Impacts of electrification of automotive transport in different OECD countries

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Abstract: This paper evaluates the effects of road transport electrification and its regionally widely differing environmental impacts. Life-cycle assessment is carried out to quantify the environmental impacts of electric cars in all OECD countries with widely different electricity generation mixes. The environmental impacts of internal combustion engine vehicles and electric vehicles are compared. For cars, the life-cycle assessment considers the environmental impacts throughout the entire life cycle, from raw material extraction and acquisition, through energy and material production and manufacturing, to use and end-of-life treatment and final disposal. For fuels and electricity, the whole life cycle from cradle to gate is considered. The results show significant differences in the environmental impacts of battery electric vehicles between the countries. Policies to advocate the electrification of road transport differ from country to country, and the still very carbon-intensive electric mixes of most countries make the environmental gains of electric vehicles questionable. Combining technology forecasting and life-cycle assessment tools can provide a foundation for policy planning towards more sustainable automobile transportation.

Keywords: life-cycle assessment; LCA; fuel cell electric vehicle; FCEV; electric vehicle; internal combustion engines; forecasting; environmental impacts; policy.

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1 Introduction

The economic and ecological significance of the automotive industry is remarkable to our modern societies. Global warming is of concern to everyone, and road transport sector is one of the biggest sources of greenhouse gas (GHG) emissions. Passenger cars alone contribute to about 12% of EU's total energy-related CO_2 emissions (Van der Vooren and Brouillat, 2015). During previous decades, different kinds of policies and technologies, such as battery electric vehicles (BEVs), fuel cells or biofuels, were considered the most promising candidates to reduce environmental impacts of road transport (Budde et al., 2015). From the sustainability perspective, the only consensus seems to be that the environmental burden caused by transport must be reduced significantly. The ability to meet the strict environmental standards will be a major success factor in future competition, which is of great interest to organisations active in this field.

Automotive industry is in a state that multiple alternative fuel and powertrain technologies are challenging the dominant gasoline or diesel-fuelled internal combustion engine vehicle (ICEV) design. Patent-based studies have noted strong interest in emerging technological paths and the potential for a new dominant design (e.g., Bakker et al., 2012; Oltra and Saint Jean, 2009; Rizzi et al., 2014). However, the actual market development of alternative powertrain technology vehicles has been slow so far as well as the installation of their recharging or refuelling stations. Currently in the world, about 80 million cars are sold every year and 97% of the transportation is powered by gasoline or diesel, including biofuels (Engerer and Kunert, 2015). Energy challenges require changes beyond incremental practises and require understanding of how large socio-technological systems evolve in transition towards a sustainable energy system (Könnölä et al., 2013).

The current technology competition is of great interest to organisations active in this field. It is well known that one large potential shift is vehicle electrification. For decision makers, it is also important to know what kind of impacts the electrification of the light-duty fleet will have. To find out these impacts, life-cycle assessment (LCA) is a valuable tool. LCA quantifies the environmental impacts of a product's manufacture, use, and end-of-life. In this paper, life-cycle environmental impacts of ICEV and BEV technologies with widely different electricity generation mixes of various OECD countries are compared using a LCA tool built by us.

Previous research (Granovskii et al., 2006; Samaras and Meisterling, 2008) has shown that the economics and environmental potential to achieve large-scale GHG emission reduction with use of an electric car is highly dependent on the energy sources of electricity production. Onat et al. (2016a) use seven indicators for electric vehicles [global warming potential (GWP), particulate matter formation, photochemical oxidant formation, vehicle ownership cost, contribution to gross domestic product, employment generation, and human health impacts] to deepen the life-cycle sustainability assessment framework. Although many studies have focused on the environmental impacts of alternative vehicle options and electricity generation mixes, not many combine these two or they focus mainly on future electricity scenarios.

Various methods have been utilised to predict the development paths of future technologies. Some of these techniques are based on a technology life cycle approach where technology is expected to follow an S-curve. Databases are valuable sources for such technology life cycle data or S-curve graphs. One method, which is known to offer different important economic indicators, is the analysis of patents. In recent years, technology forecasting and LCA studies of alternative powertrain vehicle technologies have been presented (Granovskii et al., 2006; Samaras and Meisterling, 2008; Onat et al., 2016a, 2016b; Thomas, 2009). However, currently few studies if any combine these approaches for investigating overall environmental impacts of different technological futures, powertrain technologies and electricity generation mixes.

In this paper, life cycle analysis was carried out for petroleum- and diesel-fuelled cars, which represent an average car on the road in EU (curb weight 1,300 kg, combined fuel consumption 7.6 L/100 km for a gasoline car and 5.2 L/100 km for a diesel car, lifetime mileage 195,000 km) and similar-size electric car (curb weight 1,600 kg, grid electricity consumption 0.87 MJe/km). The environmental impacts of driving an electric car in each OECD country (excluding Latvia which became the member of OECD in 2016) were calculated by determining the electricity mixes and incorporating them into the LCA tool. The GWP (i.e., carbon dioxide intensity) of driving an electric car is reported for every OECD country and certain environmental impacts for selected OECD countries. The GWPs of driving an electric vehicle powered by various electricity generation options were also determined to show the importance of renewable electricity sources in future electricity mixes.

The purpose of the article is to obtain a realistic picture of the effects of potential road transport electrification and its regionally widely differing environmental impacts using real electricity generation data of the countries, and to show that, in order to have positive environmental impacts, parallel to transport electrification the electricity production must rely much more on sustainable renewable electricity sources. Technological forecasting should take into account the environmental impacts, which can be estimated using the LCA tools.

2 Technology paths in automotive industry

We first provide a short overview of the main automotive technology trajectories and discuss the potential alternative futures. The two major technological paths are usually distinguished: the continuous improvement of conventional engine technologies and the development of alternative engine technologies.

2.1 The continued dominance of internal combustion engines

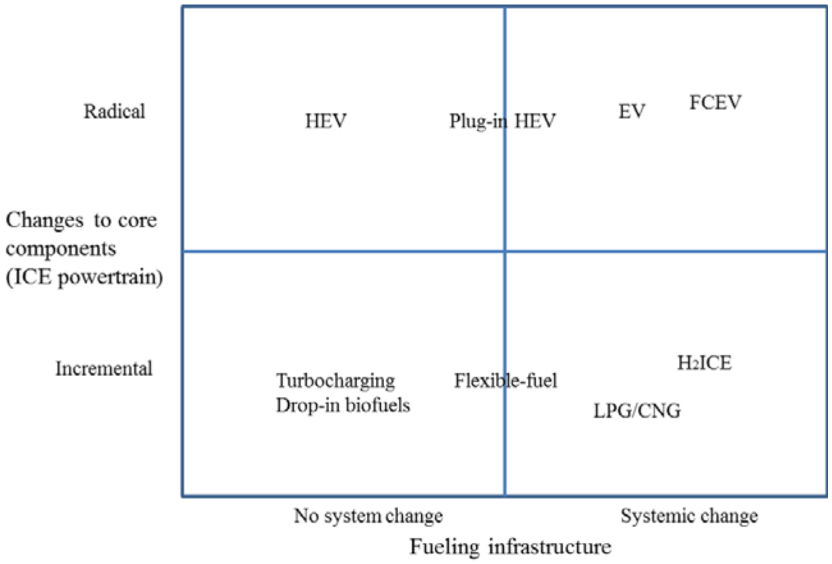
At the moment automotive industry is still characterised by a strong and persistent dominant design. Currently, in the world there are 1.2 billion cars (Organisation Internationale des Constructeurs d'Automobiles, 2015), of which about 900 million are passenger cars, and 99.9% of cars are equipped with internal combustion engine. There are about 850,000 battery electric cars, which is about 0.07% of world cars. In addition, there are about half a million plug-in hybrid electric vehicles (0.04% of world cars). Petroleum fuels 94% of cars, while the share of biofuels is about 4.5%. About 1.4% of cars are natural gas vehicles. The share of hydrogen fuel cell electric vehicles (FCEVs) is practically zero.

The significant competition outside the dominant design and the tightening emission standards have resulted in fast development of advanced ICEV (Berggren and Magnusson, 2012; Karvonen et al., 2016). Oltra and Saint Jean (2009) found in their study that still more than 50% of the patent portfolios of the companies are dedicated to the dominant design, i.e., ICE and diesel vehicles. The dominant internal combustion engine design has also made progress in terms of emissions and fuel efficiency (Taylor, 2008; Berggren and Magnusson, 2012), and the share of advanced diesel vehicles is expected to increase in the next 30 years (Oltra and Saint Jean, 2009). However, the recent Volkswagen scandal concerning the manipulation of emissions shows that reducing CO_2 and NOx emissions and fulfilling the desires of car buyers at the same time may be challenging.

2.2 The emergence of new dominant design

Zapata and Nieuwenhuis (2010) define the improvement of conventional engine technologies (liquefied petroleum gas LPG; compressed natural gas CNG; drop-in biofuels – i.e., biodiesel, bioethanol; hydrogen internal combustion H2ICE; internal combustion-electric hybrid HEV) as incremental innovation and development of alternative powertrain technologies (BEV; FCEV) as radical innovation. Sierzhula et al. (2012) consider also the infrastructure requirements in their categorisation of innovations in the automotive industry (Figure 1). In this categorisation, BEV and FCEV represent also radical innovations and potential technological discontinuity in the industry.

Figure 1 Powertrain innovations relative to the ice powertrain and fuelling infrastructure (see online version for colours)



Source: Adapted from Sierzhula et al. (2012)

The most remarkable difference between HEV and the radical innovation technologies (FCEV, BEV) is the systemic change needed in technology and infrastructure development, i.e., HEVs can rely on current fuelling infrastructure. Furthermore the development also requires new modes of cooperation between actors from different fields, such as chemical, mining, electronics and automotive sectors (e.g., Golembiewski et al., 2015). Table 1 summarises some main barriers and advantages of alternative fuel powertrains.

Table 1 An overview of low-emission vehicle technologies

	Hybrid vehicles	*BEVs*	*Fuel-cell vehicles*
Fuel	Gasoline/diesel	Electricity	Hydrogen
Propulsion technology	Combination of an ICE and an electric motor	Electric motor, powered by battery	Electric motor, powered by fuel cells using hydrogen
Advantages	Can rely on current infrastructure, lower fuel costs	No direct emissions – i.e., no smog, lower fuel costs	No direct emissions – i.e., no smog, potentially low fuel costs
Disadvantages and barriers	Higher purchase cost, battery costs, efficiency	Higher purchase cost, battery costs, low range, recharging time, lack of recharging infrastructure	Higher purchase cost, very limited or no refuelling infrastructure, safety issues, production of hydrogen, reliability concerns
Climate change mitigation potential	Still causes CO_2 emissions	More efficient, but still dependent on electricity, which is probably produced with CO_2 emitting technologies	Depending on the source of hydrogen, there are probably still CO_2 emissions

Source: Adapted from Frenken et al. (2004), Chan (2007), Sierzhula et al. (2012) and Bohnsack et al. (2014)

The electric car is not a new invention. Already in 1888 there were 24 small batteries in the early electric car of Magnus Volk and Moritz Immisch, enough to give a driving range of 80 km, not much less than today's BEVs (Smil, 2003). In the turn of 20th century, electric cars dominated the emerging US automotive market. In 1903 there were 36 recharging sites in Boston alone. Cars equipped with internal combustion engines replaced electric cars in the first decade of the 20th century. More than a century after the first electric cars, oil shocks, global warming and urban pollution have prompted renewed interest in BEVs.

Because of the potential climate change benefits, there is a political agreement on the need to deploy BEVs (e.g., Nykvist and Nilsson, 2015). Various stand-alone policies and policy mixes, such as increasingly strict environmental regulations, price subsidies, CO_2 emission taxes and a feebate system, have been implemented to stimulate the diffusion of cleaner vehicles (Van der Vooren and Broullait, 2015).

2.3 Conventional vs. battery electric vehicles

The ICEV has dominated the car market for a hundred years and still outperforms BEV on most of the characteristics that consumers value. However, even though the energy efficiencies of the ICEVs have steadily improved, there is no potential to achieve a well-to-wheel zero emission chain. With BEVs, the potential climate change benefits are much easier to achieve as the 'zero emission' is possible for the BEVs, if renewable electricity is used to power the car.

However, even though the transformative capacity of BEVs is high, it does not fit within the current mobility system and cannot compete with the ICEVs with regard to range and price, and thus the possibility of a classical diffusion process is unlikely (Augenstein, 2015). According to Augenstein, these shortcomings may turn into triggers for change towards a systemic type of change, where future e-mobility evolves as an element of a less car-dependent mobility system in transitions in the fields of energy and transport.

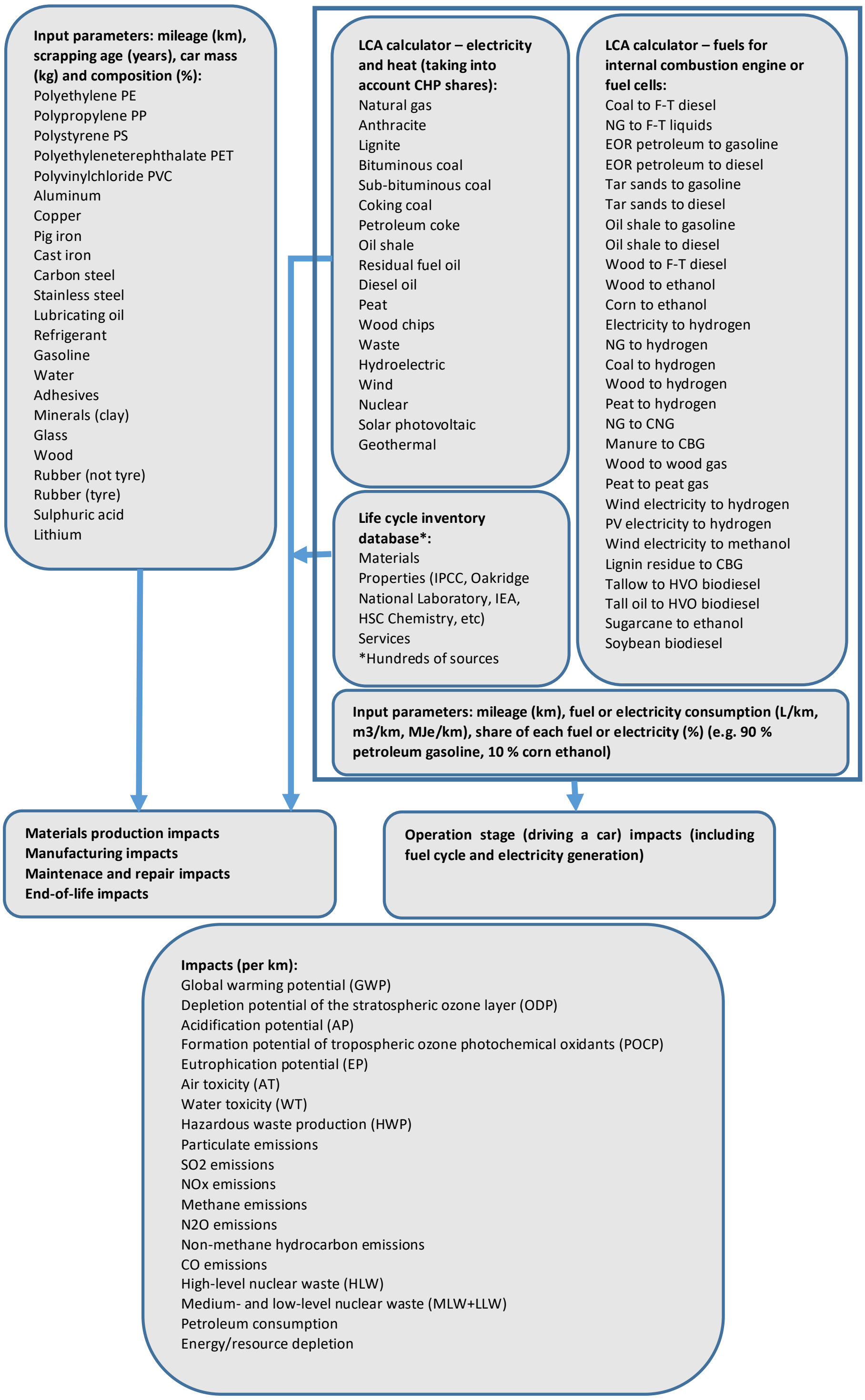
BEVs are the leading alternative powertrain and low emission technology today. BEVs are called zero emission vehicles (ZEVs), because they have no local exhaust pipe emissions such as carbon monoxide, sulphur dioxide, nitrogen dioxide, unburned hydrocarbons and particulates. However, if electricity is generated in a distant place, electric cars are just a means of switching the location of emissions. In this study, the life-cycle environmental impacts of a BEV with widely different electricity generation mixes of various The Organisation for Economic Cooperation and Development (OECD) countries are compared with ICEVs fuelled with gasoline and diesel. The base case is the average car in the fleet in EU-15 (Klemola, 2006).

BEVs store electricity in batteries, which have a limited storage capacity and must be replenished by plugging the vehicle into a recharging unit. Electricity to the batteries comes from the grid or from decentralised renewable sources such as solar or wind energy. The cost of recharging a BEV is very small, but a BEV is still expensive. Most BEVs have a range of only 100–160 km before recharging is needed.

The internal combustion engine is not an efficient energy converter. Only a small fraction, less than 25% of the energy in gasoline, is available for propulsion. An electric vehicle running on batteries is a much better energy-conversion device. Starting with 11% loss in battery charge, 6% loss in discharge, and another 11% loss in moving the energy from the battery to the wheels, one ends up with 74% conversion efficiency from grid electricity to wheels (Abu-Rub et al., 2014). On the other hand, burning coal and other fossil fuels to generate electricity is an inherently inefficient process. The electricity generation efficiency from underground coal to electricity is typically less than 30%, while the well-to-tank efficiency from crude oil to gasoline or diesel is about 85%. Depending on how the electricity is generated for BEVs, electric cars either decrease or increase overall emissions.

According to International Energy Agency (2014), presently 43% of all CO_2 emissions originate from coal, which is the major source of power production, while oil, which is necessary for the transport, stands for 38% of the emissions. The transport sector accounts for about a quarter (23%) of global energy-related GHG emissions. It seems that managing the climate change without massive introduction of clean and efficient energy technologies is impossible (e.g., Lund, 2016) and climate change related benefits of BEVs can be fully harvested under the condition that their use is coupled with a decarbonised grid (IEA, 2016).

Figure 2 The principle of life cycle analysis for determining environmental impacts of using a car during the whole life cycle (see online version for colours)



3 Methods and data

3.1 LCA of light-duty fleet electrification

Life-cycle analysis is carried out for the following stages: operation (including fuel burning, fuel production and electricity generation), car materials extraction and production, car manufacturing, maintenance and repair and end-of-life. The principle of LCA carried out in this study is shown in Figure 2.

The life-cycle impacts of the operation stage are either for fuel cycle (internal combustion engine and FCEV) or for electricity generation (BEVs). For fuels, such as petroleum-based diesel or plant-based biodiesel, the extraction of crude or cultivation of plants, processing the feedstock to fuels and burning in internal combustion engine are taken into account in calculating the emissions and impacts per MJ of fuel. The life-cycle energy demand of gasoline and diesel production and the venting, flaring and fugitive emissions of crude, natural gas and coal extraction were calculated using the data from the reports of Wang (1999), European Commission (2014), Jacobs Consultancy (2009) and IPCC (2006).

In calculating the emissions and impacts of electricity per MJe, the electricity generation mix and the share of combined heat and power (CHP) of each electricity source in the mix are given to the calculation tool. In allocating CHP production impacts to electricity, the benefit sharing method was used (Viinikainen et al., 2007). Benefit sharing method of CHP allocates higher share of fuel used and consequently higher share of emissions to the less efficient electricity generation than to the more efficient heat generation. The electricity generation mix is composed of the following sources of electricity: petroleum, natural gas, coal, lignite, bituminous coal, sub-bituminous coal, coking coal, petroleum coke, oil shale, residual fuel oil, diesel oil, peat, wood chips, wood pellets, waste, hydroelectric, wind, nuclear, solar photovoltaic and geothermal. The fuel or electricity consumption is given as an input parameter and the emissions and other impacts are obtained 'per km'.

The life-cycle analyser databank includes the materials database (stainless steel, plastics etc.), which gives the emissions and other impacts of the materials needed for manufacturing a car. Also the energy inputs and emissions associated with car materials extraction and production, car manufacturing, maintenance and repair and end-of-life are calculated (Sullivan et al., 1998; Maclean and Lave, 1998). The parameters given to the life-cycle analysis tool include the life-time mileage, the scrapping age, the curb weight of the car and the fuel or electricity consumption.

In calculating GWP the following GHGs are taken into account: carbon dioxide, methane, nitrous oxide (N_2O), carbon monoxide and Freons. The global warming effect of aerosols and carbon black is location and time dependent and difficult to quantify, thus they are not included in calculations. Similarly, depletion potential of the stratospheric ozone layer (ODP), acidification potential (AP) and formation potential of tropospheric ozone photochemical oxidants (POCP) are caused by a number of compounds.

For car manufacturing, the LCA considers the environmental impacts throughout the entire life cycle, from raw material extraction and acquisition, through energy and material production and manufacturing, to maintenance and end-of-life treatment and final disposal. For fuels and electricity, the whole life cycle from cradle to gate is considered. Table 2 gives the vehicle components of an average new light-duty vehicle sold in EU-15 in 2006 (ICEV and similar-size BEV). A light-duty vehicle refers to a passenger car, a sport utility vehicle (SUV), a van and a pickup truck.

Table 2 Vehicle components of an average new EU-15 light-duty vehicle (passenger car, SUV, van and pickup truck) in 2006

Component group	*All vehicles (kg)*	*ICEV only (kg)*	*BEV only (kg)*	*ICEV (kg)*	*BEV (kg)*
Body and doors	563.76				
Brakes	13.11				
Chassis	16.63				
Fluids ICEV and BEV	5.35				
Vehicle interior and exterior	254.48				
Tyres and wheels	84.97				
Total	938.31				
Engine (ICEV)		182.24			
Fluids (ICEV only)		5.35			
Other ICEV powertrain		98.78			
ICEV transmission		55.53			
ICEV battery		17.63			
Total		359.54			
EV motor and transmission			405.04		
EV differential transmission			26.77		
EV Li-NCM battery			229.14		
Total			660.95		
Car weight				*1,297.85*	*1,599.26*

Notes: It is assumed that this is an average light-duty vehicle on the road in EU in 2016.
ICEV = ICEV, BEV = BEV.

Source: Klemola (2006) and Hawkins et al. (2013)

The base case is the average car in the fleet in EU-15 (Klemola, 2006). The average car in the fleet is assumed to be the average new car in EU-15 sold in 2006, i.e., gasoline or diesel-powered ICEV with a curb weight of 1,298 kg. Because of the batteries, a BEV with the same size weighs considerably more than ICEV, 1,599 kg in this case (Hawkins et al., 2013). The average distance travelled during the life time of the car in EU-15 is about 195,000 km (Klemola, 2006).

Using the data of 1,700 model year 2006 cars, a 1,298 kg gasoline-fuelled car was found to have a city/highway fuel economy of 7.6 L/100 km and a similar-size diesel car 5.2 L/100 km. A 1,599 kg electric car is assumed to consume 0.87 MJe/km grid electricity (Kampman et al., 2008).

The simplified material compositions of both ICEV and BEV are given in Table 3. The data are used in the LCA.

Table 3 The simplified material composition of a generic vehicle

Material	*ICEV %*	*BEV %*
Plastics	*14.7*	*10.6*
Polyethylene	1.34	0.99
Polypropylene	6.87	4.21
Polystyrene	2.81	2.45
Polyethylene terephthalate	2.42	1.96
Polyvinylchloride	1.24	1.00
Metals (non-ferrous)	*9.0*	*30.1*
Aluminum	6.02	17.72
Copper	3.02	12.41
Metals (ferrous)	*66.4*	*43.2*
Pig iron	1.98	0.28
Cast iron	10.85	0.31
Steel RR	52.25	40.99
Steel OK	1.34	1.61
Fluids	*1.2*	*3.8*
Lubricating oil	0.58	0.07
Refrigerant	0.33	0.20
Water	0.27	3.54
Other materials	*8.7*	*12.3*
Various plastics	2.78	2.26
Adhesives	0.33	1.26
Minerals (clay)	0.49	0.20
Glass	2.61	2.31
Wood	0.00	1.54
Rubber (not tyre)	0.83	0.58
Rubber (tyre)	1.51	1.23
Sulphuric acid	0.14	0.02
Lithium	0.00	0.20
Graphite	0.00	2.67

Notes: ICEV = internal combustion engine vehicle, BEV = battery electric vehicle.
The battery chosen to this study; cathode: $LiMn_2O_4$, anode: graphite.

Source: Hawkins et al. (2013), Sullivan et al. (1998) and Gaines et al. (2011)

The electricity generation mixes of selected OECD countries in 2010 (IEA, 2012) were chosen to analyse the environmental effects of BEVs. The electricity generation mixes of Iceland, Israel, Estonia, Finland, France and Norway are given in Table 4. Iceland and Norway are using a lot of renewable sources of electricity, while Israel and Estonia rely on fossil-fired electricity generation. France is using predominantly nuclear electricity and Finland is a country generating electricity from multiple sources. The future changes, possibly dramatic, in electricity generation mixes were not analysed in this study.

Table 4 The electricity generation mixes (%) of different OECD countries in 2010

Electricity source	*Estonia*		*Finland*		*France*		*Iceland*		*Israel*		*Norway*	
	Share %	*CHP* %	*Share* %	*CHP* %	*Share* %	*CHP* %	*Share* %	*CHP* %	*Share* %	*CHP* %	*Share* %	*CHP* %
Natural gas	2.34	100.00	13.96	98.18	4.18	57.01	0.00	0.00	37.51	0.00	3.92	0.00
Coal	3.16	20.05	0.73	11.22	0.52	1.45	0.00	0.00	0.00	0.00	0.05	0.00
Anthracite	0.00	0.00	18.02	30.65	4.11	2.11	0.00	0.00	58.51	0.00	0.03	100.00
Lignite	85.22	2.86	0.02	6.67	0.00	0.00	0.00	0.00	0.08	0.00	0.00	0.00
Crude oil	0.32	7.32	0.60	72.93	1.02	18.97	0.01	0.00	3.66	0.00	0.02	0.00
Peat	0.94	100.00	7.79	58.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Wood (biomass)	5.71	65.54	13.22	84.97	0.46	58.28	0.00	0.00	0.05	0.00	0.21	1.56
Other	0.00	0.00	0.37	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.16	100.00
Waste	0.00	50.00	0.64	68.23	0.74	41.03	0.00	0.00	0.01	0.00	0.19	95.28
Hydro electricity	0.00		16.00		11.75		74.99		0.00		94.69	
Wind power	2.31		0.37		1.76		0.00		0.00		0.72	
Nuclear power	0.00		28.28		75.36		0.00		0.00		0.00	
Solar PV	0.00		0.00		0.11		0.00		0.17		0.00	
Geothermal	0.00		0.00		0.00		25.00		0.00		0.00	
Electricity mix	100.00		100.00		100.00		100.00		100.00		100.00	

Note: Exports and imports are not taken into account.

Source: IEA (2012)

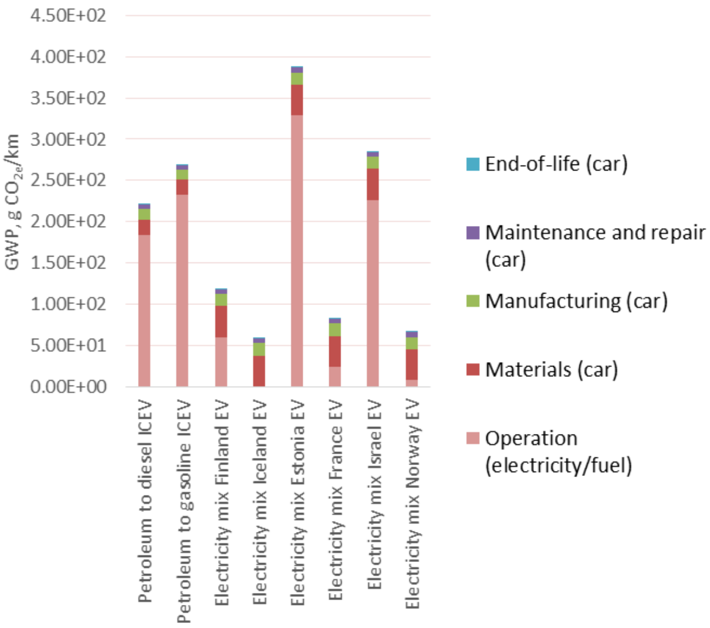
4 Results

4.1 Environmental impacts of BEVs in different OECD countries

LCA calculations were carried out to find out the environmental impacts of driving the average-size gasoline-powered and diesel-powered internal combustion engine light-duty vehicles the average driving distance of the light-duty vehicles in European Union (about 195,000 km in EU-15). LCAs were also carried out for similar-size (but heavier because of battery packs) electric vehicles powered with electricity mixes of selected OECD countries.

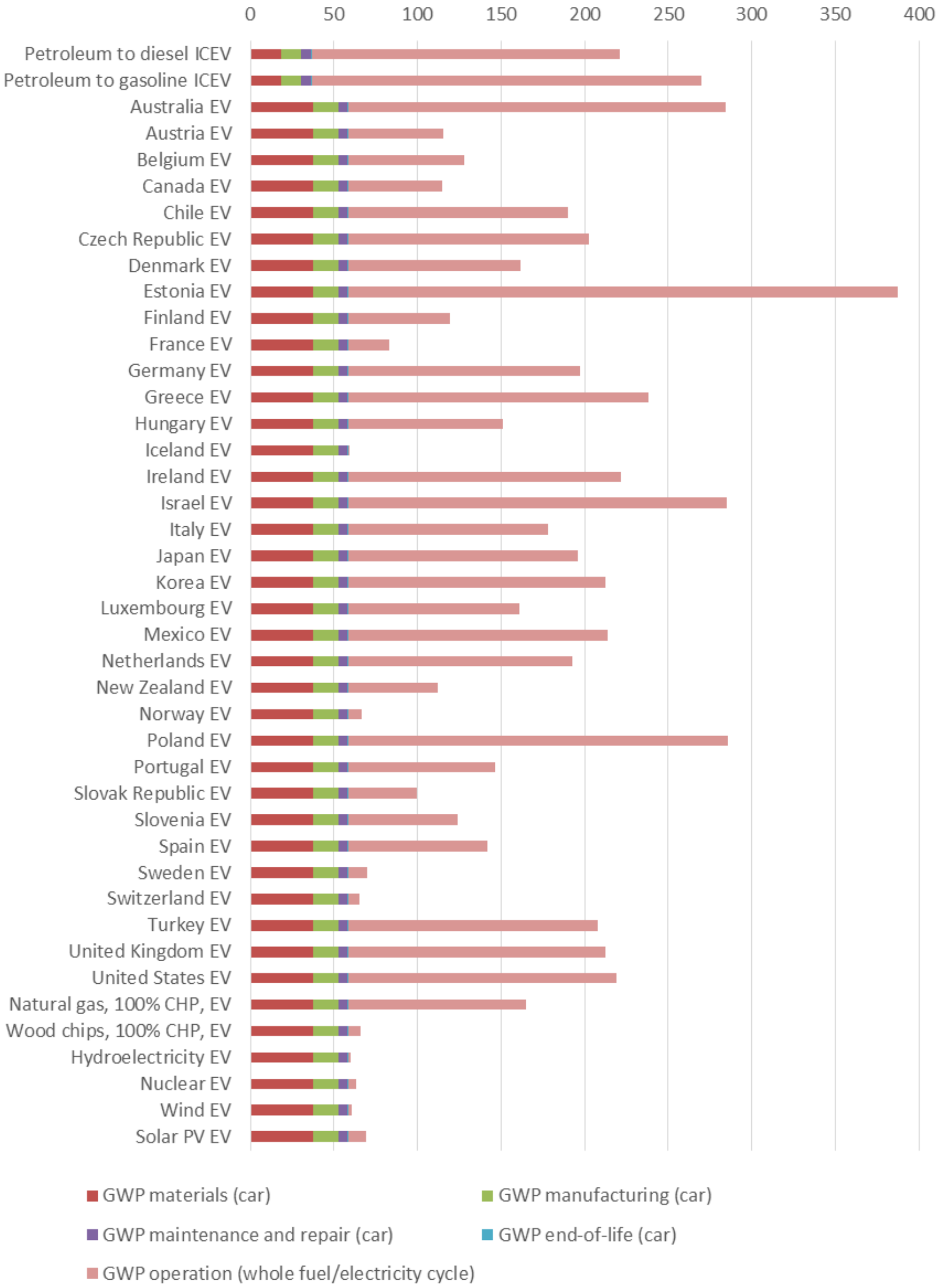
The following impacts were assessed and the results are given in Figures 3 to 11: GWP (Figures 3 and 4), ozone depleting potential (ODP) (Figure 5), acidification potential (Figure 6), photochemical ozone creation potential (Figure 7), particulate emissions (Figure 8), creation of high-level radioactive waste (Figure 9), petroleum consumption (Figure 10) and primary energy inputs (Figure 11). Certain impacts and emissions (e.g., photochemical ozone creation potential and particulate emissions) are related to local air quality and personal health. Typically electric vehicles are effective in cutting local emissions. However, most impacts are more or less global and electric vehicles are just switching the location of impacts and emissions.

Figure 3 Life-cycle GWP (expressed as g carbon dioxide equivalent) per kilometre of a gasoline and diesel ICEV and a BEV powered with electricity mixes of selected OECD countries (see online version for colours)



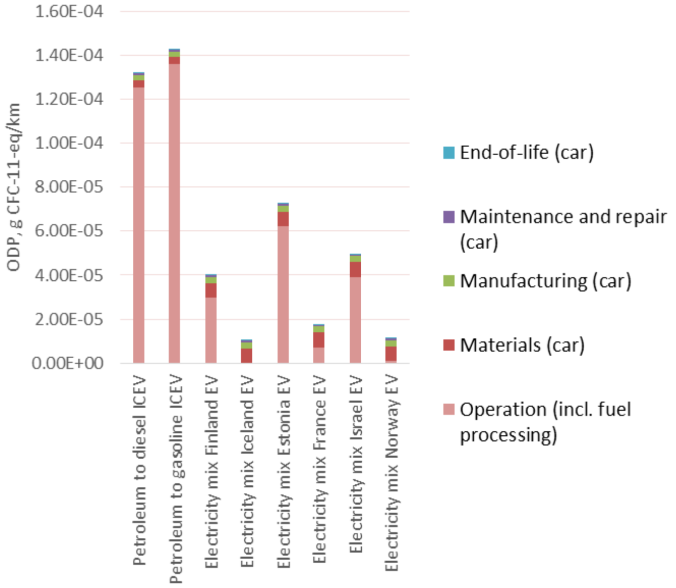
Note: The vehicle is an average-size passenger car on the road and the life-cycle driving distance is the average driving distance of light-duty vehicles in EU-15.

Figure 4 Life-cycle GWP (expressed as g carbon dioxide equivalent) per kilometre of a gasoline and diesel ICEV and a BEV powered with electricity mixes of all OECD countries (except Latvia) and various electricity generation options (see online version for colours)



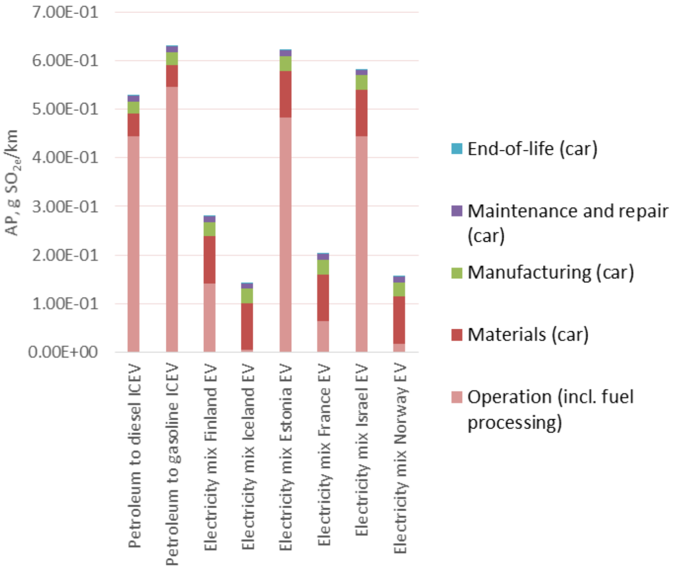
Note: The vehicle is an average-size passenger car on the road and the life-cycle driving distance is the average driving distance of light-duty vehicles in EU-15.

Figure 5 Life-cycle ODP (expressed as g CFC-11-equivalent) per kilometre of a gasoline and diesel ICEV and a BEV powered with electricity mixes of selected OECD countries (see online version for colours)



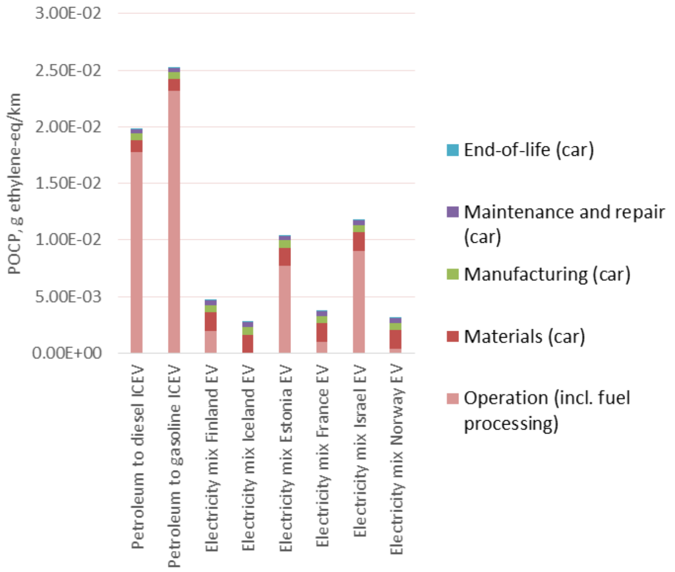
Note: The vehicle is an average-size passenger car on the road and the life-cycle driving distance is the average driving distance of light-duty vehicles in EU-15.

Figure 6 Life-cycle AP (expressed as g SO_2e) per kilometre of a gasoline and diesel ICEV and a BEV powered with electricity mixes of selected OECD countries (see online version for colours)



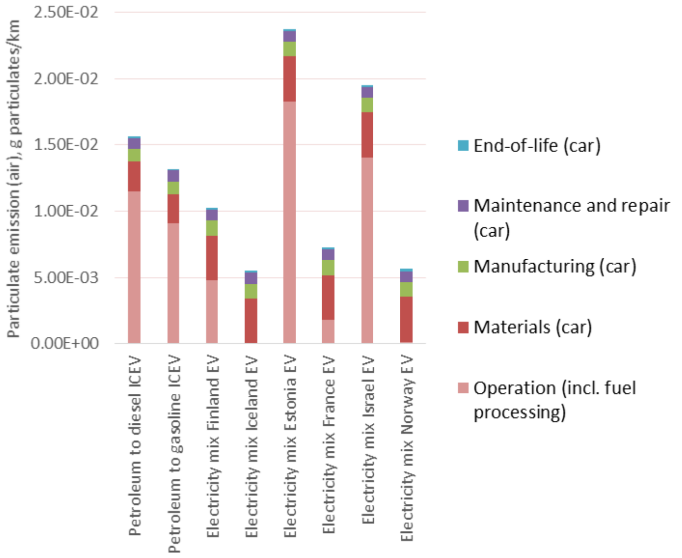
Note: The vehicle is an average-size passenger car on the road and the life-cycle driving distance is the average driving distance of light-duty vehicles in EU-15.

Figure 7 Life-cycle POCP (expressed as g ethylene-eq) per kilometre of a gasoline and diesel ICEV and a BEV powered with electricity mixes of selected OECD countries (see online version for colours)



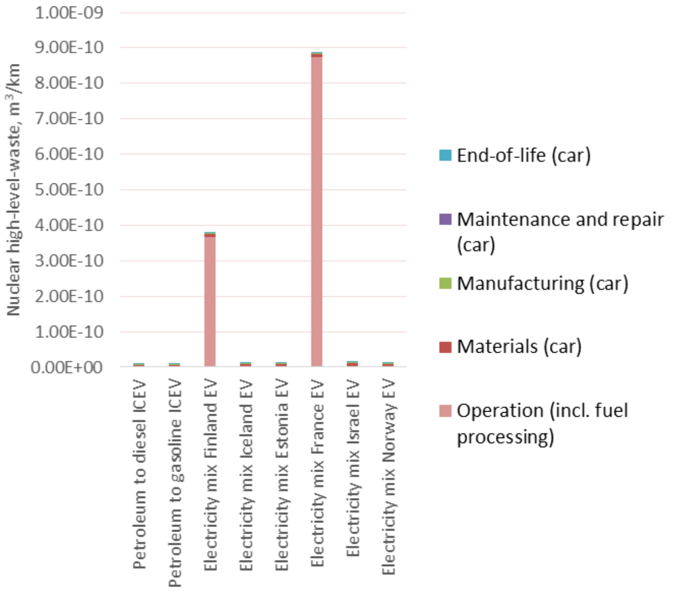
Note: The vehicle is an average-size passenger car on the road and the life-cycle driving distance is the average driving distance of light-duty vehicles in EU-15.

Figure 8 Life-cycle particulate emissions per kilometre of a gasoline and diesel ICEV and a BEV powered with electricity mixes of selected OECD countries (see online version for colours)



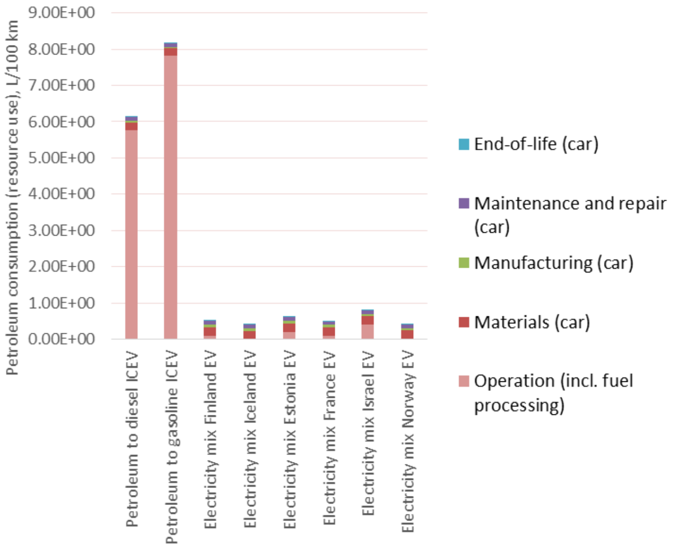
Note: The vehicle is an average-size passenger car on the road and the life-cycle driving distance is the average driving distance of light-duty vehicles in EU-15.

Figure 9 Life-cycle creation of high-level radioactive waste per kilometre of a gasoline and diesel ICEV and a BEV powered with electricity mixes of selected OECD countries (see online version for colours)



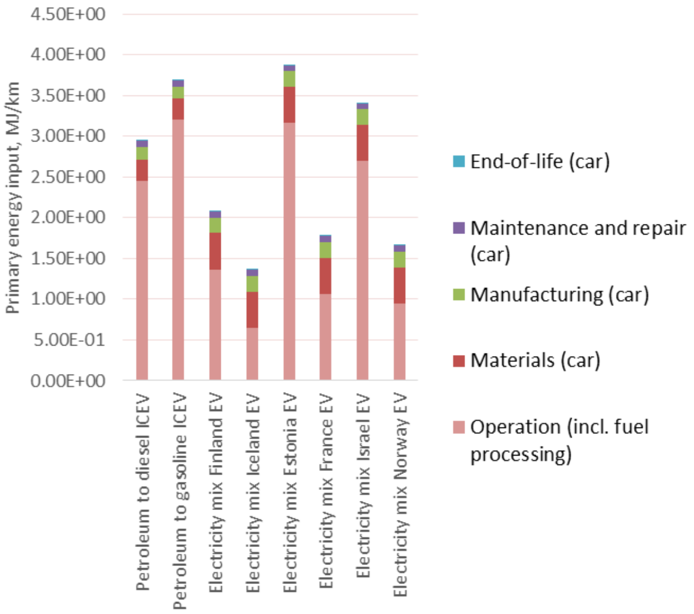
Note: The vehicle is an average-size passenger car on the road and the life-cycle driving distance is the average driving distance of light-duty vehicles in EU-15.

Figure 10 Life-cycle petroleum consumption per 100 km of a gasoline and diesel ICEV and a BEV powered with electricity mixes of selected OECD countries (see online version for colours)



Note: The vehicle is an average-size passenger car on the road and the life-cycle driving distance is the average driving distance of light-duty vehicles in EU-15.

Figure 11 Life-cycle primary energy inputs per kilometre of a gasoline and diesel ICEV and a BEV powered with electricity mixes of selected OECD countries (see online version for colours)



Note: The vehicle is an average-size passenger car on the road and the life-cycle driving distance is the average driving distance of light-duty vehicles in EU-15.

Because of battery packs, electric vehicles are heavier and there are more exotic materials in them. Thus the materials production stage impacts are higher for electric vehicles than for internal combustion vehicles. It depends on electricity generation mix, whether BEVs increase or decrease GHG emissions (GWP) compared to ICEVs. High shares of low-carbon electricity generation (wind, solar, hydro, biomass, nuclear) and cogeneration (CHP) decrease the operation stage (fuel burning and fuel/electricity processing) GWP.

The differences between electricity mixes of different countries may be substantial. The operational stage GWP of driving a BEV in Estonia is about twice as high as driving a similar-size diesel powered ICEV and more than 2000 times higher than driving a BEV in Iceland. Regardless, Estonia has been promoting BEVs very actively in recent years (e.g., *The Guardian*, 2013).

Another goal of electrification of road transport is getting rid of the use of petroleum in transportation. Figure 10 shows that BEVs are in every country effective in decreasing petroleum consumption. However, electric cars increase petroleum consumption in some parts of the world, if grid electricity is used (e.g., Malta, Lebanon and Hawaii). In Figure 9, the life-cycle creation of high-level radioactive waste per kilometre for different driving options is given. If nuclear power is used in considerable amounts in electricity generation mix, GHG emissions and petroleum consumption are cut but with the price of a nuclear waste problem. In Figure 11, the primary energy inputs of different driving options are given. Primary energies are the fossil energies (including peat), hydroelectricity and nuclear electricity.

5 Discussions and conclusions

The main goal of the paper was to evaluate the environmental impacts of the current internal combustion engine powered cars and the BEVs powered with various electricity mixes of different OECD countries to find out the regionally very different environmental gains of road transport electrification. Technology development and its rapid diffusion are considered crucial for tackling the climate change challenge. However, while waiting the future development of decentralised energy development, smart grids and driverless cars among others, the fundamental issues in the current political and public discussion need to be understood.

The standard view of literature (e.g., Bakker et al., 2012; Frenken et al., 2004), has been to classify hybrid, battery electric and fuel-cell electric vehicles as low emission vehicles. Low emission vehicles do not guarantee sustainability benefits, and they may even worsen the situation in the transport sector by adding vehicles that are energy- and CO_2-intensive as well as resource-intensive, considering e.g., the production of batteries. The enhanced environmental performance of advanced gasoline and diesel engines is making them more and more comparative to the low emission vehicles. However, battery electric or fuel-cell electric vehicles probably remain superb candidates in cutting local urban emissions.

In the long run, petroleum as a power source for cars should be replaced either by biofuels, hydrogen or electricity. In some countries, a significant amount of new cars is already battery electric cars. However, widely differing electricity generation mixes and government policies are a challenge for large-scale and clean electric road transport. Technological changes, such as electrification of road transport, may affect the environmental impacts of transport positively, but clean sources of electricity are required.

We need policy changes, if our target is more sustainable road transport. Cutting the subsidies of non-renewable energies and fully taking into account the hidden costs of fossil fuels and nuclear electricity is a necessity. The prices of fossil fuels and electricity do not reflect the real costs because of past and ongoing subsidies and the long-lasting adverse effects of extraction, distribution and conversion of energy resources on human health and ecosystems. For nuclear power, decommissioning of nuclear facilities, long-term storage of wastes and limited accident liabilities are remarkable cost externalities. In sustainable road transport that relies on electric vehicles, we need to build a decentralised electricity system that is based on renewable sources such as photovoltaics and wind electricity. These intermittent sources of electricity are a challenge to electricity grids, and electricity storages are needed in large scale. BEVs enable higher share of intermittent electricity as they can effectively store excess electricity. Second-hand battery packs from BEVs can also serve as electricity storage.

LCAs were carried out to find out the environmental impacts of driving the average-size gasoline-powered and diesel-powered internal combustion engine and similar-size BEVs powered with electricity mixes of the OECD countries. Environmental impacts such as GWP, ozone depletion potential, petroleum consumption and the primary energy inputs represent global impacts. Based on results, it is clear that if the electricity comes from the ordinary grid dominated by nuclear and fossil power production, the total environmental gains are not at all obvious. The differences between electricity mixes of different OECD countries may be substantial. For example, the operational stage GWP (‘carbon footprint’) including fuel processing of driving a BEV in Estonia is about twice as high as driving a similar-size diesel powered ICEV and more than 2000 times higher than driving a BEV in Iceland.

Environmental impacts of acidification potential, ozone creation potential and particulate emissions represent local impacts. Generally electric vehicles are effective in cutting local emissions such as particulate emissions and ozone creation potential. However, most impacts are more or less global, and electric vehicles are just switching the location of impacts and emissions and the everlasting question concerning the source of electricity exists.

In the automotive industry, many political, economic and environmental forces are driving the development. The policy-push regulation has been one of the key drivers in increased R&D and innovative activities of car manufacturers and their suppliers in the electric vehicle sector. For example, the LCA results of Estonian electric vehicles revealed that currently electric vehicles cause more harm to environment than internal combustion vehicles. Regardless, Estonia has been promoting and supporting politically BEVs very actively in recent years. Overall, the environmental gains and potential shift of vehicle electrification is an interesting subject, but it seems to be a long and far from straightforward process in different countries and markets.

The electricity mix data of this study are from year 2010. The electricity mixes in most countries are today about the same as in 2010. However, the Fukushima nuclear accident changed Japan's electricity supply structure quite dramatically and 'die Energiewende' in Germany and many other countries has meant the multiplication of solar and wind electricity capacity. The limitation of our study is that we have not been able to make any forecasts of neither the future car fleets nor electricity mixes. Further research is needed to combine technology forecasting and life cycle analysis tools in order to make more realistic future scenarios of the impacts of transportation.

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