 min UDC.

ICE vehicle	TH!NK city Norway				TH!NK city Nordic Grid				TH!NK city Western European Grid			
Model	-10˚C	-5˚C	0˚C	5˚C	-10˚C	-5˚C	0˚C	5˚C	-10˚C	-5˚C	0˚C	5˚C
Toyota Prius (H)	-94,1 %	-94,5 %	-94,9 %	-96,0 %	-67,0 %	-71,0 %	-73,0 %	-77,5 %	-5,3 %	-16,9 %	-21,9 %	-34,1 %
Nissan Micra (P)	-95,7 %	-96,0 %	-96,4 %	-97,1 %	-75,9 %	-79,0 %	-80,6 %	-83,9 %	-30,7 %	-39,7 %	-43,7 %	-52,9 %
Citroen C1 (D)	-94,9 %	-95,2 %	-95,5 %	-96,5 %	-71,2 %	-74,4 %	-76,2 %	-80,3 %	-17,2 %	-26,6 %	-31,2 %	-42,4 %

Table 4: Percentage reduction in CO2 emissions comparing the EV with ICE cars in cold conditions, 60 min driving (30 min UDC + 30min MUDC).

ICE vehicle	TH!NK city Norway				TH!NK city Nordic Grid				TH!NK city Western European Grid			
Model	-10˚C	-5˚C	0˚C	5˚C	-10˚C	-5˚C	0˚C	5˚C	-10˚C	-5˚C	0˚C	5˚C
Toyota Prius (H)	-93,2 %	-94,5 %	-95,1 %	-95,0 %	-63,3 %	-69,7 %	-72,7 %	-74,5 %	5,4 %	-12,4 %	-21,0 %	-26,2 %
Nissan Micra (P)	-95,0 %	-96,0 %	-96,4 %	-96,4 %	-73,1 %	-77,9 %	-80,2 %	-81,6 %	-22,9 %	-36,2 %	-42,6 %	-46,9 %
Citroen C1 (D)	-93,7 %	-94,8 %	-95,5 %	-95,4 %	-65,8 %	-71,6 %	-74,7 %	-76,3 %	-1,9 %	-18,1 %	-26,6 %	-31,6 %

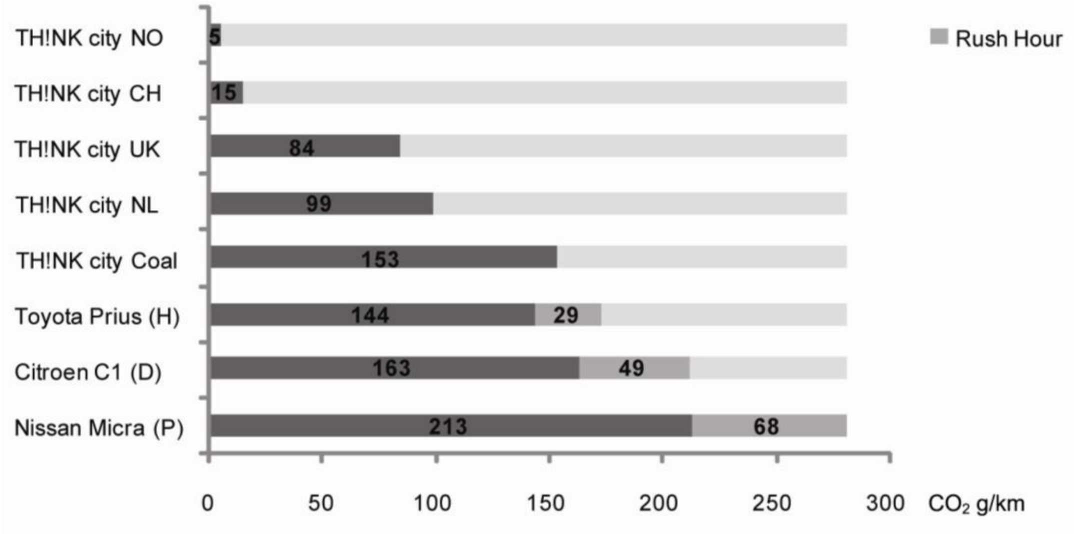

Figure 3: UDC and associated rush hour fuel consumption. The generation of electricity from hard coal power stations creates CO2 emissions of 1030 g/kWh (Dones et al. 2007)

3.4 Scenario 2: Rush hour

For a lot of people living in urban areas, driving in rush hour is part of the daily life. The road typically takes them from a sub-urban area to a highway and into the city. Driving in congested traffic typically includes frequent accelerations and braking, low average speed, idling, stop – and-go situations, and wasted time queuing. The UDC is used as the baseline for estimating the rush hour performance. Figure 3 shows that the EV is ideal for rush hour traffic and provides considerably CO2 reductions compared to ICE vehicles, regardless of electricity mix used to charge the vehicle. The CO2 reductions in Norway were 97.1% and 51.4% in the UK per driven km compared with the hybrid drive and as much 70.1% compared with the petrol ICE. The well to wheel efficiency of the EV is further demonstrated by comparing the electricity generated from hard coal power stations. The saving potential of the EV is still significant, being 11.5% per km compared with the hybrid drive and as much as 45.6% reduction per km compared with the petrol vehicle.

4 Discussion

An electric vehicle, here exemplified by the TH!NK city, will due to its energy efficiency create a significant reduction of global CO2 emissions compared with ICE vehicles. This is true for all countries and urban driving patterns regardless of the electricity mixes analysed in this study. For urban driving, the reductions amount to about 95% in Norway, 90% in Switzerland, ranges from 40 to 60% in the UK, and 30-50% in the Netherlands. The reduction varies depending on the choice of ICE vehicle, driving pattern, temperature, and traffic conditions. However, driving an EV will move the CO2 emissions from the transport sector to the electricity sector, but will reduce the overall global emissions considerably. Other well to wheels studies considering electric options have reached the same conclusion [6, 16, 17].

The manufacturing stage of vehicles should not be considered negligible, but research has showed that the manufacturing accounts for about 10% of the lifecycle emissions for ICE vehicles [4]. EVs often have lighter constructions, but may contain more electronics and a heavy battery. In the case of TH!NK city, the battery accounts for about 25% of the weight. The battery is expected to last for the lifetime of the vehicle. EVs may have higher environmental impact in the manufacturing stage than an ICE car of the same size due to higher precious metal content. However, as illustrated in this study, this would be compensated by superior performance in its usage stage. The impacts of the vehicle weight on CO2 emissions in the use phase are in any case fully counted for by using the vehicle type approval data.

The method of conducting a well-to-wheel analysis is well established. In this report, the Ecoinvent database is used which includes e.g., the environmental load of constructing and maintaining installations such as power stations and grid infrastructure, and factors such as power loss and cross country trading. Other calculations such as from the International Energy Agency do not include such life cycle impacts or effects on grid mix due to electricity trade [1]. This consequently leads to lower overall emissions than the Ecoinvent database varying from 9 to 77% depending on the country in question. The GREET model developed by Argonne National Laboratory estimates the emissions of electricity generated from coal to be 1084 grams per kwh [10] compared with 1030 g/kwh in the Netherlands as given by the Ecoinvent database [18]. The estimates for electricity in this study can therefore be considered as conservative estimations. Ecoinvent is also applied for fuel production. The GREET model applies well-to-tank emissions of 402 grams per liter of conventional gasoline [10] whereas Ecoinvent applies a higher rate of 478.5 grams per liter [9]. Nevertheless, it is fundamental to apply the same dataset and methodology to ensure equal conditions for comparing alternatives.

5 Conclusions and outlook

The EU vehicle fleet consists of 215 million cars with average emissions of 160 g/km [19], and related well to wheel emissions of 186 g/km [9]. Given Norwegian electricity mix, replacing only 10% of the European car fleet would reduce the yearly CO2 emissions with 46.7 million tons which is more than the Norwegian CO2 emissions were in 2005 [1]. The electricity needed for powering 21.5 million EVs would be 44.4 Twh or 36% of the Norwegian production of 121.4 Twh for 2006 [7]. The required growth in electricity production is therefore relatively modest.

An EV reduces noise, and eliminates local air pollutions such as nitrogen oxides, particle matter, and ground level ozone. These culprits are associated with major health hazards in cities. In addition, it is easier to control few but big point sources of emissions (power stations) than millions of small point sources (cars) in terms of e.g. replacing technology or targeting environmental policies. Widespread use of EVs will due to increased energy efficiency create a significant reduction of global CO2 emissions compared with ICE vehicles. It reduces global emissions at all types of driving patterns and temperatures. In rush hour the EV reduces emissions even though powered with electricity from hard coal. Improving the energy share of renewables in the country will, as a result, also improve the EV performance. The EV outperforms all other ICE alternatives if charged on electricity from a renewable source. Moving from a combustion engine to an electric engine for vehicles will be a necessary change to reduce the impacts of transport on climate change. The electrical vehicles environmental benefits are significant.

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