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Well to wheel analysis of low carbon alternatives for road traffic

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Several alternative fuel–vehicle combinations are being considered for replacement of the internal combustion engine (ICE) vehicles to reduce greenhouse gas (GHG) emissions and the dependence on fossil fuels. The International Energy Agency has proposed the inclusion of low carbon alternatives such as electricity, hydrogen and biofuels in the transport sector for reducing the GHG emissions and providing a sustainable future. This paper compares the use of these alternative fuels, *viz.* electricity, hydrogen and bio-ethanol in combination with battery electric vehicle (BEV) and fuel cell electric vehicle (FCEV) technologies on the basis of their overall efficiency and GHG emissions involved in the conversion of the primary energy source to the actual energy required at wheels through a well-to-wheel analysis. The source of energy for electricity production plays a major role in determining the overall efficiency and the GHG emissions of a BEV. Hence electricity production mix of Germany (60% fossil fuel energy), France (76% nuclear energy), Sweden and Austria (60 and 76% renewable energy, respectively), the European Union mix (48% fossil fuel energy) and the United States of America (68% fossil fuel energy) are considered for the BEV analysis. In addition to the standard hydrogen based FCEVs, CNG and bio-ethanol based FCEVs are analysed. The influence of a direct ethanol fuel cell (DEFC) on GHG emissions and overall chain efficiency is discussed. In addition to the standard sources of bio-ethanol (like sugarcane, corn, *etc.*), sources like wood waste and wheat straw are included in the analysis. The results of this study suggest that a BEV powered by an electricity production mix dominated by renewable energy and bio-ethanol based DEFC electric vehicles offer the best solution in terms of GHG emissions, efficiency and fossil fuel dependency. Bio-ethanol as a fuel has the additional advantage to be implemented readily in ICE vehicles followed by advancements through reformer based FCEVs and DEFC electric vehicles. Although important, this analysis does not include the health effects of the alternative vehicles. Bio-ethanol used in an ICE may lead to increased emission of acetaldehydes which however might not be the case if it is used in fuel cells.

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Broader context

GHG emissions of battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) are compared with respect to conventional internal combustion engine (ICE) based vehicles. BEVs show clear advantages regarding GHG emissions, especially for countries with low fossil fuel based electricity. Their major drawback, the limited range, can be overcome by FCEVs based on hydrogen. In the well-to-wheel analysis the output of GHG emissions is, however, considerable since hydrogen is largely made from natural gas. While hydrogen may be available from renewable peak power, the amount remains too small to serve a broader application. Hydrogen from renewable electricity is an unlikely pathway for the intermediate future since for many decades to come electricity from solar and wind is needed to offset fossil fuel based electricity production in order to reduce global GHG emissions. In addition, the pathway electricity-to-hydrogen-to-electricity suffers from a low efficiency of approx. 30%. An alternative to using hydrogen in a FCEV is bio-ethanol which is derived from organic waste. This would allow for a grossly simplified fuel infrastructure which can also serve ICE based vehicles. Using a direct ethanol fuel cell (DEFC) at intermediate temperatures can result in complete oxidation of ethanol and in high efficiencies.

1. Introduction

The International Energy Agency (IEA) has estimated that the transportation sector accounts for 22% of the global CO_2 emissions which are responsible for the climate change issues.[1] Presently, the road transportation sector uses in large parts

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internal combustion engine (ICE) vehicles whose energy needs are supplied largely by oil based fuels.[2] To encounter issues like climate change and dependence on foreign oil (accompanied by their fluctuating prices), engineers and policy makers are looking into sustainable alternatives that are less emissive and have the ability to use the limited resources at higher efficiencies. Along with policies encouraging a shift towards public transportation from individual mobility, the IEA proposes the inclusion of the low carbon alternatives, *viz.* electricity, hydrogen and bio-fuels in transportation sector.[1] These are considered as preferred alternatives because of their potentially low carbon footprint and renewable nature. This paper aims at comparing battery electric vehicles (BEVs, powered by different electricity production mixes), hydrogen/compressed natural gas (CNG) based fuel cell electric vehicles (FCEVs) and bio-ethanol based vehicles based on their energy use and greenhouse gas (GHG) emissions. The vehicle segment that shall be addressed in this paper is a C-segment compact car.

Life cycle analysis (LCA) addresses the environmental aspects throughout the life cycle of a product, from raw material acquisition, through production, use, end of life treatment and final disposal.[3] Well-to-wheel (WTW) analysis is an application of LCA which is used to compare drivetrains/vehicles from a global perspective. Such an analysis gives the overall picture of the energy resource utilisation and its emissions involved right from the point of primary energy source extraction (well) to its point of utilisation (wheels). This analysis shows not only the emissions caused by burning of the fuels, but also takes into account the emissions involved in production, transportation and distribution of the fuels.

Several studies have been done based on WTW analysis for comparing various vehicle–fuel combinations. Sheldon S. Williamson and Ali Emandi compared hybrid electric vehicles (HEVs) and FCEVs that run on conventional hydrocarbon fuels (petrol and diesel) based on their WTW efficiencies.[4] G. J. Offer *et al.*, compared BEVs, hydrogen based FCEVs and fuel cell hybrid electric vehicles based on their lifecycle costs.[5] Stefano Campanari *et al.*, compared the BEVs and the FCEVs through WTW analysis based on drive cycle simulations to assess the influence of the primary energy supply and range on the emissions and the efficiency.[6] C. E. Thomas compared alternative vehicles including partially electrified drivetrains such as HEV fuelled by gasoline, ethanol and hydrogen and fully electric vehicles powered by batteries or hydrogen-fuel cell combinations through dynamic computer simulations to gauge their societal benefits.[7] U. Eberle *et al.* compared the WTW GHG emissions of ICE vehicles, HEVs, CNG vehicles, BEVs and FCEVs.[8] They also analysed the technological needs and infrastructural efforts required for the implementation of FCEVs. W. G. Colella *et al.* examined the potential changes in primary emissions and energy use by replacing the U.S. fleet of conventional on-road vehicles with HEVs and hydrogen based FCEVs (powered by different sources for hydrogen *viz.* steam reforming of natural gas, electrolysis powered by wind turbine and gasification of coal) through a LCA.[9] M. Jacobson compared BEVs, hydrogen based FCEVs and ethanol based flex fuel vehicles (that run on E85) based on the multiple externality impact, which includes life cycle CO_2 emissions, mortality, water consumption, *etc.*[10] The JEC Consortium study carried out jointly by experts from the JRC (European Union (EU) Commission's Joint Research Centre), EUCAR (the European Council for Automotive research and development) and CONCAWE (the oil companies' European association for environment, health and safety in refining and distribution) analysed in detail the future of automotive fuels and powertrains in the European context through a WTW analysis to evaluate the WTW energy use and GHG emissions for a wide range of potential future fuel and powertrain options.[11]

In this work, we compare the three low carbon alternatives proposed by the IEA through a WTW analysis. In addition to the work done in the above mentioned sources, we analyse the impact of the electricity production mix of a country on the emissions and the energy use of a BEV. Though BEVs have zero tailpipe emissions, their WTW emissions depend on the energy mix used for electricity generation. By taking example cases of the following European countries along with the United States of America, the impact of the electricity production mix (E mix) on a BEV is illustrated.

(1) Germany (fossil fuel dominated)
(2) France (nuclear energy dominated)
(3) Sweden (renewable energy dominated with very little fossil fuel energy)
(4) Austria (renewable energy dominated with part of power from fossil fuel energy)
(5) The EU mix
(6) United States of America (USA, fossil fuel dominated)

The effect of including hydrogen in the transport sector shall be analysed using H_2-polymer electrolyte membrane (PEM) FCEVs. Since the major source of hydrogen is natural gas (NG, through steam reforming),[12] the other option of using CNG directly in FCEVs with an on board reformer will be evaluated as well. Bio-ethanol has been chosen as the bio-fuel of choice owing to its high energy density, non-toxicity and renewable nature. It is the largest amount of bio-fuel that is being produced globally followed by bio-diesel.[13] The influence of bio-ethanol inclusion in transport sector shall be analysed through the WTW analysis of ethanol reformate based FCEVs. These reformate based fuel cells (FCs) could use bio-ethanol at efficiencies higher than a normal ICE since they are not restricted by the Carnot efficiency.[14] The volumetric energy density of ethanol based FC systems is higher than its other counterparts such as methanol and liquid hydrogen.[14] Apart from the standard sources for bio-ethanol like corn, sugarcane, *etc.*, which compete with the food chain the potential for bio-ethanol production from sources such as agricultural waste, wood chips, *etc.* shall be discussed. In addition to this, the impact of a novel concept, a direct ethanol fuel cell (DEFC), on the overall energy usage and the global GHG emissions, which has not been dealt with before, shall be discussed in this paper. The DEFC converts the chemical energy in ethanol directly into electrical energy thus avoiding the necessity of a separate intermediate reformation step. Direct alcohol fuel cells are attractive technologies because of the high volumetric energy density of fuels, which translates into system compactness and simplicity. They have high theoretical energy conversion efficiencies and are promising power sources for automotive and portable applications.

Apart from the global GHG emissions there are other factors which are important for choosing a certain vehicle and energy chain. The sustainability of the alternative solutions is studied in terms of the possibilities for inclusion of renewable energy sources in the overall energy chain. This paper shall also discuss the issues involved with the implementation of these alternatives and compare them based on the ease and readiness of their implementation. In order to better understand what each energy chain has to offer, a general comparison of the alternatives considered based on their most prominent features, advantages and disadvantages is made. The emissions and energy use associated with the initial development of infrastructure (power plants, cars, *etc.*) and end of life disposal is beyond the scope of this paper. One of the major criteria for the selection of a more sustainable alternative is GHG emissions. However, other factors such as health, local emissions, water use, land use, mortality, *etc.* should not be ignored while making the right choice. A number of studies have been carried out for evaluation of these issues.[9,10,15,16] However, in this paper, we restrict ourselves only to the GHG emissions of the alternatives.

2. Methods for evaluation

This WTW analysis can be further split into well-to-tank (WTT) and tank-to-wheel (TTW) evaluations. The TTW evaluation accounts for the energy expended and the associated emissions of the vehicle–fuel combinations for achieving a range of 200 km driven through the New European Drive Cycle. The energy demand in the tank is expressed in terms of 'litres of gasoline equivalent/100 km (l_gas_eq/100 km)' to make the comparison among different drivetrains more intuitive. The emissions are expressed as 'grams of CO_2 equivalent/km (g_CO_2_eq/km)'. The WTT evaluation accounts for the energy expended and the associated emissions emitted in the steps required to deliver the finished fuel (derived from raw materials) into the on-board tank of the vehicle.[11] Integration of these two evaluations gives the overall WTW energy consumption and emissions.

2.1. Tank-to-wheel evaluation

Good specific energy, lack of the memory effect and slow self-discharge rates make lithium-ion (Li-ion) batteries a suitable choice for BEVs.[17] The developments in the Li-ion battery technology in the recent years have made them a standard choice of power source in BEVs.[18] Hence only Li-ion batteries are considered for evaluation of BEVs in this paper. Since BEVs do not possess a tank, this evaluation should be termed as a 'plug-to-wheel' evaluation. However, the term 'tank-to-wheel' is maintained for the sake of uniformity. The use of hydrogen as a fuel in road transport sector is evaluated through FCEVs. Of the many FCs available, only the PEM FC which has been accepted by the car manufacturers as having the highest potential to be used in vehicle applications[6] is considered in this study. The use of CNG and bio-ethanol as fuels for a PEM FC with an intermediate reformation step is included in this work as well. In addition to this, a DEFC electric vehicle in combination with bio-ethanol is evaluated in this paper. The hybrid electric vehicle (HEV) concept has been gaining popularity recently since it helps combine the advantages of BEV and ICE vehicles. HEVs improve the fuel consumption of ICE vehicles by allowing the engine to operate at higher efficiencies and utilising the braking energy through recuperative braking. HEVs are a combination of BEVs and ICE vehicles having the all-electric capability of a BEV in urban areas and the extended range capability of ICE vehicles.[19] However, owing to intricacies associated with the control strategy, degree of electrification, type of hybridisation, *etc.*, the analysis of HEVs has not been included in this paper.

The amount of energy required to drive the vehicle through a 200 km range is the integral of the power demand at the tank. The power required at the tank is calculated by evaluating the power demand at the wheel and then dividing it by the efficiency of the drivetrain involved. The basic configuration of the drivetrains under consideration is shown in Fig. 1. The efficiency value for the components in the drivetrain is given in

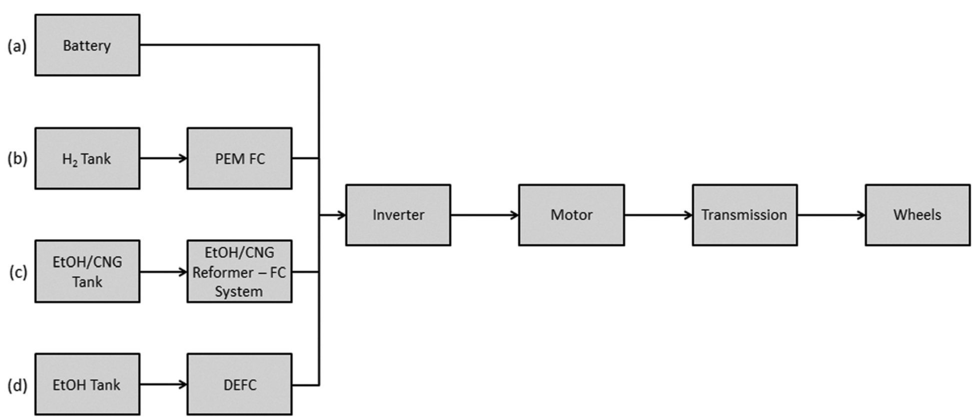

Fig. 1 Schematic representation of the drivetrain of a (a) BEV, (b) H_2-FCEV, (c) ethanol or CNG reformate based FCEV, and (d) DEFC electric vehicle.

Table 6 in the Appendix. The power demand at the wheels is calculated using MATLAB simulations based on eqn (1)–(5),[20]

$$P_{\text{accln}} = m \cdot v \cdot a \cdot f_{\text{rot}} \quad (1)$$

$$P_{\text{ad}} = 0.5 \cdot c_{\text{w}} \cdot A \cdot \rho \cdot v^3 \quad (2)$$

$$P_{\text{roll}} = f \cdot m \cdot g \cdot \cos\theta \cdot v \quad (3)$$

$$P_{\text{inc}} = m \cdot g \cdot \sin\theta \cdot v \quad (4)$$

$$P_{\text{total\_wheel}} = P_{\text{accln}} + P_{\text{ad}} + P_{\text{roll}} + P_{\text{inc}} \quad (5)$$

where, 'P_{accl}', 'P_{ad}', 'P_{roll}', 'P_{inc}' and '$P_{\text{total\_wheel}}$', represent the power required for acceleration, the power required to overcome air drag, the power required to overcome rolling resistance, the power required to climb incline and the total power required at wheels, respectively. The total mass of the vehicle is given by 'm' and the slope of the road ('θ') is assumed to be zero. The acceleration and velocity of the vehicle are represented by 'a' and 'v', respectively. The values of the other variables used in eqn (1)–(4) which are defined by the vehicle being simulated can be found in Table 5 in the Appendix. The symbols used in eqn (1)–(5) are explained in the glossary.

From eqn (1)–(5), it is evident that the power demand of the vehicle at its wheel is determined by the drive cycle (time dependant speed and slope values), the form (shape) and its mass. While the first 2 factors are the same for both BEVs and FCEVs, the vehicle mass varies greatly since the source of energy for providing the driving power is different. Batteries have a much lower gravimetric energy density compared to that of the other fuels considered. Hence BEVs are generally heavier than their counterparts. Therefore, to calculate the energy consumption of both vehicles fairly, a kerb mass (mass excluding the storage/conversion device, *i.e.*, FC, battery, storage tank) of 1100 kg is assumed.[6] The weight of the storage device required to provide the energy demands of the vehicle is calculated and added to the kerb mass to get the total vehicles mass. The effect of regenerative braking on a BEV is easy to calculate due to the bidirectional flow of energy. For a FCEV, the following methodology is adopted to evaluate the effect of regenerative braking on the fuel consumption of the vehicle. It is estimated that the fuel consumption of a FCEV decreases by 9% upon inclusion of an additional battery pack with a weight of 15 kg[6]. This technique is commonly adapted for all kinds of FCEVs under consideration in our evaluation including the DEFC vehicle.

Iterative mass estimation. The size/mass of a storage device (battery/fuel storage tank) is determined by the energy demand of the vehicle. However, the mass of the storage device itself affects the mass of the vehicle and hence its energy demand. Therefore, there is a necessity for iterative solving to achieve the suitable mass/size of the storage system for obtaining the required range. This is executed with the help of MATLAB scripts. The specifications of the storage devices used are given in the Table 7 in the Appendix. The tank-to-wheel efficiency of the BEV and H_2-FCEV considered is 83% and 48%, respectively, and is comparable to the values from similar studies.[6,21] The power to weight ratios of the PEMFC stack and the reformer are considered to be 1000 W kg^{-1} and 800 W kg^{-1},[6] respectively. The DEFC is assumed to have a power density of 500 W kg^{-1} due to its compact design. For additional masses greater than 200 kg, a corrective weight equal to 15%[6] of the added weight is included to account for the structural modification required. The importance of iterative mass estimation is better understood when the impact of the range on the overall mass of the vehicle is examined. The simulation results show that the total mass of a BEV (the kerb mass plus the mass of the battery system) is 1473 kg for a 200 km range but 2364 kg for a 500 km range. On the other hand, the mass of a CNG based FCEV (the kerb mass plus the mass of fuel tank, reformer system and the fuel cell) is 1236 kg for a 200 km range and 1263 kg for a 500 km range. The additional weight of the battery added to cover the longer range has a considerable impact on the power consumption of vehicles and makes them less efficient. Therefore BEVs that are based on current energy storage technologies are not well suited for long distance applications. This aspect has also been covered in the work of U. Eberle *et al.* which demonstrates that the weight of a BEV increases by 1.6 times for an increase in range from 200 to 500 km (for a LA 92 drive cycle).[8] This is comparable to the above value.

Emissions. The TTW emissions for a BEV and a H_2 based FCEV are zero. The CO_2 emissions of bio-ethanol and CNG based vehicles are calculated based on stoichiometry and are found to be 71.29 g CO_2 per MJ_{ethanol} and 51.19 g CO_2 per MJ_{CNG}, respectively. In our evaluation, we restrict ourselves only to the CO_2 emissions. Other emissions such as water vapour are not being evaluated.

2.2. Well-to-tank evaluation

This section of the paper deals with the evaluation of efficiency and emissions involved in the production, transportation and distribution of fuels from their source (well) to the tank. Most of the studies/calculations associated with this part are based on the WTT report version 4.a published by the JRC for the JEC (JRC, EUCAR, CONCAWE consortium) well-to-wheel analysis.[22] The JRC is the European Commission's in-house science service which employs scientists to carry out research in order to provide independent scientific advice and support to the EU policy.[23] The reports and their corresponding appendices of this study can be found in this web link.[24]

In this comprehensive study done by the JEC, the process of producing, transporting, manufacturing and distributing a number of fuels suitable for road transport powertrains have been described. It covers all the steps from extracting, capturing and growing the primary energy carrier to refuelling the vehicles with the finished fuel.[22] The primary focus of the study by the JEC is to establish the energy and GHG balance for different energy routes. The major steps involved in the WTT evaluation are production and conditioning of primary energy at the source, transformation of primary energy at the source, transportation of the fuel, transformation at the site and conditioning and distribution of the fuel. All energy requirements involved in the above steps and the efficiencies involved in the transformation have been calculated on the basis of 1 MJ of the final fuel calculated based on its LHV and expressed as 'MJ/MJ fuel'. This makes the integration of WTT and TTW easier. The fuels/energy sources which are relevant to us are electricity, hydrogen, CNG and bio-ethanol. Though there are multiple pathways for producing them, we limit them to the more prominent ones. The pathways considered and the corresponding energy and emission factors are calculated using the WTW Appendix 2 – version 4a (summary of energy and GHG balance of individual pathways) of the well-to-wheel report version 4.a published by the JRC.[25] In this report, each fuel/electricity production pathway is referred to by a pathway code. This pathway code (henceforth referred to as the WTT code) is included with each fuel/electricity production pathway studied in this paper. This will act as a reference to the corresponding pathway considered from the report. CO_2 emissions caused by burning of biomass/biofuel do not count as GHG emissions. The rationale for this assumption is that this carbon in crops was sequestered from the atmosphere during the previous growing season. In order to conserve the correct balance, emissions from combustion of this renewable carbon are credited to the relevant fuels (WTT pathway) before the WTW integration is carried out. The GHG emissions associated with cultivating the crop, processing it into a finished fuel and transporting it are taken into account. Since biofuel production pathways produce 'co-products' such as slops, animal feed, *etc.*, along with the main fuel, they need to be accounted for while evaluating the GHG emissions and energy use. The JRC report has accounted for this by crediting the energy and emissions saved by not producing the material that the co-products are most likely to replace to the fuel produced. The nitrous oxides released in the process of bio-fuel production have been accounted for while evaluating the global GHG emissions.[22]

The above mentioned study has made a thorough analysis to evaluate the emission and fuel consumption of different fuel–drivetrain combinations powered by a varied range of energy sources through a well-to-wheel analysis. The influence of inclusion of DEFCs in vehicle drivetrains has not been covered, but is discussed here. In addition, we shall also evaluate the effect that the energy mix of electricity production of a country has on the overall emissions of a BEV.

Electricity. The breakdown of electricity generation by the primary energy source for different countries used in our evaluation has been plotted in Fig. 2 based on the 'The World Bank – World Development Indicator' data source.[26] The fuel consumption and emission factor associated with electricity production and transmission in the countries considered is calculated based on its energy mix of electricity production and values of the emissions and the primary energy consumption associated with electricity production from each energy source (individually) taken from the JRC report[25] (found as Table 8 in Appendix) and tabulated in Table 1 along with the corresponding WTT codes.

Hydrogen. The major source of hydrogen is natural gas. Natural gas could either be transported through pipelines and then reformed on site (OS) (WTT code: GPCH1b), or reformed centrally (Centr.) (WTT Code: GPCH2b) into hydrogen and then transported through road/pipelines. Table 1 shows the energy efficiency and emissions involved in both these processes. The reformation in both central and on site scenarios is done by steam reforming.

CNG. Natural gas is transported by pipelines. The WTT emissions and fuel consumption for the same are shown in Table 1 (WTT code: GPCG1b).

Bio-ethanol. In addition to the major sources of bio-ethanol such as corn, sugarcane and sugar beet, non-conventional sources like wheat straw and wood waste are considered in this assessment (WTT code in the corresponding order: CRETus, SCET1, SBET1c, STET1, WWET1). The reasons behind the choice of corn, sugarcane and sugar beet are,

Corn – major source of bio-ethanol production in USA which is the largest producer of ethanol.[27]

Sugarcane – major source of bio-ethanol production in Brazil, the second largest producer of ethanol.[27]

Sugar beet – sugar beet is considered as a source of bio-ethanol owing to its higher yield per hectare[27] in spite of wheat currently being the major source of bio-ethanol production in the European Union[28] (which is the third largest producer[29] and the third largest market[30] for ethanol).

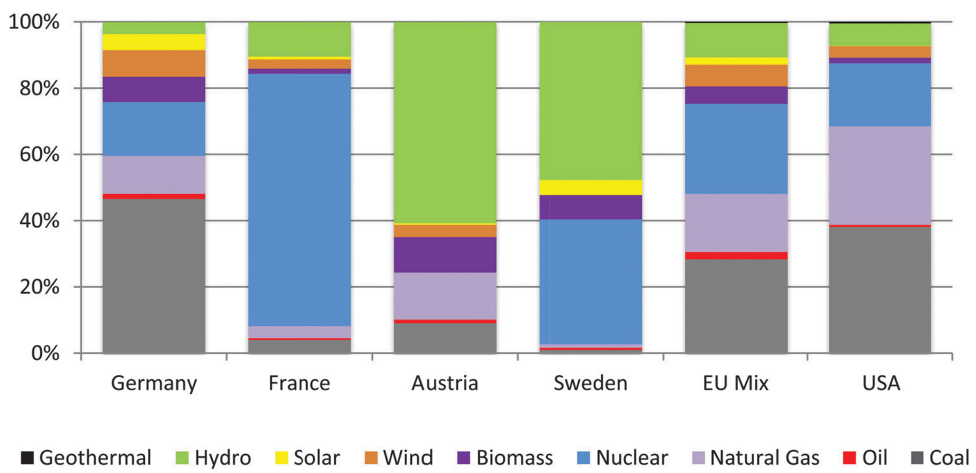

Fig. 2 Energy mix for electricity production of the different countries.[26]

Table 1 Well-to-tank factors for fuel consumption and emissions of different fuel types[25]

Source/pathway	Fuel ref. code	WTT factor: Fuel consumption (MJ/MJ fuel)	WTT factor: GHG emission ($g\_CO_2\_eq$/MJ fuel)
Electricity			
Germany E mix	EGE	1.79	156.92
Austria E mix	EAU	0.80	49.37
Sweden E mix	ESW	1.52	8.77
France E mix	EFR	2.54	21.87
EU mix E mix	EEU	1.80	113.48
USA E mix	EUS	1.71	153.58
Hydrogen			
NG 4000 km OS reforming	HNO	1.05	117.70
NG 4000 km centr. reforming	HNC	0.81	104.40
Natural gas			
Pipeline 4000 Km	NGP	0.21	16.10
Bio-ethanol			
Sugar beet	BSB	0.92	−53.49
Corn	BCO	1.65	−2.39
Sugarcane	BSC	2.09	−46.49
Wheat straw	BWS	1.32	−62.09
Wood waste	BWW	1.95	−51.79

Table 2 Well-to-wheel and tank-to-wheel emission and fuel consumptions for the different fuel vehicle combinations

Fuel–vehicle combination	Fuel consumption (l_gas_eq/100 km) WTW	Fuel consumption (l_gas_eq/100 km) TTW	Emissions ($g\_CO_2\_eq$/km) WTW	Emissions ($g\_CO_2\_eq$/km) TTW
Battery electric vehicles				
EGE–BEV	3.85	1.38	69.73	0.00
EAU–BEV	2.48	1.38	21.94	0.00
ESW–BEV	3.48	1.38	3.48	0.00
EFR–BEV	4.88	1.38	9.72	0.00
EEU–BEV	3.87	1.38	50.43	0.00
EUS–BEV	3.74	1.38	68.24	0.00
Hydrogen				
HNO–FCEV	4.53	2.21	83.66	0.00
HNC–FCEV	4.00	2.21	74.21	0.00
Compressed natural gas				
NGP–FCEV	4.94	4.09	88.52	67.34
Ethanol-reformate based FCEV (PEMFC)				
BSB–FCEV	5.89	3.08	17.63	70.68
BCO–FCEV	8.15	3.08	68.23	70.68
BSC–FCEV	9.51	3.08	24.56	70.68
BWS–FCEV	7.15	3.08	9.11	70.68
BWW–FCEV	9.07	3.08	19.31	70.68
Ethanol–DEFC				
BSB–DEFC	4.70	2.45	14.07	56.34
BCO–DEFC	6.50	2.45	54.45	56.34
BSC–DEFC	7.59	2.45	19.60	56.34
BWS–DEFC	5.70	2.45	7.27	56.34
BWW–DEFC	7.24	2.45	15.41	56.34
Conventional vehicles				
Petrol-ICE vehicle	6.00	5.10	144.00	121.00
Diesel-ICE vehicle	4.70	3.90	113.00	93.00

Note: values for petrol and diesel ICE vehicles are taken directly from the appendix of the JRC report[11,31] and normalised to the vehicle under our consideration.

3. Results and analysis

3.1. Battery electric vehicles

The results of this analysis suggest that the emissions of BEVs are in general lower than that of existing ICE vehicles even for countries with a large amount of coal based electricity production. However, the global GHG emissions vary largely by a factor of 20 and lie in the range 3.5–70 $g\_CO_2\_eq$/km. This suggests that the emissions caused by a BEV largely depend on the energy mix used for electricity production. It can be seen from the results that with higher dependence on fossil fuels for electricity production as in the case of Germany (60%[26] fossil fuels), the emissions caused are as high as 61% of the existing diesel based ICE vehicles. This is further substantiated in the case of the USA electricity mix and the EU electricity mix which are also largely dependent on fossil fuels (68.5%[26] and 48%[26] fossil fuels respectively). The GHG emissions of a BEV driven by the EU mix electricity is approximately 45% of the existing diesel based ICE vehicles which is comparable to the results shown in the work of U. Eberle, *et al.*[8] With 67%[26] of the present global energy mix for electricity production coming from fossil fuels, the carbon footprint of the BEV may deteriorate further from the value of 69.7 $g\_CO_2\_eq$/km of that of Germany (depending on the type of fossil fuel).

On the contrary, a BEV driven by a nuclear dominated electricity mix, like that of France has a very low carbon footprint of 9.7 $g\_CO_2\_eq$/km. This is because the emission associated with nuclear electricity arises only from fossil fuel energy used in mining, transport and enrichment of the nuclear fuel and the maintenance of power plants.[22] Although nuclear electricity is mostly carbon free, it is not a renewable source of energy with other issues like safety and radioactive waste disposal associated with it. Due to these factors, the total amount of nuclear electricity produced globally has reduced to 2300 TW h in 2012, which is 12% lower than its peak value of 2600 TW h in 2006. Countries like Germany and Switzerland have already initiated phasing out of nuclear energy.[32,33] A considerable increase in installation costs of nuclear power plants contested by a decrease in costs for renewable electricity contributes further to this development. The IEA predicts that by 2035, only 12–13%[34] of the global electricity demand will be supplied by nuclear power.

The results shown in Table 2 suggest that if the BEV is driven by a carbon free renewable energy source like in the case of Austria and Sweden, the emissions would be as low as 21.9 $g\_CO_2\_eq$/km and 3.5 $g\_CO_2\_eq$/km, respectively. Austria which has close to 76% renewable electricity has higher emission values as compared to Sweden with a lower renewable electricity fraction (60%) since Austria has 24% dependence on fossil fuels whereas Sweden is nearly fossil fuel free (less than 3%). It has to be noted that the major portion of the renewable energy comes from hydro power (which is more stable and predictable) for both countries. Yet, the immediate integration of other renewable energy sources such as wind and solar energy into the grid on a large scale is problematic due to factors such as variability of

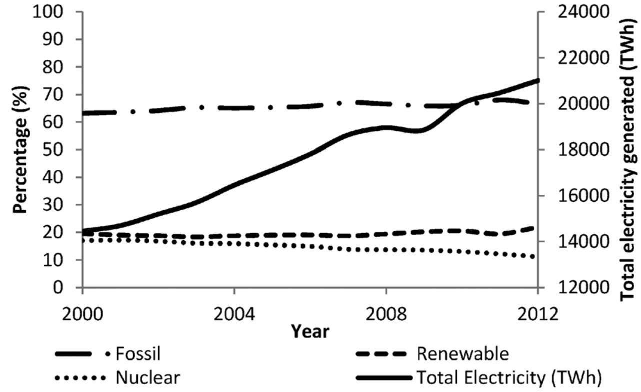

Fig. 3 Total electricity generated globally and the percentage contribution from fossil, nuclear and renewable sources for the years 2000–2012.[26]

renewable energy sources, frequency response, system balancing, solar and wind forecasting, *etc.*[35] The practical difficulties involved in inclusion of wind power on a large scale were seen in the case of Germany. When wind power production exceeds the demand, rather than switching off or curbing the output at coal and nuclear plants (which take hours to return to the full output), certain producers keep generating excess power, but sell it at negative prices which is undesirable.[36]

The absolute amount of renewable electricity generated in the year 2012 was 4587 TW h which is 1.6 times as much as the total renewable electricity produced in the year 2000. However, the share of renewable electricity in the total electricity produced has increased by a meagre 2% owing to the fact that the total electricity demand has grown 1.5 times in the same time period. With the contribution from nuclear electricity reducing to 11% (from 17%), fossil fuel based electricity increasing to 67% (from 63%) to compensate the lost nuclear capacity and the contribution from renewable energy remaining stagnant in the range 20–22%, the carbon foot print of electricity produced has increased (refer to Fig. 3).

Assuming that the entire fleet of passenger cars in Sweden and France are replaced by electric vehicles, there shall be an increase in electrical energy demand of 5.1%† and 9.8%‡ of the total power produced in Sweden and France, respectively. If busses and trucks are included, this shall increase further which calls for an increase in power production capacity. Other factors which work against the BEV are its limited range and extended charging time. Non-residential fast charging stations are required for the proper implementation of the BEV[37] which involves high capital cost of investment.

3.2. Fuel cell electric vehicle

3.2.1. Hydrogen as fuel. As seen from the results, the WTW emissions of a FCEV powered by pure hydrogen lies in a range which is better than the conventional vehicles but higher than a BEV (even if it is operated with electricity produced by a fossil fuel dominated energy mix). Because hydrogen production is majorly dependent on natural gas, hydrogen production itself has a high carbon footprint (104.4–117.7 g_CO_2_eq/MJ fuel). However these vehicles do not produce any local emissions. The lower emission value of 74.2 g_CO_2_eq/km for hydrogen production by central reforming compared to an emission value of 83.7 g_CO_2_eq/km for on-site reforming suggests central reforming is more efficient for hydrogen production. The GHG emissions of these vehicles are about 47–66% higher than that of a BEV driven by the EU electricity mix which follows the result of the work of U. Eberle, *et al.*[8] Table 3 shows the comparison of a BEV and a FCEV that obtain their energy completely from the same source – natural gas. The results show that using natural gas to produce electricity in a combined cycle gas turbine power plant and subsequently using it in a BEV is more efficient and less emissive than using the same natural gas to produce hydrogen and subsequently using it in a H_2-FCEV.

The alternative drivetrain needs to offer a sustainable solution and using renewable electricity to produce hydrogen from electrolysis which powers a FCEV offers a promising solution. However, the results shown in Table 4 imply that the energy use of such an alternative is notably higher compared to the direct use of renewable electricity in a BEV. For a given amount of solar/wind energy, the achievable range of a BEV will be almost thrice as much as a FCEV. This is attributed to the low efficiency of the electrolysis process and the fuel cell (in comparison to batteries). However, the intermittent nature of renewable energy sources like solar/wind power calls for integration of a storage mechanism with the grid to ensure grid stability, especially for the excess power production periods. Storing this excess electricity as hydrogen and subsequently using it to power FCEVs could provide a solution. Nonetheless, the quantity of hydrogen that could be produced from excess electricity may not be large enough to make a substantial contribution to the overall amount of hydrogen needed.

Table 3 Comparison of a BEV and a hydrogen based FCEV that has NG as its primary energy source

	Fuel consumption (l_gas_eq/100 km)		Emissions (g_CO_2_eq/km)	
Fuel vehicle combination	WTW	TTW	WTW	TTW
NG–electricity–Li-ion battery–BEV	3.02	1.38	58.83	0.00
NG-centr. reforming-pipeline–H_2 FCEV	4.00	2.21	74.21	0.00

Table 4 Comparison of a BEV and a hydrogen based FCEV that has solar and wind energy as its primary energy sources

	Fuel consumption (l_gas_eq/100 km)		Emissions (g_CO_2_eq/km)	
Fuel vehicle combination	WTW	TTW	WTW	TTW
Solar/wind power–electricity–Li-ion battery–BEV	1.54	1.38	0.00	0.00
NG-centr. reforming-pipeline–H_2 FCEV	4.44	2.21	2.99	0.00

† Calculated based on the fact that Sweden has 5.3 million passenger cars,[38] 12 200 km average annual driving distance[38] and 92.96% average grid efficiency.[39] The energy consumption values of BEVs are taken from Table 2.

‡ Calculated based on the fact that France has 31.6 million passenger cars,[40] 12 700 km average annual driving distance[40] and 94.78% average grid efficiency.[39] The energy consumption values of BEVs are taken from Table 2.

The technical advantages that the hydrogen based FCEV offers over a BEV are an extended range per recharge, a reduced refuelling/recharge time and availability of waste heat for cabin heating for winter conditions (possibly also cooling). The higher energy densities of hydrogen storage as compared to batteries give H_2-FCEVs an advantage over BEVs while addressing larger vehicle segments. Hydrogen fuel cell based alternatives require the installation of new infrastructure such as refuelling stations, hydrogen transportation systems, reformer stations (for on-site CNG reformation), hydrogen storage, *etc.*[41] This hinders the immediate implementation of a hydrogen based FCEV as an alternative solution.

3.2.2. CNG as fuel. Since natural gas is the major source of hydrogen, we could store CNG in the vehicle, reform it on board and utilise the reformate to power the FC stack. The results for this configuration as shown in Table 2 suggest a WTW fuel consumption of 4.9 l_gas_eq/100 km and 88.5 g_CO_2_eq/km. The use of CNG directly in the FCEV through a reformer is less efficient and produces somewhat more GHG emissions compared to on the on-site reformation of CNG to produce hydrogen for a H_2-FCEV. However, the existence of established NG grids and ease in storage of CNG implies that the CNG reformate FCEV could be considered as an intermediate alternative. Nevertheless on board reforming is a much more complex process.

3.3. Bio-ethanol as fuel

3.3.1. Ethanol reformer fuel cell. The results shown in Table 2 suggest that the global GHG emissions of the bio-ethanol reformate based FCEV are lower than the conventional vehicles. But the GHG emissions and the overall fuel consumption of the vehicles vary largely based on the source of bio-ethanol. The FCEV driven by bio-ethanol from corn and wheat straw has the highest carbon footprint (68.2 g_CO_2_eq/km) and the lowest carbon footprint (9.1 g_CO_2_eq/km), respectively. The lowest value of fuel consumption for the FCEV driven by bio-ethanol from derived from sugar beet (5.9 l_gas_eq/km) compared to other bio-ethanol sources proposes that it is the most efficient bio-ethanol production process. Though these ethanol reformate based vehicles produce some tailpipe emissions unlike the other alternatives considered so far (except NGP–FCEV), all CO_2 released during the energy conversion of bio-ethanol in vehicles is originally absorbed from the atmosphere by the plants that are used to produce bio-ethanol. This is indicated by the negative value of WTT emissions for bio-ethanol as shown in Table 1. The CO_2 that is associated with bio-ethanol in the WTW analysis arises from energy used for transportation and production of bio-ethanol which uses fossil fuels as its energy source.[22] The global GHG emissions of these vehicles lie in the range 16–43% (excluding bio-ethanol from corn) of the emissions of a BEV operated by the fossil fuel dominated energy mix of Germany. Nevertheless, the emissions are higher than a BEV operated by renewable and nuclear dominated electricity mixes of Sweden and France. Hence, the ethanol reformate based FCEV proves to be less emissive for countries which uses fossil fuel based energy mixes for their electricity production.

A major drawback of bio fuels in general and bio-ethanol in specific is the land usage. It competes with food crops for agricultural land.[42] This however can be countered by producing bio-ethanol from wheat straw (agricultural waste) or wood waste. The global GHG emissions of this vehicle fuel combination are as low as 19.3 g_CO_2_eq/km and 9.1 g_CO_2_eq/km for bio-ethanol from wood waste and wheat straw, respectively. Though the overall chain efficiency may be low, one has to keep in mind that these resources are of renewable nature and would be wasted if they are not utilised. In addition, if the organic waste enter landfills, it produces additional GHG emissions in the form of CO_2 and methane (please refer to Section 3.3.3 for further information).

3.3.2. Direct ethanol fuel cell electric vehicle. The results for the DEFC EV powered by bio-ethanol suggests that global GHG emissions would lie in the range 10.7–22% (barring ethanol from corn) of that of a BEV powered by the fossil fuel dominated energy mix of Germany. The emission rate of 7.3 g_CO_2_eq/km for the DEFC powered by bio-ethanol from wheat straw is even lower than the 9.7 g_CO_2_eq/km GHG emission of a BEV operated by the nuclear dominated energy mix of France. The only fuel vehicle combination that is better than BWS–DEFC is the ESW–BEV. The DEFC could have power densities and efficiencies higher than the ethanol reformate based FC systems. The higher efficiencies of the DEFC combined with the low carbon footprint of bio-ethanol makes it a good solution. The DEFC is simpler in construction and has a reduced number of components. Bio-ethanol offers a number of advantages apart from low global GHG emissions such as good energy density (66 v/v% of gasoline) and a renewable nature. It also has the advantage of immediate implementation as it could be used as a combination with gasoline as gasohol (95% gasoline and 5% ethanol) without any modification in the engine or at even higher ratios of ethanol with small modification to the engine[27] (as in the case of Brazil). It does not require the development of new infrastructure such as charging stations, special storage tanks, *etc.* for transportation and distribution of ethanol.

3.3.3. Non-conventional sources for bio-ethanol. As discussed before, the production of bio-ethanol from conventional crops like corn, sugarcane, *etc.*, results in the 'food *vs.* fuel' debate due to agricultural land use issues. However, bio-ethanol can be produced from non-conventional waste sources like food waste, agricultural waste and wood waste. The Food and Agricultural Organisation has estimated that one third of the edible part of the food is wasted globally which amounts to 1.3 billion tons per year.[43] A total amount of 106.2 billion litres per year§ of bio-ethanol could be produced from it. It is estimated that 491 billion litres per year of bio-ethanol can be produced from agricultural residues which are rich in lignocellulose.[44] The 'Global woodchip trade for energy' suggests that 108 million tonnes of wood chips and wood residues are available every year.[45] This corresponds to 32.5 billion litres per year¶ of bio-ethanol.

Hence, a total of 630 billion litres per year of bio-ethanol could be produced from waste. This bio-ethanol can replace close to 54%‖

§ It is calculated based on the assumption that 19%[46] of the food waste is the total solid (TS) waste and a conversion rate of 0.43 g EtOH/g_TS.[46]

¶ Calculated based on the WTT fuel consumption for bio-ethanol from wood values in Table 1 and a calorific value for wood of 12.5 GJ per ton.[47]

‖ Calculated based on TTW fuel consumption values for the ethanol reformate based FCEV, DEFC electric vehicle and petrol-ICE vehicle found in Table 2 and a global gasoline consumption value of 22065.6 thousand barrels per day.[53]

of the current gasoline consumption if used in the ethanol reformate based FCEV and almost 68%‖ of current gasoline consumption if used in the DEFC vehicle. Another way to avoid the competition of energy crops with food crops for cultivable lands is to cultivate energy crops in contaminated agricultural lands which have lost their ability to produce food crops (see China).

The production of bio-ethanol from waste could be viewed as a novel waste disposal method. Landfilling is currently the most popular waste disposal method. Though release of CO_2 from organic sources is considered to have no global warming potential (GWP), the anaerobic decay of the organic matter in landfills produces methane whose GWP is 25 times as potent as CO_2. Hence, there is a net positive GHG emission from landfills.[48] Heinz Stithnothe and Adisa Azapagic have done a life cycle estimation of the GHG saving potential (compared to the existing waste disposal scenario) of bio-ethanol from municipal solid waste (MSW) in the UK.[49] They have pointed out that compared to the current waste disposal methods, production of bio-ethanol from MSW could reduce the GHG emission by 69–81%, considering just the production of bio-ethanol (and not its use). If bio-ethanol generated is credited for displacing petrol (by use in ICE), the authors suggested that the total GHG savings would be in the range of 177–196 kg_CO_2_eq per ton of MSW (compared to the baseline scenario). With the low global GHG emission, the DEFC EV powered by bio-ethanol from waste sources seems to offer a solution for a future of high sustainability.

4. Conclusions

BEVs offer solutions which are less emissive than the conventional vehicles. They produce zero local emissions but the global GHG emissions vary largely based on the electricity production mix. The global GHG emissions are directly dependent upon the amount of fossil fuels used for electricity production. Of all the alternatives considered, BEVs powered by the renewable and nuclear energy dominated electricity production mix of Sweden produce the least GHG emission. However, global electricity generation is 67% dependant on fossil fuels. On a global scale, the reduction in the nuclear energy capacity has not been compensated with the increase in renewable energy capacity (refer to Fig. 3). Since the global demand for electricity is increasing, the dependence on fossil fuels for electricity production is going to increase which shall increase the carbon footprint of electricity production further. BEVs in their current configuration offer a good potential for addressing the global climate change concern but still suffer from aspects like limited range, setting up new infrastructure and being highly dependent on decarbonising the electricity production.

The global GHG emissions of hydrogen (from NG) based FCEVs are lower than conventional vehicles but higher than BEVs. However, FCEVs offer zero local emissions and extended range coupled with shorter recharge times; in addition, for larger vehicle segments the higher energy storage densities of hydrogen as compared to batteries are advantageous. On the other hand, as seen from Table 4, hydrogen based FCEVs do not offer the best solution for including renewable sources of electricity (like wind and solar) because of their much lower efficiency as compared to BEVs.

Bio-ethanol as a fuel seems to offer a sustainable solution due to its renewable nature, ability to be produced from existing waste streams and low GHG emissions. GHG emissions can even become negative if one considers the rotting of bio waste on landfills when not used for energy purposes. A potential drawback is that they produce tailpipe emissions unlike hydrogen-FCEVs and BEVs. One important advantage, however, is that bio-ethanol does not require the development of new infrastructure for transportation, distribution and refuelling of bio-ethanol. As compared to the other alternatives, bio-ethanol offers additional advantages in terms of its ability to be readily implemented through existing ICE vehicles. The important discussion which evaluates the health effects of ethanol by comparing E85 and gasoline (used in ICE vehicles) indicates increased health risks for ethanol.[16,50] While this is certainly of concern, recent studies show that in Sweden, an E85 *vs.* gasoline scenario leads to 1.6 less preterm deaths per year for the E85 scenario.[51] The socio-economic costs from acetaldehyde emission caused due to the use of E85 (in ICE vehicles) for the Oslo area (Norway) were evaluated in economic terms, by taking into account the health and environmental effects.[52] While the use of E85 increased the cancer rate (as compared to gasoline), the overall socio-economic costs are reduced due to lower CO_2 and NO_x emissions.[52] The use of bio-ethanol in ICE vehicles just as a transition scenario would not only result in lower GHG emissions but may also reduce health hazards.[51,52] The health effects of bio-ethanol when used in fuel cell based applications need to be further explored; it can be anticipated from the fuel cell process however, that all the contaminants present with ICE vehicles would be lower by orders of magnitude in bio-ethanol based FCEVs. The ultimate goal of using bio-ethanol (based on organic waste) in a fuel cell would result in considerably lower GHG emissions compared to H_2 (from NG) based fuel cells for many decades to come.

Appendix

Table 5 Basic configuration of the vehicle which is simulated[54]

Variable	Symbol	Units	Value
Air drag coefficient	c_w	(–)	0.31
Coefficient of rolling resistance	f	(–)	0.011
Frontal area	A	m^2	2.2
Rotational inertia coefficient	f_{rot}	(–)	1.1
Mass of kerb vehicle	M	kg	1100
Slope	θ	deg	0
Density of air	ρ	kg m^{-3}	1.225
Acceleration due to gravity	g	m s^{-2}	9.81

Table 6 Efficiency of the drivetrain components

Component	Efficiency
Battery-lithium ion	0.95[55]
Inverter	0.97[56]
Motor	0.95[57]
Transmission	0.95[58]
H_2 PEM FC system	0.55[6]
CNG reformer–H_2 PEM FC system	0.31[a]
EtOH reformer–H_2 PEM FC system	0.41[59]
DEFC	0.5[a]

[a] Estimated values.

Table 7 Specification of the storage devices[6]

Component	Specific energy (MJ kg^{-1})	Storage tank mass ratio (kg tank/kg fuel)
Li-ion battery	0.432	—
Compressed H_2	120	17.4
CNG	48	1.75
Ethanol	26.8	0.10

Table 8 Well-to-tank factors for electricity production from different primary energy sources[25]

Source	Type of power plant	WTT code	WTT factors (MJ/MJ elec.)	WTT factors ($g\_CO_2\_eq$/MJ elec.)
Coal	Conventional coal power plant	KOEL1	1.81	292.40
Oil	Heavy fuel oil in conventional power plant	FOEL1	1.94	237.80
Natural gas	Combined cycle gas turbine power plant, 4000 km NG pipeline	GPEL1b	1.19	132.40
Nuclear	Fission reactor	NUEL	3.08	5.00
Biomass and waste	Biogas ex municipal waste, local	OWEL1a	3.40	13.60
Wind	Wind turbines	WDEL	0.12	0.00
Solar	Solar PV	Same as wind	0.12	0.00
Hydro	Hydro power plants	Same as wind	0.12	0.00

Note: in general, the WTT factor is expressed as MJ/MJ_{fuel}. This represents the total primary energy expended, regardless of its origin, to produce one MJ of the finished fuel. These figures exclude the heat content of the fuel itself (*i.e.* 1 MJ/MJ fuel means that as much energy is required to produce the fuel as is available to the final user). MJ/MJ elec. The WTT factor refers to the total amount of energy expended (accounting for the inefficiency in transformation, transportation and distribution, *etc.*) per MJ of electricity production. For fossil fuel based power plants, the primary energy input is calculated from the thermal energy content of the fuel. For renewable energy sources the energy conversion efficiency is considered to be 100% (since the resource is considered to be unlimited). The inefficiency indicated accounts for transmission and distribution losses.[22]

Glossary

List of abbreviations used

ICE	Internal combustion engine
GHG	Greenhouse gas
BEV	Battery electric vehicle
FCEV	Fuel cell electric vehicle
DEFC	Direct ethanol fuel cell
IEA	International energy agency
CNG	Compressed natural gas
LCA	Life cycle analysis
WTW	Well to wheel
HEV	Hybrid electric vehicle
JEC	JRC, EUCAR and CONCAWE
JRC	Joint research centre
EUCAR	European council for automotive research and development
CONCAWE	The oil companies' European association for environment, health and safety in refining and distribution
E mix	Electricity production mix
EU	European Union
USA	United States of America
PEM	Polymer electrolyte membrane
NG	Natural gas
FC	Fuel cell
WTT	Well to tank
TTW	Tank to wheel
Li-ion	Lithium-ion
OS	On site
centr.	Central
MSW	Municipal solid waste
EGE	Electricity mix of Germany
EAU	Electricity mix of Austria
ESW	Electricity mix of Sweden
EFR	Electricity mix of France
EEU	Electricity mix of European Union mix
EUS	Electricity mix of United States of America
HNO	Natural Gas – On Site reforming
HNC	Natural Gas – Central reforming
NGP	Natural Gas – pipeline
BSB	Bioethanol from sugar beet
BCO	Bioethanol from corn
BSC	Bioethanol from sugar cane
BWS	Bioethanol from wheat straw
BWW	Bioethanol from waste wood
GWP	Global warming potential
elec.	Electricity

Nomenclature of symbols used

P	Power (W)
m	Mass of vehicle (kg)
v	Velocity (m s^{-1})
a	Acceleration (m s^{-2})
f_{rot}	Rotational inertia coefficient (–)
c_w	Air drag coefficient (–)
A	Frontal area (m^2)
ρ	Density of air (kg m^{-3})
f	Coefficient of rolling resistance (–)
g	Acceleration due to gravity (m s^{-2})
θ	Slope of the road (–)

Nomenclature of subscripts used

accln	Acceleration
ad	Air drag
roll	Rolling resistance
inc	Incline
total_wheel	Total demand at wheels

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