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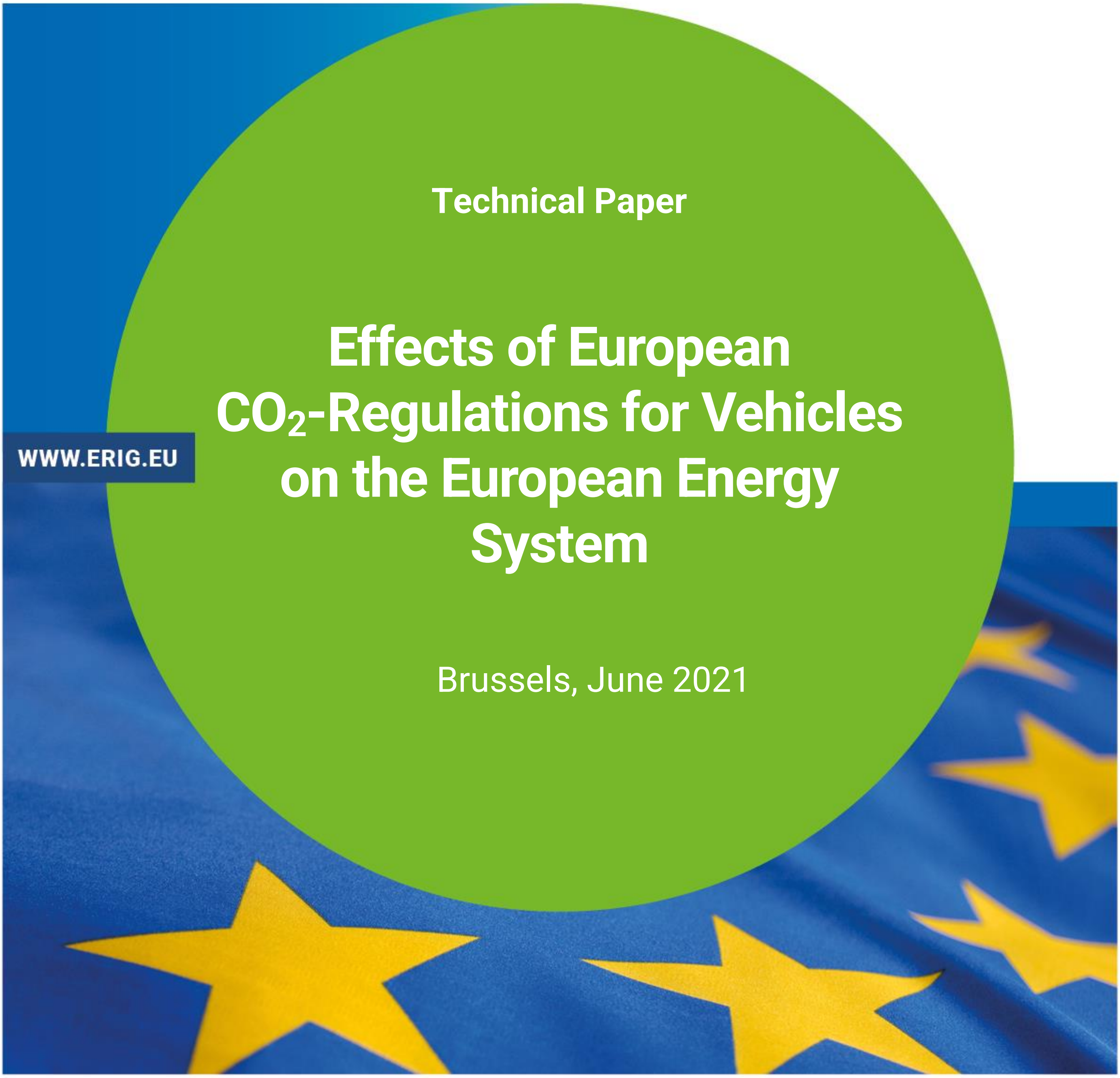

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Technical Paper

# Effects of European $CO_2$-Regulations for Vehicles on the European Energy System

Brussels, June 2021

DVGW  OST Ostschweizer Fachhochschule  DVGW Forschungsstelle ebi  Empa Materials Science and Technology

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# Abstract

The current EU ambition to reduce green house gas emissions have recently been sharpened in the EU Green Deal. This also includes emissions from road transport, specified in the “Sustainable and Smart Mobility Strategy” of the EU. The ambitions stand in stark contrast to the current emissions development we are seeing in the road transport sector. In this article, the current regulatory framework for greenhouse gas emissions reduction of cars and fuels, based on Tank-to-wheel and Well-to-tank approaches addressing different stakeholder groups is mirrored against the scientific full life cycle assessment and the Well-to-wheel approach. In an analysis of the combined emissions from Well-to-tank and Tank-to-wheel for different energy carriers and vehicle technologies, it is showed that the individual values can be drastically misleading in regard to the total actual emissions in the Well-to-wheel perspective. In consequence, not only are the real total emissions values of different energy carrier-vehicle technology combinations misrepresented, but it also sets unjustifiable biased incentives for certain energy carriers and vehicle technologies over others. Gas and gas internal combustion vehicles are especially negatively influenced. The article shows that this is in conflict with the green house reduction potential of gas in road transport and stands in contrast to the important role gas will have for the future net-zero energy system in total. In the final part, suggestions are made how current regulation flaws could be mended leading to a regulation and incentives that are closer to representing the real total emissions theoretically represented in the life cycle assessment.

# Contents

# Terminology

As in all areas of expertise, there are many technical terms also in the domain of emissions of greenhouse gases in road traffic. The following list gives an overview on the terms and abbreviations used in this text. In order to make reading of this article easier and at the same time allow referencing the European legislation, this article repeats the full terminology.

| | |
|---|---|
| Advanced biofuels: | Biofuels with raw material of non-food origin. Biofuels that are not in competition to food production. |
| BEV: | Battery electric vehicle |
| CBM | Compressed biomethane |
| CNG: | Compressed natural gas, a standardised technology to store methane under pressures of up to 200 barg. The methane can not only be natural gas but also biogas (CBM) or synthetic methane produced in a power-to-gas process. If the latter uses renewable electricity, the methane is considered renewable. |
| Cradle-to-grave: | Concept to consider the lifetime of a product from production until the end-of-life for e.g. environmental impact, see Table 2 Page 9 |
| e-fuel: | Chemical liquid or gaseous fuel produced in a power-to-x plant from renewable electricity. |
| EU-27: | All member countries of the European Union from 1 February 2020. |
| EU-28: | EU member countries including UK |
| EU-KP: | EU member countries including UK and Iceland (Kyoto-Protocol) |
| ETS: | Emission trading system |
| FCEV: | Fuel cell electric vehicle, meaning a HFCEV |
| GHG: | Greenhouse gases |
| GWP: | Global warming potential |
| HDV: | Heavy-duty vehicles |
| HEV: | Hybrid electric vehicle |
| HFCEV: | Hydrogen fuel cell electric vehicle |
| HVO: | Hydrotreated vegetable oil, a fuel with the quality of diesel. |
| ICE: | Internal combustion engine |
| ICEV: | Internal combustion engine vehicle |

| | |
|---|---|
| LCA: | Life cycle analysis, see Table 2 Page 9 |
| LCV | Light commercial vehicle |
| LDV: | Light duty vehicles (passenger cars and LCV) |
| LEV: | Low emission vehicles |
| LNG: | Liquefied natural gas, a standardised technology to store methane in liquefied form in cooling it to 160 °C. The methane can not only be natural gas but also biogas or synthetic methane produced in a power-to-gas process. If the latter uses renewable electricity, the methane is considered renewable. |
| LPG: | Liquefied petroleum gas, a mixture of mainly propane and butane which is stored in tanks at pressures above the vapour pressure. The latter is between 2 bara and 20 bara depending on the exact composition and the temperature. |
| NEDC | New European driving cycle |
| OEM | Original equipment manufacturer, in the context of this paper vehicle manufacturers |
| PHEV: | Plug-in hybrid electric vehicle |
| RED II: | Renewable Energy Directive II, Directive (EU) 2018/2001, see Table 3 page 11. |
| Tank-to-wheel: | Concept to determine the environmental impact of a vehicle in only considering emissions while the vehicle is in use and the energy available in the vehicle's tank or battery is transmitted through the drivetrain to the wheels, see Table 2 page 9 |
| Well-to-tank: | Concept to determine the environmental impact of fuel production or extraction (including electricity) through the fuelling station or charging station until the energy is stored in the vehicle, see Table 2 page 9 |
| Well-to-wheel: | Concept to determine the environmental impact of a vehicle in combining Well-to-tank and Tank-to-wheel, see Table 2 page 9 |
| WLTP: | Worldwide Harmonized Light Vehicles Test Procedure |
| ZEV: | Zero emission vehicles |
| ZLEV: | Zero and low emission vehicles, <50 g $CO_2$/km |

# 1 Introduction

In the end of 2019, the European Commission published its ambitious plan of action, the European Green Deal. It states that a transformation of the European economic strategy is necessary in order to reach net-zero emission of greenhouse gases (GHG) in the EU by 2050, decouple economic growth from use of resources and accomplish these goals as a united effort including all people and regions throughout the EU.

In December 2020, the European Commission introduced the “Sustainable and Smart Mobility Strategy”. The strategy formulates the three objectives of future mobility: “Sustainable Mobility”, “Smart Mobility” and “Resilient Mobility”. The overall goal and the main subject of sustainable mobility is a greenhouse gas reduction in transport of 90 % until 2050. As a consequence, the use of renewable energies should be strengthened and alternative low $CO_2$ emission modes of transport encouraged. Additionally, the strategy foresees the internalisation of environmental costs of transport [1]. Furthermore, the EU emission trading system (ETS) shall be expanded to cover not only the energy sector but also include the transport sector [2].

The European Union and its member countries have set ambitious goals for protecting the climate. Looking at the historical development of greenhouse gas emissions in road transport, one must conclude that they are in blatant contrast to the set ambitions. Since 1990 the greenhouse gas emissions have been continuously increased until 2007. Followed only by a brief period of decline until 2013, since when the emissions are continuously rising again. This development results in about 27 % higher emissions in 2018 compared to 1990 in the EU-27 [3] and 24 % more in the EU, UK and Iceland (EU-KP) combined [4][6]. This calls for urgent adaption of the regulatory instruments to turn this negative trend around in time not to jeopardise the $CO_2$ reduction target.

In this article, we give an overview on current regulation and mirrors it with the state of knowledge concerning the energy system, mobility technologies and energy carriers and it´s intended objectives of emissions reduction in section 2-4. This is followed by a critical discussion in section 5 and suggestions for improvements in section 6.

# 2 Europe's Future Energy System

In order to fulfil its goals in reducing $CO_2$ emissions, Europe has to transform its energy system. The latter accounts for almost 80 % of Europe's total greenhouse gas emissions [5][7]. The energy arriving at the end user, i.e. final energy consumption, in the year 2019 was about 23 % electricity and 73 % [6] energy carriers in the form of molecules, with the remaining part being mainly heat. Europe's energy consumption relies by up to about 81 % [7] on fossil energy sources, where most of the molecule energy carriers (about 86 % [6]) and a considerable share of electricity (about 65 % in 2019 and about 62 % in 2020, [8]) are of fossil origin.

Numerous concepts and visions have been published on how Europe's sustainable energy system could work. An overview is given in Table 5 on page 24 in the Appendix. There are publications focusing on the electric part of the energy system (Eurel), none of which suggest that Europe's future renewable energy system is based on electricity only. The overview in Table 5 shows that electricity is predicted to become more important in the final energy consumption. This is due to electrification, meaning that more applications like heating systems and passenger cars rely on electricity as the final energy (heat pumps and battery electric vehicles (BEV)), which today very often use other fuels in molecule form (liquid, gaseous

[6] Page 239 (259/997)

[7] Page 8 (10/192)

or solid). In all scenarios however, molecule energy carriers like hydrogen, methane and liquids also play an important role. These molecule energy carriers have to be produced from renewable or decarbonised sources, where renewable sources are both biomass and power-to-x processes operated with renewable electricity. Some scenarios aiming for 90-95% reduction in greenhouse gas emissions, still allow a small share to be of fossil origin.

Regardless of the inaccuracies and different assumptions of the numerous studies, it is clear, that molecules will remain a substantial part of the European energy system. Amongst the energy molecules, the two gases hydrogen and methane are the ones closest to the electrical world with a clean combustion behaviour. Generally acknowledged for having a crucial partner role to play to an electrical energy system dominated by intermittent renewable power production. The two gases can provide low emissions flexibility, stability, efficient and economic long-distance transport and seasonal energy storage capability. For these reasons, the corresponding gas infrastructure for transmission, storage and distribution can play an important role in the transformation up to 2050 and possibly also beyond.

In 1990 road transport (in the following also road traffic) caused about 13 % of greenhouse gas emissions in the EU, UK and Iceland (EU-KP) [4][8] and was mainly based on fossil energy sources. Where the term “road transport” not only comprises the passenger cars, but also includes utility vehicles in different sizes, trucks and busses. Almost 30 years later in 2018, the situation has not improved, since 21 % of EU-KP's greenhouse gas emissions [4][9] are caused by road transport, which uses 29 % (EU-28) of the final energy consumption [6] [9]. What has changed, is the availability of vehicles operable by renewable energies listed in Table 1 and the ongoing build-up of the respective infrastructures.

[8] Pages iii (7/997), 239 (259/997)

[9] Page 239 (259/997)

**Table 1: Commercially available technologies for road traffic that can be operated using renewable energy. LPG (= butane-propane mixture) is not listed because the authors are not aware of production of renewable LPG.**

| Short name | Technology | Drivetrain | Renewable energy source | Fossil energy source |
|---|---|---|---|---|
| HEV, PHEV | Hybrid electric vehicle and Plugin hybrid electric vehicle | Internal combustion engine, small battery, electric motor | Bio-gasoline, renewable electricity charged to PHEV | fossil gasoline, fossil-based electricity charged to PHEV |
| BEV | Battery electric vehicles | Battery, electric motor | Renewable electricity | Electricity produced from fossil energy carriers (e.g. coal, natural gas) |
| FCEV | Fuel cell electric vehicles | Fuel cell and electric motor | Green hydrogen | Grey hydrogen |
| CNG | Vehicles running on compressed methane | Internal combustion engine (ICE) | Biogas, methane as e-fuel | Natural gas |
| LNG | Vehicles running on liquefied methane | | | |
| Diesel | Vehicles ready for bio-diesel[10] | | Bio-diesel (mainly HVO), diesel as e-fuel | Conventional fossil diesel |
| Petrol | Vehicles ready for bio-petrol[10] | | Bio-petrol (mainly bio-ethanol), petrol as e-fuel | Conventional fossil petrol |

The technologies from Table 1 are commercially available. Existing vehicles running on fossil liquified fuels can be retrofitted for compressed natural gas (CNG), liquefied natural gas (LNG), bio-diesel or bio-petrol depending on the type of vehicle. All technologies are faced with challenges when competing with conventional fossil diesel or petrol, which are well proven technologies with well-established infrastructures. New and renewable technologies are not only more expensive, but many of the involved parties like insurance companies, authorisation bodies, plant manufacturers, installers and operators lack experience. For some services (e.g. maintenance) or material (e.g. renewable fuels or spare parts like LNG pumps or hydrogen compressors) only few suppliers are available. New business relationships have to be established in order to make use of these renewable technologies. In addition to the higher investments, this requires even higher efforts for early adopters in comparison to conventional technologies. Measures like regulations, incentives for the renewable technologies and penalties for greenhouse gas emissions are being implemented by governments helping to overcome barriers. Some of the measures are discussed in section 3.

It is important to note that all technologies for road traffic listed in Table 1 – including battery-electric vehicles – can be operated with renewable energy, with fossil-based energy or with a mixture of both.

[10] Ordinary vehicles for diesel and petrol can only cope with up to 7 % bio-diesel or 10 % bio-petrol respectively. When equipped with special features (e.g. sealing in different material, filters), they are able to cope with their respective fuel from 100 % fossil to 100 % biological origin.

Depending on the energy mix, more or less greenhouse gases are emitted. While vehicles running on liquid fuels (hybrid electric vehicles, HEV, plugin hybrid electric vehicles, PHEV, Diesel and Petrol) have to be specially equipped to be able to cope with different blends of renewable fuels, vehicles running on electricity (battery electric vehicles, BEV), hydrogen (hydrogen fuel cell electric vehicles, HFCEV) or methane (compressed natural gas, CNG, liquefied natural gas, LNG) technically can always cope with both renewable and fossil-based energy. This is because the energy form is physically identical (electricity), chemically identical (hydrogen) or the impurities in methane[11] do not have negative impacts on the technical operation of the drivetrain.

**Table 2: Methodologies used to evaluate the impact of technologies. timeline in the life of a vehicle**

<table>
<tr><td rowspan="5">Cradle-to-grave, Life Cycle Assessment (LCA) or Life Cycle Analysis</td><td colspan="3">Production of materials, vehicle, spare parts, consumables (e.g. tires, lubricants) and infrastructure (e.g. roads, fuelling and charging)</td><td rowspan="5">Timeline in the life of a vehicle ↓</td></tr>
<tr><td rowspan="3">Well-to-wheel</td><td>Well-to-tank</td><td>Supply of energy to the vehicle from the primary energy through transformation processes, storage including refuelling or charging of the vehicle.</td></tr>
<tr><td colspan="2">Final energy consumption[12] = energy supplied to the vehicle</td></tr>
<tr><td>Tank-to-wheel</td><td>Direct emissions while driving = tail pipe emissions.</td></tr>
<tr><td colspan="3">End of life, recycling, disposal</td></tr>
</table>

The environmental impact can be determined with different methods listed in Table 2. Each of them has its advantages and disadvantages and makes certain simplifications with respect to the environmental impact. The easiest is an analysis according to the Tank-to-wheel approach, where only direct emissions during operation of the vehicle are considered. These emissions can be measured or determined from the fuel consumption. The most complex is a life cycle assessment (LCA), which considers all aspects of using a technology: from producing raw materials, to manufacturing the vehicle, including the building of the required infrastructure and the disposal or recycling of vehicle and infrastructure at the end of life. Additionally, the LCA also includes emissions from the Tank-to-wheel analysis and the Well-to-tank. The latter considering emissions related to the transport, storage and transformation of the fuel including the process of charging or refuelling.

From the climate's point of view, the LCA is the relevant analysis because it is the only one that considers all greenhouse gas emissions over the lifetime of the vehicle, whereas the other approaches only consider portions of this. Regarding climate warming, it is irrelevant whether the emissions of greenhouse gas stem from producing the vehicle, operating it, disposing it or from fuel production. It is the total emissions that impact the global warming. When narrowing in on only portions of the LCA, such as Tank-

[11] Impurities in methane can be small amounts of higher hydrocarbons, hydrogen sulphide and other sulphur compounds, nitrogen or hydrogen. They depend on the origin of the gas: in the case of fossil-based methane different geographical areas and gas fields, in case of biomethane, the substrate and operation of the biogas plant lead to different impurities. The purest methane is synthetic methane from power-to-methane plants.

[12] Eurostat Glossary: https://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Final_energy_consumption

to-wheel, these values can gravely differ from the real greenhouse gas impact. Considering a larger portion of the value chain, such as Well-to-wheel can help, but it is important to keep in mind that the LCA is the closest theoretical representation of reality that we can get in this concern.

The output of each methodology can be expressed in different measures per functional unit. The most popular measure is greenhouse gas emissions expressed in $CO_2$-equivalents, where emissions other than $CO_2$ are translated into equivalents of $CO_2$ proportional to their global warming potential (GWP). A functional unit is the distance driven by a passenger car or the weight transported over a distance for a transport vehicle. The result is "$CO_2$-equivalent per km driven" (g $CO_2$/km) for passenger cars and "$CO_2$-aequivalent per ton kilometre" (g $CO_2$/tkm) for transport vehicles.

# 3 European Greenhouse Gas Regulations for Road Traffic

An overview on political measures with the aim of reducing the emissions of greenhouse gases in road traffic is given in Table 3. This is a description of the current regulation as it is applied today. This serves as a background to the critical analysis and discussion on possible improvements in the following sections 4, 5 and 6 of the article.

The Renewable Energy Directive II (RED II) regulates the ratio of renewable energies in Europe's end energy. It includes energy used in road traffic. Additionally, there are regulations considering tail pipe emissions only and hence follow a Tank-to-wheel approach: The fleet emission limits on European level, direct payments for zero and low emission passenger cars in many of the member states and a European labelling system providing information on the direct emissions of passenger cars. The terms low emission vehicle (LEV) and zero emission vehicles (ZEV) – both together called "zero and low emission vehicles" (ZLEV) – also follow a Tank-to-wheel approach because they are referring to tail pipe emissions only.

Europe's Renewable Energy Directive II sets targets for each member state to increase the share of renewable final energy used in road traffic and has to be implemented in national law by June 2021. As renewable energy, the regulation considers all renewable energy sources for the technologies listed in Table 1 page 8: biofuels, advanced biofuels[13], renewable fuels from non-biological origin (i.e. from power-to-x plants) – all three in gaseous, liquid or solid form – as well as renewable electricity. RED II contains procedures restricting the use of cropland for biofuel production.

There are two elements in the directive, where aspects of the Well-to-tank approach are included:

- To be recognized as renewable fuel, biofuels need to reduce emissions of greenhouse gases "from the production and use"[14] by 65 % and e-fuels by 70 %.
- Renewable electricity is considered "four times its energy content when supplied to road vehicles" [10][15]. Apart from being a political measure to promote electric mobility, the factor might express the increased efficiency of an electric drivetrain in comparison to an internal combustion engine. Thus, this can be seen as a consideration of a Tank-to-wheel aspect within a regulation that otherwise only looks on the Well-to-tank aspects.

[13] Advanced biofuels are made of non-food biomass versus non-advanced biofuels that can be in competition with food production.

[14] RED II Annex V, Section C Methodology. The directive contains calculation methodologies and gives preset values for certain fuel supply paths.

[15] RED II Article 27, Section 2 (b)

**Table 3: Current European regulatory measures to reduce greenhouse gas emissions from road traffic.**

| Measure | Target group | Description | Approach |
|---|---|---|---|
| **Renewable Energy Directive II (RED II)** "Promotion of the Use of Energy from Renewable Sources" Directive (EU) 2018/2001 | Fuel suppliers | Renewable energy target for 2030 of at least 32% in average[16]. Fuel suppliers to supply a minimum of 14%[17] of the energy consumed in road and rail transport by 2030 as renewable energy. Renewable energies are liquid, solid and gaseous biofuels, renewable fuels of non-biological origin (power-to-x) and renewable electricity [11]. | Well-to-tank with elements of Tank-to-wheel |
| **Fleet emission limits for passenger cars and vans:** "$CO_2$ Emission Performance Standards for New Passenger Cars and for New Light Commercial Vehicles" Regulation (EU) 2019/631 | Manufacturers of LDV | Light duty vehicles (LDV) = passenger cars and vans (LCV), penalties for each vehicle of 95 €/(g/km) for car manufacturers if their fleet of newly sold cars emits more $CO_2$ per km then a limit, which is calculated for each car manufacturer based on an average European value (see Table 4) and the weight of vehicles sold by the respective manufacturer, "eco-innovations" are also counted [12]. | Tank-to-wheel |
| **Fleet emission limits for large lorries:** "Setting $CO_2$ emission performance standards for new heavy-duty vehicles" Regulation (EU) 2019/1242 | Manufacturers of HDV | For large lorries, penalties for each vehicle of 4'250 €/(g/(tkm) from 2025 and 6'800 €/(g/(tkm) from 2030, incentives for zero- and low-emission vehicles, other heavy-duty vehicles (HDV) = small lorries, buses, coaches and trailers can be included in the 2022 revision [13]. | Tank-to-wheel |
| **Energy Consumption Labelling:** Car Labelling Directive 1999/94/EC | Buyers of passenger cars | To inform consumers, energy label for passenger cars indicating direct $CO_2$ emissions. No labels exist for light commercial vehicles (LCV) and heavy-duty vehicles (HDV).   | Tank-to-wheel |

The member states charge penalties to fuel suppliers if they fail to meet the set targets. The fuel suppliers can buy credits from other organisations, who overfulfill their quota. Since the directive only considers share of renewable final energy and does not take into consideration emissions of greenhouse gases along the supply path, it is not a complete Well-to-tank approach (see Table 2 page 9).

For vehicle manufacturers (OEMs) the EU legislative framework on EU emission standards for new road vehicles ('fleet targets') is applied. Via fleet targets OEMs are forced to reduce tail pipe emissions mean-

[16] Individual targets for every member state according to their starting point and potential for renewables ranging from 10% for Malta to 49% for Sweden

[17] Also here, individual member states have individual targets, Germany aims for 22 %.

ing the focus is on Tank-to-wheel emissions. Significant penalties are due for OEMs, if they do not succeed in meeting fleet targets. In 2020/21 the average fleet target is 95 g $CO_2$/km for cars and 147 g $CO_2$/km for vans. Allowable fleet limit values will become more strict year by year.

**Table 4: Overview on fleet emission regulations. In all categories, incentives are given for zero and low emission vehicles (ZLEV). Average European limits for emissions of $CO_2$/km are measured using the New European Driving Cycle (NEDC), they are translated into emissions determined with the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) from 2021 onwards.**

| **Vehicle types in road traffic** | | | of EU $CO_2$ emissions | **2020 to 2024** | **2025 to 2029** | **2030 onwards** |
|---|---|---|---|---|---|---|
| Road traffic | Light duty vehicles (LDV):[18] Regulation (EU) 2019/631 | Passenger cars | 12 % [12] | $95 \frac{g\,CO_2}{km}$ [19] | -15 % vs. 2021 | -37.5 % vs. 2021 |
| | | Vans = light commercial vehicles (LCV) | 2.5 % [12] | $147 \frac{g\,CO_2}{km}$ [19] | -15 % vs. 2021 | -31 % vs. 2021 |
| | Heavy duty vehicle (HDV):[20] | Large lorries: Regulation (EU) 2019/1242 | 4 % [12] | no regulation | -15 % vs. 2019/2020 | -30 % vs. 2019/2020 |
| | | Small lorries, busses, coaches and trailers | 2 % [12] | no regulation | can be included in 2022 revision of (EU) 2019/1242 | |

The approach for fleet targets does not differentiate between fossil fuels and renewable fuels. For cars and vans using combustion engines the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) is used to measure emissions. It does not matter if a renewable fuel or a fossil fuel is used. Renewable fuels e.g. Biomethane are treated as if they were fossil fuels. Consequently, car producers (OEMs) cannot count vehicles using renewable fuels to reach fleet targets. The only way to reduce fleet emission is to produce and sell electric vehicles (battery electric vehicles, BEV and HFCEV hydrogen fuel cell electric vehicles, HFCEV) or other types of zero and low emission vehicles. On the side of OEMs electric vehicles (BEV and HFCEV) are counted as zero emission vehicles neglecting the fact that only BEV fuelled with 100% renewable power and HFCEV fuelled with 100% green hydrogen have zero emissions. The origin of the electricity and of the hydrogen (coal, natural gas, renewable) is not taken into consideration.

By such two regulations the EU forces an approach which implies a split of responsibility between fuel suppliers on the one side and vehicle manufacturers on the other side. The Well-to-tank approach for fuel suppliers on the one hand and the Tank-to-wheel approach for vehicle manufacturers on the other side lead to a non-consistent strategy to reduce greenhouse gas emissions in road transport.

No current regulation is based on life cycle analysis, which is the only approach relevant to global warming. Apart from being the most complicated to be implemented in regulations and directives, international commitments like the Paris Agreement are based on territorial emissions of greenhouse gases. This means for a vehicle built in Europe, the emissions generated in the production of imported components are attributed to the country of origin, since the emissions are caused by the economy of the country of origin and not by Europe. There is no motivation of European legislators to reduce greenhouse gas emissions in foreign countries. Today, it is mostly battery-electric vehicles built in Europe using batteries from Asia that can profit from the lack of regulation based on the LCA approach.

[18] [32]

[19] 2020 for 95% of the fleet, 2021 to 2024for the full fleet

[20] [10] [33] [34] [35]

# 4 Well-to-wheel Emission Depending on Drive Train and Fuel

To illustrate the effects of the different approaches introduced in section 2, Figure 1 and Figure 2 show the Well-to-wheel emissions for passenger cars and heavy-duty vehicles (HDV) in $CO_2$ equivalent per kilometre (g $CO_2$ eq/km) and $CO_2$ equivalent per tonne-kilometre (g $CO_2$ eq/t.km) broken down by the respective Well-to-tank and Tank-to-wheel components. These values are calculations of the authors and based on the data provided by the cited sources.

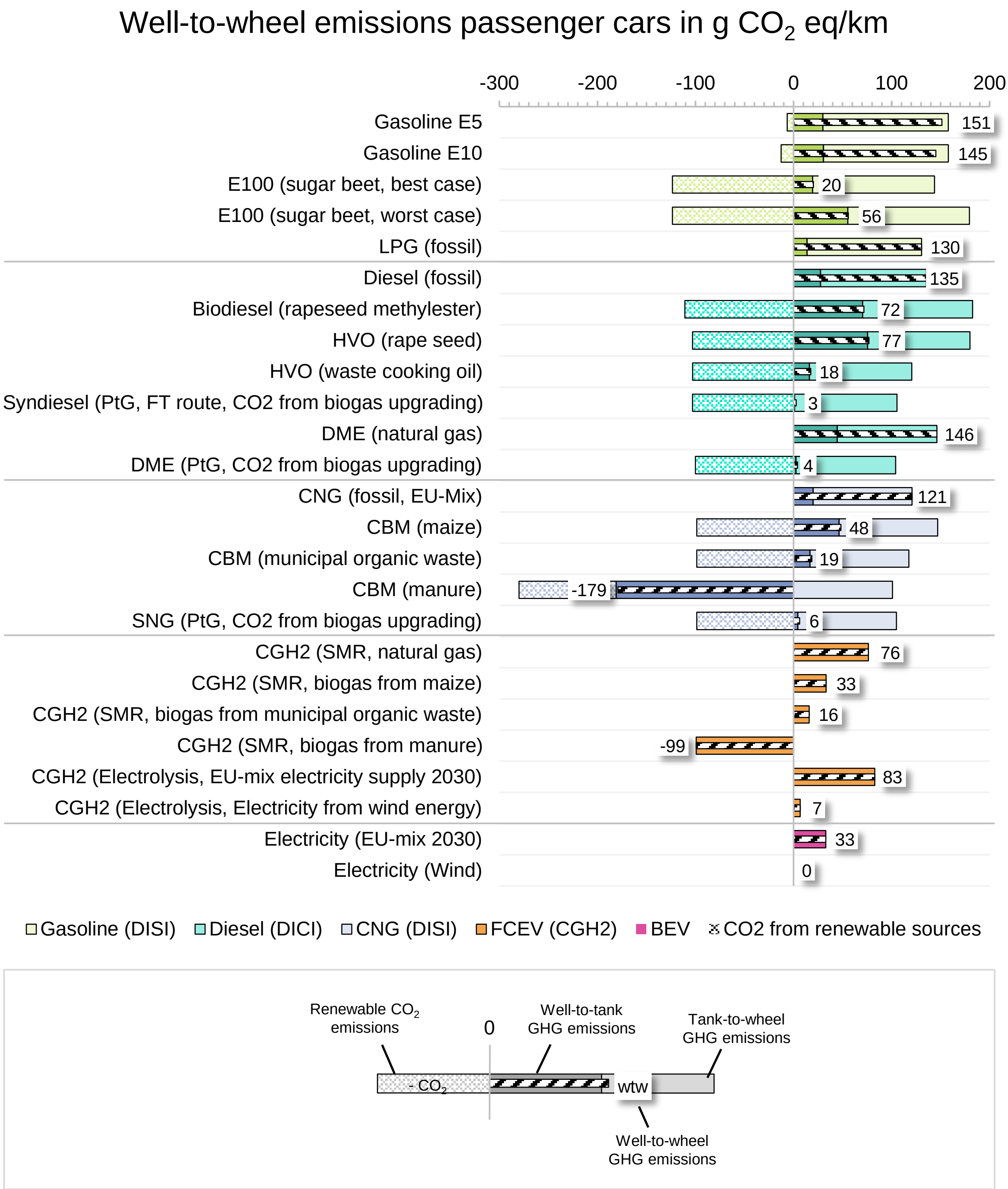
The values show that vehicles with internal combustion engines (ICEV) with renewable fuels can contribute significantly to reducing greenhouse gas emissions. However, the underlying sustainability criteria of the recast of Renewable Energy Directive II must be considered. According to the RED II, only biomass with a low risk of indirect land use change or low impact on biodiversity should be considered. In particular fuels from waste and residual materials show a high potential for a sustainable reduction of greenhouse gas emissions. For example, in the case of gas vehicles fuelled with waste-derived biomethane (compressed biomethane, CBM), greenhouse gas emissions are reduced by 87 % compared to conventional diesel vehicles. Negative greenhouse gas emissions can be achieved by using substrates whose fermentation leads to an avoidance of natural degradation processes for biomethane production. For example, by using liquid manure as fertiliser, climate-affecting gases such as nitrous oxide ($N_2O$) or methane ($CH_4$) are released through natural degradation processes. However, if the manure was previously "pre-treated" in a biogas plant, significantly fewer greenhouse gases are released due to the preceding anaerobic fermentation. According to RED II, a credit for avoided greenhouse gas emissions in the amount of -45 g $CO_2$-eq/MJ can be attributed when manure is used as a substrate for biogas plants [10][21].

In addition to biogenic fuels, electricity-based synthetic fuels from power-to-x processes will also be available in the future, which allows practically climate-neutral driving with a greenhouse gas reduction of approx. 96 % [14].

Another insight from Figure 1 is that vehicles defined as zero emission vehicles are not necessarily climate friendly. As with vehicles with internal combustion engines, the origin of the energy sources is decisive for the greenhouse gas reduction potential of the drivetrain. For example, if battery electric vehicles are charged with grid electricity, the greenhouse gas savings are rather low (-63 % compared to a conventional diesel vehicle) despite the high efficiency of the powertrain. For climate-neutral driving, the charging process should therefore be carried out exclusively with renewable electricity, even though the influence of battery production still has to be considered in a life cycle analysis.

For fuel cell electric vehicles (FCEV), too, the origin of the energy carrier (here: hydrogen) is the decisive criterion for the greenhouse gas reduction potential. While green hydrogen, which is produced e. g. from biogas or via the electrolysis of water with renewable electricity, allows almost greenhouse gas neutral vehicle operation (greenhouse gas savings of 84 % and 93 %, respectively), the greenhouse gas reduction potential of natural gas-derived "grey" hydrogen is limited and offers only minor advantages compared to conventional diesel vehicles (-22 %). The same applies to electrolysis hydrogen if the electrolyser is not operated exclusively with renewable electrical energy (-15 % lower greenhouse gas emissions when compared to the conventional diesel vehicles).

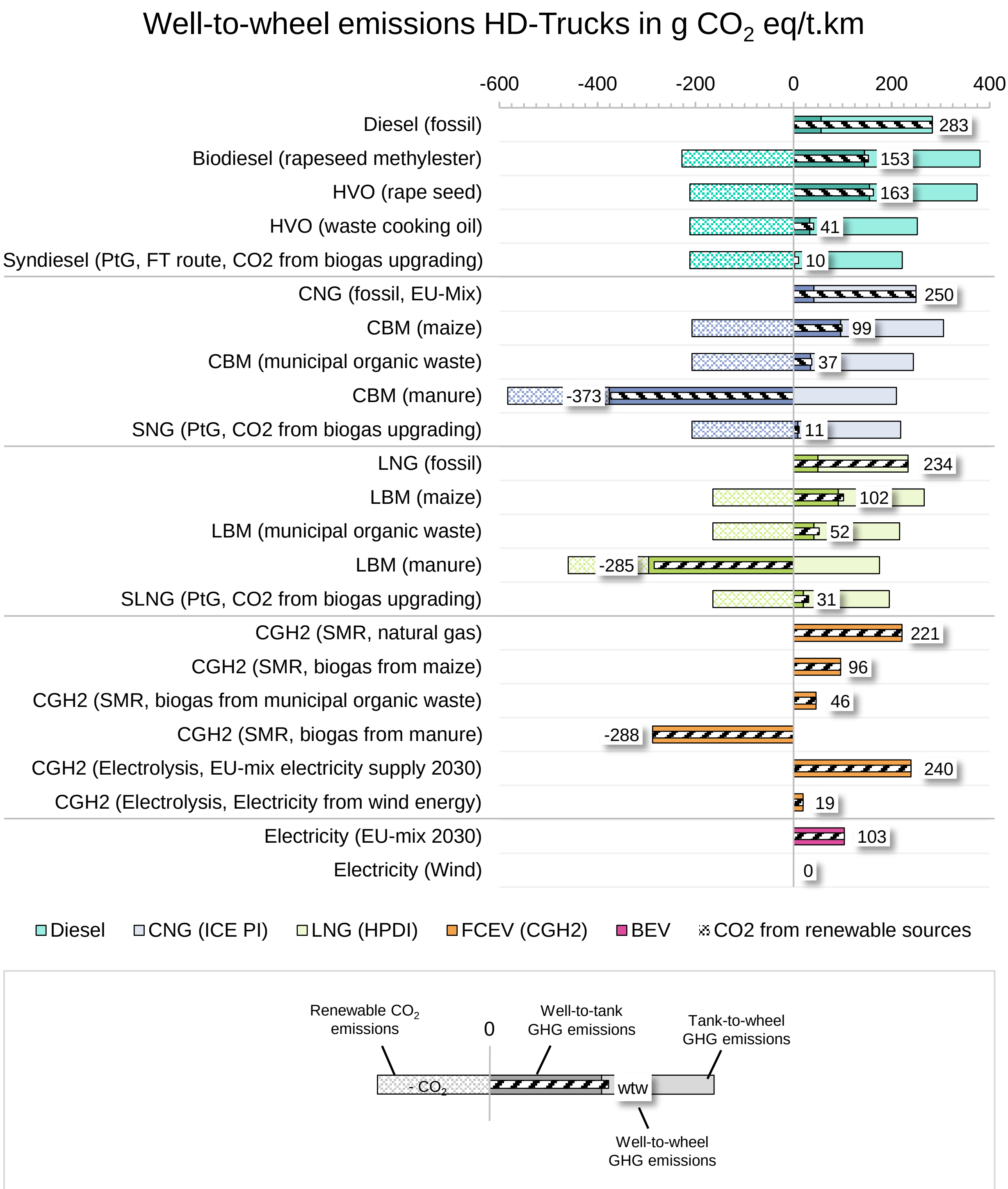
[21] Page 176 (95/128)




**Abbreviations**:

- BEV: Battery electric vehicle
- CBM: Compressed biomethane
- CGH2: Compressed gaseous hydrogen
- CNG: Compressed natural gas
- DICI: Direct Injection Compression Ignition
- DISI: Direct Injection Spark Ignition
- DME: Dimethyl ether
- E100: Ethanol (fuel)
- FCEV: Fuel cell electric vehicle
- FT: Fischer-Tropsch synthesis
- LPG: Liquefied petroleum gas
- SMR: Steam methane reforming
- PtG: Power to Gas
- SNG: Synthetic natural gas

**Figure 1: WTW emissions from passenger cars for different fuels and drivetrains, own calculations based on sources [15] [16]**




**Abbreviations**:

- HVO: Hydrogenated vegetable oil
- CNG: Compressed natural gas
- CBM: Compressed biomethane
- SNG: Synthetic natural gas
- ICE: Internal combustion engine
- FCEV: Fuel cell electric vehicle
- FT: Fischer-Tropsch synthesis
- PtG: Power to Gas (methanation)
- LNG: Liquefied natural gas
- LBM: Liquefied biomethane
- PI: Positive ignition
- BEV: Battery electric vehicle
- SLNG: Synthetic liquefied natural gas
- SMR: Steam methane reforming
- CGH2: Compressed gaseous hydrogen
- HPDI: High pressure direct injection

**Figure 2: WTW emissions from HD trucks; VECTO regional-delivery cycle; weighted payload (2.650 kg); own calculations based on sources [15] [17]**

# 5 Consequences of Greenhouse Gas Regulations

In section 3 we showed that different political measures for greenhouse gas reduction in road traffic are divided into separate regulations for Well-to-tank and Tank-to-wheel and are addressing different target groups. In section 4, the actual Well-to-wheel emissions for the different drive trains and corresponding energy carriers were stated, including the subsets of the emissions of Well-to-tank and Tank-to-wheel. In the overall analysis of this information, it has the following consequences to energy carriers, vehicle technologies and greenhouse gas emissions:

a) The regulation does not regard the greenhouse gas emissions in the manufacturing process or at the end of life. Vehicle technologies and corresponding energy carriers that have low emissions in those stages are not recognised and thus emissions emitted that influence global warming are not considered.

b) In the Renewable Energy Directive II, all energy carriers with less emissions in a Well-to-tank approach like renewable fuels and renewable electricity profit from this approach. Some caps limit the profit of some biobased fuels. Vehicle technologies are not relevant in this regulation, except regarding renewable electricity, where a four-times-factor have been implemented. Thus, all renewable fuels profit, but renewable electricity profit more.

c) As the fleet-emission regulation adopts a Tank-to-wheel approach, energy carriers with no emissions at the "tailpipe" in the category counting to greenhouse gases like electricity and hydrogen, profit regardless of being renewable origin or not. Thus, corresponding vehicle technologies profit as well. This approach takes no consideration of the portion of emission that would influence global warming.

d) The same applies to the energy labelling regulation, which is also a Tank-to-wheel approach

Since the regulations only consider portions of a full life cycle assessment and in addition to the Well-to-wheel emissions stated in section 4, it is also relevant to objectively address the ongoing debate on greenhouse gas emissions from battery production. Depending on the battery size in a battery electric vehicle and depending on the assumptions a study is based on, the production of the battery contributes more or less to the total greenhouse gas emissions during a vehicle's lifetime [18] [19] [20] [21]. Despite the disagreement on the exact scale of the problem, there is a consensus that BEV have higher greenhouse gas emissions in the production process than vehicles with internal combustion engines. It is a positive development that both consumers and manufacturers are aware of this fact. Some vehicle manufacturers respond by making production processes more efficient and by using renewable energy or by implementing battery recycling [22]. On the long run, this problem seems solvable [23] but is important to note that it is not tackled by European legislation discussed in section 3.

From a target group perspective, vehicle manufacturers are motivated to change from internal combustion engines to vehicles with battery and hydrogen energy carriers. This is independent of whether the vehicle operators use renewable electricity or electricity from a fossil power plant or whether they use green hydrogen or hydrogen produced from fossil sources.[22] Plugin hybrid electric vehicles (PHEV) are treated by fleet emission regulations as if all owners fully charge their vehicle every 100 km with no tailpipe emissions for this part of their energy use. In reality, owners can behave differently [24]. From the buyers of passenger cars perspective, it is similar. Not fully informed buyers can be somewhat deceived

[22] Most hydrogen today is produced from fossil sources, i.e. from oil or from natural gas (grey hydrogen) and is not used as energy carrier but as raw material.

by putting too much trust into the energy labelling of the vehicle as such, not regarding the actual greenhouse gas emission impact of the energy carrier deployed by them while using the vehicle, nor the impact of start and end of life of the vehicle.

The direst consequences from a stakeholder perspective are however on the fuel suppliers that serve the internal combustion engine vehicles. While they are required to supply increasing renewable chemical fuels and could potentially contribute substantially to greenhouse gas emission reduction both in short term and in long term, the vehicle manufacturers no longer have incentives to develop new vehicles for these fuels. Each regulation and the overall impact of the set of regulations set a very strong trend towards battery-electric vehicles and hydrogen fuel cell electric vehicles. Both cannot be retrofitted in existing vehicles and hence require completely new vehicle fleets. This means for example that in EU-27, 237 million passenger cars [25][23] have to be replaced, which is more than 16 years of EU-27's passenger car production[24]. Furthermore battery-electric vehicle and hydrogen fuel cell electric vehicles require new infrastructures. It is a positive development that an increasing number of both vehicle types are put into service and the respective infrastructures are being built. However, this regulation is hitting the gaseous fuels and vehicles especially hard. This is because, unlike the other internal combustion fuels and vehicles, they do not have a widespread existing fleet and thus are dependent on further development and production of the vehicle producers. This is of special concern as gaseous fuelled internal combustion engine vehicles at the same time are offering the largest potential greenhouse gas emissions reduction – going even into the sub-zero range with negative emissions, while also having a low impact in a full life cycle analysis perspective.

Our own calculations in section 4 and different studies have shown [18] that when vehicles with internal combustion engines are operated with renewable fuels, they have considerably lower greenhouse gas emissions than the current European vehicle fleet powered with fossil fuels. Renewable fuels can reduce emissions of greenhouse gas already on the short term in making use of existing infrastructures and with the possibility to retrofit existing vehicles. Furthermore, we have showed in section 2 that according to scenarios from multiple sources, chemical energy carriers are important in the future energy system. Even if intended differently by the regulators, renewable liquid fuels and renewable methane (compressed or liquefied) have difficulties to step in and utilise their short-term potential for reducing greenhouse gas emissions.

From the energy system point of view, current regulation gives a strong incentive for electrification of road traffic – which is a good development on the long run – but does not allow the biological and renewable chemical energy carriers to assume their role foreseen in the future energy system (see section 2). The consequence for the climate is that emissions of greenhouse gases are only reduced on a long run. During the transition consisting of manufacturing new vehicles and building up new infrastructure, the carbon budget available to remain below 1.5 °C warming is at severe risk of being depleted, leading to a failure of the overall ambition of the set climate targets.

[23] Page 4

[24] In 2019, EU-27 produced 14.5 Mio passenger cars according to Statista.

# 6 Suggestions for Improvement of the Greenhouse Gas Regulations and a Look to Current Suggestions in Germany and Switzerland

From a climate and scientific perspective, the life cycle assessment approach is the best available theoretical construction to mirror real greenhouse gas emissions of the technologies and energy carriers. Due to political and practical considerations mentioned in previous sections (not considering the national borders and corresponding political responsibility and its complexity), it is not regarded as a viable method to be implemented in regulation. It is important however to use it as a benchmark and starting point of discussion when comparing different regulatory options.

The current regulations are de facto pure Well-to-tank or Tank-to-wheel considerations acting on different target groups and thus very far away from a life cycle assessment approach – with all the corresponding negative implications as mentioned in the previous section. If instead applying a Well-to-wheel approach, the most crucial parts of the complete value chain would be covered. This would allow an efficient regulation supporting real reduction of greenhouse gas emissions in transport. To achieve this, a link between both regulations could be introduced. To compensate for the fact that it is still not a complete LCA and to avoid too much deviation from the actual total climate impact, it is important that the legislator monitors start of life and end of life issues. If certain vehicle technologies or energy carriers are over/undervalued in these stages, caps and factors could be implemented in the Well-to-wheel approach for compensation.

The German Federal Ministry for Economic Affairs and Energy has submitted a proposal [26] in May 2020 which aims on implementing a Well-to-wheel approach while also consider other factors. Central points are:

- **Level playing field:** A credit system for advanced, renewable gaseous and liquid fuels creates a level playing field for all alternative drive technologies to reduce greenhouse gas emissions in the transport sector and increases the scope for vehicle manufacturers who bring vehicles for these fuels to the market. Other greenhouse gas avoidance options like battery electric vehicles and fuel cell electric vehicles are not displaced, but the solution space is enlarged.
- **Permitted fuels:** Building on the existing sustainability certification system for fuels according to the Renewable Energy Directive II it must be ensured that the strict sustainability criteria are met and that fuels are not counted towards the fuel quota by the fuel suppliers **and** by the vehicle manufacturers against fleet emissions (no double counting).
- **Tradability of certificates:** Certificates for advanced, renewable gaseous and liquid fuels can be traded. OEMs are not supposed to become fuel providers themselves, but rather finance additional green fuel quantities for their own account, which fuel providers then bring onto the market.
- **Effective contribution to climate change in the transport sector**: The crediting of advanced, renewable gaseous and liquid fuels offers those OEMs an alternative to reduce emissions that would otherwise exceed their fleet target and would have to pay a fine. Without the proposed credit system, these resources would be lost. Companies are free to decide whether they want to go this route or not.
- **Maintaining affordable mobility:** Expanding emissions reduction options for OEMs will lower the economic costs of meeting sector targets. This also creates an economical, low-emission mobility option for applications in which there will be no cost-effective and practical alternatives based on alternative drives (battery electric vehicle or fuel cell electric vehicle) in the near future. The vehicle-specific approach would also enable customers who drive a green combustion engine to benefit.

By registering in the registration papers, customers receive additional advantages for vehicle tax or truck tolls.

Switzerland is currently looking to implement another approach, but with a similar intent. In a recent study, among other things, the $CO_2$ emissions of road traffic, the legal requirements (chapter 3.4) and the need for low-$CO_2$ vehicles to meet the target values, including an estimate of the $CO_2$ reduction potential of synthetic gas (chapter 3.5) have been examined [27]. Chapter 3.6 deals with real-world emissions, distinguishing between different segments and mileages.

The exact calculations are complex and require an appropriate data framework. It was found, for example, that the segmentation or mileage of the vehicles plays an important role. Therefore, a clustering method for passenger cars has been developed and submitted for publication, which will be used for vehicle market studies in the future.

The regulation in Switzerland[25] provides that, instead of paying for a penalty, emission pools can put synthetic fuels on the market if the $CO_2$ target values are exceeded. For an estimate of the cost situation, it can be calculated that 1 g$CO_2$ of exceeding the target value for a car per km with an assumed lifetime mileage of 220'000 km corresponds to a $CO_2$ emission of 0.220 t$CO_2$. Assuming a fine of CHF 95 per gram of target value exceeded, this results in a value of CHF 430/t$CO_2$. Converted into synthetic methane, this corresponds to 0.09 CHF/kWh. This can be seen as the maximum price that is conceivable for placing synthetic methane on the market.

This regulation is not yet in force but has been included in the proposal for the new $CO_2$ Act. A referendum on the $CO_2$ Act is currently underway and has been dated to June 2021.

# 7 Summary and Conclusions

The European Union and its member countries have set ambitious goals for protecting the climate. Since 1990 the greenhouse gas emissions in road transport have almost continuously increased – not decreased. In 2018 emission rates where 27% higher than in 1990. This calls for urgent adaption of the regulatory instruments to turn this negative trend around in time and for openness to all technical solutions that can contribute to real emissions reduction already today.

A critical overview of greenhouse gas emissions reduction scenarios in relation to the energy system of today and tomorrow indicates that molecule energy carriers and associated infrastructure will still have a substantial part in 2050, ranging between 60 and 40% of total energy demand. Amongst the molecule energy carriers, gas is widely considered to be the best match and crucial partner to the renewable electrical energy system offering stability, resilience and lower overall costs of the energy transition in total. Thus, technical solutions building on this form of energy should not be ruled out, but rather viewed in the light of their objective possible contribution to the solution.

In this article the boundary conditions and the mechanics of the current regulatory instruments were investigated in relation to the addressed part of the complete life cycle emissions as well as corresponding portions of the value chain and stakeholders. Systemic flaws were identified showing that there is a

[25] The regulation in the draft $CO_2$ Act (Art. 18) can be viewed at: https://www.fedlex.admin.ch/eli/fga/2020/2013/de and the implementing regulation under the following link: https://www.newsd.admin.ch/newsd/message/attachments/66110.pdf (Art. 37, Annex 5).

mismatch between the regulations (Renewable Energy Directive II and Fleet-Emissions-Regulation), the incentives of addressed stakeholders and the overall ambition of greenhouse gas reduction.

The authors recognise that this has severe consequences in relation to the ambition of the EU, not only to achieve the aspired greenhouse gas emission reduction at a minimum of costs and at minimum systemic strain, but to achieve the goal at all.

In the deeper analysis of specific effects of the current regulation on greenhouse gas emissions, target groups and corresponding vehicle technologies and energy carriers in section 5, the following major conclusions can be derived:

1. Emissions at the start and end of lifetime are not considered, which is a disadvantage for internal combustion vehicles and thus also for corresponding energy carriers and stakeholders. It is also already at this stage a deviation from considering the total emissions relevant for the climate.
2. The division between de facto Well-to-tank and Tank-to-wheel regulation for the individual target groups implies a preference for electric and hydrogen fuel cell vehicles – without correct correlation to actual total greenhouse gas emissions impacting the climate.
3. Amongst the energy carriers, gas for internal combustion vehicles is the most disadvantaged. The regulation is thereby not only disregarding the positive impact gaseous fueled internal combustion vehicles could have on emission reduction in road traffic in specific, but also stands in contrast to the crucial role gas and corresponding infrastructure will play for the energy transition in total.

In the final part of the article, suggestions were made how to mend the disruption of incentives in favour of actual total emissions reduction, at a minimum of costs and systemic strain and under consideration of practicability. In conclusion the following recommendations are given:

1. It is suggested to implement an overarching Well-to-wheel approach to achieve greenhouse gas emissions reduction in road traffic – the life cycle assessment should serve as benchmark for the legislators and compensations should be considered in regulation if appropriate.
2. It is necessary to recognize green vehicles using alternative gaseous and liquid fuels as sustainable. Extending the $CO_2$ fleet regulation and include the option for vehicle manufacturers to count additional renewable, gaseous and liquid fuels against their $CO_2$ fleet targets on a voluntary basis would provide the necessary incentive to further develop the market for climate-neutral vehicles that use advanced, renewable gaseous and liquid fuels and reduce greenhouse gas emissions.
3. The aim of a $CO_2$ regulation should be climate neutrality as early as possible. Important for a $CO_2$ regulation is that no further $CO_2$ is emitted. A vehicle fully supplied with renewable fuels (e.g. biomethane) over lifetime should be treated as a zero-$CO_2$ emission vehicle. If this is done, intermediate targets could become even stricter as additional options would become available to reduce $CO_2$ emissions faster and at lower cost specifically in long distance mobility.
4. Current suggestions discussed in Germany and prepared for implementation in Switzerland, as discussed in section 6, lead in the right direction and can serve as role models to be considered.

Vehicle manufactures should have more than just two options available to fulfil their targets and should have more flexibility during the ramp-up of the electric mobility (e.g., charging infrastructure, battery price, customer acceptance). Renewable fuels and electric vehicles have different strengths and weaknesses. The electric mobility stays superior for many customer needs. To cover other needs like long range mobility or high payload cars, while still reducing greenhouse gas emissions, manufacturers should have the possibility to implement other solutions using advanced renewable fuels in combustion engines.

In order to achieve climate goals in the mobility sector quickly and efficiently and at the same time continue to enable affordable mobility, a technology-open approach to the greenhouse gas reduction options should be permitted. The team of authors recommend using the review process of the fleet target legislation planned at EU level to create a level playing field for all renewable alternative drive options.

# 8 Bibliography


[1] European Commission, „Sustainable and Smart Mobility Strategy," Brussels, 2020.

[2] IHK Karlsruhe, „EU Green Deal: Ziele, Strategien, Maßnahmen für Klima, Umwelt, Energie, Verkehr," [Online]. Available: https://www.karlsruhe.ihk.de/fachthemen/umwelt/aktuellesumwelt/eu-green-deal-ziele-strategien-massnahmen-fuer-klima-umwelt-energie-verkehr-4909904. [Zugriff am 01 03 2021].

[3] European Energy Agency, „Greenhouse gas emissions from transport in Europe," [Online]. Available: https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-greenhouse-gases-7/assessment. [Zugriff am 01 03 2021].

[4] European Commission, DG Climate Action, European Envrionment Agency, „Annual European Union greenhouse gas inventory 1990–2018 and inventory report 2020," Brussels, 2020.

[5] European Commission, „Energy Roadmap 2050 - Impact assessment and scenario analysis, Commission staff working paper," Brussels, 2011.

[6] European Commission, „Eurostat - Final energy consumption by product," 24 01 2021. [Online]. Available: https://ec.europa.eu/eurostat/databrowser/view/ten00123/default/table?lang=en. [Zugriff am 29 01 2021].

[7] European Commission, „Eurostat - Share of renewable energy in gross final energy consumption," 27 01 2021. [Online]. Available: https://ec.europa.eu/eurostat/databrowser/view/t2020_31/default/table?lang=en. [Zugriff am 2021 01 29].

[8] Agora Energiewende and Ember, „The European Power Sector in 2020: Up-to-Date Analysis on the Electricity Transition," 2021.

[9] European Commission, „Eurostat - Final energy consumption in road transport by type of fuel," 08 02 2021. [Online]. Available: https://ec.europa.eu/eurostat/web/products-datasets/-/ten00127. [Zugriff am 05 03 2021].

[10] European Parliament, Council of the European Union, „Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources," [Online]. Available: https://eur-lex.europa.eu/eli/dir/2018/2001/oj.

[11] European Commission, „Renewable Energy – Recast to 2030 (RED II)," 23 07 2019. [Online]. Available: https://ec.europa.eu/jrc/en/jec/renewable-energy-recast-2030-red-ii. [Zugriff am 15 02 2021].

[12] European Commission, „$CO_2$ emission performance standards for cars and vans (2020 onwards)," [Online]. Available: https://ec.europa.eu/clima/policies/transport/vehicles/regulation_en. [Zugriff am 15 02 2021].

[13] European Commission, „Reducing CO2 emissions from heavy-duty vehicles," [Online]. Available: https://ec.europa.eu/clima/policies/transport/vehicles/heavy_en. [Zugriff am 15 02 2021].

[14] M. Heneka, W. Köppel, N. Trudel, S. Dr.-Ing. Bajohr, T. Henrich und J. Prof. Dr.-Ing. Sauer, „Vergleichende Bewertung von PtX-Prozessen zur Bereitstellung von Kraftstoffen aus erneuerbaren Quellen: Abschlussbericht," DVGW e.V., Bonn.

[15] M. Prussi, M. Yugo, L. De Prada, M. Padella, R. Edwards und L. Lonza, „JEC Well-to-Tank report v5," 2020. [Online]. Available: https://publications.jrc.ec.europa.eu/repository/handle/JRC119036. [Zugriff am 30 11 2020].

[16] A. Huss und P. Weingerl, „JEC Tank-to-Wheel report v5: Passenger cars," 2020. [Online]. Available: 30.

[17] M. Röck, R. Martin und S. Hausberger, „JEC Tank-to-Wheels Report v5: Heavy duty vehicles," 2020. [Online]. Available: https://publications.jrc.ec.europa.eu/repository/handle/JRC117564. [Zugriff am 30 11 2020].

[18] G. Jungmeier, L. Canella, J. Pucker-Singer und M. Beermann, „Geschätzte Treibhausgasemissionen und Primärenergieverbrauch in der Lebenszyklusanalyse von Pkw-basierten Verkehrssystemen," Graz, 2019.

[19] M. Thomas und V. Kelmelyte, „Research for TRAN Committee - Battery-powered electric vehicles: market development and lifecycle emissions," 2018. [Online]. Available: https://www.europarl.europa.eu/RegData/etudes/STUD/2018/617457/IPOL_STU(2018)617457_EN.pdf.

[20] The International Council on Clean Transportation, „Effects of battery manufacturing on electric vehicle life-cycle greenhouse gas emissions," 2018.

[21] E. Helmers, J. Dietz und M. Weiss, „Sensitivity Analysis in the Life-Cycle Assessment of Electric vs. Combustion Engine Cars under Approximate Real-World Conditions," *Sustainability,* 09 02 2020.

[22] „Fokus Ökologie: Tesla plant eigenes Batterierecycling," 24 04 2019. [Online]. Available: https://www.ingenieur.de/technik/fachbereiche/e-mobilitaet/fokus-oekologie-tesla-plant-eigenes-batterie-recycling/. [Zugriff am 21 04 2021].

[23] A. Hoekstra, „The Underestimated Potential of Battery Electric Vehicles to Reduce Emissions," *Joule,* Nr. Volume 3, Issue 6, pp. 1412-1414, 2019.

[24] D. Chakrabory, S. Hardman und G. Tal, „Why do some consumers not charge their plug-in hybrid vehicles? Evidence from Californian plug-in hybrid owners," 05 08 2020. [Online]. Available: https://iopscience.iop.org/article/10.1088/1748-9326/ab8ca5/pdf. [Zugriff am 08 03 2021].

[25] European Commission, „Transport statistics at regional level," 03 2020. [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/pdfscache/14273.pdf. [Zugriff am 12 02 2021].

[26] D. Dr. Bothe, M. Zähringer, J. Bauer, C. Dr. Sieberg und F. Korbmacher, „Crediting System for renewable fuels in EU emission standards for road transport," 2020.

[27] S. L. Teske, M. Rüdisüli, C. Bach und T. Schildhauer, „Potentialanalyse Power-to-Gas in der Schweiz," Dübendorf, 2019.

[28] Eurelectric, „Decarbonization Pathways - Full study results," 2018.

[29] Eurelectric, „Decarbonisation pathways - report," 2018.

[30] European Commission, „A Clean Planet for all, A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy," Brussels, 2018.

[31] Schweizerisches Bundesamt für Energie BFE, „Energieperspektiven 2050+," Bern, 2020.

[32] Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (DE), „Das System der CO2-Flottengrenzwerte für Pkw und leichte Nutzfahrzeuge," 2020.

[33] European Parliament, Council of the European Union, „Regulation (EU) 2019/631 on setting CO2 emission performance standards for new passenger cars and for new light commercial vehicles," [Online]. Available: https://eur-lex.europa.eu/eli/reg/2019/631/oj.

[34] European Parliament, Council of the European Union, „Regulation (EU) 2019/1242 on setting CO2 emission performance standards for new heavy-duty vehicles," [Online]. Available: https://eur-lex.europa.eu/eli/reg/2019/1242/oj.

[35] European Parliament, Council of the European Union, „Directive 1999/94/EC on the availability of consumer information on fuel economy and CO2 emissions in respect of the marketing of new passenger cars," [Online]. Available: https://eur-lex.europa.eu/eli/dir/1999/94/2008-12-11.

# Appendix

**Table 5: Visions and concepts of Europe's future and sustainable energy system. In 1990, EU28 emitted 4'172 Mio t of $CO_2$ and the final energy consumption was 37.8 TJ = 10.5 GWh**

| | | | | 2050 compared to 1990 | | Share of chemical energy carriers in final energy consumption 2050 | | |
|---|---|---|---|---|---|---|---|---|
| | **Organisation, Study, Report, Scenario, Source** | **Publication Year** | **Scenario** | **Energy related GHG emissions** | **Final energy consumption** | **fossil** | **renewable** | **total** |
| Europe | Real data | 1990 | Reality | 100 % | 100 % | 62.6 % | 10.4 % | 73 % |
| | European Commission, "Energy Roadmap 2050", Commission staff working paper [5] | 2011 | Reference scenario | 60 %[26] | 136 %[27] | 54 %[28] | 3 %[29] | 57 % |
| | | | Decarbonisation scenarios | 17 to 19 % | 81 to 90 %[30] | 27 to 29 %[31] | 9 %[32] | 36 to 38 % |
| | Eurelectric[33] "Decarbonisation Pathways" [28] [29] | 2018 | Scenario 1 | 20 %[34] | 81 %[35] | 36 %[36] | 26 % | 62 % |
| | | | Scenario 2 | 10 % | 72 % | 25 % | 27 % | 52 % |
| | | | Scenario 3 | 5 % | 64 % | 13 % | 27 % | 40 % |
| | European Commission, "A Clean Planet for All", Communication, [30] | 2018 | Power-to-X | 20 % | 70 %[37] | - | - | 59 %[38] |
| | | | Energy Efficiency | 20 % | 56 %[37] | - | - | 52 %[38] |
| | | | 1.5 °C Technical | 0 % | 58 %[37] | 0 % | 48 %[39] | 48 %[38] |
| CH | Real Data | 1990 | Reality | 100 % | 100 % | 72 % | 5 % | 77 % |
| | Swiss Energy Perspective 2050 plus from Swiss Federal Office of Energy [31] | 2020 | ZERO-Base | 0 % | 66 % | 2 % | 43 % | 45 % |

[26] Pages 19, 81
[27] Page 74, calculated
[28] Page 74, figure 7
[29] Pages 141, 158, calculated
[30] Page 121, calculated
[31] Page 122, calculated
[32] Page 141, calculated
[33] Eurelectric represents the electricity industry in Europe, www.eurelectric.org
[34] Page 9
[35] Page 17
[36] Page 19
[37] Page 70/71, compared to 2005
[38] Page 72
[39] Page 73

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