ROAD TRANSPORTATION: WHAT ALTERNATIVE MOTORISATIONS ARE SUITABLE FOR THE CLIMATE?

A comparison of the life cycle emissions, in France and Europe

Mobility Practice

Stéphane Amant
Senior Manager, Head of the Mobility Practice
Nicolas Meunier
Mobility Consultant
Côme de Cossé Brissac
Consultant

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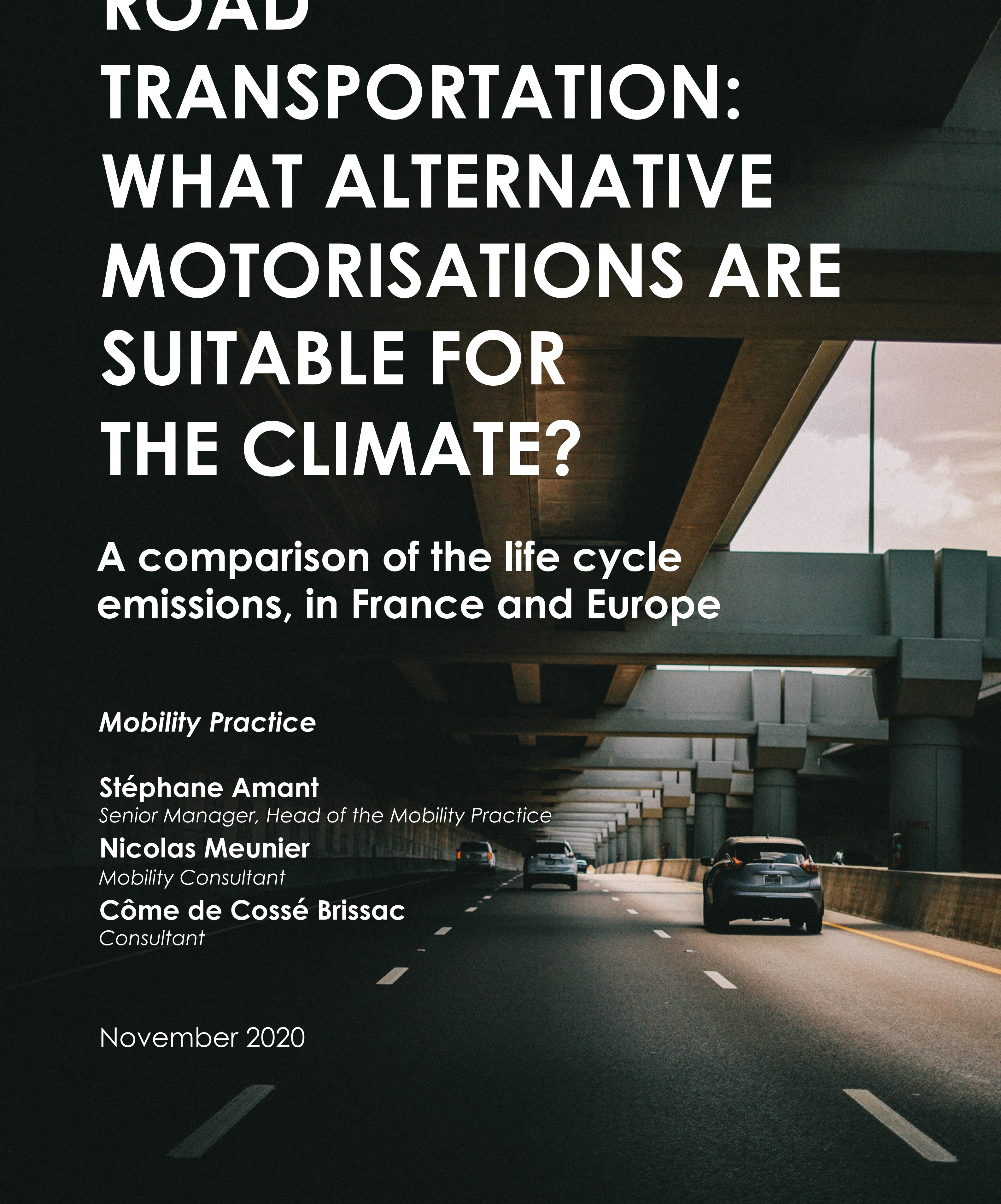

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Introduction

Why carry out this study?

In order to respond to the climate challenge, the mobility sector has no choice but to reinvent itself. Through new technologies, new uses and by acting on demand: the challenge is so great that all the levers will have to be activated.

In France, 95% of GHG emissions from transport are attributable to road transport[1]. Most of the vehicle flows, and therefore emissions, are based on the use of passenger cars, commercial vehicles and trucks. Taking an interest in the low-carbon mobility transition therefore inevitably means putting a particular focus on the energy transition of road vehicles, regardless of the necessary modal shift and moderation of demand.

In this field, mobility operators and vehicle users in general have every interest in anticipating the changes that are going to occur, so that they can be participants and not have to suffer as a result. For economic players, this foresight enables them to become resilient in the transition, and thus ensures the economic sustainability of their activity. For households, it is the guarantee of access to individual mobility that is compatible with civic engagement.

However, despite government announcements and the positions taken by major industrial players, the technological path of the energy transition has not yet been clearly mapped out: no one can say today with certainty what the most suitable alternatives to the current fuels will be in the future. Won't hydrogen technology with fuel cells be preferable to battery electrification? Shouldn't gas technologies be favoured, in particular through the use of bioNGV? Won't liquid biofuels have a decisive role to play in this transition?

In order to rank these different available energy options, one of the main metrics to compare will be the carbon footprint over its life-cycle for different types of vehicles: private cars, light commercial vehicles, buses and semi-trailer truckss. This publication summarizes the most recent results obtained by Carbone 4, in order to inform the debate and help stakeholders make the best decisions with full knowledge of the facts.

Glossary

EF	Emissions Factor
GHG	Greenhouse Gas
RE	Renewable Energies
ICEV	Internal Combustion Engine Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
BEV	Battery Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
NGV / CNG / LNG	Natural Gas for Vehicle / Compressed / Liquefied

1. From EEA, Progress of EU transport sector towards its environment and climate objectives, 2018.

GHG emissions from road transport in France and Europe, today... and tomorrow

The carbon footprint assessment is carried out for the entire life of a vehicle, taking into account manufacture, use and end of life, for all greenhouse gases. It is considered in CO_2 equivalent (CO_2e) and is then reduced to a conventional functional unit, the km travelled by the vehicle. This same unit allows a comparison in carbon intensity of the different engines within a vehicle category.

The different types of vehicles considered are shown in **Table 1** below; there are five in total. Different motor vehicles and energies have been considered depending on their type, such as: liquid fuels (with a variable proportion of biofuel), NGV and bioNGV, electricity (with or without hybridisation) and hydrogen.

A "Well-To-Wheel" approach was chosen for our specific analysis of propulsion energies. As an example, for hydrogen, the scope considers the production (by methane steam reforming or water electrolysis), compression, transport and distribution.

	Passenger car		Light Duty Vehicle	Bus	Truck
	City car Segment B	Sedan Segment D	Large van	12 m	PMWT[5] 40 t
Gasoline	✔	✔			
Diesel		✔	✔	✔	✔
CNG[1]	✔	✔	✔	✔	✔
LNG[1]					✔
Electric[2]	✔	✔	✔	✔	✔
PHEV[3]	✔	✔			✔
Hydrogen[4]		✔	✔	✔	✔

Notes: 1 Variable share of biofuel, different scenarios envisaged; 2 Battery-electric; 3 Plug-in Hybrid Electric Vehicle; 4 Different production options envisaged.; 5 Permissible Maximum Weight of Trucks

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Table 1 – Motor vehicles considered by vehicle segment

Assessments are carried out for every new vehicle put on the road between 2020 and 2030, considering on the one hand the most likely changes in vehicle characteristics, and on the other hand a prospective approach for the CO_2e footprint linked to manufacturing.

For the vehicle use phase, time series have been established up until 2041 in order to also integrate the evolution of the carbon footprint of the different energy carriers over time. For example, for a vehicle sold in 2021, the emissions linked to its use are averaged over 12 years, from 2021 to 2032.

In addition, to provide a better view than the French perimeter alone, we have extended the analysis to cover the average for the EU.

Finally, the approach implemented has been designed so that the results do not reflect specific features, but rather more global situations, reflecting the performance of different types of vehicles at the level of a country or region (in this case, the EU). This is why, with few exceptions, we have not focused on specific cases, which may be potentially interesting in very specific contexts, but which are not replicable on a large scale (e.g. 100% biodiesel or bioethanol for private vehicles).

All the sources used for our work can be consulted in the list in the appendix.

A sensitivity assessment to limit uncertainties

In this type of analysis, there are inevitably uncertainties related to the different sources on the one hand, and to the forward-looking dimension of the study on the other. To overcome this difficulty and make the conclusions as robust as possible, we have therefore implemented an approach based on three complementary analyses:

- ✓ **a general and more in-depth consistency check** on the mass and consumption of the vehicles, in order to reinforce the overall consistency of the assumptions ;
- ✓ **a sensitivity analysis** to identify the model parameters that have the greatest impact on the carbon footprint of vehicles;
- ✓ **the construction of scenarios that vary only those parameters that are the most influential** in determining the range within which the results evolve.

In this way, the results presented in this publication are essentially derived from the central scenario; the assumptions of which have been screened within our consistency tests. However, in the chapter ‘Alternative Scenarios’, the results relate to two other scenarios, which are based on different sets of assumptions.

Main common assumptions for the different types of vehicles (energy and other characteristics)

The main common assumptions for all segments are detailed in the table below. The assumptions specific to each vehicle segment are explained in each of the dedicated sections. In addition, the sensitivity analysis on these different assumptions mentioned above is detailed in the appendix.

Energy vector	Underlying assumption		2020	2035
Gasoline & Bioethanol	Conventional[1] : 50% maize / 25% wheat / 25% beet in 2020 Advanced: wheat straw	Incorporation rate	66% E10	60% E10 40% E20
		Share of bioethanol	4.3% convent. 0% advanced	7.5% convent. 2.5% advanced
Diesel & Biodiesel	Conventional2 : 50% rapeseed / 25% soya / 25% palm oil Advanced: waste-residue	Incorporation rate	73% B7	45% B7 55% B10
		Share of advanced biodiesel	4.9% convent. 0% advanced	5.9% convent. 2.5% advanced
Natural gas & Biogas	Biogas 2020: 96% from agriculture and livestock farming / 2% from sewage treatment plant / 2% biowaste Biogas 2050: 70% from agriculture & livestock / 15% from STEP / 15% biowaste	Incorporation rate	0,5%	11%
		Emission factor for natural gas & biogas	225 gCO2e/kWh 51 gCO2e/kWh	203 gCO2e/kWh 40 gCO2e/kWh
Electricity	Electricity mix projections based on IEA studies and country national plans	Emission factor: 100% RE	18 gCO2e/kWh	16 gCO2e/kWh
		Emission factor: France	51 gCO2e/kWh	39 gCO2e/kWh
		Emission factor: EU	306 gCO2e/kWh	126 gCO2e/kWh
Hydrogen	Centralised steam reforming (75% efficiency) Electrolysis carried out on site (53% efficiency) Electricity compression	Emission factor: Electrolysis EU	714 gCO2e/kWh	345 gCO2e/kWh
		Emission factor: Electrolysis EN	119 gCO2e/kWh	97 gCO2e/kWh
		Emission factor: Steamref. NG EU	447 gCO2e/kWh	342 gCO2e/kWh
		Emission factor: Biometh.steamref.	206 gCO2e/kWh	127 gCO2e/kWh

[1]The relative share of conventional ethanol inputs evolves to 33%/33%/33% in 2035.
[2]The relative share of conventional biodiesel inputs evolves to 100% rapeseed in 2035

Table 2 – Common energy assumptions for all segments studied[2]

	Frame manufacturing EF[1]		Tank manufacturing EF				
	ICE vehicle kgCO2e/kg	Electric vehicle kgCO2e/kg	Hydrogen[2] kgCO2e/kg	CNG kgCO2e/kg	LNG kgCO2e/kg	Battery manufacturing EF kgCO2e/kWh	End-of-life vehicle EF kgCO2e/kg
2020	5,2	4,8	420	11	5,1	101	0,4
2030	4,2	3,9	380	10	4,6	81	0,4

[1]Emission Factor from the vehicule manufacture (excluding the tank and battery)
[2]The same carbon footprint for types III (350 bars) and IV (700 bars)

Table 3 – Common assumptions for all segments studied, excluding energy

2. The kWh refers to the energy content of each energy carrier. The 100% ENR mix is composed of 50% wind electricity, 15% photovoltaic electricity and 35% electricity from hydroelectric dams, which corresponds to the current mix in the European Union.

1 Private vehicles:

electrification and biogas come out on top

Things to remember

The passenger vehicles with the lowest carbon footprint are:

✓ **Vehicles running on bioNGV**

The very small carbon footprint is due to the assumption that gas vehicles would be developed with a light hybridisation (as with conventional ICE vehicles). Moreover, the biomethane emission factor varies only slightly according to the country of production.

✓ **Battery electric vehicles, whatever the electric mix of the region under consideration**

A decarbonised mix (France, renewable electricity) provides the best performance, but even an electric vehicle sold today in Germany, or even in Poland, remains less emissive than a combustion vehicle.

✓ **Electric vehicles using hydrogen produced by electrolysis or biomethane steam reforming, with decarbonised electricity** (French grid or renewable)

The FCEV's carbon footprint is heavily dependent on the electricity mix, with its performance similar to a BEV with decarbonised electricity, and similar or even superior to an ICEV in the opposite case.

The prospective vision in 2030 reduces the differences seen in the emissions between motor vehicles, without changing the conclusions already seen in 2020

✓ *Light hybridisation makes it possible to make up part of the gap with the BEVs, the latter improving more slowly due to the increase in battery capacity, which counteracts the fall in the EF of the electricity.*

✓ *Particularly for hydrogen vehicles, the decarbonisation of European electricity grid is not sufficient to match the CO_2 performance of the electric vehicles or ICEV running on bioNGV.*

A focus on segment B

Segment B *Motor Vehicle Type*	*Time-Invariant* Weight	 Service life	*Varying over time*	2020	2030
ICEV Gasoline	1,145 kg	150,000 km 12 years old	Real consumption (MHEV)	6.3 L/100 km	4.7 L/100 km
			Ethanol* share	9%	13%
ICEV NGV	1,214 kg of which tank: 69 kg	150,000 km 12 years old	Real consumption (MHEV)	4.4 kg/100 km	3.3 kg/100 km
			BioNGV share*	5%	11%
PHEV Gasoline	1,268 kg *of which battery: 63 kg*	150,000 km 12 years old	Real consumption	6.3 L/100 km 16 kWh/100 km	4.7 L/100 km 15.2 kWh/100 km
			Battery capacity	10 kWh 30% km elec	17 kWh 50% km elec
BEV	1,333 kg *of which battery: 313 kg*	150,000 km 12 years old	Real consumption	16 kWh/100 km	15.2 kWh/100 km
			Battery capacity	50 kWh	60 kWh

*The share of ethanol (by volume) and bioNGV is averaged over the lifetime of the vehicle.

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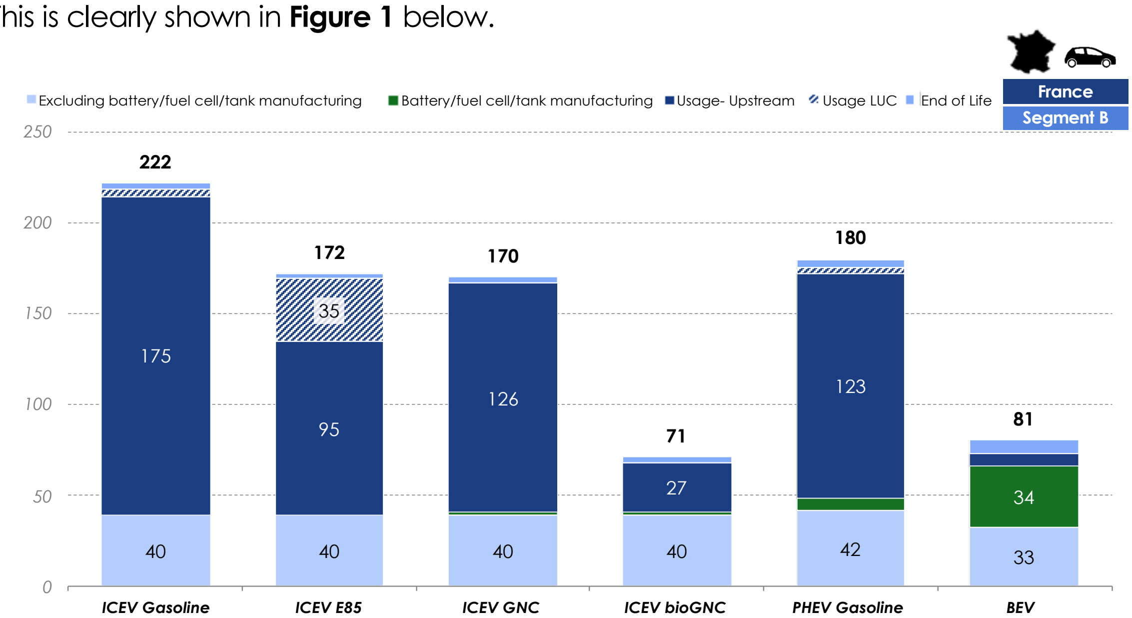
Table 4 – Main assumptions specific to segment B

In France in 2020, in the B segment category, BEVs and ICEVs running on bioCNG stand out clearly by their carbon footprint which is approximately 3 times lower than that of an ICEV running on gasoline.

This is clearly shown in **Figure 1** below.



Sources: Carbon 4 Analysis

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Figure 1 – The average carbon footprint over the lifetime of a car sold in 2020 France - Segment B | gCO_2e/km

It is clear that **the most significant part of the carbon footprint over the life cycle for a BEV used in France is the manufacture of the vehicle itself and its battery**, which confirms analyses that we had already published in a summary note on the electric vehicle and corroborates other recent work[3 4 5]. However, the improvement in the batteries' carbon footprint has been very clear over the last 5 years (going from nearly 200 kgCO_2e/kWh to about 100 kgCO_2e/kWh, on average), which is not enough to drastically reduce these emissions. It will be necessary to produce these batteries preferably in countries where there is low carbon electricity (potential gain of 25%) and also and above all **to encourage the adoption of batteries with a reasonable capacity, while not seeking at all costs to increase their size**. This is a major systemic issue, due to combining recharging infrastructure, user experience, usage costs and changes in use.

By 2030, mild hybridisation will enable a significant improvement in ICEVs by 2030, narrowing the gap with BEVs, whose carbon performance does not improve due to an increase in battery capacity. PFCEVs are also gaining in relevance and will eventually surpass the ICEV running on E85, assuming that the users are more aware of the benefits of electric recharging and therefore use this mode more intensively (50% of kilometers in 2030 instead of 30% in 2020). **Figure 2** illustrates the evolution of the different carbon footprints over time. It should be noted that each point represents the average emissions of a vehicle sold that year, over its lifetime.

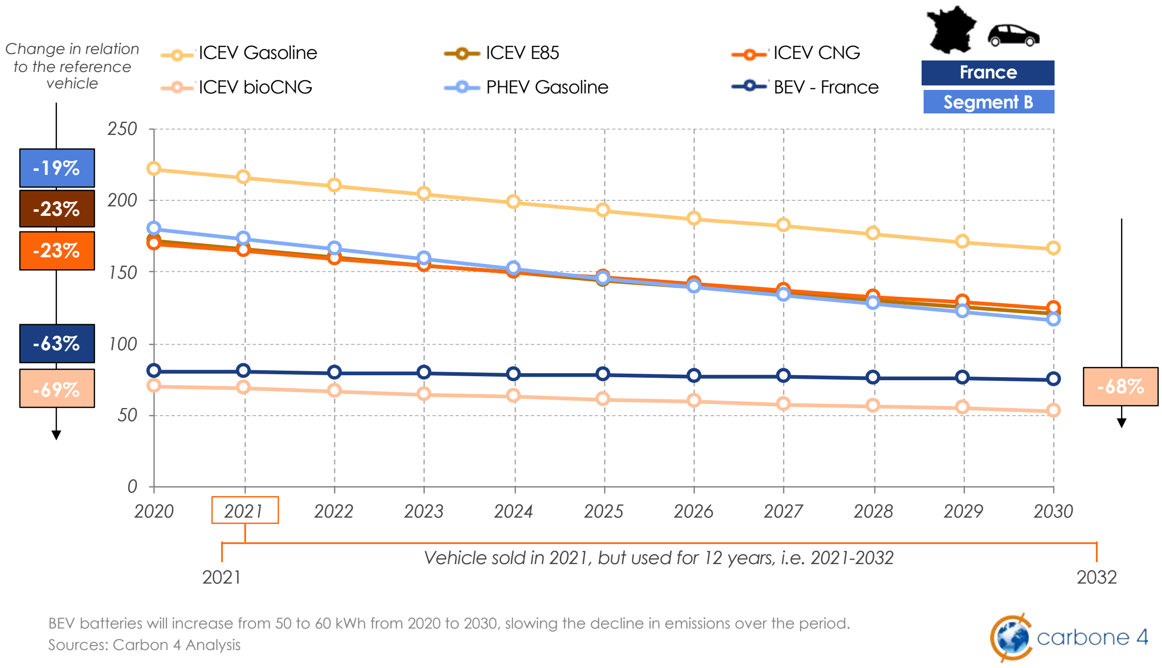

Figure 2 - Average carbon footprint over the lifetime of the vintage under consideration France - Segment B | gCO_2e/km

3. T&E, "How clean are electric cars?", 2020.
4. EAFO, " How 'green' is the electricity we use to charge our EVs? ", 2020.
5. TU/e, " Comparing the lifetime green house gas emissions of electric cars with the emissions of cars using gasoline or diesel ", 2020.

At the European level, in an average 2020 vision, the results are very similar to France, i.e. that ICE-bioCNG is the least emitting, but that BEVs remain better placed than ICEVs and even PFCEVs. Note that this is the case even in Poland, where the electricity mix is very carbon intensive. This is due to the significant reduction in battery manufacturing emissions in recent years, as already mentioned, and the gradual decarbonisation of all European electric mixes. **Figure 3** compares all the alternatives for segment B.

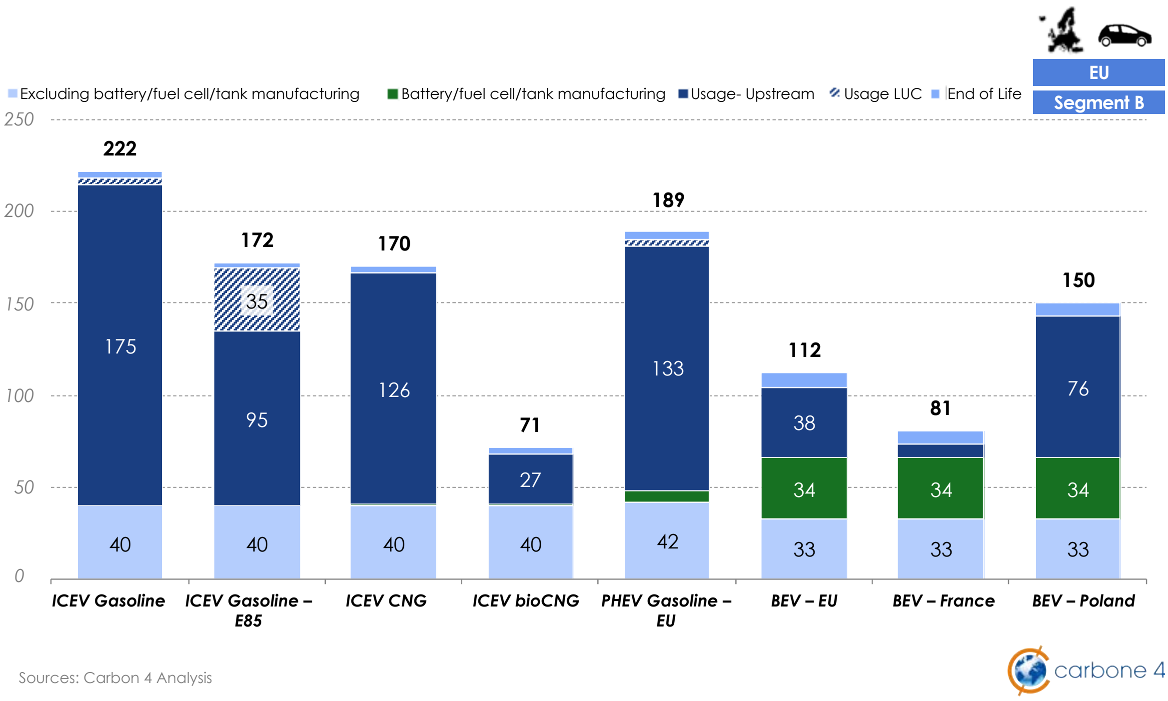

Figure 3 - Average carbon footprint over the lifetime of a car sold in 2020
Europe - Segment B | gCO_2e/km

A focus on segment D

Segment D *Motor Vehicle Type*	*Time-Invariant* Weight	Service life	*Varying over time*	*2020*	*2030*
ICEV Gasoline	1,520 kg	200,000 km 12 years old	**Real consumption (MHEV)**	8.3 L/100 km	6.2 L/100 km
			Ethanol* share	9%	13%
ICEV Diesel	1,560 kg	200,000 km 12 years old	**Real consumption (MHEV)**	6.9 L/100 km	5.2 L/100 km
			Biodiesel share*	6%	8%
ICEV NGV	1,609 kg *of which tank: 89 kg*	200,000 km 12 years old	**Real consumption (MHEV)**	5.8 kg/100 km	4.3 kg/100 km
			BioNGV share*	5%	11%
BEV	1,770 kg *of which battery: 375 kg*	200,000 km 12 years old	**Real consumption**	21 kWh/100 km	20 kWh/100 km
			Battery capacity	60 kWh	90 kWh
FCEV	1,595 kg *of which battery+tank: 137 kg*	200,000 km 12 years old	**Real consumption**	1.3 kg/100 km	1.2 kg/100 km
			Tank size	6.3 kgH_2	= 6.3 kgH_2
PHEV	Gasoline: 1,791 kg Diesel: 1,731 kg	200,000 km 12 years old	**Battery capacity**	13 kWh 30% km elec	20 kWh 50% km elec

*The share of ethanol / biodiesel (by volume) and bioNGV is averaged over the lifetime of the vehicle.

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Table 5 - Main assumptions specific to segment D

Unlike segment B, segment D offers a new technology: the FCEV, which is equipped with a fuel cell that powers an electric motor from hydrogen stored on board.

Thus, in France in 2020, the segment D category vehicles have similar carbon footprints, which includes BEVs, ICEVs running on bio-CNG and FCEVs using H_2 made from 100% renewable energy. They perform much better than ICEVs (factor 2.5 to 4).

Again, the very low EF of bio-CNG and French electricity allow biogas and electric vehicles to lead the way, with BEVs having the lowest emissions in use (9 gCO_2e/km) but are penalised by their battery manufacturing. The FCEV is 2 to 2.5 times less emitting over its lifecycle than an ICEV or a PHEV, when the hydrogen is produced by electrolysis with the French grid EF. However, its carbon performance is somewhat degraded by the low overall efficiency of the energy conversion chain: with the same electric motor as a BEV, the emissions in use are 5 times higher (44 gCO_2e/km versus 9 gCO_2e/km).

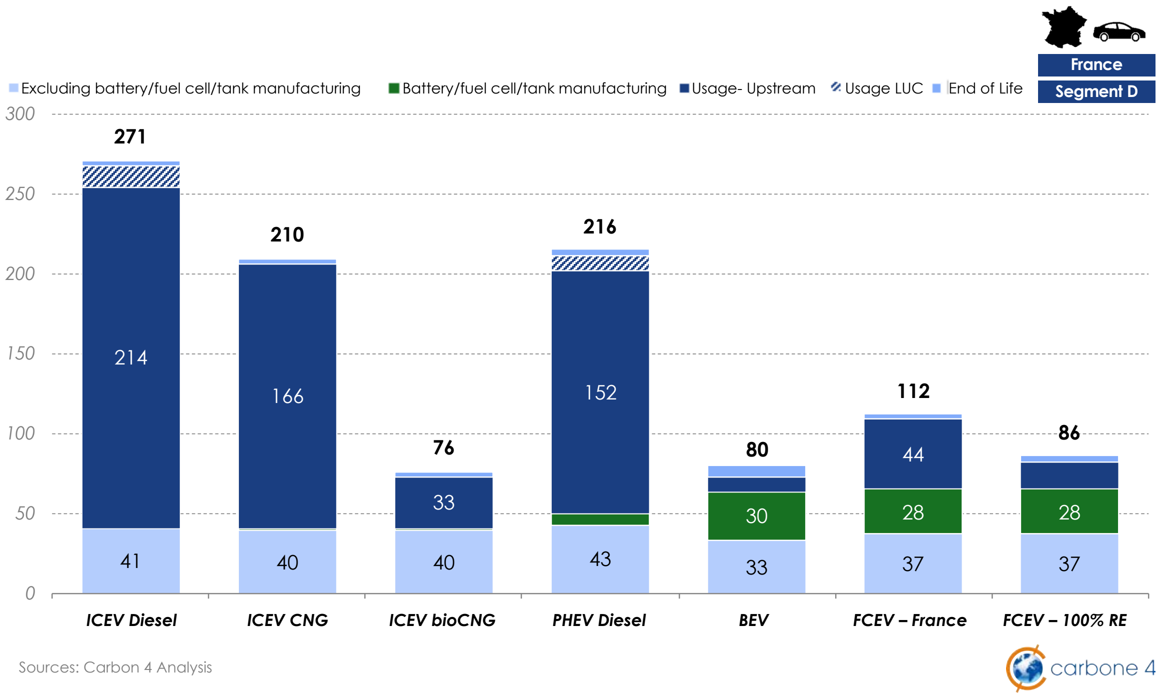

Figure 4 - Average carbon footprint over the lifetime of a car sold in 2020 Europe - Segment D | gCO_2e/km

When the electrolysis is powered by a 100% renewable Energy (RE) mix, the gain in emissions from hydrogen production makes it possible to reach the BEV level (running with the network mix instead).

By 2030, mild hybridisation allows for a significant improvement in ICEVs by 2030, thus reducing the gap between BEVs and FCEVs. PHEV is also becoming more relevant and eventually outperforming ICEV running on CNG, for the same reasons as Segment B. **Considering significant advances in the manufacturing of specific equipment for FCEV (the fuel cells and tanks reduce manufacturing emissions by approximately 30%); FCEVs and BEVs are becoming almost equivalent, depending on whether the electrical electrolysis mix is that of the grid or 100% RE**. Finally, the bioCNG formula is still the most efficient in terms of the carbon footprint.

Figure 5 illustrates the evolution of the different carbon footprints over time. Note that each point represents the average emissions of a vehicle sold that year, over its lifetime.

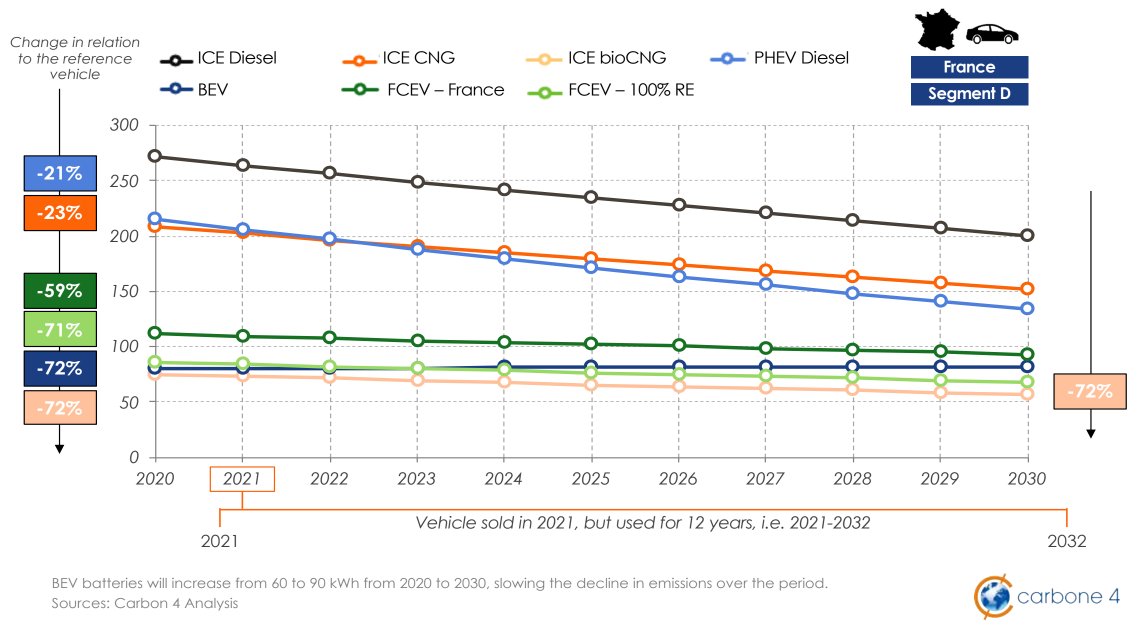

Figure 5 - Average carbon footprint over the lifetime of the vintage in question France - Segment D | gCO_2e/km

What really differentiates the comparison in France and the comparison in terms of the "EU average" in 2020 is the carbon performance of FCEVs. Indeed, with a much **more carbon-intensive electricity mix at the European level (about 6 times more in our assumptions), electrolysis produces a much more carbon-intensive hydrogen**, leading to emissions in excess of 300 gCO_2e/km, or even 400 gCO_2e/km in Germany. These values are higher than conventional ICEVS. The development of FCEVs can therefore only be envisaged with low-carbon hydrogen production, i.e. by electrolysis from low-carbon electricity (as in the typical French mix or 100% RE mix). **Figure 6** below summarizes the 2020 situation for segments D in the EU.

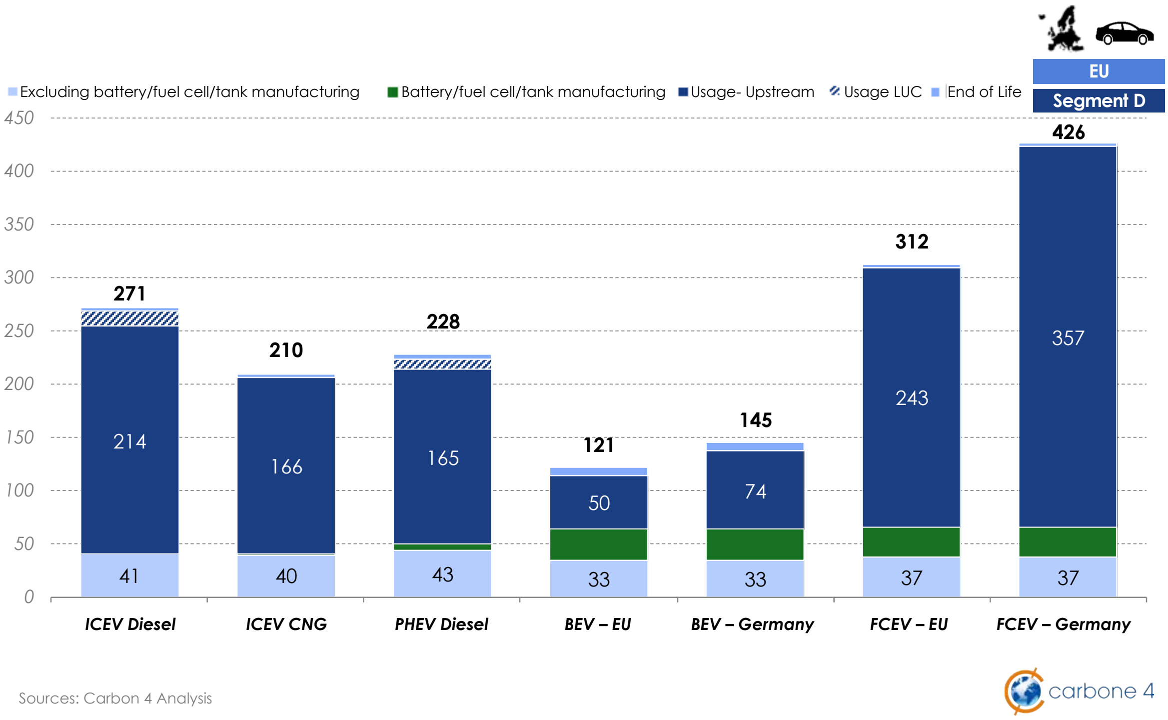

Figure 6 - Average carbon footprint over the lifetime of a car sold in 2020
Europe - Segment D | gCO_2e/km

Looking ahead to 2030, all the solutions are evolving, **with the most spectacular progress being observed on the hydrogen-powered FCEVs, as the grid electricity is assumed to decarbonise rapidly over the next 10 years**, according to the available energy projections [IEA RTS scenario, national energy plans], which would make the hydrogen production phase by electrolysis much less emissive (-37.5% on average in the EU).

A focus on lightweight materials

Is it beneficial to reduce the weight by substituting steel with lighter, but more emitting materials during the manufacturing process?

To our knowledge, this question has rarely been investigated, but it is nevertheless a point of attention to be considered when considering the life cycle analysis. Indeed, it is accepted that the automotive industry is already using so-called "lighter" materials to limit the increase in mass of its vehicles. If in the future, the tendency to limit or even reduce the mass of vehicles on the road is maintained, then the amount of aluminum, plastics, special steels, and perhaps even composite materials (such as carbon fibre, for instance) will increase in road vehicles, instead of standard steel.

This substitution will have a beneficial effect on the energy consumption of the vehicle during the use phase, which is obvious. On the other hand, the manufacture of these substitute materials proves in many cases to be more emitting than that of the conventional steel they replace, so the question arises as to whether the benefit to the energy consumption is cancelled out by these increased manufacturing emissions.

To answer this question, we have chosen the case of a particular vehicle (segment D), because due to its lower use compared to other road vehicles, it is in this category that the question is most acutely raised. In addition, we have chosen two quite distinct motor vehicle scenarios to cover the opposing cases in terms of use-related emissions: the ICEVs running on diesel and BEVs, both of which will be sold in 2020. To be conservative in our conclusions, we have also taken manufacturing emission factors in the high range for the substitute materials and considered them as new (sources: French Base Carbone Base and Base Impacts). Finally, we studied different substitution configurations, by analysing different mixes of aluminum / plastics / carbon fibres, the latter being by far the most emitting to produce (about 3 times more than the new aluminum average).

The results for the ICEVs running on diesel show that, even in the worst case for manufacturing (90% carbon fibre and 10% aluminium as a substitute for steel), the comparative life cycle balance is neutral to slightly favourable. With a more common substitution (50% aluminum and 50% plastics), the net gain is about 10 gCO_2e/km (or -4%) for a reduction of 200 kg in mass. **Figure 7** below illustrates this second case, clearly distinguishing between increased manufacturing emissions and reduced usage emissions.

Thus, even if their production is CO_2-intensive, the materials that are lighter than steel are more favourable in the overall reduction of emissions for the ICEVs.

Photo credit: website Le Point.

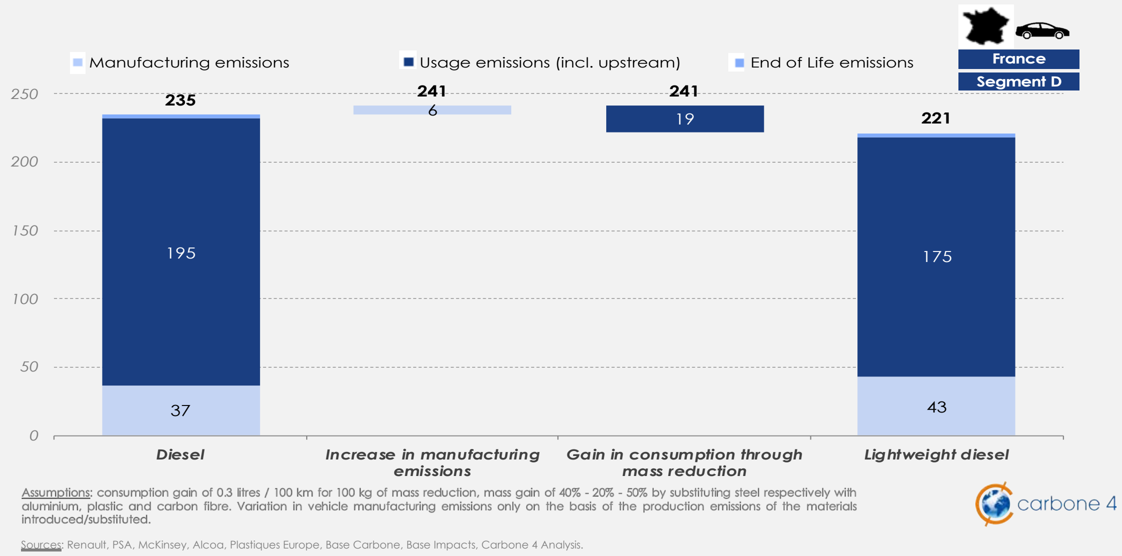

Figure 7 - The effect of reducing the mass by 200 kg of steel to 50% aluminium and 50% plastic on the average carbon footprint of a diesel vehicle sold in 2020 France - Segment D | gCO_2e/km

For BEVs, the conclusion is different, at least in France (and by extension for all countries where the electricity mix is low carbon, and de facto the emissions of use). **Figure 8** below thus shows that **manufacturing emissions are much higher than the gain obtained by the mass reduction of usage emissions.** The benefits of mass reduction are the same from a physical point of view, but as the in-use emissions are only 9 gCO_2/km (compared to 197 gCO_2/km for ICEVs running on diesel), it is not possible to achieve more than about 1 gCO_2/km gain. It should be noted that the mix of substitute materials (50% aluminium and 50% plastic) is not however the most emissive to produce in this example. In the end, in France, the BEV emissions (segment D) increase in this case by about 5 gCO_2e/km (i.e. +6%).

Hence, introducing lighter materials in BEVs can lead to an increase in life cycle emissions in France, contrary to ICEVs. In conclusion, the strategy of reducing the BEVs' weight is still relevant, but should preferably be achieved through lighter batteries, lighter design (less materials) and the increased use of recycled materials whose manufacturing carbon footprint can be significantly lower.

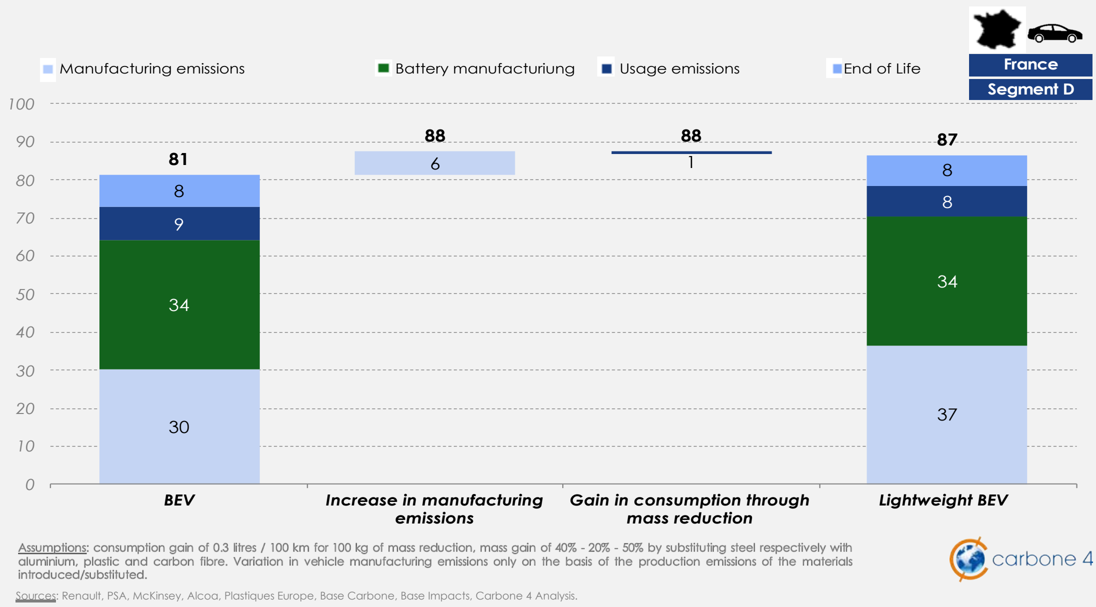

Figure 8 - The effect of reducing the mass of 200 kg of steel to 50% aluminium and 50% plastic on the average carbon footprint of an electric vehicle sold in 2020 France - Segment D | gCO_2e/km

2 Commercial vehicles

Things to remember

The commercial vehicles with the lowest lifecycle carbon footprint are:

✓ **Vehicles running on bioNGV**

The very low carbon footprint is due to the assumption that gas vehicles would be developed with mild hybridisation (as with conventional combustion vehicles). Moreover, the emission factor of biomethane varies little according to the country of production.

✓ **Battery-powered electric vehicles, whatever the electricity mix** of the region in question.

A decarbonised mix (France, renewable electricity) provides the best performance, but even a BEV sold today in Germany or even Poland remains less emissive than a comparable ICEV.

✓ **Electric vehicles using hydrogen produced by electrolysis or biomethane steam reforming, with decarbonised electricity** (French grid or renewable electricity)

The FCEV's carbon footprint depends very strongly on the electricity mix, with performances similar to the BEV using decarbonised electricity, and similar or even superior to the ICEV in the opposite case.

The prospective vision for 2030 reduces the differences in emissions between motor vehicles, without changing the conclusions already visible in 2020.

✓ *Mild hybridisation makes it possible to make up for part of the gap with BEVs, the latter improving more slowly due to the increase in battery capacity, which counteracts the drop in the electricity EF (except for buses).*

✓ *For hydrogen vehicles, the decarbonisation of the European electricity grid is not sufficient to match the CO_2 performance of the BEV or the ICEV running on bioNGV.*

For **buses operating in urban areas**, BEVs and FCEVs are to be preferred **thanks to the significant energy recovery** during frequent braking and the absence of **fine particle emissions** (exhaust).

Conversely, **biogas is the only truly decarbonising technological solution available to date for semi-trailer trucks**, pending the arrival of "zero emission" solutions. However, the massive deployment of gas vehicles may lead to **the fleet being locked** into this energy carrier, with the use of fossil gas **if the biomethane resource is not available in sufficient quantities**, which seems to be the case (see Focus on specific energy carriers).

Light Commercial Vehicles

LCV Motor Vehicle Type	Time-Invariant: Weight	Time-Invariant: Service life	Varying over time	2020	2030
ICEV Diesel	1,830 kg	200,000 km 12 years old	Real consumption (MHEV)	10.2 L/100 km	7.6 L/100 km
			Biodiesel share*	6%	8%
ICEV NGV	1,960 kg *of which tank: 180 kg*	200,000 km 12 years old	Real console (MHEV)	8.5 kg/100 km	6.3 kg/100 km
			BioNGV share*	5%	11%
BEV	1,943 kg *of which battery: 313 kg*	200,000 km 12 years old	Real consumption	31 kWh/100 km	29 kWh/100 km
			Battery capacity	50 kWh	75 kWh
FCEV	1,833 kg *of which battery+tank: 173 kg*	200,000 km 12 years old	Real consumption	2.0 kg/100 km	1.8 kg/100 km
			Tank size	5.4 kgH_2	= 5.4 kgH_2

*The share of biodiesel (by volume) and bioNGV is averaged over the lifetime of the vehicle.

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Table 6 - Main assumptions specific to light commercial vehicles

Light commercial vehicles are characterised by higher energy consumption than passenger vehicles, but also generally have a lower range requirement in general. This explains **an even greater reduction in the carbon footprint than for passenger vehicles, by a factor of 3 to 4,** between an ICEV running on diesel or CNG, and a BEV or an ICEV running on bio-CNG, in France in 2020.

It should be noted that **the carbon performance of the BEV is slightly better than that of the bio-CNG vehicle** (see **Figure 9**) because the battery is relatively small (allowing only a range of around 160 km), which **reduces the carbon weight of the vehicle's manufacture.** In both cases, emissions remain very low in France. On the other hand, with the increase in the size of batteries on the one hand and the mild hybridisation of ICEVs on the other, the footprint of the biomethane vehicle decreases over time while that of the BEV remains stable, reversing the hierarchy in 2030, with the two engines remaining comparable from a carbon point of view (see **Figure 10**).

The FCEV, although it reduces the carbon footprint by a factor of 2 to 3 compared to fossil fuel vehicles, remains 50% more emissive than the BEV and the ICEV running on bioCNG in 2020, if hydrogen is produced with grid electricity. This difference reduces in 2030 but remains present.

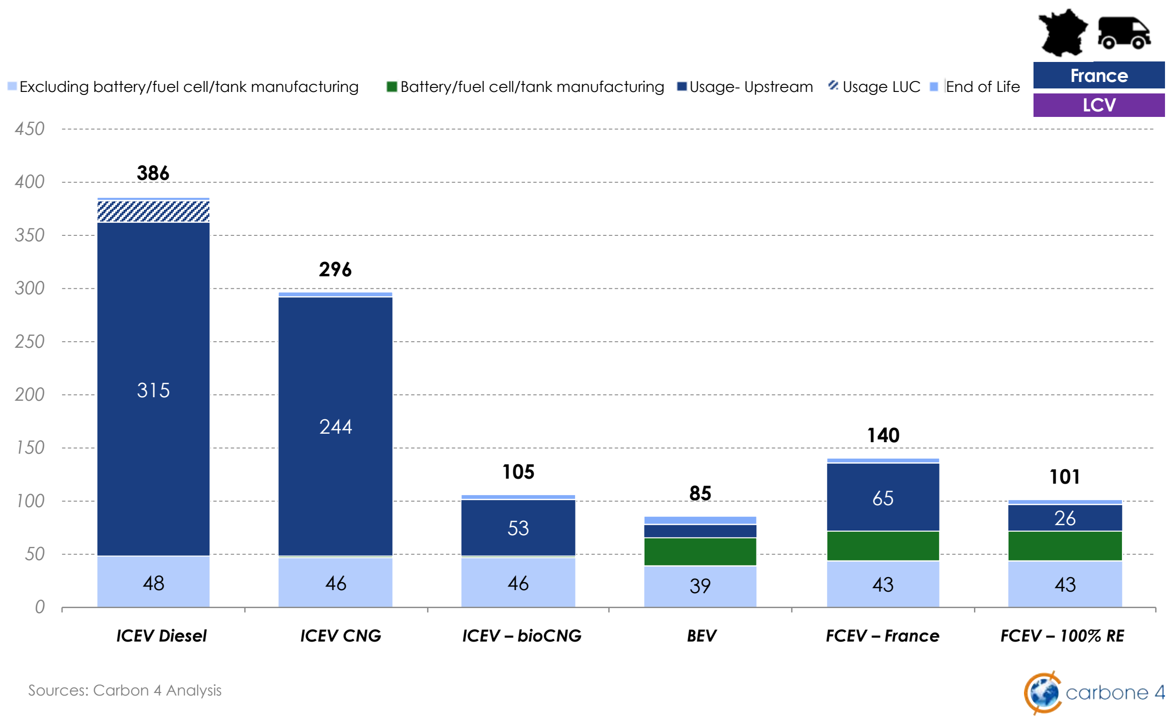

Figure 9 - Average carbon footprint over the lifetime of an LCV sold in 2020
France | gCO_2e/km

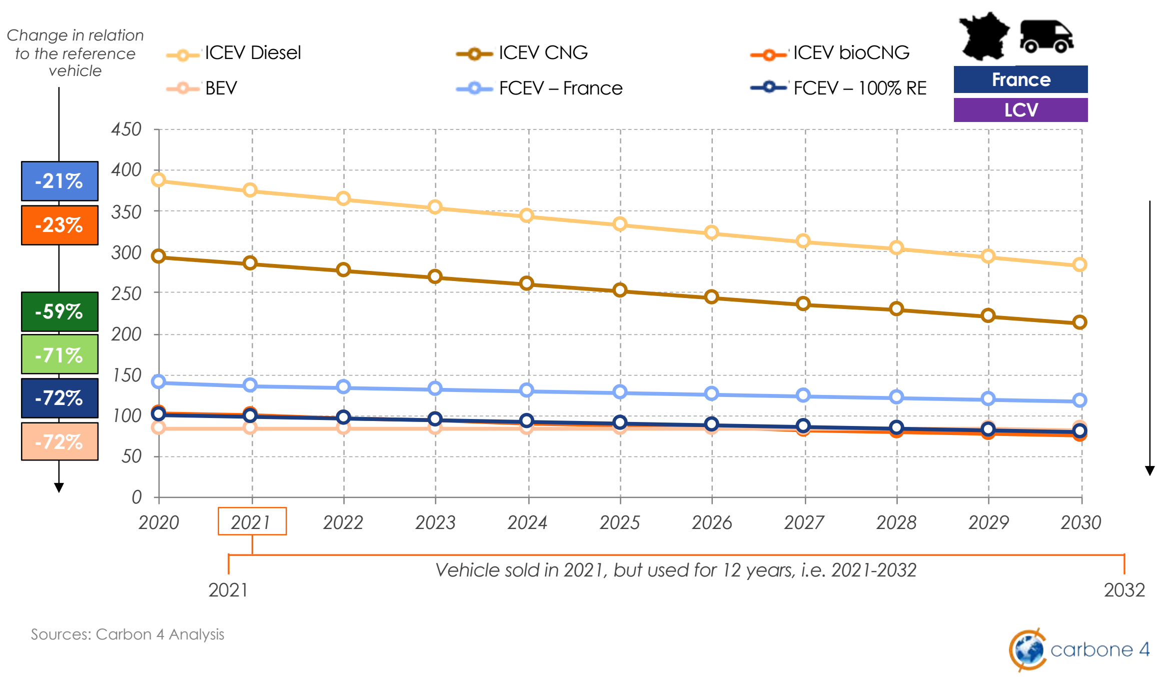

Figure 10 - Average carbon footprint over the lifetime of the vintage under consideration
France - Light commercial vehicle | gCO_2e/km

Looking at the **European Union (Figure 11),** the electricity emissions factor has a rather significant influence on the carbon performance of BEVs and FCEVs. For the BEV, the performances are slightly degraded compared to the French case and are **50% higher**, or even 100% in Germany, **than those of the ICEV running on bioCNG**. However, this is still **much lower than for ICEVS** running on diesel or CNG.

On the other hand, **the carbon footprint of the FCEV explodes with the electrolysis made from the average European electricity mix** (around 300 gCO_2e/kWh in 2020), and it then becomes more emissive than an ICEV, even considering the strong decarbonisation of the European or German mix by 2030. Only the **steam-reforming of biomethane or electrolysis with 100% RE electricity** can in this case achieve a real decarbonisation of the FCEV.

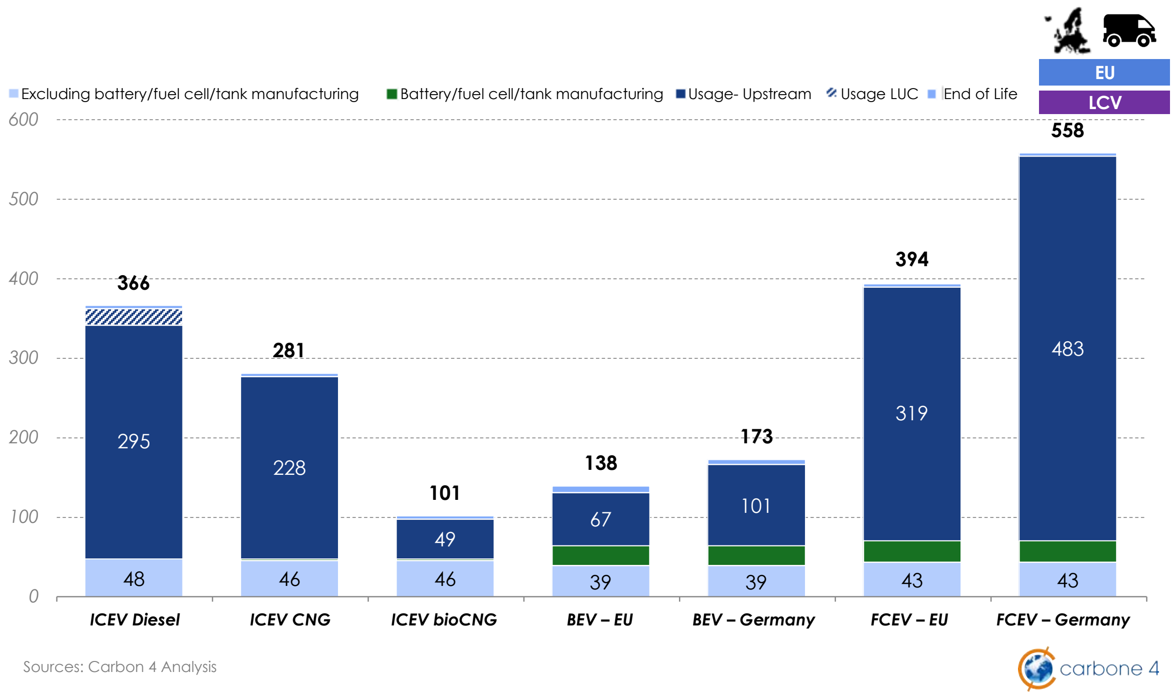

Figure 11 - Average carbon footprint over the lifetime of an LCV sold in 2020 Europe | gCO_2e/km

Bus

Bus *Motor Vehicle Type*	*Time-Invariant*		*Varying over time*	*2020*	*2030*
	Weight	Service life			
ICEV Diesel	10,800 kg	480,000 km 12 years old	Real consumption	43 L/100 km	40 L/100 km
			Biodiesel share*	6%	8%
ICEV CNG	11,650 kg *of which tank: 950 kg*	480,000 km 12 years old	Real consumption	37 kg/100 km	34 kg/100 km
			BioNGV share*	5%	11%
BEV	12,250 kg *of which battery: 2,000 kg*	480,000 km 12 years old	Real consumption	130 kWh/100 km	124 kWh/100 km
			Battery capacity	320 kWh	= 320 kWh
FCEV	11,050 kg *of which battery+tank: 700 kg*	480,000 km 12 years old	Real consumption	8.3 kg/100 km	7.5 kg/100 km
			Tank size	28 kgH_2	25 kgH_2

*The share of biodiesel (by volume) and bioNGV is averaged over the lifetime of the vehicle.

Table 7 - The main assumptions that are specific to buses

In the case of buses, the key specific elements include the **intensive use** (40,000 km/year, i.e. 2 to 3 times more than passenger cars), **a moderate average daily distance** (around 150 km, which limits the size of the batteries and tanks), and a relatively low average speed with **a lot of acceleration and braking, which favours the electric engines (BEV and FCEV)** allowing for energy recovery during deceleration.

Thus, **in France, Figure 12 clearly illustrates that the best vehicle type is undoubtedly the battery-electric bus, or the bus powered by 100% renewable hydrogen**, benefiting from the large share of the use phase compared with that of the manufacturing of the specific equipment phase (batteries, fuel cells, tanks), relative to passenger cas or LCVs. For a bus running on hydrogen produced with grid electricity, **the carbon weight translates into an overall footprint that is 80% greater than that of the battery-electric bus** (438 gCO_2e/km compared to 244), and slightly greater than that of the bio-NGV vehicle. Nevertheless, **all these motorisations are still 3 to 4 times less emitting than diesel or NGV buses,** which have very high emissions linked to their use phase. The difference is even of the order of 1000 gCO_2e/km between a battery-electric bus and a diesel/NGV bus, which is far from negligible.

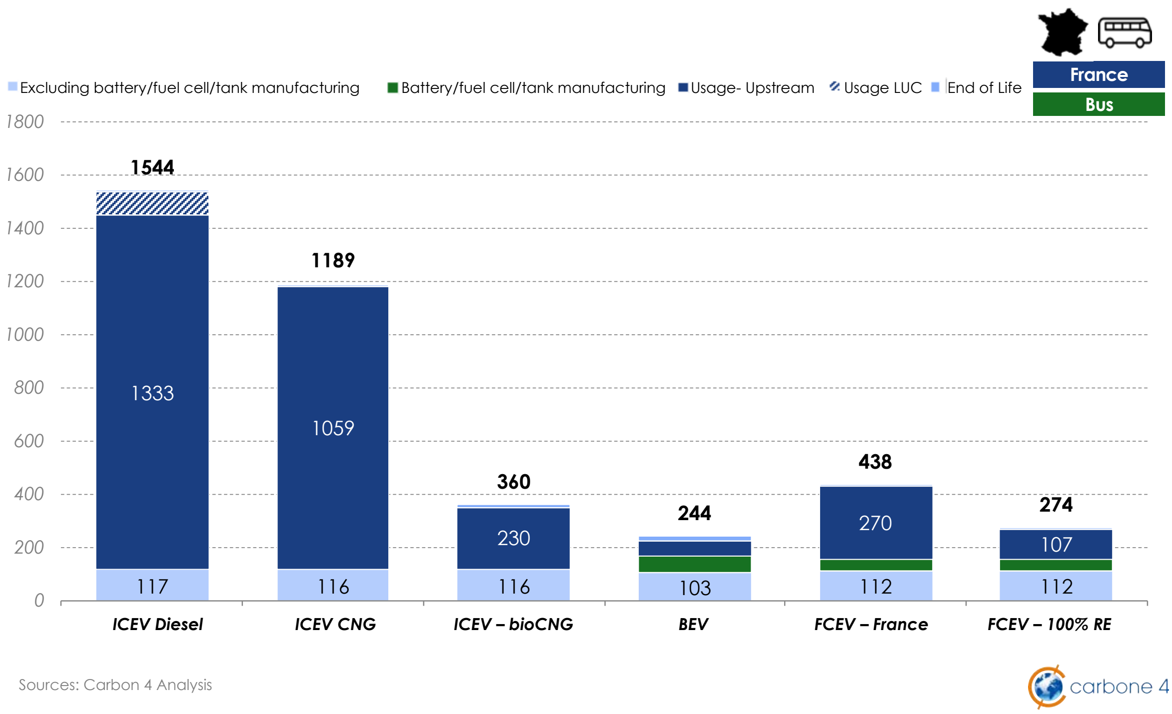

Figure 12 - Average carbon footprint over the life of a bus sold in 2020
France | gCO_2e/km

Furthermore, as shown in **Figure 13**, we should not count on the future mild hybridisation of ICEVs to modify the hierarchy by 2030, because although it will allow a slight reduction in the gaps, it will change neither the ranking of vehicles nor the orders of magnitude.

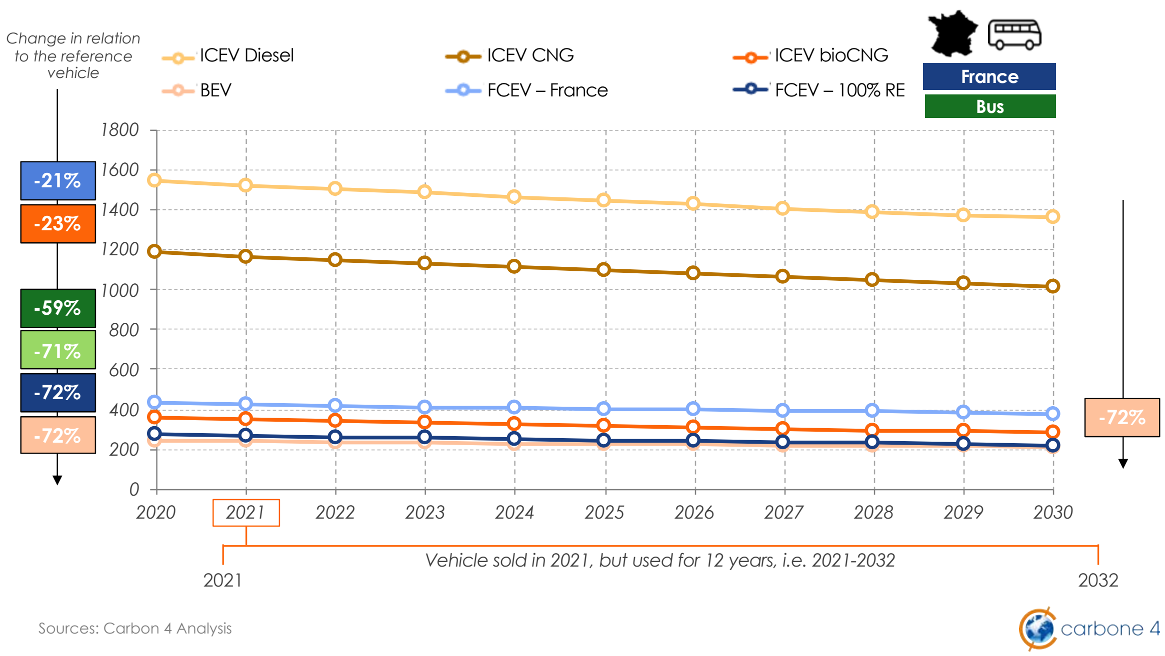

Figure 13 - Average carbon footprint over the lifetime of the vintage under consideration
France - Bus | gCO_2e/km

At the **European Union level, the share of use is increasing for battery-electric buses** with the more carbon-intensive electricity (factor 6 compared to French grid electricity). They are therefore **more emitting than ICE buses running on bioCNG (+25%), but still 3 to 4 times less emissive than diesel or CNG buses** (see **Figure 14**).

Finally, FCEVs using **hydrogen produced by electrolysis from the average European electricity mix** is once again proving to be **irrelevant from a carbon point of view**, with a footprint **similar or even greater than that of conventional ICE buses**. Only the production of hydrogen from biomethane steam reforming or electrolysis with 100% RE electricity is a viable solution for making this engine low carbon.

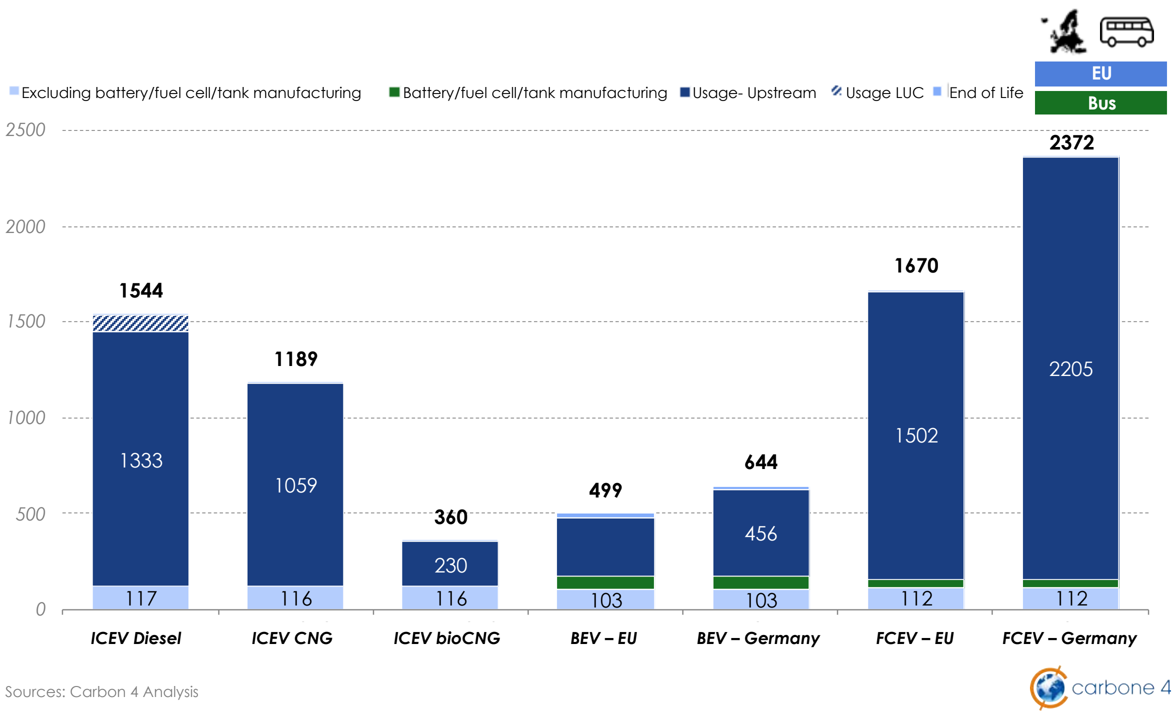

Figure 14 - Average carbon footprint over the life of a bus sold in 2020
Europe | gCO_2e/km

Semi-trailer trucks

Semi-trailer truck Motor Vehicle Type	Time-Invariant		Varying over time	2020	2030
	Weight	Service life			
ICEV Diesel	7,100 kg	1,200,000 km 12 years old	Real consumption (MHEV)	33 L/100 km	28 L/100 km
			Biodiesel share*	6%	8%
ICEV CNG	7,700 kg *of which tank: 750 kg*	1,200,000 km 12 years old	Real consumption (MHEV)	29 kg/100 km	25 kg/100 km
			BioCNG share*	5%	11%
ICEV LNG	7,179 kg *of which tank: 229 kg*	1,200,000 km 12 years old	Real consumption (MHEV)	29 kg/100 km	25 kg/100 km
			BioLNG share*	5%	11%
BEV	10,900 kg *of which battery: 4,500 kg*	1,200,000 km 12 years old	Real consumption	135 kWh/100 km	128 kWh/100 km
			Battery capacity	720 kWh	1,000 kWh
FCEV	9,175 kg *of which battery+tank: 2,675 kg*	1,200,000 km 12 years old	Real consumption	8.6 kg/100 km	7.8 kg/100 km
			Tank size	45 kgH_2	60 kgH_2
PHEV	7,838 kg *of which battery: 438 kg*	1,200,000 km 12 years old	*Actual consumption identical to those of MHEV and BEV*		
			Battery capacity	70 kWh 10% km elec	70 kWh 10% km elec

*The share of biodiesel (by volume) and bioCNG/bioLNG is averaged over the lifetime of the vehicle.

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Table 8 - The main assumptions specific to semi-trailer trucks

Because of the need for **long-range autonomy** for semi-trailer trucks, battery electric versions are **not yet available** for these types of vehicles[6]. For other reasons, **hydrogen versions are slow to emerge,** even if some manufacturers (Nikola and Hyundai) have announced their first models. **However**, taking into account the **very high annual mileage** of road tractors (100,000 km/year in our model), **they are expected to provide very strong decarbonising solution**s because they are all the more advantageous when **used intensively** (e.g. the carbon weight of the equipment - battery/ fuel cell / tank - being therefore very quickly amortised, see § on buses).

Thus, if we place ourselves **in France 2030[7], the battery-electric semi-trailer truck and its bioNGV counterpart have a carbon footprint 6 times lower than that of the diesel vehicle**, taking into account the mild hybridisation of ICEVs. **The hydrogen-powered truck is also a less emissive solution** if hydrogen is produced by electrolysis with renewable electricity, the footprint is as small as that of the BEV; with grid electricity, the footprint remains small although it is twice as large as that of the BEV and ICE-V running on bioNGV.

On the other hand, we can observe that the PHEV does not bring any real CO_2 savings, as the electric part only concerns 10% of the use (in urban areas, for reasons of local pollution). Also, trucks running on fossil NGV have a relatively small carbon footprint reduction compared to diesel vehicles. Especially when considering LNG, the gains brought by gas are partly offset by gas liquefaction operations, which reduce the energy efficiency of the vehicle from well to wheel.

6. Only prototypes (at best early series) are being rolled out at the time of writing.
7. We then make the assumptions that battery and hydrogen offers will exist.

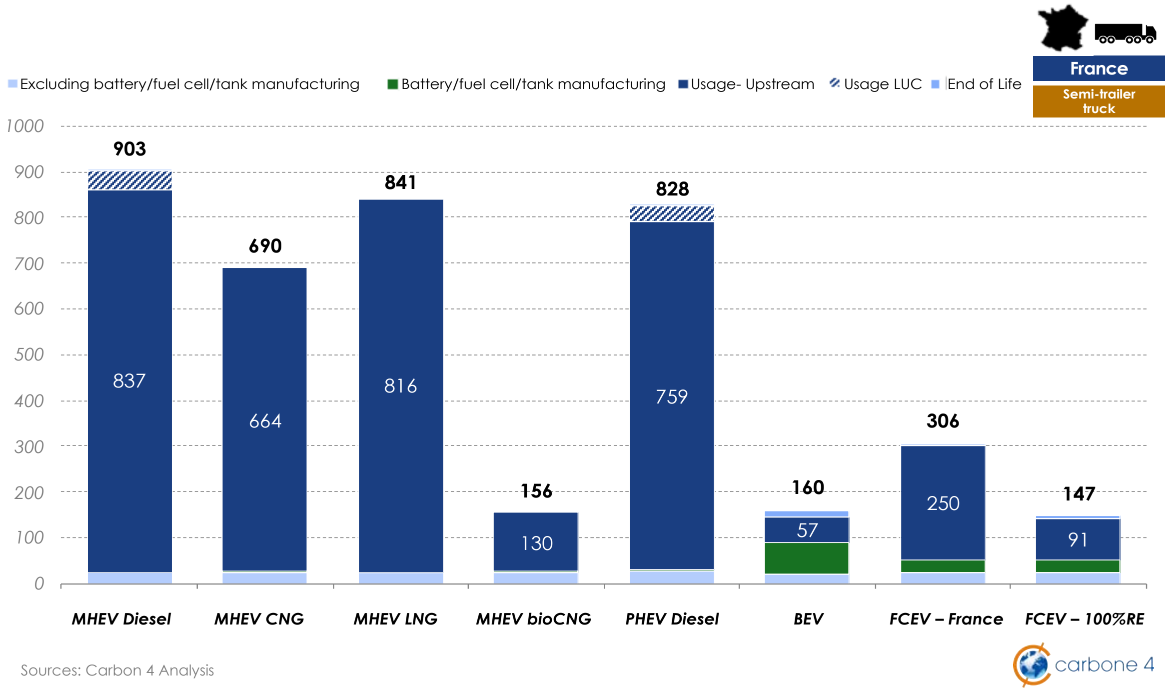


Figure 15 - Average carbon footprint over the lifetime of a semi-trailer truck sold in 2030 in France | gCO_2e/km

With the European prism summarised in Figure 16, the carbon footprint of the electric semi-trailer truck is doubled, while remaining 3 times smaller than that of the diesel and therefore significantly advantageous, just like the ICE truck running on bioNGV. On the other hand, **the semi-trailer truck running on H_2 produced by electrolysis with the European electric mix has a higher carbon footprint than the conventional ICEV**. Thus, when grid electricity is not low carbon enough, hydrogen **must be produced either by biomethane steam reforming or by electrolysis of 100% RE electricity.**

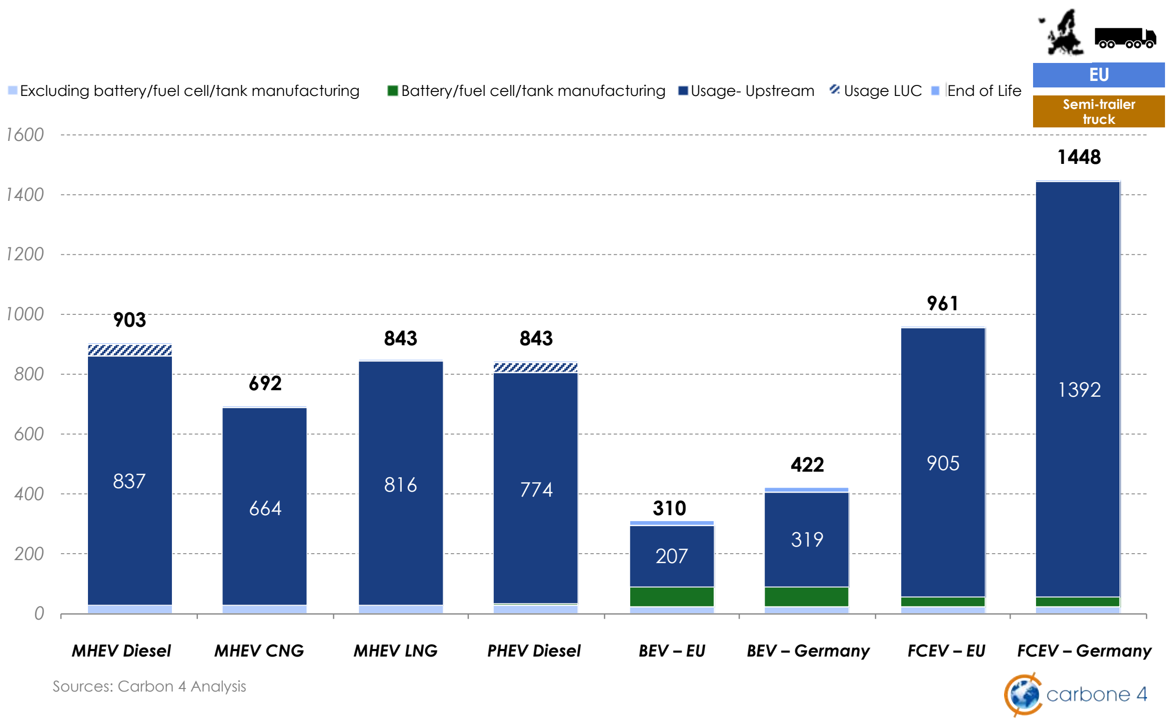
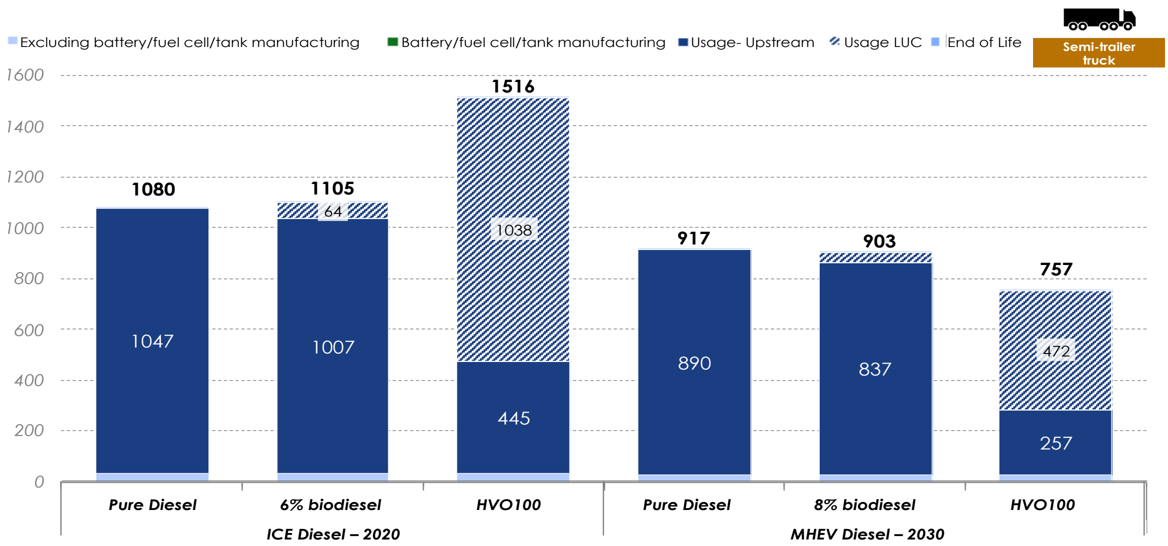


Figure 16 - Average carbon footprint over the lifetime of a semi-trailer truck sold in 2030 in Europe | gCO_2e/km

3 A focus on specific energy carriers

A focus on biofuels



Sources: Carbon 4 Analysis

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Figure 17 - Comparison of the average carbon footprint over the lifetime of a semi-trailer truck sold in 2020 and 2030 | gCO_2e/km

Liquid biofuels allow only modest decarbonisation, because on the one hand their incorporation rate is relatively low (~5% of the energy share in Europe in 2020, estimated at around ~10% in 2035), and on the other hand the carbon footprint of some agrofuels is similar or even higher than that of fossil fuels, considering changes in land use[8].

Thus, **for biodiesel in 2030**, even assuming an 8%[9] incorporation of the volume and a change in the input mix in biodiesel production[10] (elimination of palm oil, which accounts for 25% of biodiesel consumption in Europe in 2019), **the carbon footprint is barely improved.**

8. Direct and indirect land-use changes taken into account in the study, contrary to European regulations to date.
9. Incorporation rates here refer to physical volume, and comply with RED II regulatory guidelines.
10. The input mixes considered are 50% rapeseed, 25% soybean, and 25% palm in 2020; 70% rapeseed and 30% advanced fuels (used cooking oil and other waste / residues) in 2030.

When using pure biofuels (HVO100[11]), the footprint is reduced by only 20% (including land-use change); while the large-scale deployment of 100% liquid biofuels raises the question of adapting engines and, above all, of the potential of the reserves. All these conclusions are clearly visible in **Figure 17**.

Similarly, bioethanol only slightly decarbonises petrol vehicles (not shown in **Figure 17)**. The emission factors are similar to those of petrol, except for beet and advanced biofuels based on wheat straw, but they are still relatively unavailable. There again, only a massive use of bioethanol, with E85 for example, would allow a significant reduction in the carbon footprint (about -20% to -25%), and this reduction in emissions remains low compared to electric engines or ICE using biogas, and should also be compared with the availability of the resource and its competition with food production and other sectors (e.g. aeronautics).

Land use changes

For biofuels, combustion emissions are conventionally considered to be zero, because during its growth, the plant absorbs CO_2 that will be released during combustion. This is the natural short carbon cycle. **GHG emissions from biofuels are therefore upstream of use** (cultivation, harvesting, processing, delivery to the pump) as well as land-use changes. For example, the production of agrofuels may require deforestation of land (direct land-use change) or may replace food production that will be moved to uncultivated areas (indirect land-use change).

Emissions from indirect land-use change are **very difficult to estimate**, as it requires a systemic view of the agricultural situation in a region and a good allocation of emissions at each stage of the production cycle. However, it is certain that they are not zero and therefore cannot be neglected. For example, they are **very high for palm oil** because of the deforestation of primary forests and the destruction of peat bogs in Indonesia and Malaysia (85% of world production), as well as **for soy** because of Amazon deforestation in Brazil and land clearance in Argentina. This explains why the EFs of palm oil and soy are **2 to 3 times higher[12] than those of fossil diese**l (including combustion)!

There is still considerable uncertainty about the absolute level of emissions from land-use change. The emission factors thus vary enormously depending on the case under consideration: age of plantation (deforestation already 'amortised' or not), type of soil (mineral, peat), amortisation period of the carbon released (between 20 and 30 years). Nevertheless, the estimation of these emissions in order of magnitude makes it possible to **properly take into account the climate impact of the production of these crops** (albeit with hindsight) and shows that the potential for decarbonisation **varies greatly according to the type of input** (palm, rapeseed, sunflower, etc.).

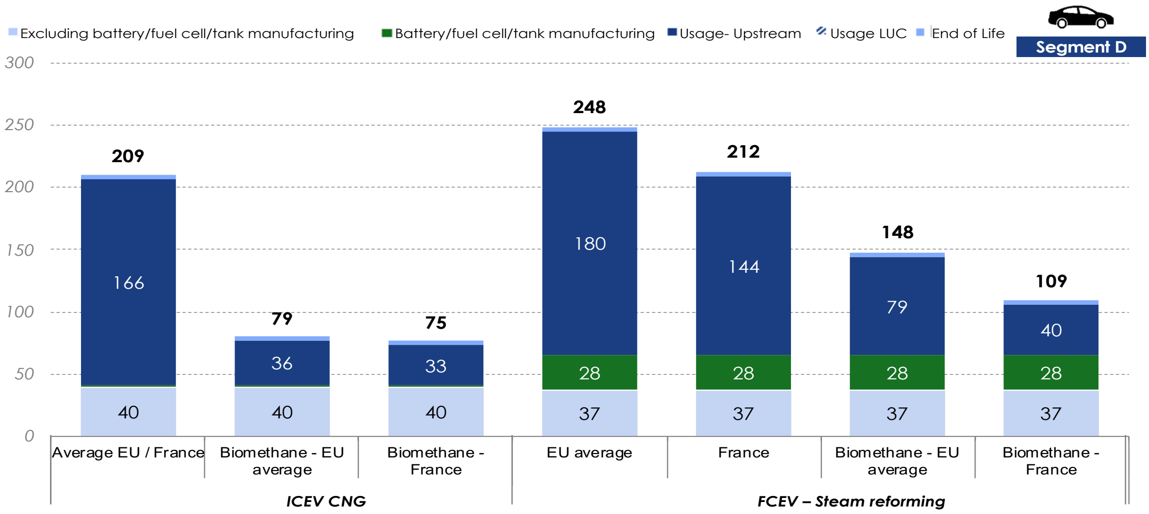
With the arrival of **advanced biofuels** (from agricultural or forestry residues and waste), **land-use change is no longer an issue**, although there is already competition for uses of these new resources (liquid biofuels, biogas, renewable heat production, etc.).

11. Same composition of inputs as in the case of an incorporation rate of 6%/8% respectively.
12. Globiom (2015), ICCT (source: GREET 2018, Valin et al. 2015).

A focus on biomethane

The distinguishing feature of this energy carrier is that its use can be envisaged in two different ways in mobility: either as a gaseous fuel that can be burned in a combustion engine, **or as a primary energy source that can be transformed into hydrogen** by steam reforming. So, what is the comparative assessment of these different ways of use, in terms of the life-cycle carbon footprint?

We use the example of segment D in 2020 and the semi-trailer truck in 2030 to illustrate our point. **Figures 18 and 19** below allow us to draw some clear lessons.



For an ICEV running on CNG from network (4% biomethane), the carbon footprint is almost identical for the EU and France (variation <1gCO2e/100km due to the slight difference in the biomethane emission factor).

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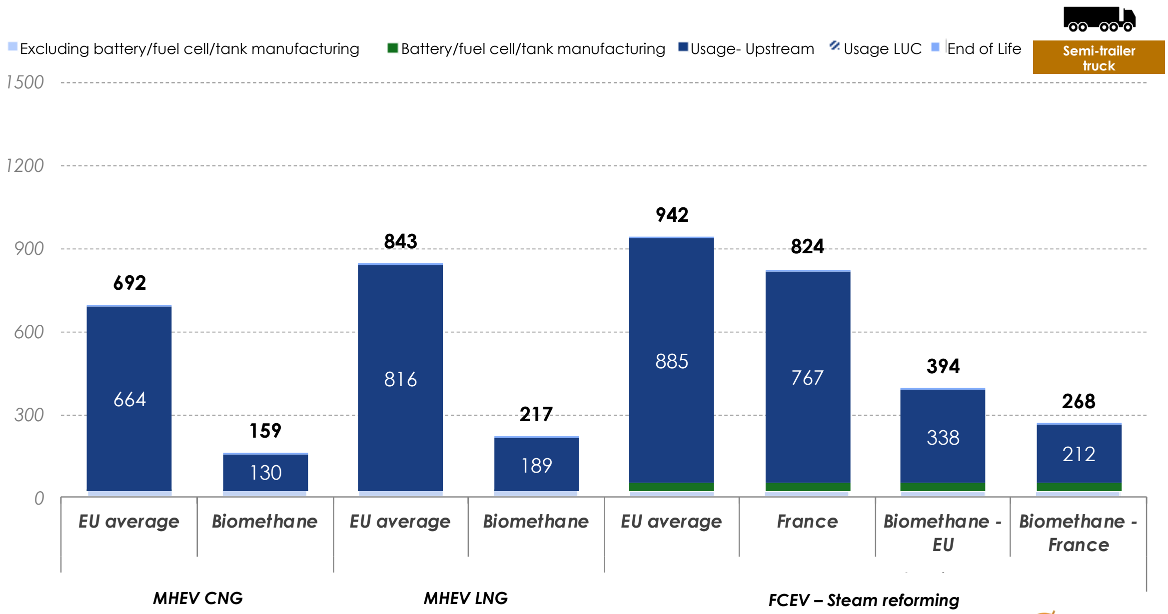
Figure 18 - A comparison of the average carbon footprint over the lifetime of a D-segment vehicle sold in 2020 in France and Europe | gCO_2e/km



Sources: Carbon 4 Analysis

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Figure 19 - A comparison of the average carbon footprint over the lifetime of a semi-trailer truck sold in 2030, in France and in Europe | gCO_2e/km

Let's start with fossil natural gas: this solution is not at all up to the task of decarbonising transport, and does not stand up to the comparison with biomethane, wherever it is and whatever the chosen energy route. For the record, it should be noted that natural gas steam reforming in France has a carbon performance similar to a vehicle running on NGV (network gas, including a portion of biomethane[13]). But at European level, it is better to use natural gas directly in an internal combustion engine (in the form of NGV) than to produce hydrogen which would then be used to power a FCEV: the emissions are about 20% higher in the latter case.

As far as the biomethane sector is concerned, the calculations reveal two strong conclusions:

1. **in France or in the EU, bioNGV used in an ICEV is the least emissive solution in terms of its life-cycle,**

2. the steam reforming of biomethane to produce hydrogen does not allow the same level of carbon performance to be obtained, even in France where usage emissions are lower than in the EU (40 gCO_2e/km in France compared to 79 gCO_2e/km in the EU for a segment D vehicle) due to the low EF of the electricity for the compression stage. This solution is mainly penalised by the manufacturing emissions of the specific equipment of the FCEV, i.e. the fuel cell and tank, which are non-existent in the case of the ICEV running on bioNGV, although their manufacturing footprint decreases by 30% between 2020 and 2030 in our scenario, for segment D, the LCV and the bus (stable for the truck).

Are there avoided emissions in the biomethane EF?

In this study, we have only considered the induced emissions during the energy life cycle, and not the avoided emissions where applicable. Thus, we used an EF for bioCNG in France of 45.1 gCO_2e/kWh[14] (i.e. -80% compared to fossil CNG).

Although **carbon accounting norms and standards (such as the ISO or the GHG Protocol) clearly prohibit adding avoided emissions to emission reductions**, some actors aggregate induced and avoided emissions, so that the EFs shown may become very low or even negative. However, the concept of avoided emissions is far removed from induced emissions: in the first case, it is simply defined as the conventional difference in emissions between two hypothetical situations, possibly spread over time, whereas in the second case, it is the instantaneous emissions that actually end up in the atmosphere at instant T. For the latter, the impact on climate change is direct and proven. In the case of avoided emissions, the expected climate benefit remains arbitrary and uncertain. International standards propose methods for evaluating these avoided emissions, depending on the type of project in particular, in order to make them as robust as possible.

In order not to compare apples and oranges, our approach is to compare the energies between them on the basis of induced emissions only, as this is the most

13. Incidentally, an FCEV running on H_2 produced by steam reforming in France is globally less emissive in 2020 than a conventional (petrol or diesel) ICEV.
14. Source: Quantis and GRDF, March 2020, "EVALUATION OF THE GHG IMPACTS OF THE PRODUCTION AND INJECTION OF BIOMETHANE IN THE NATURAL GAS NETWORK - SYNTHETIC REPORT".

indisputable metric. However, avoided emissions when demonstrated with a sufficient level of rigour can be assessed, but separately and not in an aggregated manner with induced emissions.

In the case of biomethane, the methanisation production process has co-benefits that result in avoided emissions at the level of the waste treatment system (by avoiding, for example, methane leakage or the production of mineral fertilisers), or at the agricultural system level (by replacing chemical fertilisers with digestate). These avoided emissions, although they may be convetional, reflect with a good level of confidence for the situation on the ground. However, a transport operator using French bioNGV cannot claim the avoided emissions due to methanisation in the French agricultural system, even if they are real and contribute to the significant benefits of this agricultural practice.

To sum up, in a holistic vision of the fight against climate change, **the avoided emissions in the other sectors are a co-benefit that is not applicable to the emission factor of a given energy**, but which can be fully **valued as a contribution to the decarbonisation** of the other sectors (cf. the Net Zero Initiative[15] reference framework). In or words, the climate virtues of biomethane production cannot all be transferred to the exhaust but can be fully captured in the differentiated accounting approach, represented schematically in **Figure 20** below.

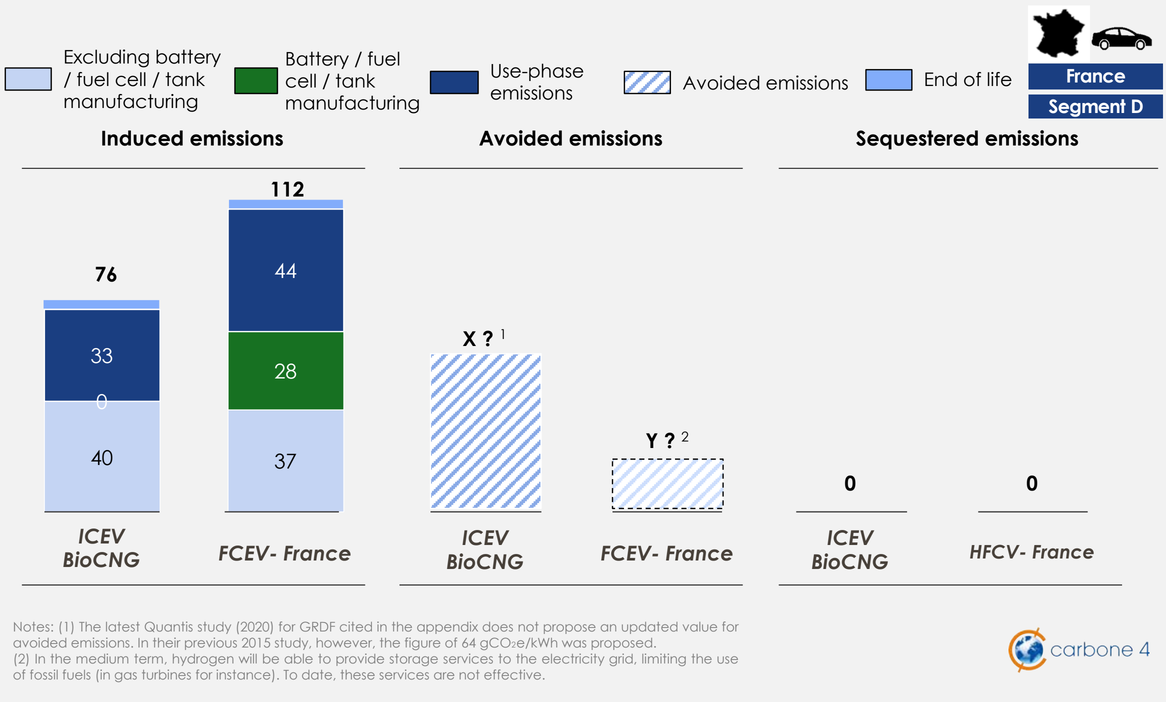

Figure 20 - The Net Zero Initiative dashboard to visualise the induced, avoided and sequestered emissions - Segment D sold in 2020, in France | gCO_2e/km

15. The **Net Zero Initiative's dashboard** makes it possible to **view** and **value** separately the **induced**, **avoided** and **sequestered** emissions. Carbone 4 recommends using this representation in order to **communicate the information effectively, accurately and transparently**.

A focus on hydrogen (and "zero emissions")

The case of hydrogen used in an FCEV is the most complex, as it can be produced in two different ways, and in countries with different electricity characteristics. In addition, like the BEV, the FCEV uses an electric motor. Therefore, we think it is useful to focus here on the FCEV, in order to identify the main lessons learned from the hydrogen as an anergy carrier.

Figures 21 and 22 below give a broad overview of the situation in 2020 for segment D for the so-called "zero emissions" (exhaust) and buses, i.e. BEV and FCEV.

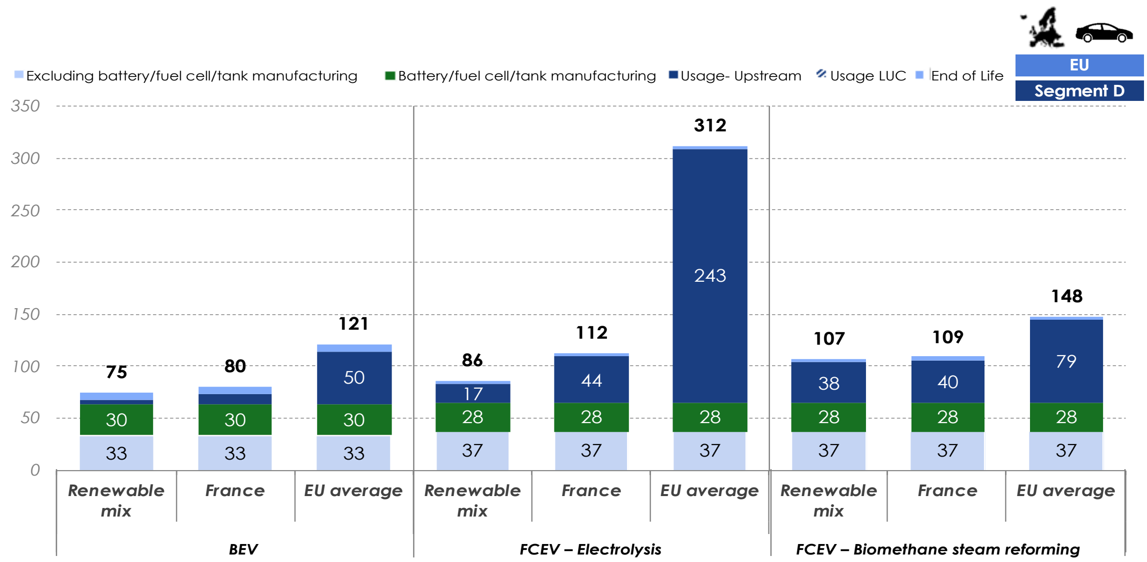

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Figure 21 - A comparison of the average carbon footprint over the lifetime of a segment D vehicle sold in 2020 in France and Europe | gCO_2e/km

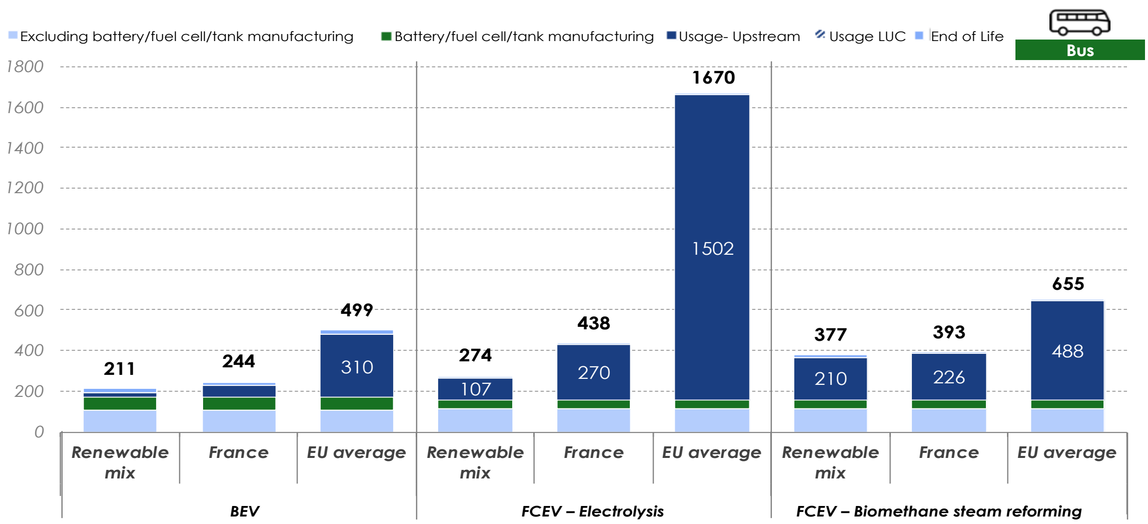

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Figure 22 - A comparison of the average carbon footprint over the lifetime of a bus sold in 2020, in France and in Europe | gCO_2e/km

In France, electrolysis and biomethane steam-reforming lead to equivalent carbon footprints for the FCEV, close to those of the BEV, even if they are slightly larger (around 110 gCO_2e/km compared with 80 for a segment D vehicle).

Outside France, the FCEV solution is only relevant if the electricity used for electrolysis is low carbon (for example, from a renewable mix). **Producing hydrogen from the average EU electricity mix is to be banned** as it leads to higher life-cycle emissions than conventional ICEVs. In this case, it is better to produce hydrogen by biomethane steam reforming, which leads to an FCEV close to the BEV in terms of carbon performance. Let us not forget, however, as we have shown above, that the most rational use of biomethane, according to the sole criterion of CO_2 emissions, is to burn it in the form of bioNGV in a combustion engine. We will come back later on to the other considerations that may come into play in the choice of technical solutions, over and above the carbon criterion.

Concerning "zero emissions" vehicles as a whole, although the average European electricity mix disqualifies electrolysis and fossil natural gas steam-reforming remains highly emitting, the other possibilities, i.e. **biomethane steam-reforming, low-carbon electrolysis and battery technology are all real solutions**. They make it possible to divide the carbon footprint by 2 or even 3 compared to a diesel vehicle, and up to 6 in the case of an electric bus running on the French electricity mix or renewable energies, making it a truly decarbonising solution.

As we will develop in a later chapter (5), **these "zero emissions" vehicles also have the added advantages of significantly reducing noise pollution and producing neither NOx nor exhaust particles[16].** These are features that are highly valued in densely populated areas, making "zero emissions" technologies all the more preferable solutions for vehicles that have to circulate regularly in urban areas.

16. Particles are, however, produced by brake abrasion, tyre wear and potentially during electricity generation and steam-reforming.

4 Alternative Scenarios

Approach

The central scenario for the evolution of the assumptions is the one that we have judged to be the most plausible, given the sources gathered for this work. This is why all the results commented on above fall within the framework of this scenario.

However, **it seems useful to us, in order to shed light on the future trends, to describe other possible scenarios, although they are less aligned with the trends observed**. Naturally, these scenarios may seem unrealistic to some, but we have ensured that they are not based on any technological breakthrough. As a result, their level of realism is matched only by the ability of regulators, industry and users to modify current trends by making decisions within their reach.

This approach also makes it possible to answer certain recurring questions, in order to feed the debate on the evolution of technologies, regulations and behaviours. Thus, we have constructed the following two alternative scenarios for private vehicles:

- ✓ **n°1: the "thermal-friendly" scenario**, to push the possibilities of ICEs into their their retrenchments, while being more conservative about the climate benefits of BEVs. To do this, the incorporation rates of advanced liquid biofuels are increased, the overall energy efficiency of the vehicle is increased, and its weight is slightly reduced. In addition, the progressive decarbonisation of the electricity mix is slower than in the central scenario and the race to increase battery capacity is amplified. **This scenario thus makes it possible to check whether a reversal of hierarchy can take place between ultra-efficient ICEVs and less efficient BEVs.** And if so, under what conditions.

- ✓ **n°2: "sobriety" scenario**, in order to measure **what emission reductions can be expected from tomorrow's road vehicles** (whatever their energy), **assuming that sobriety practices are put in place, from design to use**. This in a context where the transport sector must aim for almost complete decarbonisation by 2050, in France and in Europe. In order to achieve this, the average mass of vehicles has been reduced to that of the early 2000s (i.e. around -25%, through gains in the design itself and thanks to substitution of lighter materials), the capacity of batteries has been slightly reduced, in order to maintain the BEVs autonomy constant (thanks to the improvement in vehicle performance) and the life of the vehicles has been extended.

The associated sets of assumptions are summarised in **Table 9** below, indicating how they deviate from the central scenario (by default, anything not shown in this table is considered invariant compared to the central scenario).

				Variants	
Category		Parameter	Central scenario	Thermal-friendly	Sobriety
Energies	Electricity	**Network EF**	Normal scenario	Conservative scenario (-20% compared to the decarbonation targets of the national plans)	No changes vs. central scenario
	Liquid biofuels	**Ethanol incorporation rate in 2035 (PCI energy)**	Conventional: 7%. Advanced: 2.5%.	Conventional: 7%. Advanced: 5.0%.	No changes vs. central scenario
		Biodiesel incorporation rate in 2035 (PCI energy)	Conventional: 4.9%. Advanced: 2.5%.	Conventional: 5.9%. Advanced: 5.0%.	No changes vs. central scenario
Vehicles	Weight	**Frame mass**	Validated assumptions	-5% vs. 2020, with substitute materials (50% aluminium, 50% plastic)	-25% vs 2020 (average car mass in 2000) (25% design gains, 75% material substitution gains)
	Autonomy	**Battery capacity (BEV/FCEV)**	Validated assumptions	+20% battery/tank capacity in 2030	Autonomy maintained between 2020 and 2030
	Consumption	**Technological improvements**	-25% in 2030 vs 2020 (-17% hybridization, -8% vehicle performance excluding hybridization)	-30% in 2030 vs 2020 (-20% hybridization, -10% vehicle performance excluding hybridization)	No changes vs. central scenario
		Vehicle weight reduction gains	/	Evolution deduced from the variation in weight of each vehicle	Evolution deduced from the variation in weight of each vehicle
	Mileage	**Service life**	12 years	No changes vs. central scenario	15 years

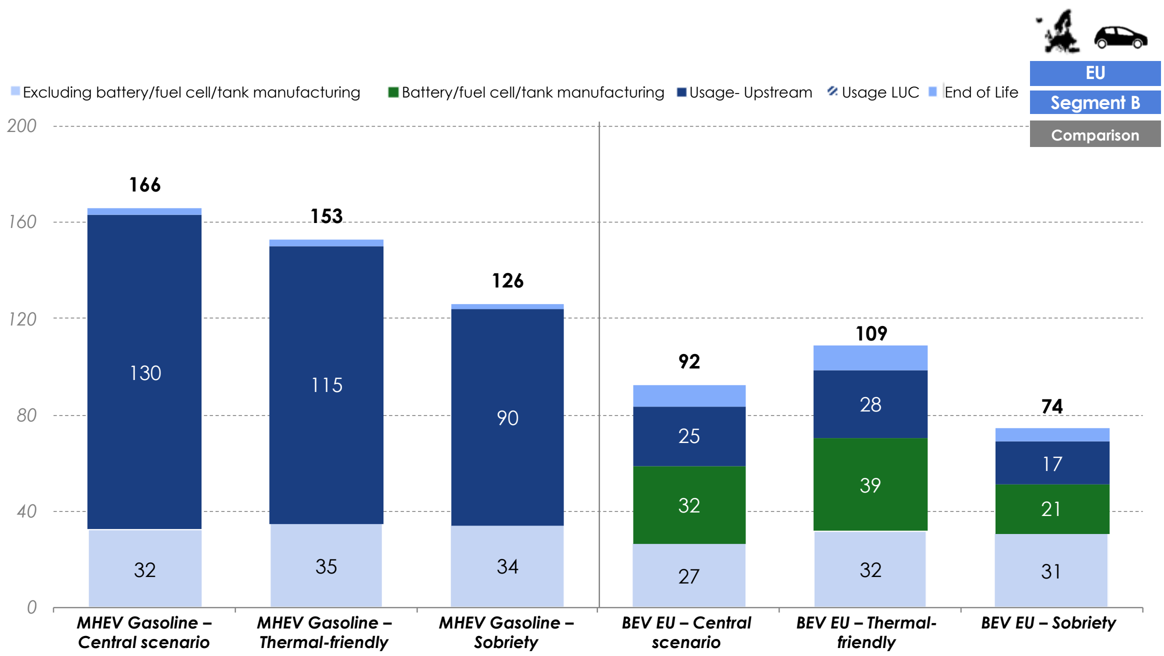
Table 9 - Alternative scenario assumptions that differ from the central scenario

Segment B

A comparison of the results of the central scenario with those of the two alternative scenarios, in segment B, provides some initial insights. This is revealed in **Figure 23** below. In fact, two strong conclusions emerge, in response to the questions posed above:

✓ **by taking very favourable assumptions for the ICEV, and at the same time lowering the carbon performance of the BEV, the life cycle hierarchy does not change**. Even with a European electricity mix that is more carbon-intensive than that of France, the BEV will in the future be much less emissive than an ICEV, even if it is ultra-efficient (-30% in the "thermal-friendly" scenario).

✓ **Better consideration of the sobriety issues** (weight reduction to return as standard as the beginning of the 2000s, stopping the race to increase battery capacity and extending the battery life) can generate very significant gains, whatever the technology: -24% on the ICEV and -20% on the BEV between the central scenario and the "sobriety" scenario. Given the very strong ambition of the public authorities on the decarbonisation of the sector by 2050, this is undoubtedly a lever that we cannot do without. It now remains to be determined how this can be implemented progressively.



Sources: Carbon 4 Analysis

carbone 4

Figure 23 - Comparison of the average carbon footprint over the lifetime of a segment B vehicle sold in 2030 in Europe | gCO_2e/km

Segment D

Reproducing this exercise in segment D enables these conclusions to be completed on a wider range of vehicles. The lessons are the same, unsurprisingly, since the mechanisms at work are identical. This is shown in **Figure 24** below:

- ✓ **In the "thermal-friendly" scenario, the BEV remains much less emissive than the ICEV** (about -34% on average for the EU, and -50% for France[17]), despite a reduction of about 10% of the ICEV emissions compared to the central scenario.
- ✓ On the "sobriety" scenario, the most interesting conclusion concerns the potential gains obtained, both for the ICEV (-27%) and for the BEV (-28%), compared to the central scenario. **These double-digit reductions argue very strongly for a reversal of certain current trends (**such as the uninterrupted weight gain over the past 40 years or the end of the race to increase battery capacity). However, the conditions for the success of this reversal remain to be defined: **the uncompromising stance of the public authorities, the user's awareness and the willingness of the manufacturers will be essential pillars.** It should be noted that no technological revolution is necessary for this.

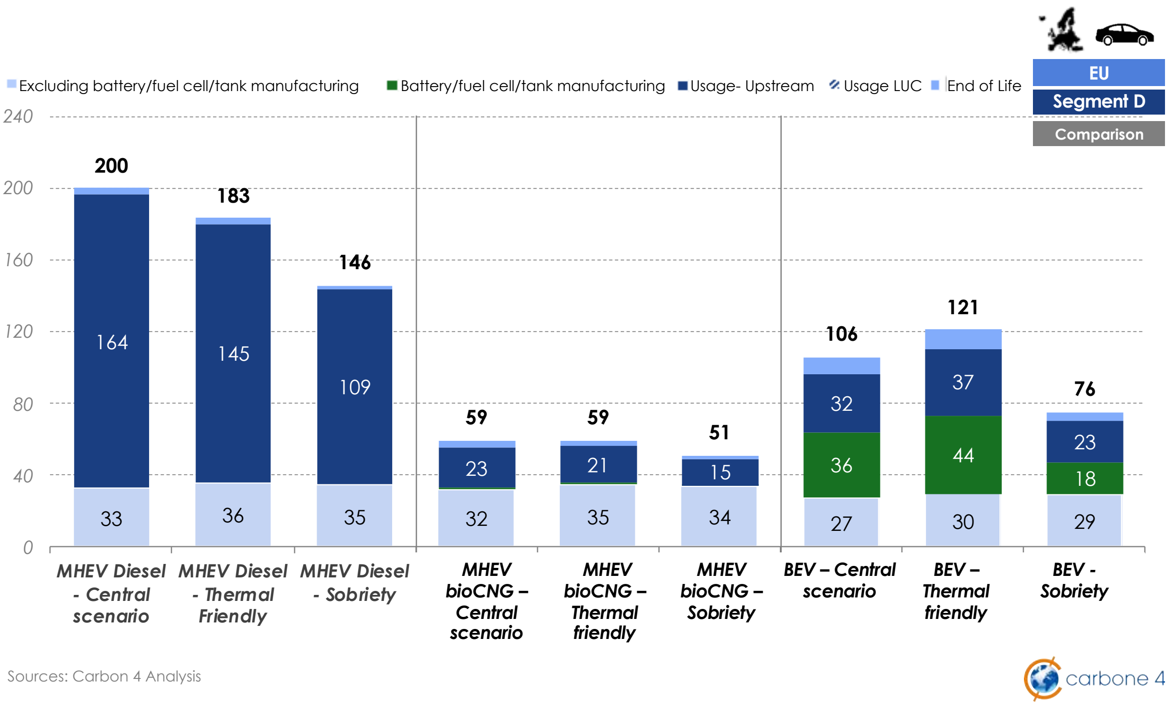


Figure 24 - Comparison of the average carbon footprint over the lifetime of a segment D vehicle sold in 2030 in Europe | gCO$_2$e/km

17. Not visible on the graph.

5 A Systemic Vision:
It is not just about the GHG emissions!

While the fight against climate change is clearly a priority for our societies, trade-offs between technologies cannot be made on the basis of GHG emissions alone. The latter is clearly paramount, which is why, according to the work on the previous pages, it would not be credible to continue encouraging the production of ICEVs to decarbonise road transport. On the other hand, of all the alternatives, it is not easy to decide which solution is better and should be favoured to the detriment of the others. To do so, **we must move away from a purely carbon vision and reason within the framework of a systemic approach that allows us to embrace the strengths and weaknesses of each technological solution more broadly**. Indeed, in order to decarbonise the sector as quickly as possible, we are faced with a problem of dynamics that puts at stake our capacity to implement more or less rapidly and to generalise more or less widely the various alternative solutions. To understand this, the GHG emissions criterion is no longer sufficient and it is necessary to consider environmental (other than climate change), resources, infrastructures issues, competition of uses, acceptance and of course costs.

Table 10 below provides a quick overview of these issues for the various alternative technologies to ICE.

Energy carrier	The advantages	The disadvantages
Electricity	• **Contribution to network management** (2nd life in the form of stationary batteries, V2G) • Little impact on **power generation capacity** • Co-benefits for **noise** and **air pollution**	• **Batteries: significant pressure on certain mineral resources** (lithium, cobalt, etc.), **the** extraction of which can pose socio-environmental problems. • **Battery: Embryonic recycling** channel • **Recharging** time and **autonomy** sometimes restrictive • Possible **local** impacts on **networks**
Biomethane	• **Positive externalities thanks to avoided emissions in the** agricultural and waste treatment sectors • **Fast refuelling** of bioCNG • Unrestricted mileage range	• Highly variable estimates of **the accessible biomethane supply in France / EU** • **Strong competition** with perhaps **more relevant** uses (industry, construction) • **High** cost of biomethane (~90€/MWh, 4x higher than natural gas)
Green hydrogen	• **Fast refuelling** of H_2 • Unrestricted mileage range • Management of **intermittency of** RE • Co-benefits on **noise** and **air pollution**	• **Competition with perhaps more economically relevant uses** (industry) • **Fairly high cost of hydrogen** • Supply and infrastructure still in its **infancy**

Sources: Carbon 4 Analysis

carbone 4

Table 10 - Main advantages and disadvantages other than the carbon footprint for each energy carrier applied to transport

Biomethane: it is very low in carbon, but what about its actual availability for transport?

Our calculations have confirmed that **biomethane (in the form of bioNGV) is an excellent avenue for decarbonising transport**. Moreover, the methanisation process that produces most of the biomethane today (and for many years to come) offers additional environmental co-benefits, notably via avoided GHG emissions in the agricultural and waste treatment sectors. Unfortunately however, **the use of bioNGV for transport is not as effective as BEVs or FCEVs in reducing air pollution or noise in dense areas.**

The big question mark concerning biomethane is its actual large-scale availability for transport. The box below provides an overview of the potential as seen by different actors, which helps to characterise the field of possibilities. Our conservative approach thus shows that at best **24% of heavy goods vehicles could be driving with 100% bioNGV in France in 2050 (slightly the same in Europe).**

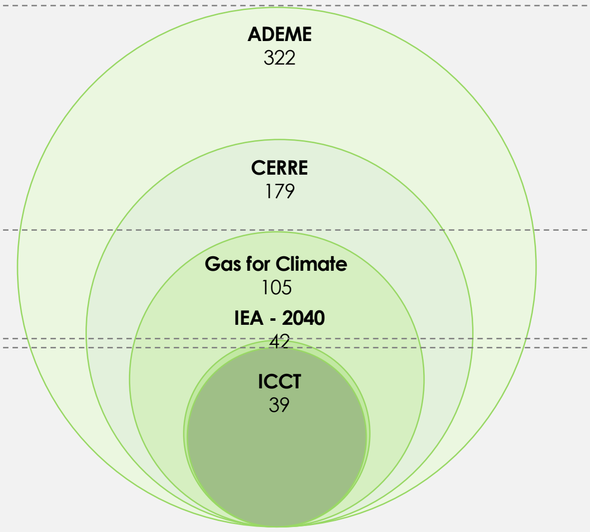
However, whether we are optimistic or pessimistic about our ability to develop this production at the right pace, particularly in Europe, the fact that this gas will still be demanded for other uses will not change. Indeed, it is necessary to decarbonise the entire economy (such as industry or the residential / tertiary sector): for many sectors, biogas is a ready-made substitute for fossil natural gas. **There is thus a strong de facto competition on the potential uses of biomethane**. A more detailed analysis of the relevance of gas uses must be carried out in order to better understand where its climate and economic added value is the highest (without this type of analysis, the players in the various gas-consuming sectors, such as industry or transport, will all be able to shout out loud and clear that biogas should above all be reserved for them, for a whole host of "good" reasons).

An apparently strong advantage of the gas sector is that **the transport and distribution networks are already in place**, which limits the question of refueling infrastructures. **This does not pose great difficulties of implementation, nor does it induce a high cost**. Nevertheless, this apparent advantage can also be a risk for the climate: indeed, if biogas does not replace fossil natural gas in significant proportions, the users of ICEVs compatible with NGV will primarily burn fossil NGV, which will not allow GHG emissions to be reduced in the right proportions. Worse still, **if the potential of biomethane turns out to be in the low range of estimates, the accelerated development of gas mobility could above all lead to locked-in GHG emissions from transport over one or two decades, via essentially fossil natural gas**, before redirecting public and industrial policies towards another technology if necessary.

Biomethane: what potential is there for mobility?

As far as France is concerned, **there is a very wide disparity in the estimation of biogas reserves, as well as the capacity to mobilise them**. **Figure 25** gives an overview of some recent reference studies on the subject.

Mobilisable biomethane potential[1] in 2050 according to various studies - *TWh*



Details of the estimated potential

ADEME :
" Economically viable " potential[2] of 293 TWh.
Total potential of 460 TWh by adding Power-to-gas (PtG).

Gas for Climate: EU-wide study, extrapolated for the French perimeter

ICCT: supply is between 22 TWh (biogas "economically viable"[3]) and 70 TWh (total potential, with pyro-gasification)

IEA: EU-wide study, extrapolated for the French perimeter

[1] Technically exploitable supply (e.g. livestock manure recovered from stables, while manure from grassland is not included).
[2] For ADEME, almost the entire supply is economically viable (biomethane at less than €120/MWh, for a carbon price of €200/tCO2).
[3] For the ICCT, economically viable is defined as a price per MWh lower than that of natural gas, for a given public policy. In this case, it is a subsidy of €500/MWh.

Sources: ADEME, IEA, Gas for Climate, ICCT .

carbone 4

Figure 25 - The potential of biomethane that can be mobilised in France in 2050

For methodological reasons, it is not surprising to find the ADEME estimate at the top of the list, with a mobilisable potential of 322 TWh in 2050. Indeed, the approach in this case is to find the price at which the reserves needed by the SNBC[18] in its 2050 scenarios become accessible. It considers intermediate energy crops, despite the potential competition with other uses such as food or biofuels. The assumptions are very optimistic, whether on the practical feasibility of the solutions envisaged, on the large-scale passage of a few pilot projects or on the costs of deploying the technologies.

Conversely, the ICCT's estimate is radically different (39 TWh of mobilisable potential in 2050) because this study is mainly a critical review of the ADEME assumptions (and of Gas for Climate) on the timber sector and intermediate energy crops reserves (on the aspect of competition between uses and cost of technologies), their industrial deployment, the public policies put in place and the mobilisation of the envisaged reserves. This study is thus intended to be very conservative on the potential of biogas that can really be mobilised.

18. SNBC: Stratégie Nationale Bas Carbone.

The work of the International Energy Agency (IEA) has been extrapolated to assess France's potential, based on the potential of the EU. Without calling into question other work by name, as the ICCT may do; the IEA nevertheless reaches the same conclusions. It should be noted that the authors do not consider technologies that have not proved their effectiveness today, except for pyrogazification. Power-to-Gas is thus not considered in the scope of the study and therefore we have also removed it from the data in the other sources. Finally, intermediate crops are not considered by the IEA as they are not considered "sustainable".

Other work by Gas for Climate and the Centre on Regulation in Europe (CERRE) leads to intermediate estimates, both based on a bottom-up approach that allows existing reserves to be reconstructed from what is physically accessible. Both studies are more optimistic in their assumptions than the IEA, notably on the possibility of mobilising intermediate energy crops on a European scale or the potential for wood pyrogasification.

It should be noted that **these differences observed for France are also verified at a European level,** by comparing the 4 studies CERRE, Gas for Climate, IEA and ICCT.

The range of possibilities thus appears relatively vast for biomethane production by 2050. To better frame the implications of this uncertain availability for transport, we have translated in accounting terms what the SNBC objective on renewable gas in transport would mean in terms of supplying the fleet of vehicles running on bioNGV by 2050. For this purpose, we have made assumptions in favour of bioNGV in order to estimate the upper bound:

✓ 40 TWh[19] of renewable gas of the SNBC 2050 for transport are available as biomethane alone

✓ all of the biomethane is allocated to heavy duty vehicles, whose fleet is assumed to be stable compared with today (in terms of number of vehicles)

Table 11 below summarises our analytical approach.

France - vision 2050		Comments
Demand of biomethane for mobility (SNBC)	**40 TWh**	• Obj: 200-300 TWh of renewable gas (biomethane and hydrogen) in 2050, of which 40 TWh will be allocated to transport • Optimistic assumption: all the renewable gas in transport is biomethane
Average consumption of a bus / HDV	**306,700 kWh/year**	• Consumption and mileage recovery of the model for vehicles produced in 2030
Number of vehicles running on bioNGV	**130 000**	• French CNG/LNG vehicle fleet consisting solely of buses and HDVs
Share of the road vehicle fleet	**12%**	• Assumption for a stable road vehicle fleet of circa 1 M buses/HDVs

Sources : SNBC, MTES, gaz-mobilité.fr

carbone 4

Table 11 - Estimation of the potential share of French heavy-duty vehicles running on biomethane in 2050

19. This would represent 20% of the 200 TWh of total biogas production in 2050. This compares to the 2 TWh produced approximately in France in 2019.

In this favourable configuration, **the proportion of heavy duty vehicles that could run with 100% bioNGV in 2050 is around 12% of all HDVs (including buses),** which would be quite a minority.

Doubling the amount of biomethane available for transport[20] (from 40 to 80 TWh), we would then reach **a high value of 24% of heavy goods vehicles able to drive with 100% bioNGV in France in 2050.**

Our GHG emissions calculations over the life cycle have demonstrated the relevance of this energy carrier for decarbonising transport, but because of this potential intrinsic limitation, **it is clear that this technology must be seen as a complement to electrification (batteries or hydrogen), even for heavy mobility.**

This approach reproduced **in the EU** leads to quite similar results. Indeed, according to CERRE for example, the potential for biogas production on the scale of the EU-28 is about 7 times higher than in France. As the comparison of fleet sizes leads to a ratio of 8 for cars and 6 for trucks (according to URF 2019 data), the previous conclusion valid for France is also valid for the EU: **about 1/4 of European heavy goods vehicles at best will be able to drive with 100% bioNGV in 2050, 1/10 being probably more realistic.**

20. Either because the total production is higher than anticipated (closer to 300 TWh than to 200 TWh), or because the share reserved for transport is increased (e.g. 40% of 200 TWh, instead of the 20% planned today).

Hydrogen: do the numerous assets need to be directed primarily elsewhere rather than towards mobility?

The use of hydrogen for transport is very much in fashion, at least in the speeches. The fact that it allows "**zero emissions" mobility (exhaust emissions), without local pollution, without noise, and above all without the constraints of recharging time and land use imposed by battery technology, makes it particularly attractive**. These are all virtues that make it, in a way, an essential part of the landscape of a carbon-free Europe in 2050.

However, just like biogas, even if it does not hold the upper hand, **it seems that the most relevant uses of low-carbon hydrogen are not in transport, but in heavy industry** (such as the steel industry and refining) **or petrochemicals** (for the production of ammonia for fertilisers). It is no mistake that Germany is going to devote 60% of its 9 billion investment in hydrogen outside of mobility.

As the hydrogen economy is only in its infancy, there is **a major strategic challenge here, which is to know how to best use a very versatile molecule in various applications, but also in limited quantities for a long time to come** (at least relative to the amount of electricity available, especially for mobility). Infrastructures only exist on a small scale and although development projects are increasingly numerous, particularly on the "green" hydrogen supply side, the question of transport, distribution and refuelling is still in its infancy. The public and industrial players are right to invest in this sector of the future, but knowing that at least two less emissiive alternatives exist for mobility (bioNGV and BEV), as the results of this work show), they must address the question of competition of uses by orienting the use of hydrogen rather towards uses other than transport, in the medium term. One nuance, however: is that **some heavy transport** (of people or goods), especially long-distance transport requiring high utilisation rates, **may represent a useful outlet because (i) the battery alternative has its limits** (loss of useful charge[21] , operational constraints) **and (ii) bioNGV may not be produced in sufficient quantities for these needs.**

Encouraging the development of short-term hydrogen mobility to the detriment of its alternatives would require the use of highly emissive hydrogen (because it is obtained by steam-reforming methane or electrolysis from an insufficiently low carbon electric mix) to power the IFCEVs: this would also **run the risk of locking in transport GHG emissions at a high level for many years, which we cannot afford**. In the **longer term**, driven by demand from the heavy industry, precisely when the sector has been structured, when the infrastructures for the production of "green" hydrogen[22] are sufficient, when the costs have fallen sufficiently on the molecule side, then **FCEVs too will be able to find their place in low-carbon mobility**, in order to complete the BEV and ICEV-bioNGV supply, mainly for HDVs. It is therefore very much a question of time.

21. Insufficient space in the chassis of a long-haul truck.
22. Electrolysis using low-carbon electricity can possibly be supplemented by hydrogen production by steam reforming with CO_2 capture and sequestration.

Batteries: its limits will not allow it to play all the roles

The analyses carried out as part of this study showed that, **except for the ICEV running on bioNGV, the carbon footprint over the life cycle of BEVs is always the smallest, regardless of the type of vehicle[23].**

The other factors in favour of electrifying road transport via batteries are numerous: significant noise reduction, almost total elimination of local air pollution, technological and industrial maturity, an abundant manufacturer's offer (soon), etc. Moreover, in the coming years, technological advances in vehicles and meters will make it possible to deploy **Vehicle-to-Grid solutions aimed at providing services to the network by better managing supply and demand**, with (in theory) cost reductions for the user. Similarly, **the stationary use of second life batteries, which have been used extensively for mobility**, will increase, also to provide energy services to the user and to the network.

Would we thus have to make do with the ideal solution? Is BEV a strategic choice without any regrets, faced with the challenges of the low-carbon transition? The answer is no...

Indeed, the widespread use of the BEV at the scale of the current fleet of vehicles would come up against a very serious problem in terms of **the availability of the metals used in the composition of the batteries**. While the concern is not directed at nickel or manganese, the situation is more worrying for lithium and above all cobalt. Over the next 5-10 years, the exploitation of new resources seems feasible, but beyond that, the prospects are much more uncertain, especially in a context of very strong growth in the demand for batteries, and more so if the extraction conditions become harsher in order to reduce mining impacts. **The reduction of the role of cobalt in battery chemistry, the systematic recycling of the units at the end of their life** (the sector is embryonic but is being structured in Europe for example) **are responses** capable of mitigating this risk, but from there to the idea that the production of several hundreds of millions of BEVs in the world is conceivable in 10 or 20 years[24], remains a gamble. In our opinion, this is **an inherent weakness of battery-powered electromobility, but it can be modulated** in at least two ways:

- ✓ **by stopping the race to increase the size of the batteries**: having two 50 kWh batteries, rather than a single 100 kWh battery, makes it possible to put two BEVs on the road instead of one…

- ✓ **by optimising the size of the fleet of light vehicles, thanks to the strengthening of public policies to better fill up private vehicles** (not just electric): to satisfy the same need for mobility, i.e. the same flows of passengers.km, fewer vehicles.km would be needed, and therefore fewer vehicles altogether.

Generalising BEV to the detriment of other solutions could also lead to problems of balancing the electricity network at a local level, due to high power demands at times when the network is already under heavy strain. For example, in France, **RTE[25] has demonstrated that the national electricity network could easily absorb very high penetration rates caused by the BEVs but did not rule out the possibility that this could lead to rare but critical situations in some areas where the network is less resilient than elsewhere, if it is not strengthened locally.**

23. The FCEV running on 100% RE H_2 sometimes plays the same game, or even a little better depending on the type of vehicle.
24. Today, there are just over a billion vehicles of all types in the world.
25. RTE, " Enjeux de développement de l'électromobilité pour le système électrique ", May 2019.

There are still the questions of costs and user experience: acquisition costs are still a major obstacle for many motorists tempted by electromobility, but they will gradually disappear in the next few years as industrial costs continue to fall. Already, acquisition via leasing solutions makes it possible to spread the investment over several years, like a traditional loan, with monthly rents close to those of the ICE versions.

On the other hand, **the widespread adoption of the BEV comes up against a classic obstacle, that of kilometric range. Switching to electric mobility can therefore only be envisaged for many motorists if it is possible to retain the same "Swiss army knife" uses** with a BEV as with an ICEV. In practice today, for road users, making a long-distance journey is thus the most restrictive aspect of electric mobility, although for most of them this represents only a small fraction of their journeys, but it does carry a high symbolic importance, as it is linked, for example, to holiday trips. There is a crucial user experience issue here for the BEV’s democratisation: for example, finding a free charging point, waiting for the time to recharge, etc. To make the BEV perpetually available and rechargeable in a few minutes, charging services on terminals would have to be paid for at a high price (rapid or even ultra-rapid terminals in large numbers, are faced with the problem of available land and reinforcement of the electricity network) and the vehicles themselves would be more expensive (larger batteries and chargers compatible with very high powers), all this to the detriment of the spread of electromobility.

We can of course bet on a gradual change in the behaviour of motorists who would agree to spend more time on the road (for recharging), in favour of reducing their environmental footprint, thereby limiting the headlong rush described above. However, it would be utopian to imagine that this could become generalised in the medium term in people's mindsets...

It is therefore easy to understand that the all-battery vehicle has its limits, even in the case of private vehicles. Neither bioNGVs nor hydrogen will be confronted with these types of constraints and **the offer of alternative vehicles will in fact necessarily have to be diverse in order to meet the different needs**, even if the BEV will be able to cover the vast majority of them.

Conclusion

Based on the assumptions of the central scenario, which we believe is the most likely to occur over the next two decades, **our analyses clearly show that "battery electrification" (BEV) and "bioNGV" (ICE-bioNGV) technologies are leading the way in terms of reducing the carbon footprint** over the life cycle, regardless of the vehicle considered.

For a passenger car sold in 2020 in France and running until 2031, this means a reduction of between 65 and 70% in CO_2e emissions. These benefits are even more prominent in the case of heavy vehicles, which are used more intensively (buses, semi-trailor trucks), and are therefore favourable to electrification; achieving reductions of around -75 to -85%. These spectacular gains are notably made possible by the combination of 2 factors:

✓ very low usage emissions, due to France's low-carbon electricity mix

✓ the manufacturing emissions from specific equipment such as batteries, which have fallen sharply in recent years and will continue to do so in the future (due to industrial efficiency gains and lower EFs from process electricity)

It should be noted that outside of France, whether it is a passenger car, LCV or bus, **a BEV sold today in Germany, or even in Poland, remains less emissive than a comparable ICEV**. The carbon performance of the ICEV running on bioNGV varies little from one country to another, and thus remains the least emitting as a rule.

Even in a scenario favourable to the thermal vehicle, in which we have deliberately opted for optimistic assumptions for the ICEV and pessimistic ones for the BEV, **there is no inversion of the hierarchy: whatever the type of vehicle, the BEV remains less emissive than the ICEV** in its life cycle, whether the latter is fuelled by petroleum fuels or fossil gas.

However, the hydrogen carrier has not said its last word, because **the hydrogen vehicle (FCEV) presents quite similar results under certain conditions, notably the decarbonisation of the electricity mix** (as in France or with renewable energies) allowing it to be produced by electrolysis. On the other hand, under the current conditions of the carbon content of the electricity mix in Europe, the production by electrolysis with grid electricity leads **to very unfavourable results** in countries such as Germany or the Benelux countries. To date, the lifeline for hydrogen is either biomethane steam reforming or electrolysis with 100% renewable electricity.

In their **rechargeable hybrid** form (PHEV), thermal vehicles certainly show **a substantial improvement** (of the order of -10 to -35%) but remain **below what alternatives such as ICEV-bioNGV, BEV or FCEV with low-carbon hydrogen can offer**, even when considering 50% of the km travelled in electric vehicles in 2030.

Nevertheless, in the face of these decarbonising solutions, it is necessary to compare the resources that can be mobilised, which vary greatly according to the energy carriers and face strong competition from other sectors. Thus, **the bioNGV cannot claim to decarbonise mobility on its own because its availability will remain a major obstacle**, even in the most favourable potential assumptions. Similarly, the production of "green" hydrogen is only in its infancy and should gradually increase in power by following the development of renewable energies or biomethane. Finally, while electricity is not a scarce resource as such, electric vehicle batteries are based on mineral resources that are neither infinite nor immediately mobilisable.

As a result, **the electrification of vehicles should account for most of the greening of the fleet of passenger cars and LCVs**, and this penetration could be all the greater if the size of the batteries remains limited so as not to increase the strain on mineral resources. Technologies based on bioNGV and "green" hydrogen (less abundant energy resources) should complement the BEV and should aim primarily at heavy mobility where batteries are reaching their limits (required volume, vehicle autonomy and recharging speed). And even then, they will only provide partial solutions: by reserving its use in mobility only for heavy duty vehicles, we estimate that at best about 1/4 of European HDVs will be able to drive with 100% bioNGV in 2050, 1/10 being probably more realistic. **BioNGV and hydrogen are therefore essential solutions to meet the needs of road mobility and to overcome the limitations of battery vehicles, but they cannot represent an answer on their own for the decarbonisation of the sector.**

As for liquid biofuels, they will contribute little, if anything at all, to decarbonising road transport, at the incorporation rates that are (and will be) present in Europe (a maximum of 18% bioethanol and 11% biodiesel by volume, in our most ambitious scenario). The carbon benefit is marginal for bioethanol and in many cases the carbon footprint worsens for biodiesels due to emissions from land-use change caused by dedicated crops. This problem could largely be solved by the rise in so-called advanced biofuels (such as those using plant lignocellulose), but their progress will be too slow over the next 20 years to make a difference.

Finally, it is crucial to bear in mind that the relevance of the choice of this or that vehicle cannot be made solely based on the carbon criterion. The manufacturer's offer, the micro-economic equation, the availability of the energy carrier, the constraints of use, the other environmental impacts are all parameters that must be considered in the decision. **No technology ticks all the boxes, which is why a systemic approach is necessary** to guide public policies and industrial choices towards the fastest possible decarbonisation of road transport.

Beyond motorisations, this study confirms the importance of considering the entire life cycle of the vehicle in the analysis of the carbon footprint:

- ✓ **On the one hand, the carbon weight of the production and end-of-life phase of the vehicles and specific equipment (batteries, fuel cells, tanks) for the alternative technologies such as BEV and FCEV can be very significant (up to 90% of the the total carbon footprint for a BEV in France!).** This observation amounts to questioning the relevance of a European regulation that is based solely on exhaust emissions, without taking into account all the life cycle emissions (including upstream of the energy carriers).

- ✓ **On the other hand, our work clearly highlights the decisive role that can be played by sobriety, in the broadest sense of the term, with more fuel-efficient vehicles.** By focusing simply on passenger cars, we have shown that additional gains of around 25%, all vehicle types combined, can be obtained without technological revolution, simply by adopting assumptions in the direction of sobriety (reduction in weight, extension of service life, stopping the race for battery capacity).

Thus, from a carbon point of view, a high-power BEV carrying a battery pack of 90 kWh or more (e.g. SUV Type Audi e-tron) can generate in a country like Germany (Europe's largest automotive market) **life cycle emissions comparable to or even greater than a smaller ICEV.** In this case, the regulation is perfectly misleading because it will qualify the former as virtuous, while the latter will be penalised ... In the light of our analysis, **we therefore recommend that public authorities reconsider the "rules of the game" on the measurement of CO_2 emissions from new vehicles in Europe** (passenger cars/ LCVs and HDVs), in order to avoid that the supposedly incentive-based rules are counterproductive in many cases, and **to encourage sobriety with rules based on vehicle mass and battery capacity.**

Finally, **it is crucial to remember that technology alone will not make it possible to reduce our emissions sufficiently** in the coming decades. As shown by our calculations, we can, in order of magnitude, expect a reduction factor of 3 to 4 via technologies, once they have been widely disseminated. However, we should aim instead for a reduction factor of 5 to 6 in order to reduce our emissions sufficiently by 2050. If we take into account population growth, which is leading to a trend increase in energy consumption, the equation is even less favourable.

Moreover, many of the alternative solutions studied here have **other impacts that must also be controlled** at the risk of choosing from the lesser of two evils: the conditions of the mineral resource extraction, artificialisation and changes of land use for plants or electricity production, etc. For these multiple reasons, a purely **technological prism is largely insufficient to think about the decarbonisation of mobility**. Other particularly effective reduction levers exist which must be mobilised in parallel; it is essential to mention them in this conclusion:

- ✓ reducing flows at source (number and scope of journeys), both for people and goods
- ✓ better sharing of private vehicles (prevent lone driving) and better filling of heavy vehicles (eliminate empty returns, reduce non-optimised express deliveries)
- ✓ encouraging a modal shift as much as possible towards active modes of transport and more carbon-efficient public (passenger) or massified (freight) transport, depending on the situation

Annex:

Sensitivity analyses confirm the preponderance of mass and energy consumption!

These sensitivity analyses have two main justifications.

Firstly, they make it possible to **answer recurring questions about the importance of one factor or another, relative to the others**. Thus, for a PHEV, how important is the electric mode % in relation to the intrinsic performance of the combustion engine? For a BEV, is the electricity emission factor more influential than the battery capacity? For a FCEV, is the improvement of electrolysis efficiency more important than the transport distance of the hydrogen?

In doing so, they offer the possibility of **clearly identifying the parameters that have the greatest influence on the results, which are ultimately limited in number**. It is then much simpler to define new scenarios and variants of the central scenario by varying only these key parameters. This ensures that (i) the analysis remains relevant, even if a large part of the assumptions remain unchanged and also that (ii) the scenarios are simple to define, making them easier to read and interpret.

Of course, this approach is not intended to cover all possible scenarios. One could well imagine disruptive technological situations or very specific cases related to the energy supply. The reason we have not made this choice is so that **our results do not reflect specific circumstances, but rather a more global situation**, reflecting the performance of different types of vehicles, on the scale of a country or a region (in this case, the EU).

Key take-aways

For internal combustion engines (ICEs), energy consumption and vehicle mass are largely dominant in the sensitivity analysis, well ahead of the incorporation rate of biofuels or the biofuel EF (including biomethane). For the latter two parameters to have more weight, the average incorporation rate would have to be much higher (which is not an expected trend in Europe over the next 15-20 years) and biofuels, especially biodiesels, would have to be less penalised by direct and indirect land-use change emissions.

In contrast to ICEVs, **PHEVs are quite sensitive to a third variable, which is the vehicle's % of use in electric mode.** Indeed, by their very design, PHEV users will have the option of recharging their vehicle or not (unlike ICEVs, even when they are converted to a " mild hybrid "), which can have a considerable influence on the carbon footprint of this technological solution.

Figure 26 below illustrates the results obtained for the ICEV and PHEV passenger cars, segment D.

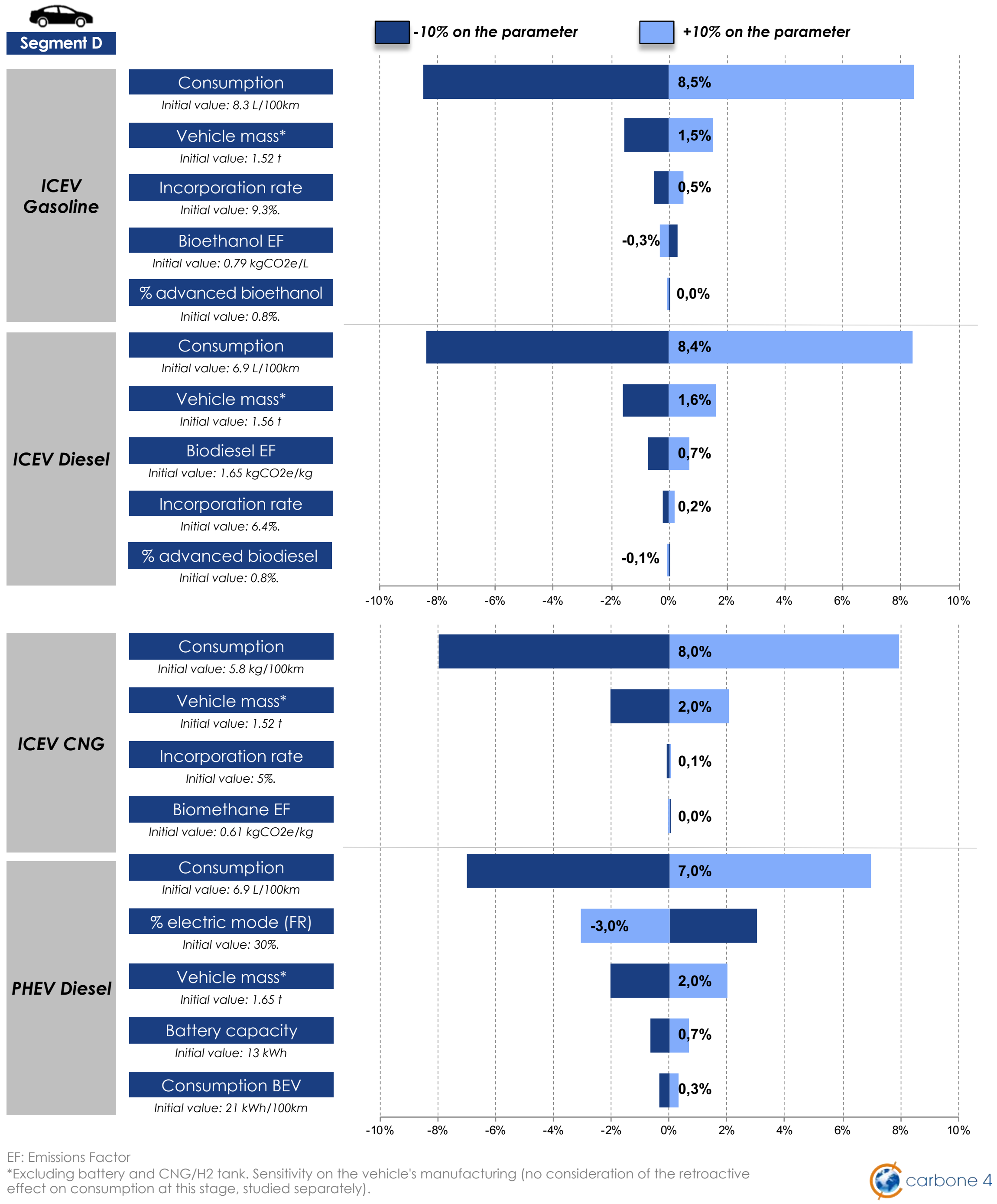


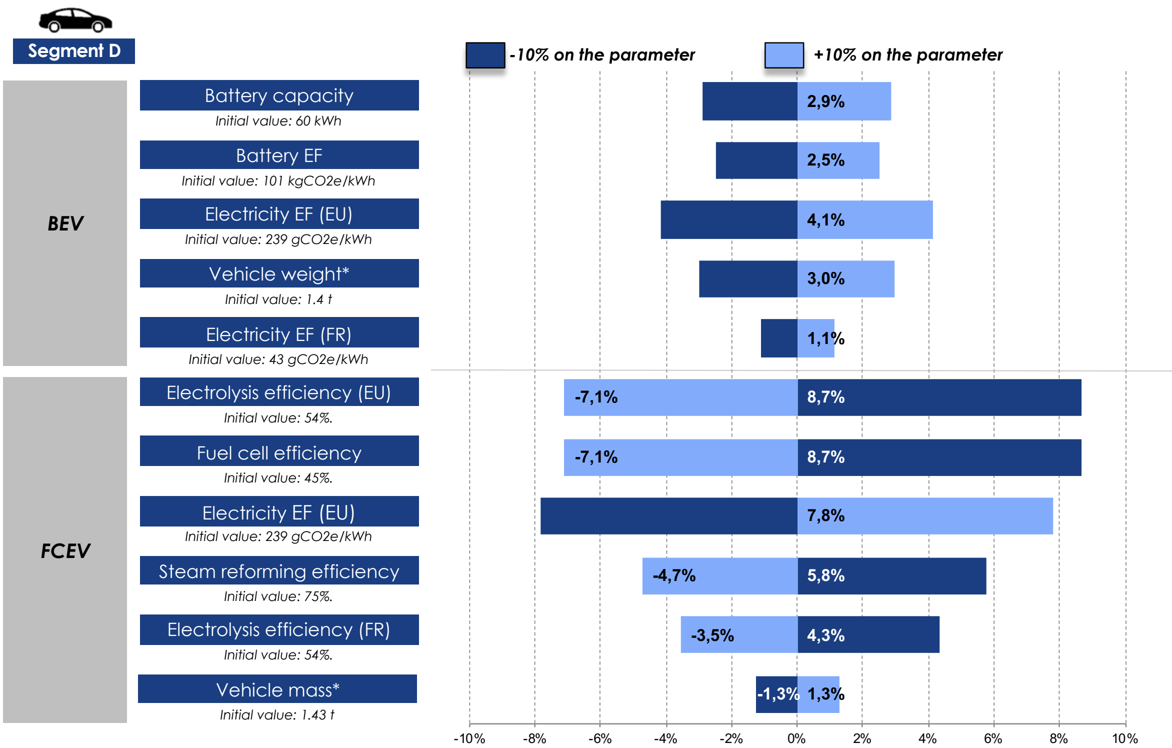
Figure 26 - Sensitivity analysis of the parameters most influential on the carbon footprint of internal combustion vehicles

For the BEV, four parameters prove to be much more influential than the others. Unsurprisingly, we find the **electricity EF**, all the more influential as it is high in the short term (i.e. a 10% decrease in the EF of the EU mix will have more effect than a 10% decrease in the EF of France, which is much lower today). Similarly, we can also find **the battery manufacturing EF**, especially in countries where electricity is low carbon because the share of manufacturing is then dominant.

Perhaps more unexpectedly, two other factors nevertheless emerge from this analysis, the **mass of the vehicle** (which is an argument against the manufacture of the heaviest electric vehicles, such as SUVs) and the **capacity of the batteries**. Our analysis confirms that this last parameter is a major carbon challenge, and that electric mobility must be an opportunity to rethink our relationship with the usage, i.e. not wanting at all costs to regain the autonomy performance of internal combustion vehicles but reasoning more at the systemic level (the journey time, recharging, alternatives, etc.).

The case of the FCEV is unique, which can be explained by the specific nature of its energy carrier, hydrogen. Thus, the most influential parameters are of course **the consumption of hydrogen per 100 km** (or the EF of the electricity, which is the equivalent in the case of electrolysis), but also **the conversion efficiencies to produce the said hydrogen**, whether by steam reforming or electrolysis. Finally, **the mass is, as always, a determining factor** in carbon performance, even in the case of the FCEV.

Figure 27 below illustrates the results obtained for the BEV and FCEV passenger cars, segment D.



EF: Emission Factor.
Sensitivities for BEV and FCEV are determined for the EU perimeter, except for the French electricity EF and for the electrolysis efficiency, where the BEV / FCEV are considered in France, of course.
*Excluding the battery and CNG/H2 tank. Sensitivity on vehicle manufacturing (no consideration taken of the retroactive effect on consumption at this stage, studied separately).

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Figure 27 - Sensitivity analysis of the most influential parameters on the electric vehicle's carbon footprint (BEV/FCEV)

Annex:
The sources used

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Contact: mobilite@carbone4.com