Science for a
moving society

FINAL REPORT

1313 | 2022 – Frankfurt am Main

Zukünftige Kraftstoffe: FVV-Kraftstoffstudie IVb

Transformation der Mobilität im klimaneutralen und postfossilen Zeitalter

Future Fuels: FVV Fuel Study IVb

Transformation of mobility to the GHG-neutral post-fossil age

Future Fuels: FVV Fuels Study IVb

Project no. 1452

Follow-up study: Transformation of Mobility to the GHG-neutral Post-fossil Age

---

Final report

Abstract:

Following the results of the FVV study IV "Transformation of Mobility to the GHG-neutral Post-fossil Age" FVV has asked Frontier Economics to expand the analytical framework in a follow-up study.

This study includes four important features: A more pronounced focus on the road sector, the addition of new energy carriers/powertrains (plug-in hybrid electric vehicles and Methanol-to-Gasoline drop-in fuel), explicit considerations of the technical ramp-up potential of defossilised transportation pathways ("technical bottlenecks"), as well as allowing for a combination of different energy carriers/powertrains to achieve GHG neutrality as early as possible.

In particular, this study includes achievable ramp-ups of new vehicle technologies, as well as (amongst other) power generation and distribution infrastructure and raw material supply on a quantitative basis. The ramp-up potential is of high importance to stay within the remaining theoretical GHG budget assumed for Europe in accordance with the Paris climate targets. The majority of GHG emissions is caused by the phase-out of the vehicle legacy fleet still operated with fossil fuel. Therefore, the faster a complete defossilised vehicle fleet can be introduced, the lower are the cumulative GHG emissions and thus the impact on climate change. Taking into account the technical ramp-up potential, Frontier Economics carried out an analysis of a technology-neutral mixed technologies scenario allowing for a combination of different energy carrier/powertrain pathways to achieve GHG neutrality as early as possible.

The new model-based optimisation and analytical framework used in this study explicitly addresses the question how cumulated GHG emissions in the EU27+UK road sector could be minimised. Results show that a mix of carbon-neutral pathways (energy forms and powertrain technologies) can speed up the transition to GHG neutrality significantly compared to scenarios with only one technology option. A mix of technologies thereby reduces cumulated GHG emissions over time considerably. In the context of this study, a scenario focussing on BEV ("Battery Electric Vehicles" with domestic energy sourcing) as the only GHG-neutral powertrain technology available yields 39% higher cumulated GHG emissions by 2050 compared to a mix of GHG-neutral powertrain technologies. This further translates in the single technology BEV pathway only achieving a 76 % defosssilisation rate of the EU27+UK vehicle stock by 2050 – while the GHG optimised mixed technology scenario achieves carbon-neutrality (100% defossolisation rate) by the year 2039 already.

The objective of the research project was achieved.

Duration:	01.11.2021 – 30.09.2022
Funding organisation(s):	FVV eV // Science for a moving society (FVV)
Funding number(s):	FVV 601452

RTD performer:
Frontier Economics Ltd., Köln
Head: Dr. David Bothe

Authors:
Dr.-Ing. Ulrich Kramer (Ford-Werke GmbH)
Dr. David Bothe (Frontier Economics Ltd.)
Dr. Christoph Gatzen (Frontier Economics Ltd.)
André Pfannenschmidt (Frontier Economics Ltd.)
Carolin Baum (Frontier Economics Ltd.)
Fabian Schrogl (Frontier Economics Ltd.)
Osama Mahmood (Frontier Economics Ltd.)

Counsellors:
Dr.-Ing. Karsten Wilbrand (Shell Global Solutions GmbH)
Dr.-Ing. Ingo Mikulic (Shell Global Solutions GmbH)
Svetlana van Bavel (Shell Global Solutions B.V.)
Andreas Schleiffer (Deutsche BP AG Global Fuels Technology)
Dr. Norbert Neumann (Deutsche BP AG Global Fuels Technology)
Dr.-Ing. Uta Weiss (Mabanaft GmbH & Co. KG)
Dr. William Lilley (Aramco Fuel Research Center)
Victor Gordillo (Aramco Fuel Research Center)
Dipl.-Ing. Dietmar Schwarzenthal (Porsche AG)
Dr. Lars Menger (BMW AG)
Corentin Prié (Audi AG)
Dr. rer. nat. Jörg Wind (Mercedes Benz AG Cell Technology)
Dipl.-Ing. (FH) Paul Decker-Brentano (Toyota Gazoo Racing Europe GmbH)
Stefan Kaimer (Ford-Werke GmbH)
Christian Hofmann (Ford-Werke GmbH)
Dr.-Ing. Sebastian Barth (Honda R&D Europe GmbH)
Dipl.-Ing. Florian Raß (Honda R&D Europe GmbH)
Dr. Uwe Heßler (Rolls-Royce Deutschland Ltd. &Co KG)
Dr. Stefan Koch (MAN Energy Solutions SE)
Christian Obermeier (MAN Energy Solutions SE)
Torsten Buddenberg (Mitsubishi Heavy Industries EMEA Ltd.)
Florian Möllenbruck (Mitsubishi Heavy Industries EMEA Ltd.)
Dr.-Ing. Ansgar Christ (Robert Bosch GmbH)
Matthias Mansbart (Robert Bosch GmbH)
Mario Kuschel (CAC Chemieanlagenbau Chemnitz GmbH)
Dr.-Ing. Toni Raabe (CAC Chemieanlagenbau Chemnitz GmbH)
Klaus Reuhl (CAC Chemieanlagenbau Chemnitz GmbH)
Dr. Peter Prenninger (AVL List GmbH)
Dipl.-Ing. Marc Sens (IAV GmbH)
Dr. rer. nat. Michael Harenbrock (MANN+HUMMEL GmbH)
Dr.-Ing. Thorsten Schnorbus (FEV Europe GmbH)
Dr. Benjamin Rausch (Freyberger Engineering GmbH)
Dipl.-Ing. Maximilian Heneka (DVGW-Forschungsstelle am Engler-Bunte-Institut des Karlsruher Instituts für Technologie)
Wolfgang Köppel (DVGW-Forschungsstelle am Engler-Bunte-Institut des Karlsruher Instituts für Technologie)
Dr.-Ing. Olaf Toedter (KIT Campus Transfer GmbH)
Frank Dünnebeil (ifeu GmbH Institut für Energie- und Umweltforschung Heidelberg)

Dr. Monika Dittrich (Institut für Energie- und Umweltforschung Heidelberg GmbH, ifeu)
Axel Liebich (Institut für Energie- und Umweltforschung Heidelberg GmbH, ifeu)
Dipl.-Geol. Siyamend Al Barazi (Deutsche Rohstoffagentur at the Federal Institute for Geosciences and Natural Resources)
BEng, CEng, MIMechE Trevor Downes (Ricardo UK Ltd.)
Dr. Richard Osborne (Ricardo UK Ltd.)
Dr. Simon Edwards (Ricardo UK Ltd.)
Simon Terry (Ricardo UK Ltd.)
Dipl.-Wirt.-Ing. Ralf Thee (FVV)

Project coordination / user committee: Dr.-Ing. Ulrich Kramer (Ford-Werke GmbH)

Scientific advisory committee chair: Dr.-Ing. Andreas Kufferath (Robert Bosch GmbH)

Related reports: R603 (2022)

Note

The FVV Fuels Study IVb “Follow-up study: Transformation of Mobility to the GHG-neutral Post-fossil Age” has been prepared for general guidance only. The reader should not act on any information provided in this study without receiving specific professional advice. FVV does not guarantee the correctness, accuracy and completeness of the information and shall not be liable for any damage resulting from the use of information contained in this study.

Acknowledgement

This report is the scientific result of a research project (follow-up study) undertaken by the FVV eV and performed by Frontier Economics Ltd. in Cologne under the direction of Dr. David Bothe.

The FVV would like to thank Dr. Bothe and his colleagues – Dr. Christoph Gatzen, André Pfannenschmidt, Carolin Baum, Fabian Schrogl, Osama Mahmood (all Frontier Economics Ltd.) – for the implementation of the project. The project was conducted by an expert group led by Dr.-Ing. Ulrich Kramer (Ford-Werke GmbH). We gratefully acknowledge the support received from the project coordination and from all members of the project user committee.

In addition, the authors gratefully acknowledge the support received from the FVV and from all those involved in the project.

The research project was self-financed (funding no. 601452) by the FVV eV.

Table of contents

1 Executive summary

1.1 Executive summary (EN)

As part of its “Green Deal” the European Union (EU) is striving to achieve zero net emissions of greenhouse gases (GHG) across all sectors by 2050.[1] For the European road sector this goal can only be achieved with carbon-neutral energy carriers and accordingly compatible powertrains, replacing combustion engine powered vehicles using fossil energy carriers such as diesel and gasoline prevalent today. As such, to reach a carbon-neutral road sector and meet both, national as well as European CO_2 reduction targets, appropriate concepts for the road sector are required.

However, it is yet a fundamental deficit of the current EU policy approach, such as the EU “Fit for 55” package, as well as EU’s “Green Deal” aiming for net zero emissions by 2050 across all sectors, to predominantly focus on sector-specific measures. Fleet emission targets as laid out in the EU “Fit for 55” package, as well as (amongst others) the 100% GHG emission reduction target by 2035 for passenger cars, exclusively take into account tailpipe emissions of the respective vehicles (so called “Tank-to-Wheel” (TtW) emissions) – while ignoring any emissions from vehicle production or the associated energy supply chain (so called “Well-to-Tank” (WtT) emissions). Many studies, including FVV’s life-cycle analysis meta study[2], evidence why a narrow regulatory focus on sector-specific policy interventions may fail to reach the climate objectives by neglecting the benefits of an effective technology mix across sectors.

In 2021 FVV provided a comprehensive analysis (Fuels Study IV) of 7 different powertrain technology / energy carrier pathways “technology pathways”for the European transport sector with regards to their overall infrastructure requirement, costs and associated emissions (“Well-to-Wheel” (WtW) emissions).[3] The study concluded that overall cumulated emissions vary much less across different technology pathways (e.g. electric vehicles vs. vehicles with combustion engines operated with carbon-neutral energy carriers) than typically expected. In fact, **the speed of deploying GHG-neutral mobility solutions (complete GHG-neutral technology pathways on a WtW basis) is much more important than the choice of technologies.** The faster a defossilised vehicle fleet can be introduced, the lower are the cumulative GHG emissions and thus the impact on climate change.

In this context, this FVV Fuels Study IVb further explores the transition of the European road sector towards climate-neutrality by 2050. Consistent with the previous Fuels Study IV we consider various powertrain technologies and energy carrier pathways, all of which are exclusively based on renewable energy sourcing through wind and solar generation capacities.

Compared to the precedent study, this study includes four important features: A more pronounced focus on the road sector, the addition of new energy carrier/powertrain pathways (plug-in hybrid electric

---

[1] European Commission (2022), „A European Green Deal”, https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en#timeline (last accessed: 08.09.2022).

[2] FVV (2020), “Primemovers – Bilanz gezogen: FVV-Metastudie zur Lebenszyklusanalyse alternativer Antriebe“, https://www.primemovers.de/de/denken/bilanz-gezogen (last accessed: 08.09.2022).

[3] FVV (2021), “FVV Future Fuels Study IV: Transformation of Mobility to the GHG-neutral Post-fossil Age”, https://www.fvv-net.de/fileadmin/user_upload/medien/download/FVV__Future_Fuels__StudyIV_The_Transformation_of_Mobility__H1269_2021-10__EN.pdf (last accessed: 08.09.2022).

vehicles and Methanol-to-Gasoline drop-in fuel), explicit considerations of the technical ramp-up potential of defossilised transportation pathways (“technical bottlenecks”), as well as allowing for a combination of different energy carriers/powertrains to achieve GHG neutrality as early as possible.

In particular, this study includes achievable ramp-ups of new vehicle technology, power generation and distribution infrastructure as well as raw material supply on a quantitative basis. In seven expert groups over 50 experts from more than 40 companies and organisations identified the maximum (technically) achievable build-up rate for production and installation of vehicles and infrastructure – assuming ideal legal and financial conditions for each investigated energy carrier/powertrain pathway. As shown in the preceding study (FVV Fuels Study IV), the ramp-up potential is of high importance to meet the Paris climate targets. The majority of GHG emissions is caused by the phase-out of the vehicle legacy fleet which is still operated with fossil energy carriers. Therefore, the faster a defossilised vehicle fleet can be introduced, the lower are the cumulative GHG emissions and thus the impact on climate change. Taking into account the technical ramp-up potential, Frontier carried out an analysis of technology-neutral mixed technologies scenarios allowing for a combination of different energy carriers/powertrains to achieve GHG neutrality as early as possible.

In line with national GHG emission inventories, this study properly reflects GHG emissions in the year when they physically occur. Accordingly, we do not artificially distribute emissions resulting from vehicle production and energy supply chain infrastructure over their operational life (e.g. in terms of years, km, energy output) as assumed in many other studies evaluating the environmental impact of the transition towards a decarbonised energy system.[4]

Our new model-based optimisation in combination with the analytical framework used in this study, therefore, explicitly addresses the question how cumulated GHG emissions in the EU27+UK road sector could be minimised.

We evaluate a total of 11 carbon neutral pathways, both in their respective single technology scenarios (where only a single carbon-neutral energy carrier/powertrain selected upfront is available for all vehicles) as well as in a technology-neutral mixed technologies scenario (where all carbon-neutral energy carriers/powertrains are available and, therefore, may vary over vehicle types and time). In each case, we explicitly take into account achievable ramp-ups of new vehicle technology, power generation and distribution infrastructure and raw material supply on a quantitative basis. Our main optimisation target is to minimise cumulated GHG emissions over the period 2020 to 2050.

The results can be summarised as follows:

- **A mix of carbon-neutral energy carrier/powertrain pathways can speed up the transition to GHG neutrality for the EU27+UK road sector:** Our study shows that all carbon-neutral pathways face bottlenecks of various kinds, constraining the maximal deployment rate for each individual technology. A mix of technologies can, therefore, accelerate the penetration of carbon-neutral energy carrier and powertrain technology pathways (“technology pathways”) significantly (see **Figure 1** and **Figure 2** below). A combination of technology pathways could

---

[4] See deep-dive in Section 3.1 of this study.

thereby reduce cumulated GHG emissions significantly: For example, a scenario focussing on BEV (with domestic energy sourcing) as the only GHG-neutral technology pathway available yields to 39% higher cumulated GHG emissions by 2050 compared to a mix of GHG-neutral technology pathways. This further translates in the single technology BEV pathyway only achieving a 76 % defossilisation rate of the EU27+UK vehicle stock until 2050 – while the GHG optimised mixed technology scenario allows to achieve carbon-neutrality (100% defossolisation rate) by the year 2039 already.

- **The decisive factor to minimise GHG emissions is the fastest possible departure from fossil fuels – infrastructure and material bottlenecks need to be addressed quickly:** In order to minimise GHG emissions in the EU27+UK road sector infrastructure and material bottlenecks need to be addressed quickly. This holds in particular for the necessary scale-up of infrastructure and material availability across technologies.
- **E-fuels provide a unique technology option to carbon-neutrally operate the existing fleet:** Backward compatible energy carriers such as e-gasoline and e-diesel (e.g. via Methanol-to-Gasoline and Fischer-Tropsch pathways) allow a quick defossilisation of the existing vehicle fleet once they become available at large scale. Despite long lead times for setting up synthesis plants, they can, therefore, accelerate overall GHG reductions.
- **Banning ICE vehicles from 2035 would lead to higher GHG emissions than necessary:** While a defossilisation of the EU27+UK road sector could also be achieved without ICE vehicles, this would in turn increase cumulated emissions and cumulated total costs, as it further reinforces dependencies on critical technical bottlenecks and limits the option to accelerate further defossilisation through compatible synthetic energy carriers (e-gasoline, e-diesel) to any existing ICE vehicle fleet.[5]
- **Shifting the heavy-duty segment towards carbon-neutral technology pathways is a big lever to enable significant GHG emission savings:** While heavy-duty vehicles only make up for approx. 2% of the EU27+UK vehicle stock, they account for approx. 45% of today's overall total fuel consumption of the European road sector.[6] Therefore, they hold an enormous potential for GHG emission savings.

---

[5] We note that in the ICE ban scenarios considered in this study it is still possible to operate the existing legacy fleet with e-fuels until the end of their lifetime, see Section 6.2. In contrast, new vehicles registered after an effective ICE ban (i.e. in 2035) cannot be operated with e-fuels and therefore rely on technology pathways excluding internal combustion engines. While this approach may seem unrealistic under the current EU "Fit for 55" policy approach, it is consistent with our general assumption in this study assuming ideal financial and legal conditions for all powertrain technologies available.

[6] Assessment by Frontier Economics based on ACEA data. See ACEA (2022a), "Vehicles in use Europe 2022", https://www.acea.auto/files/ACEA-report-vehicles-in-use-europe-2022.pdf (last accessed: 08.09.2022).

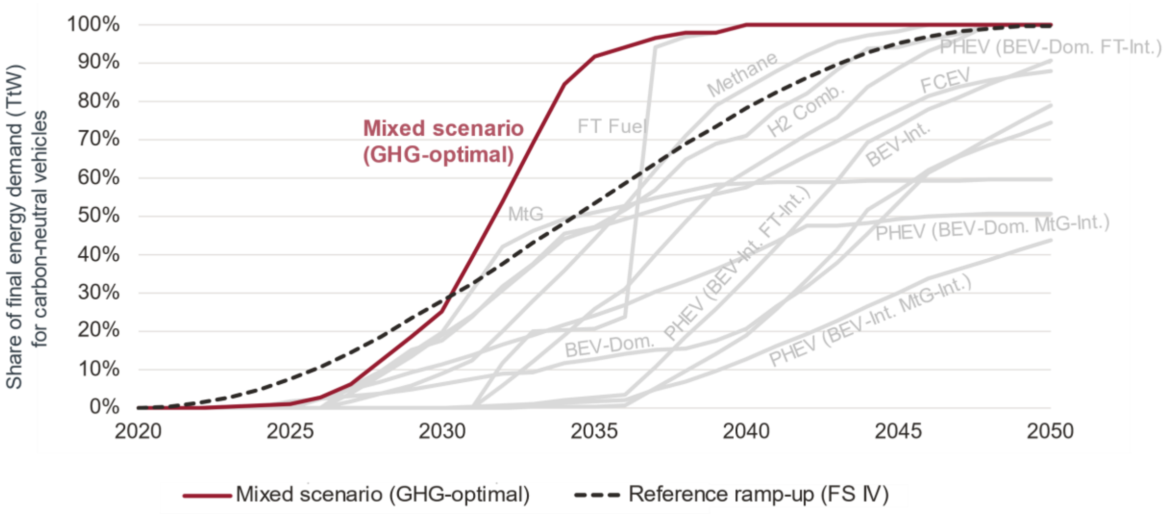


Figure 1: Share of carbon-neutral TtW energy demand in GHG-optimal mixed technologies scenario; single technology scenarios greyed out.

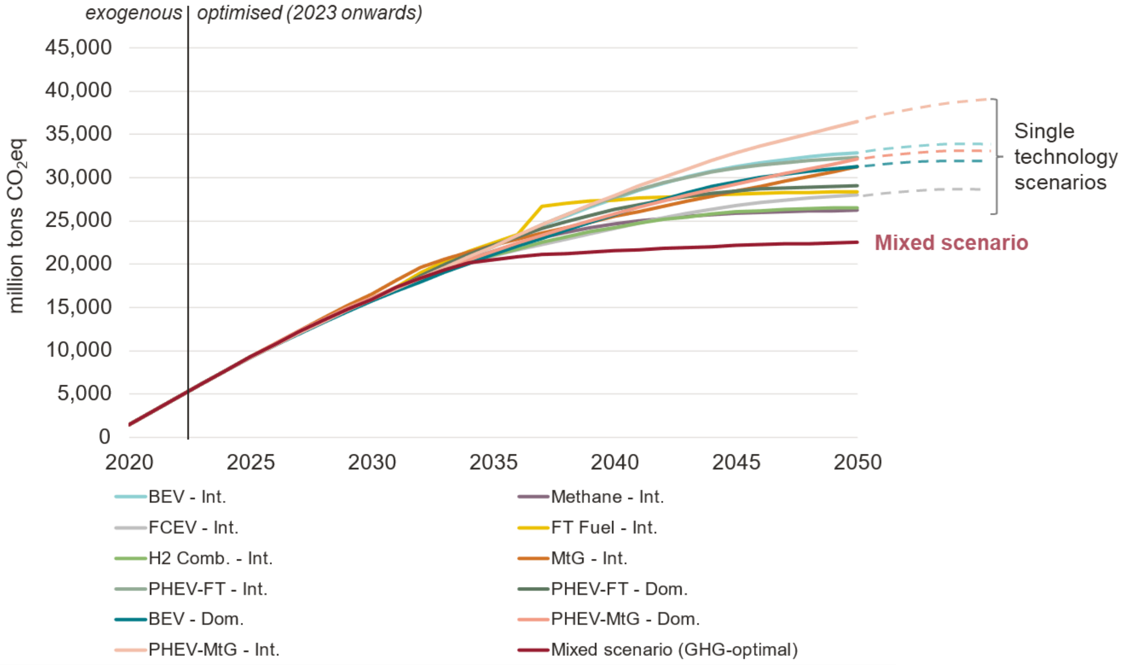


Figure 2: Cumulated GHG emissions in mixed technologies scenario and single technology scenarios. Note: Given technical bottlenecks and vehicle lifetime assumptions, no full decarbonisation is reached in single technology scenarios of BEV Dom./Int., FCEV, PHEV-FT Int. and PHEV-MtG Int. by 2050 (dashed lines).

1.2 Executive summary (DE)

Im Rahmen des "Green Deal" strebt die Europäische Union (EU) an, bis zum Jahr 2050 über alle Sektoren hinweg den Nettoausstoß von Treibhausgasen (THG) auf Null zu reduzieren.[7] Für den europäischen Straßenverkehrssektor kann dieses Ziel nur mit THG-neutralen Kraftstoffen und Antriebssträngen erreicht werden, die den heute noch üblichen Fahrzeugbetrieb mit Verbrennungsmotoren und fossilen Kraftstoffen wie Diesel und Benzin ablösen. Um einen klimaneutralen Straßenverkehrssektor zu

---

[7] Europäische Kommission (2022), „A European Green Deal“, https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en#timeline (zuletzt abgerufen: 08.09.2022).

erreichen und sowohl die nationalen als auch die europäischen CO_2-Reduktionsziele zu erfüllen, sind daher zukunftsorientierte Konzepte für den Straßenverkehrssektor erforderlich.

Es ist jedoch ein zentrales Defizit des aktuellen EU-Politikansatzes, wie z.B. des EU-Pakets "Fit for 55" sowie des "Green Deal", sich vorwiegend auf sektorspezifische Maßnahmen zu konzentrieren. Flottenemissionsziele, wie sie im „Fit for 55"-Paket der EU festgelegt sind, sowie (unter anderem) das Ziel einer 100-prozentigen Reduzierung der THG-Emissionen bis 2035 für PKW, berücksichtigen ausschließlich die direkten Emissionen der Fahrzeuge am Auspuff (sog. „Tank-to-Wheel"-Emissionen), während Emissionen aus der Fahrzeugproduktion oder der zugehörigen Versorgungskette für Energie von der Förderung bis zum Endverbrauch (sog. „Well-to-Tank"-Emissionen) außer Acht gelassen werden. Viele Studien, darunter auch die Lebenszyklusanalyse-Metastudie der FVV[8], belegen, wie ein enger regulatorischer Fokus auf sektorspezifische Maßnahmen zu verfehlten Klimazielen führen kann, da die Vorteile eines effektiven, sektorübergreifenden Technologie-Mixes vernachlässigt werden.

Im Jahr 2021 hat die FVV eine umfassende Analyse (Kraftstoffstudie IV) von 7 verschiedenen Fahrzeug-Antriebstechnologien ("Powertrains") für den europäischen Verkehrssektor im Hinblick auf ihren gesamten Infrastrukturbedarf, ihre Kosten und die damit verbundenen THG-Emissionen (WtW-Emissionen) vorgelegt.[9] Die Studie kam zu dem Ergebnis, dass die kumulierten Gesamtemissionen zwischen den verschiedenen Antriebsarten (z.B. Elektro- vs. Verbrennungsmotoren, die mit THG-neutralen Kraftstoffen betrieben werden) weit weniger variieren als üblicherweise erwartet. **Tatsächlich ist die Geschwindigkeit, mit der THG-neutrale Mobilitätslösungen (vollständige THG-neutrale Pfade auf WtW-Basis) eingeführt werden, viel wichtiger als die Wahl der Technologien.** Je schneller eine defossilisierte Fahrzeugflotte verfügbar ist, desto geringer sind die kumulierten THG-Emissionen und damit die Effekte auf den Klimawandel.

In diesem Zusammenhang untersucht die FVV-Kraftstoffstudie IVb den Übergang des europäischen Straßenverkehrssektors zur Klimaneutralität bis 2050 weiter. In Anlehnung an die vorangegangene Kraftstoffstudie IV werden verschiedene Fahrzeug-Antriebstechnologien und Wertschöpfungsketten der THG-neutralen Energieträger betrachtet, die alle ausschließlich auf erneuerbaren Energien aus Wind- und Solaranlagen basieren.

Im Vergleich zur Vorgängerstudie weist diese Studie vier wichtige, zusätzliche Charakteristika auf: Eine stärkere Fokussierung auf den Straßenverkehrssektor, die Hinzunahme neuer Energieträger-/ Antriebspfade (Plug-in-Hybrid-Fahrzeuge und Methanol-to-Gasoline als Drop-In-Kraftstoff), die explizite Berücksichtigung des technischen Hochlauf-Potenzials THG-neutraler Wertschöpfungsketten ("technische Bottlenecks") sowie die Berücksichtigung einer Kombination verschiedener Energieträger und Fahrzeug-Antriebspfade im „Mix-Szenario“, um möglichst früh Treibhausgasneutralität im europäischen Straßenverkehrssektor zu erreichen.

---

[8] FVV (2020), “Primemovers – Bilanz gezogen: FVV-Metastudie zur Lebenszyklusanalyse alternativer Antriebe“, https://www.primemovers.de/de/denken/bilanz-gezogen (zuletzt abgerufen: 08.09.2022).

[9] FVV (2021), “FVV Future Fuels Study IV: Transformation of Mobility to the GHG-neutral Post-fossil Age”, https://www.fvv-net.de/fileadmin/user_upload/medien/download/FVV__Future_Fuels__StudyIV_The_Transformation_of_Mobility__H1269_2021-10__EN.pdf (zuletzt abgerufen: 08.09.2022).

Insbesondere werden in dieser Studie maximal erreichbare Hochläufe („Ramp-Ups“) neuer Fahrzeugtechnologien, die dafür notwendigen Stromerzeugungskapazitäten und Infrastruktur der Wertschöpfungskette bis zum Endverbraucher sowie die Rohstoffverfügbarkeit auf quantitativer Basis berücksichtigt. In sieben Expertengruppen ermittelten über 50 Experten aus mehr als 40 Unternehmen und Organisationen die maximal (technisch) erreichbaren Hochläufe für die Produktion und Installation von THG-neutralen Fahrzeugen und dazugehöriger Infrastruktur der benötigten Wertschöpfungskette je Fahrzeug-Antriebsart. Zentrale Annahme waren ideale rechtliche und finanzielle Rahmenbedingungen für jede untersuchte THG-neutrale Energieform und den dazugehörigen Fahrzeug-Antriebspfad.

Wie in der vorangegangenen Studie (FVV-Kraftstoffstudie IV) gezeigt, ist das Ausbaupotenzial der gesamten Wertschöpfungskette, die für die Nutzung THG-neutraler Energieträger und Fahrzeug-Antriebe notwendig ist, von großer Bedeutung, um die Pariser Klimaziele zu erreichen. Der Großteil der THG-Emissionen wird durch den Ausstoß durch den Teil der Fahrzeugflotte verursacht, der noch mit fossilen Energieträgern betrieben wird. Je schneller eine defossilisierte Fahrzeugflotte eingeführt werden kann, desto geringer sind die kumulierten THG-Emissionen und damit die Effekte auf den Klimawandel. Unter Berücksichtigung des technischen Hochlauf-Potenzials hat Frontier eine Analyse durchgeführt, die unter anderem eine Kombination verschiedener Energieträger bzw. Fahrzeug-Antriebsstränge ermöglicht, um so früh wie möglich THG-Neutralität zu erreichen und technische Restriktionen einzelner THG-neutraler Mobilitätspfade zu umgehen.

In Übereinstimmung mit der Methodologie nationaler THG-Bilanzen spiegelt diese Studie die Treibhausgasemissionen vollständig in dem Jahr wider, in dem sie tatsächlich anfallen. Dementsprechend verteilen wir die Emissionen, die aus der Fahrzeugproduktion und der Infrastruktur der Energie-Wertschöpfungskette resultieren, nicht künstlich über ihre Betriebsdauer (z. B. in Form von Jahren, Kilometern oder Energiemenge), wie dies in vielen anderen Studien zur Bewertung der Umweltauswirkungen des Übergangs in ein dekarbonisiertes Energiesystem angenommen wird.[10]

Unsere neue modellbasierte Optimierung in Kombination mit dem in dieser Studie verwendeten analytischen Rahmen befasst sich daher explizit mit der Frage, wie die kumulierten THG-Emissionen im Straßenverkehrssektor der EU27+UK minimiert werden können.

Wir bewerten insgesamt 11 THG-neutrale Pfade, sowohl in ihren jeweiligen Einzeltechnologieszenarien (in denen jeweils nur ein einziger, zuvor festgelegter THG-neutraler Energieträger bzw. Fahrzeug-Antriebsstrang für alle Fahrzeuge verfügbar ist) als auch in einem technologieneutralen „Mix-Szenario“ (in dem alle THG-neutralen Energieträger bzw. Fahrzeug-Antriebsstränge verfügbar sind und über Fahrzeugtypen und Zeit variieren können). In jedem Fall berücksichtigen wir explizit die erreichbaren Hochläufe der neuen Fahrzeugtechnologie, die dafür notwendigen Stromerzeugungskapazitäten und Infrastruktur der Wertschöpfungskette bis zum Endverbraucher sowie die Rohstoffverfügbarkeit auf quantitativer Basis. Unser zentrales Ziel der mathematischen Optimierung ist die Minimierung der kumulierten Treibhausgasemissionen im Zeitraum 2020 bis 2050.

---

[10] Siehe Deep-Dive in Sektion 3.1 dieses Reports.

Die Ergebnisse lassen sich wie folgt zusammenfassen:

- **Ein Mix aus THG-neutralen Energieträgern bzw. Fahrzeug-Antriebspfaden kann den Übergang zur THG-Neutralität für den Straßenverkehrssektor der EU27+UK beschleunigen:** Unsere Studie zeigt, dass alle THG-neutralen Antriebspfade mit technischen Engpässen („Bottlenecks“) verschiedener Art konfrontiert sind, die den maximalen Hochlauf für jede einzelne THG-neutrale Technologie einschränken. Ein Technologiemix kann daher den Hochlauf THG-neutraler Fahrzeug-Antriebe erheblich beschleunigen (siehe **Abbildung 1** und **Abbildung 2** unten). Eine Kombination von Antriebstechnologien könnte somit die kumulierten Treibhausgasemissionen erheblich reduzieren: Beispielsweise führt ein Szenario, das sich auf batterieelektrische Fahrzeuge (mit europäischer Energieversorgung) als einzige verfügbare THG-neutrale Antriebstechnologie konzentriert, zu 39 % höheren kumulierten THG-Emissionen bis 2050 im Vergleich zu einem Mix aus THG-neutralen Antriebstechnologien. Weiterhin wird bei Konzentration auf BEV als einzige verfügbare THG-neutrale Antriebstechnologie nur eine Defosssilisierungsrate von 76 % des EU27+UK-Fahrzeugbestands bis 2050 erreicht. Demgegenüber ermöglicht das THG-optimierte Technologiemix-Szenario bereits bis zum Jahr 2039 Klimaneutralität (100% Defossolisierungsrate).
- **Entscheidend für die Minimierung der THG-Emissionen ist der schnellstmögliche Ausstieg aus fossilen Energieträgern - Infrastruktur- und Rohstoffengpässe müssen schnell behoben werden:** Um die THG-Emissionen im Straßenverkehrssektor der EU27+UK zu minimieren, müssen Infrastruktur- und Rohstoffengpässe schnell behoben werden. Dies gilt insbesondere für den notwendigen Hochlauf der benötigten Infrastruktur für alternative Antriebsarten und die Verfügbarkeit von Materialien für die verschiedenen Technologien.
- **E-Fuels bieten eine einzigartige technologische Option für den klimaneutralen Betrieb der Bestandsflotte:** Rückwärtskompatible Kraftstoffe wie synthetisches Benzin und synthetischer Diesel (z. B. über Methanol-to-Gasoline- und Fischer-Tropsch-Herstellungspfade) ermöglichen eine schnelle Defossilisierung der bestehenden Flotte, sobald diese in großem Maßstab verfügbar sind. Trotz der langen Vorlaufzeiten und Planungshorizonte für die Errichtung der notwendigen Syntheseanlagen können E-Fuels daher die THG-Reduktion deutlich beschleunigen.
- **Ein Verbot von Verbrennungsmotoren ab 2035 würde zu höheren THG-Emissionen führen als nötig:** Zwar ließe sich eine Defossilisierung des Straßenverkehrssektors der EU27+UK in der vorliegenden Modellierung ohne Fahrzeuge mit Verbrennungsmotor erreichen, doch würde dies die kumulierten THG-Emissionen und kumulierten Gesamtkosten bis 2050 gegenüber dem technologieneutralen Mix-Szenario erhöhen. Ein Verbot von Verbrennungsmotoren verstärkt die Abhängigkeiten gegenüber kritischen technischen Hochläufen der notwendigen Infrastruktur für alternative Antriebstechnologien entlang der gesamten Wertschöpfungskette. Es schränkt zudem die Möglichkeit ein, die weitere Defossilisierung der Fahrzeug-Flotte durch den Einsatz kompatibler synthetischer

Energieträger (E-Benzin, E-Diesel) in Fahrzeugen mit Verbrennungsmotoren zu beschleunigen.[11]

- **Die Umstellung des Lastkraftverkehrs und schwerer Nutzfahrzeuge auf THG-neutrale Antriebe ist ein wichtiger Hebel, um erhebliche Emissionseinsparungen zu realisieren:** Während der Lastkraftverkehr und schwere Nutzfahrzeuge nur ca. 2 % des Fahrzeugbestands in der EU27+UK ausmachen, sind sie für ca. 45 % des heutigen Gesamtkraftstoffverbrauchs im europäischen Straßenverkehrssektor verantwortlich.[12] Sie bergen damit enormes Potenzial für die Einsparung von Treibhausgasemissionen bei Umstellung auf THG-neutrale Antriebe.

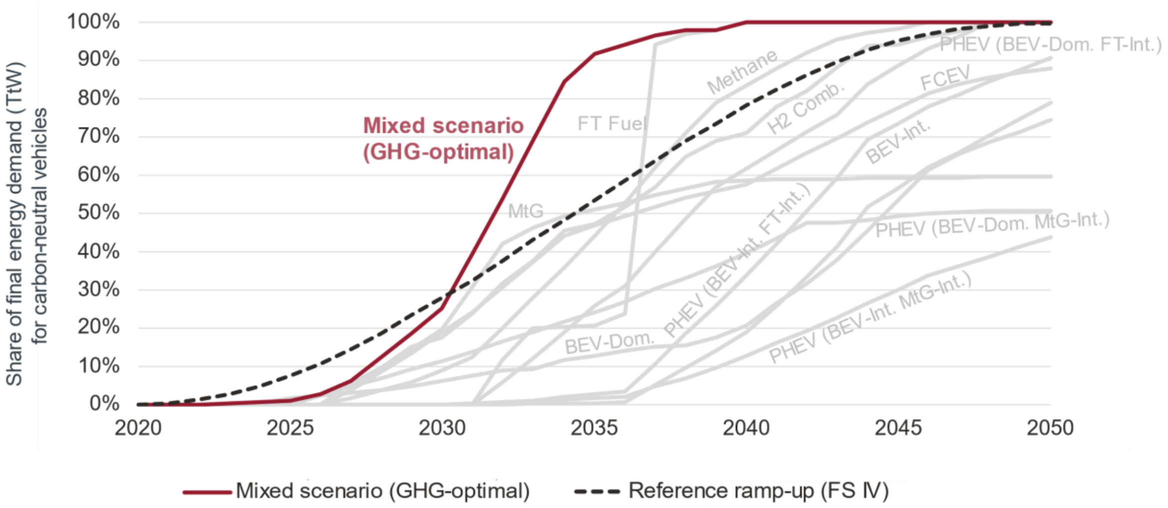


Abbildung 1: Anteil THG-neutraler TtW Energiebedarf im THG-optimal technologieneutralen Mix-Szenario; Einzeltechnologieszenarien in grau hinterlegt.

---

[11] Wir stellen fest, dass es in den in dieser Studie betrachteten Szenarien für das Verbot von Verbrennungsmotoren immer noch möglich ist, die bereits zugelassene Bestandsflotte bis zum Ende ihrer Lebensdauer mit E-Fuels zu betreiben. Im Gegensatz dazu können Neufahrzeuge, die nach einem effektiven Verbrenner-Verbot (d. h. im Jahr 2035) zugelassen werden, nicht mit E-Kraftstoffen betrieben werden und sind daher auf Technologiepfade ohne Verbrennungsmotoren angewiesen. Auch wenn dieser Ansatz im Rahmen des derzeitigen EU-Pakets "Fit for 55" unrealistisch erscheint, entspricht er unserer allgemeinen Annahme in dieser Studie, die von idealen finanziellen und rechtlichen Bedingungen für alle verfügbaren Antriebstechnologien ausgeht. Siehe auch Council of the EU (2022),”Fit for 55 package: Council reaches general approaches relating to emissions reductions and their social impacts”, https://www.consilium.europa.eu/en/press/press-releases/2022/06/29/fit-for-55-council-reaches-general-approaches-relating-to-emissions-reductions-and-removals-and-their-social-impacts/ (zuletzt abgerufen: 08.09.2022).

[12] Analyse von Frontier auf Basis von ACEA-Daten. Siehe auch ACEA (2022), “Vehicles in use Europe 2022”, https://www.acea.auto/files/ACEA-report-vehicles-in-use-europe-2022.pdf (zuletzt abgerufen: 08.09.2022).

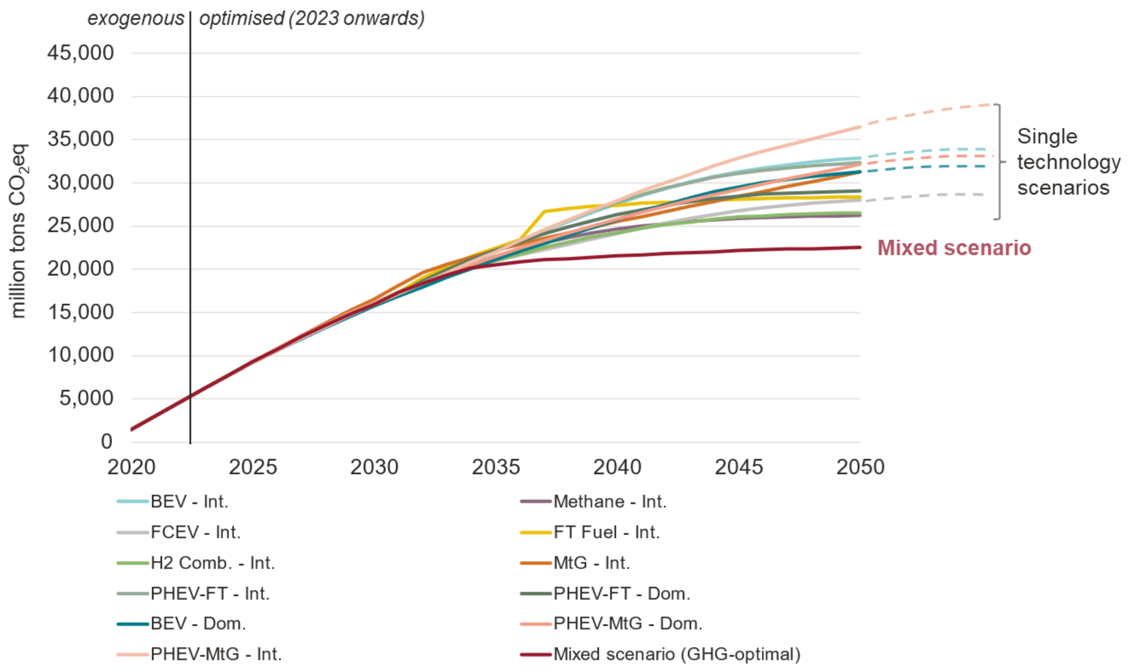


Abbildung 2: Kumulierte THG Emissionen im technologieneutralen „Mix-Szenario“ und Einzeltechnologieszenarien. Hinweis: In Anbetracht technischer Hochlauf-Restriktionen und Annahmen zur Lebenszeit der Fahrzeuge erreichen die folgenden Einzeltechnologieszenarien keinen 100-prozentige Dekarbonisierung bis 2050: BEV Dom./Int., FCEV, PHEV-FT Int. and PHEV-MtG Int. (siehe gestrichelte Linien).

2 Background and objective of the study

As part of its “Green Deal” the European Union (EU) is striving to achieve zero net emissions of greenhouse gases (GHG) across all sectors by 2050.[13]

In 2020 the European road sector yet accounted for more than 20% of the EU’s total GHG emissions of more than 3,000 $MtCO_2eq$.[14] Ambitious changes are, therefore, required to meet the European, as well as national GHG emission targets. This holds in particular for the prevailing use of fossil fuels such as gasoline and diesel in the European road sector today.

Against this background, stakeholders from politics, economy and society call for swift actions by developing and implementing appropriate concepts to pave the way towards a carbon-neutral European road sector.

The challenge of carbon neutrality by 2050 faced by the European road sector is particularly difficult: While other sectors such as the power or industrial sector have already achieved significant reductions in GHG emissions in the past years, the emissions stemming from the road sector has remained on a high level. Growing demand in mobility has (partially) overcompensated efficiency gains in technology and the technological progress.

Most recently, the transition of the European road sector towards carbon neutrality has formed part of wider political debates in Europe. A possible ban of internal combustion engine vehicles (“ICEVs”) for passenger cars and light-duty vehicles such as vans from 2035 onwards, as well as the eligibility of synthetic fuels (“e-fuels”), are at the centre of the debate. In line with this, the Council of the EU in its “Fit for 55” package recently agreed to raise the targets for reducing GHG emissions for new passenger cars and vans by 2030 from 50% to 55% and further agreed to introduce a 100% GHG emission reduction target by 2035.[15]

Consistent with the example above it is a fundamental deficit of the current EU policy approach such as the EU “Fit for 55” package, as well as EU’s “Green Deal” aiming for net zero emissions by 2050 across all sectors, to predominantly focus on sector-specific measures. Fleet emission targets as laid out in the EU “Fit for 55” package, and (amongst others) the 100% GHG emission reduction target by 2035 for passenger cars, exclusively take into account tailpipe emissions of the respective vehicles (so called “Tank-to-Wheel” (TtW) emissions) – while ignoring any emissions from vehicle production or the associated energy supply chain (so called “Well-to-Tank” (WtT) emissions). Many studies, including FVV’s life-cycle analysis meta study[16], evidence why a narrow regulatory focus on sector-specific policy interventions may fail to reach the climate objectives by neglecting the benefits of an effective technology mix across sectors.

---

[13] European Commission (2020).

[14] EEA/Eurostat (2022a), “Greenhouse gas emissions by source sector”, variables “Fuel combustion in road sector” and “Total”, https://ec.europa.eu/eurostat/web/environment/air-emissions (last accessed: 08.09.2022).

[15] Council of the EU (2022),”Fit for 55 package: Council reaches general approaches relating to emissions reductions and their social impacts”, https://www.consilium.europa.eu/en/press/press-releases/2022/06/29/fit-for-55-council-reaches-general-approaches-relating-to-emissions-reductions-and-removals-and-their-social-impacts/ (last accessed: 08.09.2022).

[16] FVV (2020).

In 2021 FVV provided a comprehensive analysis (Fuels Study IV) of 7 different powertrain technology / energy carrier pathways ("technology pathways") for the European transport sector with regards to their overall infrastructure requirement, costs and associated emissions.[17] The study concluded that overall cumulated emissions vary much less across different technology pathways (e.g. electric vs. combustion engines operated with carbon-neutral fuel) than typically expected. In fact, the speed of deploying GHG-neutral mobility solutions (complete GHG-neutral pathways on a "WtW" basis) is much more important than the choice of technologies. The faster a defossilised vehicle fleet can be introduced, the lower are the cumulative GHG emissions and thus the impact on climate change. In this context, our FVV Fuels Study IVb further explores the transition of the European road sector towards climate neutrality by 2050. Consistent with the previous Fuels Study IV, we consider various powertrain technologies and fuel/energy carrier pathways ("fuels"), all of which are exclusively based on renewable energy sourcing through wind and solar generation capacities.

However, compared to Fuels Study IV we add four important features in this study:

First, we explicitly focus on the road sector. The road sector accounted for more than 95% of the total GHG-emissions by fuel combustion in the European transport sector (domestic road, rail, shipping and aviation) in 2020.[18]

Second, we include additional technology pathways for the GHG-neutral road sector, namely Methanol-to-Gasoline (MtG) drop-in capable fuel for ICEVs and Plug-in-hybrid electric vehicles (PHEVs operated with a combination of BEV and e-fuels such as MtG and Fischer-Tropsch fuel).

Third, we now explicitly take into account the technical ramp-up potential of defossilised transportation pathways. This includes achievable ramp-ups of new vehicle technology, power generation and distribution infrastructure as well as raw material supply ("technical bottlenecks") in our modelling of the road sector. Consistent with our focus on the EU27+UK road sector in this study, we apply "fair share" assumption to the global capacities available for the different elements considered in each transportation pathway to account for demand from outside Europe and the non-road sector (i.e. other transport modes as well as industry and households). As shown in the preceding study (Fuels Study IV), the ramp-up potential is of high importance to meet the Paris climate targets. The majority of GHG emissions is caused by the phase-out of the vehicle fleet still operated with fossil fuel. Therefore, the faster a completely defossilised vehicle fleet can be introduced, the lower are the cumulative GHG emissions and thus the impact on climate change.

Fourth, in an effort to minimise GHG emissions in the road sector, we further expand our analysis from "single technology scenarios" (now including technical bottlenecks), in which all segments of the road are powered by a single carbon-neutral energy carrier selected upfront, in favour of a mix of different fuels across segments in the so-called "mixed technologies scenario" (again including technical bottlenecks).

---

[17] FVV (2021).

[18] EEA/Eurostat (2022b), "Greenhouse gas emissions by source sector", variables "Fuel combustion in road sector" and "Fuel combustion in transport", https://ec.europa.eu/eurostat/web/environment/air-emissions (last accessed: 08.09.2022).

Similar to Fuels Study IV, we first examine and compare all fuels in "single technology scenarios"[19], in which all segments of the road sector (i.e. small passenger cars, long-haul trucks) are powered by the respective GHG-neutral fuel/energy carrier over time. However, we now expand our quantitative analysis on potential challenges associated with the large-scale ramp-up of infrastructure and raw material needs under ideal legal and financial investment conditions.[20] These single technology scenarios – including technical bottlenecks – indeed allow for a better comparison of fuel/energy carrier pathways and the ramp-up speed achievable for the different fuel/energy carrier pathways in light of the technical bottlenecks considered.

Following a comparison of the single technology scenarios, we then explore a combination of the different fuel/energy carrier pathways and powertrain technologies across vehicle segments in our "mixed technologies scenario" (i.e. small vehicles, as well as other vehicle segments, running on a combination of powertrains such as direct electrification or fuel cells). As such, our mixed modelling is technology-neutral with the aim of minimising cumulated GHG emissions by 2050 while simultaneously considering technical bottlenecks prevalent for the different energy carrier over time. In other words, our mixed modelling optimisation looks for the fastest transition towards a GHG-neutral European road sector subject to infrastructure and raw material availability under ideal investment conditions.[21]

As with Fuels Study IV, this follow-up study has been developed in close cooperation with the FVV Working Group "Fuels & Energy". More than 50 experts from over 40 companies and organisations from the transport and energy industry have contributed their expertise and industry insights to our analysis. Across several expert groups, key assumptions and methodological questions have been jointly discussed and agreed on. Thus, all underlying assumptions and parameters reflect the shared views of all FVV participants involved.

Based on the FVV experts' input, Frontier Economics carried out the modelling exercise laid out in this study. We are, therefore, confident to reflect the current state of industry knowledge in our analysis.

In this study, we consider the following technology pathways:

- Battery electric vehicles ("BEVs"), whereby we assume a catenary grid system for long-haul and super-long-haul trucks heavy-duty (HD) vehicles (smaller HD vehicles, such as delivery vans, are modelled as pure BEVs);
- Fuel cell electric vehicles ("FCEVs") supplied with hydrogen;
- Internal combustion engine vehicles ("ICEVs") operated with different synthetic fuels/energy carriers, including:
  - Hydrogen ("H_2 combustion");
  - Synthetic Methane ("Methane"/"CH_4");

---

[19] In Fuels Study IV, we referred to the single technology scenarios as "100% scenarios", which assumed an identical vehicle ramp-up and achieved a fully carbon-neutral vehicle fleet in 2050. In this study we use a different terminology ("single technology scenario") because not all GHG-neutral technology pathways reach full decarbonisation by 2050 when considering technical bottlenecks and vehicle lifetime assumptions.

[20] Worldwide demand of material, production capacity and energy demand of all sectors and transportation modes is considered with fair share assumptions, see Section 4.4 of this study for more details.

[21] See Section 4.2.3 of this study for a more detailed description of the assessment for infrastructure and raw material availability under ideal investment conditions.

  - Fischer-Tropsch based synthetic gasoline or diesel drop-in fuels (“FT fuel”);
  - Methanol-to-Gasoline (“MtG fuel”) only available for passenger cars, not for HD vehicles(drop-in fuel for gasoline vehicles); and
- Plug-in-hybrid electric vehicles (“PHEVs”); whereby we assume a combination of BEV and e-fuels (FT fuel or MtG) pathways.

In our system-wide analysis of the single technology scenarios and the mixed technologies scenario we evaluate the different fuel/energy pathways (or combinations of those) in terms of GHG emissions, costs, infrastructure and raw materials required over time. Our approach, therefore, translates into a holistic view on the requirements for a carbon-neutral European road sector compared to today’s status quo.

The remainder of this study is structured as follows:

- In Section 3, we describe the **approach** used in more detail;
- In Section 4, we set out our expanded **modelling setup** used in this study for the single technology scenarios and the mixed technologies scenario;
- In Section 5, we discuss the **results from the single technology scenarios** including technical bottlenecks;
- In Section 6, we turn to the **mixed technologies scenario result** with the objective of minimising GHG emissions including technical bottlenecks; and
- In Section 7 we close the study with our **main conclusions**.

3 Approach

In this chapter we provide an overview on the approach used. In particular, we explain which key assumptions and results from the previous Fuels Study IV fed into our follow-up work (**Section 3.1**). In **Section 3.2** we provide an overview on the additional considerations for this study, including the updated choice of technology pathways and scenario selections.

3.1 Starting point: FVV Fuels Study IV

As a starting point, we build up on the key assumptions made and results retrieved from the FVV Fuels Study IV. As set out in the previous study in more detail, crucial assumptions and deciding methodological questions underlying Fuels Study IV have been extensively discussed and agreed on in several FVV expert groups. In this Fuels Study IVb we adopted most of the assumptions and methodological choices from Fuels Study IV.

This holds in particular for the assumptions on the modelling of mobility and fuel demand, the stages of the different energy supply chains, associated technical parameters (i.e. full load hours of renewable generation, efficiency of electrolysis, etc.), costs, GHG emissions and material demand of the different infrastructure elements.[22] Similarly, the technical specifications of vehicles are equivalent to those used in Fuels Study IV but now include updates for additional powertrains and minor corrections for some vehicle specifications compared to the previous study (see **Section 3.2** below).

As in Fuels Study IV, we further assume that the world is in a “steady state” at the beginning of our analysis. This means that realistically there is no excess infrastructure available to supply the needs from the EU27+UK road sector for our modelling but infrastructure and vehicle components must be built up in the context of our analysis.

In line with national GHG emission inventories and the approach taken in Fuels Study IV, our study properly reflects GHG emissions in the year when they physically occur. Accordingly, we do not artificially distribute emissions resulting from vehicle production and fuel supply chain infrastructure over their operational life (years, km, fuel output – see following “deep dive”) as often assumed in many other studies evaluating the environmental impact of the transition towards a decarbonised energy system. Instead, we reflect the physical emissions by fully accounting them in the year an infrastructure element is built.[23]

---

[22] FVV (2021), Sections 4-8, 12 and 16.

[23] FVV (2021), Section 10.1.1.

Deep dive: Accounting approach for GHG emissions

Choosing an appropriate accounting approach for GHG emissions is a decisive factor for evaluating the environmental impact of investments contributing to a fully decarbonised energy system in the long-run.

There are at least two different approaches (theoretically) allowing to accounting for GHG emissions:

1. Following more or less standardised financial account typically suggest that capital assets, including long-term asset investments should be financially depreciated, discounted or amortised over their lifetime (“**depreciation approach**”).
2. Environmental accounting would in turn suggest to account for the entirety of GHG emissions related to investments contributing to a fully decarbonised energy system at the time they physically occur (“**one-off approach**”).

Following the fundamental differences between the two approaches presented above, there is an inherent need to review the appropriateness of the respective accounting approaches for GHG emissions in the context of the respective research question.

In the context of our study, a depreciation approach for GHG emissions would imply that only a specific share of the GHG emissions of a respective infrastructure element would be accounted for in the year the investment physically ocurred and, therefore, be added to the annual “Well-to-Wheel” emissions (i.e. GHG emissions from installing an onshore wind turbine in a given year would be artificially split over the total lifetime of 25 years).

However, such a depreciation approach neglects the environmental realities associated with the physical installment of long-term assets for a fully decarbonised energy system and could, therefore, result in misleading conclusions. For example, the deprecitation approach will errenously still show GHG emissions at a time, where the system is in fact already fully carbon-neutral.

In fact, the GHG emission investment associated with fuel supply chain elements is associated with “one-off” GHG emissions at the time of their installation (and very low / close to zero emissions from recurring O&M). Considering the example of an onshore wind turbine it is reasonable to assume that the GHG emissions from installation are barely linked to the energy produced over its lifetime. In fact the GHG emissions from installation (i.e. GHG emissions by MW) are the same irrespective of the wind onshore turbine running on full capacity over its entire lifetime or not producing any energy at all (MWh produced).

Consistent with the accounting approach used for national GHG emission inventories, FVV Fuels Study IV as well as this study, therefore, take into account emissions from long-term assets such as onshore wind turbines, at the point in time when they are physically set up (which in turn translates in adding the “one-off” GHG emissions from installation to the overall “Well-to-Wheel” emissions in the year the infrastructure element is built).

In summary, we rely on the enriched set of data and information available from the FVV Fuels Study IV. However, for our expanded modelling setup of Fuels Study IVb we break down the aforementioned data available by introducing a per-vehicle analysis. Within this approach, we separately estimate the required infrastructure needs (and therefore associated material demand, costs and GHG emissions) for the different vehicle types and powertrains considered (see **Section 4** for more detail).

3.2 Additional considerations in this FVV Fuels Study IVb

A major focus of this study is the quantitative assessment of achievable ramp-up gradients under ideal legal and financial conditions for each investigated fuel/energy pathway supporting a fully renewable EU27+UK road sector by 2050 the latest.

In contrast to FVV Fuel Study IV, where an identical, theoretical gradient (only determined by an assumed vehicle fleet exchange rate) was used for all fuel/energy pathways, FVV Fuels Study IVb now explicitly considers more realistic technical bottlenecks. These technical bottlenecks could significantly delay the transitions to a GHG-neutral EU27+UK road sector for each fuel/energy pathway by 2050 the latest. For all these bottlenecks only technical restrictions are considered, assuming ideal legal and financial boundary conditions are assumed.[24]

Compared to the preceding study, we further refine the analytical approach used to assess and compare different fuels that are technically suitable to achieve a carbon-neutral European road sector until 2050. This relates to five key dimensions:

- Updated choice of technology pathways;
- Focus on “International Energy Sourcing” for all fuels (“Domestic Energy Sourcing” is considered additionally for BEV and the electric share of PHEV);
- Focus on “Balanced” scenario for long-term technological progress;
- Updated vehicle fleet for the period 2020-2022;
- Minor changes of assumptions used in Fuels Study IV.

<u>Updated choice of technology pathways</u>

In terms of powertrain technology / energy carrier pathways, our follow-up study focuses on the pathways depicted on the left side of **Figure 3** below.

---

[24] Similar to the COVID-19 vaccine development observed during the COVID-19 outbreak; this was possible in approximately one year instead of lasting the usual 10 years.

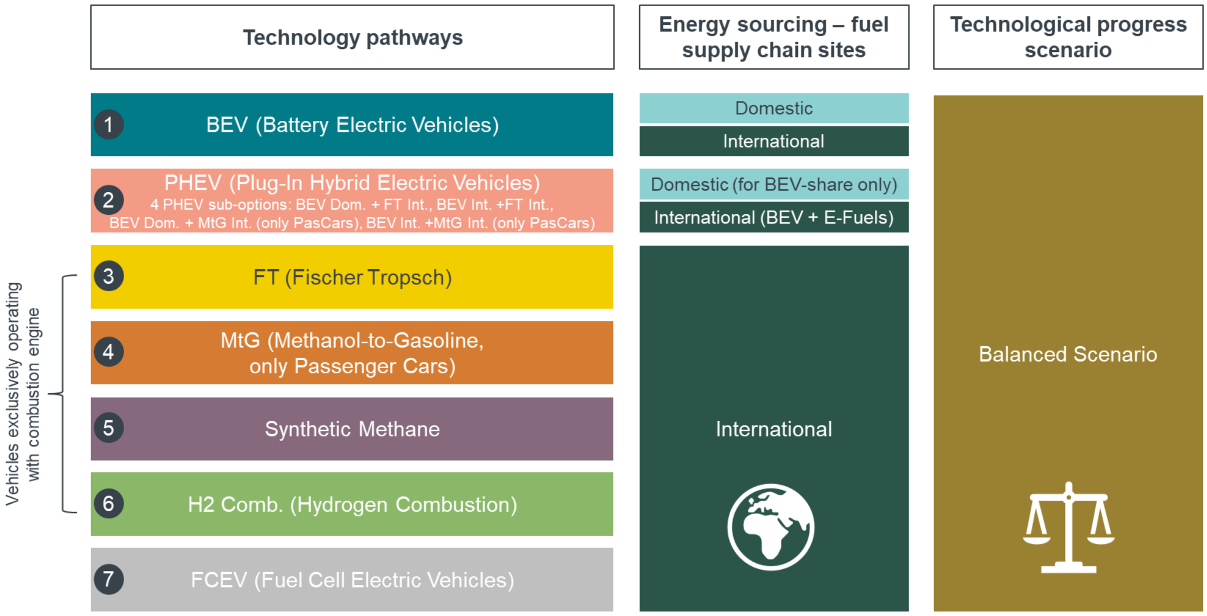


Figure 3: Choice of technologies in Fuels Study IVb based on definitions in Fuels Study IV.

Compared to the preceding study, we have added PHEVs and MtG as new technology pathways.[25] The technology pathway for **PHEVs** consists of a mix of vehicle and infrastructure elements from both BEV and e-fuel technology pathways (FT fuel for passenger cars and heavy-duty vehicles / MtG for passenger cars only). The material and infrastructure requirements of PHEVs are therefore derived from the share of kilometres driven on electric motor versus kilometres driven on combustion engine in each vehicle segment. For instance, in 2030 a medium-sized vehicle (C-class) is assumed to run around 70% of all kilometres on electric-driving. It therefore requires around 70% of the infrastructure and material requirements of a BEV and around 30% of a medium-sized vehicle exclusively operated with FT or MtG (subject to the PHEV powertrain option selected).[26] Consistent with all other pathways, PHEVs are assumed to operate on renewable energy sourcing only. Given their limited availability today, we model PHEVs in the heavy-duty segment only from 2025 onwards.

For **MtG** the fuel supply chain is identical to the MeOH pathway included in the FVV Fuels Study IV but now includes an additional synthesis step from methanol to gasoline. In this study the MtG pathway is exclusively available for passenger cars. Heavy-duty vehicles are almost exclusively diesel-fuelled today and the expert group considered any potential switch to e-gasoline in large scale to be unreasonable.

We determined vehicle costs following the same building-kit-approach as in Fuels Study IV. Vehicle costs for the MtG pathway correspond to the ICEV gasoline pathway (see Fuels Study IV, Table 212). More details on the underlying assumptions for PHEV and MtG technology pathways are provided in the Appendix of this study.

---

[25] The technology pathway „Dimethylether (DME)“ has not been considered in Fuels Study IVb due to its inferior results in Fuels Study IV when comparing with other pathways.

[26] We further assume an efficiency loss of 10% across all vehicle segments for PHEVs to account for the fact that two different fuel supply chains have to be ramped up for PHEVs.

Focus on “International Energy Sourcing” for all fuels

A key result of Fuels Study IV is that “International Energy Sourcing” (“International”), where renewable energy might be imported from suitable locations across the globe, is the preferred energy sourcing strategy in terms of GHG emissions and costs (i.e. high share of imports from MENA). This holds in particular when comparing the results from Fuels Study IV with the alternative “Domestic Energy Sourcing” (“Domestic”) scenario which considered European energy generation only. The main driver of the results is the higher efficiency of renewable energy generation outside Europe which outweighs the benefits of shorter transportation routes in the “Domestic” scenario.

In line with today’s energy sourcing strategy for the EU27+UK road sector, we only consider the “International” scenario for liquid and gaseous pathways in this study.

However, for BEV and the electric share of the PHEV powertrains we consider both scenarios “International” and “Domestic” sourcing. As Fuels Study IV showed for BEVs, electric powertrains tend to require lower amounts of energy in absolute terms (lower conversion losses compared to liquid and gaseous pathways) which is beneficiary for densely populated areas such as the EU27+UK. Moreover, by including “Domestic” sourcing for electric powertrains we further aim to provide a more comprehensive view on the implications of inner-European energy generation for an (largely) electrified EU27+UK road sector aiming for a higher degree of energy autonomy and self-sufficient energy generation compared to today.

Focus on “Balanced” scenario for long-term technological progress

Additionally, our follow-up study focuses on the “Balanced” scenario in terms of the long-term technological progress expected. The “Balanced” scenario corresponds to the middle of the three scenarios considered in Fuels Study IV (“Status Quo”, “Balanced” and “All-In”). As such, the “Balanced” scenario assumes a moderate degree of innovation for improved efficiency in future years which is expected to have a positive net benefit in terms of costs. This is particularly relevant for all combustion engine vehicles, which are assumed to be fully hybridised (i.e. equipped with a small battery for electric driving on short distances) in the “Balanced” scenario in the period 2025 to 2050.

Updated vehicle fleet for the period 2020 to 2022

In this follow-up study, we consider the period 2020 to 2050 which is consistent with the time span covered in Fuels Study IV. However, in an effort to provide a more realistic starting point for our expanded modelling approach, we have reflected recent developments in the EU27+UK vehicle fleet composition for the years bygone (2020-2021) and estimate trends in the year 2022 based on the most recent data available.[27] For the period 2023 to 2050, the future development of the fleet is projected in a “cohort model” approach consistent with the analysis undertaken in Fuels Study IV.[28]

---

[27] Assessment by Frontier Economics based on ACEA data. See ACEA (2022a), “Vehicles in use Europe 2022”, https://www.acea.auto/files/ACEA-report-vehicles-in-use-europe-2022.pdf (last accessed: 08.09.2022).

[28] FVV (2021), Section 6.

In other words: The vehicle fleet composition for the EU27+UK road sector is closely linked to real-world developments until the end of 2022 before we start the ramping-up a GHG-neutral vehicle fleet from 2023 onwards within our modelling exercise.

Minor changes of assumptions used in Fuels Study IV

Compared to Fuels Study IV, the expert groups have revised the assumptions for the fuel cell size in the heavy-duty segment. The underlying reasoning is that the expert group considered the “reference vehicle” initially assumed in Fuels Study IV in some segments to have a too small fuel cell size to meet customer demands. Following a recommendation of the expert group, the fuel cell size for all heavy-duty vehicles (excl. city busses) was increased (which also translates in higher vehicle costs) for this study. In contrast, the fuel cell size of city busses was lowered (and vehicle costs decreased consequently).[29] We show the updated assumptions in the Appendix.

Furthermore, we have updated the assumptions on the split between renewable energy sources considered (mix of onshore wind, offshore wind and PV), which has been a fixed input in the previous study. In this study, we now allow for more flexible approach in terms of the renewable energy sources used to account for potential technical bottlenecks of specific technologies (e.g. offshore wind) in the short run.[30]

---

[29] For completeness, we note that the adjustments in fuel cell size for heavy-duty vehicles do not translate into changes of fuel demand compared to Fuels Study IV, see FVV (2021).

[30] For example, this more flexible approach allows to trade-off onshore and offshore wind energy in case the ramp-up of offshore energy sourcing would reach a binding constraint but additional production capacities for onshore wind would be available to meet the required demand.

4 Modelling setup: Minimising GHG emissions for the European road sector

This section illustrates our modelling setup targeting a minimisation of the cumulated GHG emissions from the EU27+UK road sector until 2050.

In **Section 4.1** provides a high-level overview of the methodical approach and input factors. We then explain in **Section 4.2, 4.3** and **4.4** the data inputs required for infrastructure and material requirements and describe our approach reflecting technical bottlenecks associated with the different technology pathways towards a decarbonised EU27+UK road sector in more detail. Finally, **Section 4.5** provides insides to the optimisation logic and outputs available from our modelling.

4.1 Overview on input factors

In this study we develop a linear optimisation model minimising the cumulated GHG emissions from the EU27+UK road sector until 2050. In its optimisation process the model explicitly takes into account the infrastructure and raw material needs of the different technology pathways considered as well as technical bottlenecks associated with the ramp-up of a decarbonised EU27+UK vehicle fleet in different settings.

The different settings include so-called “single technology scenarios” (only allowing one specific GHG-neutral powertrain/energy pathway) and a “mixed technologies scenario” in which the model endogenously decides on the GHG-minimising combination of powertrain/energy pathways in the vehicle fleet.

Our linear optimisation model requires three key sets of data input[31]:

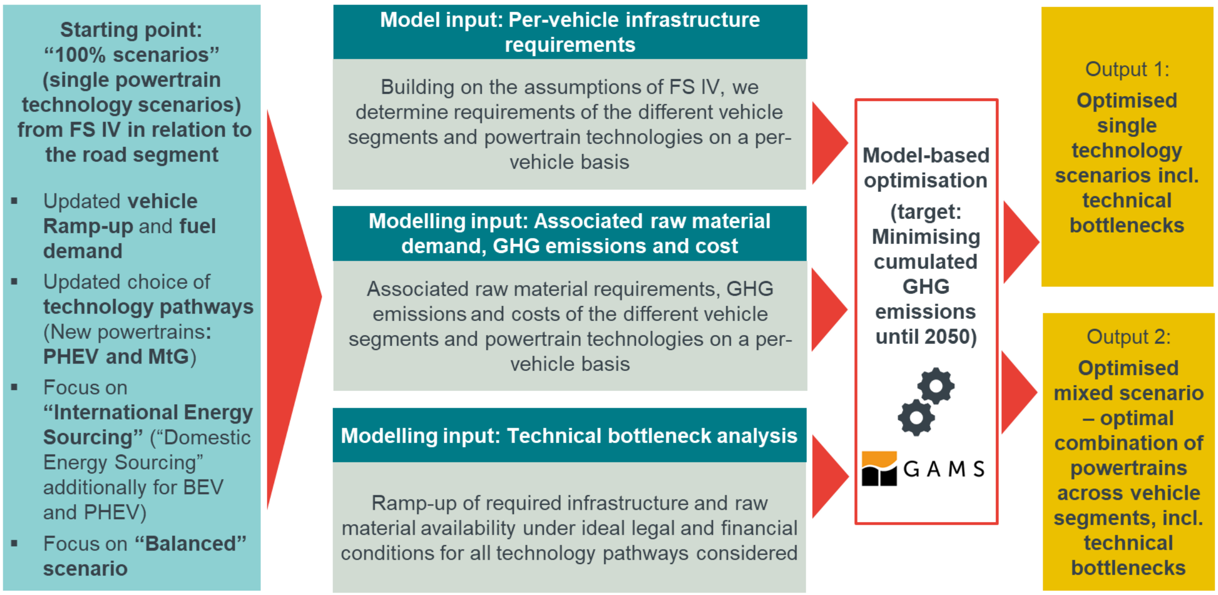
- **Per-vehicle requirements for all vehicle segments and powertrain technologies:** Building on the assumptions made in Fuels Study IV, we determine the requirements of the different vehicle segments and powertrain technologies on a per-vehicle basis (**Section 4.2)**.
- **Associated raw material demand, GHG emissions and cost:** We then estimate the associated raw material demand, GHG emissions and costs by vehicle segment and powertrain technologies on a per-vehicle basis. In this context we use the specific per-unit investment and operating costs of all infrastructure elements of each powertrain / energy supply chain set out in Fuels Study IV by vehicle segment. In addition, ifeu provided values of the associated raw material demand and GHG emissions of all infrastructure elements of each powertrain / energy supply chain by vehicle segment (**Section 4.3)**.
- **Technical bottleneck analysis:** Reflecting the need for the ramp-up of raw material and infrastructure elements associated with the different pathways considered, several FVV expert groups (in close collaboration with Frontier) estimated the build-up of infrastructure elements and raw material under ideal legal and financial conditions. **(Section 4.4)**.

---

[31] For additional input we rely on the assumptions of Fuels Study IV, see FVV (2021), Appendix 2. Amongst others, this includes assumptions on the vehicle fleet ramp-up, vehicle and infrastructure lifetimes (subject to the updates set out in Section 3.2 of this study).

Figure 4 below provides a simplified schematic overview of our modelling-setup. The three main sets of data inputs are then used in the model-based optimisation operated with GAMS, a computer software tailored for large-scale mathematical modelling applications.[32]

In the context of this study, we generate two major outputs: The aforementioned "single technology scenarios", which for comparison purposes model the fastest achievable market penetration of a single energy carrier/powertrain technology, as well as the "mixed technologies scenario", which aims for a minimisation of cumulated GHG emissions until 2050 based on an optimised mix of technologies.



Starting point: "100% scenarios" (single powertrain technology scenarios) from FS IV in relation to the road segment

- Updated **vehicle Ramp-up** and **fuel demand**
- Updated choice of **technology pathways** (New powertrains: **PHEV and MtG**)
- Focus on **"International Energy Sourcing"** ("Domestic Energy Sourcing" additionally for BEV and PHEV)
- Focus on **"Balanced" scenario**

Model input: Per-vehicle infrastructure requirements

Building on the assumptions of FS IV, we determine requirements of the different vehicle segments and powertrain technologies on a per-vehicle basis

Modelling input: Associated raw material demand, GHG emissions and cost

Associated raw material requirements, GHG emissions and costs of the different vehicle segments and powertrain technologies on a per-vehicle basis

Modelling input: Technical bottleneck analysis

Ramp-up of required infrastructure and raw material availability under ideal legal and financial conditions for all technology pathways considered

Model-based optimisation

(target: Minimising cumulated GHG emissions until 2050)

Output 1:

Optimised single technology scenarios incl. technical bottlenecks

Output 2:

Optimised mixed scenario – optimal combination of powertrains across vehicle segments, incl. technical bottlenecks

Figure 4: Schematic overview of the modelling setup.

4.2 Per-vehicle requirements for all vehicle segments and powertrain technologies

We determine the requirements of the different vehicle segments and powertrain technologies on a per-vehicle basis throughout the whole fuel supply chain.

As a starting point we use the cumulated infrastructure requirements of Fuels Study IV for the EU27+UK road sector. The parameters from Fuels Study IV are available for the different technology pathways and vehicle segments for the years 2030 and 2050 throughout the whole fuel supply chain.[33]

For our model-based optimisation in this study we break down the cumulated infrastructure requirements by powertrain technology and vehicle segments on a per-vehicle basis. Our approach therefore reflects the average material and infrastructure requirement of a single vehicle in each of the vehicle segments considered:[34]

- **Passenger cars / light-duty vehicles**: small, medium, large, SUV and LCV (N1) vehicles;

---

[32] The General Algebraic Modelling System (GAMS) is a high-level modelling system for mathematical optimisation. GAMS is designed for modelling and solving linear, nonlinear, and mixed-integer optimisation problems.

[33] Subject to the additional considerations set out in Section 3.2 of this report.

[34] In the context of this study, we use the simplifying assumption of a linear relationship between the number of vehicles in a certain segment and the associated material and infrastructure requirements for each vehicle. Our approach therefore abstracts from any economies of scale that may be observed under real-world conditions.

- **Heavy-duty vehicles**: rigid (N2), regional delivery (N3), long haul (N3), super long haul (N3), public transport coaches, coaches.

Figure 5 below illustrates our per-vehicle approach for a medium-sized passenger car with BEV (domestic energy sourcing) powertrain newly registered in the year 2030.

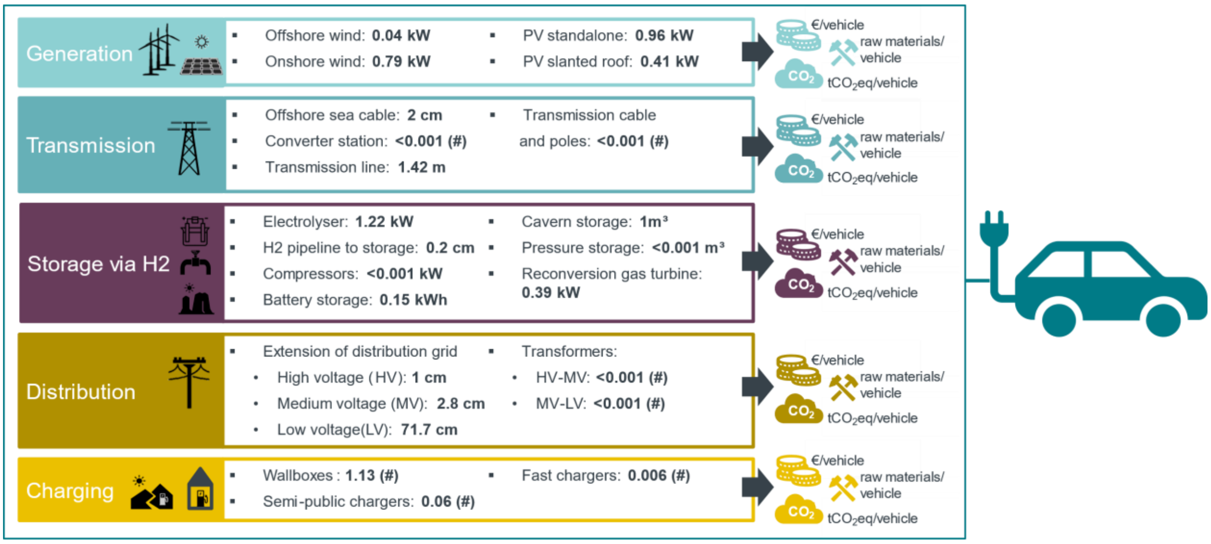


Figure 5: Infrastructure requirements of a medium-sized BEV passenger car with domestic energy sourcing newly registered in 2030. Note: Throughout the assumed lifetime of the vehicle, some infrastructure (e.g. fast chargers) will need to be replaced, while longer-lasting infrastructure can be used by vehicles of several generations (e.g. converter stations).

4.3 Associated raw material demand, GHG emissions and cost

In a second step, we match the per-vehicle requirements for all vehicle segments and technology pathways considered with the associated raw material demand, GHG emissions and costs.

This includes “upfront” investment costs (i.e. material demand, GHG emissions and financial costs from producing an onshore wind generation turbine) as well as those associated with the operation (i.e. financial costs from maintenance of infrastructure).[35]

With regards to raw material demand and GHG emissions, ifeu provided the parameters required for the modelling approach on each infrastructure element of the different fuel supply chain. Details on the material demand and GHG emission factors are provided in ifeu’s supplementary technical report.

In particular, ifeu provided the below parameters for the modelling in this study:

- **Raw material demand –** for vehicle production, as well as all infrastructure elements along the fuel supply chain of each technology pathway considered and relevant rates of raw materials; and
- **GHG emission factors –** in particular in relation to vehicle production and disposal, emissions from the construction of infrastructure elements across the technology pathways considered and parameters on operating emissions of fossil-fuelled powertrains (i.e. conventional diesel/gasoline and CNG/LNG). GHG emissions arising from the sourcing of raw material,

---

[35] The Operation and Maintenance (O&M) cost are pulled into one cost item, associated with operating and maintaining that infrastructure element.

construction of infrastructure and production/disposal of vehicles are fully accounted for in the year in which they physically occur.[36]

In combination with the per-vehicle requirements the data on raw material demand and GHG emission factors therefore allows to calculate a “rucksack” of material demand and GHG emissions for each newly registered vehicle in a given vehicle segment.[37]

With regards to the financial costs of the infrastructure elements for the different technology pathways considered “upfront” investment costs and operational costs we rely on the information available from Fuels Study IV[38], supplemented with new data for the powertrains additionally considered in this study (see **Section 3.2** and Appendix 1).

A particular challenge in this modelling setup is to properly consider the different lifetimes associated with the vehicles and infrastructure elements. For instance, we assume a vehicle lifetime of 17 years for passenger cars but 25 years for an onshore wind turbine.[39] This implies that more than one vehicle can use the onshore wind turbine over its lifetime. Within our modelling we consequently account for differences in lifetimes and accurately reflect the replacement of infrastructure at the end of the respective lifetime (see also **Section 4.3**).

4.4 Technical bottleneck analysis: Infrastructure and raw material

We further consider technical bottlenecks on raw material and infrastructure availability in our modelling. The previous study highlighted the role of temporal and long-term bottlenecks for a decarbonised EU27+UK road sector.[40] In particular, the qualitative analysis and joint discussions with the expert groups concluded that infrastructure and raw material availability is a decisive factor for the ramp-up speed of GHG-neutral vehicles in Europe. It became evident that a quantitative assessment of infrastructure and raw material availability (“technical bottlenecks”) would be a meaningful addition in this follow-up study. It therefore forms an integral input for our model-based optimisation.[41]

For the purpose of this study, more than 50 experts from over 40 companies and organisations contributed (in close collaboration with Frontier Economics) to seven bottleneck expert groups: Power generation, electrical power transmission and distribution, electrolysis, fuel synthesis, H_2/CH_4 transport

---

[36] In contrast to accounting for GHG emisisons arising from the construction of infrastructure or production/disposal of vehicles through a depreciation over their lifetime, our approach allows for a more accurate consideration attributing the GHG emissions to the point in time when then truly occur. See also FVV (2021), Section 10.1.1.

[37] As set out before, we use the simplifying assumption of a linear relationship between the number of vehicles in a certain segment and the associated material and infrastructure requirements for each vehicle. Our approach therefore abstracts from any economies of scale or network effects that may be observed under real-world conditions.

[38] FVV (2021), Sections 15.3 and 16.6.

[39] FVV (2021), Section 16.5.

[40] As set out in FVV (2021) even under the assumption of the ramp-up gradient solely limited by fleet exchange rate around 70 % of the cumulative GHG emissions of the transport sector were expected to be emitted by the combustion of fossil fuels in the outphasing vehicle legacy fleet yet existing, irrespective of the fuel/energy pathway considered. Thus, the decisive factor to reduce cumulative GHG emissions is a significant acceleration of the transition to GHG-neutral fuel/energy pathways.

[41] In contrast to FVV (2021), which assumed a simplified linear ramp-up of infrastructure and raw material availability consistent with the GHG-neutral vehicle ramp-up across powertrainsthis study thus explicitly takes into account the different infrastructure and raw material bottlenecks across all technology pathways considered.

and storage, vehicles and components as well as raw material supply.[42] The aim of the discussions held in all expert groups was to estimate the maximum ramp-up rate of respective infrastructure elements and raw material supply under an “ideal investment scenario”. This ideal investment scenario should reflect the maximum efforts of all share- and stakeholders in society to reach a fully decarbonised EU27+UK road sector as quickly as possible.

We characterise the ideal investment scenario as follows:

- **Ideal financial and legal conditions:** Decisive financial and legal factors observed in reality such as high Capex, investment risks or lengthy approval procedures should not be taken into account.
- **Focus on technical restrictions:** In contrast the ideal investment scenario should reflect technical restrictions and complexities such as construction times, required R&D lead times to reach industrial scale, availability of space and skilled workforce.

Against this background, each expert group relied on a top-down approach to determine the maximum ramp-up gradients for all relevant technical bottlenecks in a three-step approach:

- First, each expert group identified critical infrastructure (or raw material supply) elements shown in **Table 1** which – according to the FVV expert group – could translate into potential temporal or long-term technical bottlenecks for different technology pathways considered in this study.[43]
- In a second step, each expert group discussed and agreed on maximum ramp-up gradients that are achievable in the aforementioned “ideal investment scenario” for the respective technical bottlenecks. In each case the expert groups defined the parameters until 2050 based on publicly available information and industry knowledge. The results retrieved in this step represent what would be achievable on a global level and accessible to all sectors.
- Finally, the expert groups determined a “Fair Share” for the EU27+UK road sector for the respective technical bottlenecks in order to account for the demand from other regions of the world (outside EU27+UK) and other sectors (e.g. industry, households).

We provide the full list of parameters for all technical bottlenecks (including the “Fair Shares” for EU27+UK road sector) used as an input for our modelling exercise in **Table 10**, **Table 11** and **Table 12** of Appendix 1.

In addition, all powertrain technology / energy carrier pathways, except FT and MtG (both are drop-in capable fuels available for the existing legacy fleet of diesel and gasoline vehicles with remaining lifetimes), are further limited by the vehicle fleet exchange rate assumed in FS IV.[44]

---

[42] For the raw material supply expert group, FVV has further cooperated with ifeu and DERA (Deutsche Rohstoffagentur) at the Federal Institute for Geosciences and Natural Resources (BGR).

[43] Expert groups concluded that other infrastructure elements beside those listed in Table 1 would not form relevant restrictions for the ramp-up of a GHG-neutral EU27+UK road sector (i.e. because other technical bottlenecks pose more significant constraints).

[44] See FVV (2021), Section 6.

Expert group	Relevant technical bottlenecks for modelling	Technology pathways affected
1 Power generation	Wind onshore	All powertrains
	Wind offshore	All powertrains
	Photovoltaic (standalone and slanted roofs)	All powertrains
2 Electrical power transmission and distribution	HVDC power line from MENA to EU	BEV, PHEV (only relevant for “International Energy Sourcing”)
	Extension of EU transmission grid	BEV, PHEV
	Extension of EU distribution grid	BEV, PHEV
	Charging infrastructure (wallboxes, fast chargers, semi-public chargers)	BEV, PHEV
	Catenary system	BEV (only relevant for long-haul and super long-haul trucks)
3 Electrolysis	Electrolysis	All powertrains
4 Fuel synthesis	FT synthesis	FT Fuel
	MtG synthesis	MtG
	Methanation	Methane
5 H_2/CH_4 transport and storage	Construction of H_2 pipelines from MENA to Europe	H_2 Comb., FCEV
	Construction of CH_4 pipelines from MENA to Europe	Methane
6 Vehicles and components	Batteries	All powertrains[45]
	Fuel cell stacks	FCEV
7 Raw material supply	Lithium	All powertrains
	PGM (platinum and palladium)	FCEV, H_2 Comb., Methane, MtG, FT Fuel, PHEV
	Cobalt	All powertrains
	Nickel	All powertrains
	Copper	All powertrains

Table 1: Infrastructure and material elements with achievable ramp-up gradients determined by FVV expert groups.

The results retrieved from the expert groups indicate that especially in the short- and medium-term technical bottlenecks across the different technology pathways considered are likely to delay the ramp-up of GHG-neutral vehicles in the EU27+UK.

We illustrate this with an example (see **Figure 6**): Following the expert group discussions the installed electrolysis and synthesis (MtG, FT) capacities (amongst other infrastructure elements) available for the EU27+UK road sector can be expected to remain scarce until the 2030s. Electrolysis capacities are particularly important for most non-electric powertrains (i.e. hydrogen or e-fuel vehicles) and, therefore, limit their availability for the ramp-up of a GHG-neutral vehicle fleet in the short run. While the FVV

---

[45] ICEVs are assumed to be fully hybridised (i.e. equipped with a battery) from 2026 onwards (see Fuels Study IV, Section 4.2).

experts agreed that underlying technology for electrolysis and MtG plants is mature and production facilities could be scaled up rather quickly in the forthcoming years under an “ideal investment scenario”, they consider significantly longer lead times for FT synthesis plants as reverse water gas shift reaction (RWGS) catalysts are not yet commercially available and require further optimisation (i.e. reduction of reaction temperature).

More specifically, in the context of this study, FVV experts consider the first large-scale plants for FT synthesis could be operational around six years after the final investment decision (i.e. 2029 if the final investment decision is taken at the beginning of the modelling period in 2023). However, even under ideal investment conditions FVV experts consider the supply of FT synthesis capacity could be constrained until 2036 in the context of this study.

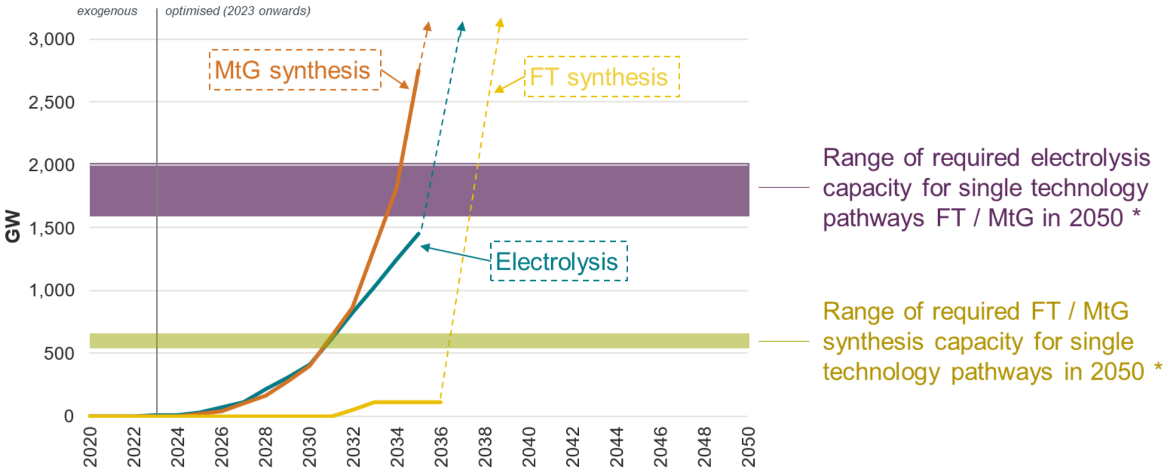


*Figure 6: Maximum electrolysis and synthesis capacity available for the EU27+UK road sector in an ideal investment scenario, dashed lines indicate further possibility to significantly scale-up capacities under the ideal investment scenario from mid-2030s onwards (if required); * estimated on the basis of results retrieved from FVV Fuels Study IV.*

4.5 Model-based optimisation and outputs

Our comprehensive linear optimisation model aims to minimise cumulated GHG emissions of the EU27+UK road sector until 2050, subject to different side constraints. We summarise the main input and output dimensions in **Figure 7** below.

By combining all information available from the input dimensions (i.e. on vehicle fleet, infrastructure requirements, GHG emissions and raw materials, CAPEX and OPEX as well as technical bottlenecks) the model minimises the cumulated GHG emissions from the EU27+UK road sector until 2050 while securing that the assumed road mobility demand can be met.

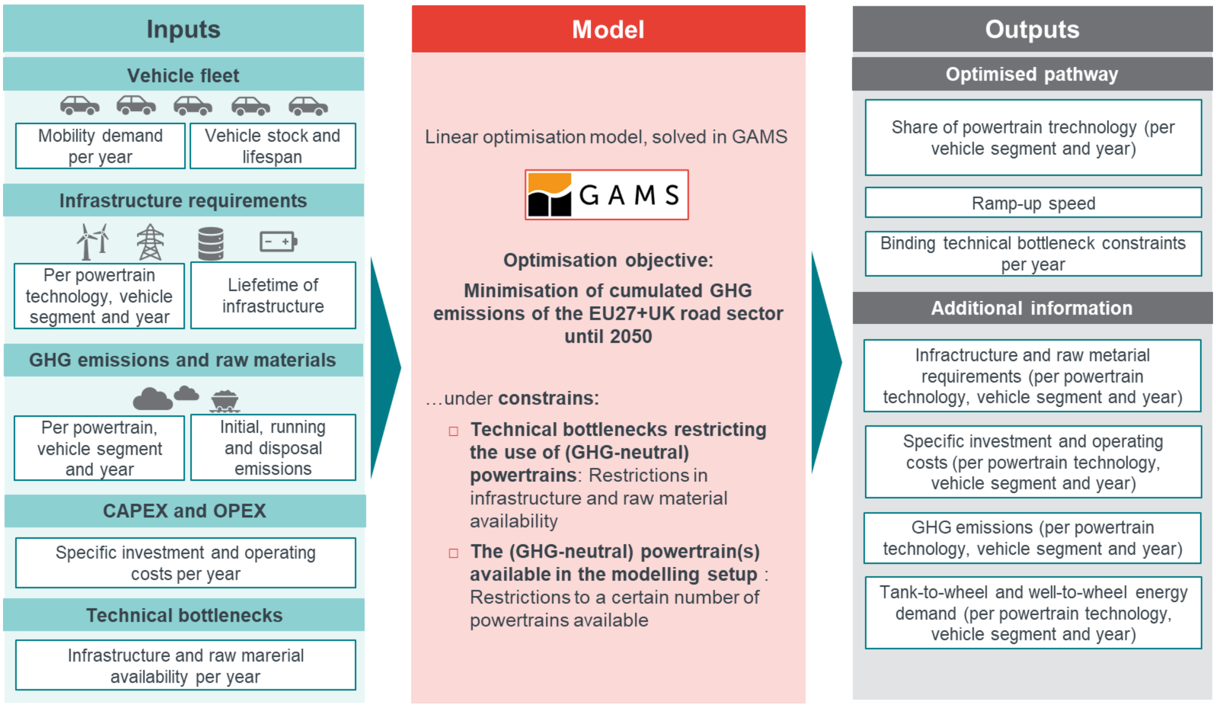


Figure 7: Schematic overview on model inputs and outputs.

At the core of its optimisation logic to minimise cumulated GHG emissions, the model is constrained by two major factors. Both are affecting the current and future vehicle fleet development in the EU27+UK road sector over time:

- **The (GHG-neutral) powertrain(s) available in the modelling setup** – e.g. in the case of single technology scenarios only one (GHG-neutral) powertrain is available for all vehicle segments while in the mixed technologies scenario the model endogenously selects the least GHG-intense powertrain by vehicle segment (see **Sections 5** and **6**); and
- **Technical bottlenecks restricting the use of (GHG-neutral) powertrains** – in case of binding technical bottlenecks the model may be forced to rely on more GHG-intense powertrains to meet the EU27+UK road mobility demand assumed (i.e. in case GHG-neutral powertrains are restricted by technical bottlenecks the registration of conventional diesel/gasoline vehicles emitting GHG in operation remains possible)

Following the above input factors and major constraints, our model-based optimisation delivers an optimised pathway as output, including the split of (GHG-neutral) powertrain technologies by vehicle segment over time, the associated ramp-up speed of (GHG-neutral) vehicles and information on binding technical bottlenecks. It further generates additional information including the infrastructure and raw material requirements, investment and operating financial costs, GHG emissions as well as the associated energy demand (tank-to-wheel, well-to-wheel) by powertrain and vehicle segment over time.

Deep dive: "Drop-in" of e-fuels usable for the existing vehicle fleet in the modelling setup

We primarily focus on the potential (GHG-neutral) technology pathways for newly registered vehicles in the EU27+UK road sector in our modelling period until 2050.

Additionally we introduce the option to operate the existing vehicle fleet on conventional diesel/gasoline with "drop-in" e-fuels in this study. Drop-in fuels are compatible in large amounts to the existing vehicle fleet in accordance with current technical standards (i.e. FT diesel is drop-in capable up to 100% in diesel vehicles released for diesel fuel in accordance to EN 15940 and to approximately 30% in diesel vehicles released for diesel fuel in accordance to EN 590, MtG is drop-in capable up to 100% in gasoline vehicles released for EN 228 gasoline). In case technical bottlenecks (i.e. ramp-up of FT and MtG synthesis plants) allow for it, the model can endogenously decide for vehicles in stock to switch to e-fuels for the remainder of their lifetimes (if favourable from a GHG minimisation perspective). By doing so, the operating emissions of these vehicles decrease to zero (while accounting for GHG emissions from ramping-up the FT/MtG fuel supply chain for fuelling these vehicles).

Therefore, while all other modelling decisions "lock in" a certain a powertrain technology for the entire lifetime of the respective vehicle, new registrations as well as the stock of ICEVs initially using conventional diesel/gasoline can be operated on e-fuels throughout their lifetime.

As set out in **Section 2**, FT fuel (e-gasoline, e-diesel) is available for both, passenger cars and heavy-duty vehicles running on conventional gasoline/diesel. In contrast MtG (e-gasoline) is limited to passenger cars only (due to the assumption of non-applicability of e-gasoline in the heavy-duty segment).

Consistent with the different scenario settings (see below), the option of using e-fuels on ICEVs with conventional gasoline/diesel engine is only available in the respective single technology scenarios

In more detail, our model follows an iterative decision-making process. We illustrate this schematically in **Figure 8** below for the registration of a single new vehicle in the year 2030 in the mixed modelling approach.

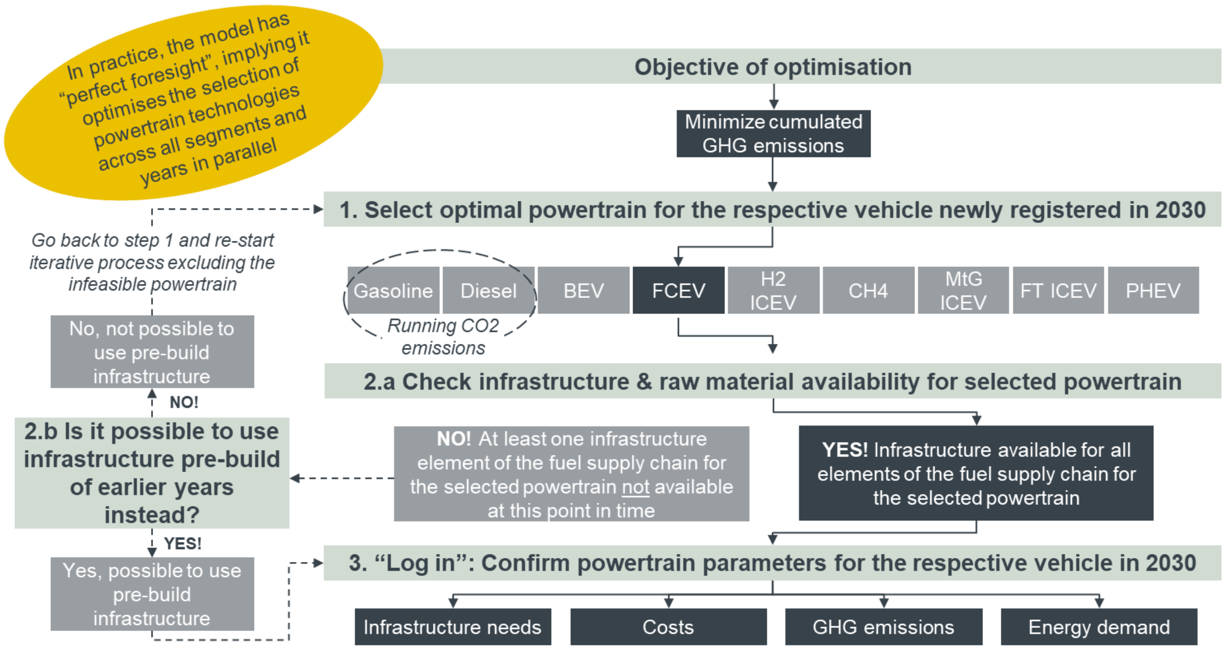


Figure 8: Simplified model decision making process for a single vehicle newly registered in 2030. For BEV and PHEV an additional differentiation between domestic/international energy sourcing is possible. For ICEV share of PHEV MtG/FT fuel is possible for passenger cars, only FT fuel for heavy-duty vehicles. Infrastructure availability is the sum of potential infrastructure expansion (newbuilt), re-usable capacities minus disposed capacities at the end of their lifetime.

In a first step, the model selects the optimal (GHG-neutral) powertrain for the respective vehicle newly registered in 2030. Taking into account the objective of the optimisation, the model chooses the least GHG-intense powertrain (and associated fuel supply chain) available over the vehicle lifetime. In our stylised example the model opts for the FCEV powertrain.[46]

In a second step, the model examines if the energy supply chain infrastructure and raw material associated with the newly registered vehicle are available for the vehicle at stake.

- If this is the case, the model "logs in" the vehicle as a newly registered FCEV in 2030 and confirms corresponding output parameters (i.e. infrastructure and material demand, financial costs, GHG emissions and energy demand).
- If this is not the case (i.e. because at least one infrastructure element such as electrolysis capacity for the FCEV is not available due to a technical bottleneck), the model considers if pre-building the respective infrastructure element in earlier years is possible (i.e. building up required electrolysis capacity for this vehicle in 2029 or earlier) or re-usable capacities are available (i.e. because a FCEV is disposed in 2030 but the infrastructure associated with it has not reached the end of its lifetime). If pre-build is possible (or re-usable capacity is available),

---

[46] Absent any technical bottlenecks the model would therefore choose the optimal (GHG-neutral) powertrain technology in terms of emissions for all vehicle segments across time solely on the basis of the available GHG emission input data (sum of GHG emissions from infrastructure build-up, as well as from production and disposal of associated vehicles) and the pre-defined pathway for new vehicle registrations in light of the EU27+UK road mobility demand assumed.

the model “logs in” the vehicle as a newly registered FCEV in 2030 and confirms corresponding parameters.[47]

If neither the infrastructure and raw material for the selected powertrain is available in the given year nor in earlier years, the model re-starts the iterative process on selecting the optimal powertrain. However, it now excludes the infeasible powertrain (i.e. FCEV). It therefore re-runs the process outlined above with the “next-best” powertrain in terms of GHG emissions until a feasible (GHG-neutral) powertrain is found.[48]

The process outlined above is closely linked to the (GHG-neutral) powertrains available. As briefly mentioned earlier in the report (**Section 2**), we allow for two major specifications:

- **Single technology scenarios**: In the single technology scenarios, all segments of the road sector (from small passenger cars to long-haul trucks) are operated with a single predefined GHG-neutral powertrain with the aim of minimising cumulated GHG emissions until 2050. In case the predefined GHG-neutral powertrain is unavailable for newly registered vehicles in light of technical bottleneck constraints in a given year, the remaining EU27+UK mobility demand in this year is covered by conventional (fossil) diesel/gasoline vehicles as a fallback-option.
- **Mixed modelling**: In the mixed modelling, the model endogenously selects the optimal GHG-minimising combination of all eleven GHG-neutral technology pathways available for the different segments of the EU27+UK road sector. Again, in case all GHG-neutral powertrains unavailable for newly registered vehicles in light of technical bottleneck constraints in a given year, the remaining EU27+UK mobility demand in this year is covered by conventional (fossil) diesel/gasoline vehicles as a fallback-option.

Background: Exogenous vs. optimised modelling decisions

In oder to ensure consistency and comparability with Fuels Study IV, this study considers the identical timeframe from 2020 to 2050.

To properly account for real-world developments since the publication of Fuels Study IV, the first three years of modelling (2020-2022) take into account historic data available for 2020 and 2021, as well as projection for 2022. New registrations to the vehicle fleet in these years are therefore not optimised by the model, but exogenously determined (referred to as “exogenous” in the graphs). Consequently the optimised modelling, in which the model itself decides on the fuel/energy pathways, then starts in the year 2023 (referred to as “optimised” in the graphs).

---

[47] Pre-build infrastructure requires investment cost and causes initial GHG-emissions. Operating cost and emissions only arise for infrastructure that is currently in use (excluding “pre-build” infrastructure and similarly “stranded infrastructure” which is no longer used despite remaining lifetime).

[48] In case all (GHG-neutral) powertrains available in the respective modelling setting are restricted by technical bottlenecks, the model can use conventional (fossil) diesel/gasoline vehicles as a “back-up” option to meet the EU27+UK mobility demand assumed for each vehicle segment and year.

Despite the schematic illustration in **Figure 8** providing an overview on the underlying iterative process at the core of the modelling, the full optimisation methodology developed by Frontier Economics is more complex. In fact, in an effort to minimise cumulated GHG emissions until 2050 we introduce “perfect foresight” for the model. Perfect foresight is a feature typically used in comprehensive economic modelling exercises which include a range of optimisation decisions and constraints over time.

In the context of this study, we introduce perfect foresight to fully exploit the benefits GHG-minimisation of the EU27+UK road sector until 2050 which result from a parallel optimisation of vehicle segments and years. By doing so, our model takes into account potential synergies arising from path- and cross-dependencies between powertrains. For example, the model avoids large overcapacities (“stranded infrastructure”) of infrastructure (and therefore GHG emissions). In fact, the model can re-use a respective infrastructure element with remaining lifetime for a newly registered vehicle having similar requirements after the vehicle initially associated with the infrastructure element has been disposed. In other words: The model chooses the best-possible option for GHG-minimisation in the EU27+UK road sector over all vehicles and time, considering current and future availability of all resources.

5 Results from single technology scenarios including infrastructure and material bottlenecks

In this section we present the results of the single technology scenarios taking into account infrastructure and material availability. We first discuss the vehicle ramp-up and Tank-to-Wheel (TtW) energy demand (representing the final energy consumption by the vehicle fleet) across the different powertrains including technical bottlenecks (**Section 5.1**). We then turn to the associated GHG emissions (**Section 5.2**).

5.1 Vehicle ramp-up and TtW energy demand in single technology scenarios with technical bottlenecks

As set out in **Section 4** in more detail, in our comparison of the vehicle ramp-up and TtW energy demand of GHG-neutral powertrains in the “single technology scenarios” all segments of the road sector (from small passenger cars to long-haul trucks) are powered by a predefined GHG-neutral fuel with the aim of minimising cumulated GHG emissions until 2050. For each powertrain selected in the respective single technology scenario our optimisation logic explicitly considers technical bottlenecks. In case technical bottlenecks prevent new registrations of GHG-neutral vehicles for a single technology scenario in a given year, the registration of fossil fuelled vehicles (gasoline or diesel) remains available as a “fallback option” in order to meet the mobility demand assumed for EU27+UK in the respective year.

Our results show that different needs of infrastructure and material demand by each GHG-neutral powertrain in combination with the technical bottlenecks lead to different ramp-up speeds of a GHG-neutral vehicle stock across the single technology scenarios. We illustrate this in **Figure 9** (share of GHG-neutral vehicles in stock) and **Figure 10** (share of GHG-neutral TtW energy demand) below.

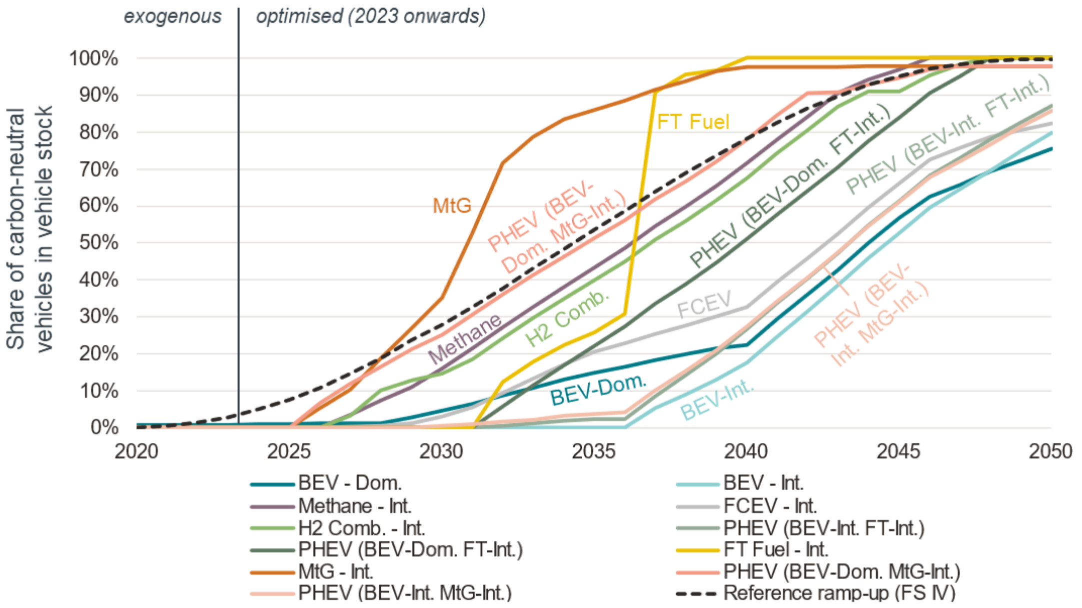


Figure 9: GHG-neutral vehicle ramp-up in single technology scenarios incl. technical bottlenecks.

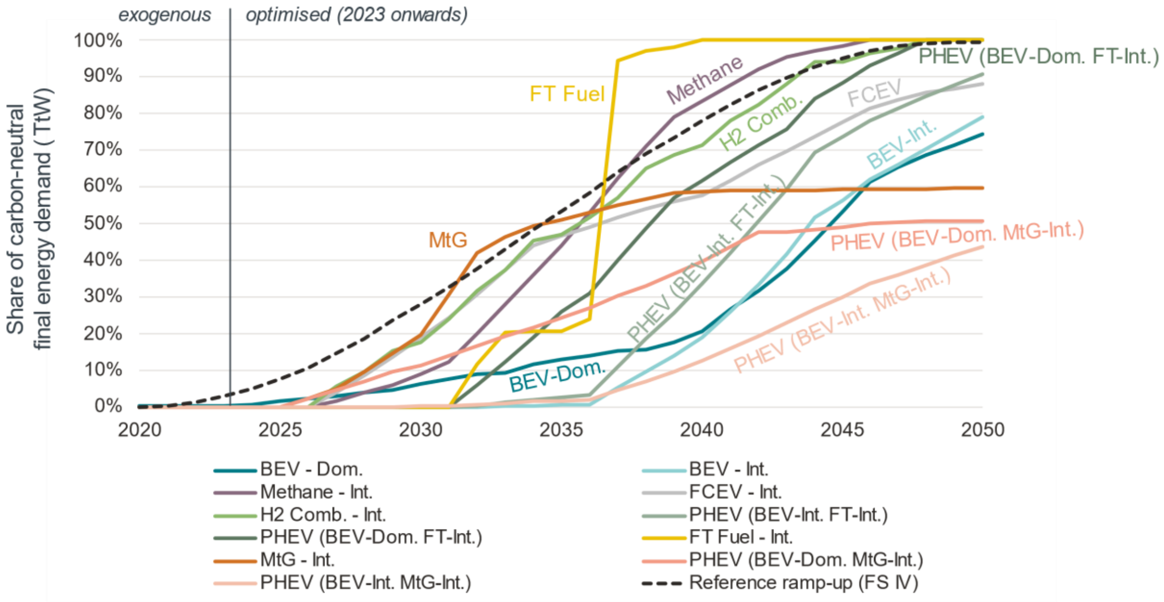


Figure 10: GHG-neutral TtW energy demand in single technology scenarios incl. technical bottlenecks

Compared to Fuels Study IV, which – for simplification – exemplarily assumed an continuous increase in GHG-neutral vehicle[49] (limited exclusively by the vehicle fleet exchange rate) and their corresponding GHG-neutral TtW energy demand without considering technical bottlenecks[50], the results retrieved from this study (see **Figure 9** and **Figure 10** above) vividly demonstrate the importance of infrastructure and raw material availability for decarbonising the EU27+UK road sector. We summarise the key results below.

---

[49] In FVV (2021), we apply a backcasting approach: The share of the carbon-neutral powertrain of total new registrations is continuously ramped up so that 100% market penetration of the technology is achieved in 2050. For more details see Fuels Study IV, Section 6.

[50] FVV (2021) did not quantitively take into account technical bottlenecks (infrastructure and raw material availability). However, Fuels Study IV did take into account vehicle lifetime assumptions (e.g. passenger cars in operation for 17 years) which thereby impact the vehicle ramp-up previously considered.

For the majority of powertrain technology / energy carrier pathways, the considered technical bottlenecks delay the transition towards a GHG-neutral EU27+UK road sector compared to the assumed linear ramp-up in Fuels Study IV – this holds in particular for the early decades (2020s and partially 2030s). This development can be explained by a combination of two factors: The later start of the modelling in this study (2023 vs. 2020 in FS IV) and most importantly the restrictions in infrastructure and raw material availability due to technical bottlenecks (see **Table 2** at the end of this section).

However, in terms of the share of GHG-neutral vehicles (passenger cars and heavy-duty vehicles) in stock (**Figure 9**) over time few powertrain technology / energy carrier pathways such as MtG, FT and in selected years PHEVs (BEV Dom. / MtG Int.) as well as Methane can achieve a significantly faster GHG-neutral vehicle ramp-up than other fuel/powertrain combinations.

The increased ramp-up speed of GHG-neutral vehicles running on e-fuels (MtG and FT) observed in **Figure 9** is of particular interest. Both fuels have the large advantage that – once technical bottlenecks such as the availability of large scale MtG and FT synthesis production capacities are resolved[51] – these drop-in capable e-fuels cannot only be used by vehicles newly registered in a given year. The existing vehicle stock is largely backward-compatible and can "switch" from fossil fuels to drop-in capable e-fuels once they become available at large scale (see strong uptakes for MtG and FT in **Figure 9** and **Figure 10**). This holds for passenger cars running on conventional gasoline or diesel (drop-in of MtG and FT e-fuel possible) and heavy-duty vehicles on diesel (drop-in of FT fuel only). E-fuels therefore provide a unique technology option to operate large shares of the operational vehicle fleet with carbon-neutral e-fuels within a limited period of time and therefore reduce cumulated GHG emissions.

The above conclusions drawn from the share of GHG-neutral vehicles depicted in **Figure 9** are largely led by the ramp-up of passenger cars. In fact, passenger cars account for around 98% of the vehicle stock for the EU27+UK road sector considered in this study. The remaining approximately 2% consist of heavy-duty vehicles. However, heavy-duty vehicles make up for around 40%-50% of the TtW energy demand. For example, in the FT fuel pathway, heavy-duty vehicles account for 41% of TtW energy demand (see **Figure 11**), which is mainly driven by the high share of long-haul trucks. This can be explained by their relatively high operational milage compared to passenger cars. Therefore, any assessment of the single technology scenarios including technical bottlenecks should be expanded to a comparison of GHG-neutral TtW demand over time.

---

[51] Following the technical bottleneck discussions, the expert group considered that MtG synthesis plants could be operational on an industrial scale in the late 2020s while FT synthesis plants would take longer lead times and are assumed to be available on an industrial scale by the mid-2030s. However, other technical bottlenecks (e.g. electrolysis capacity) can further affect the ramp-up of GHG-neutral vehicles in both pathways.

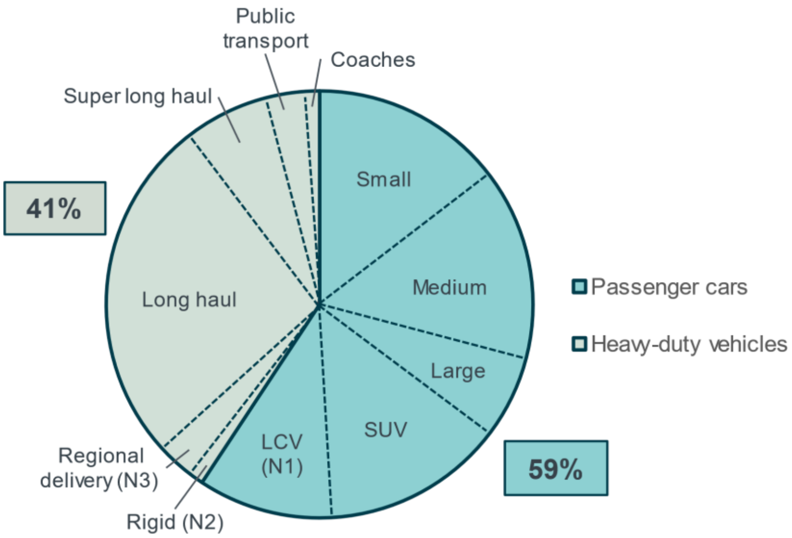


Figure 11: TtW energy demand in 2050 in the single technology FT Fuel scenario by segment.

Considering the share of GHG-neutral TtW energy demand until 2050 (see **Figure 10**) only FT and Methane technology pathways achieve a significantly higher ramp-up rate than assumed in Fuels Study IV, starting in the mid-2030s onwards after key technical bottlenecks are resolved (i.e. Methanation and FT synthesis plants as well as electrolysis capacity). All other fuel/powertrain combinations lag behind the (quite arbitrarily) assumed linear ramp-up in the Fuels Study IV. In fact, the modelling results indicate that an FT fuel pathway would be the by far quickest single technology scenario achieving a fully decarbonised vehicle stock and corresponding TtW energy demand for the EU27+UK road sector by 2040. Despite a significantly lower ramp-up rate in early years due to technical bottlenecks, the single technology FT pathway can achieve full decarbonisation of the EU27+UK road sector in 2040 already, where many other technologies would struggle to even achieve full defossilisation until 2050 (which was the assumed ramp-up in Fuels Study IV).

In particular, the aforementioned MtG as well as PHEV (BEV Dom. / MtG Int.) single technology pathways fall short in terms of reaching 100% GHG-neutral TtW energy demand over time. For these powertrain technology / energy carrier pathways , FVV made the assumption that heavy-duty vehicles which are largely running on conventional diesel should not be replaced by e-gasoline vehicles (but instead remain fuelled by fossil diesel).

Despite a lack of similar restrictions as in MtG and PHEV (BEV Dom. / MtG Int. or BEV Int. / MtG Int.) for passenger cars by assumption, the following single technology pathways do not achieve a full decarbonisation by 2050 in our modelling: BEV Int., BEV Dom., FCEV and PHEV (BEV Int. / FT Int.). We explain the key drivers below.

- **BEV Dom. / BEV Int.:** Technical bottlenecks in the short- and medium-term such as cobalt availability, the power transmission grid and catenary lines limit the ramp-up of both BEV powertrains significantly until 2040 requiring new registrations of fossil-fuelled passenger cars after 2033 to meet the mobility demand assumed. However, in order to achieve a fully decarbonised vehicle stock in 2050, it would be required that only carbon-neutral passenger cars are registered from 2033 onwards (vehicle lifetime assumption of 17 years for passenger cars).[52]

- **FCEV:** The FCEV single technology scenario is primarily restricted by the limited availability of platinum group metals (PGM) for the EU27+UK road sector in the long-term requiring the registration of conventional vehicles until 2040.[53] In combination with the vehicle lifetime assumption discussed above, no full decarbonisation is reached by 2050 despite other technical restrictions (i.e. H_2 import pipelines, battery production capacities) are resolved by mid 2030s the latest.
- **PHEV (BEV Int. / FT Int.):** Similar to BEV Int. restricted by power transmission capacities (incl. sea power cable) in the early decades and additional technical restrictions in the medium-term expected due to long lead times of FT synthesis plants. In combination with the aforementioned vehicle lifetime assumption no full decarbonisation is achieved by 2050.

Table 2 below provides a summary of the main technical bottlenecks (infrastructure and raw material availability) restricting the defossilisation of the EU27+UK road sector across all different single technology scenarios.

Selected single technology scenario	**Technical bottlenecks in 2020-2029**	**Technical bottlenecks in 2030-2039**	**Technical bottlenecks in 2040-2049**
BEV – Dom.	Power transmission grid, catenary lines, cobalt, battery production, wallboxes	Power transmission grid, catenary lines, cobalt, battery production, wallboxes	Power transmission grid, cobalt
BEV – Int.	Sea power cable, catenary lines, cobalt, power transmission grid	Sea power cable, catenary lines, cobalt, power transmission grid	Cobalt, power transmission grid
Methane – Int.	Methanation, CH_4 import pipelines, electrolysis	Methanation, electrolysis	
FCEV – Int.	H_2 import pipeline, platinum, battery production,	H_2 import pipeline, platinum	Platinum
H_2 Comb. – Int.	H_2 import pipeline, electrolysis	H_2 import pipeline, electrolysis	H_2 import pipeline
FT Fuel – Int.	FT synthesis, nickel, electrolysis	FT synthesis, nickel, electrolysis	
MtG – Int.	Electrolysis, renewable electricity generation, MtG synthesis	Electrolysis, renewable electricity generation	
PHEV (BEV-Dom. FT-Int.)	FT synthesis, battery production, electrolysis, wallboxes	FT synthesis	

---

[52] In Section 8.3.3 of this study we provide a sensitivity of the BEV (with domestic energy sourcing) single technology pathway without cobalt and power transmission grid restrictions.

[53] Platinum is primarily used as catalyst for the production of FCEVs. Following a discussion in the FVV expert group, we assume that platinum can at least partly be replaced by palladium.

PHEV (BEV-Int. FT-Int.)	FT synthesis, sea power cable, battery production, electrolysis, wallboxes	FT synthesis, sea power cable	
PHEV (BEV-Dom. MtG-Int.)	Wallboxes, public chargers, electrolysis	Wallboxes, public chargers	
PHEV (BEV-Int. MtG-Int.)	Sea power cable, wallboxes, public chargers	Sea power cable, wallboxes, public chargers	

Table 2: Main technical bottlenecks restricting the ramp-up of GHG-neutral technology pathways in single technology scenarios.

5.2 GHG emissions in single technology scenarios with technical bottlenecks

In this section, we compare the results from our single technology scenarios incl. technical bottlenecks for the EU27+UK road sector with a self-defined hypothetical CO_2 budget remaining for EU27+UK in accordance with the Paris climate target.

The Paris climate target sets out the goal to limit global warming to well below 2°C, preferably 1.5°C, compared to pre-industrial levels.[54] Based on recent IPCC reports on global CO_2 emission budgets, this translates into a hypothetically remaining cumulated CO_2 budget of 16 to 42 gigatons (1.5°C to 1.75°C target reached with 67% probability) for the EU27+UK (all sectors) until 2050.[55]

Our modelling results for all single technology scenarios including technical bottlenecks indicate that the cumulated GHG emissions for the EU27+UK road sector alone exceed our self defined 1.5°C budget for EU27+UK for all sectors but theoretically remain below our 1.75°C budget for EU27+UK (all sectors). However, in line with the findings already made in the FVV Fuels Study IV, the differences between the single technology scenarios including technical bottlenecks until 2050 considered are typically less than 20-30% of total emissions for most powertrain/energy combinations.

However, the absolute differences as displayed in **Figure 12** are still significant. For example, the Methane fuel pathway leads to approximately 7 $GtCO_2eq$ less cumulated emissions than the BEV pathway (Int. energy sourcing), which is the most GHG-intense single technology pathway until 2050 that provides a GHG-neutral powertrain for both passenger cars and heavy-duty vehicles (as noted below in **Figure 12,** PHEV-MtG is only available for passenger cars while heavy-duty vehicles remain operated with fossil diesel fuel). The difference between both scenarios (Methane vs. BEV Int.) equals 10 years of annual emissions from fuel combustion in the European road sector.[56]

It should further be noted that those single technology scenarios considered in our modelling that have not reached a carbon-neutral vehicle stock by 2050 (BEV Int., BEV Dom., FCEVs, MtG Int., PHEVs with

---

[54] UNFCC (2021), “The Paris Agreement”, https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement (last accessed: 08.09.2022).

[55] The theoretical EU27+UK CO_2 budget is estimated by the current population share: 6.6% (515 million of 7.8 billion). See FVV (2021), Section 10.3.4.

[56] Emissions from fuel combustion in the European road sector were around 0.68 $GtCO_2eq$ in 2020. See EEA/Eurostat (2022), “Greenhouse gas emissions by source sector”, variables “Fuel combustion in road sector”, https://ec.europa.eu/eurostat/web/environment/air-emissions (last accessed: 08.09.2022).

MtG Int. and PHEVs with BEV Int. and FT Int.) would cause additional emissions post-2050 (see dotted lines for powertrains in **Figure 12**).[57]

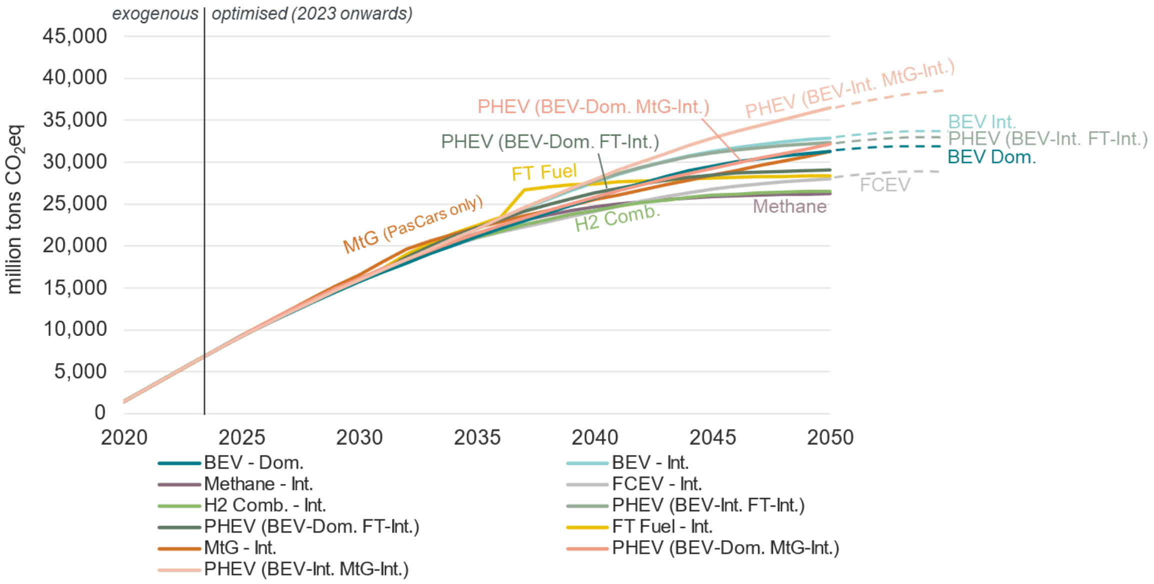


Figure 12: Cumulated GHG emissions in single technology scenarios, 2020-2050. Note: Given technical bottlenecks and vehicle lifetime assumptions, no full decarbonisation is reached in BEV Dom./Int., FCEV, PHEV-FT Int. and PHEV-MtG Int. single technology scenarios by 2050 (dashed lines). MtG and PHEV-MtG pathways only allow for replacement of gasoline vehicles, fossil diesel vehicles cannot be replaced with e-gasoline.

In fact, our modelling indicates that in all single technology scenarios the cumulated emissions from the EU27+UK road sector alone exceed our self-defined hypothetical 1.5°C CO_2 emission budget (c. 16 gigatons CO_2eq) available for the EU27+UK for all sectors around the year 2030. As set out in the previous section, this can be explained by the technical bottlenecks restricting faster ramp-ups of carbon-neutral vehicles in the early years (2020s and partially 2030s). Therefore, at least in this period, a large share of the vehicle fleet remains running on fossil fuels and causes significant running emissions.

Consequently, the decisive factor for the different level of cumulated GHG emissions across the single technology scenarios including technical bottlenecks is the ramp-up speed of carbon-neutral vehicles over time, which is subject to the relevant technical bottlenecks for each carbon-neutral powertrain.[58] In particular, our modelling indicates that those powertrains achieving high shares of carbon-neutral vehicles (and associated TtW energy consumption) relatively early on have the lowest cumulated GHG emissions by 2050 (i.e. Methane, FT and H_2 Comb.). This is because cumulative GHG emissions in all pathways are dominated by the operation of the remaining gasoline/diesel vehicle fleet with fossil fuels.

Figure 12 additionally shows that the curve of cumulated GHG emissions flattens over time while the share of carbon-neutral vehicles increases. This implies that – in terms of GHG emissions – upfront investments in for GHG-neutral vehicles and the required infrastructure underlying pay off in later years.

---

[57] The exact amount of additional emissions post-2050 for the relevant powertrains has not been assessed in the context of this study but indicative trends have been added to **Figure 12**.

[58] As shown in FVV (2021) with identical ramp-up speed across all scenarios, cumulated GHG emissions were in a comparable magnitude in all scenarios despite the different vehicle and infrastructure requirements (and therefore associated emissions) across the powertrains considered. See FVV (2021), Section 10.3.2.

This can be illustrated by the example of the FT powertrain and its backward-compatible FT fuel for the existing vehicle fleet. By 2037, FT synthesis plants become available at a large scale implying a significant jump in GHG-neutral vehicles and TtW energy consumption (**Figure 9** and **Figure 10**), as well as associated cumulated GHG emissions (**Figure 12**). However, once the required infrastructure for FT is in place, only small amounts of additional GHG emissions linked to the maintenance of infrastructure and the production of new vehicles increase cumulated emissions until 2050.

In contrast, scenarios with a relatively high share of conventional vehicles (ICEVs running on fossil gasoline or diesel due to technical bottlenecks prevalent for carbon-neutral vehicles) until 2050 (e.g. PHEV BEV Dom. / FT Int.) and those not reaching full decarbonisation by 2050 at all (e.g. BEV Int. or BEV Dom.) are expected to have the highest cumulated GHG emissions. In other words: The speed at which a low-carbon technology can be deployed could have a greater impact on overall emissions than other factors, including the absolute efficiency of the technology or the relative differences between technologies.

In summary, our results for the single technology scenarios including technical bottlenecks therefore confirm the conclusion of Fuels Study IV that *“the faster carbon neutral energy can penetrate the existing market, the lower the cumulative GHG emissions and thus the impact on climate change.”* [59]

---

[59] See FVV (2021), Section 1.

6 Results from mixed technologies scenario including infrastructure and material bottlenecks

In this section, we present the results of the GHG-optimal mixed technologies scenario taking into account infrastructure and raw material availability, which we consider the key outcome of this study. We first discuss the results of our main specification in terms of vehicle ramp-up and TtW energy demand, as well as technical bottlenecks and cumulated GHG emissions (**Section 6.1**). We then provide the results of our sensitivity analysis to determine the impact of adapting parameters for technical bottlenecks and available technologies on our GHG-optimal mixed technologies scenario (**Section 6.2**).

6.1 Main specification

In our technology neutral GHG-optimal mixed technologies scenario ("mixed technologies scenario") the model minimises cumulated GHG emissions between 2023 and 2050 subject to technical bottlenecks (infrastructure and material availability) over time. As described in Section 4 in more detail, the model therefore endogenously selects the optimal GHG-minimising combination of all eleven GHG-neutral technology pathways available for the different segments of the EU27+UK road sector.[60]

Our results show that a mix of carbon-neutral powertrain technology / energy carrier pathways can speed up the transition to GHG neutrality for the EU27+UK road sector significantly compared to scenarios with only one technology option. It thereby reduces cumulated GHG emissions over time.

In principle, technical bottlenecks affect the GHG-neutral vehicle ramp-up in the mixed technologies scenario over time, similar to the single technology scenarios previously discussed (**Section 4**). However, a combination of different technology pathways across vehicle segments and time allows to circumvent restricting technical bottlenecks of specific GHG-neutral powertrain technology / energy carrier pathways, in particular in the early years. A technology-neutral mixed modelling approach therefore can achieve a quicker ramp-up of GHG-neutral vehicles for the EU27+UK road sector.

In the following subsections, we discuss the results of our main specification of the mixed modelling in the following key dimensions in more detail:

- Share of GHG-neutral vehicles and energy demand;
- Technical bottlenecks;
- Cumulated GHG emissions; and
- Total energy demand and selected infrastructure requirements.

<u>Share of GHG-neutral vehicles and energy demand</u>

In the main specification of our mixed modelling results including technical bottlenecks the EU27+UK road sector achieves a 100% carbon-neutral vehicle stock and corresponding carbon-neutral TtW energy demand by 2040 (see **Figure 13** and **Figure 14**).

---

[60] As before, technical bottlenecks can prevent new registrations of GHG-neutral vehicles in a given year. If this is the case, new registrations of fossil fuelled vehicles (gasoline or diesel) remain available as a "fallback option" in order to meet the mobility demand assumed for EU27+UK in the respective year.

Compared to the reference ramp-up of Fuels Study IV, which assumed to reach a fully decarbonised EU27+UK road sector in 2050 with one technology, allowing for a combination of powertrains can achieve the target of full carbon-neutrality ten years earlier. Additionally, our mixed modelling indicates a significantly higher share of carbon-neutral vehicles and carbon-neutral TtW energy demand in the period until full decarbonisation is reached. In fact, already by the late 2020s, the mixed modelling ramp-up exceeds the optimistically assumed reference ramp-up of Fuels Study IV (despite explicitly considering technical bottlenecks and the later start of the modelling period in 2023 in this study).

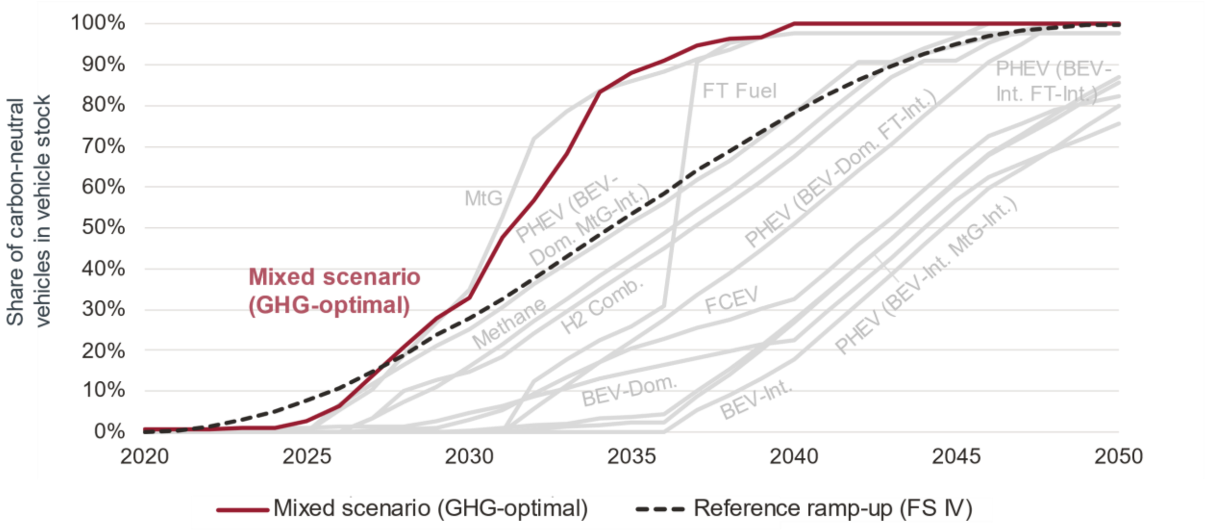


Figure 13: Share of carbon-neutral vehicles in stock in GHG-optimal mixed technologies scenario; single technology scenarios greyed out.

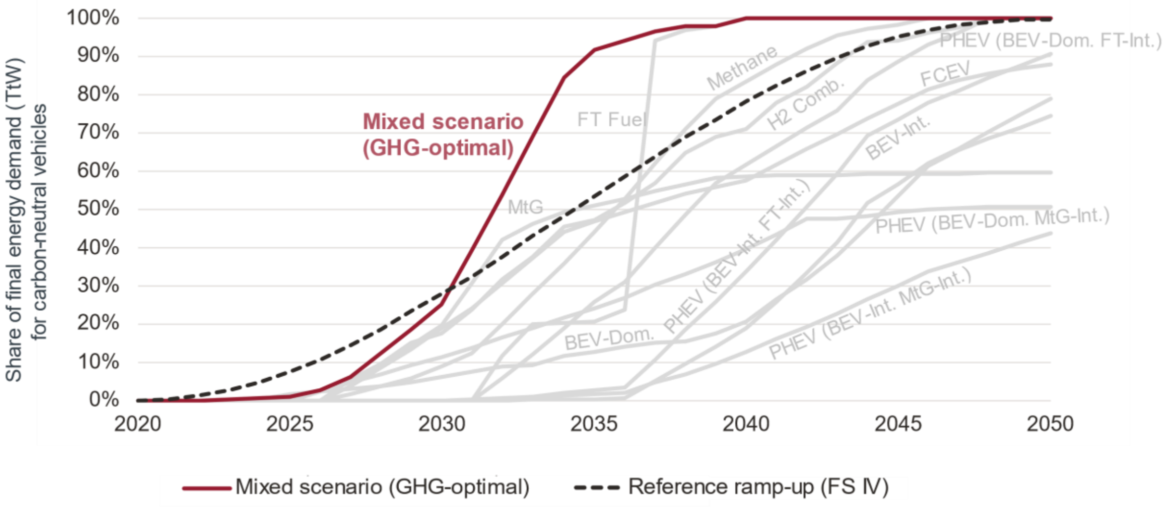


Figure 14: Share of carbon-neutral TtW energy demand in GHG-optimal mixed technologies scenario; single technology scenarios greyed out.

As set out above, the mixed modelling reaches full decarbonisation of the EU27+UK road sector in 2040. This is the same year in which the FT single technology pathway, which is the quickest single technology scenario, achieves a fully decarbonised vehicle stock and corresponding TtW demand (see **Section 4**). However, in contrast to the FT single technology pathway, whose availability is strongly limited until the mid-2030s due to technical bottlenecks[61], the mixed modelling achieves a significantly higher share of carbon-neutral vehicles and carbon-neutral TtW energy demand from the 2020s onwards by leveraging on alternative GHG-neutral powertrains available.[62]

A more in-depth analysis of the mixed modelling results further shows that a combination of powertrains is optimal to minimise cumulated GHG emissions over time. Secondly, the choice of the optimal powertrains differs between passenger cars and heavy-duty vehicles. **Figure 15** and **Figure 16** below display the developments of the vehicle fleet by powertrain for passenger cars, while **Figure 17** and **Figure 18** display the developments in the heavy-duty segment.[63]

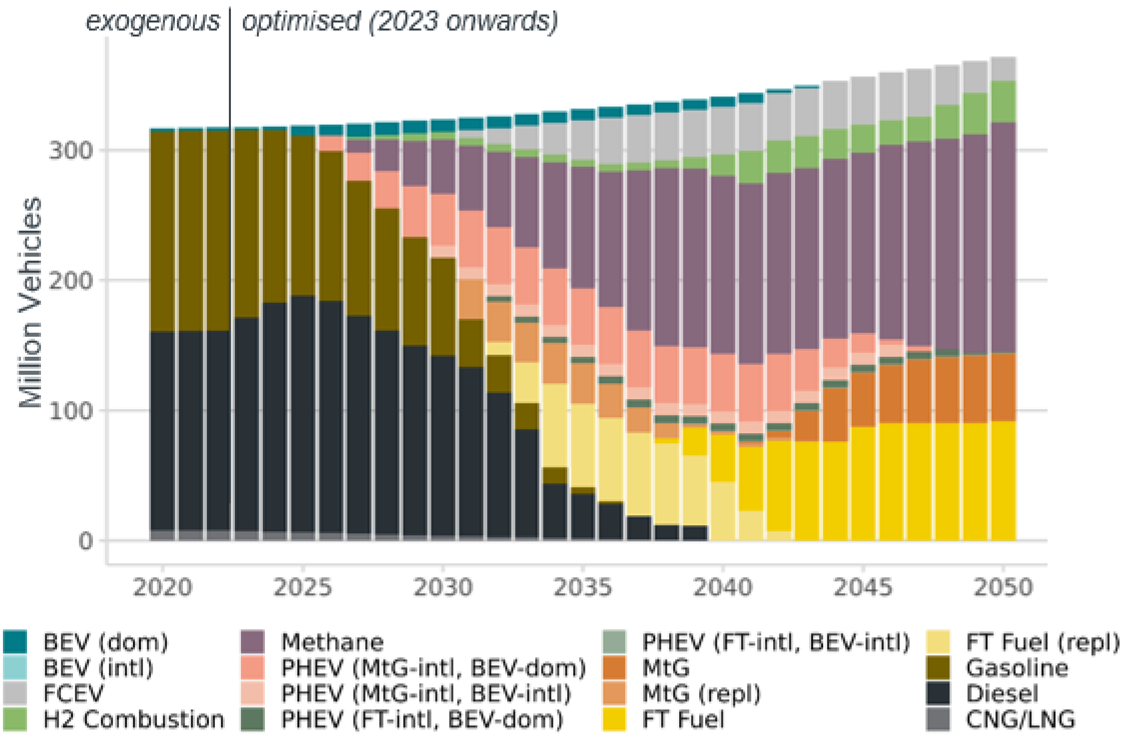


Figure 15: Powertrains in vehicle stock in GHG-optimal mixed technologies scenario – only passenger cars. Note: Replacements (repl) describe vehicles that are initially fuelled with fossil fuels but switch to e-fuels during their lifetime.

---

[61] Technical bottlenecks, in particular FT synthesis and electrolysis capacity, delay the carbon-neutral vehicle ramp-up in the FT single technology pathway until the mid-2030s. However, carbon-neutral vehicles are then rolled-out on a large scale in a short period of time (use of drop-in capabable e-fuel in previously fossil fuelled vehicles), see Section 5 for more details.

[62] Compared to the MtG single technology scenario, it appears counterintuitive that the mixed modelling leads to a slower ramp-up of GHG-neutral vehicles until the early 2030s (see **Figure 13**). However, as set out before, the MtG single technology scenario is limited to passenger cars. Therefore, by assumption, the MtG pathway does not consider any GHG-neutral vehicle ramp-up of the small but energy-intense heavy-duty segment operating on diesel fuel (see Section 5 of this study). With regards to GHG-neutral TtW consumption it can therefore be seen that the mixed technologies scenario (which aims for 100% GHG-neutral passenger cars and heavy-duty vehicles) reaches a significantly higher share than all single technology scenarios in the early years, including the MtG pathway (see **Figure 14**).

[63] We note that we display the results for passenger cars and heavy-duty vehicles separately to account for the different trends in powertrains selection between the two segments. However, as set out in Section 4 of this study, the model optimises the selection of powertrains for both passenger car and heavy-duty segments in a combined single model run.

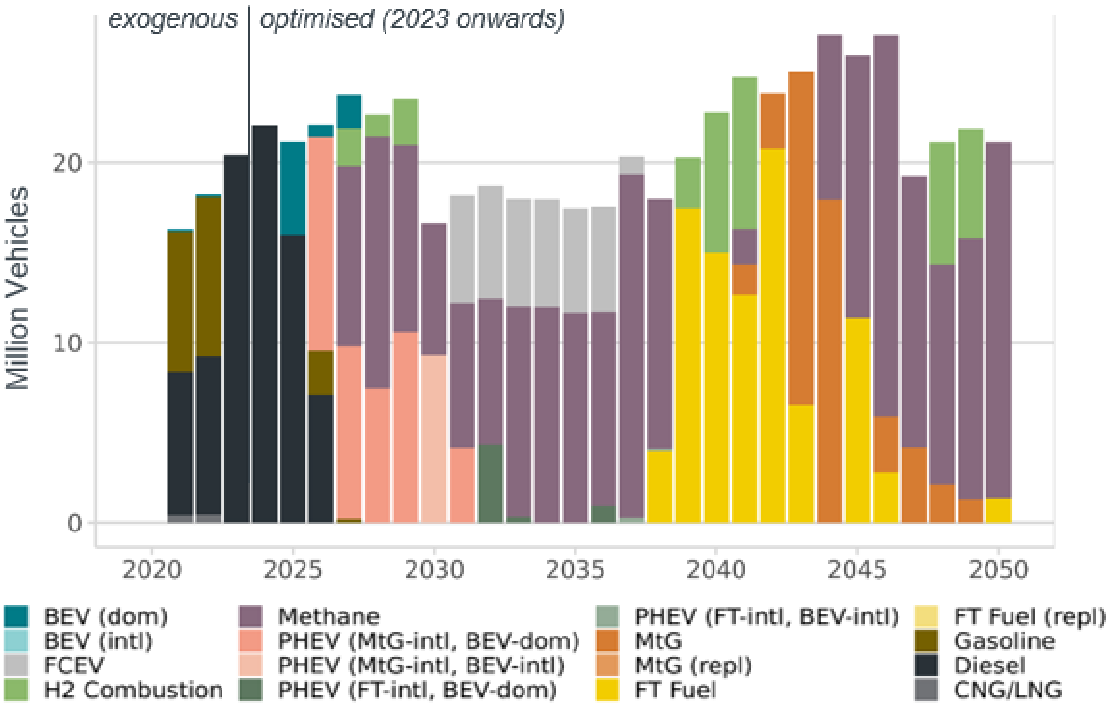


Figure 16: Newly registered vehicles per powertrain and year in GHG-optimal mixed technologies scenario – only passenger cars. Note: Replacements (repl) describe vehicles that are initially fuelled with fossil fuels but switch to e-fuels during their lifetime.

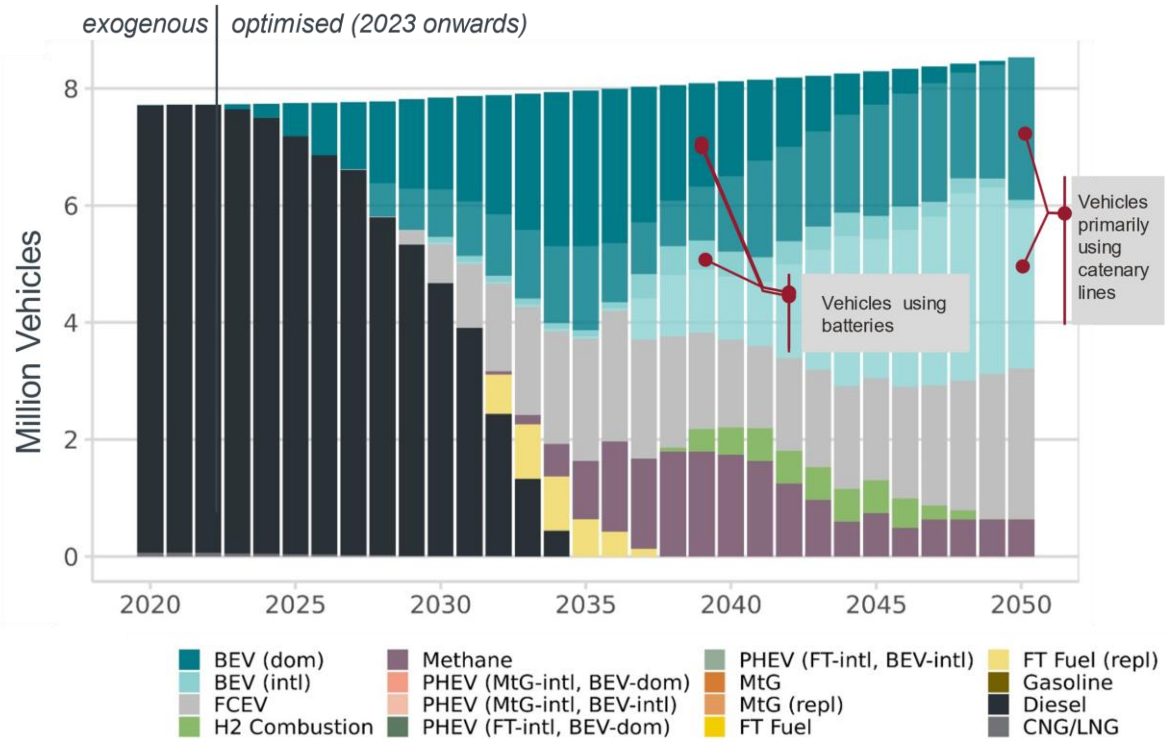


Figure 17: Powertrains in vehicle stock in GHG-optimal mixed technologies scenario – only heavy-duty vehicles. Note: Replacements (repl) describe vehicles that are initially fuelled with fossil fuels but switch to e-fuels during their lifetime.

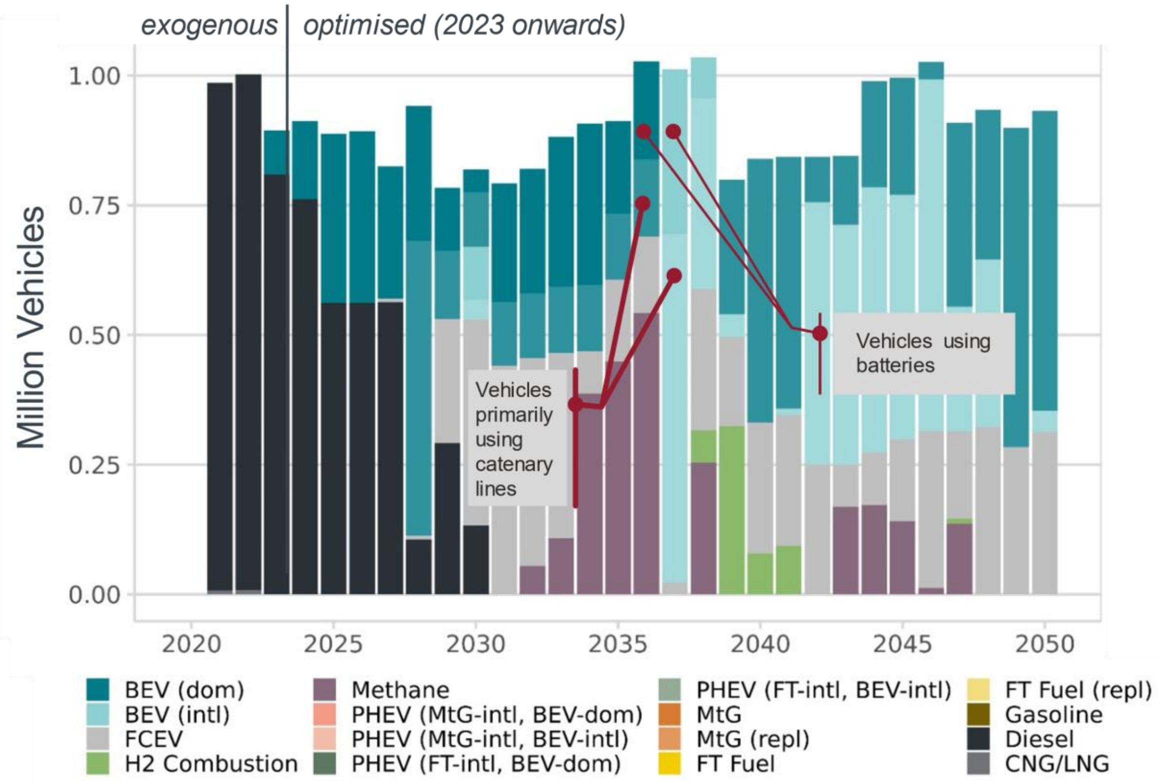


Figure 18: Newly registered vehicles per powertrain and year in GHG-optimal mixed technologies scenario – only heavy-duty vehicles. Note: Replacements (repl) describe vehicles that are initially fuelled with fossil fuels but switch to e-fuels during their lifetime.

For the passenger car segment, Methane is the dominant pathway in the long term to minimise overall GHG emissions for the EU27+UK road sector.[64] Methane vehicles are complemented by significant shares of e-fuels (MtG and FT pathways) from 2030s onwards and smaller shares of other GHG-neutral powertrains (e.g. H_2 Comb. and FCEV in the long run).

The availability of e-fuels in the 2030s in combination with the backward-compatibility of fossil fuelled passenger cars in the existing vehicle stock further has a positive impact on minimising cumulated GHG emissions for the EU27+UK road sector. As can be seen in **Figure 13** above, the share of GHG-neutral vehicles in stock significantly increases once MtG and FT capacities become largely available (in the mid-2020s and early 2030s respectively) for new vehicle registrations, as well as the existing vehicle fleet (replacement of fossil fuels with “drop-in” e-fuels). Therefore, e-fuels significantly speed up the pathway to carbon-neutrality in the optimised mixed modelling.

For the heavy-duty segment, a fully decarbonised vehicle stock can already be achieved in 2035 – five years earlier than for the passenger car segment. In terms of powertrain selection, BEV including catenary lines (BEV Dom. or BEV Int.) and FCEV are dominating technologies for the heavy-duty segment in the long term in order to minimise overall GHG-emissions for the EU27+UK road sector. In

---

[64] The substantial selection of Methane for passenger cars is coherent with the results of FVV (2021) in which Methane has been identified as the pathway with the lowest overall GHG emissions in the short-term (e.g. in the year 2030). The investment in Methane infrastructure in earlier years therefore allows the model in this study to replace Methane vehicles at the end of their lifetime with new Methane vehicles at a later point in time with no additional GHG infrastructure emission costs for long-lasting infrastructure assets such as CH_4 pipelines (as these emissions have been already fully accounted for in the year of their physical installation). This results in a cyclical pattern of Methane vehicles newly registered over time which can be observed in **Figure 16** (Methane vehicle and infrastructure ramp-up in late 2020s / early 2030s and replacement of Methane vehicles at the end of their lifetime with new Methane vehicles in 2040s).

fact, more than 90% of the carbon-neutral vehicle fleet consists of BEVs and FCEVs in 2050 (see **Figure 17**). In the short to medium term, the model additionally chooses some new methane vehicles as well as the backward-compatible FT fuel to decarbonise shares of the heavy-duty diesel vehicles in the operating fleet in the 2030s.

The role of both BEV pathways used in the heavy-duty segment is of particular interest (see light and dark blue bars in **Figure 17**). If one were to consider only the two BEV pathways, BEV Dom. and BEV Int., the latter is the preferred choice in terms of minimising cumulated GHG emissions over time if one were to exclude technical bottlenecks. More favourable energy sourcing conditions (higher wind/PV full-load hours) in the "International" scenario reduce the need for installing renewable power plant capacities and therefore associated GHG emissions. However, "International" sourcing in this study requires the transmission of electric power via a sea cable from MENA to Europe which is not available today and – according to the FVV experts – requires significant construction lead times. Therefore, in order to keep GHG emissions as low as possible, the model uses primarily European power generation capacities built at the beginning of the modelling period before gradually replacing "Domestic" wind/PV capacities at the end of their lifetimes with new capacities installed under the "International" scenario once technical bottlenecks such as the MENA sea power cable are resolved.

Deep dive: Why the GHG-optimal scenario considers direct electrification (BEV pathways) in the heavy-duty segment but hardly for passenger cars

As **Figure 16** and **Figure 17** above indicate, the GHG-optimal scenario considers direct electrification (BEV pathways) primarily for the ramp-up of carbon-neutral heavy-duty vehicles. In contrast, the ramp-up of carbon-neutral passenger cars is largely dominated by gaseous and liquid fuels.

Taking into account current trends in the European automotive sector, as well as recent political discussions on the phase-out of combustion engines for new passenger cars and light-duty vehicles from 2035 onwards, the result of our mixed modelling may seem counterintuitive.

We explain the key factors driving the results of our modelling below.

1. Infrastructure and raw material required for BEV powertrains are scarce: The ramp-up of BEV powertrains (Dom. / Int.) is strongly constrained by technical bottlenecks, in particular in the 2020s and 2030s. This relates for example to the required transmission grid expansion, cobalt availability, battery manufacturing capacities and wallboxes (see for example the technical bottlenecks in the BEV single technology scenarios in **Table 2**). In order to minimise overall GHG emissions, the limited resources for the vehicle ramp-up available should therefore be used most efficiently. Consequently, our model allocates these resources to vehicle segments in which the largest GHG emission saving is achieved “per invested amount of scarce raw material”.

2. In light of the technical bottlenecks for BEVs, the heavy-duty segment achieves relatively higher GHG emission savings: Consistent with the previous study, we assume that large trucks (long-haul and super long-haul vehicles with >16 t) are not exclusively equipped with very large batteries allowing them to operate the same milage as observed today. Instead, these trucks rely on overhead grid lines for a significant part of their journey reducing the battery requirements for these trucks. This in turn lowers the battery production capacity and cobalt demand associated with a single truck. For example, our modelling assumes a long-haul truck using a catenary system to require only a battery size of 268 kWh compared to a battery size of 360 kWh in a (smaller and lighter) regional distribution truck which is assumed to operate without access to a catenary line system. In combination with the high milage of heavy-duty vehicles compared to passenger cars, a relatively high share of GHG emissions can be saved by electrifying the heavy-duty segment, e.g. via a catenary system.

3. Even absent technical bottlenecks for BEVs, a significant share of directly electrified passenger cars is unlikely and would further translate into higher cumulated GHG emissions: With regards to the passenger car segment in particular, it is worth noting that other GHG-neutral powertrains such as Methane typically translate into lower cumulated GHG emissions (on a Well-to-Wheel basis) than the BEV powertrains on a per-vehicle basis (see also footnote 60). Therefore, even in absence of technical bottlenecks for BEVs, the model would not opt for a significant share of BEVs in the passenger car segment. This would only be plausible in case other (less GHG-intense powertrains) would be heavily constrained by technical bottlenecks implying the BEV technology pathway would be the “best option” in terms of GHG emissions available. In any case this would translate in higher cumulated GHG emissions compared to the mixed technologies scenario (see **Section 6.2**).

Technical bottlenecks

Despite the accelerated deployment in the GHG-optimal mixed modelling the ramp-up of carbon-neutral vehicles remains restricted by technical bottlenecks, in particular in the short and medium term. **Figure 19** below groups the binding technical bottlenecks[65] observed in the mixed modelling by three major phases:[66]

- **Phase 1 – Years 2023-2029:** The first phase can be best described as the introduction of carbon-neutral vehicles at a reasonable scale. In light of the limited capacities for ramping up infrastructure and material supply in the short term across all GHG-neutral powertrains a range of technical bottlenecks restrict the ramp-up of carbon-neutral vehicles, in particular in the very early years (until 2025).
- **Phase 2 – Years 2030-2034:** This phase is characterised by a significant growth of carbon-neutral vehicles in stock. Compared to the first phase, some technical bottlenecks (methanation, wallboxes, H_2 import pipelines and MtG synthesis) are already resolved at the beginning of the phase. Moreover, a large share of remaining technical bottlenecks is eliminated by 2034 the latest (electrolysis, FT synthesis, power transmission grid and battery manufacturing capacity). In particular, the availability of e-fuels at large scale and the possibility to use these as “drop-in fuels” for the existing vehicle stock (replacing fossil gasoline/diesel) positively impacts the growth of carbon-neutral vehicles in stock.
- **Phase 3 – Years 2035-2039:** At the end of this period, the last technical bottlenecks are resolved (catenary lines, MENA sea power cable). This translates into a 100% carbon-neutral vehicle stock in 2040.

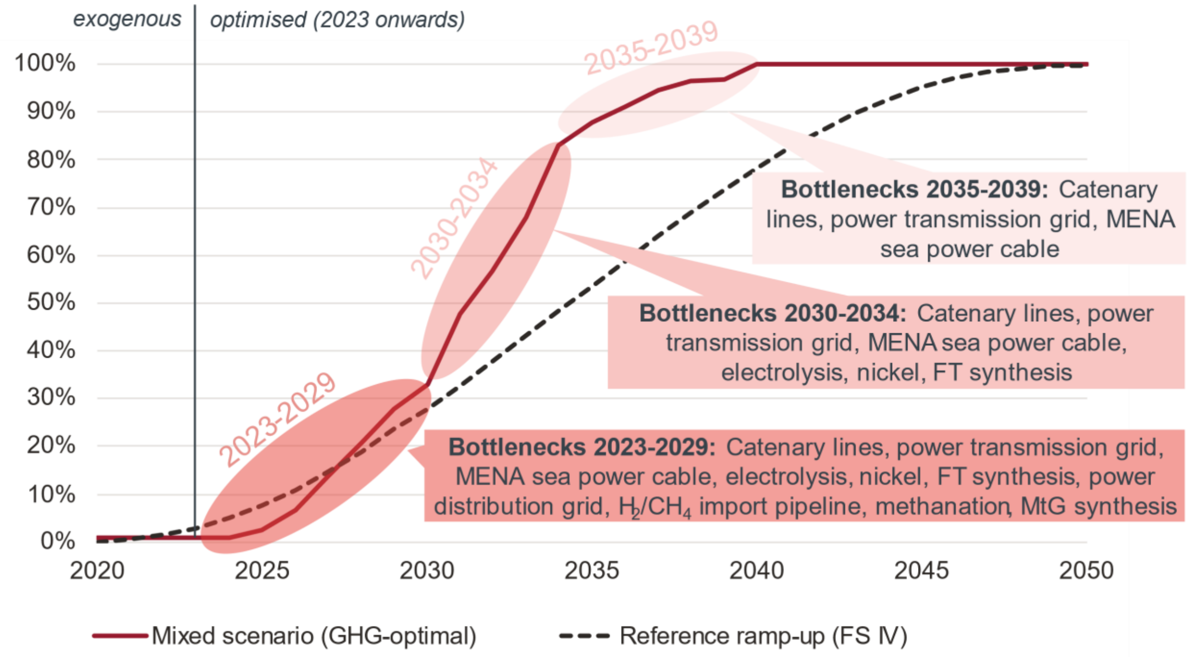


Figure 19: Main technical bottlenecks restricting the ramp-up of carbon-neutral vehicles in the GHG-optimal mixed technologies scenario over time.

---

[65] We show the “binding” bottleneck (here: catenary lines) and the next five bottlenecks that would restrict the ramp-up even if the previously binding bottlenecks were hypothetically to be solved, as well as all infrastructure that has zero capacity up to a certain year.

[66] For a better understanding, we have grouped the technical constraints in three phases in **Figure 19**Figure 19. However, in some occasions, not each technical bottleneck listed is a binding constraint for the full period (e.g. electrolysis is a binding constraint until the year 2033). More details on the duration of the technical constraints can be found in the Appendix 1.

Cumulated GHG emissions

As set out earlier in this section, the mixed technologies scenario increases the ramp-up speed of carbon-neutral vehicles and thereby reduces cumulated GHG emissions from the EU27+UK road sector over time.

Figure 20 below shows that cumulated GHG emissions in the mixed technologies scenario are significantly lower than those associated with the single technology scenarios. In fact, emissions in the mixed technologies scenario cumulate to approximately 22.5 $GtCO_2eq$ by 2050. This translates into an additional absolute saving of 3.5 $GtCO_2eq$ (around -14%) compared to the single technology scenario with the lowest GHG emissions (Methane).

As can be seen in **Figure 20**, cumulated GHG emissions in the mixed technologies scenario tend to be significantly lower compared to the single technology scenarios from 2030 onwards. This development is linked to the increased ramp-up speed achieved in the mixed technologies scenario in the period from 2030 onwards when several technical bottlenecks restricting the ramp-up of carbon-neutral vehicles in the mixed technologies scenario are resolved.

Therefore, though a significantly lower level of cumulated GHG emissions by 2050 can be achieved, even the GHG-optimal mixed technologies scenario for the EU27+UK road sector exceeds our self defined 1.5°C emissions budget for the EU27+UK (all sectors) theoretically available by 2030 similar to the single technology scenarios discussed above (see **Section 4**).

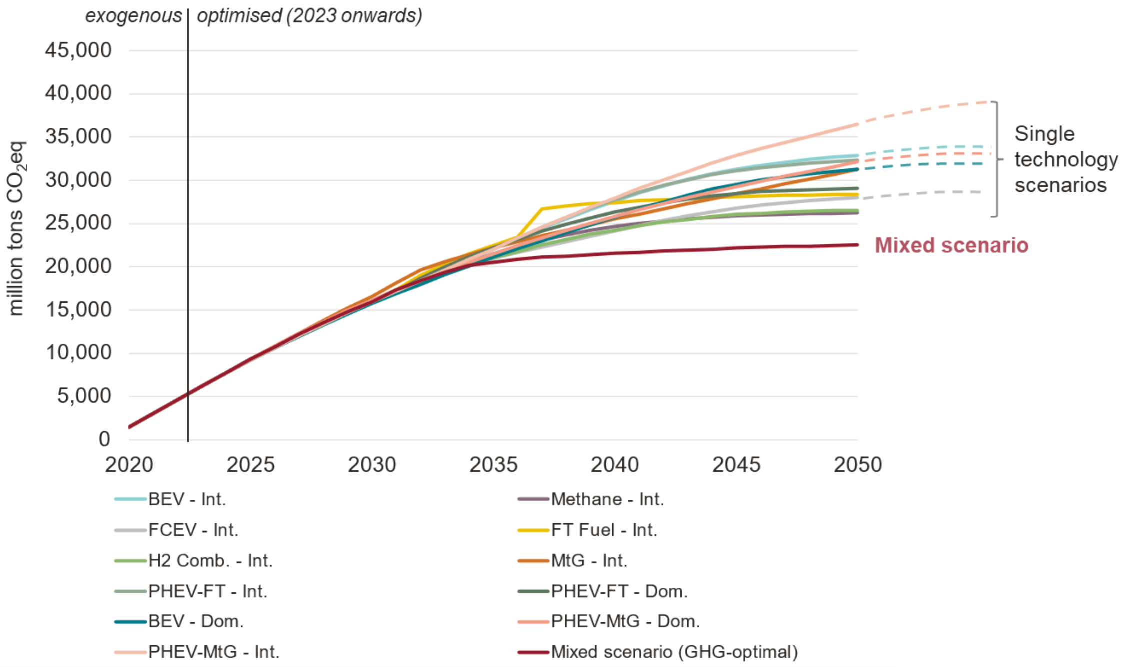


Figure 20: Cumulated GHG emissions in mixed technologies scenario and single technology scenarios. Note: Given technical bottlenecks and vehicle lifetime assumptions, no full decarbonisation is reached in BEV Dom./Int., FCEV, PHEV-FT Int. and PHEV-MtG Int. single technology scenarios by 2050 (dashed lines).

Total energy demand and selected infrastructure requirements

The required renewable WtW energy for the EU27+UK road sector in the GHG-optimal mixed technologies scenario determines the requirement for initial electricity generation capacities (PV and wind plants), as well as any infrastructure requirements further down the supply chains used in the different technology pathways considered.

Below, we provide an initial overview on the WtW renewable energy demand (primary energy demand), electricity generation capacities and selected infrastructure elements (electrolysis and synthesis capacities) for the GHG optimised mixed technologies scenario.

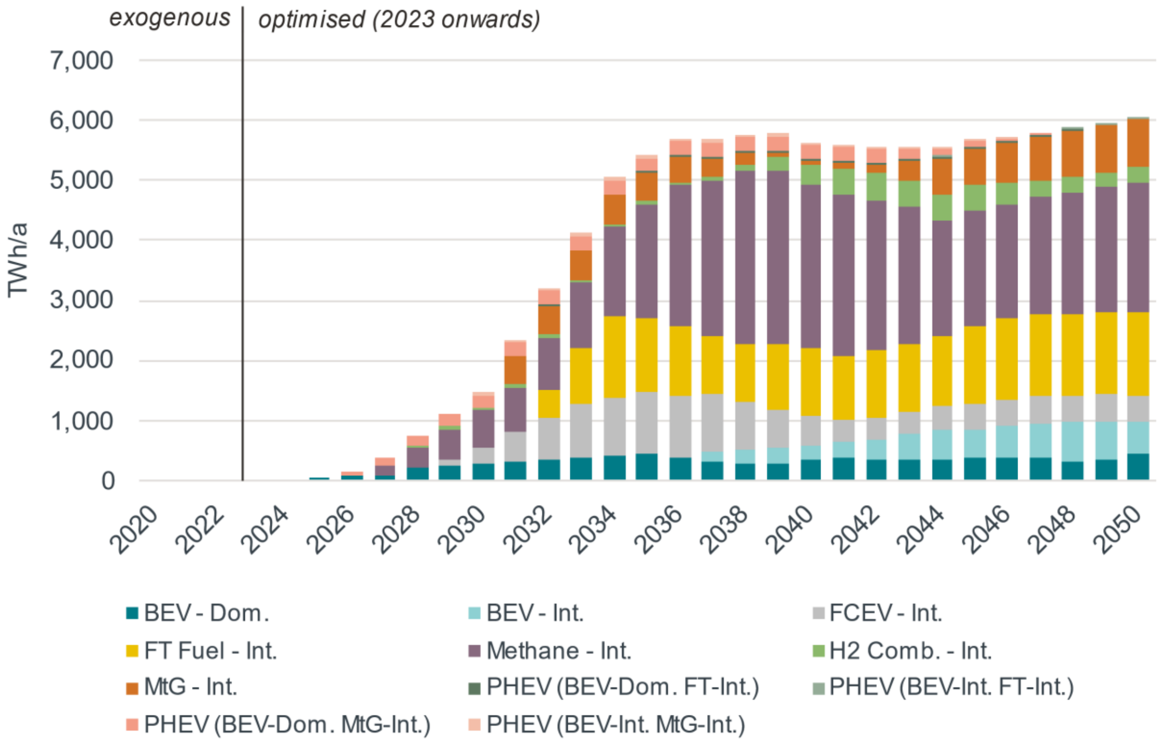


Figure 21: Primary renewable energy demand (WtW) in GHG-optimal mixed technologies scenario by powertrain over time. Note: MtG and FT Fuel include the use of the fuel in new and existing ICEVs (i.e. replacement of fossil fuel with e-fuels for vehicles in the existing fleet).

Regarding renewable WtW energy demand (**Figure 21**), our GHG-optimal mixed technologies scenario requires around 6,000 TWh/a for the EU27+UK road sector in 2050 which is equivalent to 38% of the EU27+UK primary energy consumption in 2019 (all sectors).[67] The slight decrease in renewable energy demand in the early 2040s is due to the development of the vehicle fleet and the efficiency of the selected powertrains. The majority of the renewable WtW energy demand (about 60% in 2050) is made up of Methane and FT Fuel, which are mainly chosen for passenger cars. The WtW energy demand of BEVs is mainly due to the heavy-duty segment, which on the one hand accounts for approximately 30% of final energy demand (TtW) in 2050, but for which on the other hand the most efficient pathway is selected for the majority of vehicles, i.e. due to lower efficiency losses along the energy supply chain of BEV, the least primary energy is required for the same final energy demand.

Consistent with the increased share of GHG-neutral WtW energy demand, the installed renewable electricity generation capacities increase over time (**Figure 22**) reaching a sustainable state in 2036.

---

[67] Frontier Economics based on Eurostat (2022), “Simplified energy balances”, variable “NRG_BAL_S” (last accessed: 08.09.2022).

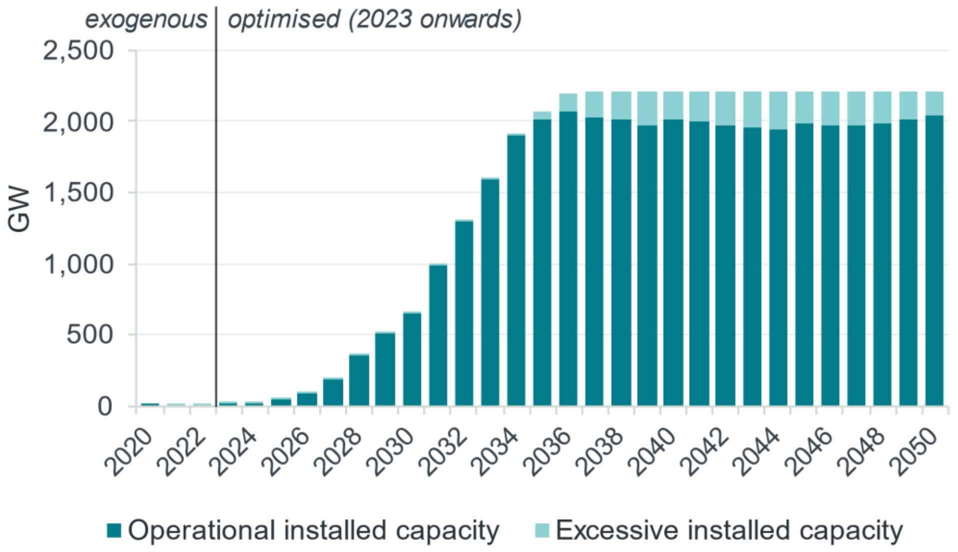


Figure 22: Installed renewable electricity generation capacity in GHG-optimal mixed technologies scenario over time. Note: Operational installed capacity relates to capacity used by the vehicle stock in a given year, excessive installed capacity relates to infrastructure available but not used by the vehicle stock in the given year.

The GHG-optimal mixed modelling further requires a significant scale-up of electrolysis capacity for the EU27+UK road sector (see **Figure 23**). In fact, around 1,500 GW of electrolysis capacity would be needed by 2050 for the EU27+UK road sector alone. This is equivalent to more than 40% of the global electrolysis capacity required for all sectors under IEA's *"Net-Zero-Emissions"* scenario (3,600 GW in 2050).[68]

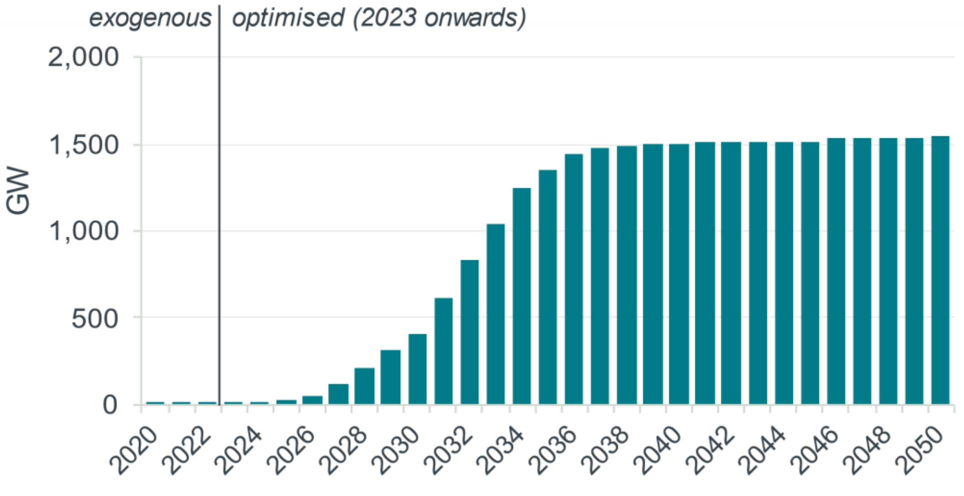


Figure 23: Installed electrolysis capacity in GHG-optimal mixed technologies scenario.

Taking into account the large share of gaseous and liquid fuels in our GHG-optimal mixed modelling, we display the required ramp-up of synthesis capacity for vehicles using methane and e-fuels (MtG and FT) in **Figure 24** below. A combined capacity of around 300 GW would be required in 2050 to meet the EU27+UK road sector demand in our mixed modelling, thereof slightly less than two thirds for Methanation.

---

[68] IEA (2021), „Net Zero by 2050" (page 109), https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf (last accessed: 08.09.2022).

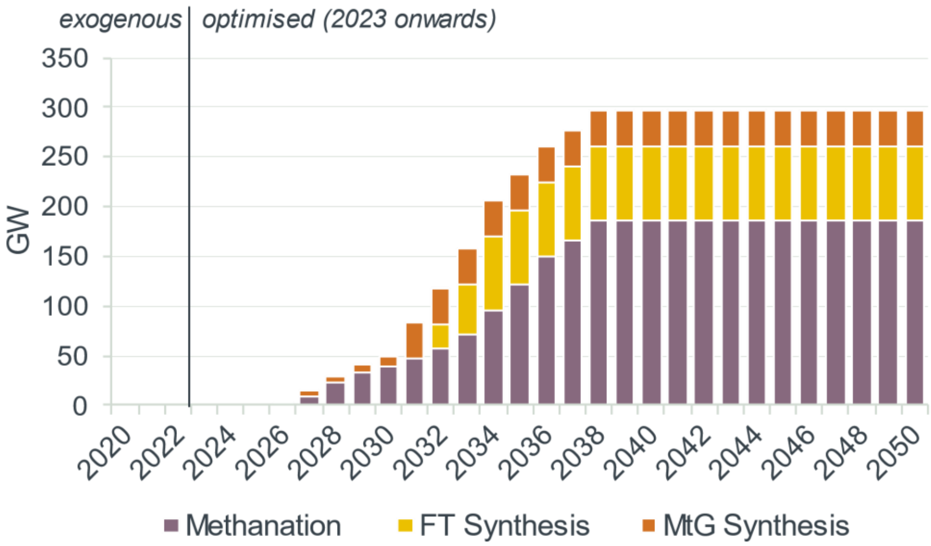


Figure 24: Installed synthesis capacity in GHG-optimal mixed technologies scenario.

6.2 Sensitivities

To ensure the robustness of the results retrieved from the GHG-optimal mixed technologies scenario (see previous section), we have further carried out different sensitivities.

The sensitivities can be split into two categories:

- **Sensitivities 1 – relaxed technical bottleneck assumptions:** In these sensitivities, we ease the technical restrictions for certain infrastructure elements (e.g. no catenary line and/or transmission grid restrictions); and
- **Sensitivities 2 – reduced number of (GHG-neutral) technology pathways:** In these sensitivities, we reduce the numbers of powertrains available for a GHG-neutral EU27+UK road sector until 2050 (i.e. an ICE ban from 2035 onwards, a focus on powertrains currently in high demand, etc.).

Below we explain the underlying rationale for each of the different sensitivities and compare their results with the GHG-optimal mixed technologies scenario (“base case”) in terms of GHG emissions and costs.

Description of sensitivities

Table 3 below provides an overview on the sensitivities considered in the context of this study. In total, we have conducted seven sensitivities: Two related to relaxed bottleneck assumptions and five in the context of a reduced number of (GHG-neutral) technology pathways.

With regards to the relaxed technical bottlenecks assumptions (Sensitivities 1 in **Table 3**), our analysis particularly focused on the technical bottlenecks restricting the ramp-up of battery-electric vehicles in the medium to long term. In the mixed modelling, e.g. catenary lines required for the heavy-duty segment (long-haul and super-long-haul vehicles) remain a binding technical constraint until the late 2030s.

Similarly, the expansion of the transmission grid is a binding constraint until the mid-2030s. In these sensitives, we remove these technical constraints for the full modelling period 2023-2050.[69]

For the reduced number of technologies (Sensitivities 2 in **Table 3**), our analysis considers different “cuts” of technology pathways available for the new vehicle registrations in the EU27+UK road sector until 2050.

This includes an ICE ban from 2035 onwards (Sensitivity 2a, in which new registrations are restricted to BEV, FCEV and H_2 Comb. from 2035) as well as a “strict” ICE ban (Sensitivity 2b, in which new registrations are restricted to only BEV and FCEV from 2035). In both Sensitivities, e-fuels can be used to power existing internal combustion engine vehicles.

In Sensitivity 2c we focus on so-called long-run technologies (BEV, FCEV, FT and MtG) in the context of our modelling. These technologies are equivalent to powertrains currently developed in the automotive sector at a large scale in the long-term (e.g. eliminating Methane and H_2 Comb. due to limited R&D of manufacturers today, as well as PHEVs which are considered to be a “bridge technology” for the short- and medium-term only).

In contrast, in Sensitivity 2d we restrict the available set of technologies to those currently in high demand based on new vehicle registrations. In 2021, fossil fuelled ICEVs (fossil gasoline and diesel), BEVs and (P)HEVs made up for around 97% of the newly registered passenger cars in Europe.[70] The technologies included in our modelling exercise are therefore BEVs, PHEVs and ICEVs. For the latter we consequently assume that ICEVs are allowed to operate exclusively on e-fuels (FT, MtG).

Lastly, in Sensitivity 2e we restrict the availability of BEV powertrains to passenger cars only. This sensitivity takes into account the fact that the electrification of the heavy-duty segment is yet in its infancy and a catenary system (as assumed in this study for long-haul and super-long-haul vehicles) has not yet been widely discussed for a decarbonised EU27+UK heavy-duty segment.

Name	**Description**	**Powertrains allowed for new vehicle registrations**
Sensitivities 1: Relaxed technical bottleneck assumptions		
Sensitivity 1a	No catenary line restriction	All
Sensitivity 1b	No catenary line and transmission grid restriction	All
Sensitivities 2: Reduced number of (GHG-neutral) technology pathways		
Sensitivity 2a	ICE ban from 2035	BEV, FCEV and H_2 Comb. from 2035 (e-fuel usage in existing vehicle legacy fleet)
Sensitivity 2b	Strict ICE ban from 2035	BEV and FCEV from 2035 (e-fuel usage in existing vehicle legacy fleet)

---

[69] We note that in the mixed modelling the sea power cable from MENA to Europe is a longer lasting binding constraint than the transmission grid expansion for battery-electric vehicles. However, the MENA sea power cable is only required for the BEV Int. scenario. In contrast, the transmission grid expansion affects both BEV Dom. and BEV Int. scenarios which is why we focus on this infrastructure element in the sensitivity analysis.

[70] ACEA (2022b), „Fuel types of new passenger cars in the EU”, https://www.acea.auto/figure/fuel-types-of-new-passenger-cars-in-eu/ (last accessed: 08.09.2022).

Sensitivity 2c	Only long-run technologies	BEV, FCEV, FT Fuel and MtG from 2023
Sensitivity 2d	Focus on powertrains currently in high demand	BEV, FT Fuel, MtG and PHEV from 2023
Sensitivity 2e	No catenary system/BEV for heavy-duty segment	Passenger cars: All Heavy-duty vehicles: FCEV, H_2 Comb., FT Fuel, Methane

Table 3: Modelling sensitivities for GHG-optimal mixed technologies scenario. Note: Consistent with the single technology scenarios and the GHG-optimal mixed technologies scenario, fossil fuelled vehicles are registered in case technical bottlenecks restrict the ramp-up of the powertrains allowed to meet the mobility demand assumed for the EU27+UK road sector.

Background: Cost comparisons between the scenarios have limited explanatory power

In this study, we report cumulative nominal total costs (infrastructure plus vehicle costs) between 2020 and 2050 for the GHG-optimal scenario and its sensitivities as well as the single technology scenarios. These cost estimations and comparisons between the scenarios should be considered cautiously and should take into account caveats set out below:

- Consistent to other studies, cost projections until 2050 are subject to uncertainties for various reasons, including political, economical, legal and technical factors;
- Any defossilisation of production processes is likely to drastically change costs for respective raw material and infrastructure components which can not be fully anticipated today;
- Costs developments relate to the prevalence of the infrastructure element (“economies of scale” and “economies of scope”);
- Any investment costs (as well as GHG emissions) are accounted for in our model in the year that they occur (“cash-flow” / “one”off” approach) – we do not apply a depreciation factor of the asset lifetime and do not discount costs;
- O&M costs for excess capacities (e.g. for transition technologies), as well as R&D costs in the period 2020-2050 are not factored in; and
- Any recurring maintenance investments which may be necessary after 2050 are not considered.

Results of the sensitivities

Overall, the seven sensitivities considered only lead to minor deviations from the base case with regards to GHG emissions (see **Figure 25** and **Figure 26** below).

As Sensitivities 1 generally relax various constraints, they can only further decrease GHG emissions compared to the base case. In contrast, Sensitivities 2 though impose additional constraints and therefore can only worsen the overall results related to GHG emissions.

We summarise the main findings below. Detailed results, including the absolute total GHG emissions and costs[71] as well as the share of GHG-neutral vehicles and powertrains selected in each sensitivity, are provided in Appendix 1.

Figure 25 shows how much more (Sensitivities 2) or less (Sensitivities 1) GHG emissions are emitted in the period 2020-2050 in the sensitivities compared to the base case.

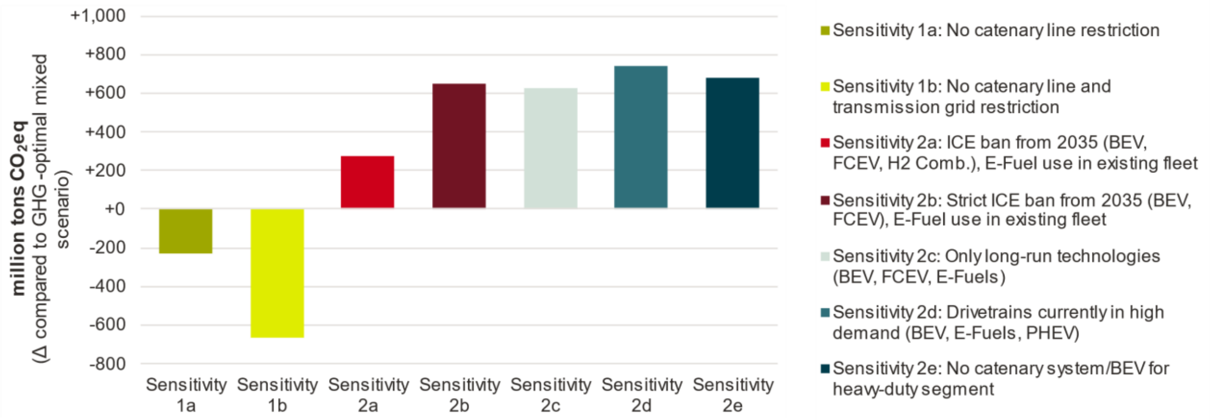


Figure 25: Cumulated GHG emissions in sensitivities compared to GHG-optimal mixed technologies scenario. Note: Sensitivities 2a and 2b use e-fuels to operate significant shares of remaining diesel and gasoline vehicles from the existing legacy fleet until their phase-out at the end of the vehicle lifetime.

Figure 26 shows the relative difference in cumulated GHG emissions in comparison to the GHG-optimal mixed technologies scenario (on the x-axis) and the relative difference in cumulated cost in comparison to the GHG-optimal mixed technologies scenario (on the y-axis) until 2050, for all sensitivities as well as all single technology scenarios.[72] The further to the right a respective scenario is located on the y-axis, the more GHG emission intensive, in terms of cumulated GHG emissions, it is in comparison to the GHG-optimal mixed technologies scenario. The further down a respective scenario is located on the x-axis, the cheaper (in terms of cumulated cost) it is in comparison to the GHG-optimal mixed technologies scenario. Relative costs differences are shown for the cumulated **oncost of defossilisation**, i.e. only oncost to achieve a defossilised fleet are taken into account – that excludes baseline vehicle cost. Those baseline vehicle costs are the cumulated costs for the vehicles which would have been hypothetically sold until 2050 without any defossilisation ambitions, translating into diesel/gasoline vehicles still operated with 100% fossil fuel.[73]

---

[71] The cumulative costs shown here are not directly comparable with the costs shown in Fuels Study IV for two reasons. In Fuels Study IV, results were expressed as net present value (assuming a discount rate of 6%) and in terms of incremental costs, i.e. costs that incur independently of the defossilisation scenarios are subtracted. In this study, we show total cost and do not discount future costs in order to have a like-for-like comparison given the different timings of infrastructure investments across all scenarios.

[72] It is important to note that not all single technology scenarios achieve a fully carbon-neutral fleet by 2050 (see Section 6.1). Therefore, each single technology scenario is labelled with the per centage of achieved defossilisation level in 2050 next to its data point in the graph. For those pathways further GHG emissions would be emitted and additional investments are required to achieve 100% defossilised vehicle fleet after 2050.

[73] The cumulated oncosts of defossilisation are more comparable with the costs shown in Fuels Study IV. However, unlike Fuels Study IV, which expressed cost as net present value (assuming a discount rate of 6%), Fuels Study IVb shows total cost and does not discount future costs. The approach in this study is required in order to have a better like-for-like comparison of scenario costs within Fuel Study IVb, which is particularly driven by the different timings of infrastructure investments across all scenarios. considered in light of the technical bottlenecks. Furthermore Fuels Study IVb explicitly focuses on the "balanced" scenario for long-term technological progress (see Section 3.2).

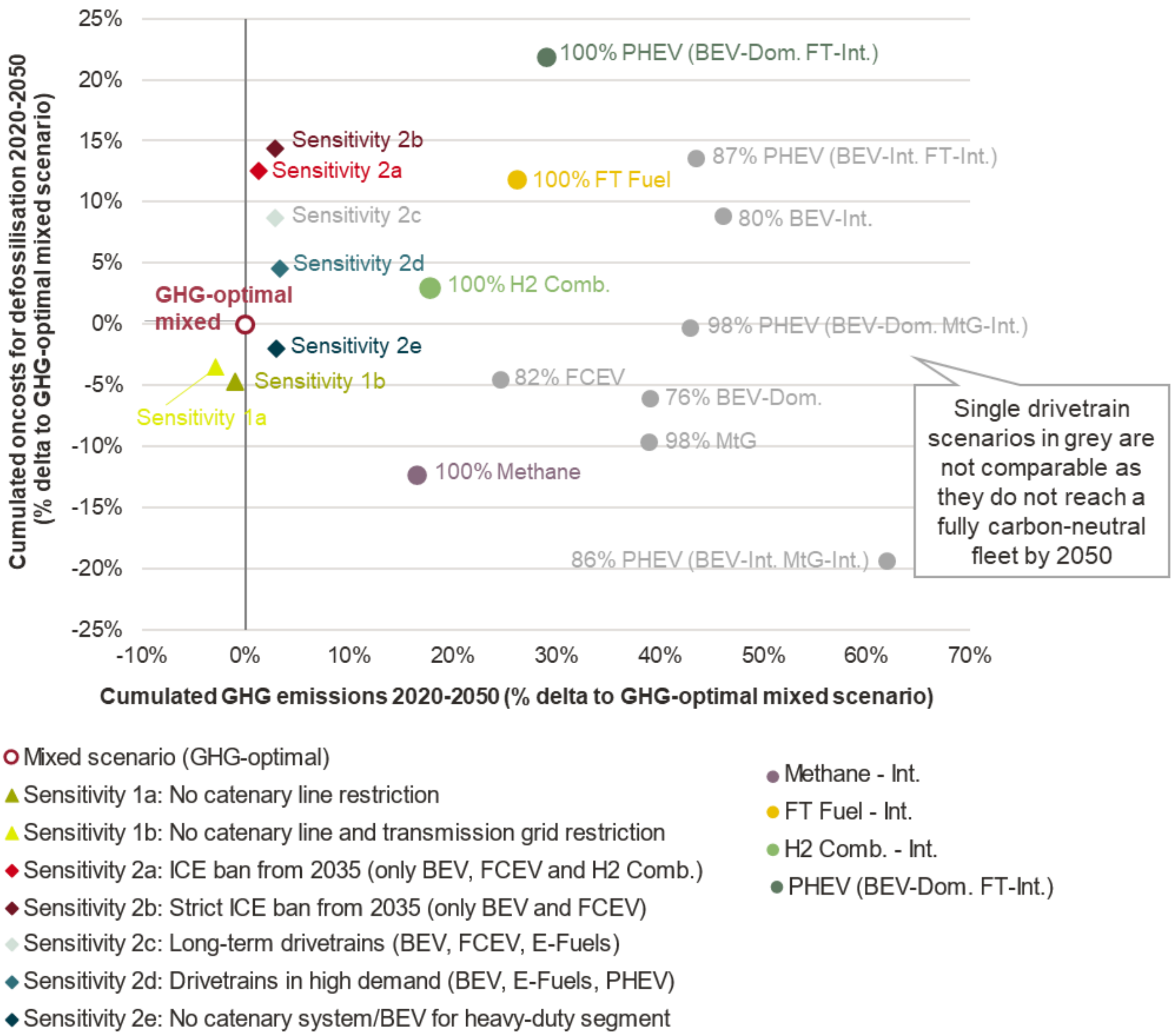


Figure 26: Cumulated GHG emissions and costs 2020-2050 compared to the GHG-optimal mixed technologies scenario. Note: Cost estimations have limited explanatory power, see Section 6.2. For cost differences only oncost for defossilisation technology of vehicles compared to a hypothetical 'would-be' diesel/gasoline ICEV fleet[74] *are taken into account (see Fuel Study IV). Scenarios that do not reach full decarbonisation by 2050 given technical bottlenecks and lifetime assumptions (and therefore display lower costs and cumulated GHG emissions than required for a full decarbonised EU27+UK road sector) are greyed out. Percentages indicate the maximum achievable share of carbon-neutral vehicles in 2050 in light of technical bottleneck constraints (see Figure 9). Sensitivities 2a and 2b use e-fuels to operate significant shares of remaining diesel and gasoline vehicles from the existing fleet until their phase-out at the end of the vehicle lifetime.*

Sensitivity 1a (no catenary line restriction) yields to slightly lower GHG emissions than the base case. Lifting the catenary line restriction, which imposed a long-term bottleneck in the base case, allows for a slightly faster ramp-up of battery-electric heavy-duty vehicles (long-haul and super-long-haul). We further observe a spill-over effect on the passenger car segment.[75] In fact, a stronger electrification in the HD segment "frees up" FT fuel infrastructure capacities available in the 2030s which is then used in

---

[74] The hypothetical 'would-be' fossil diesel/gasoline ICEV scenario as well as all defossilisation scenarios are based on the same vehicle fleet exchange rate assumptions.

[75] See illustrations on the ramp-up speed of passenger cars and heavy-duty vehicles for each sensitivity in Appendix 1 of this study.

the passenger car segment. In total, this elimination of catenary line restrictions reduces cumulated GHG emissions until 2050 by approximately 1% and costs until 2050 by approximately 5% compared to the base case (see **Figure 26**).[76]

Eliminating the power transmission grid bottleneck in addition to the catenary line restrictions (**Sensitivity 1b**) leads to a more pronounced effect on GHG emission savings: Compared to the base case, cumulated GHG emissions would be approximately 3% lower (see **Figure 26**). In absolute terms this would translate into a GHG emission saving of 663 $MtCO_2eq$ (see **Figure 25**), which corresponds to approximately one year of total GHG emissions from fuel combustion in Europe's road sector in 2020.[77] It is further worth noting that eliminating the catenary line and power transmission grid bottleneck would translate into a full decarbonised vehicle stock by 2038 already, two years earlier than in the base case. Again this can be explained by a stronger electrification in the heavy-duty segment (mainly for BEV Dom.) which allows to use limited FT fuel capacities in the 2030s for passenger cars.

In contrast to the sensitivities eliminating technical bottlenecks discussed above, the sensitivities restricting the number of (GHG-neutral) technology pathways consistently lead to higher GHG emissions in the range of 1-3% compared to the base case. Narrowing down the technology options for a GHG-neutral EU27+UK road sector available in our modelling therefore delays the ramp-up of a carbon-neutral vehicle stock and leads to higher than necessary cumulated GHG emissions by 2050.

Compared to the base case an ICE ban restricting new registrations to BEV, FCEV and H_2 Comb. from 2035 onwards (**Sensitivity 2a**) has the smallest implications in terms additional GHG emissions compared to the base case (+1%). This can be explained by the fact that the ramp-up speed of GHG-neutral vehicles is only marginally affected by the ICE ban from 2035 onwards. Instead of introducing new Methane or FT Fuel vehicles from 2035 onwards (as observed in the base case), more vehicles are registered with H_2 Comb. powertrain (see **Figure 27**). While the stronger selection of H_2 Comb. does not significantly delay the ramp-up speed compared to the base case, cumulated costs by 2050 are around 13% higher (see **Figure 26** above). E-fuels are used to decarbonise the existing diesel and gasoline vehicles well before their natural end of life. As a result, the road sector is already carbon-neutral in 2040 instead of 2044 as it would be without the use of e-fuels.

---

[76] Removing constraints in an optimisation problem will by definition lead to a better or the same result (in our context: lower or equal GHG emissions).

[77] Emissions from fuel combustion in the European road sector were around 0.68 $GtCO_2eq$ in 2020. See EEA/Eurostat (2022), “Greenhouse gas emissions by source sector”, variables “Fuel combustion in road sector”, https://ec.europa.eu/eurostat/web/environment/air-emissions (last accessed: 08.09.2022).

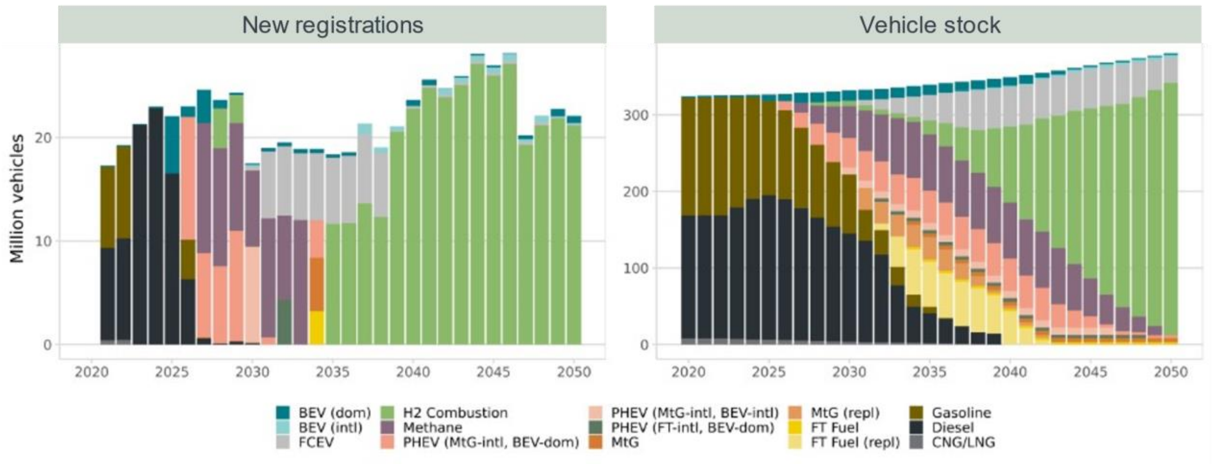


*Figure 27: New vehicle registrations (left) and vehicle stock (right) by powertrain in Sensitivity 2a, all vehicle segments combined. Note: The equivalent graphs for the GHG-optimal mixed technologies scenario are shown in **Figure 41** in Section 8.3.3.*

A stricter version of the ICE ban only allowing BEV and FCEV new vehicle registrations from 2035 onwards (**Sensitivity 2b**) has more significant implications in relation to additional GHG emissions compared to the base case (+3%). In fact, in order to minimise cumulated GHG emissions the model then mainly chooses FCEVs for passenger cars and similar shares for FCEVs and BEVs for heavy-duty vehicles from 2035 onwards. However, as infrastructure and raw materials required for FCEVs and BEVs remain scarce in the 2030s (binding technical bottlenecks) the strict ICE ban leads to a delayed ramp-up of GHG-neutral vehicles (and therefore higher cumulated GHG-emissions) overall (see **Figure 28**). Similarly to Sensitivity 2a, e-fuels are used to power the existing combustion engine vehicle fleet and thus contribute to minimising GHG emissions. Associated costs are around 14% higher compared to the base case (see **Figure 26**).

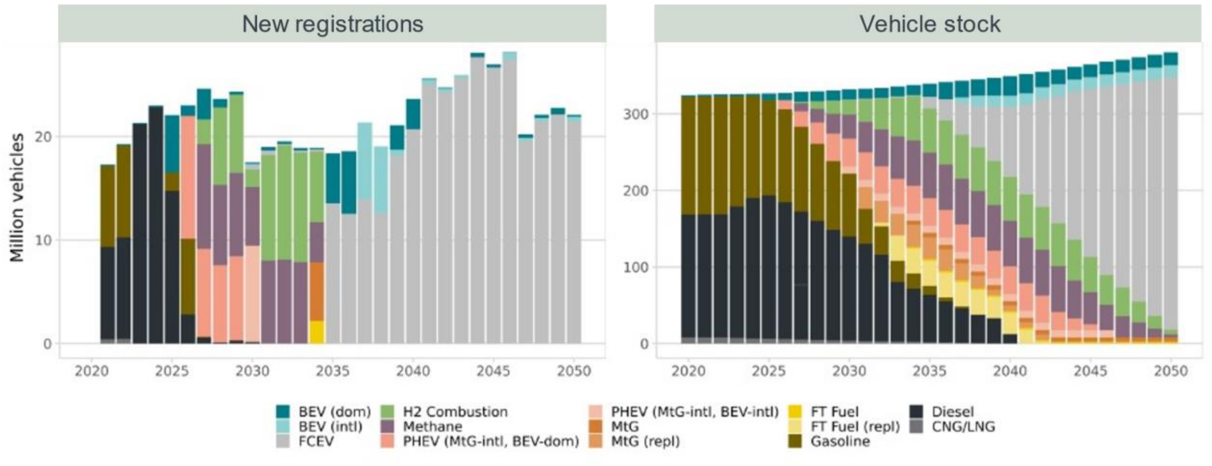


Figure 28: New vehicle registrations (left) and vehicle stock (right) by powertrain in Sensitivity 2b, all vehicle segments combined.

Similar to the previous sensitivity, cumulated GHG emissions increase by around 3% in when restricting the (GHG-neutral) technology pathways in the modelling towards “long-run technologies”, namely BEV, FCEV, MtG and FT Fuel (**Sensitivity 2c**) for new vehicle registrations. In this sensitivity, the model primarily selects e-fuels (MtG / FT fuel) and FCEV for the GHG-neutral passenger cars, as well as BEV and FCEV for the heavy-duty segment.[78] Similar to the base case, the model minimises cumulated GHG emissions for the EU27+UK road sector with a significant electrification in the heavy-duty segment (which is more efficient than using the BEV infrastructure available in the passenger car segment for minimising cumulated GHG emissions – see deep dive in Section 6.1). As shown in **Figure 26**, associated costs are around 9% higher compared to the base case.

Only considering powertrains currently in high demand (**Sensitivity 2d**) for new vehicle registrations such as BEV, PHEV and ICEVs (operated with e-fuels in the context of our modelling) also leads to higher cumulated GHG emissions compared to the base case (approx. 3%). Again, the non-availability of specific powertrains (here: FCEV, H_2 Comb. and Methane) slightly delays the GHG-neutral vehicle ramp-up. Most interestingly in this sensitivity PHEVs (BEV Dom./Int. + MtG) play a significant role for passenger cars until the late 2030s before PHEVs are replaced by ICEVs running exclusively on e-fuels (FT fuel / MtG) once the infrastructure required is available at large-scale. In contrast for the heavy-duty segment the model aims for a large share of electrification (BEV Dom. / Int.) which is complemented by ICEVs running on FT fuel. Associated costs are around 5% higher compared to the base case.

In light of the observed high share of heavy-duty electrification and the uncertainties to which a pan-European overhead line grid can realistically be installed (on which the electrification of various heavy-duty segments depends in our study) we have further conducted a sensitivity restricting the availability of BEV powertrains to newly registered passenger cars only (**Sensitivity 2e**). In this sensitivity the heavy-duty segment is largely operated with hydrogen-fuelled (FCEV and H_2 Comb.) and Methane vehicles in the long-term. However, the exclusive availability of the BEV (Dom. / Int.) for passenger does not translate in a significant vehicle ramp-up of battery-electric vehicles in this segment. Other (GHG-neutral) technology pathways such as Methane, FT fuel, FCEV and H_2 Comb. are the preferred choice to minimise cumulated GHG emissions by 2050. Compared to other (GHG-neutral) technology pathways BEV powertrains are associated with a relatively higher GHG emissions "rucksack" for passenger cars.[79] Therefore, BEV powertrains for passenger cars are only selected in case less GHG-intense technology pathways are not available – for example due to binding technical bottlenecks).[80] Compared to the base case, **Sensitivity 2e** leads to approx. 3% higher cumulated GHG emissions (but approx. 2% lower costs).

---

[78] Consistent with the illustrations on new vehicle registrations and vehicle stock for sensitivities 2a and 2b in the main body, we have prepared identical illustrations for sensitivities 2c – 2e in Appendix 1 of this study.

[79] The large proportion of total GHG emissions is emitted in the phase of vehicle production, while smaller contributions come from the ramp-up of the fuel supply chain infrastructure. See FVV (2021), Section 10.3.5. In comparison to other powertrains, BEVs have generally considerably higher (unavoidable) GHG emissions from vehicle production due to the emissions-intensive battery production. For example, the GHG emissions from the production of a BEV in the medium-sized segment in 2030 are about twice as high as from the production of a CH_4-ICEV in the same segment.

[80] The slightly higher cumulated GHG emissions compared to the base case are consistent with the objective of minimising GHG emissions in our modelling. In the base case the model prefers to electrify large shares of the heavy-duty segment. This is not possible in the sensitivity when we eliminate BEV as a technology option for the heavy-duty segment. Therefore, the model needs to opt for the "2nd-best" GHG-neutral powertrain to decarbonise the heavy-duty segment. This in turn is associated with higher cumulated GHG emissions. See also deep-dive in Section 6.1 of this study.

7 Conclusion

This study considers realistically achievable ramp-up gradients and technical bottlenecks (under ideal legal and financial boundary conditions) for each investigated fuel/energy pathway for a carbon-neutral vehicle fleet in the road sector in 2050.

Our linear optimisation model goes significantly beyond fleet emission targets focussing on tailpipe emissions of the EU27+UK road sector (such as the current EU policy approach in its “Fit for 55” package). We provide a coherent modelling approach minimising cumulated GHG emissions associated with the entire fuel supply chain (Well-to-Wheel approach) between 2020 and 2050. This allows us to evaluate potential benefits from an effective mix of fuel/energy pathways in an effort to decarbonise the EU27+UK road sector as quickly as possible.

Our modelling results show that a mix of carbon-neutral powertrain technology / energy carrier pathways can significantly speed up the transition to GHG neutrality within the EU27+UK road sector until 2050 – in particular when comparing with single technology scenarios where only a single fuel/energy pathway would be available. All individual carbon-neutral technology pathways considered face infrastructure and material bottlenecks of various kinds at different stages along the fuel supply chain, limiting the maximal deployment rate for each individual technology. Those technical bottleneck constraints can be mitigated (or in some cases avoided completely) by combining different powertrain technologies.

Our study shows that the decisive factor to minimise overall GHG emissions is the fastest possible departure from fossil fuels. GHG emissions caused by operating fossil fuelled account for the vast majority of Well-to-Wheel GHG emissions in the EU27+UK road sector. In fact, **a mix of carbon-neutral energy carrier/powertrain pathways can accelerate the penetration of carbon-neutral powertrains and, thereby, reduce cumulated GHG emissions significantly**.

For example, a scenario focussing on BEV (with domestic energy sourcing) as the only GHG-neutral powertrain technology available yields to 39% higher cumulated GHG emissions by 2050 compared to a mix of GHG-neutral powertrain technologies.

At the same time, infrastructure and material bottlenecks need to be addressed quickly. This holds in particular for the necessary scale-up of infrastructure and material availability across the different carbon-neutral fuel/energy pathways considered in order to fully materialise the benefits of a mix of carbon-neutral powertrains.

Most recently, public discussion around GHG emission reduction largely evolved around the passenger car segment which accounts for 98% of the EU27+UK vehicle stock. However, our study shows, that shifting the heavy-duty segment towards carbon-neutral powertrains is a big lever to enable significant GHG emission savings. While heavy-duty vehicles only account for approx. 2% of the EU27+UK vehicle stock they are responsible for approx. 45% of today’s overall total fuel consumption[81] in the road sector, holding an enormous potential for GHG emission savings.

---

[81] Assessment by Frontier Economics based on ACEA data. See ACEA (2022), “Vehicles in use Europe 2022”, https://www.acea.auto/files/ACEA-report-vehicles-in-use-europe-2022.pdf (last accessed: 08.09.2022).

Moreover, our study and modelling results show that across all powertrain technology / energy carrier pathways, e-fuels (MtG and FT) provide a unique technology option to carbon neutrally operate the existing fleet. Those backward compatible fuels allow a quick defossilisation of the existing fleet once they become available at large scale. Despite long lead times for setting up synthesis plants, they can, therefore, play a major role in accelerating overall GHG reductions.

Limiting the possibility to mitigate or avoid infrastructure and material bottlenecks – such as banning ICE vehicles from 2035 – on the other hand, would lead to higher GHG emissions than necessary. While a defossilisation of the EU27+UK road sector can also be achieved without ICE vehicles from a given year on, it would increase cumulated emissions, as it further reinforces dependencies on critical bottlenecks and limits the option to accelerate further defossilisation through compatible fuels to an existing ICE vehicle fleet.

8 Appendix I – Underlying assumptions and detailed results

8.1 Assumptions

8.1.1 Fuel supply chain and vehicle assumptions

Assumptions regarding the fuel supply chain of powertrain technology / energy carrier pathways as well as assumptions on the respective vehicles are stated in Appendix II of Fuels Study IV. Changes and additions to technical assumptions made in Fuels Study IVb are stated in ifeu's supplementary technical report. Changes and additions to cost assumptions are described in the following.

PHEV: Vehicle costs

We added PHEVs as an additional powertrain option in Fuels Study IVb. In line with Fuels Study IV, we follow a building-kit approach to determine the vehicle costs, using the cost of currently manufactured "conventional" ICEV as starting point (as set out in Section 12.1 of Fuels Study IV). For PHEVs, we add costs for the addition of the battery (see **Table 4**) and the e-system (see Fuels Study IV, Table 32) and apply an additional uplift of 50% to each component to cover for additional OEM-costs to the pure material costs. The resulting vehicle costs for PHEV with a gasoline or diesel engine are presented in **Table 5**.

	2020	2030	2050	Source
PHEV battery module cost (€/kWh)	240	180	120	Frontier Economics based on Ahmed et al. (2018) and California Air Resources Board (2021)

Table 4: Cost of PHEV battery module for each photo year. All values rounded.

Segment	Type	Status quo	Balanced scenario	
		2020	2030	2050
Passenger cars (small)	PHEV Gasoline	13,730 €	14,865 €	13,533 €
	PHEV Diesel	14,683 €	15,970 €	14,628 €
Passenger cars (medium)	PHEV Gasoline	21,583 €	23,135 €	21,650 €
	PHEV Diesel	23,243 €	25,060 €	23,555 €
Passenger cars (large)	PHEV Gasoline	40,385 €	44,187 €	42,109 €
	PHEV Diesel	43,891 €	48,283 €	46,156 €
Passenger cars (SUV)	PHEV Gasoline	27,853 €	31,493 €	28,942 €
	PHEV Diesel	29,998 €	34,010 €	31,413 €
Passenger cars (LCV)	PHEV Gasoline	35,096 €	38,070 €	34,912 €
	PHEV Diesel	38,206 €	41,659 €	38,398 €
Rigid (N2)	PHEV Gasoline	n/a	n/a	n/a
	PHEV Diesel	49,324 €	45,578 €	40,298 €
Regional delivery (N2/N3)	PHEV Gasoline	n/a	n/a	n/a
	PHEV Diesel	92,763 €	89,096 €	81,896 €
Long haul (N3)	PHEV Gasoline	n/a	n/a	n/a

Segment	Type	Status quo	Balanced scenario	
		2020	2030	2050
	PHEV Diesel	165,094 €	154,558 €	138,478 €
Super long haul (N3)	PHEV Gasoline	n/a	n/a	n/a
	PHEV Diesel	189,142 €	173,386 €	152,086 €
Public transport	PHEV Gasoline	n/a	n/a	n/a
	PHEV Diesel	282,626 €	293,706 €	289,206 €
Coaches	PHEV Gasoline	n/a	n/a	n/a
	PHEV Diesel	393,048 €	395,773 €	379,393 €

Table 5: Vehicle costs for PHEV in the balanced scenario. Note: No gasoline engine was modelled for the heavy-duty segment. All values rounded.

MtG synthesis plant

Table 6 shows the cost assumptions for the MtG synthesis plants required for the MtG pathway. The costs refer to the final synthesis step from methanol to gasoline and occur in addition to the costs for the methanol synthesis (as defined in Fuels Study IV). A detailed description and technical assumptions of the MtG fuel supply chain is provided in ifeu's supplementary technical report. Vehicle costs for the MtG pathway correspond to the ICEV gasoline pathway (see Fuels Study IV, Table 212).

Type	Unit	2020	2030	2050
Investment cost	EUR/MW	189,434	159,125	157,230
O&M cost	% of investment cost	2.5%	2.5%	2.5%

Table 6: Cost assumptions for MtG synthesis plants. Source: FVV working group. All values rounded.

Correction of Fuels Study IV: Vehicle cost of heavy-duty FCEV

Segment	Type	Vehicle costs		
		2020	2030	2050
Rigid (N2)	FCEV	41,955 €	37,584 €	33,606 €
Regional delivery (N2/N3)	FCEV	86,729 €	79,483 €	72,880 €
Long haul (N3)	FCEV	177,248 €	158,218 €	141,392 €
Super long haul (N3)	FCEV	177,384 €	157,042 €	138,904 €
Public transport	FCEV	285,493 €	278,776 €	272,647 €
Coaches	FCEV	392,409 €	375,423 €	359,907 €

Table 7: Updated technical specifications and vehicles costs for heavy-duty FCEV in the balanced scenario. All values rounded.

Levelised cost of energy (LCOE)

For informational purposes, we show in **Table 8**, the levelised cost of energy (LCOE) for the different electricity generation options (in ct/kWh), i.e. all locations (domestic, MENA, far-off locations) and energy sources (wind onshore, wind offshore, PV standalone, PV stanted roof) for the years 2030 and 2050. These costs are a result of Fuels Study IV, which are derived from the assumed costs, lifetime, discount rate and full load hours of the plants.

	Wind Onshore		**Wind Offshore**		**PV (standalone)**		**PV (slanted roof)**	
	2030	**2050**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**
Domestic energy sourcing (ct/kWh)	5.72	4.41	7.61	6.06	4.55	3.37	6.74	5.06
International energy sourcing (MENA or far-off location) (ct/kWh)	3.56	2.69	5.87	3.53	2.62	1.77	-	-

Table 8: LCOE in ct/kWh of domestic and international energy sourcing by energy source and year. Source: Fuels Study IV. All values rounded.

Table 9 shows the LCOE (in ct/kWh) of the electricity mix in the domestic and international scenario assuming the split of renewable energy generation sources (see Table 5 of Fuels Study IV) and the import ratio (see Section 4.3 of Fuels Study IV) made in Fuels Study IV. The BEV and hydrogen single technology pathways are shown separately because they do not consider energy generation in far-off premium locations, and additionally, the slanted rooftop PV is considered as an energy source only in the BEV pathway.

	All pathways except BEV and H_2		**BEV**		**H_2 Comb. and FCEV**	
	2030	**2050**	**2030**	**2050**	**2030**	**2050**
Electricity mix - Domestic energy sourcing	5.81	4.62	6.10	4.84	5.81	4.62
Electricity mix - International energy sourcing	4.35	3.21	4.40	3.16	4.31	3.10

Table 9: LCOE in ct/kWh of the electricity mix in the domestic and international scenario. Source: Fuels Study IV. All values rounded.

8.2 Technical bottleneck assumptions

	Offshore wind	**Onshore wind**	**PV standalone + PV slanted roof**	**HVDC power line from MENA to EU**	**Extension of EU trans-mission grid: AC overhead line**	**Extension of EU distribution grid: high voltage**
Fair share: road sector vs. other sectors	40%	40%	40%	50%	50%	50%
Fair share: EU27+UK vs. world	30%	30%	30%	100%	100%	100%
Unit	**MW**	**MW**	**MW**	**km**	**km**	**km**
2022	3,053	46,739	56,131	-	-	-
2023	4,642	68,337	82,069	-	-	-
2024	6,516	92,944	111,622	-	-	-
2025	8,676	120,561	144,788	-	5,833	5,833
2026	12,008	163,162	195,950	-	8,167	8,167
2027	16,512	220,748	265,108	-	10,500	10,500
2028	22,188	293,319	352,261	-	12,833	12,833
2029	29,036	380,873	457,410	-	15,167	15,167
2030	37,056	483,413	580,555	5,000	17,500	17,500
2031	55,330	717,057	861,151	5,000	21,000	21,000
2032	83,858	> 1,000,000	1,299,197	5,000	24,500	24,500
2033	122,641	No relevant bottleneck for modelling	> 1,800,000	5,000	28,000	28,000
2034	171,677		No relevant bottleneck for modelling	5,000	31,500	31,500
2035	230,968			5,000	35,000	35,000
2036	300,513			5,000	38,500	38,500
2037	380,312			No relevant bottleneck for modelling *	42,000	42,000
2038	470,365				45,500	45,500
2039	> 511,000				49,000	49,000
2040	No relevant bottleneck for modelling				52,500	52,500
2041					No relevant bottleneck for modelling **	No relevant bottleneck for modelling **
2042						
2043						
2044						
2045						
2046						
2047						
2048						
2049						
2050						

*Table 10:Maximum ramp-up of infrastructure (1). Values for technical bottleneck assumptions already reflect the fair share assumptions displayed in the first two rows. Source: FVV working groups. * Under ideal investment conditions HVDC power line MENA to EU is expected to be sufficiently ramped-up from 2037 onwards following the installation of initial 5,000 km with seven years of lead construction time to meet EU27-UK road sector demand in the long run. ** Under ideal investment conditions no relevant technical restrictions expected in 2040s for onshore netword grid expansion to meet EU27-UK road sector demand in the long run. All values rounded.*

	BEV charging: wallboxes (11 kW)	**BEV charging: fast chargers (passenger vehicles + trucks) (150kW)**	**BEV charging: semi-public chargers (44 kW)**	**Overhead grid for trucks**	**Electro-lysis**	**FT synthesis**
Fair share: road sector vs. other sectors	100%	100%	100%	100%	40%	85%
Fair share: EU27+UK vs. world	100%	100%	100%	100%	67%	80%
Unit	**units**	**units**	**units**	**km**	**GW**	**GW**
2022	6,794,667	57,156	663,400	5,400	2	-
2023	8,752,000	78,104	875,600	7,800	4	-
2024	10,709,333	99,052	1,087,800	10,500	8	-
2025	12,666,667	120,000	1,300,000	13,500	31	-
2026	22,800,000	216,000	2,040,000	16,500	71	-
2027	32,933,333	312,000	2,780,000	19,500	112	-
2028	43,066,667	408,000	3,520,000	22,500	210	-
2029	53,200,000	504,000	4,260,000	25,500	309	-
2030	63,333,333	600,000	5,000,000	28,500	407	-
2031	88,666,667	790,000	7,000,000	31,500	616	-
2032	114,000,000	980,000	9,000,000	34,500	824	54
2033	139,333,333	1,170,000	11,000,000	37,500	1,033	107
2034	164,666,667	1,360,000	13,000,000	40,500	1,242	107
2035	190,000,000	1,550,000	15,000,000	43,500	1,450	107
2036	215,333,333	1,740,000	17,000,000	46,500	1,659	107
2037	240,666,667	1,930,000	19,000,000	49,500	1,868	No relevant bottleneck for modelling **
2038	266,000,000	2,120,000	21,000,000	52,500	> 2,040	
2039	291,333,333	2,310,000	> 22,000,000	55,500	No relevant bottleneck for modelling	
2040	316,666,667	2,500,000	No relevant bottleneck for modelling	No relevant bottleneck for modelling *		
2041	No relevant bottleneck for modelling *	No relevant bottleneck for modelling *				
2042						
2043						
2044						
2045						
2046						
2047						
2048						
2049						
2050						

*Table 11:Maximum ramp-up of infrastructure (2). Values for technical bottleneck assumptions already reflect the fair share assumptions displayed in the first two rows. * Under ideal investment conditions no relevant technical restrictions expected in 2040s for BEV charging infrastructure expansion to meet EU27-UK road sector demand in the long run. ** Under ideal investment conditions FT synthesis is expected to be sufficiently ramped-up from 2037 onwards to meet EU27-UK road sector demand in the long run following the initial possible installation of up to 107 GW by 2036. Source: FVV working groups. All values rounded.*

	MTG synthesis	**Methanation**	**H_2 pipelines from MENA to Europe**	**CH_4 pipelines from MENA to Europe**	**Battery (vehicle component + PV storage)**	**Fuel cell stack**
Fair share: road sector vs. other sectors	100%	100%	50%	50%	100%	100%
Fair share: EU27+UK vs. world	80%	80%	100%	100%	33% of non-European production; 100% of European production	80%
Unit	**GW**	**GW**	**km**	**km**	**GWh/a**	**GW/a**
2022	-	-	-	-	580	48
2023	-	-	-	-	767	48
2024	-	-	-	-	954	48
2025	15	-	-	-	1,141	120
2026	44	16	-	-	1,282	120
2027	103	16	11,250	> 8,600 km	1,422	120
2028	162	32	11,250	No relevant bottleneck for modelling	1,562	No relevant bottleneck for modelling *
2029	279	32	22,500		1,703	
2030	397	64	22,500		1,843	
2031	> 548	64	22,500		No relevant bottleneck for modelling *	
2032	No relevant bottleneck for modelling	No relevant bottleneck for modelling *	33,750			
2033			33,750			
2034			45,000			
2035			45,000			
2036			45,000			
2037			56,250			
2038			56,250			
2039			67,500			
2040			67,500			
2041			67,500			
2042			78,750			
2043			78,750			
2044			90,000			
2045			90,000			
2046			90,000			
2047			> 94,000			
2048			No relevant bottleneck for modelling			
2049						
2050						

*Table 12: Maximum ramp-up of infrastructure (3). Values for technical bottleneck assumptions already reflect the fair share assumptions displayed in the first two rows. * Under ideal investment conditions no relevant technical restrictions expected from late 2020s / early 2030s onwards to meet EU27-UK road sector demand in the medium to long run. Source: FVV working groups. All values rounded.*

8.3 Detailed results

8.3.1 Single technology scenarios

<u>BEV domestic</u>

Main technical bottleneck: Cobalt

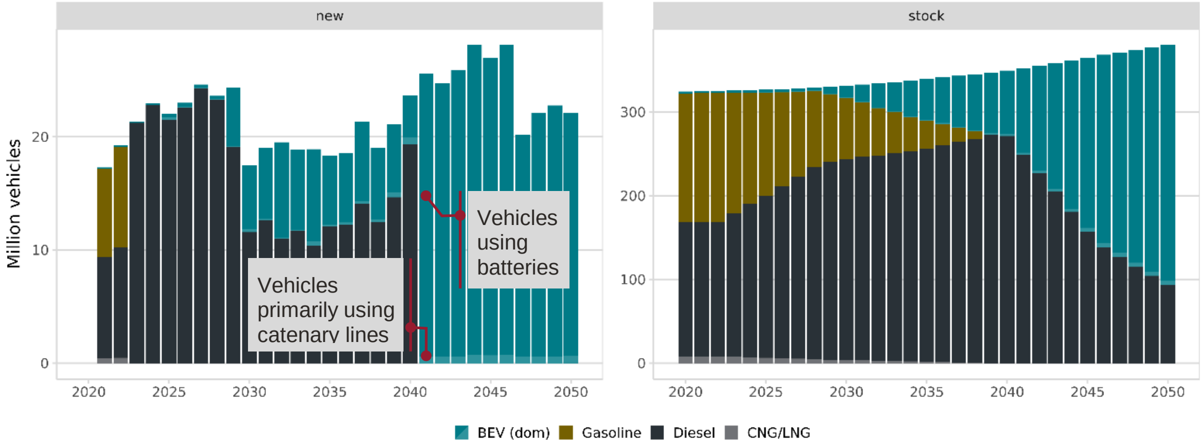


Figure 29: New vehicle registrations and vehicle stock by powertrain in single technology BEV domestic scenario, all vehicle segments combined.

<u>BEV international</u>

Main technical bottleneck: Cobalt

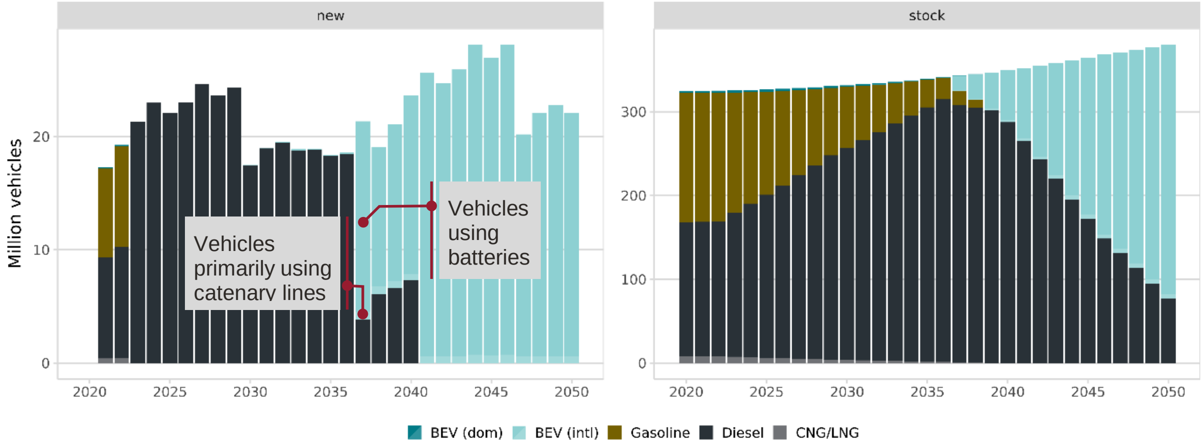


Figure 30: New vehicle registrations and vehicle stock by powertrain in single technology BEV international scenario, all vehicle segments combined.

H_2 Comb

Main technical bottleneck: H_2 import pipeline

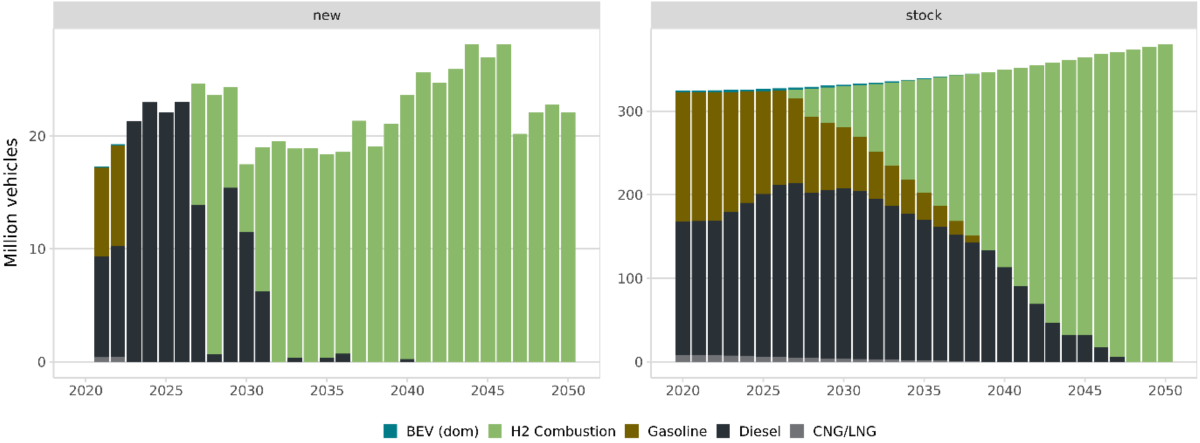


Figure 31: New vehicle registrations and vehicle stock by powertrain in single technology H_2 Comb. scenario, all vehicle segments combined.

FCEV

Main technical bottleneck: Platinum

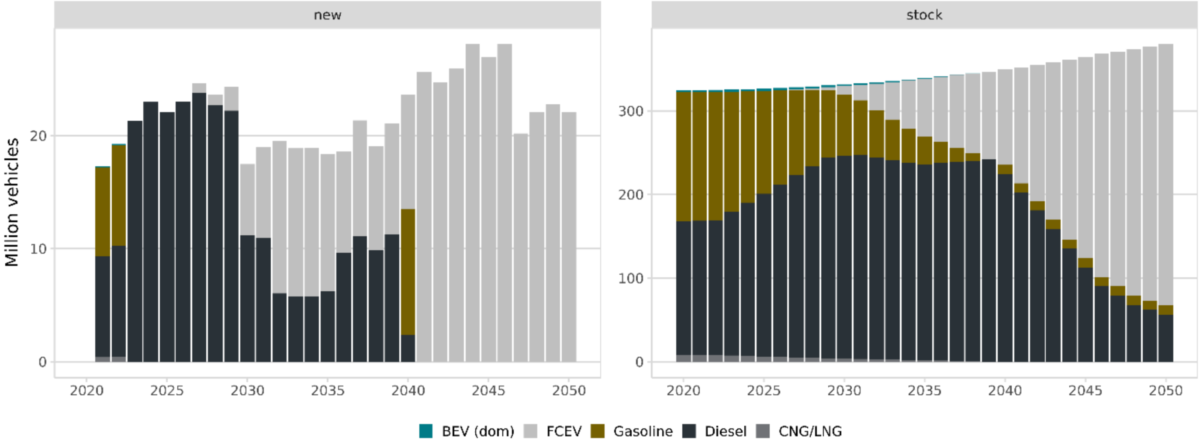


Figure 32: New vehicle registrations and vehicle stock by powertrain in single technology FCEV scenario, all vehicle segments combined.

Fischer Tropsch Fuel

Main technical bottleneck: FT synthesis

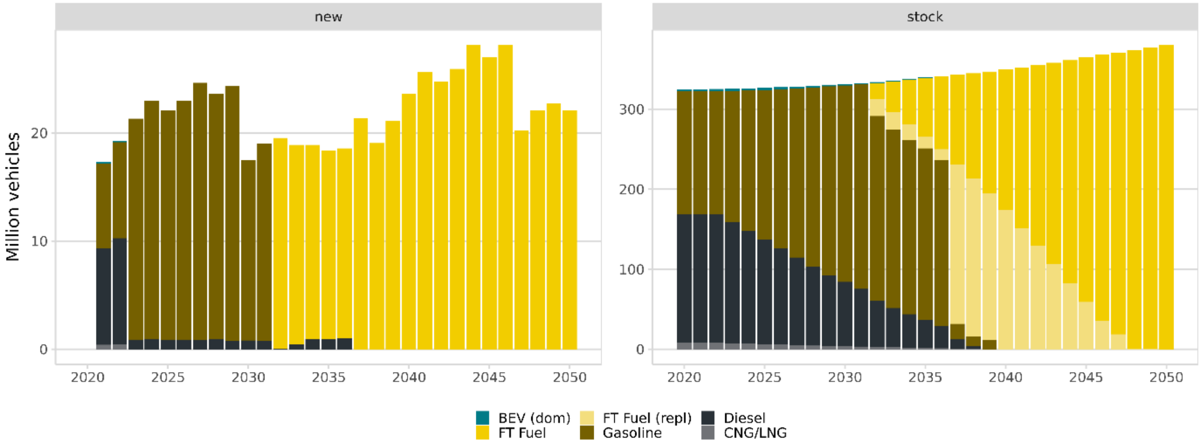


Figure 33: New vehicle registrations and vehicle stock by powertrain in single technology FT Fuel scenario, all vehicle segments combined.

MtG

Main technical bottleneck: Electrolysis

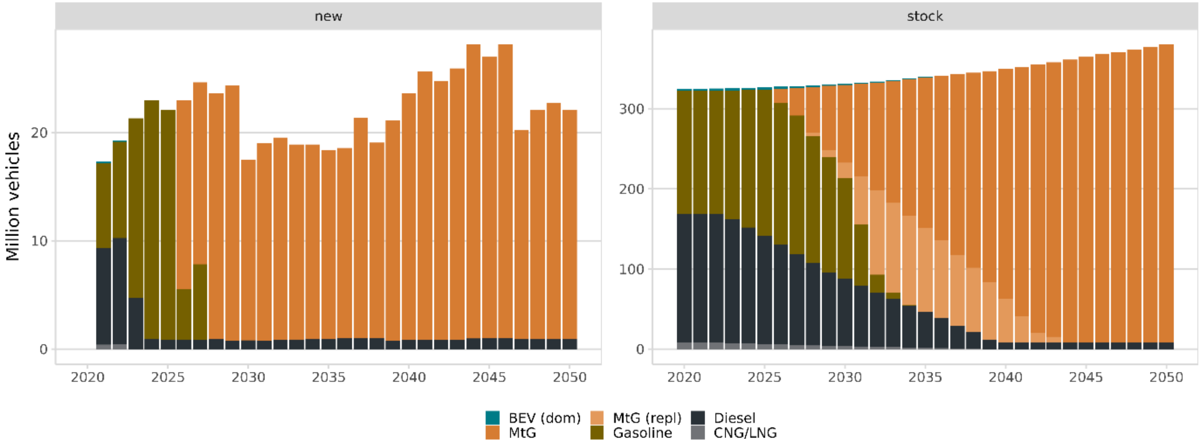


Figure 34: New vehicle registrations and vehicle stock by powertrain in single technology MtG scenario, all vehicle segments combined. Note: MtG pathway only available for passenger cars.

Methane

Main technical bottleneck: Methanation

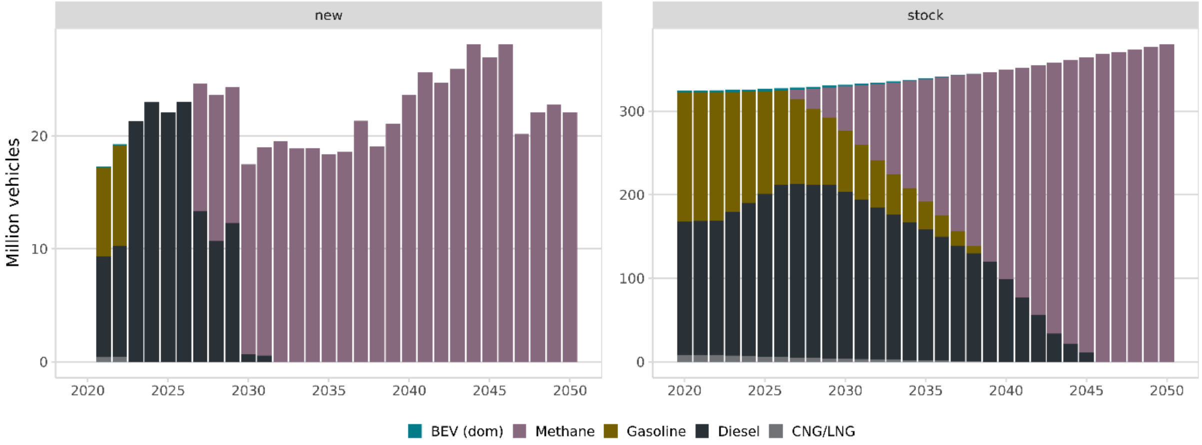


Figure 35: New vehicle registrations and vehicle stock by powertrain in single technology Methane scenario, all vehicle segments combined.

PHEV (BEV-dom. FT-dom.)

Main technical bottleneck: FT synthesis

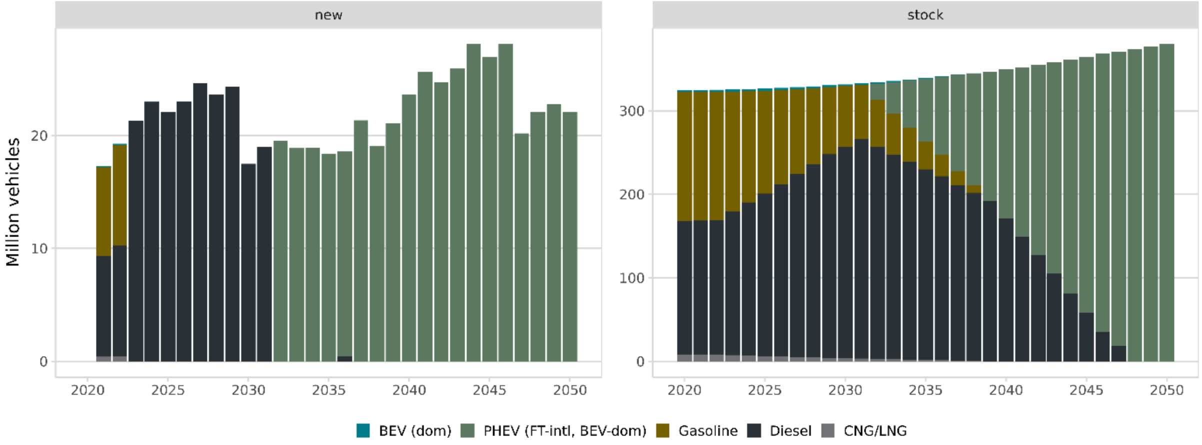


Figure 36: New vehicle registrations and vehicle stock by powertrain in single technology PHEV (BEV-dom. FT-dom.) scenario, all vehicle segments combined.

PHEV (BEV-int. FT-int.)

Main technical bottleneck: Sea power cable

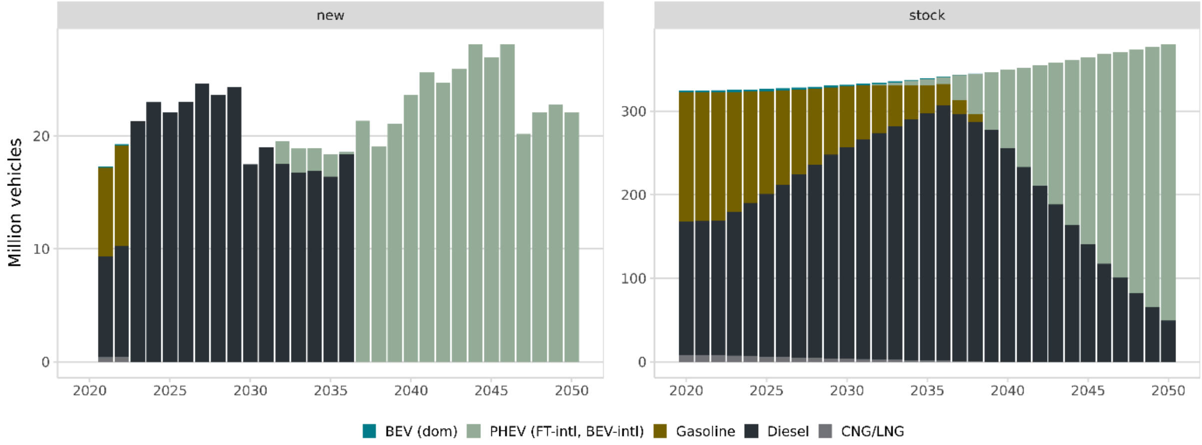


Figure 37: New vehicle registrations and vehicle stock by powertrain in single technology PHEV (BEV-int. FT-int.) scenario.

PHEV (BEV-int. MtG-int.)

Main technical bottleneck: Sea power cable

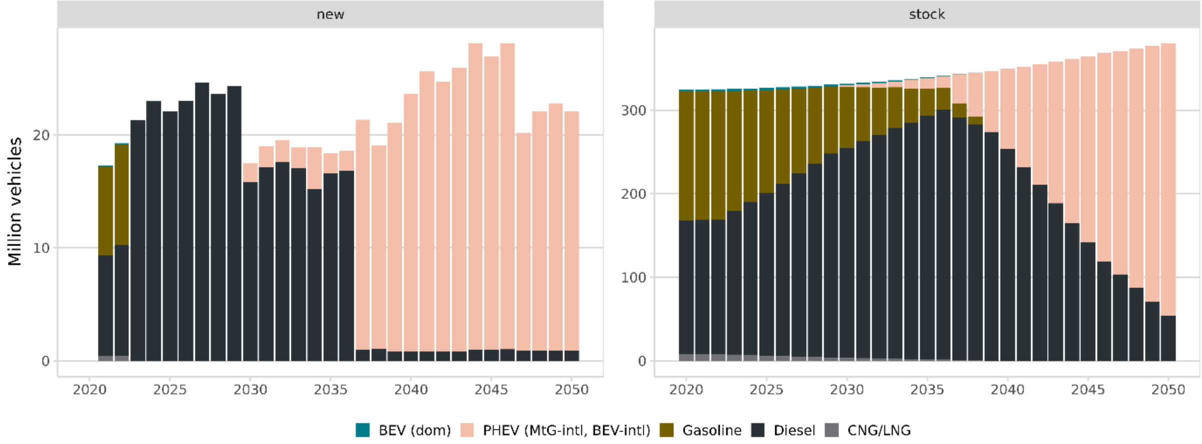


Figure 38: New vehicle registrations and vehicle stock by powertrain in single technology PHEV (BEV-int. MtG-int.) scenario, all vehicle segments combined. Note: PHEV-MtG pathway only available for passenger cars.

PHEV (BEV-dom. MtG-int.)

Main technical bottleneck: Wallboxes

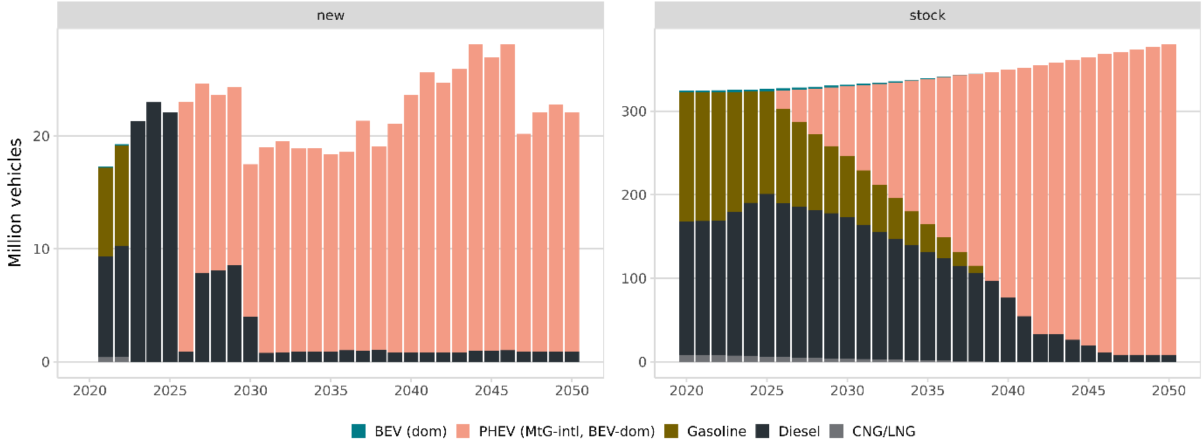


Figure 39: New vehicle registrations and vehicle stock by powertrain in single technology PHEV (BEV-dom. MtG-int.) scenario, all vehicle segments combined. Note: PHEV-MtG pathway only available for passenger cars.

Sensitivity: BEV Dom. single technology scenario without cobalt and power transmission grid restriction

The BEV Dom. pathway is mostly restricted by the availability of cobalt and the expansion of the power transmission grid until 2040 (see **Section 5.1**). The bottlenecks disappear in 2040, but a 100% BEV penetration in 2050 is still restrained by the vehicle exchange rate (i.e. the replacement of vehicles at the end of their lifetime by newly registered ones; see Fuels Study IV, Section 6). This is because, in the example of passenger cars with a lifetime of 17 years, all new registrations from 2033 onwards would need to be carbon-neutral in order to achieve a fully carbon-neutral vehicle stock in 2050 – which is not feasible due to the cobalt and power transmission grid constraints.[82]

In **Figure 40** we show two sensitivities of the BEV Dom. single technology scenario: i) without cobalt, and ii) without cobalt and transmission grid restrictions. Without both cobalt and transmission grid constraints, the BEV Dom. pathway achieves full decarbonisation in 2047. In this sensitivity, a faster ramp-up of carbon-neutral BEVs is restricted by the restricted expansion of catenary lines.

---

[82] We do not consider BEVs operated with fossil electrical energy in our modelling. A fundamental assumption of our study is that all vehicles are exclusively operated with renewable energy.

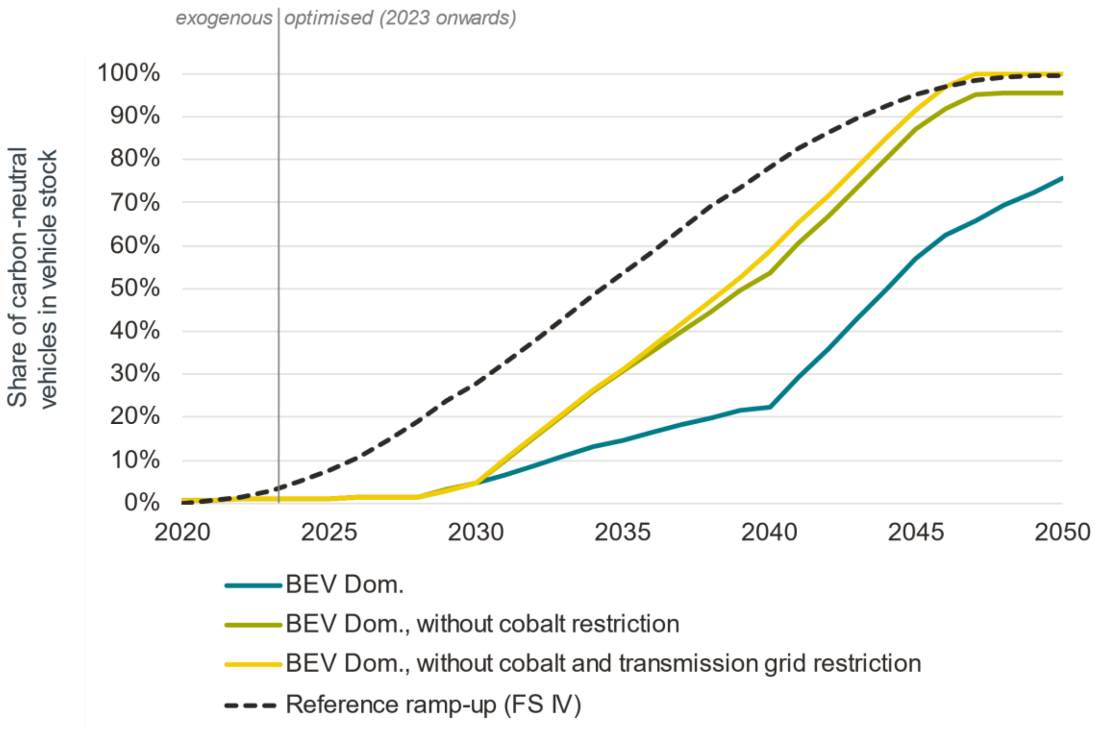


Figure 40: Share of carbon-neutral vehicles in stock in BEV Dom. single technology scenario and sensitivities with unrestricted cobalt and power transmission grid availability.

8.3.2 Comparison of single technology scenarios with mixed technologies scenario

Cumulated GHG emissions

		GHG emissions		
Scenario	**Max. achievable share of carbon-neutral vehicles in 2050**	**Cumulated 2020-2050 ($MtCO_2eq$)**	**Delta to base case ($MtCO_2eq$)**	**% Delta to base case**
GHG-optimal mixed technologies scenario				
Mixed technologies scenario (GHG-optimal)	100%	22,525	-	-
Single technology scenarios				
BEV - Dom.	76%	31,318	+8,792	+39%
BEV - Int.	80%	32,910	+10,385	+46%
Methane - Int.	100%	26,247	+3,721	+17%
FCEV - Int.	82%	28,065	+5,539	+25%
FT Fuel - Int.	100%	28,413	+5,888	+26%
H_2 Comb. - Int.	100%	26,535	+4,010	+18%
MtG - Int.	98%	31,293	+8,768	+39%
PHEV (BEV-Int. FT-Int.)	87%	32,318	+9,793	+43%
PHEV (BEV-Dom. FT-Int.)	100%	29,052	+6,527	+29%
PHEV (BEV-Int. MtG-Int.)	86%	36,479	+13,954	+62%
PHEV (BEV-Dom. MtG-Int.)	98%	32,183	+9,658	+43%

Table 13:GHG emissions and costs in GHG-optimal mixed technologies scenario and single technology scenarios. Note: The second column shows the maximum achievable share of carbon-neutral vehicles in 2050 under consideration of technical bottlenecks and vehicle lifetime assumptions. Single technology scenarios relying on the MtG pathway can – by assumption – not achieve 100% as MtG is only available for passenger cars (see Section 3.2). All values rounded.

Cumulated Costs

Table 14 shows an overview of the cumulated costs for the maximum achievable defossilisation until 2050. Not all pathways achieve 100% defossilitation until 2050, as pointed out in the 1st column.[83] The defossilisation costs as shown in Table 14 below include the complete required investment for new vehicles. Since those vehicle costs are dominating the total costs, differences between the pathways occur to be small. Therefore, the costs for exchanging the vehicle fleet with baseline vehicles (fossil diesel/gasoline vehicles, that do not have additional “defossilisation oncost”) can be subtracted from the cumulates costs in order to display a more nuanced comparison (see Table 15).

Table 14 shows total cumulated costs for infrastructure and vehicles:

Scenario	**Max. achievable share of carbon-neutral vehicles in 2050**	**Total costs**				
		Cumulated vehicle cost 2020-2050 (billion €)	**Cumulated infrastructure cost 2020-2050 (billion €)**	**Cumulated total cost 2020-2050 (billion €)**	**Delta to base case (billion €)**	**% Delta to base case**
GHG-optimal mixed technologies scenario						
Mixed technologies scenario (GHG-optimal)	100%	18,696	7,970	26,666	-	-
Single technology scenarios						
BEV - Dom.	76%	22,022	4,160	26,182	-484	-2%
BEV - Int.	80%	22,009	5,364	27,373	+707	+3%
Methane - Int.	100%	19,269	6,413	25,682	-984	-4%
FCEV - Int.	82%	22,077	4,226	26,304	-362	-1%
FT Fuel - Int.	100%	18,658	8,954	27,613	+947	+4%
H_2 Comb. - Int.	100%	21,527	5,380	26,907	+241	+1%
MtG - Int.	98%	18,959	6,938	25,898	-768	-3%
PHEV (BEV-Int. FT-Int.)	87%	20,912	6,842	27,754	+1,088	+4%
PHEV (BEV-Dom. FT-Int.)	100%	20,865	7,556	28,421	+1,755	+7%
PHEV (BEV-Int. MtG-Int.)	86%	21,004	4,110	25,114	-1,552	-6%
PHEV (BEV-Dom. MtG-Int.)	98%	20,913	5,734	26,647	-19	-0%

Table 14: Costs in GHG-optimal mixed technologies scenario and single technology scenarios. Note: Cost estimations have limited explanatory power, see Section 6.2. The second column shows the maximum achievable share of carbon-neutral vehicles in 2050 under consideration of technical bottlenecks and vehicle lifetime assumptions. Single technology scenarios relying on the MtG pathway can – by assumption – not achieve 100% as MtG is only available for passenger cars (see Section 3.2). All values rounded.

---

[83] The cumulated costs shown below are not directly comparable with the costs shown in Fuels Study IV. In Fuels Study IV, results were expressed as net present value (assuming a discount rate of 6%) while Fuels Study IVb shows total cost and does not discount future costs in order to have a like-for-like comparison given the different timings of infrastructure investments across all scenarios.

Table 15 shows total cumulated oncost for defossilisation, i.e. as in Fuel Study IV only oncost for defossilised vehicles compared to a would-be diesel/gasoline ICEV fleet[84] are taken into account.

In this approach the costs for the baseline vehicles are subtracted from the total vehicle costs. Those baseline vehicle costs are the cumulated costs for the vehicles which would have been sold until 2050 without any defossilisation, which means diesel/gasoline vehicles still operated with fossil fuel.

Scenario	**Max. achievable share of carbon-neutral vehicles in 2050**	**Oncost for defossilisation (w/o basis vehicle cost)**				
		Cum. vehicle oncost 2020-2050 (billion €)	**Cum. infrastructure oncost 2020-2050 (billion €)**	**Cumulated total oncost 2020-2050 (billion €)**	**Delta to base case (billion €)**	**% Delta to base case**
GHG-optimal mixed technologies scenario						
Mixed technologies scenario (GHG-optimal)	100%	37	7,971	8,008	-	-
Single technology scenarios						
BEV - Dom.	76%	3,364	4,160	7,524	-484	-6%
BEV - Int.	80%	3,351	5,364	8,715	707	9%
Methane - Int.	100%	610	6,413	7,023	-984	-12%
FCEV - Int.	82%	3,419	4,226	7,645	-362	-5%
FT Fuel - Int.	100%	0	8,954	8,954	947	12%
H_2 Comb. - Int.	100%	2,868	5,381	8,249	241	3%
MtG - Int.	98%	301	6,939	7,240	-768	-10%
PHEV (BEV-Int. FT-Int.)	87%	2,254	6,842	9,096	1,088	14%
PHEV (BEV-Dom. FT-Int.)	100%	2,206	7,556	9,762	1,755	22%
PHEV (BEV-Int. MtG-Int.)	86%	2,346	4,109	6,455	-1,552	-19%
PHEV (BEV-Dom. MtG-Int.)	98%	2,255	5,734	7,989	-19	0%

Table 15: Costs in GHG-optimal mixed technologies scenario and single technology scenarios. Note: Cost estimations have limited explanatory power, see Section 6.2. The second column shows the maximum achievable share of carbon-neutral vehicles in 2050 under consideration of technical bottlenecks and vehicle lifetime assumptions. Single technology scenarios relying on the MtG pathway can – by assumption – not achieve 100% as MtG is only available for passenger cars (see Section 3.2). All values rounded.

---

[84] The would-be fossil diesel/gasoline ICEV scenario as well as all defossilisation scenarios are based on the same vehicle fleet exchange rate assumptions.

8.3.3 Sensitivities

For comparison: Main specification (GHG-optimal mixed technologies scenario)

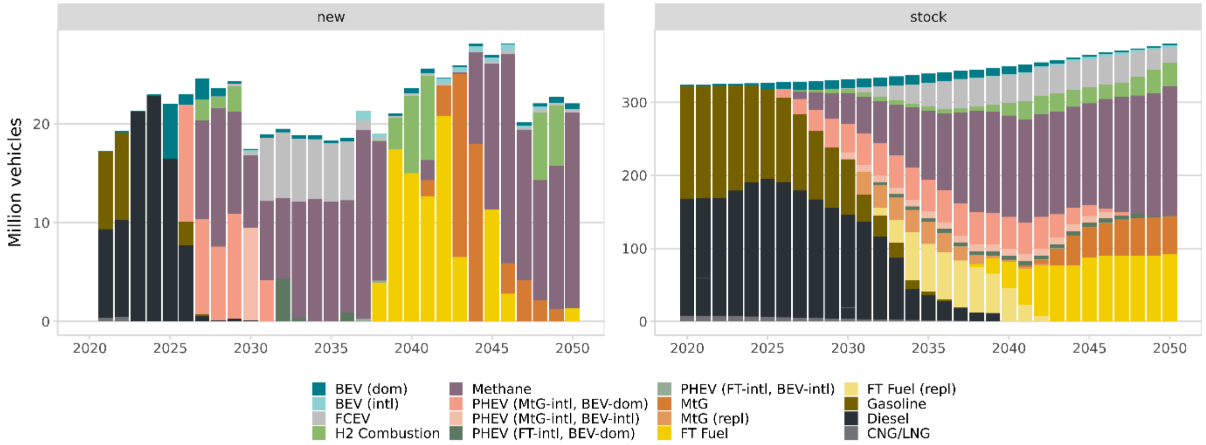


Figure 41: New vehicle registrations and vehicle stock by powertrain in the GHG-optimal mixed technologies scenario, all vehicle segments combined.

Sensitivity 1a: No catenary line restriction

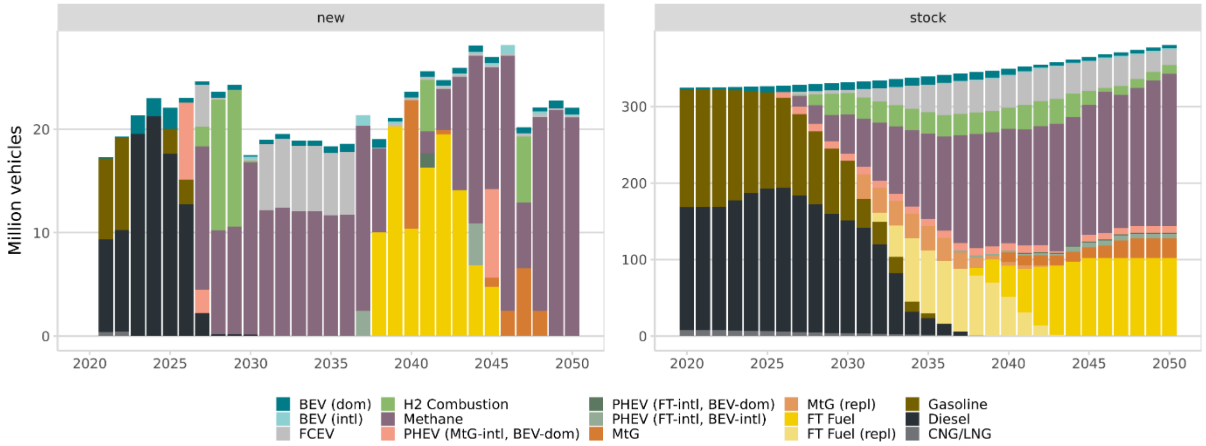


Figure 42: New vehicle registrations and vehicle stock by powertrain in Sensitivity 1a, all vehicle segments combined.

Sensitivity 1b: No catenary line and transmission grid restriction

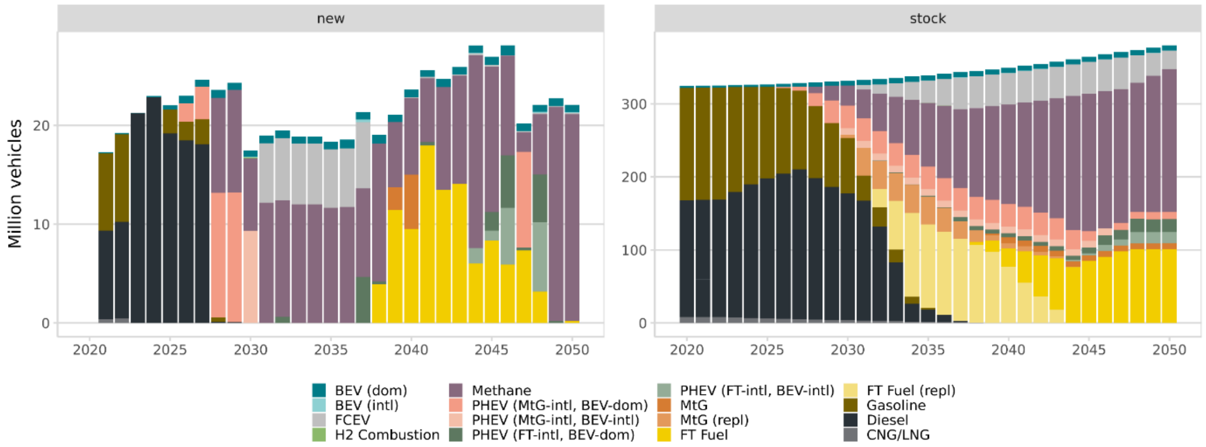


Figure 43: New vehicle registrations and vehicle stock by powertrain in Sensitivity 1b, all vehicle segments combined.

Sensitivity 2a: ICE ban from 2035 (only BEV, FCEV and H_2 Comb.)

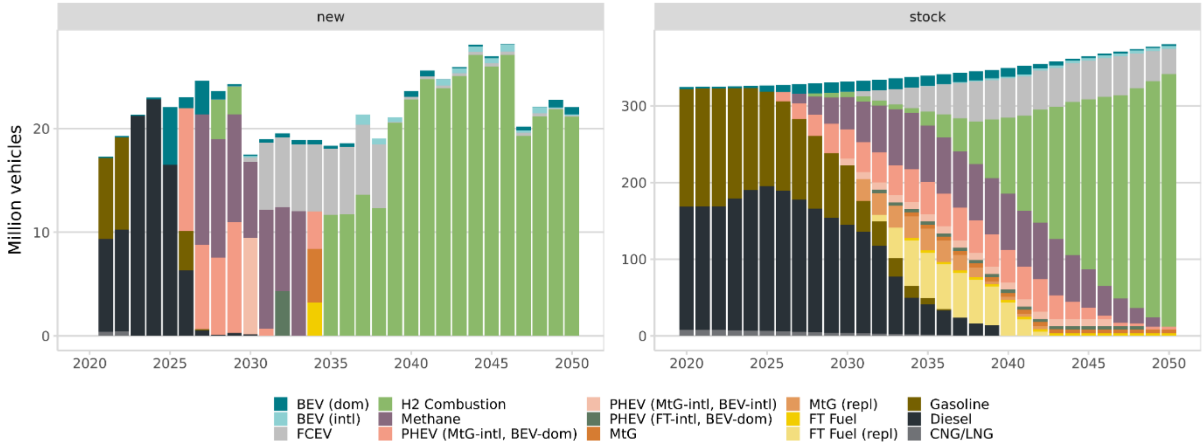


Figure 44: New vehicle registrations and vehicle stock by powertrain in Sensitivity 2a, all vehicle segments combined.

Sensitivity 2b: Strict ICE ban from 2035 (only BEV and FCEV)

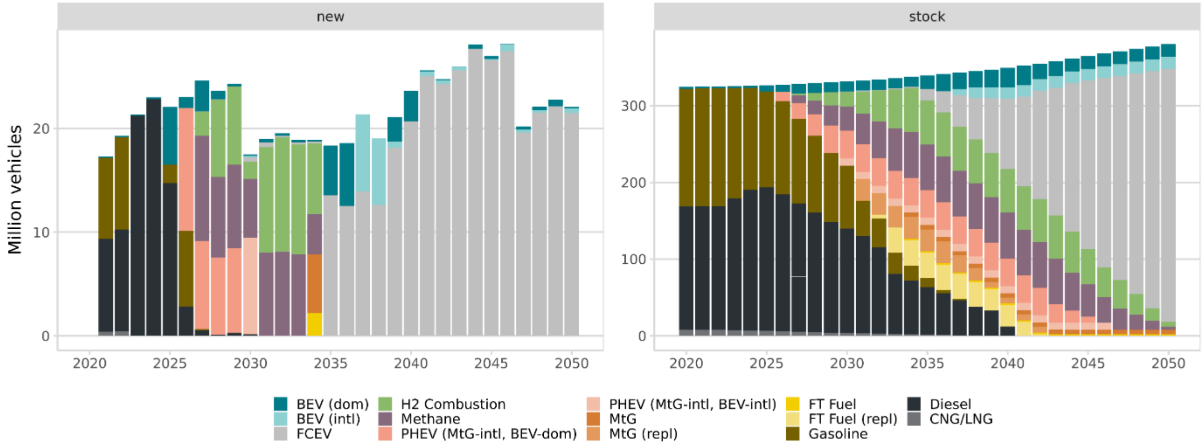


Figure 45: New vehicle registrations and vehicle stock by powertrain in Sensitivity 2b, all vehicle segments combined.

Sensitivity 2c: Long-term powertrains (BEV, FCEV, e-fuels)

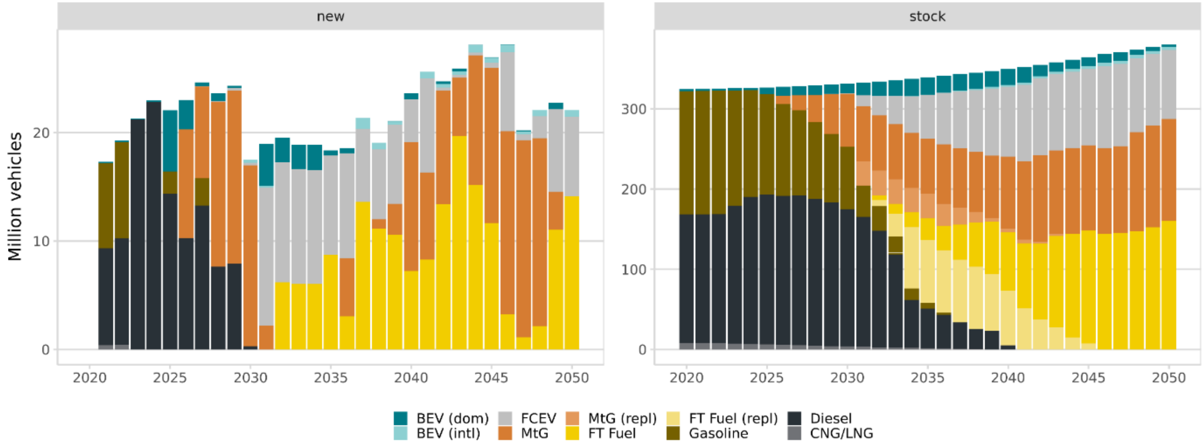


Figure 46: New vehicle registrations and vehicle stock by powertrain in Sensitivity 2c, all vehicle segments combined.

Sensitivity 2d: Powertrains in high demand (BEV, e-fuels, PHEV)

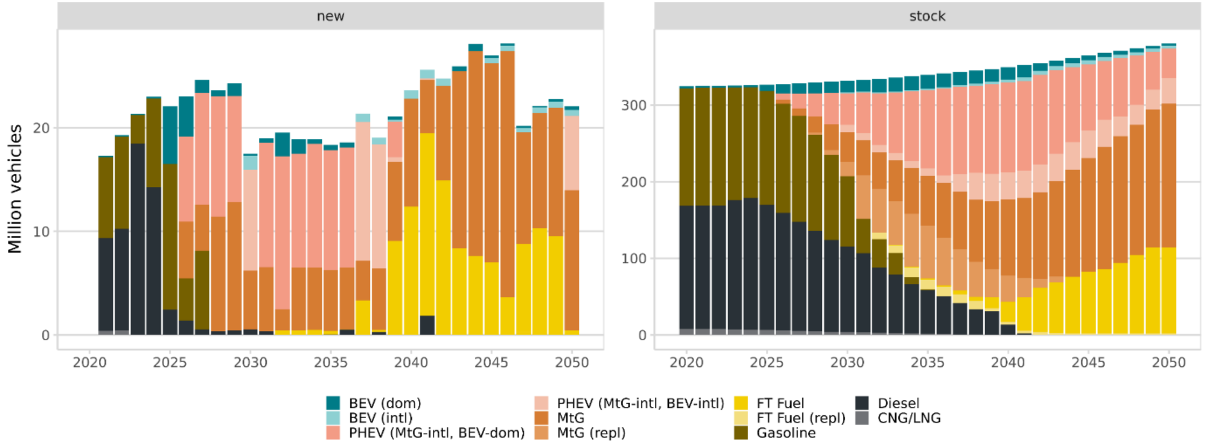


Figure 47: New vehicle registrations and vehicle stock by powertrain in Sensitivity 2d, all vehicle segments combined.

Sensitivity 2e: No catenary system/BEV for heavy-duty segment

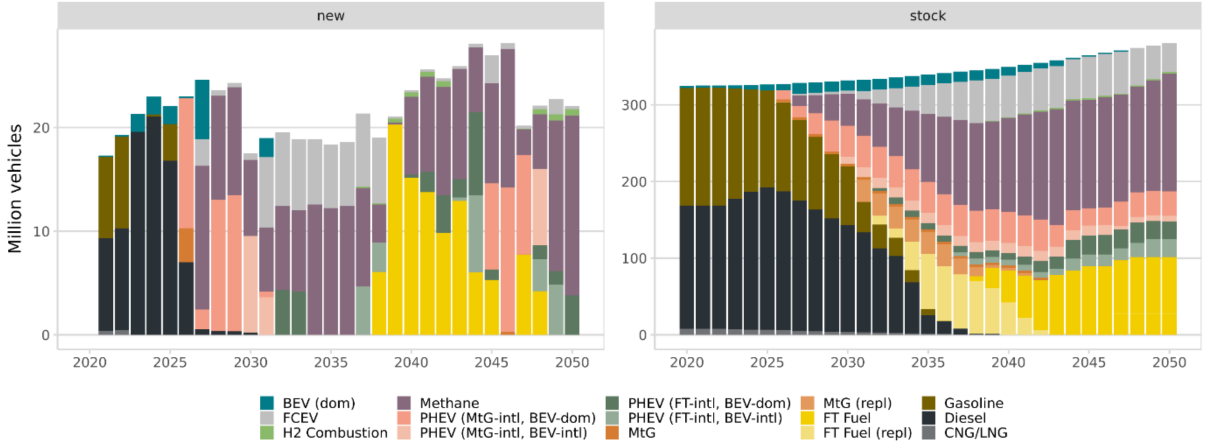


Figure 48: New vehicle registrations and vehicle stock by powertrain in Sensitivity 2e, all vehicle segments combined.

Cumulated GHG emissions

Scenario	Description	Max. achievable share of carbon-neutral vehicles in 2050	GHG emissions		
			Cumulated 2020-2050 ($MtCO_2eq$)	**Delta to base case ($MtCO_2eq$)**	**Delta to base case (in %)**
GHG-optimal mixed technologies scenario					
Mixed technologies scenario (GHG-optimal)	Optimised mixed modelling	100%	22,525	-	-
Sensitivities 1: Relaxed technical bottleneck assumptions					
Sensitivity 1a	No catenary line restriction	100%	22,294	-231	-1%
Sensitivity 1b	No catenary line and transmission grid restriction	100%	21,862	-663	-3%
Sensitivities 2: Reduced number of (GHG-neutral) technology pathways					
Sensitivity 2a	ICE ban for new vehicle registrations from 2035 (only BEV, FCEV and H_2 Comb.), e-fuel use in existing fleet allowed	100%	22,797	+272	+1%
Sensitivity 2b	Strict ICE ban for new vehicle registrations from 2035 (only BEV and FCEV), e-fuel use in existing fleet allowed	100%	23,178	+653	+3%
Sensitivity 2c	Long-term powertrains (BEV, FCEV, e-fuels)	100%	23,155	+630	+3%
Sensitivity 2d	Powertrains in high demand (BEV, e-fuels, PHEV)	100%	23,264	+739	+3%
Sensitivity 2e	No catenary system/BEV for heavy-duty segment	100%	23,202	+677	+3%

Table 16:GHG emissions in GHG-optimal mixed technologies scenario and sensitivities. Note: The third column shows the maximum achievable share of carbon-neutral vehicles in 2050 under consideration of technical bottlenecks and vehicle lifetime assumptions. All values rounded.

Cumulative costs

The cumulative costs shown below are not directly comparable with the costs shown in Fuels Study IV: In Fuels Study IV, results were expressed as net present value (assuming a discount rate of 6%) while in this study, we do not discount future costs in order to have a like-for-like comparison given the different timings of infrastructure investments across all scenarios.

Table 17 shows total cumulated costs for infrastructure and vehicles:

Scenario	Description	Max. achievable share of carbon-neutral vehicles in 2050	Total costs				
			Cumulated vehicle cost 2020-2050 (billion €)	**Cumulated infrastructure cost 2020-2050 (billion €)**	**Cumulated total cost 2020-2050 (billion €)**	**Delta to base case (billion €)**	**% Delta to base case**
GHG-optimal mixed technologies scenario							
Mixed technologies	Optimised mixed modelling	100%	18,696	7,970	26,666	-	-

scenario (GHG-optimal)							
Sensitivities 1: Relaxed technical bottleneck assumptions							
Sensitivity 1a	No catenary line restriction	100%	18,980	7,309	26,289	-377	-1%
Sensitivity 1b	No catenary line and transmission grid restriction	100%	19,158	7,229	26,386	-279	-1%
Sensitivities 2: Reduced number of (GHG-neutral) technology pathways							
Sensitivity 2a	ICE ban for new vehicle registrations from 2035 (only BEV, FCEV and H_2 Comb.), e-fuel use in existing fleet allowed	100%	19,977	7,690	27,667	+1,001	+4%
Sensitivity 2b	Strict ICE ban for new vehicle registrations from 2035 (only BEV and FCEV), e-fuel use in existing fleet allowed	100%	20,653	7,166	27,819	+1,153	+4%
Sensitivity 2c	Long-term powertrains (BEV, FCEV, e-fuels)	100%	18,890	8,469	27,358	+693	+3%
Sensitivity 2d	Powertrains in high demand (BEV, e-fuels, PHEV)	100%	17,350	9,680	27,031	+365	+1%
Sensitivity 2e	No catenary system/BEV for heavy-duty segment	100%	18,774	7,734	26,507	-159	-1%

Table 17: Cumulative costs 2020-2050 in GHG-optimal mixed technologies scenario and sensitivities. Note: Cost estimations have limited explanatory power, see Section 6.2. The third column shows the maximum achievable share of carbon-neutral vehicles in 2050 under consideration of technical bottlenecks and vehicle lifetime assumptions. All values rounded.

Table 18 shows total cumulated oncost for defossilisation, i.e. as in Fuel Study IV only oncost for defossilised vehicles compared to a would be diesel/gasoline ICEV fleet[85] are taken into account:

Scenario	**Description**	**Max. achievable share of carbon-neutral vehicles in 2050**	**Oncost for defossilisation (w/o basis vehicle cost)**				
			Cum. vehicle oncost 2020-2050 (billion €)	**Cum. infra-structure oncost 2020-2050 (billion €)**	**Cumulated total oncost 2020-2050 (billion €)**	**Delta to base case (billion €)**	**% Delta to base case**
GHG-optimal mixed technologies scenario							
Mixed technologies scenario (GHG-optimal)	Optimised mixed modelling	100%	37	7,971	8,008	-	-
Sensitivities 1: Relaxed technical bottleneck assumptions							
Sensitivity 1a	No catenary line restriction	100%	322	7309	7,631	-377	-5%

---

[85] The hypothetical 'would-be' fossil diesel/gasoline ICEV scenario as well as all defossilisation scenarios are based on the same vehicle fleet exchange rate assumptions.

Sensitivity 1b	No catenary line and transmission grid restriction	100%	499	7229	7,728	-279	-3%
Sensitivities 2: Reduced number of (GHG-neutral) technology pathways							
Sensitivity 2a	ICE ban for new vehicle registrations from 2035 (only BEV, FCEV and H_2 Comb.), e-fuel use in existing fleet allowed	100%	1,318	7,691	9,009	+1,001	13%
Sensitivity 2b	Strict ICE ban for new vehicle registrations from 2035 (only BEV and FCEV), e-fuel use in existing fleet allowed	100%	1,994	7,167	9,161	+1,153	14%
Sensitivity 2c	Long-term powertrains (BEV, FCEV, e-fuels)	100%	231	8,469	8,700	+693	9%
Sensitivity 2d	Powertrains in high demand (BEV, e-fuels, PHEV)	100%	-1,308	9,680	8,372	+365	5%
Sensitivity 2e	No catenary system/BEV for heavy-duty segment	100%	115	7,734	7,849	-159	-2%

Table 18:Cumulative costs 2020-2050 in GHG-optimal mixed technologies scenario and sensitivities. Note: Cost estimations have limited explanatory power, see Section 6.2. The third column shows the maximum achievable share of carbon-neutral vehicles in 2050 under consideration of technical bottlenecks and vehicle lifetime assumptions. All values rounded.

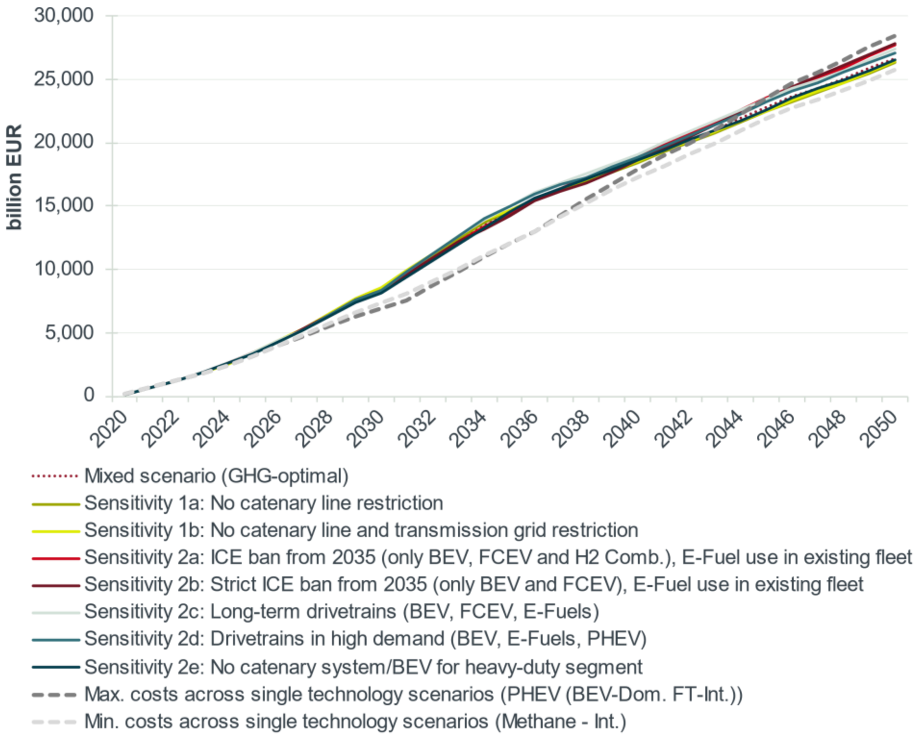


Figure 49: Cumulative costs 2020-2050. Note: We depict minimum and maximum costs across those single technology scenarios that reach a fully carbon-neutral fleet by 2050. Cost estimations have limited explanatory power, see Section 6.2.

9 Appendix II – Technical subreport (ifeu)

Abstract

Frontier Economics and ifeu had been working on an orientation study on behalf of FVV looking at different decarbonisation options of the European transport sector – including underlying fuel supply chain and infrastructure needs. The aim of the completed FVV Project 1378 (aka "FVV Fuels Study IV") is the development of transition scenarios to achieve GHG neutral mobility in 2050. Considerations are done on a European level taking into account road transport, intra-European aviation, rail and shipping. Potential technical glidepaths have been defined in 100% scenarios based on seven fuel/drivetrain technologies i.e. BEV, H2-FCEV and ICEs operated with FT fuel (gasoline/diesel mix), methane, DME, methanol and H2.

The results of the FVV Fuels Study IV have led to several follow-up questions, in particular to the achievable ramp-up gradients of complete defossilised powertrain / energy pathways, including the relevance of additional powertrain technologies and the development for effective and affordable ways to reach GHG neutral mobility from a technological perspective within the identified bottlenecks. Therefore, FVV has commissioned Frontier and ifeu with follow-up analyses.

This short technical sub-report by ifeu sets out the preparation and provision of specific input parameters, in particular GHG factors and resource requirements from the completed Fuels Study IV as well as the derivation of additional factors for the newly added supplementary technologies (PHEV, MtG). Methodology and data basis of the annually available primary material quantities of selected raw materials for defossilisation of road transport in Europe are described.

The objective of the research project was achieved.

9.1 Preparation of specific GHG and material factors from Fuels Study IV

9.1.1 Derivation of average GHG emission factors for different scenario years

In FVV Fuels Study IV (FVV 2021), specific GHG emissions for manufacturing of vehicles and build-up of fuel supply chain infrastructure were derived for the year 2020 and for two different defossilisation levels of the background system (material supply, production processes):

- 2050a "Defossilised Europe": All processes in EU27+UK are fully defossilised in 2050. The rest of the world has a time lag of 10 years reaching 75% defossilisation in 2050.
- 2050b "Defossilised World": All production processes worldwide are fully defossilised in 2050 (including all raw material extraction and processing).

In the 100% scenarios we assumed a gradual transition from today's production system to a fully defossilised world in 2050. For several fuel supply chain (FSC) components (mainly wind power generation and fuel synthesis plants), future development of emission factors additionally covers upscaling of plant capacities and related impacts on specific GHG emissions and material demands.

To provide input to Frontier economics' modelling of the EU27+UK road transport sector, considering technical bottlenecks in FVV Fuels Study IVb, we derived specific GHG emission factors and material demands for individual scenario years with different shares of background defossilisation levels. Specific emission factors for all relevant drivetrains and FSC components (including additionally supplemented PHEV and MtG process) are provided in 5-year intervals with a gliding transition from 100% today's production conditions in 2020 to a fully defossilised Europe (achieved between 2040 and 2045) to a theoretically fully defossilised world in 2050 (Figure 50). Specific GHG emission factors and material demands for all scenario years are given in the Annex.

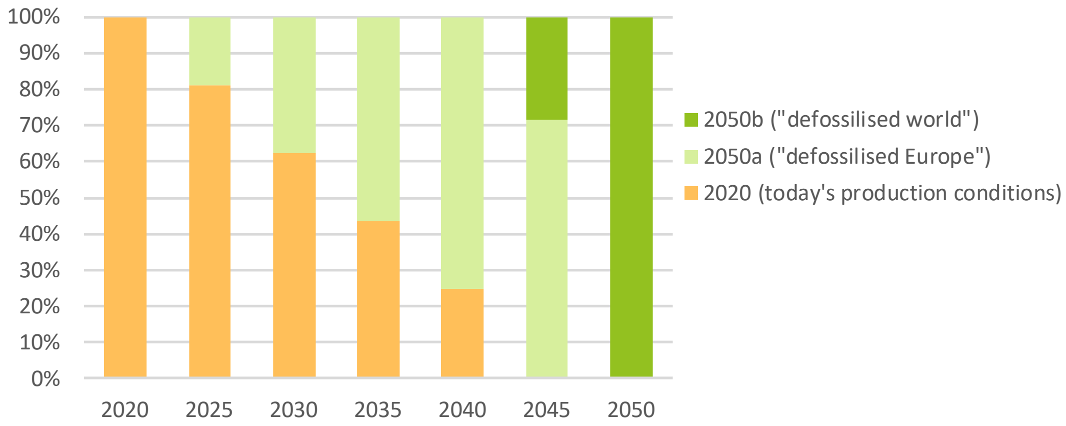


Figure 50: Assumed shares of different defossilisation levels in the background system in the scenario years.

9.1.2 Update of vehicle-specific GHG emission factors and material demand in vehicle production for different defossilisation levels (2020, 2050a and 2050b)

Vehicle configurations and environmental impacts from vehicle manufacturing in the complementary FVV Fuels Study IVb are mostly retained from FVV Fuels Study IV. Only for heavy-duty fuel cell vehicles, the FVV expert group decided to update the assumptions for 3.5-7.5 t rigid truck as well as the 7.5-16 t regional truck and to increase the power of the fuel cells. In consequence, we updated the specific GHG emissions and material demands for the new vehicle configuratio.ns as shown in Table 19.

Size	**Power (kW)**		**Empty weight (kg)**	**Gross battery capacity (kWh)**
	Electric	**Fuel Cell**	**Balanced**	**Balanced**
3.5-7.5 t Rigid	85	53.5	2,950	33
7.5-16t Regional	185	87.5	5,375	45

Table 19: Updated technical specifications for selected fuel cell heavy-duty vehicles.

9.2 Specific GHG and material factors for supplementary technologies in FVV Fuels Study IVb

9.2.1 Supplementary vehicle technologies: Plug-in hybrid vehicles (PHEV)

In addition to the vehicle technologies from FVV Fuels Study IV, we added plug-in hybrid vehicles as an additional technology in FVV Fuels Study IVb. In contrast to classical hybrid electric vehicles, PHEVs can also be charged externally. Their electric range is usually lower than for purely electric cars, thus they benefit from smaller batteries. However, achieving high shares of electric driving is important for a good environmental performance of PHEV vehicles.

An FVV expert group defined all technical specifications of the PHEV vehicles. Furthermore, the decision was to limit the technologies in Fuels study IVb to those with a higher market readiness. Thus, for PHEV vehicles only gasoline and diesel (for light-duty) and only diesel (for heavy-duty) were assessed.

Electric ranges as well as share of electric driving are shown in the following table. All other technical specifications can be found in annex 9.9.4.1.

Vehicle size	**Electrical range (km)**	
	2020	**2030 - 2050**
small	50	80
medium	50	80
large	50	100
SUV	50	100
LCV	50	80
Rigid (N2)		80
Regional delivery (N3)		100
Long haul (N3)		120
Super long haul (N3)		120
Public transport		60
Coaches		120

Table 20: Electric range of PHEV vehicles. Source: FVV working group.

Environmental modelling for Plug-in hybrid vehicles in FVV Fuels Study IVb uses the same methodological approach and LCA data bases as for other drivetrain concepts (see detailed explanations in Fuels study IV (FVV 2021)). To include PHEVs into our modelling, we had to adapt the environmental model for light-duty and heavy-duty vehicles. Since PHEVs are more or less conventional Hybrid Electric Vehicles (HEV), just equipped with a significantly larger battery and an external charging option, a PHEV drivetrain contains both, an electric motor plus battery, as well as an internal combustion engine.

Figure 51 shows the detailed results for the greenhouse gas emissions from manufacturing of a C-segment car. All drivetrain concepts have a similar glider, but different powertrains and energy storages. Since only the “Balanced” technology scenario is shown (out of three vehicle technology scenarios investigated in FVV Fuels Study IV), assuming full hybridisation of all ICE powertrains, both the gasoline / diesel baseline and the plug-in hybrid need a conventional as well as an electrical drivetrain. Overall, manufacturing of a PHEV-gasoline today leads to 20% higher greenhouse gas emissions compared to a conventional (fully hybridised) gasoline car. However, GHG emissions of the PHEV are 30% lower than for the battery electric vehicle (BEV) and 20% lower than for the fuel cell car (FCEV). This is mainly due to the large battery of the BEV and the higher greenhouse gas emissions of the fuel cell and hydrogen tank of the FCEV.

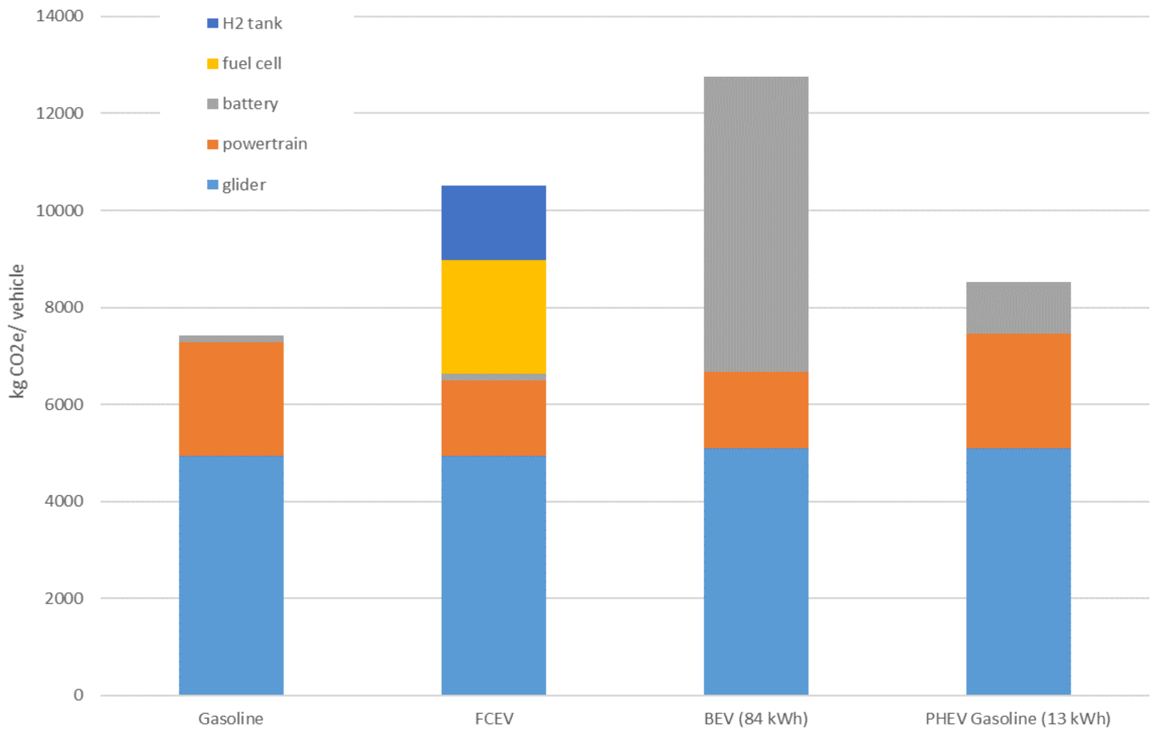


Figure 51: Detailed results: GHG emissions from manufacturing of selected C-segment cars in 2020 (with net battery capacity).

Future defossilisation (Figure 52) will lower the manufacturing greenhouse gas emissions considerably (in “2050b” only unavoidable GHG emissions remain), but does not change the ranking of the drivetrain technologies. With all defossilisation levels, PHEVs (gasoline, diesel) have higher emissions from manufacturing than gasoline and diesel cars, but lower emissions than fuel cell and battery-electric cars.

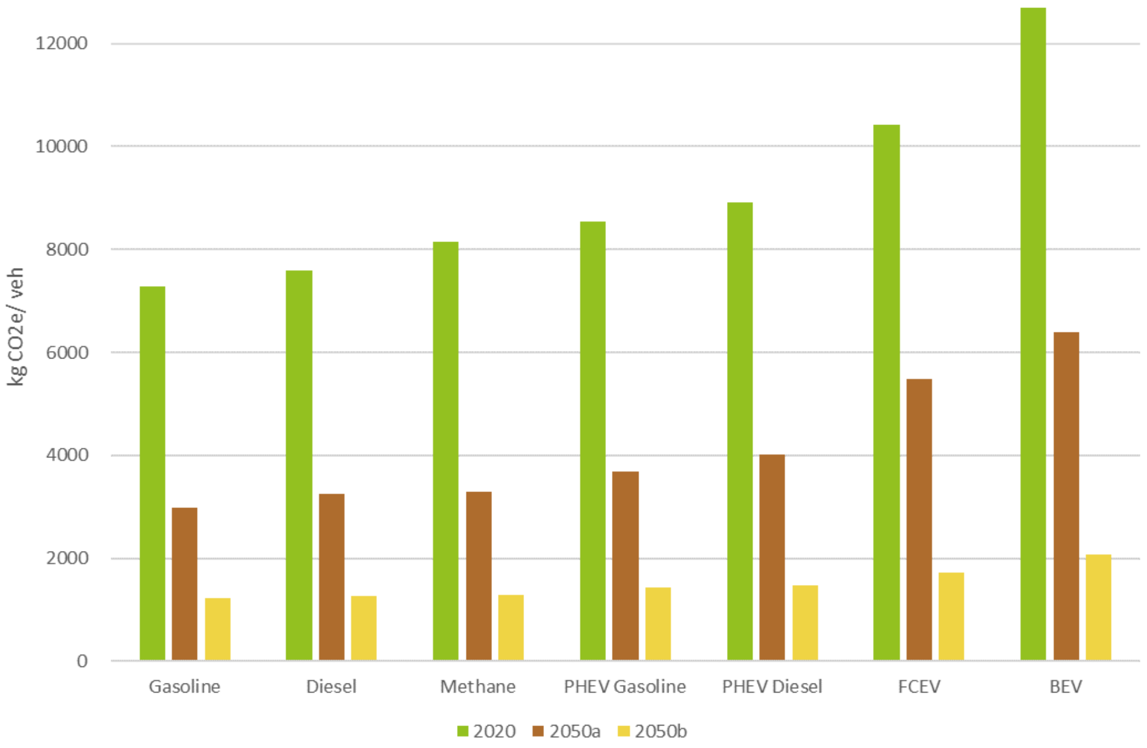


Figure 52: GHG emissions from manufacturing of a C-segment car (Balanced) with future defossilisation.

As in FVV Fuels Study IV, the modelling includes also the demand of selected materials for manufacturing plug-in hybrid vehicles. Cobalt, nickel and lithium are mainly needed for the battery, thus the battery size is the deciding factor in demand for these resources. Thus, the demand of battery materials for a plug-in hybrid is considerably lower than for a battery-electric vehicle, though still higher than for (fully hybridised) internal combustion engine vehicles or fuel cell vehicles. Copper follows a similar trend. Platinum group metals demand for plug-in hybrids is the same as for the gasoline / diesel vehicles, due to the similar exhaust gas aftertreatment.

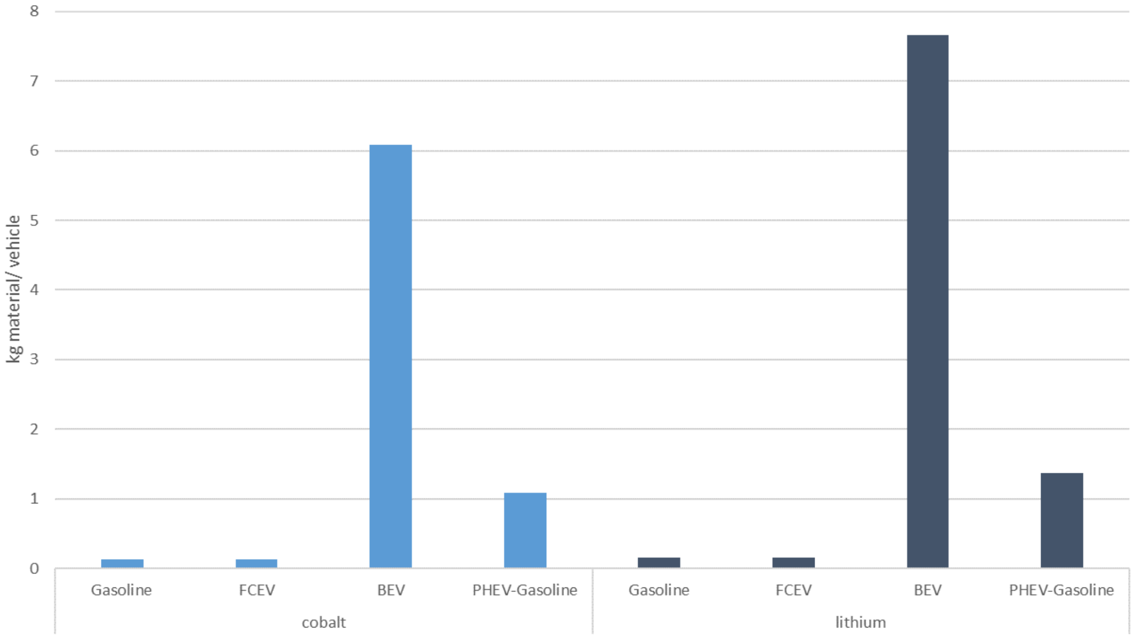


Figure 53: Cobalt and lithium in a C-segment PHEV car (balanced) compared to gasoline and BEV cars (from FS IV).

9.2.2 Cobalt- and nickel-free battery technologies

In FVV Fuels Study IV (FVV 2021), an expert group decided to focus on nickel-manganese-cobalt batteries (NMC811) with an energy density of 200 Wh/kg for the balanced technology level. However, recent market development shows a very dynamic situation for technological advancements in the sector of automotive batteries. Thus, the NMC811 battery may already be a rather conservative estimate of a future battery technology. In FVV Fuels Study IV, we showed that solid-state NMC batteries may lead to further improvements in energy density and lower the demand for cobalt and nickel. On the other hand, due to their lithium anode, solid-state NMC batteries lead to a higher lithium demand.

Recently, other battery technologies are also gaining importance in the market for automotive batteries. Especially for heavy-duty vehicles or smaller car segments, lithium iron phophate (LFP) batteries are often used. New developments suggest potential significant shares of LFP batteries in the worldwide electric vehicle market. LFP batteries do not contain cobalt and nickel, but still require a similar amount of lithium as NMC batteries. Furthermore, LFP batteries are cheaper than up-to-date NMC batteries. Literature studies on life cycle assessment of LFP batteries show similar GHG emissions compared to NMC batteries. Accordingly, the use of LFP batteries can avoid material bottlenecks for cobalt and nickel (see sensitivity analysis in FVV Fuels Study IV) and reduce incremental investment costs for electric mobility.

LFP batteries have lower energy densities compared to NMC batteries. Recent technical developments have led to increasing energy densities (but still lower than for NMC). Scientific studies see similar energy densities on cell level compared to NMC622 batteries[86]. Furthermore, higher packing ratios (e.g. CATL cell-to-pack, BYD blade battery) lead to higher energy densities on pack level. LFP batteries in recent past or currently available car models have energy densities on pack level of 125-145 Wh/kg, buses in China apparently have 146-161 Wh/kg[87]. For new LFP batteries from main manufacturers (BYD, CATL, Gotion High-tech) already available or with announced production start within next 3 years, energy densities of 140 Wh/kg up to more than 200 Wh/kg are indicated in press releases of the last 2 years (Figure 54).

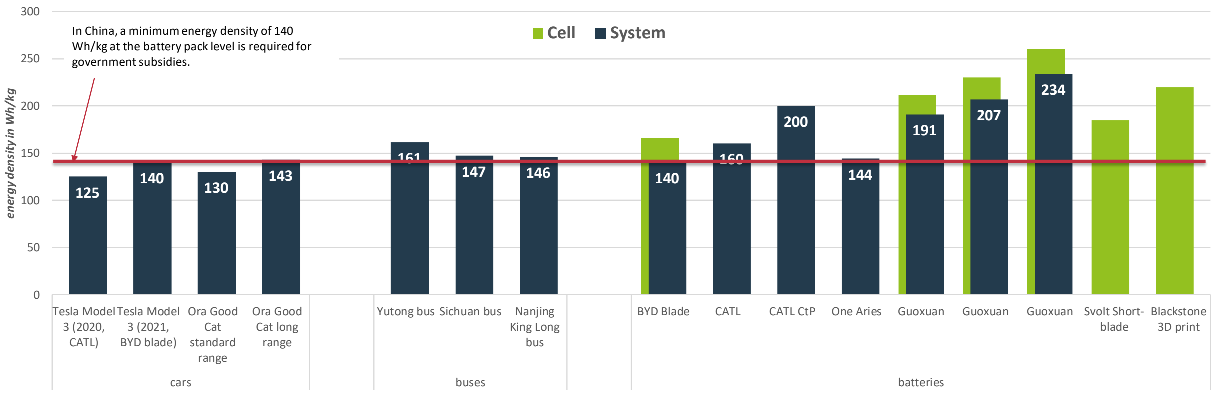


Figure 54: Energy densities of present and announced LFP car batteries.

Further new cobalt- and nickel-free battery technologies, for example sodium-ion batteries are being researched today, which could become market-ready in future years[88].

To keep consistency with the previous study, the FVV working group decided to keep in Fuels Study IVb the initial assumptions for battery technologies from the previous study for the detailed modelling of defossilisation in Europe (i.e. NMC811 with 200 Wh/kg for Balanced). Only for simplified assessing material demands in the automotive sector outside Europe we assume a share of non-NMC battery technologies in the study (see chapter 9.3.3).

---

[86] http://ecec.me.psu.edu/Pubs/2021_Yang_NatureEnergy.pdf.

[87] https://insideevs.com/news/429865/china-energy-density-lfp-battery-packs/.

[88] https://electrek.co/2022/07/14/sodium-ion-battery-breakthrough/.

9.2.3 Supplementary fuel supply chain technologies: Methanol to gasoline (MtG)

The synthesis of gasoline from hydrogen and carbon dioxide is a two-step process, with MeOH synthesis in the first step as described in the FVV Fuels Study IV (FVV 2021) and subsequent conversion of MeOH to gasoline (via DME) in the second step. Figure 55 shows the basic principle. The target product of the MtG process is synthetic fuel, which complies with the EN 228 standard (DIN EN 228 2017) for petrol.

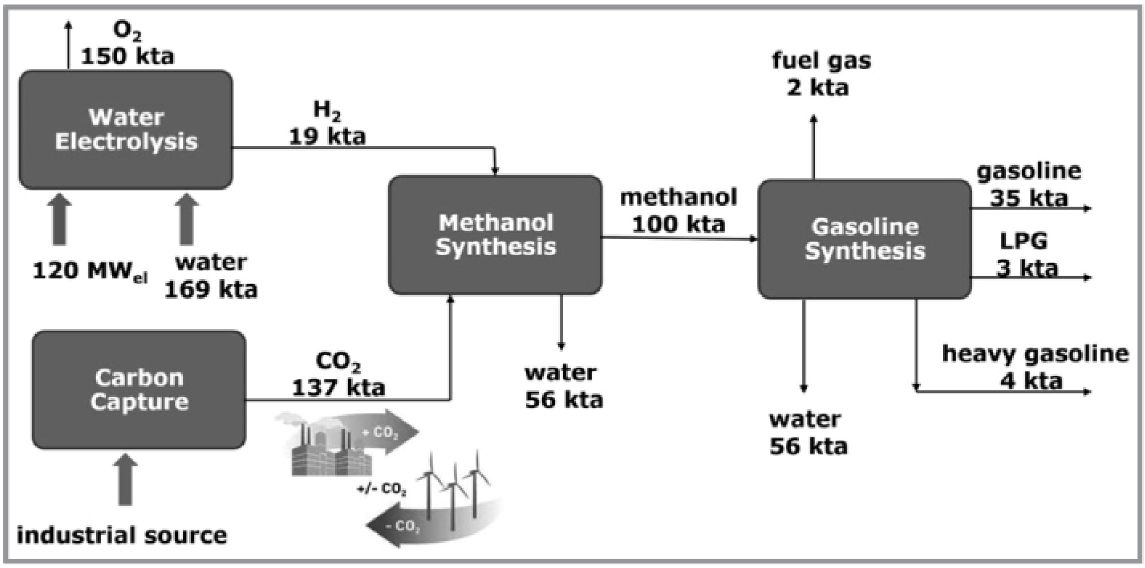


Figure 55: Basic concept of a small (35 kta) methanol-to-gasoline plant (Jung et al. 2020).

The MtG technology has already been tested in practice and implemented in various demonstration and industrial production plants. The following table shows examples:

Plant	Licensor	Start - End	Capacity
New Zealand Synfuels	ExxonMobil	1985 - 1997	15,000 t/a
JAMG (Shanxi, China)	ExxonMobil	2009	100,000 t/a
Neftegaz, Turkmenistan	Haldor Topsoe	2019	600,000 t/a
Haru Oni, Chile	ExxonMobil	End of 2022 (planned) 2024 (planned) 2026 (planned)	~100 t/a ~40,000 t/a ~410,000 t/a

Table 21:Selection of existing MtG plants and those under construction.

Technical assumptions for MtG plants in this study have been defined in a FVV working group based on process data inputs by FVV experts and comparison with data from publications. Energy efficiency of the MtG technology can be assumed to be 65 to 68 %. If the co-product "heavy gasoline" is included in the evaluation, the efficiency is approx. 82 %. Since this fraction could also be used by the road transport sector, the higher MtG process efficiency is assumed for the modelling in this study. This also fits well with other publications on MtG processes, e.g. (Schemme 2020). Table 22 shows the assumed synthesis product distribution and their heating values.

	MA.-%	LHV, MJ/kg	LHV, kWh/kg
Gasoline	75.00	43.20	12.00
LPG	8.92	45.21	12.56
Heavy Gasoline	5.50	42.8	11.89
Gas	10.58	42.64	11.84

Table 22: Assumed MtG synthesis product distribution and heating values.

Table 23 shows the most important parameters of the MtG synthesis. These assumptions were agreed and adopted in the FVV expert group. For the environmental performance of the system, the demand for renewable electricity for methanol production is decisive. However, the production of the synthesis plant (and catalysts) also plays a role in an overall defossilised world. The production of the plant is depreciated on a linear basis over its lifetime.

Parameter	All Years	Remark
Efficiency (MJ gasoline/MJ MeOH)	82%	Determination in FVV expert group
Capacity	410,000 t/a	Determination in FVV expert group
Lifetime (of synthesis plant)	25 a	Same as for synthesis plants in FVV fuels IV study
Full load hours	8,000 h/a	Same as for synthesis plants in FVV fuels IV study

Table 23:Relevant Assumptions for the MtG plants.

For the modelling of the environmental impacts of the MtG infrastructure, we used a generic LCA dataset of a synthesis plant with a capacity of 50,000 t/a and approx. 45 MW from the ecoinvent 3.6 database (Wernet et al. 2016). The output power of the MtG plant, we determined via the lower heating value of petrol, is 600 MW. Upscaling to this output power is done using the capacity method. As capacity increases, the specific production costs generally decrease, which can be described with a degression exponent (Lühe 2013). The degression of the investment-related environmental impacts (e.g. GHG emissions) is applied with a degression exponent of 0.66. Further details on the determination of LCA data and results can be found in FVV Fuels Study IV (FVV 2021), chapter 10.2.1.

The increasing defossilisation of material supply and manufacturing processes has a significant impact on environmental impacts from production of MtG synthesis plants, specific GHG emissions will decrease significantly. As in FVV Fuels Study IV, we analyse two different defossilisation levels (see (FVV 2021) chapter 10.1.2.2 for detailed explanations).

- 2050a “Defossilised Europe”: All processes in EU27+UK are fully defossilised in 2050. The rest of the world has a time lag of 10 years reaching 75% defossilisation in 2050.
- 2050b “Defossilised World”: All production processes worldwide are fully defossilised in 2050 (including all raw material extraction and processing).

Figure 56 shows the specific GHG emissions of MtG synthesis plant installation for the year 2020 and with different defossilisation levels 2050. While the GHG contribution in 2020 is still 1,177 t CO2e/MW, this decreases by 96% to 45 t CO2e/MW in a completely defossilised world (only unavoidable non-fossil GHG emissions occur).

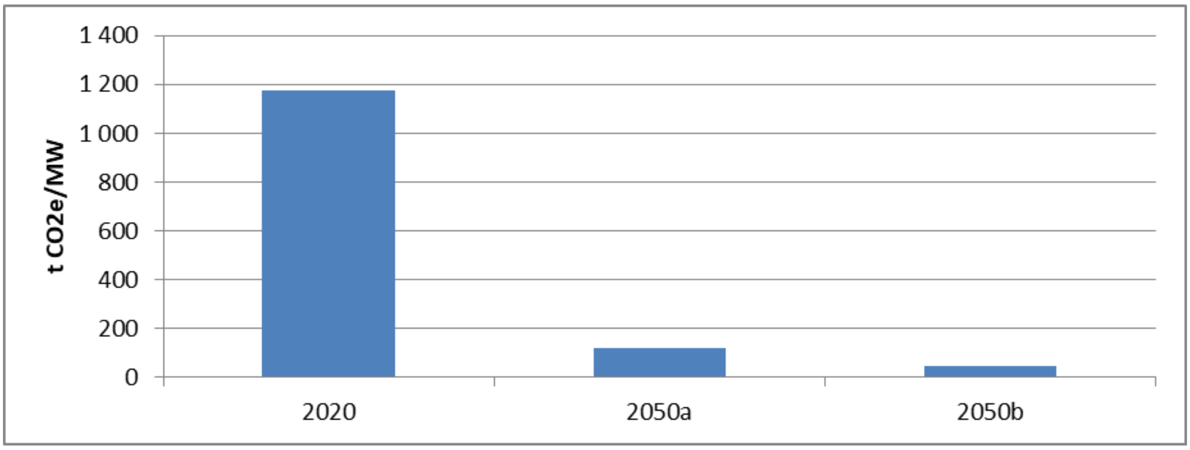


Figure 56: Specific GHG emissions from installation of MtG synthesis plants in 2020 and with different defossilisation levels of production in 2050.

9.3 Availability of primary materials

Availability of raw materials may be a potential bottleneck for the transformation of the energy systems as several studies have shown (e.g. (DERA 2021; IRENA 2021)). The FVV Fuels study IV has demonstrated that this holds true with respect to different pathways and technologies in the mobility sector (FVV 2021). In order to analyse the potential effects of limited raw material supply on ramp-up speed, two aspects have to be considered: first, the global supply with the raw materials and second, the material demand in countries outside Europe and the demand of other sectors. These two aspects will be analysed in the following chapters with respect to six selected raw materials: Lithium, cobalt, platinum and partly platinum metal group, copper, nickel and silver. The six raw materials were selected according to the results of the FVV Fuels study IV (FVV 2021).

9.3.1 Potential annual supply with primary materials

Future material supply was calculated by the Deutsche Rohstoffagentur (DERA) for the materials cobalt, platinum/PGM, copper, nickel and silver. DERA was part of the FVV expert group on materials and asked by FVV to provide potential future supply of primary materials based on a very optimistic, but still technically possible extraction development.

Based on historical time series, DERA used the method ARIMA (Autoregressive Integrated Moving Average-Models), which is a statistical method for forecasting of time series. The essence of the method is that not just extrapolations are made, but that the time series is converted into a mathematical function that considers extremes and errors in the time series. The mathematical function takes these extremes and errors into account by their duration and frequency via the weighting of mean and variance, and based on this the forecast is calculated. DERA calculated three different forecasts until 2040, (1) a low(er) supply, (2) a medium supply and (3) a high supply forecast. Based on the philosophy of the study (focus solely on technical bottlenecks, assuming ideal legal and financial boundary conditions), the FVV expert group chose the high supply scenario to be used in the study.

It should be mentioned that raw material supply is the result of a complex interaction between demand and supply, depending on geological factors, technological developments, mining allowances, prices and several further factors. ARIMA method is a consistent approach for forecasting the supply, but using another approach could arrive to a different result; e.g., the statistical method ARIMA does not consider current exploration. Thus, with respect to Lithium, the method is not appropriate as mining sites change significantly. Thus, DERA and ifeu proposed to use a supply scenario from (Greim et al. 2020); (Greim et al. 2020) analysed future sources taking technology and price developments as well as new mining sites in Latin America into account. This proposal was agreed in the respective FVV expert group.

Results for potential global primary material supply are shown in Figure 57. Supply for all raw materials is increasing until 2040. For some materials, supply increases strongly (e.g. for Lithium with new mining sites), while supply of other materials increases slower, e.g. for Platinum, a material which has been extracted for decades and rather few new mining sources are known. The specific results were provided as input to Frontier Economics' subsequent modelling of the EU27+UK road sector, considering technical bottlenecks in FVV Fuels study IVb.

9.3.2 Annual primary material demand in other (non-mobility) sectors

The demand of other (non-mobility) sectors is relevant in order to get a full picture of possible raw material bottlenecks in the defossilisation of transport. Primary demand of the raw materials Lithium, Cobalt, Platinum and Copper were taken over from the previous FVV Fuels study IV (FVV 2021). Additionally, we researched the potential demand of non-mobility-sectors for silver and nickel within this study.

With respect to nickel, we selected the source (Elshkaki et al. 2017). (Elshkaki et al. 2017) calculated the future demand of nickel for all sectors. We subtracted the demand for the transport sector[89] in the study (which does not include a full defossilisation of transport) in order to get the global non-mobility demand.

Silver is required for the defossilisation of transport only in the fuel supply chain (mainly power generation) and, thus, potentially concurring with non-transport defossilisation of global energy supply. For future global silver demand, we have chosen the source (Lo Piano et al. 2019), where the long-term silver demand from different sectors is modelled. The global silver demand in Table 24 covers the industrial demand only, excluding the energy sector. Given the fact that several options for substitution of silver in renewable energy production exist, e.g. copper in PV modules, other PV modules or even other renewable technologies such as wind power plant, we didn't further analyse any theoretical technical silver bottleneck.

The specific values in the years 2030 and 2050 which are used in the study are shown in Table 24.

	2030	**2050**	**Unit**	**Source**
Lithium	42	65	*kilotons*	FVV Fuels Study IV (FVV 2021)
Cobalt	136	240	*kilotons*	FVV Fuels Study IV (FVV 2021)
Platinum	154	207	*tons*	FVV Fuels Study IV (FVV 2021)
Copper	22,500	38,500	*kilotons*	FVV Fuels Study IV (FVV 2021)
Nickel	1,700	2,926	*kilotons*	own estimate based on (Elshkaki et al. 2017)
Silver*	20	20	*kilotons*	*industrial demand without energy sector (PV) own estimate based on (Lo Piano et al. 2019)

Table 24:Global demand of non-mobility transport sectors of the six raw materials in 2030 and 2050.

---

[89] Material demand for transport sector is driven by road transport. Thus, demand for other transport modes, e.g. ships, was neglected.

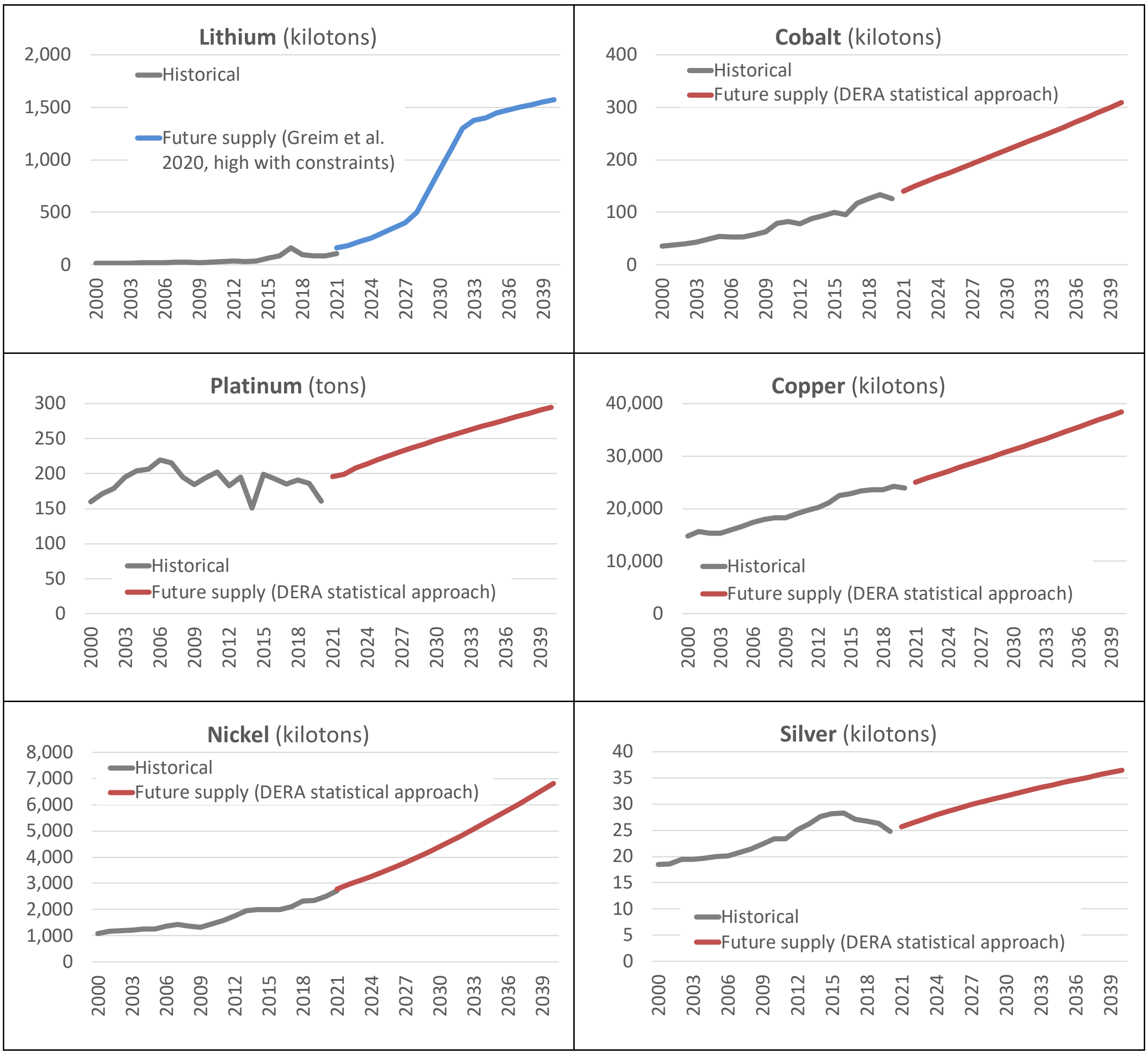


Figure 57: Model assumptions for future primary material availability [Source: DERA data supply, Greim et al. 2020].

9.3.3 Potential share of the EU27+UK transport sector on total primary material availability for defossilising worldwide transport

The European transport sector competes with other (non-mobility) sectors (chapter 9.3.2) and with transport in other world regions for the supply of primary materials needed for the defossilisation. Therefore, the EU27+UK transport sector can only “claim” a part of global material quantities available for worldwide transport. This share depends above all on the number of vehicle sales worldwide and on the shares of alternative drive concepts with their specific material requirements in the vehicle markets. Road transport is the main driver for material demand in the defossilisation of the transport sector and, therefore, the focus of the FVV Fuels Study IVb. Accordingly, the estimates of potential shares of the EU27+UK transport sector in primary material availability are based on potential future developments in global road transport.

Available scenarios of worldwide vehicle sales show a wide range of possible future developments from more or less stagnating vehicle markets in the next 15-20 years (e.g. Economic Transition Scenario in (Bloomberg 2021)) up to an increase of vehicle sales to about 150 million vehicles per year in 2030 (e.g. Stated Policies Scenario in (IEA 2022)) and 200 million vehicles in 2050/60 (e.g. Reference Technology Scenario in (IEA 2017)). In order not to overestimate the availability of raw materials for transport in

Europe, we assume the strongest growth in global sales figures for this study. Accordingly, today's EU27+UK share of global vehicle sales is around 20% but will drop to half in the future.

In the short to medium term, defossilisation efforts for the transport sector will probably be higher in Europe compared to other regions. The FVV expert groups in the study assumed that Europe will be a leading market for defossilised vehicle technologies. In consequence, the availability of key vehicle technologies for Europe's transport sector will be higher than the share of total vehicle sales. An available 45-50% share of global battery production is assumed by the FVV expert group for the years up to 2035, and 80% of global fuel cells production. Between 2035 and 2050, these shares will align with the shares of total vehicle sales and drop to 10%.

The availability of primary materials largely goes hand in hand with the technology availability. We use the following simplified assumptions, only focussing on material demand for key vehicle technologies[90]:

- Lithium and copper availability is correlated with total battery production. We assume a 50% share of total lithium availability in worldwide vehicle production for EU27+UK up to 2035.
- For cobalt and nickel availability, we make additional assumptions on different battery technologies. We assume that Europe's transport only uses NMC batteries in all vehicle segments. However, in the rest of the world, light commercial vehicles and heavy-duty vehicles are equipped with cobalt- and nickel-free batteries (e.g. LFP), which roughly reduces primary material demand for total transport outside Europe by about one third. On this assumption, EU27+UK share on total cobalt and nickel availability in the transport sector increases to 65%.
- Platinum availability is correlated with fuel cell capacities. Accordingly, in the years up to 2035 80% of platinum available for global transport can be used for defossilisation of the EU27+UK transport sector.

After 2035, with increasing worldwide defossilisation efforts, the EU27+UK share on total primary material availability in worldwide transport will decline until it is aligned with vehicle sales shares in 2050. An additional decision in the FVV expert group was to generally assume no potential copper and nickel bottlenecks after 2035 and no potential material bottlenecks at all after 2040.

Figure 58 summarises the simplified model assumptions for EU27+UK shares on total primary material availability in the global transport sector. We would like to emphasize once again that these are highly simplified assumptions, which can only provide a very rough orientation framework. Numerous factors have an influence on the global material requirements for defossilisation in transport and the shares available for Europe. Examples include the global development of vehicle sales, different defossilisation pathways pursued and varying intensities of defossilisation efforts in other regions of the world, as well as alternative vehicle technologies not included in the scenarios with different specific material requirements (e.g. lithium solid state, LFP in Europe). Accordingly, in reality the future demand for primary materials for transport outside Europe and the proportionate material availability for Europe may be significantly lower or higher than assumed for the modelling in the FVV Fuels Study IVb.

---

[90] Copper and nickel are important materials for all defossilisation pathways. In the case of electric mobility, most of the demand relates to vehicle production. In contrast, material requirements in the various fuel pathways are largely driven by fuel supply chain infrastructure demand. These complexities and interactions cannot be represented within the framework of the FVV Fuels Study IVb.

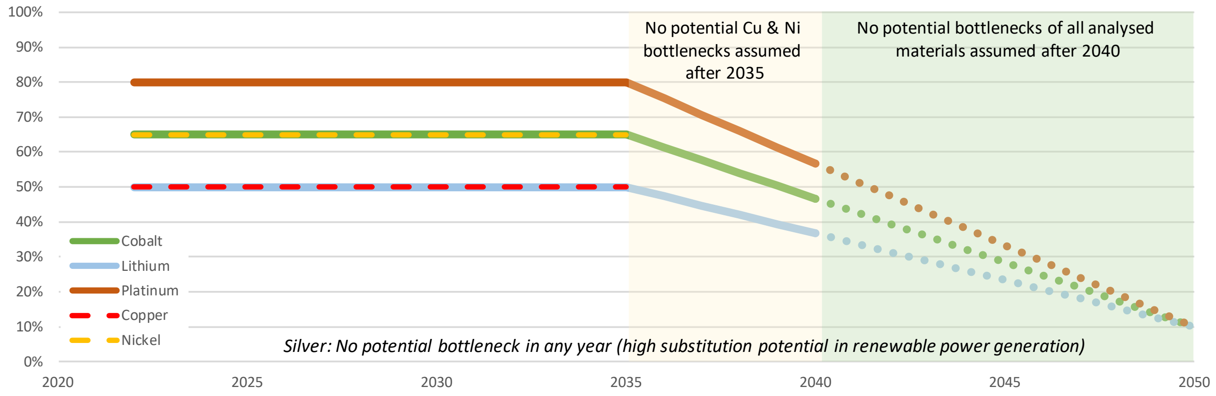


Figure 58: Simplified model assumptions for EU27+UK shares on total primary material availability for the global transport sector.

9.3.4 Resulting scenario modelling assumptions of annual primary material availability for the EU27+UK transport sector in Fuels Study IVb

Based on the assumptions on primary material supply (9.3.1), non-transport material demand (9.3.2) and EU27+UK share on remaining primary material availability for the global transport (Table 25), annual primary material availabilities for the transport sector in EU27+UK were calculated. Results are shown in the following Table 25.

	Lithium (kilotons per year)	**Cobalt** (kilotons per year)	**PGM (Pt+Pd)** (tons per year)	**Copper** (kilotons per year)	**Nickel** (kilotons per year)
2022	70	31	36	1,630	811
2023	90	34	43	1,979	912
2024	107	37	48	2,321	1,015
2025	130	39	53	2,660	1,123
2026	154	42	58	2,999	1,238
2027	179	45	62	3,339	1,358
2028	229	48	67	3,680	1,484
2029	329	51	71	4,023	1,616
2030	429	53	75	4,369	1,753
2031	528	56	77	4,318	1,854
2032	628	58	79	4,269	1,960
2033	665	60	81	4,223	2,070
2034	677	63	82	4,180	2,183
2035	701	65	84	4,139	2,299
2036	675	64	81	No relevant bottlenecks after 2035 assumed in the scenario modelling	
2037	648	63	77		
2038	619	61	73		
2039	589	59	69		
2040	558	57	65		
2041+	No relevant bottlenecks after 2035 assumed in the scenario modelling				

Table 25: Scenario modelling assumptions of annual primary material availability for the EU27+UK transport sector.

9.4 Annex – Technical subreport (ifeu)

9.4.1 Main technical specifications for Plug-in hybrid vehicles (PHEV)

All configurations and technical specifications of Plug-in hybrid vehicles (PHEV) were defined in the project-specific expert group by the participating FVV members.

Size	**Fuel type**	**Power (kW)**		**Empty weight (kg)**		**Net battery capacity (kWh)**		**Gross battery capacity (kWh)**[91]	
		ICE	**Electric**	**SQ**	**Bal**	**SQ**	**Bal**	**SQ**	**Bal**
small	PHEV gasoline	44	29	1,124	1,151	7.1	11.4	9.2	14.8
	PHEV diesel	44	29	1,175	1,202	7.1	11.5	9.3	14.9
medium	PHEV gasoline	92	61	1,429	1,460	7.9	12.7	10.3	16.5
	PHEV diesel	92	61	1,514	1,544	8.0	12.9	10.4	16.7
large	PHEV gasoline	135	90	1,770	1,826	8.8	17.8	11.4	23.1
	PHEV diesel	135	90	1,882	1,940	9.0	18.2	11.7	23.6
SUV	PHEV gasoline	127	85	1,740	1,810	10.7	21.8	14.0	28.4
	PHEV diesel	127	85	1,819	1,890	10.9	22.2	14.2	28.9
LCV	PHEV gasoline	96	64	2,063	2,129	16.6	27.0	21.6	35.1
	PHEV diesel	96	64	2,188	2,256	17.1	27.9	22.3	36.2

Table 26:Main technical specifications for PHEV light-duty vehicles.

Size	**Fuel type**	**Power (kW)**			**Empty weight (kg)**	**Gross battery capacity (kWh)**[92]
		ICE	**Electric**	**Fuel Cell**		
3.5-7.5 t Rigid	PHEV diesel	107	85	-	2,509	88
7.5-16t Regional	PHEV diesel	175	185	-	6,570	120
16-40t Long-haul	PHEV diesel	325	320	-	15,729	268
40-60t Long-haul XL	PHEV diesel	455	450	-	20,129	355
City bus	PHEV diesel	175	180	-	4,670	75
Coach	PHEV diesel	350	350	-	14,800	273

Table 27: Main technical specifications for PHEV diesel heavy-duty vehicles (balanced).

Heavy_duty (HD) vehicles with alternative drivetrains enter the market from 2025 onwards, thus no values for Status-quo vehicle technology are given here.

---

[91] Gross battery capacity is 30% higher than net capacity for light-duty PHEV vehicles.

[92] Gross battery capacity is 100% higher than net capacity for heavy-duty vehicles.

9.4.2 Fuel Demand Assumptions for PHEVs

	Vehicle size	**Share of electric driving**		**Fuel demand in kWh/km**	
		2020	**2030 - 2050**	**CD[93] mode**	**CS[94] mode**
PHEV Gasoline	small	50%	80%	0.0162	0.0382
	medium	40%	70%	0.0180	0.0384
	large	20%	50%	0.0200	0.0453
	SUV	20%	50%	0.0245	0.0460
	LCV	40%	60%	0.0378	0.0588
PHEV Diesel	small	50%	80%	0.0163	0.0322
	medium	40%	70%	0.0182	0.0356
	large	20%	50%	0.0205	0.0414
	SUV	20%	50%	0.0249	0.0431
	LCV	40%	60%	0.0390	0.0569

Table 28: Specific fuel consumption of light-duty vehicles (kWh/km, WLTP "All season") and share of electric driving. Source: FVV Working Group.

	Vehicle size	**Share of electric driving**	**Fuel demand in kWh/km**	
		2025 - 2050	**CD[95] mode**	**CS[96] mode**
PHEV Diesel	Rigid (N2)	35%	0.487	1.2
	Regional delivery (N3)	33%	0.786	1.8
	Long haul (N3)	27%	1.391	2.7
	Super long haul (N3)	29%	1.798	3.5
	Public transport	21%	1.042	2.4
	Coaches	27%	1.437	3.7

Table 29: Specific fuel consumption of heavy-duty vehicles (kWh/km, WLTP "All season") and share of electric driving. Source: FVV Working Group.

---

[93] CD = charge depletion mode (only electric motor is used).

[94] CS = charge sustaining mode (only ICE is used).

[95] CD = charge depletion mode (only electric motor is used).

[96] CS = charge sustaining mode (only ICE is used).

9.4.3 Specific GHG impacts: Build-up of fuel supply chain infrastructure

Category	**Element**	**Unit**	**2020**	**2025**	**2030**	**2040**	**2050**
Electricity generation	Offshore Windfarm	*MW*	748,146	658,242	706,091	481,562	105,117
	Onshore Windfarm	*MW*	847,220	740,421	675,229	449,160	114,613
	PV Standalone	*MW*	1,721,703	1,481,558	1,241,414	761,125	105,111
	PV Slanted Roof	*MW*	1,344,849	1,172,156	999,462	654,075	85,756
Transmission/Transport	Offshore - sea cable	*km*	362,006	319,006	276,006	190,005	71,994
	AC Overhead line	*km*	425,285	360,001	294,718	164,150	102,816
	DC cable	*km*	362,006	319,006	276,006	190,005	71,994
Distribution	HV line	*km*	123,060	114,615	106,170	89,279	37,560
	MV line	*km*	27,697	24,638	21,579	15,460	7,621
	LV line	*km*	18,326	16,043	13,760	9,194	3,878
	Distribution pipeline (CH_4)	*km*	1,009,710	919,553	829,396	649,081	149,425
Hydrogen	Electrolyser	*MW*	118,094	108,783	78,530	63,829	12,992
	Pipeline (from Electrolyser to Storage)	*km*	1,009,710	919,553	829,396	649,081	149,425
	H_2 Pressure Storage	*m^3*	*7.00*	*6.25*	*5.50*	*4.00*	*1.00*
	Hydrogen Cavern storage	*m^3*	*0.001*	*0.001*	*0.001*	*0.001*	*0.000*
	Gas Turbine (PtGtP)	*MW*	50,600	42,517	34,434	18,267	2,496
Synthesis / Direct Air Capture	Direct Air Capture	*t CO2*	607	561	515	424	89
	CO_2 Buffer storage	*t CO2*	*4.64*	*3.86*	*3.08*	*1.52*	*0.19*
	FT Synthesis	*MW*	3,444,344	2,863,297	1,289,968	633,132	58,205
	Methanisation	*MW*	24,489	20,620	9,669	5,203	2,051
	MeOH Synthesis	*MW*	3,862,907	3,211,250	1,572,322	771,715	64,868
	MtG Synthesis	*MW*	1,177,178	978,593	780,008	382,838	44,637
	Haber-Bosch Synthesis	*t(NH_3)/a*	15,745,381	13,257,877	10,770,374	5,795,366	2,285,037
Charging / Fueling	Wallboxes	*unit*	197	190	184	170	27
	Depot Charger (trucks)	*unit*	4,758	4,584	4,410	4,061	679
	Public Chargers (44kW)	*unit*	4,758	4,584	4,410	4,061	679
	Fast Chargers (150kW)	*unit*	4,758	4,584	4,410	4,061	679
	Overhead grid (trucks)	*km*	264,174	227,987	191,800	119,426	58,367
	H2 car pumps	*unit*	21,980	19,590	17,199	12,417	4,308
	H2 truck pumps	*unit*	146,535	130,597	114,659	82,783	28,721
	CH4 pumps	*unit*	40,663	36,241	31,818	22,972	7,970
Import	H2 Pipeline (international)	*km*	1,366,177	1,224,931	1,083,685	801,192	221,865
	CH4 Pipelines	*km*	1,366,177	1,224,931	1,083,685	801,192	221,865
Storage (except H2)	Methane Storage Cavern	*m3*	*0.001*	*0.001*	*0.001*	*0.001*	*0.000*
	Ammonia export storage	*unit*	3,891,000	3,475,216	3,059,433	2,227,865	557,829
	LNG Storage	*m3*	*7.00*	*6.25*	*5.50*	*4.00*	*1.00*
	Battery	*MWh*	3,420	3,159	2,769	2,267	585
Reforming	ammonia cracker	*MW*	22,022	18,542	15,063	8,105	3,196
	H2 Compressor	*kg/a*	*0.01*	*0.01*	*0.01*	*0.00*	*0.00*
	Liquefaction for LNG	*MW*	8,547	7,210	5,873	3,199	472

Table 30:Specific GHG emissions from build-up of fuel supply chain infrastructure (kg CO2eq / unit).

9.4.4 Specific GHG impacts: Vehicle production

Size	Fuel type	2020	2025	2026	2030	2040	2050
		(Status-quo)	*(Status-quo)*	*(Balanced)*	*(Balanced)*	*(Balanced)*	*(Balanced)*
small	Gasoline	5,032	4,953	4,829	4,337	3,105	1,899
	Diesel	5,368	4,784	5,162	4,667	3,429	2,140
	Methane	5,782	5,141	5,405	4,875	3,552	2,192
	H2 ICE	6,625	5,860	5,917	5,307	3,783	2,278
	FCEV	8,249	7,523	6,174	5,636	4,292	2,757
	BEV	9,236	8,346	7,251	6,601	4,976	3,168
	PHEV gasoline	6,413	5,719	5,743	5,177	3,761	2,328
	PHEV diesel	6,754	6,057	6,083	5,513	4,091	2,573
medium	Gasoline	6,343	5,604	6,440	5,793	4,177	2,570
	Diesel	6,711	5,966	6,800	6,149	4,520	2,823
	Methane	7,590	6,731	7,315	6,599	4,807	2,962
	H2 ICE	9,249	8,174	8,276	7,432	5,323	3,210
	FCEV	13,161	12,122	9,408	8,667	6,814	4,483
	BEV	14,756	13,419	11,284	10,338	7,974	5,163
	PHEV gasoline	8,329	7,435	7,439	6,712	4,892	3,036
	PHEV diesel	8,709	7,808	7,813	7,079	5,245	3,296
large	Gasoline	7,850	6,930	8,145	7,331	5,295	3,263
	Diesel	8,246	7,317	8,530	7,709	5,656	3,527
	Methane	9,271	8,211	9,151	8,252	6,005	3,698
	H2 ICE	11,234	9,923	10,323	9,275	6,655	4,022
	FCEV	17,419	16,113	12,188	11,276	8,995	5,990
	BEV	17,834	16,223	13,646	12,507	9,660	6,260
	PHEV gasoline	10,408	9,292	9,554	8,628	6,313	3,931
	PHEV diesel	10,826	9,700	9,971	9,036	6,698	4,211
SUV	Gasoline	7,182	6,346	7,930	7,136	5,153	3,174
	Diesel	8,057	7,151	8,310	7,510	5,510	3,436
	Methane	9,186	8,135	9,057	8,165	5,936	3,649
	H2 ICE	11,321	10,001	10,421	9,361	6,709	4,043
	FCEV	17,209	15,887	12,159	11,227	8,896	5,884
	BEV	20,462	18,652	15,109	13,874	10,785	7,021
	PHEV gasoline	10,357	9,252	9,631	8,707	6,395	3,993
	PHEV diesel	10,769	9,654	10,042	9,108	6,775	4,271
LCV	Gasoline	9,228	8,148	8,996	8,072	5,761	3,515
	Diesel	9,598	8,512	9,359	8,430	6,106	3,770
	Methane	11,202	9,915	10,512	9,446	6,780	4,118
	H2 ICE	14,204	12,549	12,529	11,226	7,967	4,746
	FCEV	18,278	16,663	13,661	12,471	9,494	6,061
	BEV	32,030	29,244	22,283	20,482	15,981	10,431
	PHEV gasoline	12,316	10,988	11,133	10,042	7,316	4,539
	PHEV diesel	12,747	11,408	11,563	10,463	7,713	4,828

Table 31:Specific GHG emissions of light-duty vehicle production (kg CO2eq/ vehicle).

Size	Fuel type	2020	2025	2026	2030	2040	2050
		(Status-quo)	*(Status-quo)*	*(Balanced)*	*(Balanced)*	*(Balanced)*	*(Balanced)*
3.5-7.5 t Rigid	Diesel	11,377	9,972	10,865	9,693	8,228	6,764
	Methane	12,658	11,100	11,962	10,667	9,049	7,430
	H2 ICE	14,810	13,009	13,823	12,333	10,472	8,610
	FCEV	19,192	17,269	14,707	13,284	11,505	9,726
	BEV	27,907	25,262	21,116	19,255	16,928	14,602
	PHEV diesel	-	-	15,970	14,453	12,557	10,660
7.5-16t Regional	Diesel	17,501	15,340	17,409	15,576	13,285	10,994
	Methane	20,097	17,625	19,631	17,549	14,947	12,344
	H2 ICE	24,520	21,549	23,455	20,973	17,871	14,769
	FCEV	31,548	28,407	24,335	22,007	19,097	16,187
	BEV	49,298	44,764	37,004	33,861	29,932	26,003
	PHEV diesel	-	-	24,358	22,056	19,177	16,299
16-40t Long-haul	Diesel	44,444	38,870	42,130	37,534	31,788	26,042
	Methane	45,717	39,913	43,128	38,347	32,371	26,396
	H2 ICE	63,039	55,317	58,148	51,832	43,938	36,044
	FCEV	79,658	71,529	61,452	55,437	47,919	40,400
	BEV	67,956	60,773	53,534	48,266	41,681	35,096
	PHEV diesel	-	-	57,233	51,615	44,593	37,571
40-60t Long-haul XL	Diesel	58,156	50,876	55,542	49,521	41,994	34,468
	Methane	60,092	52,462	57,058	50,757	42,881	35,005
	H2 ICE	80,806	70,909	75,052	66,937	56,793	46,650
	FCEV	102,845	92,355	79,427	71,670	61,975	52,280
	BEV	89,509	80,085	70,498	63,595	54,966	46,338
	PHEV diesel	-	-	75,574	68,198	58,979	49,759
City bus	Diesel	18,400	16,086	17,332	15,380	12,940	10,499
	Methane	20,653	18,069	19,261	17,093	14,382	11,671
	H2 ICE	24,450	21,437	22,543	20,032	16,892	13,753
	FCEV	41,135	37,345	20,128	18,632	16,763	14,893
	BEV	46,086	41,684	34,234	31,134	27,260	23,385
	PHEV diesel	-	-	24,340	21,913	18,881	15,848
Coach	Diesel	47,381	41,356	43,075	38,062	31,795	25,529
	Methane	48,784	42,505	44,174	38,958	32,438	25,918
	H2 ICE	67,672	59,302	60,553	53,664	45,053	36,442
	FCEV	78,571	70,242	29,284	26,980	24,100	21,220
	BEV	72,133	64,315	54,906	49,123	41,895	34,667
	PHEV diesel	-	-	45,584	40,401	33,923	27,444

HD vehicles with PHEV drivetrains enter the market from 2025 onwards, thus no values for Status-quo vehicle technology are given here.

Table 32: Specific GHG emissions of heavy-duty vehicle production (kg CO2eq / vehicle).

9.4.5 Specific material demand for fuel supply chain infrastructure and vehicles

Category	**Element**	**Unit**	**Lithium (g)**			**Cobalt (g)**		
			2020	**2030**	**2050**	**2020**	**2030**	**2050**
Electricity generation	Offshore Windfarm	*MW*	0.56	0.69	0.82	6.75	8.39	9.96
	Onshore Windfarm	*MW*	0.47	0.50	0.59	9.44	10.04	11.75
	PV Standalone	*MW*	0.37	0.37	0.37	17.65	17.65	17.65
	PV Slanted Roof	*MW*	0.36	0.36	0.36	27.12	27.12	27.12
Hydrogen	Electrolyser	*MW*	0.11	0.09	0.09	1,629.86	1,286.73	1,286.73
	Hydrogen Cavern storage	m^3	0.00	0.00	0.00	0.00	0.00	0.00
Synthesis / Direct Air Capture	Direct Air Capture	*t CO2*	0.00	0.00	0.00	0.05	0.05	0.05
	CO_2 Buffer storage	*t CO2*	0.00	0.00	0.00	0.00	0.00	0.00
	FT Synthesis	*MW*	2.17	1.23	0.97	315.10	178.10	140.42
	Methanisation	*MW*	0.00	0.00	0.00	6.60	3.81	3.81
	MeOH Synthesis	*MW*	2.43	1.49	1.08	353.39	217.08	156.50
	MtG Synthesis	*MW*	0.74	0.74	0.74	107.69	107.69	107.69
	Haber-Bosch Synthesis	*t(NH_3)/a*	1.97	1.97	1.97	4,246.63	4,246.63	4,246.63
Storage (except H2)	Methane Storage Cavern	m^3	0.00	0.00	0.00	0.00	0.00	0.00
Reforming	ammonia cracker	*MW*	0.00	0.00	0.00	5.94	5.94	5.94

Table 33: Specific material demand for fuel supply chain infrastructure: lithium and cobalt.

Category	**Element**	**Unit**	**PGM (g)**			**Silver (kg)**		
			2020	**2030**	**2050**	**2020**	**2030**	**2050**
Electricity generation	Offshore Windfarm	*MW*	2.62	3.26	3.87	2.49	3.10	3.68
	Onshore Windfarm	*MW*	4.38	4.66	5.45	4.87	5.19	6.07
	PV Standalone	*MW*	8.12	8.12	8.12	95.72	95.72	95.72
	PV Slanted Roof	*MW*	11.31	11.31	11.31	71.95	71.95	71.95
Hydrogen	Electrolyser	*MW*	158.33	125.00	125.00	0.21	0.17	0.17
	Hydrogen Cavern storage	m^3	0.000	0.000	0.000	0.000	0.000	0.000
Synthesis / Direct Air Capture	Direct Air Capture	*t CO2*	0.002	0.002	0.002	0.003	0.003	0.003
	CO_2 Buffer storage	*t CO2*	0.000	0.000	0.000	0.000	0.000	0.000
	FT Synthesis	*MW*	75.49	42.67	33.64	102.81	58.11	45.82
	Methanisation	*MW*	0.22	0.12	0.12	0.02	0.01	0.01
	MeOH Synthesis	*MW*	84.66	52.01	37.49	115.30	70.83	51.06
	MtG Synthesis	*MW*	25.80	25.80	25.80	35.14	35.14	35.14
	Haber-Bosch Synthesis	*t(NH_3)/a*	138.61	138.61	138.61	12.72	12.72	12.72
Storage (except H2)	Methane Storage Cavern	m^3	0.00	0.00	0.00	0.00	0.00	0.00
Reforming	ammonia cracker	*MW*	0.19	0.19	0.19	0.02	0.02	0.02

Table 34: Specific material demand for fuel supply chain infrastructure: platin group metals (PGM) and silver.

Category	Element	Unit	Copper (kg)			Nickel (kg)		
			2020	2030	2050	2020	2030	2050
Electricity generation	Offshore Windfarm	*MW*	3,233	4,022	4,771	2,575	3,203	3,800
	Onshore Windfarm	*MW*	4,314	4,590	5,370	2,569	2,733	3,197
	PV Standalone	*MW*	6,867	6,867	6,867	1,239	1,239	1,239
	PV Slanted Roof	*MW*	10,376	10,376	10,376	675	675	675
Transmission / Transport	Offshore - sea cable	*km*	28,000	28,000	28,000	-	-	-
	AC Overhead line	*km*	1,000	1,000	1,000	-	-	-
	DC cable	*km*	1,000	1,000	1,000	-	-	-
Distribution	HV line	*km*	780	780	780	-	-	-
	MV line	*km*	1,690	1,690	1,690	-	-	-
	LV line	*km*	1,380	1,380	1,380	-	-	-
	Transformer HV-MV	*unit*	7,150	7,150	7,150	-	-	-
	Transformer MV-LV	*unit*	600	600	600	-	-	-
Hydrogen	Electrolyser	*MW*	4,049	3,197	3,197	4,440	3,505	3,505
	Hydrogen Cavern storage	*m³*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Synthesis / Direct Air Capture	Direct Air Capture	*t CO2*	*1.6*	*1.6*	*1.6*	*7.5*	*7.5*	*7.5*
	CO_2 Buffer storage	*t CO2*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
	FT Synthesis	*MW*	62,353	35,243	27,788	18,003	10,176	8,023
	Methanisation	*MW*	196	113	113	52	30	30
	MeOH Synthesis	*MW*	69,930	42,957	30,969	20,191	12,403	8,942
	MtG Synthesis	*MW*	21,310	21,310	21,310	6,153	6,153	6,153
	Haber-Bosch Synthesis	$t(NH_3)/a$	126,112	126,112	126,112	33,274	33,274	33,274
Charging / Fueling	Wallboxes	*unit*	*0.3*	*0.3*	*0.3*	-	-	-
	Depot Charger (trucks)	*unit*	*7.1*	*7.1*	*7.1*	-	-	-
	Public Chargers (44kW)	*unit*	*7.1*	*7.1*	*7.1*	-	-	-
	Fast Chargers (150kW)	*unit*	*7.1*	*7.1*	*7.1*	-	-	-
	Overhead grid (trucks)	*km*	7,666	7,666	7,666	-	-	-
	H2 car pumps	*unit*	*14.5*	*14.5*	*14.5*	-	-	-
	H2 truck pumps	*unit*	*96.6*	*96.6*	*96.6*	-	-	-
Storage (except H2)	Methane Storage Cavern	*m³*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Reforming	ammonia cracker	*MW*	*176.4*	*176.4*	*176.4*	*46.5*	*46.5*	*46.5*

Table 35:Specific material demand for fuel supply chain infrastructure: copper and nickel.

Size	**Fuel type**	**Lithium**		**Cobalt**		**Nickel**		**Copper**		**PGM**	
		SQ	**Bal**	**SQ**	**Bal**	**SQ**	**Bal**	**SQ**	**Bal**	**SQ**	**Bal**
small	Gasoline	0.00	0.11	0.00	0.09	1.38	2.20	12.81	17.33	0.00	0.00
	Diesel	0.00	0.11	0.00	0.09	1.38	2.20	13.08	17.60	0.01	0.01
	Methane	0.00	0.11	0.00	0.09	1.38	2.20	12.81	17.33	0.01	0.01
	H2 ICE	0.00	0.11	0.00	0.09	4.29	4.50	12.81	17.33	0.00	0.00
	FCEV	0.15	0.11	0.23	0.09	4.06	4.05	16.92	16.61	0.02	0.01
	BEV	5.36	3.97	8.51	3.16	27.01	26.71	61.66	49.77	0.00	0.00
	PHEV gasoline	1.02	1.23	1.62	0.98	6.35	9.29	25.15	26.95	0.00	0.00
	PHEV diesel	1.65	1.24	2.62	0.98	9.35	9.35	30.84	27.29	0.01	0.01
medium	Gasoline	0.00	0.16	0.00	0.13	1.62	2.89	17.49	26.35	0.00	0.00
	Diesel	0.00	0.16	0.00	0.13	1.62	2.89	18.06	26.91	0.01	0.01
	Methane	0.00	0.16	0.00	0.13	1.62	2.89	17.49	26.35	0.01	0.01
	H2 ICE	0.00	0.16	0.00	0.13	6.92	6.77	17.49	26.35	0.00	0.00
	FCEV	0.21	0.16	0.33	0.13	6.48	6.46	25.28	24.83	0.04	0.02
	BEV	10.47	7.66	16.63	6.08	51.71	50.48	113.33	89.20	0.00	0.00
	PHEV gasoline	1.14	1.37	1.81	1.09	7.28	10.56	34.75	36.76	0.00	0.00
	PHEV diesel	1.85	1.39	2.94	1.10	10.68	10.68	41.45	37.48	0.01	0.01
large	Gasoline	0.00	0.17	0.00	0.13	1.95	3.41	22.49	34.95	0.00	0.00
	Diesel	0.00	0.17	0.00	0.13	1.95	3.41	23.32	35.78	0.01	0.01
	Methane	0.00	0.17	0.00	0.13	1.95	3.41	22.49	34.95	0.01	0.01
	H2 ICE	0.00	0.17	0.00	0.13	8.12	8.02	22.49	34.95	0.00	0.00
	FCEV	0.23	0.17	0.36	0.13	7.76	7.73	33.21	32.73	0.06	0.02
	BEV	12.18	8.80	19.36	6.99	60.37	58.22	135.86	106.80	0.00	0.00
	PHEV gasoline	1.26	1.92	2.01	1.52	8.33	14.47	44.34	49.95	0.00	0.00
	PHEV diesel	2.62	1.96	4.16	1.56	14.75	14.75	56.78	51.16	0.01	0.01
SUV	Gasoline	0.00	0.19	0.00	0.15	1.92	3.51	16.59	33.81	0.00	0.00
	Diesel	0.00	0.19	0.00	0.15	1.92	3.51	22.57	34.59	0.01	0.01
	Methane	0.00	0.19	0.00	0.15	1.92	3.51	21.79	33.81	0.01	0.01
	H2 ICE	0.00	0.19	0.00	0.15	8.58	8.79	21.79	33.81	0.00	0.00
	FCEV	0.26	0.19	0.41	0.15	8.56	8.51	32.27	31.72	0.05	0.02
	BEV	15.88	11.13	25.22	8.84	77.84	72.88	166.34	125.55	0.00	0.00
	PHEV gasoline	1.54	2.35	2.45	1.87	9.62	17.18	45.41	52.35	0.00	0.00
	PHEV diesel	3.19	2.40	5.07	1.90	17.45	17.45	60.34	53.49	0.01	0.01
LCV	Gasoline	0.00	0.22	0.00	0.17	3.83	5.49	33.92	43.62	0.00	0.00
	Diesel	0.00	0.22	0.00	0.17	3.83	5.49	34.51	44.21	0.01	0.01
	Methane	0.00	0.22	0.00	0.17	3.83	5.49	33.92	43.62	0.01	0.01
	H2 ICE	0.00	0.22	0.00	0.17	12.91	12.97	33.92	43.62	0.00	0.00
	FCEV	0.29	0.22	0.46	0.17	12.65	12.52	42.66	42.04	0.04	0.02
	BEV	28.94	19.43	45.98	15.44	141.63	127.24	288.60	206.97	0.00	0.00
	PHEV gasoline	2.39	2.91	3.79	2.31	15.44	22.54	62.23	66.75	0.00	0.00
	PHEV diesel	4.01	3.01	6.37	2.39	23.15	23.15	76.76	68.15	0.01	0.01

Table 36:Specific material demand for light-duty vehicle production (kg / vehicle).

Size	Fuel type	Lithium		Cobalt		Nickel		Copper		PGM	
		SQ	Bal	SQ	Bal	SQ	Bal	SQ	Bal	SQ	Bal
3.5-7.5 t Rigid	Diesel	0.00	0.17	0.00	0.14	0.87	2.41	11.23	21.83	0.00	0.00
	Methane	0.00	0.17	0.00	0.14	0.87	2.41	11.23	21.83	0.00	0.00
	H2 ICE	0.00	0.17	0.00	0.14	0.87	2.41	11.23	21.83	0.00	0.00
	FCEV	3.65	2.74	5.80	2.18	18.30	18.30	51.71	43.87	0.02	0.01
	BEV	21.05	15.79	33.44	12.54	100.53	100.53	201.05	155.88	0.00	0.00
	PHEV diesel	-	7.31	-	5.80	-	47.57	-	83.07	-	0.00
7.5-16t Regional	Diesel	0.00	0.25	0.00	0.20	1.47	4.05	22.02	44.04	0.00	0.00
	Methane	0.00	0.25	0.00	0.20	1.47	4.05	22.02	44.04	0.00	0.00
	H2 ICE	0.00	0.25	0.00	0.20	1.47	4.05	22.02	44.04	0.00	0.00
	FCEV	4.98	3.74	7.91	2.97	25.52	25.52	84.64	73.95	0.04	0.01
	BEV	39.83	29.87	63.27	23.73	190.35	190.35	383.75	298.28	0.00	0.00
	PHEV diesel	-	9.96	-	7.91	-	65.52	-	127.41	-	0.00
16-40t Long-haul	Diesel	0.00	1.14	0.00	0.91	3.14	12.09	71.26	115.45	0.01	0.01
	Methane	0.00	1.14	0.00	0.91	25.86	34.81	71.26	115.45	0.01	0.01
	H2 ICE	0.00	1.14	0.00	0.91	3.14	12.09	71.26	115.45	0.01	0.01
	FCEV	13.28	9.96	21.10	7.91	67.06	67.06	219.64	191.14	0.09	0.03
	BEV	29.67	22.25	47.14	17.68	143.53	143.53	360.32	296.64	0.00	0.00
	PHEV diesel	-	22.25	-	17.67	-	145.68	-	296.64	-	0.01
40-60t Long-haul XL	Diesel	0.00	1.47	0.00	1.17	4.34	16.10	95.69	156.70	0.01	0.01
	Methane	0.00	1.47	0.00	1.17	38.89	50.65	95.69	156.70	0.01	0.01
	H2 ICE	0.00	1.47	0.00	1.17	4.34	16.10	95.69	156.70	0.01	0.01
	FCEV	17.71	13.28	28.13	10.55	89.44	89.44	296.02	258.02	0.11	0.04
	BEV	39.31	29.48	62.45	23.42	190.31	190.31	481.43	397.08	0.00	0.00
	PHEV diesel	-	29.47	-	23.41	-	193.29	-	397.03	-	0.01
City bus	Diesel	0.00	0.17	0.00	0.13	24.70	26.73	46.46	67.25	0.00	0.00
	Methane	0.00	0.17	0.00	0.13	24.70	26.73	46.46	67.25	0.00	0.00
	H2 ICE	0.00	0.17	0.00	0.13	24.70	26.73	46.46	67.25	0.00	0.00
	FCEV	8.85	6.64	14.07	5.28	67.72	67.72	141.80	122.80	0.08	0.03
	BEV	34.41	25.81	54.66	20.50	187.82	187.82	361.13	287.30	0.00	0.00
	PHEV diesel	-	9.96	-	7.91	-	88.72	-	151.32	-	0.00
Coach	Diesel	0.00	1.47	0.00	1.17	77.78	89.01	148.98	199.27	0.01	0.01
	Methane	0.00	1.47	0.00	1.17	102.82	114.05	148.98	199.27	0.01	0.01
	H2 ICE	0.00	1.47	0.00	1.17	77.78	89.01	148.98	199.27	0.01	0.01
	FCEV	11.07	8.30	17.58	6.59	131.06	131.06	281.58	257.83	0.08	0.03
	BEV	30.23	22.67	48.02	18.01	220.80	220.80	446.02	381.16	0.00	0.00
	PHEV diesel	-	4.98	-	3.96	-	111.20	-	229.37	-	0.01

HD vehicles with PHEV drivetrains enter the market from 2025 onwards, thus no values for Status-quo vehicle technology are given here.

Table 37:Specific material demand for heavy-duty vehicle production (kg / vehicle).

10 Appendix III

10.1 Bibliography

ACEA (2022a), “Vehicles in use Europe 2022”, https://www.acea.auto/files/ACEA-report-vehicles-in-use-europe-2022.pdf (last accessed: 08.09.2022).

ACEA (2022b), “Fuel types of new passenger cars in the EU”, https://www.acea.auto/figure/fuel-types-of-new-passenger-cars-in-eu/ (last accessed: 08.09.2022).

Ahmed et al. (2018), “Cost of automotive lithium-ion batteries operating at high upper cutoff voltages”, Journal of Power Sources, 403, 56-65.

Bloomberg (2021): At Least Two-Thirds of Global Car Sales Will Be Electric by 2040. https://www.bloomberg.com/news/articles/2021-08-09/at-least-two-thirds-of-global-car-sales-will-be-electric-by-2040.

California Air Resources Board (2021), “2026 California Regulations for Battery Electric Vehicles”, https://www.orovel.net/insights/california-electric-vehicle-2026 (last accessed: 08.09.2022).

Council of the EU (2022),”Fit for 55 package: Council reaches general approaches relating to emissions reductions and their social impacts”, https://www.consilium.europa.eu/en/press/press-releases/2022/06/29/fit-for-55-council-reaches-general-approaches-relating-to-emissions-reductions-and-removals-and-their-social-impacts/ (last accessed: 08.09.2022).

DERA (2021): Rohstoffe für Zukunftstechnologien 2021. Auftragsstudie. https://www.deutsche-rohstoffagen-tur.de/DE/Gemeinsames/Produkte/Downloads/DERA_Rohstoffinformationen/rohstoffinformationen-50.pdf?__blob=publicationFile&v=3 (last access:27.07.2022).

DIN EN 228 (2017): DIN EN 228:2017-08, Kraftstoffe_- Unverbleite Ottokraftstoffe_- Anforderungen und Prüfverfahren; Deutsche Fassung EN_228:2012+A1:2017. Beuth Verlag GmbH. https://www.beuth.de/de/-/-/273470473 (04.07.2022).

Elshkaki, A.; Reck, B. K.; Graedel, T. E. (2017): Anthropogenic nickel supply, demand, and associated energy and water use. In: Resources, Conservation and Recycling. No.125, S. 300–307.

European Commission (2022), “A European Green Deal”, https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en#timeline (last accessed: 08.09.2022).

FVV (2020), “Primemovers – Bilanz gezogen: FVV-Metastudie zur Lebenszyklusanalyse alternativer Antriebe“, https://www.primemovers.de/de/denken/bilanz-gezogen (last accessed: 08.09.2022).

FVV (2021), “FVV Future Fuels Study IV: Transformation of Mobility to the GHG-neutral Post-fossil Age”, https://www.fvv-net.de/fileadmin/user_upload/medien/download/FVV__Future_Fuels__StudyIV_The_Transformation_of_Mobility__H1269_2021-10__EN.pdf (last accessed: 08.09.2022).

IEA (2021), “Net Zero by 2050“ (page 109), https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf (last accessed: 08.09.2022).

IEA (2022): Global Electric Vehicle Outlook 2022. International Energy Agency. https://iea.blob.core.windows.net/assets/ad8fb04c-4f75-42fc-973a-6e54c8a4449a/GlobalElectricVehicleOutlook2022.pdf.

IRENA (2021): Critical Materials for the Energy transition. Technical Paper. https://irena.org/-/media/Files/IRENA/Agency/Technical-Papers/IRENA_Critical_Materials_2021.pdf.

IPCC (2018), “Global Warming of 1.5 °C. An IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission path-ways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.”, Intergovernmental Panel on Climate Change. http://www.ipcc.ch/report/sr15/(last accessed: 08.09.2022).

Lo Piano, S.; van der Sluijs, J. P.; Saltelli, A. (2019): Silver as a Constraint for a Large-Scale Development of Solar Photovoltaics? Scenario-Making to the Year 2050 Supported by Expert Engagement and Global Sensitivity Analysis. In: Frontiers in Energy Research, 7. 10.3389/fenrg.2019.00056.

Lühe, C. (2013): Modulare Kostenschätzung als Unterstützung der Anlagenplanung für die Angebots- und frühe Basic Engineering Phase. TU Berlin, Berlin.

Schemme, S. (2020): Techno-ökonomische Bewertung von Verfahren zur Herstellung von Kraftstoffen aus H2 und CO2. Forschungszentrum Jülich.

UNFCC (2021), "The Paris Agreement", https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement (last accessed: 08.09.2022).

Wernet, G.; Bauer, C.; Steubing, B.; Reinhard, J.; Moreno-Ruiz, E.; Weidema, B. (2016): The ecoinvent database version 3 (part I): overview and methodology. In: The International Journal of Life Cycle Assessment. Vol. 21, No.9, S. 1218–1230.

10.2 List of abbrevations

AC	Alternating current
ACEA	European Automobile Manufacturers Association
BEV	Battery electric vehicle
CAPEX	Capital expenditure
CNG	Compressed natural gas
CO_2	Carbon dioxide
Dom.	Domestic
EC	European Commission
EEA	European Environmental Agency
EU	European Union
EUR	Euro
FCEV	Fuel cell electric vehicle
FS	Fuels Study
FT	Fischer-Tropsch
GHG	Greenhouse gas
GW	Gigawatt
GW/a	Gigawatt per year
GWh	Gigawatt hour
H_2	Hydrogen
HD	Heavy duty
HVDC	High voltage direct current
ICE	Internal combustion engine
ICEV	Internal combustion engine vehicle
Int.	International
IPCC	Intergovernmental Panel on Climate Change
kW	Kilowatt
kWh	Kilowatt hour
LCOE	Levelized cost of electricity
LCV	Light commercial vehicle
LNG	Liquified natural gas
MENA	Middle East North Africa

MtG	Methanol to gasoline
MW	Megawatt
MWh	Megawatt hour
OEM	Original equipment manufacturer
OPEX	Operational expenditure
PGM	Platinum group of metals
PHEV	Plug-in hybrid electric vehicles
PKW	Personenkraftwagen
PV	Photovoltaic
RWGS	Reverse water gas shift
SUV	Sports utility vehicle
THG	Treibhausgas
TW	Terawatt
TWh	Terawatt hour
UK	United Kingdom

10.3 List of figures

10.4 List of tables

Science for a
moving society

FVV e.V.
Lyoner Straße 18
60528 Frankfurt am Main
Deutschland

T +49 69 6603 1345
F +49 69 6603 2345

info@fvv-net.de
www.fvv-net.de

Member