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Identifying the fuels and energy conversion technologies necessary to meet European passenger car emissions legislation to 2020

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HIGHLIGHTS

- ► Novel transport fuels utilise diverse primary resources and production pathways.
- ► Biofuels can only meet a large part of LGV demand when blended with fossil-fuels.
- ► Fossil-fuels will continue to satisfy LGV energy and emissions requirements.
- ► Improvements to TTW efficiency and WTT emissions are needed to meet 2020 WTW limits.

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ABSTRACT

The focus of European emissions legislation for light goods vehicles centres on tank-to-wheel (TTW) operation, despite the importance of the well-to-tank (WTT) impacts of supplying transport fuels. This work presents defensible calculations of best estimate and best-in-class WTT pathways to supply conventional and non-conventional fuels. These estimates are weighted by the availability of resources. The best estimate pathway is the peak of the distribution of WTT estimates obtained from the literature. The best-in-class pathway has the lowest greenhouse gas (GHG) emissions per unit of fuel delivered and represents the state-of-the-art. These fuel pathways are paired with energy conversion (vehicle) technologies and compared with equivalent well-to-wheel (WTW) targets for 2015 and 2020. Of the 103 best estimate fuel-vehicle combinations, 42 meet the 2015 emissions legislation. By 2020, only 17 combinations meet the more strict emissions limit. Petrol production will require net negative GHG emissions, even if blended with bioethanol, to meet the equivalent WTW 2020 target. For the three main combustion energy-conversion technologies, a median efficiency improvement of 29% is required when paired with the best estimate fuel pathways. However, using best-in-class pathways indicates that all of the energy conversion technologies can meet the revised 2015 target, but some still fail to meet the 2020 target. Improvements in TTW technologies alone will not meet the legislative targets, and many fuel-vehicle combinations cannot deliver an overall reduction in GHG emissions.

1. Introduction

Vehicle emissions are functions of the fuel used, its associated supply chain, the vehicle design and its operation. The focus of legislation to reduce vehicle emissions centres on tank-to-wheel (TTW) operation alone, despite the importance of the well-to-tank (WTT) impacts the fuel supply chain. Therefore, quantifying the WTT impacts of fuel supply pathways using defensible estimates is critical to assess accurately which fuel-energy conversion technology combinations can lead to a true reduction in total emissions during operation. The first goal of this paper is to determine the shortlist of transport fuels and energy conversion technology combinations for light goods vehicles (LGVs) that meet the European Union (EU) well-to-wheel (WTW) equivalent vehicle emissions legislation in 2015 and 2020 [1]. The second goal is to quantify the improvements to the WTT[1] fuel supply chain and TTW energy

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[1] The WTT pathway comprises: transformation of the primary resource; transportation of fuel intermediates; and distribution of final fuel [26]. Each stage has associated energy and emissions penalties.

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Nomenclature

WTT	well-to-tank	PISI	port injected spark ignition
TTW	tank-to-wheel	DISI	direct injection spark ignition
WTW	well-to-wheel	DICI	direct injection compression ignition; and
GHG	greenhouse gases	FC	fuel cells
LGV	light goods (passenger) vehicle		

conversion efficiency of the combinations not shortlisted that are necessary for them to achieve the 2015 and 2020 emissions limits.

The European legislation will limit the average specific TTW emissions of the new LGV fleet to 120 g carbon dioxide (CO_2)/km. This limit is phased in over the period 2012–2015, where 65% of new LGV registered in 2012 must achieve 120 g CO_2/km, increasing to 100% of new LGV by 2015. This limit is to be met by: using energy conversion technology improvements to reach 130 g CO_2/km; and non-energy conversion technology improvements and novel fuels for the final 10 g CO_2/km [1]. Therefore, in this work, the lower 120 g CO_2/km limit is used as the potential emissions savings of using novel transport fuels is considered. The EU legislation relaxes the emissions limit by 5% for vehicles using an 85% ethanol/15% petrol blend when at least 30% of the national filling stations provide the fuel. In this work, it is assumed that the number of filling stations do not exist by 2015 or 2020. Super-credits offer an additional incentive to manufacturers to produce low emissions vehicles. Vehicles with emissions below 50 g/km will be worth 3.5 cars in 2012 and 2013, 2.5 cars in 2014, 1.5 cars in 2015 and one car from 2016. By 2020, the TTW emissions limit reduces to 95 g CO_2/km. An extension to this legislation may lead to a post-2025 limit of 70 g CO_2/km [2]. Non-conventional fuels and novel vehicle powertrain topologies have been proposed to reduce the WTW energy use and CO_2 equivalent greenhouse gases (GHGs) emissions. The five principal contributions to global WTW analyses [3–7] each comprise a WTT and TTW component. Since these studies use different representative vehicles, performance requirements, driving cycles and vehicle life impacts [6,7] in their TTW simulations, the findings across the studies cannot be compared. Despite the discrepancies in the TTW analyses, these works attribute more emissions impacts to WTT pathways to non-conventional fuels. Therefore, reducing the WTW energy used by and emissions from vehicles requires an analysis of the fuel pathways.

In this work, the extent of WTT estimates for most fuel pathways in the literature are assumed to follow a non-Gaussian distribution. The variations in studies on a fuel are based on the choice of primary natural resource, the production pathway for converting the resource to the final fuel and the system boundary used in its life cycle assessment. Using non-parametric statistical methods allows best estimates and best-in-class estimates to be obtained [8]. The best estimate pathway has the smallest Euclidean distance to the peak of the underlying distribution of WTT estimates. The best-in-class pathway has the lowest GHG impacts, represents the state of the art and is included for comparison with the best estimate. Non-parametric statistics are used where no closed form probability distribution exists or where it is not assumed. Such an approach is both robust and defensible because the distribution emerges from the data, rather than the data being forced to fit an assumed distribution. Moreover, the data-driven method [8] can both accommodate additions to the dataset and incorporate quasi-static analyses of the development of fuel production pathways with time. Many estimates in the literature do not include WTT costs with the energy and emissions impacts. Moreover, the cost of supplying a fuel is not considered in vehicle emissions legislation. Therefore, costs are explicitly omitted from this paper. Moreover, it is acknowledged that wider WTT impacts, such as land-use (space), water and material inputs per unit fuel delivered are important for a holistic assessment of a fuel supply chain. However, there is insufficient data both to assess and to incorporate adequately these broader impacts.

In this work, the adaptive kernel density method and the method of pairing the WTT estimate of MJ/MJ and g GHG/MJ with vehicle TTW efficiency to yield an overall WTW performance are described in Section 2. In Section 3.1, the variation among WTT estimates across the literature is displayed to provide the context and justification for using the adaptive kernel density estimator. In Section 3.2, a shortlist of unique fuel-energy conversion technology combinations that meet the European WTW-equivalent emissions limits is identified. Improvements to the fuel-energy conversion technology combinations which fail to meet the WTW legislation are quantified on two bases: reductions of the WTT impacts of the fuel pathway in Section 3.3; and improvements to the TTW energy conversion efficiency of the vehicle in operation in Section 3.4.

2. Method

The European emissions legislation [1] is applied to set of fuels and energy conversion technologies used in the Concawe report [3]. The Concawe report evaluated the impact of switching the fuel and/or powertrains of European vehicles on global energy use and GHG emissions. The Concawe report focused on the production of fuels and use of vehicles, but was not a life cycle analysis. The research was sponsored by the European Council for Automotive Research and Development, the European Union Commission Joint Research Centre and oil companies. The impacts of fuel and powertrain switching was demonstrated on a representative five-seater sedan. Therefore, this work excludes the performance of vehicles at the extremes of the range of size and performance. The Concawe data set omits pure electric and plug-in hybrid electric vehicles and the associated electricity supply pathways in its WTW analysis.

The non-parametric adaptive kernel density estimate (adapted from [8]) is applied to the full set of Concawe transport fuels. The challenge is to identify a bandwidth, h, which balances the bias and variability of the data to yield a representative probability density estimate. When h is small, the distribution may be undersmoothed and exhibit large variance and small bias. Conversely, a large h yields an oversmoothed distribution with large bias and small variance. The adaptive kernel density estimate method adjusts h to the changes in density of the data. That is, where the data is more concentrated, h will be small to capture the variance. When the data is sparse, h is large to avoid spurious peaks.

The kernel density estimate method is performed on each dimension (MJ/MJ and g GHG/MJ) of the set of WTT estimates individually. A histogram with m_bins = 100 is created. Empty bins are discarded to yield a new upper bin count of m_unique < m_bins. Leave-one-out least squares cross validation is employed to iterate from bin number one to m_unique. The bin with the lowest cross validation value, m_optimum, is selected. The vector 1:m_optimum is matched to its equivalent 1:h_optimum in decreasing order, such all of the observations in the bin with the highest

Table 1
Weighting factors based on annual resource potential (EJ/yr) for each fuel, overall and by its respective pathways. The overall weight for each pathway and input resource is normalised to the maximum resource potential across all pathways and input resources. The weighting factor per pathway is normalised to the maximum resource potential for that particular pathway, across all input resources. (Table 1 of 2).

Final fuel	Primary pathway	Input resource	Resource potential (EJ/yr)	Weight	
				Overall	By pathway
Petrol	Crude	Crude	171.50 [30]	1.000	1.000
Diesel	Crude	Crude	171.50 [30]	1.000	1.000
Naphtha	Crude	Crude	171.50 [30]	1.000	1.000
		Flare gas	1.10 [31]	0.009	0.009
Natural gas	Crude	Natural gas	116.03 [30]	1.000	1.000
Liquefied petroleum gas (LPG)	Crude	Crude	171.50 [30]	1.000	1.000
		Natural gas	116.03 [30]	0.677	0.677
Biogas	Biomass	Wood	25.22 [32,33]	0.168	0.168
	Wood waste		150.00 [33]	1.000	1.000
	Maize		5.96 [32,33]	0.040	0.040
	Animal waste		55.00 [33]	0.367	1.000
Synthetic diesel	Coal-to-liquids (CtL)	Coal	190.22 [30]	1.000	1.000
	Gas-to-liquids (GtL)	Natural gas	116.03 [30]	0.608	1.000
		Flare gas	1.10 [31]	0.006	0.009
Biodiesel		Rapeseed	0.85 [32,33]	0.034	1.000
		Sunflower seed	0.70 [32,33]	0.028	1.000
		Soy bean	1.26 [32,33]	0.050	1.000
		Wood	25.22 [32,33]	1.000	1.000
		Palm oil	2.04 [32,33]	0.081	1.000
DME	Crude	Natural gas	116.03 [30]	0.232	0.610
		Flare gas	1.10 [31]	0.002	0.006
		Coal	1.902 [30]	0.380	1.000
	Biomass	Wood	25.22 [32,33]	0.050	0.050
		Wood waste	150.00 [33]	0.300	0.300
		Biomass	500.00 [33]	1.000	1.000

Table 2
Weighting factors based on annual resource potential (EJ/yr) for each fuel, overall and by its respective pathways. The overall weight for each pathway and input resource is normalised to the maximum resource potential across all pathways and input resources. The weighting factor per pathway is normalised to the maximum resource potential for that particular pathway, across all input resources. (Table 2 of 2).

Final fuel	Primary pathway	Input resource	Resource potential (EJ/yr)	Weight	
				Overall	By pathway
Ethanol	Wheat		3.35 [32,33]	0.007	0.007
	Sugar cane		3.71 [32,33]	0.007	1.000
	Sugar beet		0.49 [32,33]	0.001	0.001
	Biomass	Wood	25.222 [32,33]	0.050	0.050
		Wood waste	150.00 [33]	0.300	0.300
		Biomass	500.00 [33]	1.000	1.000
	Maize		5.96 [32,33]	0.012	0.012
Methanol	Fossil	Coal	171.50 [30]	0.380	1.000
		Natural gas	116.03 [30]	0.232	0.610
		Flare gas	1.10 [31]	0.002	0.006
	Biomass	Wood	25.22 [32,33]	0.050	0.050
		Wood waste	150.00 [33]	0.300	0.300
		Biomass	500.00 [33]	1.000	1.000
Hydrogen	Gasification	Wood	25.22 [32,33]	1.000	1.000
		Wood waste	150.00 [33]	0.300	0.300
	Electrolysis	Country mix	73.21 [34]	0.146	0.385
		Natural gas	116.03 [30]	0.232	0.610
		Nuclear	9.87 [34]	0.020	0.052
		Non-combustible renewables and waste	0.47 [34]	0.001	0.002
		Coal	190.22 [30]	0.380	1.000
		Wood	25.22 [32,33]	0.050	0.133
	Steam reforming	Natural gas	116.03 [30]	0.232	1.000

frequency are assigned to the smallest h. Similarly, the largest h is assigned to all of the observations in the bin with the smallest frequency. The optimum bandwidth for each of the two dimensions is used to form a bivariate Gaussian distribution which is centred on each WTT estimate. The superposition of these bivariate Gaussian distributions yields the non-parametric distribution for the full set of WTT estimates.

Where multiple pathways are available to deliver a fuel, the analysis was performed both on all estimates (designated "All") and by pathway. A weighting factor is applied to the WTT estimates which is based on their resource potential. The factor is used as a proxy for the ability to supply the fuel at large-scale. For a final fuel which can be supplied by multiple pathways, that with the greatest resource potential is given a value of one and those with lower resource potentials are weighted as a fraction of the maximum (Tables 1 and 2). Estimates for the biofuel/fossil-fuel blends were calculated by combining the WTT impact of each individual neat fuel and its volumetric proportion in the mix.

The WTT estimate for a particular fuel is paired with the appropriate vehicle conversion technologies (as in Concawe) to

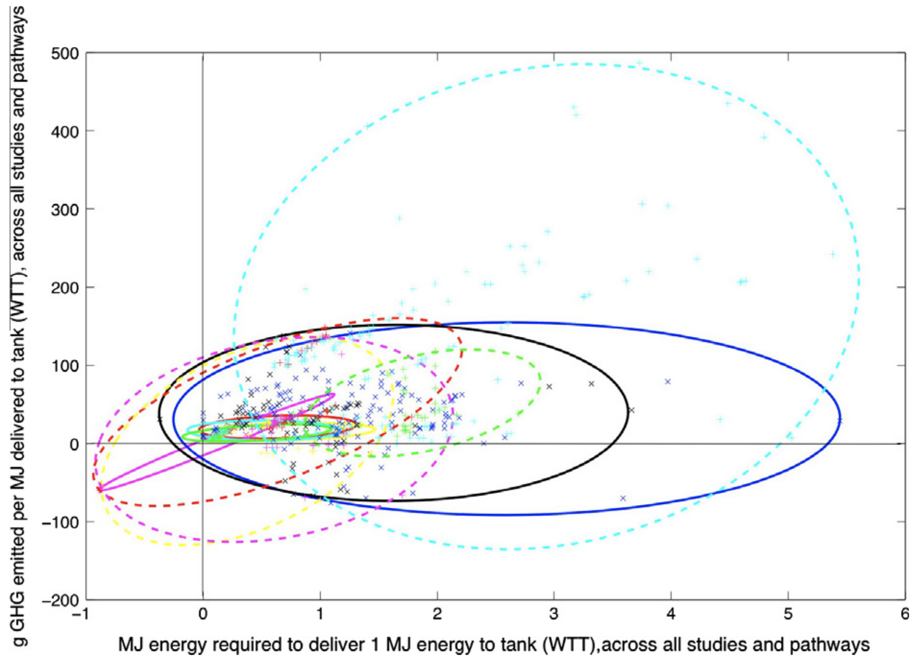

Fig. 1. Scatter of MJ and emitted g GHG when delivering 1 MJ fuel, across all studies and pathways [5,12,3,13,4,14,7,6,15–23,27–29] Key: Data represented by crosses and ellipses with solid lines: red, petrol; yellow, diesel; magenta, naphtha; cyan, natural gas; green, LPG; dark blue, ethanol; and black, biodiesel. Data represented by plus signs and ellipses with broken lines: red, synthetic diesel; yellow, DME; magenta, methanol; cyan, hydrogen; and green, biogas. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

determine the WTW performance of the combination. In this work, only the impacts due to fuel production pathway and subsequent use are considered. The emissions which arise during vehicle manufacture, maintenance, disposal and from the infrastructure which supports the technology throughout its life are beyond the scope of this paper. Their omission is justified as 85% of the life cycle emissions from a new vehicle originate during its use [9]. In Europe, average vehicle development time is at least 5 years and a vehicle remains active in the fleet for over 8 years [10]. Therefore, Concawe's simulated vehicles in 2010 are used in this analysis as it is assumed that the technology will be on the road in 2015 and still in service in 2020. The vehicle conversion technologies considered are: conventional internal combustion engine – port injected spark ignition (PISI), direct injection spark ignition (DISI) and direct injection compression ignition (DICI) – and their hybridized equivalents; and fuel cells (FC) in hybridized configurations, with and without the presence of an onboard fuel reformer.

The WTW performance of a particular fuel-energy conversion technology combination is given in [3] by Eq. (1):

Recall that the EU TTW emissions targets are for the new LGV fleet, averaged by specific emissions. Therefore, converting the TTW emissions limit to a WTW target for the Concawe representative vehicle requires the inclusion of both the vehicle mass and the WTT pathway impacts of the fuel. The specific emissions for a new car are given in [1] by Eq. (2):

The Concawe new car TTW emissions were combined with the best Concawe WTT estimates for petrol [3], as the base case, to give the corresponding WTW emissions limits. The new WTW equivalent target is given in a modified Eq. (3):

The petrol PISI energy conversion technology is the worst performing of the 2010 options in Concawe, with fuel efficiency of 190 MJ/100 km [3] and is used as the base case technology from which the WTW target is developed.[2] For Eq. (4), the Concawe best WTT g GHG/MJ estimate of 11 g GHG/MJ [3] for supplying petrol is used. The WTW equivalent for a TTW 120 g GHG/km emissions limit is 141 g GHG/km. Similarly, the WTW equivalent for a TTW 95 g CO_2/km emissions limit is 116 g GHG/km.

WTW emissions from biofuels are assessed by reducing their WTT g GHG/MJ impacts by the same value as the conventional fossil-fuels which they are displacing. For example, the emissions from supplying bioethanol are reduced by the amount used to deliver petrol to the same engine. Similarly, biodiesel WTT emissions are reduced by the amount used to deliver conventional diesel. This approach allows any additional impacts of supplying the biofuel, such as land use changes or using co-generation, to be included.

The WTW performance of a unique fuel-energy conversion technology combination which does not meet the emissions limits may be improved by addressing its WTT pathway and TTW conversion efficiency, individually or together. For a fixed TTW efficiency, there is a WTT target which meets the WTW emissions limit when combined into a WTW performance. The WTT target is derived from the WTW emissions limit in Eq. (5):

Alternatively, the TTW energy conversion efficiency may be improved for a fixed WTT pathway emissions in Eq. (6):

3. Results and discussion

3.1. WTT estimates

A scatter plot of primary WTT estimates across the conventional and non-conventional fuels illustrates the range of values, demarcated by ellipses [11] (Fig. 1).

The 581 estimates used in this study derive from 17 publicly available, published sources [5,12,3,13,4,14,7,6,15–23]. Studies are omitted which re-state the findings from any work already included in this research or that use forecast WTT impacts.

The importance of obtaining robust and defensible WTT impacts of novel transport fuels is evident by the degree of variation about the incumbent petrol (red) and diesel (yellow) estimates. The spread is determined using the Euclidean distance between

[2] The TTW energy use, fuel consumption and emissions for the full set of Concawe 2010 powertrains is given in Table 11.

Table 3
Best WTT estimate pathways with associated MJ/MJ and g GHG/MJ penalties, based on adaptive kernel sample point density estimator. "All" designates the result when the method is performed on all estimates across all pathways. The error represents the smallest distance from the best estimate to a real-world pathway from the literature. (Table 1 of 2).

Fuel	Primary resource	Best estimate			Error
		Pathway	MJ/MJ	g GHG/MJ	g GHG/MJ
Petrol	Crude	Crude [16]	0.39	15.49	0.21
Diesel	Crude	Crude oil [3]	0.18	14.58	0.38
Naphtha	Crude	Crude oil [3]	0.16	10.63	0.67
Natural gas	Crude	Natural gas, piped 4000 km [3]	0.19	16.11	0.11
LPG	Crude	Crude oil [15]	0.12	7.49	0.04
Biogas	All	Cattle manure and maize [19]	1.77	28.33	1.25
	Biomass	Double cropping [19]	1.78	28.71	4.47
	Animal	Liquid manure [3]	1.92	30.00	1.12
Synthetic	All	Remote natural gas via Fischer–Tropsch (FT) [5]	0.76	27.58	0.42
diesel	CtL	CtL via FT in slurry phase distillate [22]	1.00	104.48	1.20
	GtL	Non-North American natural gas via FT [4]	0.72	27.06	0.16
DME	All	Farmed wood [3]	0.59	19.34	0.76
	Biomass	Farmed wood [3]	1.02	−8.58	0.50
	Fossil	Natural gas [7]	0.58	26.38	1.33

the best estimate pathway of petrol and the best WTT estimates of non-petrol pathways. The unit of the Euclidean distance is g GHG/MJ energy input. The median absolute deviation (MAD) of the spread of non-conventional fuel WTT estimates about the best estimate of petrol is 12 g GHG/MJ energy input. The range of distances to the petrol best estimate are bounded by minimum and maximum deviations of 0.65 and 108 g GHG/MJ energy input, respectively.

The inclusion of non-conventional transport fuels introduces a broad and diverse set of primary resources and production pathways. New sources include additional fossil-fuels, such as natural gas and coal, fuel crops, electricity and the waste/byproducts of primary resources (Tables 3–6, and Fig. 2).

There are three main differences between the best estimate and best-in-class pathways. The first difference is that best-in-class pathways use the waste or byproducts from primary resources, rather than the resource itself, as inputs to their production processes. Examples of these production inputs include flare gas, residual woody biomass and wheat straw. The second difference is that some best-in-class pathways use primary resource byproducts in the production process, such as co-firing a wheat-based ethanol plant with natural gas and wheat straw in order to reduce emissions. The third difference arises from the use of end-of-pipe processes which allow fuels produced from fossil-fuel primary inputs to achieve low final emissions. An example is the use of carbon capture and storage (CCS) in the production of either synthetic diesel from coal or hydrogen from steam reforming of natural gas.

Table 4
Best WTT estimate pathways with associated MJ/MJ and g GHG/MJ penalties, based on adaptive kernel sample point density estimator. "All" designates the result when the method is performed on all estimates across all pathways. The error represents the smallest distance from the best estimate to a real-world pathway from the literature. (Table 2 of 2).

Fuel	Primary resource	Best estimate			Error
		Pathway	MJ/MJ	g GHG/MJ	g GHG/MJ
Ethanol	All	Wheat from France, plant fuelled by natural gas and wheat straw, ref 26 [17]	0.97	20.88	0.56
	Wheat	Wheat from France, plant fuelled by natural gas and wheat straw, ref 26 [17]	0.62	19.98	0.56
	Sugar cane	Sugar cane [12]	0.71	12.04	1.55
	Sugar beet	Sugar beet, pulp and slops to biogas/heat [3]	1.28	0.28	0.93
	Wood	Farmed wood [3]	1.70	−0.22	0.55
	Maize	Corn from China, replacement and co-product credit, ref 46, 47 [17]	1.25	51.26	8.28
Petrol/ethanol 95/5 (by volume)	Crude + All	–	0.42	15.76	–
	Wheat	–	0.40	15.72	–
	Sugar cane	–	0.41	15.32	–
	Sugar beet	–	0.44	14.73	–
	Wood	–	0.46	14.71	–
	Maize	–	0.43	17.28	–
Biodiesel	All	Rape seed from Germany, energy co-product credit, ref 19 [17]	0.69	22.04	1.41
	Rape seed	Rape seed to various locations, ref 56 [17]	0.32	23.75	0.33
	Sunflower seed	Sunflower seed to ME, glycerine as chemical, meal as feed [3]	0.92	14.70	0.13
	Soy bean	Soy beans from Australia [12]	0.91	17.81	0.51
	Wood	Forest residue from Canada, via FT in Shell middle distillate synthesis [22]	0.71	109.25	0.12
	Palm oil	Imported palm oil to FAME, glycerine as chemical + methane emissions [3]	1.32	30.06	3.76
Diesel/biodiesel 95/5 (by volume)	Crude + All	–	0.20	14.95	–
	Rape seed	–	0.18	15.04	–
	Sunflower seed	–	0.21	14.58	–
	Soy bean	–	0.21	14.74	–
	Wood	–	0.20	19.31	–
	Palm oil	–	0.20	14.50	–
Methanol	All	Non-North American natural gas [4]	0.65	21.98	0.65
	Biomass	Waste wood [3]	1.00	−3.21	0.23
	Fossil	Remote location natural gas [5]	0.64	27.57	0.57
Hydrogen	All	EU natural gas mix, central reforming [5]	1.09	92.97	3.02
	Gasification	Residual woody biomass, onsite gasification [5]	1.97	7.80	0.51
	Electrolysis	Electricity from solar photovoltaics, central electrolysis [7]	1.62	16.23	1.06
	Steam reforming	Natural gas in North America, central reforming [4]	0.85	114.91	0.26

Table 5
Best-in-class WTT pathways with associated MJ/MJ and g GHG/MJ penalties. "All" designates the result when the method is performed on all estimates across all pathways. There are no errors since the best-in-class pathway is a true pathway. (Table 1 of 2).

Fuel	Primary resource	Best-in-class estimate		
		Pathway	MJ/MJ	g GHG/MJ
Petrol	Crude	Crude [15]	0.13	8.70
Diesel	Crude	Crude [13]	0.15	5.43
Naphtha	Crude	Natural gas, flare gas [7]	−0.88	−60.29
Natural gas	Crude	Natural gas [7]	0.06	7.56
LPG	Crude	Crude [15]	0.07	2.53
Biogas	All	Dry manure [3]	0.95	0.10
	Biomass	Forest residues [19]	1.66	9.27
	Animal	Dry manure [3]	0.95	0.10
Synthetic diesel	All	Natural gas, flare gas via FT [7]	−0.88	−60.45
	CtL	CtL via FT in slurry phase synthesis with carbon capture and storage (CCS) [22]	0.77	26.33
	GtL	Natural gas, flare gas [7]	−0.88	−60.45
DME	All	Biomass [7]	1.00	−63.94
	Biomass	Biomass [7]	1.00	−63.94
	Fossil	Natural gas, flare gas [7]	−0.87	−54.57

3.2. Meeting legislated vehicle emissions targets in 2015 and 2020

The ability to meet the EU-legislated, WTW-equivalent emissions limits of 2015 and 2020 rests on the performance of the WTT fuel supply chain and TTW vehicle operation. Where the overall WTW results fails to meet the emissions limits, the necessary improvements in the individual WTT and TTW components may be quantified (positive percentage differences in Table 7). Similarly, if combinations already exceed the emissions regulations, the percentage by which they do so is shown as negative in the same Table.

The introduction of WTW-equivalent emissions limits for 2015 and 2020 results in a shortlisting of appropriate best estimate fuel pathway-energy conversion technology combinations. Of the 103 unique combinations, 61 (59%) fail to meet the 2015 emissions limit (portion of the bars to the right of the blue line in Fig. 3).

In particular: all scenarios using petrol (conventional and hybridized powertrains); diesel in conventional powertrains; ethanol, from wheat, sugar cane and maize in conventional powertrains; biodiesel, blended and neat in conventional powetrains; biodiesel from wood and palm oil in hybridized powertrains; synthetic diesel in conventional powertrains; synthetic diesel from

Table 6
Best-in-class WTT pathways with associated MJ/MJ and g GHG/MJ penalties. "All" designates the result when the method is performed on all estimates across all pathways. There are no errors since the best-in-class pathway is a true pathway. (Table 2 of 2).

Fuel	Primary resource	Best-in-class estimate		
		Pathway	MJ/MJ	g GHG/MJ
Ethanol	All	Cellulosic biomass [4]	1.09	−85.06
	Wheat	Wheat straw [3]	0.00	−0.10
	Sugar cane	Sugar cane from Brazil, bagasse credit [3]	0.00	1.10
	Sugar beet	Sugar beet pulp via enzymatic hydrolysis [5]	3.59	−79.00
	Wood	Cellulosic biomass [4]	1.09	−85.06
	Maize	Corn from US [4]	0.69	−15.88
Petrol/ethanol 95/5 (by volume)	Crude + All	–	0.18	4.01
	Wheat	–	0.13	8.26
	Sugar cane	–	0.13	8.32
	Sugar beet	–	0.30	4.32
	Wood	–	0.18	4.01
	Maize	–	0.16	7.47
Biodiesel	All	Residual woody biomass [5]	0.94	−72.83
	Rape seed	Rape seed, var 4 b) [5]	0.77	−70.63
	Sunflower seed	Sunflower seed to ME, glycerine and cake to biogas [3]	0.58	9.77
	Soy bean	Soy beans from Australia [12]	0.91	26.96
	Wood	Forest residue from Canada, via FT in Shell middle distillate synthesis	0.71	118.39
	Palm oil	Imported palm oil to FAME, glycerine as chemical, no methane emissions [3]	1.32	39.21
Diesel/biodiesel 95/5 (by volume)	Crude + All	–	0.19	1.52
	Rape seed	–	0.18	1.63
	Sunflower seed	–	0.17	5.65
	Soy bean	–	0.19	6.51
	Wood	–	0.18	11.08
	Palm oil	–	0.10	1.86
Methanol	All	Residual woody biomass via gasification [5]	0.87	81.25
	Biomass	Residual woody biomass via gasification [5]	0.87	81.25
	Fossil	Natural gas, flare gas [7]	−0.87	−56.19
Hydrogen	All	Electricity from renewables, onsite electrolysis [4]	0.59	0.00
	Gasification	Residual woody biomass, onsite gasification [5]	1.84	6.60
	Electrolysis	Electricity from renewables, onsite electrolysis [4]	0.59	0.00
	Steam reforming	Thermal cracking of natural gas [23]	1.20	35.71

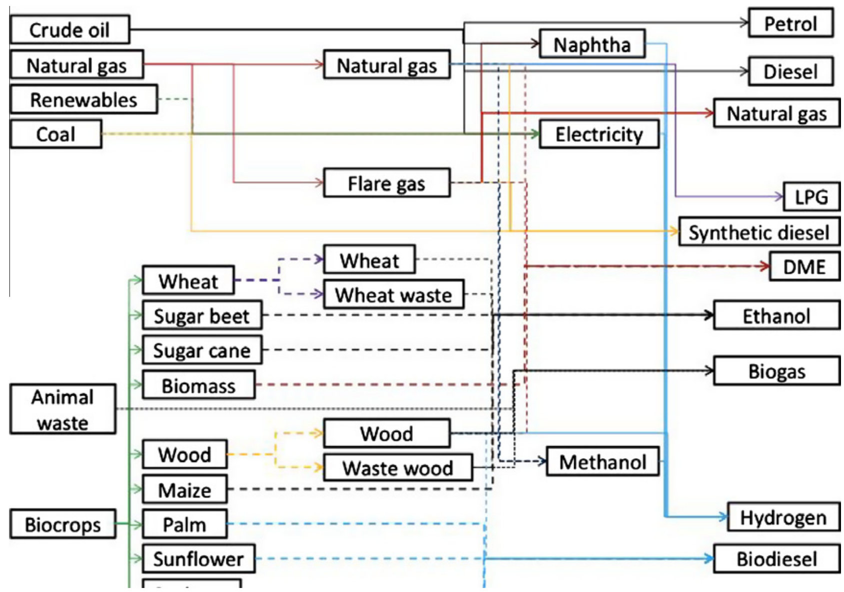

Fig. 2. Flow chart mapping primary natural resources and intermediate products to final fuels.

coal in a hybridized powertrain; and all internal combustion powertrains using hydrogen from steam reforming.

There is a set of fuel-energy conversion technology combinations which meet the 2015 emissions limit but fail to meet that in 2020 (area of the bars spanning or completely within the blue and red lines of Fig. 3). These number 25 (24%) and are: petrol in a hybridized and downsized powertrain; diesel in a hybridized powetrains; natural gas in both conventional and hybridized powertrains; biogas in a conventional powertrain; synthetic diesel from gas in a hybridized powertrain; naphtha and both DME and methanol from biomass via an onboard reformer in a hybridized FC powertrain; ethanol from both sugar beet and wood in conventional powertrains; biodiesel from rape seed, sunflower and soy in hybridized powertrains; and all blended ethanols and biodiesels in hybridized powertrains.

By 2020, the combinations which meet the emissions limit are reduced to 17 (17%, portion of the bars to the left of the red line in Fig. 3) and consist of: both natural gas and DME in conventional and hybridized powertrains; biogas in hybridized powertrains; diesel in hybridized and downsized powertrains; methanol from biomass via an onboard reformer in a hybridized FC powertrain; and all non-steam reforming hydrogen pathways in all conversion technologies.

Advanced internal combustion engine technologies – hybridization and downsizing – have a limited effect on the ability for the fuel-energy conversion technologies combination to meet the 2015 and 2020 emissions limits. Hybridization and downsizing of the internal combustion engine can extend the use of petrol and diesel into the interim 2015–2020 period, but only diesel is a viable option after 2020. Similarly, hybridization is necessary to make both blended ethanol and biodiesel feasible after 2015.

The ability of novel energy conversion technologies to meet future emissions limits depends on the fuels (primary resources and their production pathways) with which they are paired. The low emissions advantage of non-conventional fuels over the incumbent can be lost depending on the primary resource and production pathway. This is illustrated using hydrogen from steam reforming of natural gas in a PISI engine (conventional or hybridized) which fails to meet the 2015 emissions limit.

Recall that the best estimate represents the peak of the distribution of raw data points. The hydrogen best estimate bar (for example) may be converted to a set of WTW values by Eq. (3) corresponding to the raw data (Fig. 4).

Here, points representing individual pathways on each side of the legislative limit can be clearly identified. For example, steam reforming of non-North American natural gas in central plants (140.8 g GHG/km WTW) meets the 2015 limit of 140.9 g GHG/km, while electrolysis using electricity generated from natural gas in a combined cycle at 142.8 g GHG/km fails to. Similarly, steam reforming of non-North American natural gas in central plants via LNG (115.2 g GHG/km) meets the 2020 limit of 115.9 g GHG/km, but steam reforming of remote natural gas in central plants plus liquefaction at 116.1 g GHG/km fails. All pathways using gasification of wood and wood waste and electrolysis by renewables have WTW emissions of less than 57 g GHG/km. Steam reforming pathways lie in the range 30–454 g GHG/km and and the non-renewable electrolysis pathways can yield emissions as high as 816 g GHG/km.

Considering only the best-in-class pathways (Fig. 5) allows 26 additional fuel-energy conversion technologies (total 67, 65%) to meet the legislated limits, relative to using the best estimates.

Petrol neat, and when blended with bioethanol in conventional powertrains fail to meet the 2015 emissions limit. Similarly: neat biodiesel from sunflower and soy; neat ethanol from wheat and sugar cane; and synthetic diesel from coal-to-liquids (CtLs) across all applicable conversion technologies fail to be viable combinations beyond 2015. The 23 unique combinations of: petrol in a hybridized and downsized powertrain; diesel in conventional powetrains; ethanol from wheat and sugar cane in conventional powertrains; both LPG and blended ethanol in hybridized powertrains; and blended biodiesel in a conventional powertrain can only serve as interim solutions between 2015 and 2020.

Even using the state-of-the-art in transport fuel production, 57% of the set of unique fuel-energy conversion technologies (total 59) are unable to meet the emissions legislation in 2020. These combinations are: petrol; LPG; neat ethanol from wheat and sugar cane; all blended ethanols in hybridized powertrains; neat biodiesel from sunflower, soy and palm in conventional powertrains; synthetic diesel from coal in all powertrains; and diesel, natural gas and all blended biodiesels in conventional powertrains.

There is a set of fuel-energy conversion technology combinations which fails to meet the 2015 and 2020 emissions limits in

Table 7
WTW emissions (g GHG/km) from combination of the best estimate and best-in-class fuel supply pathways and 2010 energy conversion technologies used in the Concawe five-seater, representative vehicle. Percentage errors are given relative to 2015 and 2020 WTW legislative targets of 141 g GHG/km and 116 g GHG/km, respectively. Positive percentage differences indicate combination of fuel/pathway/conversion technology fails to meet the emissions limit. Combinations which at least meet the emissions limits are denoted by negative percentage differences. DISI = direct injection spark ignition; DICI = direct injection compression ignition; FC = fuel cell; and PISI = port injection spark ignition.

Fuel	Pathway	Conversion	Best estimate			Best-in-class		
			WTW	% Difference		WTW	% Difference	
			Limit	2015	2020	Limit	2015	2020
Petrol	Crude	PISI	171	21	47	158	12	36
		DISI	169	20	46	157	11	35
		DISI, 1.6 l hybrid	146	4	26	135	−4	17
		DISI, 1.3 l hybrid	138	−2	19	128	−9	10
		Reformer + FC, hybrid	146	4	26	155	−4	16
Diesel	Crude	DICI	147	4	27	132	−6	14
		DICI, 1.9 l hybrid	125	−11	8	112	−20	−3
		DICI, 1.6 l hybrid	115	−19	−1	103	−27	−11
		Reformer + FC, hybrid	144	2	24	129	−8	12
Naphtha	Crude	Reformer + FC, hybrid	135	−5	16	20	−86	−83
Natural gas	Crude	PISI	138	−2	19	122	−13	5
		PISI, hybrid	102	−27	−12	90	−36	−22
LPG	Crude	PISI	141	−0.01	22	132	−7	13
Biogas	Biomass	PISI	132	−7	13	111	−21	−4
	Animal	PISI	134	−5	16	94	−34	−19
	Biomass	PISI, hybrid	97	−31	−16	82	−42	−29
	Animal	PISI, hybrid	99	−30	−14	69	−51	−40
Synthetic diesel	CtL	DICI	292	107	152	163	16	40
	GtL	DICI	164	16	41	19	−86	−83
	CtL	DICI, hybrid	234	66	102	131	−7	13
	GtL	DICI, hybrid	131	−7	13	15	−89	−87
DME	Biomass	DICI	96	−32	−17	7	−95	−94
	Fossil	DICI	153	8	32	22	−84	−80
	Biomass	DICI, hybrid	77	−45	−33	6	−96	−96
	Fossil	DICI, hybrid	122	−13	5	18	−87	−84
Ethanol	Wheat	PISI	175	25	51	137	−3	18
	Sugar cane	PISI	160	14	38	156	−1	20
	Sugar beet	PISI	138	−2	19	−13	−111	−113
	Wood	PISI	137	−3	18	−24	−118	−122
	Maize	PISI	235	67	103	107	−24	18
	Wheat	DISI	174	23	50	136	−4	17
	Sugar cane	DISI	159	13	37	138	−2	19
	Sugar beet	DISI	137	−3	18	−12	−111	−113
	Wood	DISI	136	−4	17	−24	−118	−121
	Maize	DISI	232	65	100	106	−25	−8
Petrol, ethanol 95/5	Wheat	PISI	170	20	46	156	11	35
	Sugar cane	PISI	169	20	46	156	11	35
	Sugar beet	PISI	168	19	45	149	5	28
	Wood	PISI	168	19	45	148	5	28
	Maize	PISI	173	23	49	155	10	33
	Wheat	DISI	168	19	45	154	10	33
	Sugar cane	DISI	167	19	44	154	10	33
	Sugar beet	DISI	166	18	43	147	4	27
	Wood	DISI	166	18	43	146	4	26
	Maize	DISI	171	21	47	153	8	32
	Wheat	DISI, hybrid	138	−2	19	127	−10	9
	Sugar cane	DISI, hybrid	137	−3	18	127	−10	9
	Sugar beet	DISI, hybrid	136	−3	17	120	−14	4
	Wood	DISI, hybrid	136	−3	17	120	−15	4
	Maize	DISI, hybrid	140	−1	21	125	−11	8
Biodiesel	Rape seed	DICI	167	19	44	11	−93	−91
	Sunflower	DICI	152	8	31	144	2	24
	Soy bean	DICI	157	12	36	157	11	35
	Wood	DICI	309	119	167	7	−95	−94
	Palm	DICI	178	26	53	193	37	67
	Rape seed	DICI, hybrid	134	−5	16	9	−94	−93
Biodiesel cont'd	Sunflower seed	DICI, hybrid	122	−13	5	116	−18	−0.1
	Soy bean	DICI, hybrid	126	−10	9	126	−11	9
	Wood	DICI, hybrid	248	76	114	6	−96	−96
	Palm	DICI, hybrid	143	1	23	155	10	34

(continued on next page)

Table 7 (*continued*)

Fuel	Pathway	Conversion	Best estimate			Best-in-class		
			WTW	% Difference		WTW	% Difference	
			Limit	2015	2020	Limit	2015	2020
Diesel/biodiesel 95/5	Rape seed	DICI	147	4	27	126	−11	8
	Sunflower seed	DICI	146	4	26	132	−6	14
	Soy bean	DICI	147	4	26	133	−6	15
	Wood	DICI	154	9	33	125	−11	8
	Palm oil	DICI	147	5	27	126	−10	9
	Rape seed	DICI, hybrid	118	−16	2	101	−28	−13
	Sunflower seed	DICI, hybrid	117	−17	1	106	−25	−8
	Soy bean	DICI, hybrid	118	−17	1	107	−24	−8
	Wood	DICI, hybrid	124	−12	7	101	−29	−13
	Palm oil	DICI, hybrid	118	−16	2	101	−28	−12
Methanol	Biomass	Reformer + FC, hybrid	87	−38	−25	−1	−101	−101
	Fossil	Reformer + FC, hybrid	145	3	25	21	−85	−82
Hydrogen, compressed	Gasification	PISI	15	−89	−87	13	−91	−89
	Electrolysis	PISI	29	−79	−75	2	−99	−99
	Steam reforming	PISI	195	38	68	62	−55	−45
	Gasification	PISI, hybrid	13	−91	−89	11	−92	−90
	Electrolysis	PISI, hybrid	26	−82	−78	1	−99	−99
	Steam reforming	PISI, hybrid	173	23	49	55	−60	−51
	Gasification	FC	8	−94	−93	7	−95	−94
	Electrolysis	FC	16	−88	−86	1	−99	−99
	Steam reforming	FC	110	−22	−5	35	−75	−69
	Gasification	FC, hybrid	8	−95	−94	6	−95	−95
	Electrolysis	FC, hybrid	15	−90	−87	1	−99	−99
	Steam reforming	FC, hybrid	98	−30	−15	31	−77	−72

all cases. Across the best estimates and best-in-class pathways, vehicles with conventional powertrains using: petrol; synthetic diesel from coal; all blended ethanols; and biodiesel from sunflower, soy and palm fail to meet both the 2015 and 2020 emissions limits. Biodiesel from palm oil in a hybridized powertrain never meets the 2015 and 2020 emissions limits, regardless of best estimate or best-in-class pathway.

Significant reductions in the WTW emissions are required for many of the fuel-energy conversion technology pairs to meet the European emissions limits. Using best estimate fuel pathways, improvements are needed in the range of 0.01–119% (median 19%) by 2015 and 1–167% (median 27%) by 2020. Expectedly, using the best-in-class pathways reduces the burden: the necessary improvements being 2–37% (median 10%) in 2015 and 4–67% (median 18%) by 2020. The necessary improvements to the performance of the fuel-energy conversion technology combinations which fail to make the shortlist in 2015 and 2020 may be quantified by analyzing the emissions from the WTT pathway and the TTW efficiency of its energy conversion technology.

3.3. Improving WTT pathways

The improvements necessary to WTT pathways are quantified by the difference between the WTT emissions target to both the

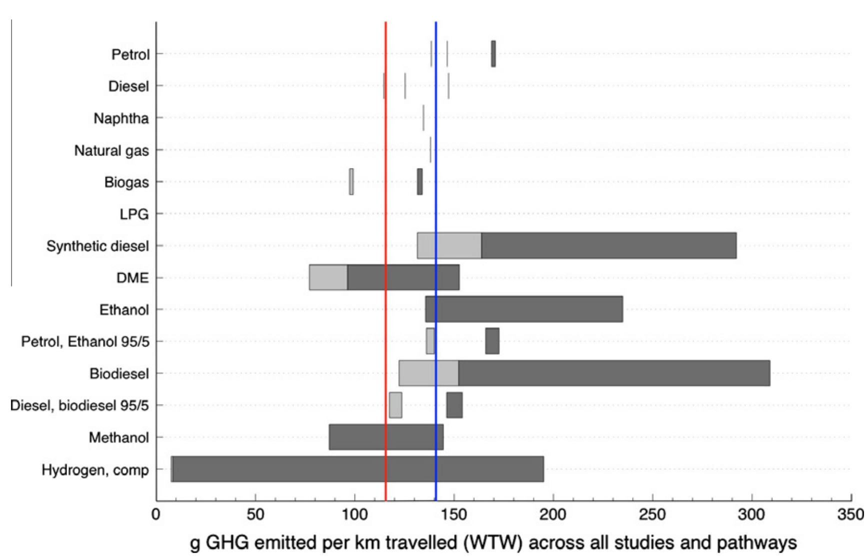

Fig. 3. Range of GHG emissions per km by fuel type (best estimate) for conventional powertrains (dark bar) and hybridized (light bars). For petrol and diesel, the left most vertical line indicates the effect of engine downsizing. The 2015 and 2020 WTW g GHG/km targets of 141 g GHG/km and 116 g GHG/km are indicated by vertical blue and red lines, respectively. *Note*: the best estimate pathway is that with the highest probability in the distribution of the raw data. Therefore, the bar limits do not represent the limits of the raw data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

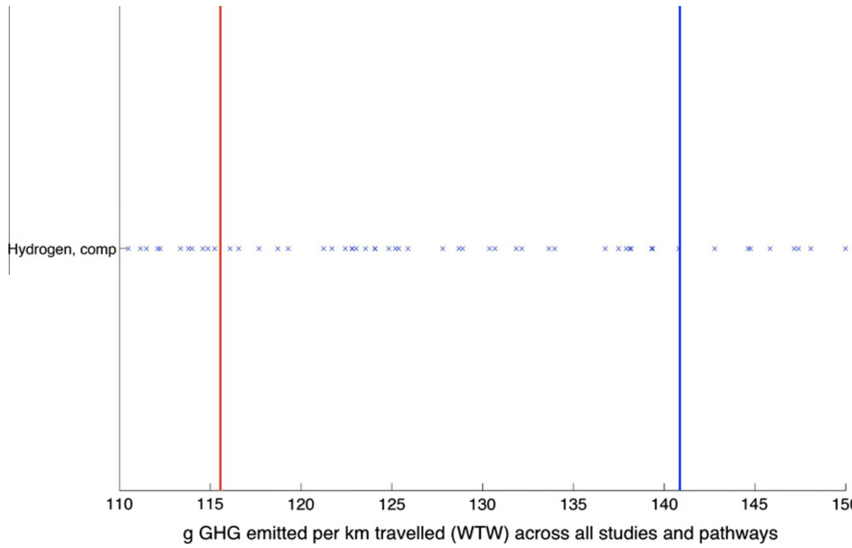

Fig. 4. GHG emissions per km from hydrogen across all powertrains and production pathways in the range 110–150 g GHG/km. The 2015 and 2020 WTW g GHG/km targets of 141 g GHG/km and 116 g GHG/km are indicated by vertical blue and red lines, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

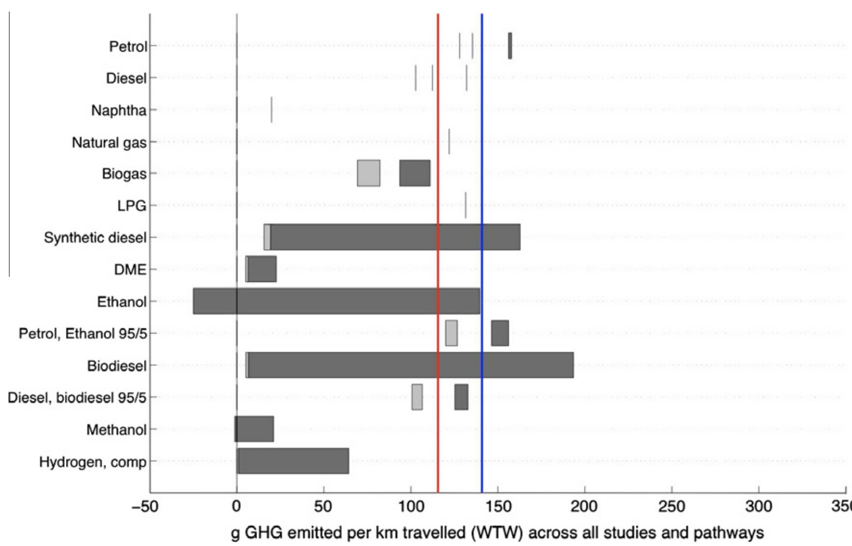

Fig. 5. Range of GHG emissions per km by fuel type (best-in-class pathway) for conventional powertrains (dark bar) and hybridized (light bars). For petrol and diesel, the left most vertical line indicates the effect of engine downsizing. The 2015 and 2020 WTW g GHG/km targets of 141 g GHG/km and 116 g GHG/km are indicated by vertical blue and red lines, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

closest and furthest pathway. The target WTT g GHG/MJ is the difference between the WTW emissions limit and the WTW vehicle emissions, divided by the TTW vehicle efficiency (second column, Tables 8 and 9). The percentage improvement necessary to a WTT fuel pathway arises by comparing the WTT target to both the best estimate and best-in-class pathways. The closest pathway requires minimum improvement to meet the WTT target ('best', Tables 8 and 9). The furthest pathway requires the maximum improvement to meet the WTT limit. Achieving maximum improvement results in all WTT pathways becoming feasible ('worst', Tables 8 and 9).

It is expected that a mixture of multiple primary resources and production pathways would be used to meet the global demand for a particular fuel. In this work, the mixture is the resource potential weighted average of primary resources that constitute the final fuel. Recall that the adaptive kernel density estimator included a weighting factor to account for resource potential. It is expected that the resource-weighted mixture of fuels which constitutes a globally distributed supply would be the same as the best estimate ('All' in Tables 3–6) derived from the adaptive kernel density estimator method.

The 2015 European emissions limit is met by at least one of the best estimate pathways for biogas, DME, ethanol, methanol and hydrogen. All naphtha and natural gas routes meet the 2015 emissions limit (Table 8). The remaining fuels require some improvement to their best performing pathway, ranging from 0.1% for LPG to 51% for synthetic diesel. In Fig. 6a: the WTT limit is illustrated by a blue mark in part a) of Fig. 6 and second column of Table 8; the red bar indicates the median absolute improvement necessary to the pathway to meet the WTT limit; and the black error bars demarcate the range of absolute improvements from the best to the worst fuel pathway to meet the WTT limit. In Fig. 6b:

Table 8
Factor improvements required for best case, global mixture and worst case best estimate and best-in-class WTT pathways to meet the 2015 European emissions legislation. The minimum factor corresponds to the difference between the best performing WTT estimate and the WTW emissions legislation. Similarly, the maximum factor represents the factor necessary to allow the worst performing WTT estimate to meet the WTW emissions limit.

Fuel	2015 WTT target (g GHG/MJ)	Best estimate pathway			Best-in-class pathway		
		Best	Mixture	Worst	Best	Mixture	Worst
Petrol	−0.22	−0.99	−0.99	−0.99	−0.97	−0.97	−0.97
Diesel	10.78	0.26	0.26	0.26	–	–	–
Naphtha	14.54	–	–	–	–	–	–
Natural gas	17.59	–	–	–	–	–	–
Biogas	17.59	–	–	–	–	–	–
LPG	7.48	–	–	–	–	–	–
Synthetic diesel	13.23	0.51	0.52	0.87	–	–	0.50
DME	19.10	–	–	0.28	–	–	–
Ethanol	1.78	–	0.89	0.97	–	–	–
Petrol/ethanol 95/5	−0.15	−0.99	−0.99	−0.99	−0.96	−0.97	−0.98
Biodiesel	7.80	0.47	0.66	0.93	–	–	0.80
Diesel/biodiesel 95/5	10.64	0.23	0.25	0.43	–	–	–
Methanol	25.10	–	–	0.09	–	–	–
Hydrogen	83.12	–	–	0.28	–	–	–

Table 9
Factor improvements required for best case, global mixture and worst case best estimate and best-in-class WTT pathways to meet the 2020 European emissions legislation. The minimum factor corresponds to the difference between the best performing WTT estimate and the WTW emissions legislation. Similarly, the maximum factor represents the factor necessary to allow the worst performing WTT estimate to meet the WTW emissions limit.

Fuel	2020 WTT target (g GHG/MJ)	Best estimate pathway			Best-in-class pathway		
		Best (%)	Mixture (%)	Worst (%)	Best (%)	Mixture (%)	Worst (%)
Petrol	−13.38	−0.14	−0.14	−0.14	1.54	1.54	1.54
Diesel	−4.30	−0.70	−0.70	−0.70	−0.21	−0.21	−0.21
Naphtha	−0.85	−0.92	−0.92	−0.92	–	–	–
Natural gas	4.31	0.73	0.73	0.73	−0.43	0.43	0.43
Biogas	4.31	0.65	0.66	0.69	–	–	–
LPG	−5.68	−0.24	−0.24	−0.24	2.25	2.25	2.25
Synthetic diesel	−1.85	−0.93	−0.93	−0.98	–	–	−0.93
DME	3.58	–	0.80	0.86	–	–	–
Ethanol	−11.38	52.11	−0.29	−0.78	–	–	10.35
Petrol/ethanol 95/5	−13.31	−0.04	−0.10	−0.19	3.72	2.44	1.69
Biodiesel	−7.28	−0.50	−0.68	−0.93	–	–	−0.81
Diesel/biodiesel 95/5	−4.44	−0.68	−0.69	−0.76	3.57	2.76	−0.23
Methanol	8.21	–	0.64	0.70	–	–	–
Hydrogen	68.19	–	–	0.41	–	–	–

the red bar indicates the median factor improvement in WTT supply pathway; and the error bars outline the range of factor improvements across the set of fuel supply pathways.

The WTT targets are sufficiently strict for some fuels – petrol, neat and blended with ethanol – that their production pathways must achieve net negative GHG emissions per MJ fuel supplied. The net negative GHG limit is illustrated by the blue marks which lie below the horizontal axis in Fig. 6b. Net negative GHG emissions arise in the literature based on deferred emissions from the production process. Examples of such production methods exist in the best-in-class pathways (Tables 5 and 6) where waste and byproducts are used instead of the primary resources from which they originate. The range of maximum improvements needed for the worst performing pathway of each fuel is 0.1% for LPG to 97% for ethanol.

By 2020, only the best performing of the best estimate WTT pathways for hydrogen and methanol require no improvement to attain the emissions limit of that year. Improvements range from 65% for biogas to 73% for natural gas. All fuels, except natural gas, biogas, DME, methanol and hydrogen, require the switch to net negative GHG emissions production methods in the worst case (maximum percentage change in Table 9) if all pathways are to meet the more strict 2020 emissions limit (part b) of Fig. 7).

At least one of the best-in-class pathways for diesel, naphtha, natural gas, biogas, synthetic diesel, DME, ethanol, biodiesel (neat and blended) methanol and hydrogen meets the 2015 European emissions limit (Table 8, Fig. 8). The remaining fuels – petrol, neat and blended with ethanol – must achieve net negative GHG emissions per MJ fuel supplied. For the worst case pathways, improvements are bounded by synthetic diesel at 50% and 80% for neat biodiesel. Petrol and blended ethanol maintain the need for negative GHG emissions production to become feasible. By 2020, the best performing of the best-in-class WTT pathways for naphtha, biogas, synthetic diesel, DME, ethanol, biodiesel, methanol and hydrogen require no improvement to attain the emissions limit (Fig. 9). The same is true for the necessary improvements to the realistic global supply of each fuel for the WTT limits to be met (Table 9). This analysis quantifies the distance that the petrol and bioethanol pathways, neat and blended, are from meeting the WTT targets in the worst case, using both the best estimates and the state of the art. Moreover, a number of WTT pathways requiring production process changes to yield net negative GHG emissions.

A comparison of Figs. 6–8 and Figs. 7–9 reinforces the differences between the best estimate and best-in-class pathways as the emissions legislation becomes more strict. The heights of the positive red bars decrease when moving from best estimate to

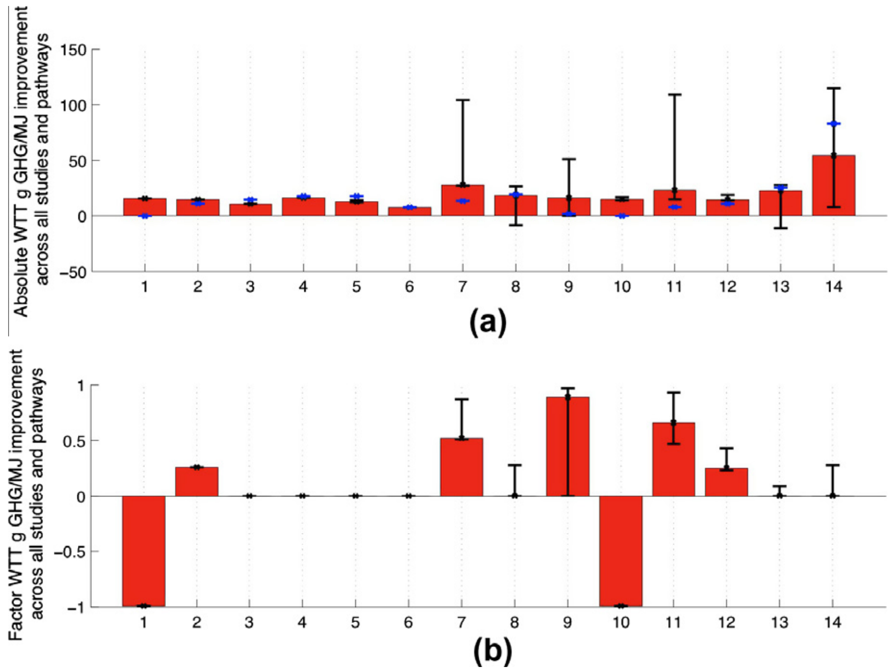

Fig. 6. Best estimate pathways in 2015: (a) Absolute WTT g GHG/MJ fuel chain improvement across all studies and pathways (red bars); (b) Factor g GHG/MJ fuel chain improvement across all studies and pathways (red bars). Black error bars denote the range of absolute and factor improvements for each fuel. Blue marks indicate the WTT target for each fuel to meet the 2015 emissions limit for fixed TTW energy conversion efficiency. Horizontal axis key: 1 = Petrol; 2 = Diesel; 3 = Naphtha; 4 = Natural gas; 5 = Biogas; 6 = LPG; 7 = Synthetic diesel; 8 = DME; 9 = Ethanol; 10 = Petrol, Ethanol 95/5; 11 = Biodiesel; 12 = Diesel, Biodiesel 95/5; 13 = Methanol; and 14 = Hydrogen, comp. *Note*: the best estimate pathway is that with the highest probability in the distribution of the raw data. Therefore, the error bar limits do not represent the limits of the raw data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

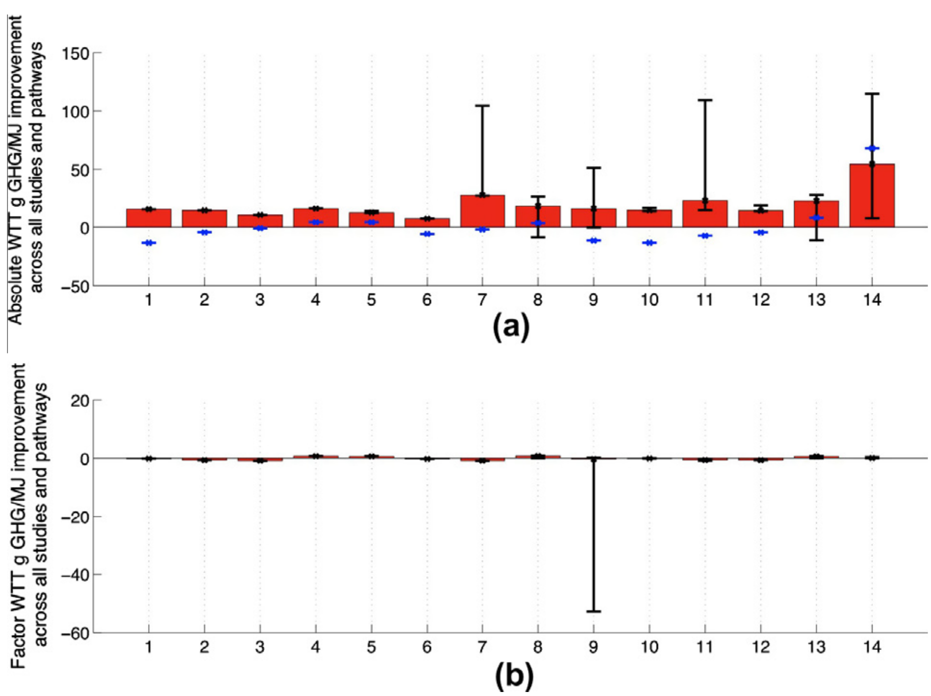

Fig. 7. Best estimate pathways in 2020: (a) Absolute WTT g GHG/MJ fuel chain improvement across all studies and pathways (red bars); (b) Factor g GHG/MJ fuel chain improvement across all studies and pathways (red bars). Black error bars denote the range of absolute and factor improvements for each fuel. Blue marks indicate the WTT target for each fuel to meet the 2020 emissions limit for fixed TTW energy conversion efficiency. Horizontal axis key: 1 = Petrol; 2 = Diesel; 3 = Naphtha; 4 = Natural gas; 5 = Biogas; 6 = LPG; 7 = Synthetic diesel; 8 = DME; 9 = Ethanol; 10 = Petrol, Ethanol 95/5; 11 = Biodiesel; 12 = Diesel, Biodiesel 95/5; 13 = Methanol; and 14 = Hydrogen, comp. *Note*: the best estimate pathway is that with the highest probability in the distribution of the raw data. Therefore, the error bar limits do not represent the limits of the raw data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

best-in-class pathway, indicating lower maximum improvements required to meet the WTT emissions limits. Moreover, the number of fuels which require no percentage improvement increases when the best-in-class pathways are used for fixed TTW energy

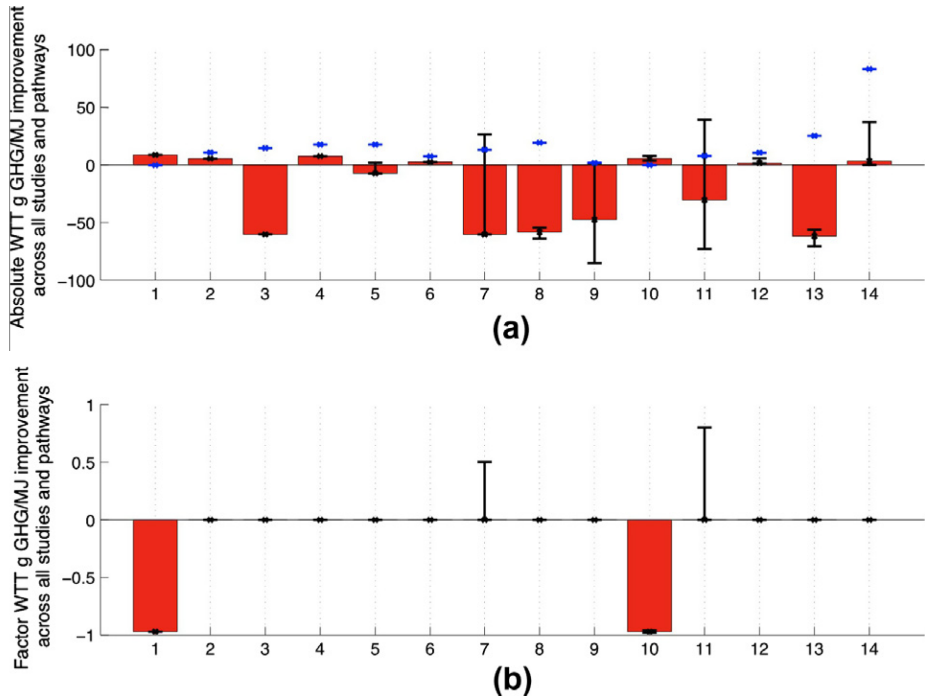

Fig. 8. Best-in-class pathways in 2015: (a) Absolute WTT g GHG/MJ fuel chain improvement across all studies and pathways (red bars); (b) Factor g GHG/MJ fuel chain improvement across all studies and pathways (red bars). Black error bars denote the range of absolute and factor improvements for each fuel. Blue marks indicate the WTT target for each fuel to meet the 2015 emissions limit for fixed TTW energy conversion efficiency. Horizontal axis key: 1 = Petrol; 2 = Diesel; 3 = Naphtha; 4 = Natural gas; 5 = Biogas; 6 = LPG; 7 = Synthetic diesel; 8 = DME; 9 = Ethanol; 10 = Petrol, Ethanol 95/5; 11 = Biodiesel; 12 = Diesel, Biodiesel 95/5; 13 = Methanol; and 14 = Hydrogen, comp. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

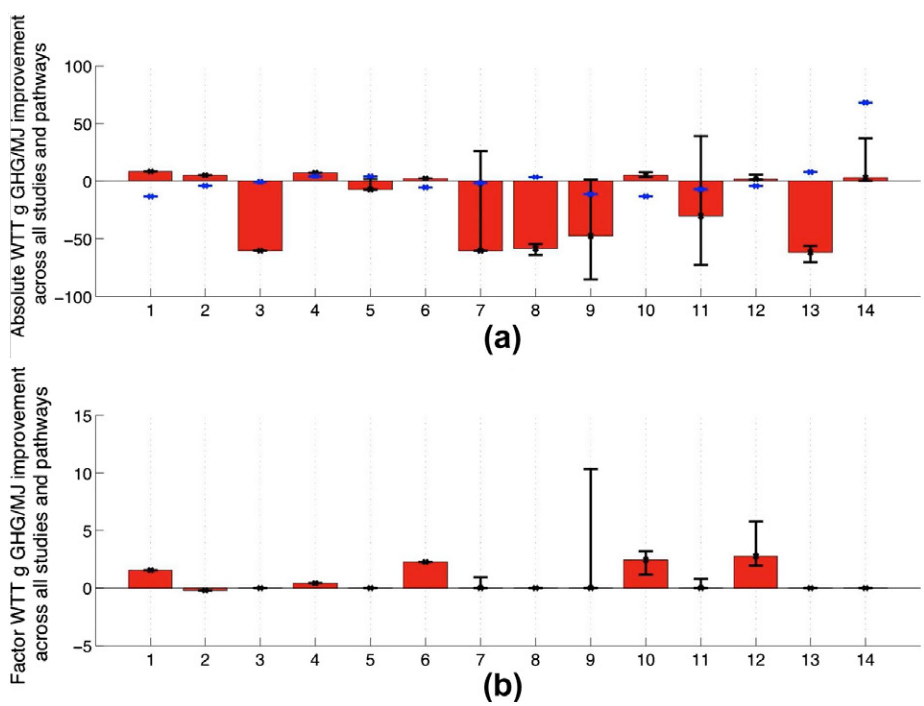

Fig. 9. Best-in-class pathways in 2020: (a) Absolute WTT g GHG/MJ fuel chain improvement across all studies and pathways (red bars); (b) Factor g GHG/MJ fuel chain improvement across all studies and pathways (red bars). Black error bars denote the range of absolute and factor improvements for each fuel. Blue marks indicate the WTT target for each fuel to meet the 2020 emissions limit for fixed TTW energy conversion efficiency. Horizontal axis key: 1 = Petrol; 2 = Diesel; 3 = Naphtha; 4 = Natural gas; 5 = Biogas; 6 = LPG; 7 = Synthetic diesel; 8 = DME; 9 = Ethanol; 10 = Petrol, Ethanol 95/5; 11 = Biodiesel; 12 = Diesel, Biodiesel 95/5; 13 = Methanol; and 14 = Hydrogen, comp. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

conversion efficiency. Finally, the number of bars which require negative percentage decreases when moving from best estimate to best-in-class, suggesting that fewer best-in-class fuel pathways must switch to net negative GHG emissions.

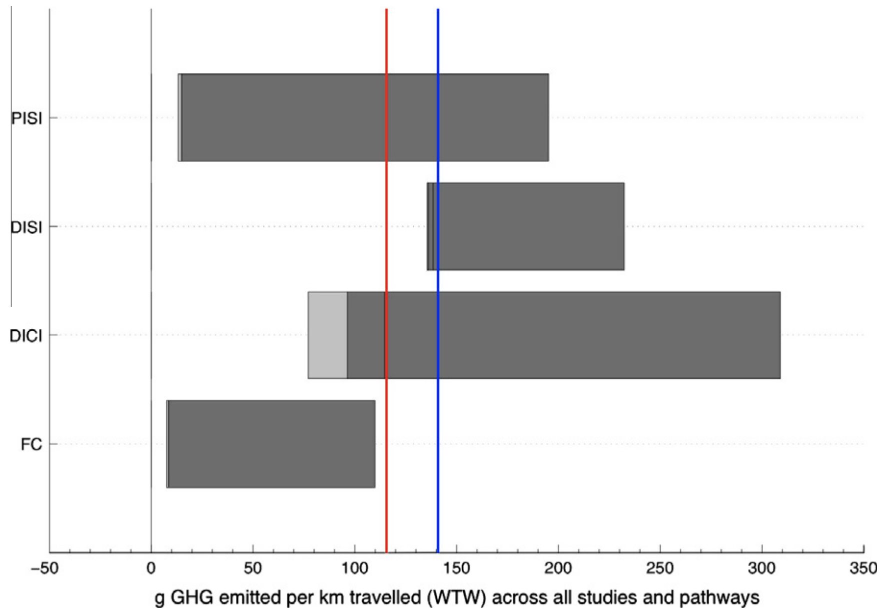

Fig. 10. Range of GHG emissions per km by conventional powertrains (dark bar) and hybridized (light bars) for best estimates of fuel pathways. The 2015 and 2020 WTW g GHG/km targets of 141 g GHG/km and 116 g GHG/km are indicated by vertical blue and red lines, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.3.1. Fuel supply potential and emissions limits

The primary resource potentials of the various fuels were combined into weighting factors to determine the best estimate pathway for supplying a fuel (Tables 1 and 2). The resource potential may be used now to assess the ability for novel fuels to displace conventional petrol and diesel use, while meeting both EU LGV energy demands and emissions limits.

In 2011, the LGV fleet in (OECD and Eastern) Europe required 8 EJ to meet its transport needs. The global LGV fleet required 41 EJ [24]. Fossil-fuels paired with a variety of vehicle powertrain types can meet the emissions targets in 2015 and 2020 and wholly satisfy the European and global LGV fleet demand. Best estimate pathways utilising: sugar beet (conventional PISI and DISI); rape seed, sunflower and soy (hybridized DICI); animal waste (hybridized PISI); wood (conventional PISI, DISI and hybridized DICI), wood residue (conventional PISI, FC and hybridized PISI, FC) and electricity from renewables (conventional and hybridized FC) are feasible by 2015. Best-in-class pathways for wheat, sugar cane, sugar beet and maize (all in conventional PISI, DISI); rape seed (conventional and hybridized DICI); sunflower and soy (hybridized DICI); wood (conventional PISI, DISI, DICI and hybridized DICI); biomass and biomass residue (both in conventional and hybridized PISI and DICI); animal waste (conventional and hybridized PISI); wood residue (conventional and hybridized PISI, FC and FC with

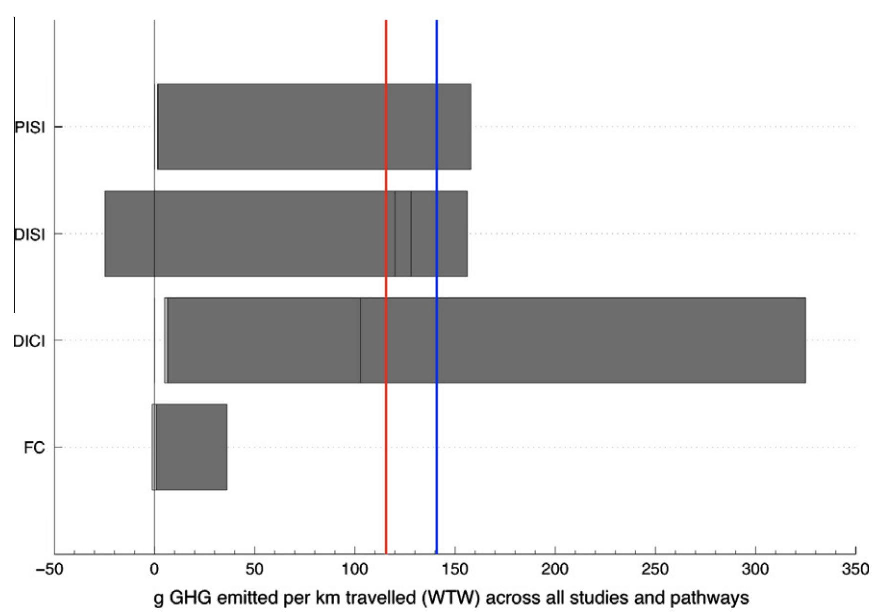

Fig. 11. Range of GHG emissions per km by conventional powertrains (dark bar) and hybridized (light bars) for best-in-class pathways to final fuels. The 2015 and 2020 WTW g GHG/km targets of 141 g GHG/km and 116 g GHG/km are indicated by vertical blue and red lines, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 10
Maximum percentage improvements required in TTW conversion efficiency to meet the 2015 and 2020 WTW targets using best estimate and best-in-class pathways. The total, maximum technical potential for powertrain and non-powertrain improvements [25] is included for comparison.

Energy conversion technology	Necessary % improvement				Total, maximum technical % improvement
	Best estimate pathway		Best-in-class pathway		
	2015	2020	2015	2020	
PISI	40	51	11	27	38
PISI, hybrid	19	33	–	–	13
DISI	40	50	10	26	13
DISI, hybrid	4	21	–	14	13
DICI	55	63	28	40	34
DICI, hybrid	43	54	10	26	13
FC	–	–	–	–	13
FC, hybrid	–	–	–	–	13
Reformer + FC, hybrid	4	21	–	14	13

reformer) are feasible by 2015, with a total, non-fossil-fuel based energy potential of 750 EJ/yr (Tables 1 and 2). However, the sum of resource potential for non-wood and non-biomass fuel crops is 5 EJ/yr. Notwithstanding the other economic uses of such crops, there is insufficient yield to displace large portions of fossil-fuel use. However, there are blends of petrol with bioethanol and diesel with biodiesel which can both meet the emissions limits and satisfy LGV demand.

By 2020, no blended fuels using best estimate pathways meet the emissions requirement. The number of fossil-fuel and neat biofuel best estimate pathways remain as in 2015, though the fuels are now paired to fewer conversion technologies to satisfy the 2020 WTW limit. Using best-in-class pathways permits all blended biodiesels. Moreover, wood residue replaces the wood. Therefore, biofuels may only be realistically used to satisfy a large proportion of LGV demand when blended with conventional fuels. Moreover, they are only feasible by 2020 when best-in-class pathways are used. Therefore, WTT pathways using fossil-fuels as the primary resource will continue to satisfy LGV energy and emissions requirements.

3.4. Improving TTW efficiency

An alternative to meeting the WTW target through fuel supply efficiency increases is to improve the energy conversion TTW phase (Figs. 10 and 11).

On a WTW basis, the bars of Figs. 10 and 11 must lie to the left of the blue and red lines if all energy conversion technologies are to meet the 2015 and 2020 emissions limits, respectively. The FC conversion technologies do not require any improvement. The hybridized DISI requires the least at 4%. By contrast, a 55% improvement in conventional DICI technology is necessary to allow all appropriate fuels to be used. The median improvement necessary is 29%. By 2020, all conversion technologies, except FC, require large scale improvements, in the range of 17–63% (Table 10).

Achieving such fuel efficiency increases may be accomplished by addressing both the energy conversion system and the characteristics of the vehicle itself, such as aerodynamics and tyres. Non-hybridized drivetrains can benefit from engine operation efficiency improvements of 0.5–25%, with variable valve timing as the largest contributor [25]. Non-engine advances can contribute 0.5–13%, dominated by lightweighting [25]. Hybridization adds 15–18% improvements to otherwise conventional petrol and diesel engines [25] (Table 10), which is higher than the 10% average used by Concawe [3].

In general, the necessary improvement to the TTW efficiency in 2015 and 2020 exceeds what the introduction of powertrain and non-powertrain technology can achieve using best estimate fuel pathways.

4. Conclusions

The focus of legislation on vehicle emissions reductions centres on TTW operation despite the importance of the WTT impacts of providing the fuel. Therefore, the assessment of the WTT impacts of fuel supply pathways using defensible estimates is critical to assessing which fuel-energy conversion technology combinations can lead to an overall reduction in total emissions. This work uses the non-parametric adaptive kernel density estimator method to find the underlying distribution of a wide range of WTT estimates from the literature. The best estimate pathway is the peak of the distribution. This robust and defensible method can accommodate future published estimates. The best-in-class pathway is that with the lowest emissions per MJ of fuel supplied.

There are 42 unique best estimate fuel pathway and appropriate energy conversion technologies combinations that meet the 2015 European emissions legislation. When considering the best-in-class fuel pathway, 67 fuel-energy conversion technology combinations meet the legislation. Under the more strict 2020 legislation, the shortlist decreases to 17 for best estimate and 44 for best-in-class pathways, respectively. There is a set of fuel-energy conversion technology combinations which fail to meet the 2015 and 2020 emissions limits, regardless of the performance of the WTT pathway. These are conventional powertrains using: petrol; synthetic diesel from coal; all blended ethanols; and biodiesel from sunflower, soy and palm. In particular, the hybridization and downsizing of internal combustion engines may be best considered only as a short-term measure.

For a number of fuels to meet either the 2015 or 2020 WTW equivalent emissions targets, their production processes would need to achieve net negative GHG emissions. The point at which the factor improvement switches from positive to negative is a function of the pathway and emissions limit under consideration. However, petrol and ethanol always require net negative GHG emissions in their production.

The present process for making transport fuel is globally distributed with very similar standards of production with only two main products (petrol and diesel). Incorporating resource weighting gives insight into the ability for a particular WTT pathway to both meet LGV demand and emissions limits. Fossil-fuel best-estimate and best-in-class pathways can meet total LGV demand in 2015 and 2020. Whereas a number of neat biofuel options exist, both competition for their use in other economic sectors and low annual yield are likely to result in little ability to displace large-scale fossil-fuel use. However, when blended with conventional petrol and diesel, there are fuel-vehicle combinations which can satisfy the fleet energy demand emissions limits simultaneously. Beyond 2020, hydrogen appears to be a strong contender as the long-term transport fuel. However, the best estimate pathways rely on using electricity entirely from renewable sources or gasification of wood or wood waste, which for many nations or areas of the world is not a realistic expectation.

The necessary improvements to the TTW energy conversion efficiency can be quantified by the difference between the emissions using the current technology and the legislated emissions limit, for fixed WTT pathway. Across the best estimate pathways, both conventional FC and hybridized FC technologies possess the necessary efficiency. For the remaining technologies, a median efficiency of 33% increase in improvement is necessary to meet the 2015 and 2020 emissions limits, bounded by 4% for hybridized

Table 11
TTW Energy use, fuel consumption and emissions normalised to distance travelled from the 2010 powertrains listed in the Concawe report [3]. Fuel consumption is expressed as litres of petrol equivalent.

Fuel	Pathway	Conversion	Energy use (MJ/100 km)	Fuel use (l/100 km)	Emissions (g GHG/km)
Petrol	Crude	PISI	190	5.9	139
		DISI	188	5.9	138
		DISI, 1.6 l hybrid	163	5.1	120
		DISI, 1.3 l hybrid	154	4.8	113
		Reformer + FC, hybrid	162	5.1	119
Diesel	Crude	DICI	166	5.2	121
		DICI, 1.9 l hybrid	141	4.4	103
		DICI, 1.6 l hybrid	129	4.0	94
		Reformer + FC, hybrid	162	5.1	119
Naphtha	Crude	Reformer + FC, hybrid	162	5.1	116
Natural gas	Crude	PISI	188	5.9	106
		PISI, hybrid	139	4.4	78
LPG	Crude	PISI	190	5.9	125
Biogas	Biomass	PISI	188	5.9	106
	Animal	PISI	188	5.9	106
	Biomass	PISI, hybrid	139	4.4	78
	Animal	PISI, hybrid	139	4.4	78
Synthetic diesel	CtL	DICI	166	5.2	117
	GtL	DICI	166	5.2	117
	CtL	DICI, hybrid	133	4.2	94
	GtL	DICI, hybrid	133	4.2	94
DME	Biomass	DICI	161	5.0	109
	Fossil	DICI	161	5.0	109
	Biomass	DICI, hybrid	129	4.0	87
	Fossil	DICI, hybrid	129	4.0	87
Ethanol	Wheat	PISI	190	5.9	136
	Sugar cane	PISI	190	5.9	136
	Sugar beet	PISI	190	5.9	136
	Wood	PISI	190	5.9	136
	Maize	PISI	190	5.9	136
	Wheat	DISI	188	5.9	134
	Sugar cane	DISI	188	5.9	134
	Sugar beet	DISI	188	5.9	134
	Wood	DISI	188	5.9	134
	Maize	DISI	188	5.9	134
Petrol, Ethanol 95/5	Wheat	PISI	190	5.9	141
	Sugar cane	PISI	190	5.9	141
	Sugar beet	PISI	190	5.9	141
	Wood	PISI	190	5.9	141
	Maize	PISI	190	5.9	141
	Wheat	DISI	188	5.9	140
	Sugar cane	DISI	188	5.9	140
	Sugar beet	DISI	188	5.9	140
	Wood	DISI	188	5.9	140
	Maize	DISI	188	5.9	140
	Wheat	DISI, hybrid	154	4.8	114
	Sugar cane	DISI, hybrid	154	4.8	114
	Sugar beet	DISI, hybrid	154	4.8	114
	Wood	DISI, hybrid	154	4.8	114
Petrol Ethanol 95/5 cont'd	Maize	DISI, hybrid	154	4.8	114
Biodiesel	Rape seed	DICI	166	5.2	126
	Sunflower	DICI	166	5.2	126
	Soy bean	DICI	166	5.2	126
	Wood	DICI	166	5.2	126
	Palm	DICI	166	5.2	126
	Rape seed	DICI, hybrid	133	4.2	101
	Sunflower seed	DICI, hybrid	133	4.2	101
	Soy bean	DICI, hybrid	133	4.2	101
	Wood	DICI, hybrid	133	4.2	101
	Palm	DICI, hybrid	133	4.2	101
Diesel/biodiesel 95/5	Rape seed	DICI	166	5.2	122
	Sunflower seed	DICI	166	5.2	122
	Soy bean	DICI	166	5.2	122
	Wood	DICI	166	5.2	122
	Palm oil	DICI	166	5.2	122
	Rape seed	DICI, hybrid	133	4.2	98
	Sunflower seed	DICI, hybrid	133	4.2	98
	Soy bean	DICI, hybrid	133	4.2	98
	Wood	DICI, hybrid	133	4.2	98
	Palm oil	DICI, hybrid	133	4.2	98

(*continued on next page*)

Table 11 (*continued*)

Fuel	Pathway	Conversion	Energy use (MJ/100 km)	Fuel use (l/100 km)	Emissions (g GHG/km)
Methanol	Biomass	Reformer + FC, hybrid	148	4.6	102
	Fossil	Reformer + FC, hybrid	148	4.6	102
Hydrogen, compressed	Gasification	PISI	168	5.2	0
	Electrolysis	PISI	168	5.2	0
	Steam reforming	PISI	168	5.2	0
	Gasification	PISI, hybrid	149	4.6	0
	Electrolysis	PISI, hybrid	149	4.6	0
	Steam reforming	PISI, hybrid	149	4.6	0
	Gasification	FC	94	2.9	0
	Electrolysis	FC	94	2.9	0
	Steam reforming	FC	94	2.9	0
	Gasification	FC, hybrid	84	2.6	0
	Electrolysis	FC, hybrid	84	2.6	0
	Steam reforming	FC, hybrid	84	2.6	0

FC plus onboard reformer at the minimum and conventional DICI at 63% in the worst case. Using best-in-class fuel pathways only, PISI, DISI and DICI powertrains must be improved by up to 28% by 2015 and up to 40% by 2020. TTW improvements alone are insufficient to allow all energy conversion technologies to meet 2020 emissions limits, whether using best estimate or best-in-class WTT fuel pathways.

If only best-in-class fuel pathways are used, current technology advances in powertrain and non-powertrain technologies are sufficient to allow all energy conversion options to meet the 2015 emissions limit. Therefore, when compared with the challenges of improving WTT efficiency in 2015, vehicle technology improvements may yield greater gain for less effort. By 2020, the necessary vehicle technology improvements exceed their forecast technical potential, even when paired with best-in-class fuel pathway solutions. Therefore, a combination of improvements to vehicle technology efficiency and WTT pathways for supplying fuels will be necessary to meet more strict vehicle emissions limits. It should be remembered that the best-in-class and best-estimate pathways for a particular fuel may have radically differing resource potentials. The split of natural resources between potential fuels or even within groups of process pathways creates a substantial engineering barrier to any alternative displacing liquid fossil-fuels.

By demonstrating some of the shortcomings of many fuels production pathways and the pairing with conversion technologies which have been proposed as fossil-fuel replacements, this work raises the question of whether it is strategically wise to try to maintain all the options open when it is clear that the resource potential cannot meet current demands. Many of the alternative fuel pathways analysed and discussed could be potentially viable if the travel demand were less.

Acknowledgements

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Appendix A. Math formulae

$$\mathrm{MJ_{WTW}} = \mathrm{MJ_{TTW}} * (1 + \mathrm{MJ_{WTT}}); \tag{1}$$

where $\mathrm{MJ_{WTW}}$ is the WTW energy efficiency of the fuel-vehicle combination in MJ/100 km; $\mathrm{MJ_{TTW}}$ is the energy efficiency of the vehicle alone in MJ/100 km; and $\mathrm{MJ_{WTT}}$ is the WTT energy impact of supplying the fuel in MJ/MJ.

$$\text{specific emissions} = 130 + a * (M - M_o); \tag{2}$$

where a = 0.0457; M is the mass of the new vehicle and M_o is 1327 kg.

$$\mathrm{g\ GHG_{WTW}} = \mathrm{g\ GHG_{TTW}} + \frac{\mathrm{MJ_{TTW}}}{100} * \mathrm{g\ GHG_{WTT}}; \tag{3}$$

where $\mathrm{g\ GHG_{WTW}}$ is the WTW emissions efficiency of the fuel-vehicle combination in g GHG/km; $\mathrm{g\ GHG_{TTW}}$ is the emissions efficiency during vehicle operation only in g GHG/km; $\mathrm{MJ_{TTW}}$ is the energy efficiency of the vehicle alone in MJ/100 km; and $\mathrm{g\ GHG_{TTW}}$ is the WTT emissions impact of supplying the fuel in g GHG/MJ.

$$\text{Target g GHG}_{\mathrm{WTW}} = \text{Target g GHG}_{\mathrm{TTW}} + \frac{\mathrm{MJ_{TTW}}}{100} * \mathrm{g\ GHG_{WTT}}; \tag{4}$$

where Target $\mathrm{g\ GHG_{WTW}}$ is the equivalent WTW emissions efficiency of the fuel-vehicle combination in g GHG/km; Target $\mathrm{g\ GHG_{TTW}}$ is the legislated emissions limit during vehicle operation in g GHG/km; $\mathrm{MJ_{TTW}}$ is the energy efficiency of the vehicle alone in MJ/100 km; and $\mathrm{g\ GHG_{TTW}}$ is the WTT emissions impact of supplying the fuel in g GHG/MJ.

$$\text{Target g GHG}_{\mathrm{WTT}} = 100 * \frac{\text{Target g GHG}_{\mathrm{WTW}} - \mathrm{g\ GHG_{TTW}}}{\mathrm{MJ_{TTW}}}; \tag{5}$$

where Target $\mathrm{g\ GHG_{WTT}}$ is the WTT fuel limit related to the particular fuel, WTW emissions limit (Target $\mathrm{g\ GHG_{WTW}}$) and energy conversion efficiency, $\mathrm{MJ_{TTW}}$.

$$\text{Target MJ}_{\mathrm{TTW}} = \frac{\text{Target g GHG}_{\mathrm{WTW}}}{100 * (\mathrm{g\ GHG_{fuel}} + \mathrm{g\ GHG_{WTT}} + 1)}; \tag{6}$$

where Target $\mathrm{MJ_{TTW}}$ is the TTW vehicle efficiency related to the particular fuel, WTW emissions limit (Target $\mathrm{g\ GHG_{WTW}}$), carbon content of the fuel ($\mathrm{g\ GHG_{fuel}}$) and WTT fuel pathway ($\mathrm{g\ GHG_{WTT}}$).

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