“Tracking the European transition from fuel dependence to sustainable mobility”

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TRACKING THE EUROPEAN TRANSITION FROM FUEL DEPENDENCE TO SUSTAINABLE MOBILITY

Abstract

This study aims to track the EU's shift from fuel dependence to sustainable mobility, assessing current impacts and future efforts for low- and zero-emission vehicles and renewable fuels to reduce crude hydrocarbon imports and greenhouse gas emissions. The paper uses methods of composite indices of fuel dependence and greenhouse gas emission intensity, decomposition analysis for crude hydrocarbon imports and greenhouse gas emissions, and the causal relationship between transport traffic and sustainable mobility objectives. Empirical results indicate that deploying sustainable mobility in the EU saved 10 million tons of crude oil imports and prevented 49 million tCO2eq emissions. Advancements in sustainable mobility were more effective in curbing greenhouse gas emissions (4.7%) than in reducing crude hydrocarbon imports (1.9%) from 2013 to 2022. Projections for the EU's 2025 objectives indicate significant efforts needed to avoid an extra 61 million tCO2eq, including adding over 13 million zero-emission transport units and producing about 2 million tons of sustainable fuel. Both targets are currently at risk. The study highlights the latent potential in other hydrocarbons that can be transformed from non-fossil energy sources. Therefore, monitoring the impact of sustainable mobility is a crucial task in reducing fuel dependence and greenhouse gas emissions from transport. It enables informed decisions and strategy adaptations and ensures that environmental and economic targets are met both timely and effectively.

Keywords fuel dependence, greenhouse gas emissions, sustainable mobility, crude hydrocarbons, motor fuel, biofuels, zero-emission fleet

JEL Classification Q51, L71, F64, K32, B17

INTRODUCTION

Since the adoption of the UNFCCC in 1992, the world has been fighting for more than 30 years to limit the concentration of greenhouse gases (GHG) in the atmosphere at the level of 450 ppm CO2-eq (UN, 1992). In 2015, the Paris Agreement outlined a new ambitious goal to keep global warming at the level of 2°C and to make efforts to reduce it even more, to 1.5°C (United Nations, 2015). Considerable progress has already been made in decoupling GHG emissions from energy use in the power sector, buildings, and some industries, but transport remains a significant contributor to climate change with steady increases in GHG emissions from fuel combustion (European Parliament, 2019). The IEA recognized that it would be difficult to reach the target level even with reductions in GHG emissions in other sectors if transport did not reduce them significantly below current levels by 2050 (IEA, 2009). Thus, there is strong global awareness that the transition to sustainable motor energy will reduce GHG emissions and eradicate fuel dependency. The share of sustainable types of motor energy must reach 93% in road transport, 85% in shipping, and 70% in aviation by 2050 (IEA, 2021).

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The EU is a pioneer and a key driver in the implementation of climate policy in the world. Its concept of sustainable mobility has evolved from the first Community Strategy for 'sustainable mobility' (EC, 1992) to the 2020 Sustainable and Smart Mobility Strategy (EC, 2020). Currently, there are specific, ambitious goals and directions for its implementation, which should overcome fuel dependence and contribute to the decarbonization of transport. Among the main points, the following are outlined:

(i) increasing the production and deployment of sustainable alternative transport fuels;

(ii) limiting the number of drastically polluting transport;

(iii) reducing the current dependence on fossil fuels through low- and zero-emission vehicles and renewable and low-carbon fuels;

(iv) shifting toward more sustainable transport modes (EC, 2019a; EC, 2020).

Therefore, tracking fuel dependence and GHG emissions from transport is a research assignment requiring effective methods for monitoring the EU's achievements in implementing sustainable mobility. The complexity of this issue is exacerbated by the disaggregation of data by origin: fuel, environment, and transport. An effective method for analyzing the impacts of sustainable mobility modes (low- or zero-emission vehicles, biofuels, and sustainable fuels) will contribute to the adjustment of strategic and commitment objectives, accelerating the transition away from fuel dependence.

1. LITERATURE REVIEW

Historically, the problem of fuel dependence in the EU dates back to the 1970s, when the global oil crisis forced it to seek independence from the OPEC monopoly (LaBelle, 2023). For several decades, it was believed that the transition to a market economy and democratic values could weaken the EU's fuel dependence on export-oriented countries (Losoncz, 2006). However, the global oil market is unstable due to political and geopolitical risks and unexpected events ("black swans"). This causes oil price volatility, forcing refineries and the EU fuel market to constantly adapt (Gupta, 2008). The issue of fuel interdependence between EU member states and oil-exporting countries escalated asymmetrically for the EU (Khaustova et al., 2024), leading to persistent concern and the erosion of energy relations in competitive and geopolitical terms (Proedrou, 2023). Fuel dependence has become a threat to the EU's economic development and diplomatic freedom (Acevedo & Lorca-Susino, 2021). Diversification of oil supply sources to increase sustainability was the main direction of overcoming fuel dependence (Tichý & Dubský, 2024). Only after the COVID-19 crisis did one understand the possibility of mobilizing various energy resources and establishing effective coordination for overcoming dependence on fossil fuels (Cappelli & Carnazza, 2023). Today, it is argued that oil-importing countries should focus on innovation in promoting environmentally sustainable mobility (Asghar et al., 2024), and renewable energy sources are seen as a way to reduce fuel dependence and protect against oil price shocks (Deniz, 2019).

Mobility has also undergone a significant scientific transformation: from a transport fossil fuel paradigm to a sustainable mobility paradigm (Dyrhauge, 2022). There are four stages of the formation of the paradigm of sustainable mobility (Holden et al., 2019). The first stage (1992–1993) concerned the limitation of transportation volumes; the second stage (1993–2000) referred to the reduction of traffic intensity; the third stage (2000–2010) brought about problems of traffic jams, fairness, and competitiveness; and in the fourth stage (2010–2018 and up to now) the issue of decarbonization evolved. Initially, it was believed that the problems of sustainable transport lay in the cohesion/exclusion dimension of environmental damage to transport and economic development (Vickerman, 1998). The decoupling of economic activity and transport that must ensure increased efficiency in the economy, limited use of non-renewable resources, and a fall in pollution

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and waste (Lasserre, 2001) were meant to solve those problems. Gradually, the above issues were aggravated by traffic congestion, air pollution, and degradation of the environment (Kehagia, 2017). Sustainable mobility became an objective of transport system planning, which focused on the effective use of technology, regulation and pricing, land-use development, and targeted personal information (Banister, 2008). This paradigm continues to evolve due to technological development, trends in integrated mobility services, and shared mobility (Gallo & Marinelli, 2020). Humanity is on the threshold of the seventh transport revolution, which is driven by the decarbonization of traction energy, autonomous guidance of vehicles, and smart mobility services (Cascetta & Henke, 2023). Among the main forms of sustainable mobility, academia considers low and zero-emission fleets (Hensher & Wei, 2024), direct and blending biofuels (Khaustova et al., 2023; Malik et al., 2024), fuel cells (Visvanathan et al., 2023) and non-fossil synthetic fuels (Richter et al., 2024). The greatest breakthroughs in sustainable mobility are seen in light road transport (Febransyah, 2024) and railways (Ahsan et al., 2023), while heavy road transport (Chatti, 2020), shipping (Koilo, 2024) and aviation (Wang et al., 2024) still face significant barriers. A complete transition to sustainable mobility means resolving contradictions between environmental awareness and a pro-environmental attitude (de las Heras-Rosas & Herrera, 2019), environmental mobility and mobility justice (Sheller, 2016), and a departure from an infrastructure-centered approach in favor of a people-centered approach (Johansson, 2019). Transition pathways presuppose changes in governance, financial resources, and local politics and increased support from regional, national, and supranational institutions (Smeds & Cavoli, 2021; Pallonetto, 2023).

Scientific concepts have shifted from fossil fuels toward sustainable mobility, demanding a pivot toward low-carbon transport modes and renewable energy sources. Diversifying motor energy emphasizes innovation and environmental sustainability. Tracking this shift means monitoring the impacts of low- and zero-emission vehicles and renewable fuels by evaluating strategies and commitments and adjusting them as needed. This continuous cycle of assessment and adjustment propels the green transition forward.

The transition from fuel dependence to sustainable mobility addresses a triple problem: energy independence, universal mobility, and environmental concerns. The aim of this study is to monitor the EU's progress in transitioning from fuel dependence to sustainable mobility by assessing both the current impacts and future efforts required of low- and zero-emission vehicles, as well as renewable and low-carbon fuels, on reducing crude hydrocarbon imports and GHG emissions. The hypotheses in this study are as follows:

H1: Europe has made partial strides in reducing fuel dependence and greenhouse gas emission intensity.

H2: The main efforts in deploying EU sustainable mobility are focused on road transport.

H3: The EU's progress in reducing fuel dependence and GHG emissions is lacking, and achieving the commitment objectives requires sustainable innovations across all transport modes.

2. METHODS

The study of the European transition from fuel dependence to sustainable mobility was conducted in three stages. In the first stage, the dynamics of fuel dependence and GHG emission intensity from fuel combustion were compared. In the second stage, a decomposition analysis of quantitative, qualitative, and structural factors' impacts on crude hydrocarbon imports and GHG emissions was carried out, with an emphasis on such types of sustainable mobility as electric transport, biofuels, and other alternatives. In the last stage, the expected reduction of GHG emissions in the EU due to the achievement of commitment objectives for the deployment of sustainable mobility by 2025 was estimated.

The assessment of fuel dependence and intensity of GHG emissions was carried out according to the general and local indicators listed in Table 1.

The decomposition analysis of the impact factors on crude hydrocarbon imports and GHG emission intensity was carried out according to the

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Table 1. The indicators of fuel dependence and GHG emission intensity from fuel combustion

Dimension	Fuel dependence	GHG emission intensity
Oil refinery	$CHD_j = \frac{NI_{CHj}}{RI_{CHj}}$	$REI = \frac{GHG_R}{\sum_{i=1}^{M} RO_{MFi}}$
Fuel consumption	$MFD_i = \frac{NI_{MFi}}{GIC_{MFi}}$	$TEI_{Tk} = \frac{GHG_{Tk}}{FC_{Tk}}$
Overall	$FD = \frac{\sum_{j=1}^{N} NI_{CHj} + \mathrm{Re}fInt \cdot \sum_{i=1}^{M} NI_{MFi}}{\sum_{j=1}^{N} RI_{CHj}}$	$EI = \frac{GHG_R + \sum_{k=1}^{L} GHG_{Tk}}{\sum_{k=1}^{L} FC_{Tk}}$

Note: CHD, MFD, FD – the dependence on crude hydrocarbons and motor fuels, as well as overall fuel dependence; *REI*, *TEI*, *EI* – GHG emission intensity from fuel combustion in oil refinery and transport, as well as the overall GHG emission intensity; NI_{CH}, NI_{MF} – net import of crude hydrocarbons and motor fuels; RI_{CH} – refinery intake of crude hydrocarbons; RO_{MF} – refinery output of motor fuels; GIC_{MF} – gross inland consumption of motor fuels; FC_T – fuel consumption by transport modes; *REfInt* – refinery intensity, which is determined by the ratio between the sum of refinery intake of crude hydrocarbons and the sum of refinery output of motor fuels; GHG_T, GHG_R – GHG emissions from fuel combustion in transport and oil refinery; $i \in [1; N]$ – the set of crude hydrocarbons, $j \in [1; M]$ – the set of motor fuels; $k \in [1; L]$ – he set of the transport modes.

LMDI-I method (Ang, 2015). Determining the impacts on the import of crude hydrocarbons required the development of a hierarchy of decomposition equations:

$$NI_{CH} = \sum_{j=1}^{N} RI_{CH} \cdot \frac{RI_{CHj}}{RI_{CH}} \cdot \frac{NI_{CHj}}{RI_{CHj}}, \quad (1)$$

$$NI_{CH} = \sum_{j=1}^{N} RO_{MF} \cdot \frac{RI_{CH}}{RO_{MF}} \cdot \frac{RI_{CHj}}{RI_{CH}} \cdot \frac{NI_{CHj}}{RI_{CHj}}, \quad (2)$$

$$NI_{CH} = \frac{\sum_{i=1}^{M}\sum_{j=1}^{N} GIC_{MF} \cdot \frac{GIC_{MFi}}{GIC_{MF}} \cdot \frac{RO_{MFi}}{GIC_{MFi}}}{\frac{RO_{MFi}}{RO_{MF}} \cdot \frac{RI_{CH}}{RO_{MF}} \cdot \frac{RI_{CHj}}{RI_{CH}} \cdot \frac{NI_{CHj}}{RI_{CHj}}}, \quad (3)$$

$$NI_{CH} = \frac{\sum_{k=1}^{L}\sum_{i=1}^{M}\sum_{j=1}^{N} TR_k \cdot \frac{GIC_{MFk}}{TR_k} \cdot \frac{GIC_{MFi}}{GIC_{MFk}} \cdot \frac{RO_{MFi}}{GIC_{MFi}}}{\frac{RO_{MFi}}{RO_{MF}} \cdot \frac{RI_{CH}}{RO_{MF}} \cdot \frac{RI_{CHj}}{RI_{CH}} \cdot \frac{NI_{CHj}}{RI_{CHj}}}, \quad (4)$$

where TR_k – traffic by transport modes. Other abbreviations are mentioned in Table 1.

The assessment of impacts on GHG emissions by means of transport was carried out according to the following decomposition equation:

$$GHG_T = \sum_{k=1}^{L} TR_k \cdot \frac{FC_{Tk}}{TR_k} \cdot \frac{GHG_{Tk}}{FC_{Tk}}. \quad (5)$$

To assess the impact of sustainable mobility, the decomposition analysis was conducted in two ways: including sustainable forms of mobility (consumption of blending biofuels and alternatives, traffic with zero-emission transport) and excluding them. The difference between them determined the impact of the forms of sustainable mobility.

Estimates of the expected reductions in GHG emissions due to achieving the EU's sustainable mobility objectives were derived using a causal loop diagram (via the Vensim PLE software package developed by Ventana Systems, Inc). This diagram assists in extrapolating traffic trends across various transport modes and interpolating the EU's objectives by illustrating causal relationships. Figure 1 depicts these relationships: on the left for road transport, and on the right for rail transport, aviation, and shipping.

The basis of this study was the data from the Eurostat database for 2013–2022; the period of 2013–2019 is defined as the pre-pandemic period, 2020 – as the pandemic period and 2021–2022 – as the post-pandemic period. The assessment of fuel dependence was carried out based on the data set representing the supply and transformation of oil and petroleum products (Eurostat, 2024a). To estimate the intensity, the data on greenhouse gas emissions by source sector were attached (Eurostat, 2024b). Meanwhile, the decomposition analysis of the impacts required data on the transport sector. The road transport analysis included data on stock and new registration of vehicles by the source of motor energy, in particular, passenger cars (Eurostat, 2024c; Eurostat, 2024d), lorries by

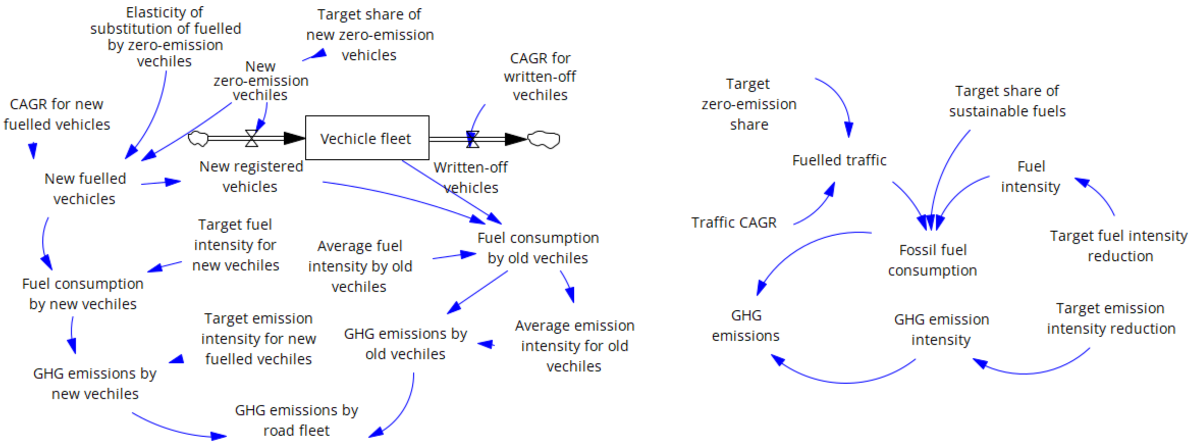

Figure 1. Causal loop diagram of the relationships in sustainable mobility objectives and GHG emissions (left: road transport; right: rail transport, aviation, and shipping)

weights (Eurostat, 2024e; Eurostat, 2024f), motor coaches, buses and trolleybuses (Eurostat, 2024g; Eurostat, 2024h), and mopeds and motorcycles (Eurostat, 2024i; (Eurostat, 2024j). To estimate aviation, it was necessary to analyze aircraft traffic by number of flights (Eurostat, 2024k); navigation assessment required the data of maritime goods transport in ton-kilometers (Eurostat, 2024l), and railways could be estimated through train traffic by source of motor energy in train-kilometers (Eurostat, 2024m).

3. RESULTS

Tracking Europe's transition from fuel dependence to sustainable mobility consists of three stages: assessment, analysis, and projection. The study establishes the baseline by comparing the EU's reliance on imported fossil fuels with GHG emissions from transport. This relationship is crucial for gauging the EU's fuel dependence and the environmental damage caused by transport. It also analyzes the impacts of sustainable mobility (low- and zero-emission vehicles, renewable fuels) on reducing crude hydrocarbon imports and GHG emissions. The paper highlights the tangible effects of sustainable mobility initiatives on the EU's energy landscape and environmental footprint. In addition, the analysis outlines a forward-looking perspective on the EU's commitments to decreasing GHG emissions via sustainable mobility. It lays out the necessary actions, wrapping up the research with a focus on future strategies and efforts.

3.1. The EU's s fuel dependence vs emission intensity

Fuel is a key commodity for ensuring sustainable economic growth and social welfare of society. Still, it is also a source of large GHG emissions. Therefore, a joint assessment of fuel dependence and intensity of GHG emissions makes it possible to determine the ecological and economic benefits of the European transition to sustainable mobility.

Figure 2 presents an assessment of the EU's fuel dependence in 2013–2022 and indicates that fuel production in the EU is based on imported crude hydrocarbons.

In 2013–2022, the import of crude hydrocarbons to the EU ranged from 464 to 549 million tons, which was from USD 127 to USD 375 billion per year, depending on crude oil prices in the global market. In total, during this period, the EU spent USD 2.38 trillion on the import of crude hydrocarbons. Import dependence on crude hydrocarbons ranged from 91.7% to 94.6%. Its highest value was recorded in 2015 due to a sharp drop in crude oil prices (from USD 99 per barrel in 2014 to USD 52 per barrel in 2015); the lowest value was in post-pandemic 2021 when the EU had significant stocks of crude oil after the reduction of an oil refinery in the pandemic period of 2020. By types of crude hydrocarbons, the dynamics of import dependence were as follows:

(i) crude oil had a variable upward trend, from 95.7% in 2014 to 98.4% in 2022;

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Source: Calculations based on Eurostat (2024a).

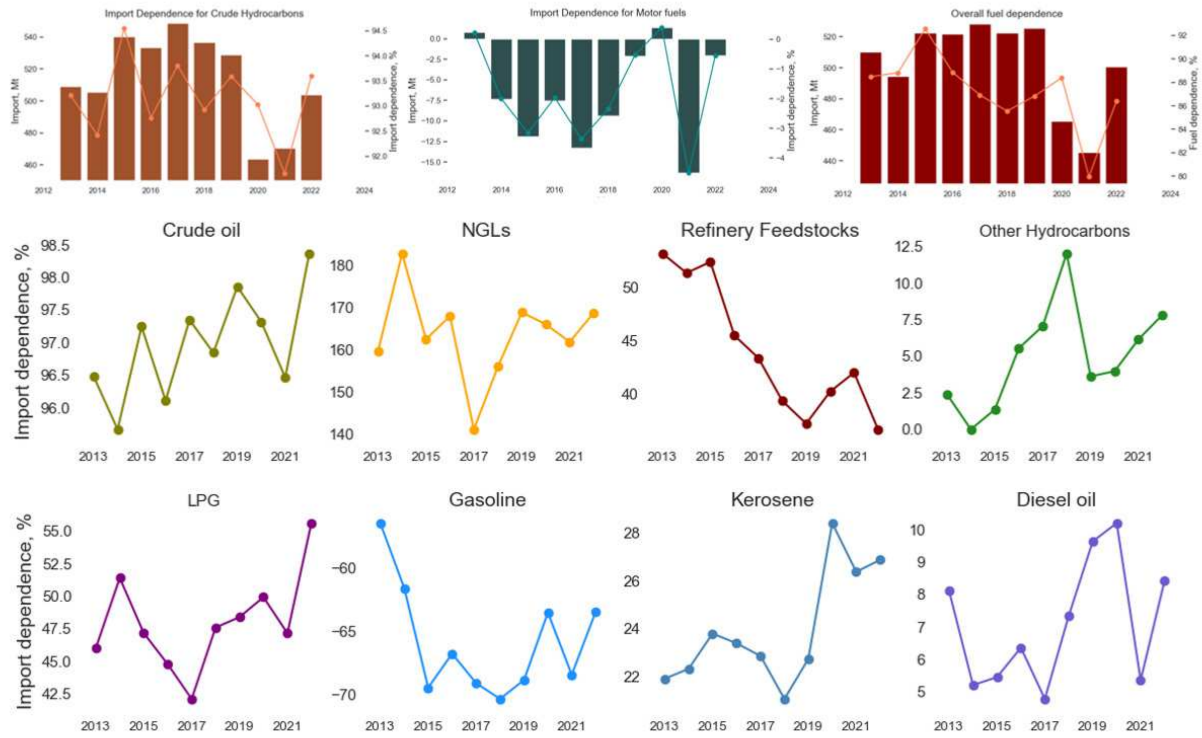

Figure 2. The EU's fuel dependence, 2013–2022

(ii) NGLs always exceeded 100%, as they were used not only as fuels but also as petrochemicals;

(iii) refinery feedstocks had a constant downward trend, from 53.2% in 2013 to 36.7%, as the EU improved its oil refinery;

(iv) other hydrocarbons had a stochastic upward trend, from 2.4% in 2013 to 12.0% in 2018 and 7.8% in 2022, as the EU tried to adapt them to fuel production.

Import dependence on motor fuels was mostly negative, decreasing from –21.5% in 2013 to –51.4% in 2022, which indicates a surplus of oil refining capacities and the strengthening of the Union's export orientation. Only in 2020 did the EU's import dependence on motor fuels have a positive value due to reduced oil refinery volumes. However, such values were ensured through an export orientation toward only one type of fuel – gasoline, the import dependence on which had negative values in the range from –70.3% (2017) to –56.4% (2022). Positive values of import dependence were observed for the rest of the fuels, and, therefore, their domestic production did not cover the EU's motor fuel needs, in particular:

(i) LPG had the highest values in the range from 42.1% (2017) to 55.6% (2022);

(ii) kerosene increased from 21.9% (2013) to 26.9% (2022), excluding the pandemic period, when its value exceeded 28.4%;

(iii) diesel had a variable tendency toward a decrease from 8.1% to 4.8% in 2013–2017, but subsequently had a reverse trend toward growth, reaching 8.4% in 2022.

It is important to note that in 2022, in the conditions of the COVID-19 recovery and under the pressure of geopolitical turbulence, import dependence increased for all types of fuel.

The overall level of fuel dependence had a downward trend, from 92.6% in 2015 to 86.4% in 2022, with exceptional levels in 2020 and 2021 attributed to the impact of the COVID-19 pandemic. As a result, the EU, importing crude hydrocarbons, did not meet its own needs for middle distillates (kerosene and diesel), but tried to obtain economic benefits from the export of light distillates with a higher added value. In total, fuel dependence cost the EU USD 2.58 trillion during 2013–2022. During 2015–2018, fuel dependence had a tendency toward a decrease, from 88.6% to 86.5%, while in 2018–2022, it increased to the level of 2013. The post-pandemic recovery causes a new challenge of increasing fuel dependence in the EU.

The assessment of the GHG emission intensity from fuel combustion in the EU is depicted in Figure 3. It demonstrates the growing impact of fuel on climate change. GHG emissions from fuel combustion accounted for ¼ of the total in the EU in 2022, of which 22.2% was from fuel consumption and 2.7% – from oil refinery. Their share increased by 3.7% from 2013 to 2022.

GHG emissions from fuel consumption had an upward trend, indicating a rise in mobility in the European space, adjusted for increased vehicle efficiency. In total, in 2013–2022, these emissions rose by 8.2%: they increased by 9.8% in the pre-pandemic period, decreased by 13.5% in the pandemic 2020, and recovered by only 11.4% in 2021–2022, which, however, was 3.6% less than in the pre-pandemic 2019. The GHG emission intensity from fuel combustion in transport can be recognized as a relatively constant value (their median was 2.718 tCO2eq/t in 2013–2022). The variation in the intensity was only 5.8%; the lowest value was recorded at the level of 2.585 tCO2eq/t in the pandemic 2020, while the highest value was recorded at the level of 2.736 tCO2eq/t in the post-pandemic 2022. The intensity of GHG emissions depended on the carbon content of the fuel and its combustion efficiency in the vehicle, in particular:

(i) in road transport, the intensity had a variable tendency to increase from 3.199 tCO2eq/t (2014) to 3.229 tCO2eq/t (2022);

(ii) in the railways, it gradually increased from 3.295 tCO2eq / t (2014) to 3.409 tCO2eq/t (2022);

Source: Calculations based on Eurostat (2024b).

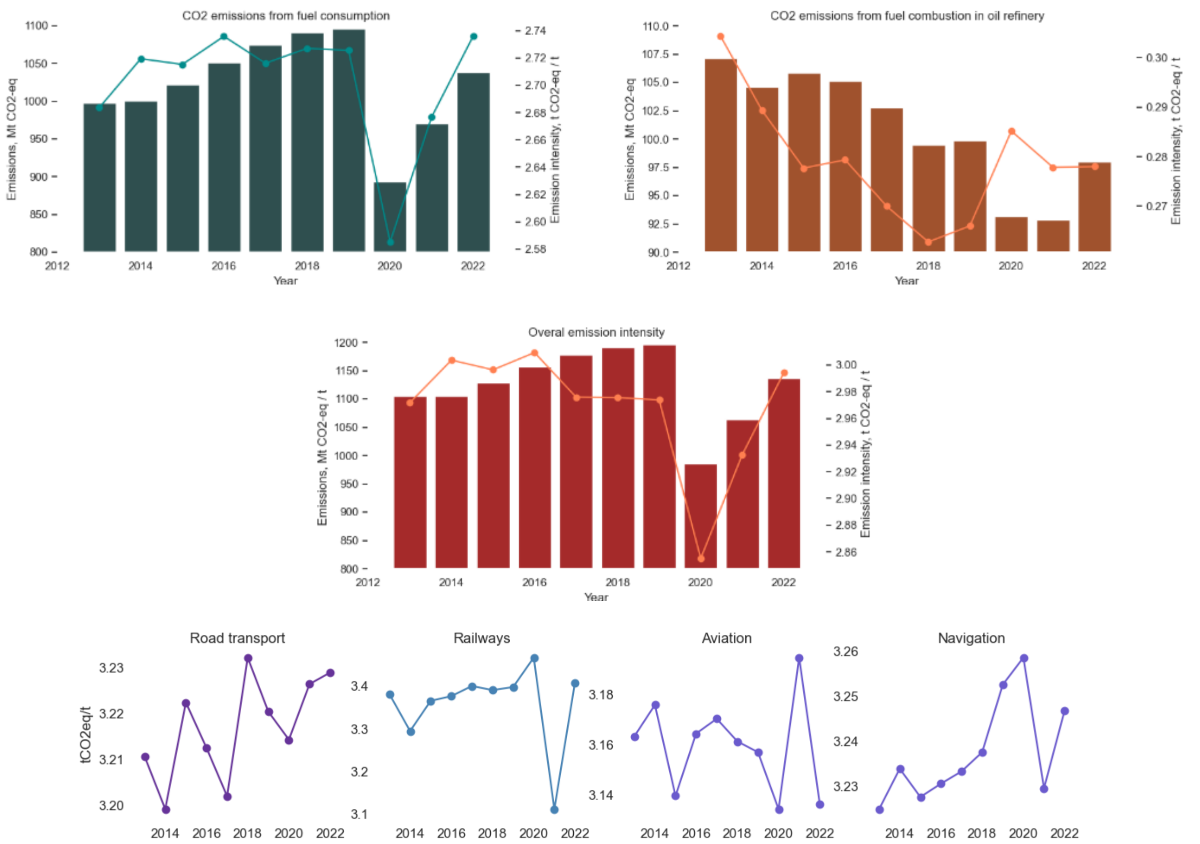

Figure 3. The EU's emission intensity from fuel combustion, 2013–2022

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(iii) aviation was characterized by a vague tendency of its decrease from 3.170 tCO2eq/t (2017) to 3.136 tCO2eq/t (2022);

(iv) in navigation, the intensity had a constant upward trend, from 3.225tCO2eq/t (2013) to 3.253 tCO2eq/t (2019).

During the pandemic 2020 and the post-pandemic 2021, significant deviations in GHG emission intensity were noted for all transport modes, which may indicate a change in consumption patterns with the growing impact of sustainable mobility.

On the other hand, GHG emissions from fuel combustion in oil refineries had a downward trend. In 2013–2022, they decreased by 8.5%, with 6.8% in the pre-pandemic years of 2013–2019 and 6.7% in 2020, while during the recovery period, they increased by 5.2%, which was still 1.8% below the pre-pandemic level of 2019. The GHG emission intensity in oil refineries fell by 12.5% to 0.266 tCO2eq/t in 2019 but rose to 0.285 tCO2eq/t during the pandemic. Subsequently, the lost gains were partially returned, and the emission intensity was 0.278 tCO2eq/t in 2021–2022. Therefore, the GHG emission intensity from oil refineries depends on the efficiency of converting crude hydrocarbons into fuel.

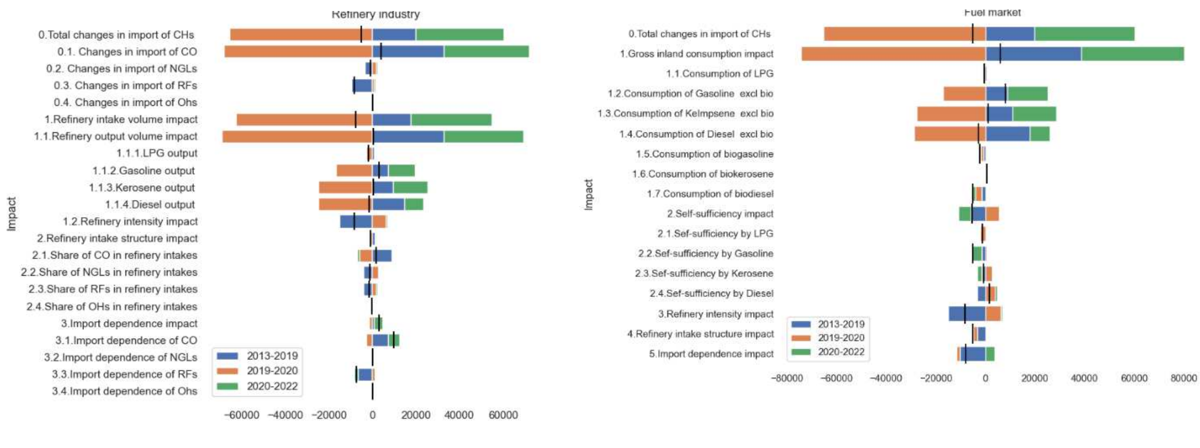
Total GHG emissions from fuel combustion in the EU amounted to 8.9 billion tCO2eq in 2013–2022, and after the COVID-19 pandemic, their growth resumed. The overall intensity of GHG emissions from fuel combustion ranged from 2.855 to 3.009 tCO2eq/t, with a median value of 2.976 tCO2eq/t. Hence, GHG emissions in the EU were directly related to fuel consumption, and to bridge the gap between them, an accelerated transition to sustainable mobility is needed.

Thus, in the pre-pandemic period, the EU faced both a decrease in fuel dependence and a decline in GHG emission intensity from fuel combustion. After the COVID-19 pandemic, these trends have reversed, making it necessary to mobilize efforts to achieve the European goal of ensuring climate neutrality.

3.2. The impact of sustainable mobility on crude hydrocarbon imports and greenhouse gas emissions

The developed equations of the decomposition analysis (1-5) allow for investigating the impact of quantitative, qualitative, and structural factors on changes in the import of crude hydrocarbons or GHG emissions, isolating the impacts of sustainable mobility forms, such as electric transport, biofuels, and other alternatives. The estimated types of impacts are presented in a hierarchical sequence, where 0 corresponds to general changes, and, for example, 3.1.3 reflects the lowest level of the decomposition of subgroup 1 in group 3 of impact factors.

Source: Calculations based on Eurostat (2024a).



Note: CO – crude oil; NGLs – natural gas liquids; RFs – refinery feedstocks; Ohs – other hydrocarbons; CHs – crude hydrocarbons; LPG – liquid petroleum gases.

Figure 4. The decomposition of changes in the import of crude hydrocarbons to the EU, 2013–2022

The import of crude hydrocarbons to the EU amounted to 504 million tons in 2022, decreasing by 5 million tons compared to 2013. In the pre-pandemic period, it rose by 20 million tons, while during the pandemic, it fell by 65 million tons, and in the post-pandemic period, it recovered by 40 million tons. The main reason for the decrease in the import of crude hydrocarbons was not the fall in the import of crude oil, which rose by 4 million tons, but the decrease in the import of refinery feedstocks by 8.2 million tons; the decrease in the import of NGLs accounted for another 0.9 million ton fall. Meanwhile, the import of other hydrocarbons amounted to only 84 thousand tons in 2022, which, however, was 3 times higher than in 2013. The decomposition of the import of crude hydrocarbons by impact factors is presented in Figure 4. The internal impacts that were observed inside the oil refinery are highlighted on the left, while the external signals that came from the fuel market are shown on the right.

The change in the volume of oil refinery of crude hydrocarbons is related to a decrease in their import by 7.4 million tons. Moreover, due to the increase in the refinery efficiency, it was possible to save 8.1 million tons (15 million tons in the pre-pandemic period, while later, the reverse effect took place). In the pre-pandemic period, 45% of additional crude hydrocarbon import was associated with diesel production, while, in the post-pandemic period, 43% was attributed to kerosene production. Structural shifts in the amounts of crude oil for the refinery led to a decrease in imports by 0.7 million tons, with 2.6 million ton savings on the import of NGLs and refinery feedstocks, which were replaced by 1.9 million tons of crude oil. The decline in the production of crude hydrocarbons in the EU brought about an increase in imports by 3.1 million tons, in particular, by 9.8 million tons of crude oil and 0.3 million tons of NGLs, while due to the deepening of the refinery efficiency, it was possible to reduce import dependence on refinery feedstocks by 7.1 million tons. A simple rise in fuel consumption would require the doubling of the import of crude hydrocarbons – potentially by 6 million tons against the current 5 million tons. However, due to the structural and intensive factors of the oil refinery, it was possible to avoid the import of crude hydrocarbons of 13 million tons (with 18 million tons in the pre-pandemic period, while later, the negative impact of the reduction in the refinery efficiency outweighed the positive structural one). In the pre-pandemic period, 47% of additional crude hydrocarbon imports were attributed to increased consumption of diesel, 28% of kerosene, and 23% of gasoline. During the COVID-19 pandemic, 39% of the reduction in crude hydrocarbon import was associated with a fall in diesel consumption, 37% in kerosene, and 23% in gasoline. In the post-pandemic period, the situation changed dramatically: kerosene accounted for 43% of additional crude hydrocarbon imports, gasoline – for 39%, and diesel – for only 19%. In the pre-pandemic period, the narrowing of the self-sufficiency of the EU market in self-produced fuel led to insufficient imports of crude hydrocarbons by 3.2 million tons for diesel and 1.5 million tons each for kerosene and gasoline. In the post-pandemic period, underfinancing of crude hydrocarbon imports was observed by 4.1 million tons for gasoline and by 1.9 million tons for kerosene. Among biofuels (as a type of sustainable fuel), the use of biodiesel made it possible to save 5.2 million tons of crude hydrocarbon imports, and biogasoline – by 2.3 million tons, while the use of biokerosene was observed only in 2022. Taking into account the average price of crude oil, it can be estimated that biofuels saved USD 2.7 billion on the import of crude hydrocarbons to the EU in 2013–2022, of which 27% was typical of the pre-pandemic period, 37% of the pandemic period and 35% of the post-pandemic period.

The impact of fuel consumption by means of transport on the import of crude hydrocarbons is presented in more detail in Figure 5, highlighting such methods of sustainable mobility as the electrification of transport, the use of biofuels and other alternatives.

Due to an increase in fuel consumption in road transport by 9.2 million tons, the import of crude hydrocarbons rose by 12.4 million tons, including an increase in imports of 23.2 million tons related to the pre-pandemic period, a decrease of 40.9 million tons during the pandemic, and an increase of 30.2 million tons in the post-pandemic period. Also, 88% of the total increase in imports was associated with diesel demand and 15% – with gasoline, while –3% was due to a reduction in LPG consumption. Replacement of fossil fuels with bio

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components made it possible to save 5.4 million tons on the import of crude hydrocarbons, of which 67% was biodiesel and the rest was biogasoline. Over 10 years, the EU road vehicle fleet grew by 42.3 million units, which should have led to an increase in the import of crude hydrocarbons by 146.8 million tons. However, the fleet itself was improved, and due to a reduction in fuel intensity, 134.4 million tons were saved on the import of crude hydrocarbons. The rapid drop in fossil fuel intensity was associated with the expansion of the use of hybrids from 574 thousand units in 2013 to 9.444 million units in 2022. The intensity of fuel consumption in petroleum and petrol hybrids decreased from 0.653 to 0.430 tons per unit per year, and diesel and diesel hybrids – from 2.208 to 1.3677 tons per unit per year. In addition, the road fleet of the EU totaled 3,741 million units of electric transport in 2022 against 239 thousand units in 2013. Road transport, which runs on alternative fuels, also increased from 923 thousand units to 1.5 million units. The expansion of electric transport and transport on alternative fuels made it possible to save 3.3 million tons and 0.4 million tons, respectively, on the import of crude hydrocarbons. In general, due to the deployment of sustainable mobility in road transport, it was possible to avoid an extra 9.1 million tons of crude hydrocarbon imports, which can be estimated at USD 3.7 billion in total at the average crude oil prices of the corresponding years.

Diesel consumption by railways decreased by 0.4 million tons, 58% of this reduction occurred in the pre-pandemic period, 34% – in the pandemic period, and 7% – in the post-pandemic period. Such a decrease made it possible to save 0.6 million tons of crude hydrocarbon imports. 0.2 million ton savings resulted from a 10% reduction in diesel rail traffic (including 16% in the pre-pandemic period, 11% during the pandemic, and 21% in the post-pandemic period). Another 0.4 million tons of savings were achieved due to the reduction of fuel consumption, which fell from 1.15 to 0.89 tons per train-kilometer. The share of biodiesel used in the railways remained insignificant, although it increased from 2% to 3.8%, which contributed to saving an additional 32 thousand tons of crude oil imports. The main direction of reducing fuel dependence was the electrification of railways. The share of electrified transportation rose from 61% to 68%, which helped to save 0.5 million tons of crude hydrocarbon imports, of which 75% – in the pre-pandemic period, 7% – in the pandemic period, and the rest – in the post-pandemic period. Thus, the development of sustainable mobility in the railways made it possible to avoid an extra 0.55 million tons of crude hydrocarbon imports, which can be estimated at USD 186 million.

The increase in kerosene consumption by aviation amounted to 2.5 million tons, reaching 39.2 million tons in 2022, due to a rise of 10 million tons in the pre-pandemic period, a fall of 26 million tons during the pandemic, and a recovery of 19 million tons in the post-pandemic period. This led to an increased import of crude hydrocarbons

Source: Calculations based on Eurostat (2024a, 2024c, 2024e, 2024g, 2024i, 2024k, 2024l, 2024m).

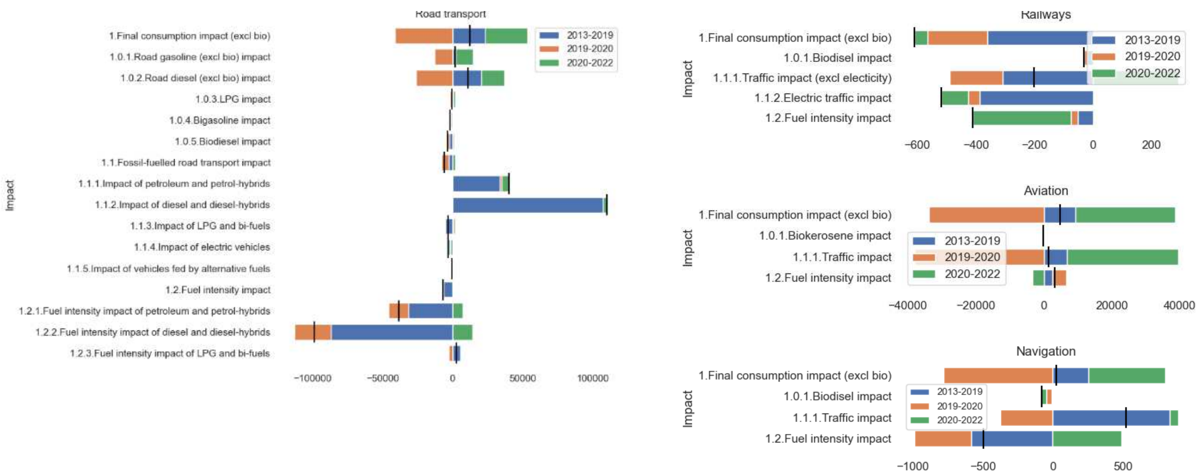
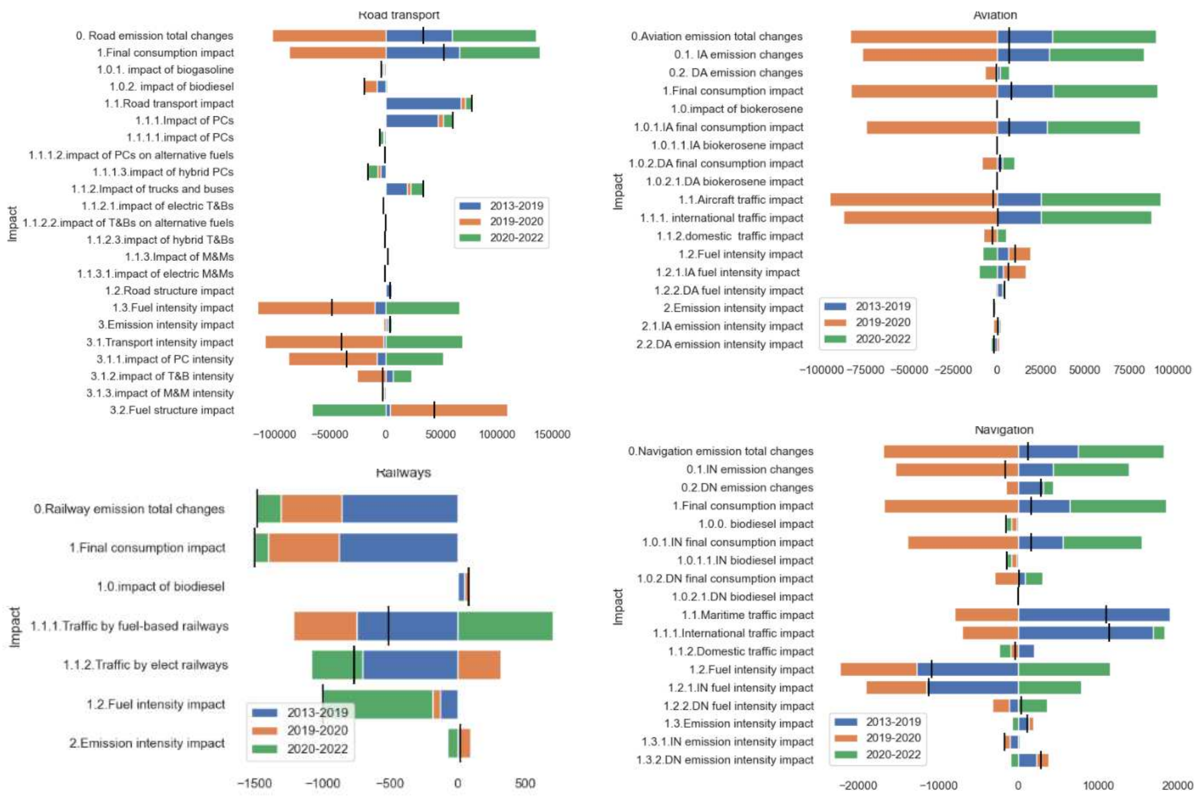


Figure 5. Decomposition of the impact of fuel consumption on the import of crude hydrocarbons by transport modes in the EU, 2013–2022

by 4.8 million tons, with 9.3 million tons in the pre-pandemic period, –33.7 million tons in the pandemic period, and 29.3 million tons in the post-pandemic period. One of the reasons for the increase in kerosene consumption was the rapid growth in the number of air flights. In the pre-pandemic year of 2019, 10.9 million flights were operated against 8.8 million in 2013; during the pandemic, their number decreased to 4.6 million, while in the post-pandemic year of 2022, there were only 8.6 million flights. This required a rise in the import of crude hydrocarbons by 6.9 million tons in the pre-pandemic period, a fall of 38 million tons in the pandemic period, and an increase of 32.6 million tons in the post-pandemic period. Yet, the main reason for the growth was the increase in air travel distance and, accordingly, fuel intensity, which went up from 4.14 tons per flight in 2013 to 4.42 tons per flight in 2019, 4.90 tons per flight in 2020, and 4.54 tons per flight in 2022. That is why importing an extra 3.3 million tons of crude hydrocarbons was necessary. The consumption of biokerosene was recorded only in 2022 in the amount of 53 thousand tons, which made it possible to save 61 thousand tons of crude hydrocarbon imports.

In navigation, fuel consumption remained almost unchanged in 2022 compared to 2013: it increased by 1.7 million tons in the pre-pandemic period, decreased by 4.7 million tons in the pandemic period, and recovered by 3 million tons in the post-pandemic period. Such an increase in fuel consumption required an additional import of crude hydrocarbons in the amount of 158 thousand tons. The zero impact on crude hydrocarbon imports was due to the opposite effect of a rise in sea traffic by 402 thousand ton-kilometers, which resulted in an additional need to import 3.1 million tons of crude hydrocarbons and a reduction in fuel intensity from 8.98 to 8.27 tons per ton-kilometer, which helped to save 2.9 million tons on imports. The use of biodiesel in navigation began to develop in 2018 and accounted for only 1.1% of the total fuel consumption in 2022. The expansion of biodiesel consumption saved 0.48 million tons of crude oil imports.

Source: Calculations based on Eurostat (2024b, 2024c, 2024e, 2024g, 2024i, 2024k, 2024l, 2024m).



Note: PCs – passenger cars; T&Bs – trucks and buses; M&M – motorcycles and mopeds; IA – international aviation; DA – domestic aviation; IN – international navigation; DN – domestic navigation.

Figure 6. Decomposition of changes in GHG emissions in the EU by means of transport, 2013–2022

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Consequently, the development of sustainable mobility reduced the import of crude hydrocarbons by 10.2 million tons, of which 90% was attributed to road transport, while the impacts on other transport modes are still barely noticeable.

Among GHG emissions in transport, road transport accounted for 73.5% in 2022 (passenger cars – 43%, trucks and buses – 29%, motorcycles and mopeds – the rest), navigation accounted for 14.3%, aviation – 11.8% and the railways – only 0.4 %. The decomposition of GHG emissions in transport (Figure 6) makes it possible to investigate the impact factors that led to their changes, singling out the forms of sustainable mobility.

In 2013–2022, GHG emissions from fuel combustion in road transport increased by 34 million tCO2eq, reaching 764 million tCO2eq in 2022. In addition, in the pre-pandemic period, they went up by 60 million tCO2eq, during the pandemic, they went down by 102 million tCO2eq, and, in the post-pandemic period – recovered by 76 million tCO2eq. The main impact factor was a rise in fuel consumption due to the growth in the number of vehicles. A simple quantitative rise in fuel consumption would have increased these emissions by 52.5 million tCO2eq, but replacing fossil fuels with blending biofuels saved 23 million tCO2eq. Of the saved volume, 9 million tCO2eq was in the pre-pandemic period, with 89% resulting from the expansion of biodiesel, and the rest was due to biogasoline. During the pandemic period, the reduction of GHG emissions by 14 million tCO2eq was associated with a fall in their physical consumption and not with a decrease in the share of their use. Whereas in the post-pandemic period, there was an expansion of the share of biogasoline and a narrowing of the share of biodiesel, which in total had zero impact on the change in GHG emissions. The increase in the number of passenger cars led to a rise in GHG emissions by 39 million tCO2eq. Reduced GHG emissions in electric vehicles and hybrids brought about savings of 5 million tCO2eq and 16 million tCO2eq, respectively, while alternative fuels had an insignificant impact. The growth in the number of heavy vehicles resulted in an increase in GHG emissions by 32 million tCO2eq, among which GHG savings due to the expansion of electric vehicles and hybrids amounted to 2 million tCO2eq. Increased GHG emissions from motorcycles and mopeds amounted to 2 million tCO2eq, of which only 0.09 million tCO2eq savings were associated with sustainable mobility. There was also a change in the transport modes with the transition from public to individual transport, which led to a rise in GHG emissions by 4 million tCO2eq. However, GHG emissions fell by 48 million tCO2eq as a consequence of a reduction in road traffic, including by 10 million tCO2eq in the pre-pandemic period and by 105 million tCO2eq in the pandemic period, while post-pandemic recovery brought about additional 67 million tCO2eq emissions. The growth of the efficiency of vehicles is responsible for reducing GHG emission intensity. Reducing the intensity of GHG emissions from passenger cars from 2,022 tCO2eq/t to 1,881 tCO2eq/t avoided 35 million tCO2eq; heavy transport reduced its GHG emission intensity from 9.384 tCO2eq/t to 9.318 tCO2eq/t, which translated into savings of 2 million tCO2eq, GHG emission intensity of motorcycles and mopeds decreased from 0.365 tCO2eq/t to 0.265 tCO2eq/t representing 3 million tCO2eq in savings. In general, the growth of sustainable mobility forms can be associated with a reduction of GHG emissions by 46 million tCO2eq, of which 15 million tCO2eq was in the pre-pandemic period, 17 million tCO2eq - during the pandemic and 13 million tCO2eq – in the post-pandemic period.

In 2022, GHG emissions from railways reduced by 1.5 million tCO2eq compared to 2013 and amounted to 3.5 million tCO2eq. 58% of the reduction was typical of the pre-pandemic, 30% – of the pandemic, and the rest was typical of the post-pandemic period. The improvement to the railway fleet and reduction in the fuel intensity made it possible to avoid nearly 1 million tCO2eq of GHG emissions. Another 0.5 million tCO2eq savings could be associated with reduced rail traffic running on fossil fuel. The EU has a developed network of electric railways, annual transportation by electric railways increased from 61% to 68%, which contributed to saving 0.8 million tCO2eq. The impact of biofuels on GHG emissions from railways was barely noticeable; it manifested itself in savings of 80 thousand tCO2eq.

GHG emissions from aviation rose from 116 million tCO2eq in 2013 to 123 million tCO2eq in

2022, reaching its peak of 147 million tCO2eq in pre-pandemic 2019 and decreasing to 64 million tCO2eq in 2020. Among these emissions, international aviation accounted for 89%, whilst domestic aviation accounted for the rest; their structure remained almost unchanged throughout the period. Due to the increase in fuel consumption, GHG emissions should have increased by 8 million tCO2eq, but the increase in the efficiency of the aviation fleet allowed them to decrease by 1.5 million tCO2eq. The growth in the number of international flights led to a rise in GHG emissions by 0.4 million tCO2eq (a rise of 25 million tCO2eq in the pre-pandemic period, a fall of 87 million tCO2eq during the pandemic and an increase of 63 million tCO2eq in the post-pandemic period). At the same time, the reduction in the number of domestic flights caused a fall in GHG emissions by 2.6 million tCO2eq (including in the pre-pandemic period by only +80 thousand tCO2eq, during the pandemic by –7.7 million tCO2eq and in the post-pandemic period by +5 million tCO2eq). Due to the boost in flight distance, the fuel intensity grew, which led to an increase in GHG emissions from international aviation by 6.3 million tCO2eq and from domestic aviation by 4.2 million tCO2eq. The use of biokerosene as a sustainable fuel in aviation took place only in 2022, which reduced GHG emissions by 134 thousand tCO2eq.

GHG emissions from navigation amounted to 148 million tCO2eq in 2022, increasing by 1% compared to 2013; they increased by 5% in the pre-pandemic period, decreased by 11% in the pandemic period, and recovered by 8% in the post-pandemic period. However, in 2013, international shipping accounted for 90% of these emissions, while, within 10 years, there was a 2% rise in the share of domestic emissions. Therefore, GHG emissions from international navigation went down by 1%, whereas domestic navigation went up by 19%. The main reason for the increase in GHG emissions in international navigation was the traffic growth, but this growth was almost completely offset by the decrease in fuel intensity per ton-kilometer, which curtailed GHG emissions by 118 thousand tCO2eq. In addition, 1.7 million tCO2eq of emissions were avoided due to the improved efficiency of the international navigation fleet. The reduction of GHG emissions associated with the use of biodiesel in maritime transport amounted to 1.4 million tCO2eq. Reverse trends were observed in domestic navigation: the reduction of domestic traffic should have cut GHG emissions by 0.38 million tCO2eq, but the increase in fuel intensity led to their increase by 0.4 million tCO2eq. The rise in GHG emissions in domestic navigation was primarily caused by the declining efficiency of its navigation fleet, which resulted in 2.8 million tCO2eq of emissions. The use of biodiesel in domestic navigation was insignificant, which prevented 53 thousand tCO2eq of GHG emission.

Hence, the deployment of sustainable mobility made it possible to avoid 49.1 million tCO2eq, which amounted to 4.7% of transport-related emissions in 2022, of which 90% referred to passenger cars (39% to road biodiesel and 32% to hybrid cars), 4% is associated with heavy vehicles, 3% – with navigation, 2% – with railways, and only 0.2% – with aviation.

3.3. The EU’s objectives for reducing GHG emissions through sustainable mobility

The EU aims to reduce GHG by at least 55% compared to 1990 levels by 2030 and become climate neutral by 2050; in particular, for transport, a 90% reduction in GHG emission is projected by 2050 compared to 1990 (EC, 2019a). In order to achieve sustainable mobility in the EU, relevant regulations were adopted, which set commitment objectives until 2030:

- for new passenger cars (EC, 2019b; EC, 2023a), a 15% (55%) average GHG emission reduction of the target in 2021 and a 25% (35 %) share of the zero- and low-emission vehicles’ fleets by 2025 (2030);
- for new light commercial vehicles (EC, 2019b; EC, 2023a), a 15% (50%) average GHG emission reduction of the target in 2021 and a 17% (30%) share of the zero- and low-emission vehicles’ fleets by 2025 (2030);
- for new heavy-duty vehicles (EC, 2019c), a 15% (50%) average GHG emission reduction of the target in the reference period;

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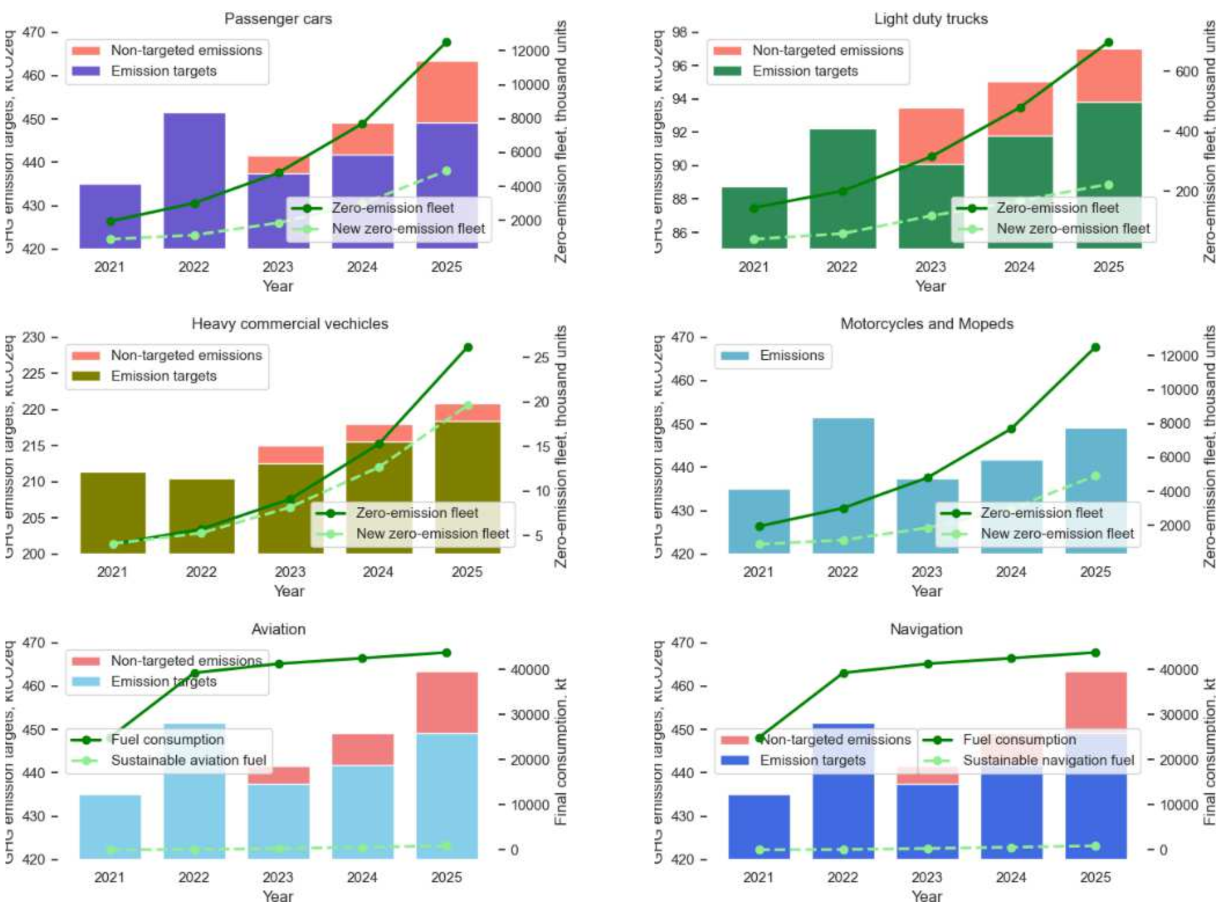
- for aviation (EC, 2023), a minimum share of 2% (6%) of sustainable aviation fuels by 2025 (2030);
- for navigation (EC, 2023c), a 2% (6%) reduction of average GHG intensity of the energy used on board by 2025 (2030);
- for railways, proposals are only considered (EC, 2024).

Based on the extrapolation of traffics by transport modes and interpolation of EU objectives, a quantitative assessment of GHG emission reductions by 2025 through the deployment of sustainable mobility is given in Figure 7.

Sales of new passenger cars grew at an accelerated pace in the pre-pandemic period (CAGR = 16.6%) but slowed down in the post-pandemic period (CAGR = 6.4%). Based on retrospective trends, the total passenger car fleet may reach 276 million units in 2025, of which 21.3% will be zero-emission cars, leading to an increase in GHG emissions to 463 million tCO2eq (at the optimal intensity of GHG emissions from passenger cars at the level of 2021). Achieving the EU's objectives for a 25% share of new passenger cars with zero

Source: Calculations based on Eurostat (2024a, 2024b, 2024c, 2024d, 2024e, 2024f, 2024g, 2024h, 2024i, 2024j, 2024k, 2024l, 2024m) and EC (2019b, 2019c, 2023a, 2023b, 2023c).



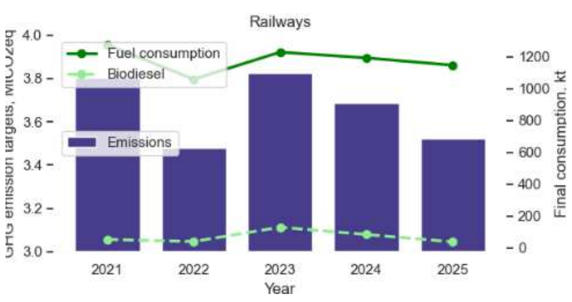


Figure 7. A quantitative assessment of GHG emission reductions by 2025 through the deployment of sustainable mobility

emissions and a 15% decrease in the average GHG emission intensity for other new cars (EC, 2019b; EC, 2023a) will reduce GHG emissions to 449 million tCO2eq. Achieving the EU's objectives will prevent an additional 25.4 million tCO2eq emissions during 2023–2025. The total number of zero-emission passenger cars should be 12.5 million units or 4.5% of the total fleet of passenger cars in 2025. Additional sales of 1.1 million zero-emission passenger cars will substitute the sale of 831 thousand units of cars fueled by diesel.

Sales of new light commercial vehicles grew rapidly in the pre-pandemic period (CAGR = 5.2%) and tried to recover in the post-pandemic year of 2021 (GR = 10.6%), but the tense economic situation led to a decline in sales in 2022. Due to the recovery of pre-pandemic trends, GHG emissions may increase to 97 million tCO2eq in 2025, i.e., by 5.2% compared to 2022, while the share of new light commercial electric vehicles will be only 8.4% in 2025 compared to 5.2% in 2022. The total share of light commercial electric vehicles will be 1.6% or 463 thousand units. Achieving the EU's objectives for a 17% share of zero-emission light commercial vehicles and a 15% reduction in the average intensity of GHG emissions by other new vehicles (EC, 2019b; EC, 2023a) should ensure their growth to only 93.8 million tCO2eq, which will help to prevent additional GHG emissions of 9.9 million tCO2eq in 2023–2025. The fleet of light commercial electric vehicles should amount to more than 698 thousand units, including the substitution of 117 thousands diesel vehicles with electric ones.

As the pre-pandemic trends recover (CAGR = 2.6%), sales of new heavy commercial vehicles will increase to 334 thousand units, and the total fleet will reach 4.2 million units in 2025, which is 4.6% more compared to 2022. 0.6% of this fleet will be vehicles with zero GHG emissions, mainly intercity coaches, buses, and trolleybuses. At the average intensity of GHG emissions, their volume will increase to 221 million tCO2eq, or by 5% compared to 2022. Achieving the EU's objectives for a 15% reduction in the average intensity of GHG emissions from the new fleet by 2025 (EC, 2019c) will limit the growth of GHG emissions to 218 million tCO2eq. In this way, 7.4 million tCO2eq will be avoided in 2023–2025.

As for motorcycles and mopeds, no special strategic goals have been established. In the post-pandemic period, there was a recovery of the pre-pandemic trends (CAGR = 4.5%) with an active deployment of electrification for these modes of transport (CAGR = 47.5%). If these trends continue, the share of new zero-emission mopeds and motorcycles will rise to 25.1% in 2025 from 12.6% in 2022, and their overall share will be 5.1% versus 3.4%, respectively. At the average intensity, GHG emissions may reach 10.1 million tCO2eq in 2025 compared to 9.4 million tCO2eq in 2022.

Thus, the achievement of the EU's objectives will allow GHG emissions in road transport to be reduced by 1.4% compared to 3.6% according to the basic trend. In general, 42.8 million tCO2eq must be avoided in 2023–2025.

Aviation traffic had a fast growth rate until 2020 (CAGR = 3%), which, in 2022, did not recover even to the level of 2013. Making it possible to grow rapidly, at least according to pre-pandemic trends, it can amount to more than 9.4 million flights in 2025. ReFuelEU Aviation will usher in the era of sustainable aviation fuels; among them are synthetic aviation fuel, aviation biofuels, and recycled carbon aviation fuels (EC, 2023b). The first EU commitment objective is the achievement of a minimum share of 2% from 2025. The linear interpolation of such a share requires the provision of sustainable aviation fuel of 875 thousand tons already in 2025. Under such conditions, GHG emissions may amount to 135.7 million tCO2eq in 2025; the use of sustainable aviation fuel will help to avoid 5.4 million tCO2eq over the next 3 years. Therefore, the intensity of aviation emissions should decrease by 1%, amounting to 3.10 tCO2eq per ton of aviation fuel.

Navigation traffic had slightly lower growth rates in the pre-pandemic period (CAGR = 2.1%), which recovered after the pandemic. Therefore, a return to past growth is possible, and it may amount to 5.2 million ton-kilometers in 2025. FuelEU Maritime envisages a gradual decrease in the average GHG intensity of the energy used on board by a ship, in particular, due to the development of emerging alternative fuels, eco-design, bio-based materials, wind propulsion, and wind-assisted propulsion (EC, 2023c). The objective indicator is the reduc-

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tion of GHG intensity by 2% from 2025, which requires the provision of 1,044 thousand tons of sustainable navigation fuels, and therefore sustainable share should increase from 1.1% in 2022 to 2.2% in 2025. GHG emissions may amount to 147.9 million tCO2eq in 2025, which is 0.7 million tons less than in 2022. The achievements will save 12.5 million tCO2eq or 2.7% of navigation emissions within 3 years.

Railway traffic was characterized by a slow growth rate in the pre-pandemic period (CAGR = 0.9%); fossil-fueled traffic has declined (CAGR = –2.9% in 2013–2019 and CAGR = –1.1% in 2013–2022) as a result of being replaced by electric traffic (CAGR = 2.8% in 2013–2019 and CAGR = 2.1% in 2013–2022). Currently, the EU's regulatory legislation on ensuring the sustainability of railways is still under consideration (EC, 2024). However, let one assume that its objective values will be similar to navigation, namely the reduction of GHG intensity by 2% from 2025, as well as the growth in the share of electric transportation by 2% to 70% in 2025. Under such conditions, fossil-fueled traffic should amount to 1.1 million train-kilometers and electric traffic – to 2.6 million train-kilometers in 2025. The interpolation of such goals will increase the share of sustainable fuels in railways from 3.8% to 5.0%, although this will be equal to only 50 thousand tons in 2025. GHG emissions may amount to 3.2 million tCO2eq, which is 7.9% less than in 2022, and it will help to prevent 268 thousand tCO2eq.

Hence, achieving the EU's objectives for sustainable mobility will contribute to avoiding 61 million tCO2eq in 2023–2025.

4. DISCUSSION

Fossil fuel consumption leads to double losses in ensuring a sustainable future for the EU. First, it is a constant outflow of EU funds for the import of crude hydrocarbons and motor fuel. The lack of domestic deposits and the uneven composition of crude hydrocarbons means that the EU cannot overcome import dependence in the traditional way, without creating excess capacities. The trends of the EU's fuel dependence on export-oriented countries, as argued by Losoncz (2006) and Gupta (2008), continued during the pre-pandemic years (2013–2019), with negligible impact from sustainable mobility. The main efforts were associated with deploying highly efficient vehicles fed by fossil fuels. However, the extensive growth in the total number of vehicles overshadowed the benefits of higher efficiency. However, trends noted by Cappelli and Carnazza (2023) in mobilizing efforts to overcome fuel dependence were only in pandemic 2020, driven by reduced mobility, which spurred the adoption of sustainable modes. Post-COVID-19 recovery in mobility activity surpassed the adoption of sustainable modes. During the pre-pandemic period, concerns about fuel dependence centered on stable and diverse crude hydrocarbon imports (Acevedo & Lorca-Susino, 2021; Tichý & Dubský, 2024). However, in the post-pandemic period, there has been a growing dependence on motor fuels. Geopolitical and economic risks related to oil supplies (Khaustova et al., 2024) have also become relevant for motor fuels.

Second, the growth of fossil fuel consumption leads to a proportional increase in GHG emissions. Reducing the intensity of GHG emissions from fuel combustion is technologically limited by transport efficiency, whereas increasing EU mobility results in a rise in GHG emissions. This dual problem has one solution – the transition to sustainable mobility, which consists of complementary directions: (i) the use of non-fossil motor energy, and (ii) the deployment of zero-emission (electric, hydrogen) and low-emission (hybrid) transport. Holden et al. (2019) stated that the sustainable mobility paradigm is currently in its fourth stage of evolution, focusing on decarbonization. However, the main practical achievements so far have been in transport system planning and technological advancements in fossil-fueled vehicles, referred to as the third stage mentioned by Banister (2008). Crucial impacts of zero-carbon transport, argued by Hensher and Wei (2024), have been modest and primarily linked to light road vehicles. Direct and blending biofuels, insisted by Malik et al. (2024), have had minor impacts, while vehicles powered by alternative fuels, noted by Visvanathan et al. (2023), are still in the early stages of deployment. As previously, the main concerns are particularly connected with heavy commercial transport (Winkelmann et al., 2024), navigation (Koilo, 2024), and aviation (Wang et al., 2024) as their electrification is not possible, and biofuels are limited in their blending capabilities.

The EU's 2025 commitment objectives require saving an additional 61 million tCO2eq to stay on track for a 90% reduction in transport GHG emissions by 2050. This target appears out of reach since the seventh transport revolution, as claimed by Cascetta and Henke (2023), has not materialized, and the European transport sector still continues to depend on imported crude hydrocarbons and/or fossil motor fuels.

The solution to this challenge may be the use of other hydrocarbons in oil refineries instead of fossil hydrocarbons. In the decomposition analysis of the net import of crude hydrocarbons by oil refineries (Figure 3), they had an invisible impact on the EU due to the stochasticity of their use. This group consists of

(i) unconventional fossil hydrocarbons (extra-heavy oils extracted from oil sands, coal, and oil shale), as well as

(ii) liquid hydrocarbons transferred from other sources (including gas, solid fuel, and renewables) (UN Statistical Commission, 2017).

Among EU countries, unconventional hydrocarbons were extracted only in Italy. Eleven countries processed natural gas to get them, with the largest volumes in Poland, Sweden, Slovakia, and Bulgaria. Only Estonia produces other hydrocarbons from oil shale but for fuel oil, not motor fuel. Producing motor fuel from other hydrocarbons, like renewable fuels at liquefaction plants, is seen as promising. South Africa, China, Qatar, and Malaysia have experience producing synthetic fuels from coal and/or natural gas, with efficiency between 35% and 54% in 2021 (UN Statistical Division, 2021). However, this path is unacceptable for the EU, with non-competitiveness and extra CO2 emissions compared to conventional fuels (Dai et al., 2023; Shulga et al., 2024). Nevertheless, the transfer of other hydrocarbons from renewables and non-fossil energy as equivalents of conventional oil, which can be used in transport without mixing, might be a major breakthrough. Currently, such pilot projects are already being implemented in the world, in particular: in Canada (Huron air to fuels facility), the United Kingdom (Altalto waste-to-transport-fuels plant), and the USA (Bayou Fuels. Woody waste to fuels in rural America). The EU has also set a target of a 2% share of sustainable aviation fuel from 2025, but projects are only under consideration by Horizon Europe (Ail & Dasappa, 2016; Mesfun, 2021), and none are currently being implemented. If synthetic renewable fuels take off, they could be a 'black swan' in the global oil market. Despite higher costs, keeping production within the EU would retain funds, create jobs, and add value. Therefore, synthetic non-fossil hydrocarbons can be considered a direct substitute, making them a game-changer for greening heavy commercial transport, aviation, and navigation.

CONCLUSION

This paper aims to monitor the EU's progress in transitioning from fuel dependence to sustainable mobility by assessing current impacts and future efforts required of low- and zero-emission vehicles, as well as renewable and low-carbon fuels, on reducing crude hydrocarbon imports and GHG emissions.

The fuel dependence and GHG emission intensity from fuel combustion were estimated using indicators based on oil refinery and fuel consumption stages. It is possible to determine fuel dependence by types of crude hydrocarbons and motor fuels, and GHG emissions intensity by transport modes. The EU managed to save 10 million tons of crude oil imports and avoid 49 million tCO2eq emissions.

The decomposition analysis assessed changes in crude hydrocarbon imports for nine types of impacts and GHG emissions for three types of impacts. Each mode of transport had specific traffic measurement units. In general, deployment of sustainable mobility had a greater impact on limiting GHG emissions growth (4.7%) than on reducing crude hydrocarbon imports (1.9% in 2022).

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Shifts in sustainable mobility were identified through causal relationships between traffic trends, GHG intensity reduction targets, and the deployment of sustainable transport modes and fuels.

The reductions resulted from efficient oil processing, biofuel blending, and an increased zero- and low-emission transport fleet. Road transport, especially hybrids, contributed the most, followed by electric railways, biofuel use in navigation, and initial biofuel development in aviation.

Achieving the EU's 2025 commitment objectives requires preventing an additional 61 million tCO2eq emissions, expanding the zero-emission transport fleet by over 13 million units, and producing about 2 million tons of sustainable fuel. The first target is in doubt, and the second one is not on track.

To overcome fuel dependence and bridge the gap between fuel consumption and GHG emissions, exploring the latent potential locked in other hydrocarbons from non-fossil energy sources, particularly synthetic renewable fuels, is vital.

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