Comparative Economic Research. Central and Eastern Europe
Volume 27, Number 4, 2024
https://doi.org/10.18778/1508-2008.27.36

Alternative Fuels as a Sustainable Innovation in Vehicle Fleet Across the EU–27: Diagnosis and Prospects for Development

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Abstract

The deployment of alternatively fueled (AF) vehicles constitutes an important measure in meeting the European Union's (EU's) climate goals. The study aims to characterize and evaluate, in a comparative manner, the current stage of the adoption of AF passenger cars into the general (M1) passenger car fleet in the EU member states. The focal point of the study is the exploration of similarities and differences observed between the EU countries regarding the current structure of AF passenger car fleets, as well as development trends in this area. In this context, a clear scheme of "two speeds" emerges – parallel to the rapid diffusion of electric vehicles in the Nordic and Western European countries, the size and structure of the AF M1 vehicle stock remained largely unchanged in the Central-European countries, with the dominant role of widely established liquified petroleum

Received: 28.01.2024. Verified: 8.04.2024. Accepted: 24.09.2024

gas (LPG). The findings highlight the need to diversify the range of alternative fuels, which should be introduced gradually, in line with the classification proposed by the European Parliament and the Council.

Keywords: alternative fuels, sustainable innovation, sustainable development, passenger car fleet, EU–27, environment

JEL: O33, O57, Q01, Q42, Q55

Introduction

Over the past few decades, an increasing number of governments worldwide have declared a policy to transition towards a zero-emission environment. In Europe and the European Union of the 27 member states (EU–27), the goal of a carbon-neutral continent is to be achieved by 2050. A significant portion of Europe's greenhouse gas emissions originates from the transport industry, especially road transport: fuels in passenger and private cars, buses used in public transportation, and trucks used for business purposes. Therefore, the basic logic adopted by the global leaders so far is that to strengthen the efforts to achieve the goal of a zero-pollution environment, the fossil fuels still used in the motor fleet, such as oil and gasoline, should be replaced. The revolution that is already taking place in technology also includes the possibility of using alternative, more sustainable types of fuels in new engines that are already being designed and put into production for the manufacture of cars with modern technology. According to the European Commission's "2050 Long-term Climate Strategy" (European Environment Agency 2020), there is no single fuel solution for the future of low-emission mobility, but all main alternative fuel options are likely to be required, to different extents, in each of the transport modes (European Alternative Fuels Observatory n.d., *Alternative…*). The existence and availability of new types of fuels is the main challenge that needs to be addressed effectively and continuously to enable a sustainable transition to a society that will not pollute the environment in the same way as in the past, but instead, one that has taken a big step in the direction of sustainable development for the future of humanity.

Achieving climate neutrality by 2050 through the use of alternative fuels in transport requires the active participation of each member state, coordinated and supervised at an institutional level. Under the current legislative framework, by January 1, 2024, each Member State of the EU–27 was required to prepare and submit to the European Commission an interim national policy framework for the market development of alternative fuel infrastructure in the transport sector and the installation of the relevant infrastructure. On that basis, the European Commission will be able to issue recommendations to each member state within six months. These recommendations are expected to focus on the degree of ambition of the goals and objectives necessary to fulfill the obligations, as well as the policies and measures linked to the objectives and purposes of each member state. Each Member State must take due account of the recommendations it receives from the European Commission for its national policy frameworks. Consequently, by January 1, 2025, each Member State is obliged to notify the European Commission of its definitive national policy framework.

Given their pivotal role in the European Union's (EU's) (and also global) climate policy, alternative fuels are at the center of research and science that explores the possibilities of production, storage, disposal, and consumption by end-users in a value chain that will contribute achieving zero-emission of exhaust gases into the atmosphere. The rate of adoption of alternatively fueled (AF) fleets is monitored and publicly reported through multiple institutions at both national and international levels. In this context, the European Alternative Fuels Observatory serves as the most comprehensive reference point. It consolidates data from both general sources (i.e., Eurostat, the European Commission's Mobility and Transport Department, the Urban Mobility Observatory, and the European Environment Agency) and country-specific ones (i.e., governmental sources, transport departments, local automotive associations). Periodic reports and occasional publications on the most recent developments in the auto industry on an international scale are also published by, inter alia, the European Automobile Manufacturers' Association and the International Energy Agency, with a strong emphasis on electric mobility.

The study aims to synthesize and evaluate, in a comparative manner, the current stage of adoption of AF passenger cars into the passenger car stock (M1) in the EU member states. It offers an alternative perspective on the issue. The emphasis is on the structure of the AF passenger car fleet, and the specific types of fuels are assessed based on their contribution to the overall growth or decrease of the AF M1 fleet as a whole. The relevant trends, market shares, and progression of the structure of AF car fleets are analyzed and internationally compared within a two-group framework, with countries divided according to the alternative fuel of primary use (electric/hybrid; transitional).

The article is structured as follows. After the introduction, which provides the general context of the study, the "Theoretical background" section defines and characterizes the alternative fuels utilized in the transport sector and briefly outlines their sustainable properties. The subsequent part ("Research method") presents the data sources and limitations, as well as a more detailed description of the analytical framework. Section four, the "Results", consists of three parts, where the development of the AF passenger car fleet is presented at different levels of aggregation – for the EU–27 as a whole and two previously identified groups: Group 1 (highest level of electrification) and Group 2 (lowest level of electrification). The main findings of the study are summarized in the "Conclusion" section.

Theoretical background

Based on the Proposal for a Regulation of the European Parliament and of the Council on the deployment of alternative fuels infrastructure and repealing Directive 2014/94/EU of the European Parliament and of the Council COME/2021/559 (European Commission 2021), alternative fuels are defined as fuels or power sources that serve as a substitute for fossil oil sources in the energy supply to transport and which have the potential to contribute to decarbonization and enhance the environmental performance of the transport sector. In that sense, alternative fuels can be described as sustainable innovation, defined as the newly developed products, processes, and technologies aimed to meet the market's needs with the capacity to generate positive social and environmental impacts (Cillo et al. 2019; Adomako and Nguyen 2023)[1]. Importantly, the positive effects of alternative fuels in relation to the environment and the associated economic consequences are indicated by the literature (Breitkreuz, Menne, and Kraft 2014; Martin, Larrazabal, and Perez-Ramirez 2015; Kumar 2020; Farghali et al. 2023; Liu 2023), although research is still being conducted on this topic.

A brief and basic description of the chosen type of alternative fuel is given below, along with the main characteristics and the important parameters that frame each one (Alternative Fuels Data Center n.d., *Alternative…*). There are eight types of alternative fuels (European Council for an Energy Efficient Economy 2023):

- electricity,
- hydrogen,
- ammonia,
- biofuels,
- synthetic and paraffinic fuels,
- natural gas, including biomethane, in gaseous form (compressed natural gas – CNG),
- liquefied natural gas (liquefied natural gas – LNG),
- liquefied petroleum gas (LPG).

They are classified into three categories: alternative fossil fuels for a transitional phase (CNG, LNG, LPG, synthetic and paraffinic fuels produced from non-renewable energy), alternative fuels for zero-emission vehicles (electricity, hydrogen, ammonia),

1 Therefore, sustainable innovation is associated with the broader concept of sustainability (Basiago 1995; DesJardins 2015) and examined within its three dimensions: economic, social, and environmental (Nasiri et al. 2022).

and renewable fuels (biofuels – biomass fuels and biofuels) (European Alternative Fuels Observatory n.d., *Alternative…*).

Electricity can be used to power electric vehicles, which are increasingly available. In general, the market contains three types of electric vehicles: a) battery electric vehicles (BEVs), b) plug-in hybrid electric vehicles (PHEVs), and c) hybrid electric vehicles (HEVs). All use electricity to improve vehicle efficiency, while some of them still use liquid fuels in conjunction with electricity (EVgo n.d.).

BEVs are fully electric vehicles with rechargeable batteries and no gasoline engine. The energy required for the car is produced from a battery pack, which is recharged from the grid. BEVs are zero-emission vehicles, and they do not generate any harmful emissions.

PHEVs have both an engine and an electric motor to drive the car. They can recharge their batteries through regenerative braking, which recoups energy that is otherwise lost in braking to assist the gasoline engine during acceleration. Their main difference from hybrids is that they have a much larger battery and can plug into the grid to recharge. PHEVs can travel approximately 10–50 kilometers before their gas engines come into operation, and then they run as regular hybrids and can travel several hundred kilometers on a tank of gasoline.

Like PHEVs, HEVs have both a gas-powered engine and an electric motor, and the energy that is required for the battery is produced by regenerative braking. However, unlike PHEVs, HEVs cannot plug into the grid to recharge.

Hydrogen is seen as one of the most promising fuels that can contribute to achieving a zero-carbon economy. It is abundant in the environment, and it is stored in water, hydrocarbons (such as methane), and other organic matter. One of the main challenges seems to be having available hydrogen as a fuel that can be efficiently extracted from these compounds. At the same time, hydrogen's energy content by volume is low, which creates problems with its storage and related conditions as it requires high pressures, low temperatures, or chemical processes to be stored properly. It is very important to overcome such obstacles since, for light-duty vehicles, there is a limited size and weight capacity for fuel storage. As per the existing market situation, light-duty fuel cell electric vehicles (FCEVs) can be fueled up at retail stations in less than five minutes and obtain a driving range of more than 400 kilometers distance (Alternative Fuels Data Center n.d., *Hydrogen*). Hydrogen production from fossil fuels emits a lot of carbon dioxide, but using renewable energy sources (hydropower, wind power, and photovoltaic) provides a nonpolluting alternative (Luo et al. 2020).

The use of ammonia as a fuel is not recent, but its importance has recently increased due to the possibility of decarbonizing various specific sectors. Ammonia is a molecule with the chemical formula NH3. In internal combustion engines (ICE), ammonia efficiency improves when it is blended with other fuels. Doping ammonia with other fossil fuels (especially diesel) is the most technically efficient option, reducing CO_2 and NOx emissions (European Alternative Fuels Observatory n.d., *Alternative…*). Ammonia has several favorable attributes, the primary one being its high capacity for hydrogen storage (Thomas and Parks 2006).

Biofuels mean "biomass fuels" – gaseous and solid fuels produced from biomass. Biodiesel is considered a renewable fuel that is produced from animal fats, vegetable oils, and recycled cooking grease. It can be used in vehicles that consume diesel as a fuel. Biodiesel feedstocks can be categorized into several groups (Huang, Zhou, and Lin 2012):

- oil crops, including soybeans,
- oil trees, including pistachio and palm oil,
- other animal fat, waste oil food.

In particular, fatty acid methyl ester is of great importance as the raw materials used for its production are natural and renewable. All these types of biodiesels come either from vegetables or animal fat, and thus, they are biodegradable and non-toxic. The feedstock of biodiesel depends heavily on climate and local soil conditions, and because of that, different geographical regions align their intentions with different types of oil. For example, soybean oil is mainly used as a raw material in the US, while Germany uses mostly rapeseed oil.

Renewable diesel is a biomass-derived transportation fuel suitable for use in diesel engines. Its production is different from that of conventional biodiesel, allowing it to serve as a drop-in fuel where biodiesel blending is required. In addition, if waste feedstocks such as used cooking oil or animal fats are used, renewable diesel can offer significant CO_2 emissions reductions, qualifying it as a 2nd generation or advanced biofuel (IDTechEx n.d.). Recent fuel regulations support the production of renewable diesel from bio-feedstocks. However, one of the current issues with renewable diesel from vegetable oils and fats is the high level of n-paraffins, which leads to the careful selection of the right process technology to meet diesel cold flow specifications. The latest research shows that proper process technologies are being developed to produce renewable diesel from bio-feedstocks, offering refiners sustainable renewable diesel production options that align with seasonal product specifications (ExxonMobil n.d.).

Synthetic and paraffinic fuels are liquid fuels that typically have the same properties as fossil fuels and can be used in the same way as fossil fuels (No. 2019). The main difference between fossil and synthetic fuels is how they are produced: fossil fuels are formed over millions of years underground from organic matter that is turned into coal, natural gas, or oil. Synthetic fuels are produced by mimicking these natural processes using renewable resources. The production of synthetic fuels requires syngas, which is a mixture of hydrogen (H) and carbon monoxide (CO). Turning syngas into fuel is an established industrial process where coal and natural gas are used as feedstocks. However, the main challenge is to produce syngas sustainably, which requires a large amount of energy from renewable resources, such as biomass, solar, wind, or hydro.

Compressed natural gas (CNG) technology has reached maturity for the general market. Natural gas is available and produced in specific geographical areas and can be supplied through an extensive natural gas distribution system. It is a ready-to-use fuel that is considered a clean-burning alternative fuel that must be compressed or liquefied for use in vehicles.

Natural gas vehicles (NGVs) are very similar to conventional vehicles in terms of performance. However, their share in the car market is much less than that of conventional vehicles such as gasoline and diesel vehicles because the main obstacle with natural gas is that less energy content can be stored in the same size tank. In heavy-duty vehicles, compression-ignited engines are slightly more fuel-efficient than spark-ignited natural gas engines. A dual-fuel engine increases the complexity of the fuel-storage system as it needs more storage of both types of fuel and the integration of diesel aftertreatment devices (Alternative Fuels Data Center n.d., *Natural…*).

Ethanol (CH_3CH_2OH) is a clear, colorless liquid, and it is considered a renewable fuel that is made from starch- or sugar-based feedstocks, such as corn grain (mainly in the United States), sugar cane (mainly in Brazil), or cellulosic feedstocks (i.e., wood chips or crop residues). It is also known as ethyl alcohol, grain alcohol, and EtOH. Ethanol has a higher octane number than gasoline, providing premium blending properties. Lower-octane gasoline can be blended with 10% ethanol to reach the standard 87 octane. It can be used in vehicles as a fuel in a blended form that contains both gasoline and diesel and ethanol's impact on fuel economy is dependent on the ethanol content in the fuel and engine specification (Alternative Fuels Data Center n.d., *Ethanol…*).

Propane is also well known as liquefied petroleum gas (LPG) or propane autogas, and has been used as vehicle fuel for several decades. There is quite a good variety of medium- and heavy-duty propane vehicle models that are already available on the market through original equipment manufacturers (OEMs). Propane is available for light- and medium-duty vehicles as they are designed to handle propane's higher temperatures and lower lubricity (Alternative Fuels Data Center n.d., *Propane…*).

It is important to understand that not all alternative fuels are fully sustainable since the term is mainly used to refer to all unconventional and untraditional energy sources. A typical example is gas – either in the form of natural gas or liquefied natural gas (LNG) – a fossil fuel that produces fewer greenhouse gas emissions and has a role to play in the energy transition in the short term. In the long run, however, alternative fuels must be truly sustainable, and for that, they need to be produced from renewable sources that do not harm the environment (DHL n.d.).

The types of alternative fuels and their features affecting sustainable development are summarized in Table 1.

Table 1. Alternative fuels as sustainable innovation

Type of alternative fuels	Features of sustainable innovation
Electricity	– Supplied by electricity from the grid, coming increasingly from low-CO_2 energy sources – Emits no pollutants or noise
Hydrogen	– It is considered an alternative fuel for zero-emission vehicles – It is a zero-emissions alternative fuel produced from diverse energy sources – It is abundant in the environment
Ammonia	– No carbon emissions at the point of use – More energy-efficient to transport than hydrogen
Biofuels	– Renewable, biodegradable – Replacing fossil fuels with biofuels has several benefits in contrast to fossil fuels, which are exhaustible resources, while biofuels are produced from renewable feedstocks
Synthetic and paraffinic fuels	– They are considered alternative fossil fuels for a transitional phase – They are fully compatible with the existing global fuel infrastructure, and they can be used in conventional internal combustion engines – Renewable synthetic fuels are generally seen as a solution to decarbonize, in particular, those transportation sectors that cannot be electrified
Natural Gas	– It is considered an alternative fossil fuel for a transitional phase – Using natural gas will help reduce the amount of harmful emissions released into the atmosphere. – It is non-toxic, non-corrosive, and non-carcinogenic and can be used in spark-ignited internal combustion engines, like traditional fossil fuels, without being a threat to soil, surface water, or groundwater
Liquefied Petroleum gas (LPG)	– It is considered an alternative fossil fuel for a transitional phase – LPG is stored, shipped, and transported in tanks or cylinders – Primary uses for LPG include powering heating appliances and cooking equipment, as well as fueling vehicles
Liquefied natural gas (LNG)	– It is considered an alternative fossil fuel for a transitional phase – LNG is stored and shipped in purpose-built cryogenic tanks, and thus, LNG is sometimes not a viable option in many developing nations

Source: own elaboration.

Materials and methods

Scope of the study

The study aims to characterize and evaluate the current stage of adoption of AF passenger cars in the passenger car stock (M1) in EU member states. As the study emphasizes the heterogeneity of fuels considered a substitute for fossil oil sources, they were analyzed following the classification provided in the previously mentioned "Proposal for a regulation…", which includes three groups (European Commission 2021):

1. Alternative fuels for zero-emission vehicles: electricity, hydrogen, and ammonia.
2. Renewable fuels: biomass fuels and biofuels as defined in Article 2, points (27) and (33) of Directive (EU) 2018/2001; synthetic and paraffinic fuels, including ammonia, produced from renewable energy.
3. "Alternative fossil fuels" for a transitional phase: natural gas, in gaseous form (compressed natural gas (CNG)) and liquefied form (LNG); LPG; synthetic and paraffinic fuels produced from non-renewable energy.

In practice, the original classification could not be fully employed due to limited data availability, especially in relation to renewable fuels. The most consistent, internationally comparable data could be gathered from the database of the European Alternative Fuels Observatory, which constitutes *a key information support tool for the European Commission in the implementation process of Directive 2014/94/EU* (European Alternative Fuels Observatory n.d., *About*…). By default (apart from individual data shortages – see Table 2), the platform provides a detailed annual breakdown of the alternative vehicle fleet utilizing six types of alternative fuels (BEV, PHEV, H2, LPG, CNG, LNG) from 2009 to 2022. Consequently, the initial classification was transformed into binary form, with two categories:

1) alternative fuels for zero-emission vehicles: BEVs, PHEVs, and hydrogen (H);
2) 'alternative fossil fuels' for a transitional phase: LPG, LNG, and CNG.

In terms of vehicle fleet, the EAFO database presents data in line with the standards developed by the United Nations Economic Commission for Europe (UNECE), which includes passenger cars (M1), light commercial vehicles (N1), buses (M2 & M3), and trucks (N2 & N3)[2]. To preserve conciseness and clarity of information, the study focuses only on one, dominant vehicle class – M1. During the research period, it equaled 95.78% of the AF vehicle stock and had the biggest impact on the reduction

2 The full breakdown of the vehicle categories is presented in "Consolidated Resolution on the Construction of Vehicles (R.E.3)", (United Nations Economic Commission for Europe 2023).

of carbon emissions from road transport.[3] For the same reason, the study evaluates the changes within the total stock of M1 vehicles, leaving aside market share shifts pertaining to new registrations.

Table 2. Data availability concerning the passenger car fleet (M1)

	First obs.	Last obs.		First obs.	Last obs.
Austria	2011	2022	Italy	2009	2022
Belgium	2009	2022	Latvia	2010	2022
Bulgaria	2009	2022	Lithuania	2009	2022
Croatia	2009	2022	Luxembourg	2013	2022
Cyprus	2013	2022	Malta	2012	2022
Czechia	2009	2022	Netherlands	2009	2022
Denmark	2012	2022	Poland	2009	2022
Estonia	2012	2022	Portugal	2010	2022
Finland	2012	2022	Romania	2009	2022
France	2013	2022	Slovakia	2009	2022
Germany	2009	2022	Slovenia	2009	2022
Greece	2009	2022	Spain	2013	2022
Hungary	2009	2022	Sweden	2009	2022
Ireland	2012	2022			

Source: own elaboration, based on EAFO Database (European Alternative Fuels Observatory 2023).

Analytical framework

The current stage of development of the AF passenger car fleet (M1) in the EU–27 was diagnosed using a two-stage analytical framework. In the first step, the market shares of AF vehicles were analyzed to evaluate the collective progress of the European Community in its pursuit of a (more) sustainable road transport sector. The analysis starts with an overview of the current state of adoption of an alternative fleet, represented by the share of AF vehicles in the total passenger car stock (M1) at the end of the research period (2022). The descriptive, static approach is followed by an evaluation of changes concerning the abovementioned ratio observed over the research period (2009–2022). Both stages of the investigation consider the AF fleet at three levels

3 A detailed description of the M1 category reads as "Vehicles used for the carriage of passengers and comprising not more than eight seats in addition to the driver's seat" (United Nations Economic Commission for Europe 2023). The percentage is derived from our calculations based on the EAFO database.

of aggregation: fully aggregated (total), semi-aggregated (zero-emission/transitional), and disaggregated (BEV, PHEV, H2, LPG, CNG, LNG).

The second stage analyzed individual differences between the countries in terms of the development of an alternative fleet of passenger cars. The main focus was on the degree of electrification of the AF M1 car fleet in a given country at the end of the research period, expressed through the ratio of cars utilizing the "alternative fuels for zero-emission vehicles" in relation to "alternative fossil fuels for a transitional phase". Two groups were then created:

1) countries with a dominant share (50% or more) of passenger cars that utilize "alternative fuels for zero-emission vehicles" in the total AF M1 vehicle stock;
2) the remaining countries, where the main alternative fuels constitute "alternative fuels for a transitional phase".

In the next step, the groups were examined in terms of the current relative size of the AF vehicle fleet, its structure, and growth over time, as well as the sources of the overall growth or decrease in the AF M1 fleet. The study is not intended to provide in-depth explanations for the identified trends, and only general, publicly accessible explanations are given to signal the potential directions for further research.

Results, discussion, and implications

The alternatively fueled passenger car fleet of the EU–27

In 2022, vehicles powered by alternative fuels accounted for 5.75% of the total EU–27 M1 passenger car fleet. Despite progress in electrifying road transport, at the end of the research period, the majority (60.75%) of AF M1 fleets still utilized fuels "for a transitional phase" – primarily LPG and CNG as an alternative. The use of LNG could be described as marginal, as it has been statistically demonstrated only in Lithuania and the Netherlands. Nearly all the clean-energy vehicle stock comprised one of the two variants of electric cars – BEVs or PHEVs, with a balanced ratio and similar growth rates (Table 3). As of 2022, hydrogen (H2) could not be considered a significant alternative energy source, as it was used in only 0.002% of passenger cars.

Table 3. Development of AF passenger car fleet within the M1 vehicle stock in the EU–27 (%)

	BEV	PHEV	H2	LPG	CNG	LNG	AF fleet (Total)	Share (1)	Share (2)
2013	0.021	0.015	0.000	3.068	0.417	–	3.520	98.998	1.002
2014	0.034	0.025	0.000	3.087	0.445	–	3.592	98.358	1.642
2015	0.052	0.055	0.000	3.103	0.464	–	3.674	97.073	2.927

	BEV	PHEV	H2	LPG	CNG	LNG	AF fleet (Total)	Share (1)	Share (2)
2016	0.071	0.081	0.000	3.099	0.467	–	3.718	95.909	4.091
2017	0.103	0.107	0.000	3.048	0.468	–	3.726	94.361	5.639
2018	0.155	0.144	0.000	3.142	0.478	–	3.920	92.363	7.637
2019	0.249	0.194	0.000	3.131	0.486	–	4.060	89.070	10.930
2020	0.450	0.385	0.001	3.069	0.492	0.000	4.397	80.989	19.011
2021	0.800	0.731	0.001	3.034	0.483	0.000	5.050	69.659	30.341
2022	1.189	1.066	0.002	3.011	0.482	0.000	5.750	60.748	39.252

Explanatory notes:

Share (1) of the AF passenger car stock (M1) that utilizes "alternative fuels for a transitional phase".

Share (2) of the AF passenger car stock (M1) that utilizes "alternative fuels for zero-emission vehicles".

Source: own calculations based on EAFO Database (European Alternative Fuels Observatory 2023).

Between 2013 and 2022, the EU–27 stock of AF passenger cars grew by 63.34%, from 3.52% to 5.75% of the total M1 fleet. Although the growth was generally consistent, it was hardly noticeable from 2013 to 2017, when the relative size of the AF fleet was almost entirely determined by the prevalence of its major components – LPG and CNG-fueled vehicles, which remained steady over the research period. This trend was ended by the rapid growth of BEV and PHEV fleets in recent years (mainly after 2019), which resulted in a 2.26% share of the clean-energy fleet in total M1 stock in 2022 (Figure 1).

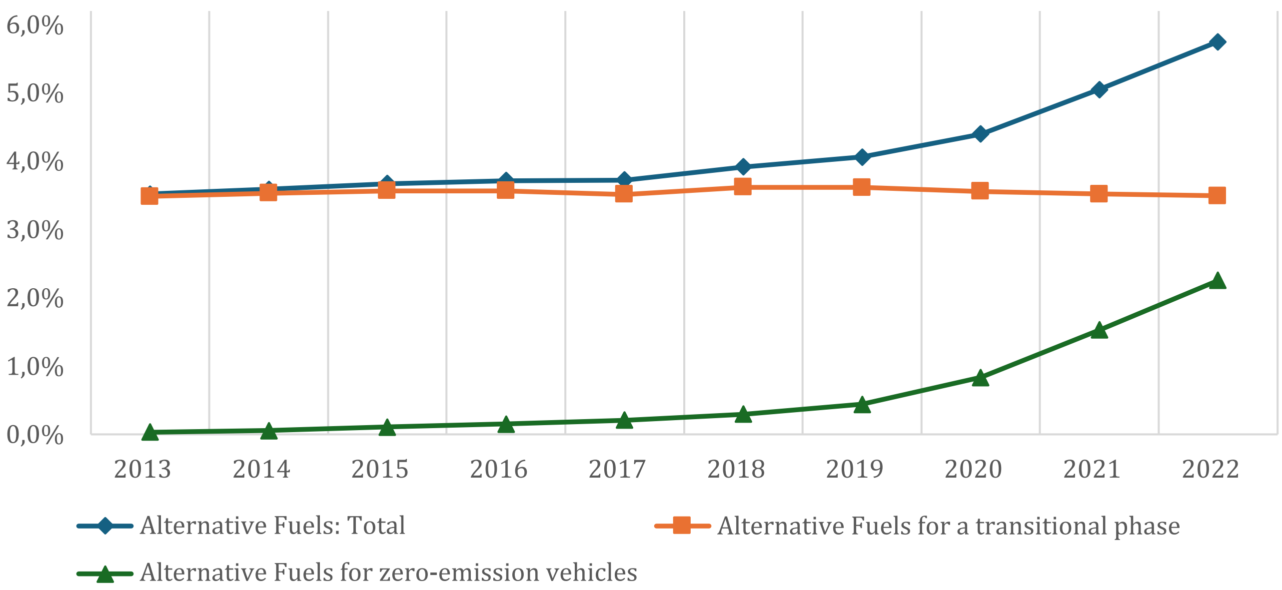

Figure 1. Visual presentation of growth in alternatively fueled passenger car fleet within the M1 vehicle stock in the EU–27

Source: own calculations based on EAFO Database (European Alternative Fuels Observatory 2023).

Group 1 – countries where zero-emission alternative fuels (BEV, PHEV, H2) play a predominant role

Given the steady share of passenger cars that use transitional fuels, the growth of AF M1 stock was determined by the speed of its electrification. At the end of the research period, the electric (BEV) and hybrid (PHEV) passenger cars were the leading AF fleets in 15 of the 27 EU member states, comprised mainly of Nordic and Western European countries (Table 4). The ratio of 84.16% to 15.84% indicates an advanced stage of the process, which was characterized by extraordinary dynamism. For the vast majority of the countries in Group 1, the proportion of transitional to clean-energy fuels fully reversed over less than a decade, which is illustrated in Figure 2. The turning point came in 2019 when, following Regulation (EU) 2019/631, the EV fleet finally outnumbered gas-powered vehicles. This began a rapid (exponential) growth phase, which led to a share of 3.33% EVs in total M1 vehicle stock at the end of the research period – significantly higher than the EU average (2.26%) (Figure 3).

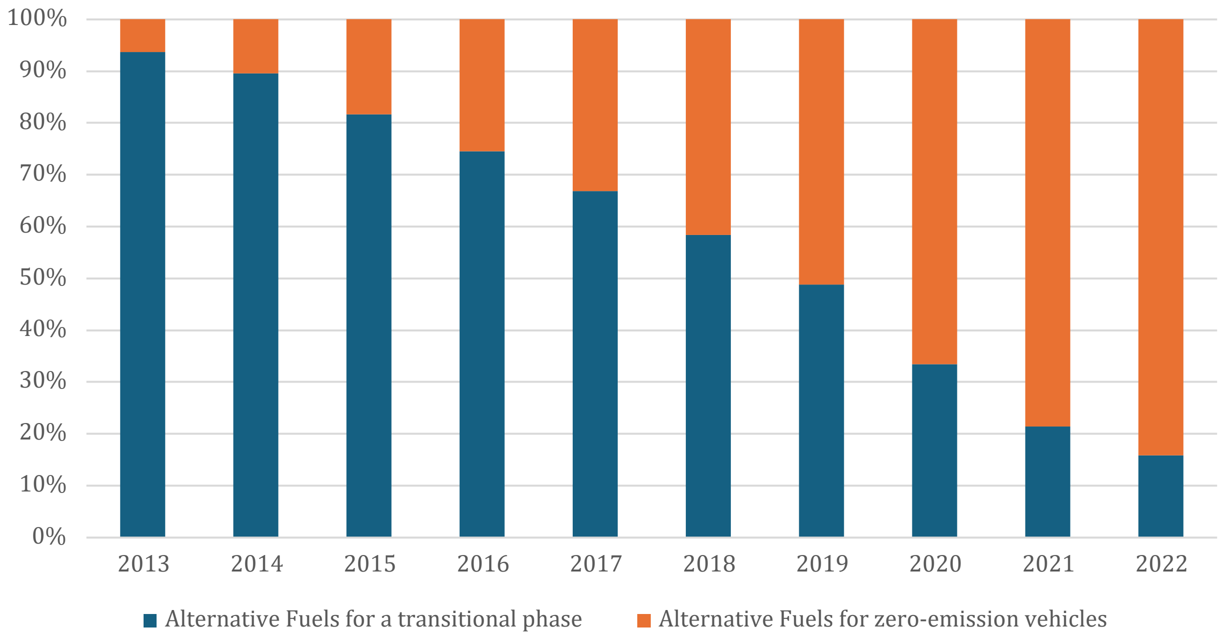

Figure 2. The progression of the structure of the passenger car fleet powered by alternative fuels in Group 1

Source: own calculations based on EAFO Database (European Alternative Fuels Observatory 2023).

At the current stage of development, the Group 1's share of the AF fleet in total M1 stock remains lower (3.96%) than the analogous fraction calculated for the EU-27 as a whole (5.75%).[4] On an individual level, the ratio was highest in Sweden, which also

4 Since the highest shares of AF fleet were observed in countries with lower population levels (Sweden, Netherlands, Denmark, Luxembourg), which jointly accounted only for 10.85% of group's total AF vehicle fleet, the difference is reduced when the medians (group 1: 3.22%; EU–27: 3.38%) or averages (group 1: 4.17%; EU–27: 4.62%) are compared.

achieved the highest growth rate of the AF fleet in the EU–27. The rapid adoption of BEV and PHEV vehicles in the Nordic countries is attributed primarily to the purchase incentives aimed at reducing the price gap between EVs and internal combustion engine vehicles. Among them, fiscal incentives played the biggest role, primarily exemptions from or reductions in vehicle registration taxes (which are exceptionally high compared to the rest of the EU), with the rates differentiated based on CO_2 emissions or fuel economy ratings (International Energy Agency 2018). In Sweden, with the lower standard registration tax rates, the main government-based incentive constituted a one-off "super green car rebate" subsidy (*supermiljöbilspremie*) of a varying amount, granted after the purchase of a new car with less than 60 g/km CO_2 emission rate. Introduced in 2012, the scheme was abruptly abolished on November 8th, 2022.

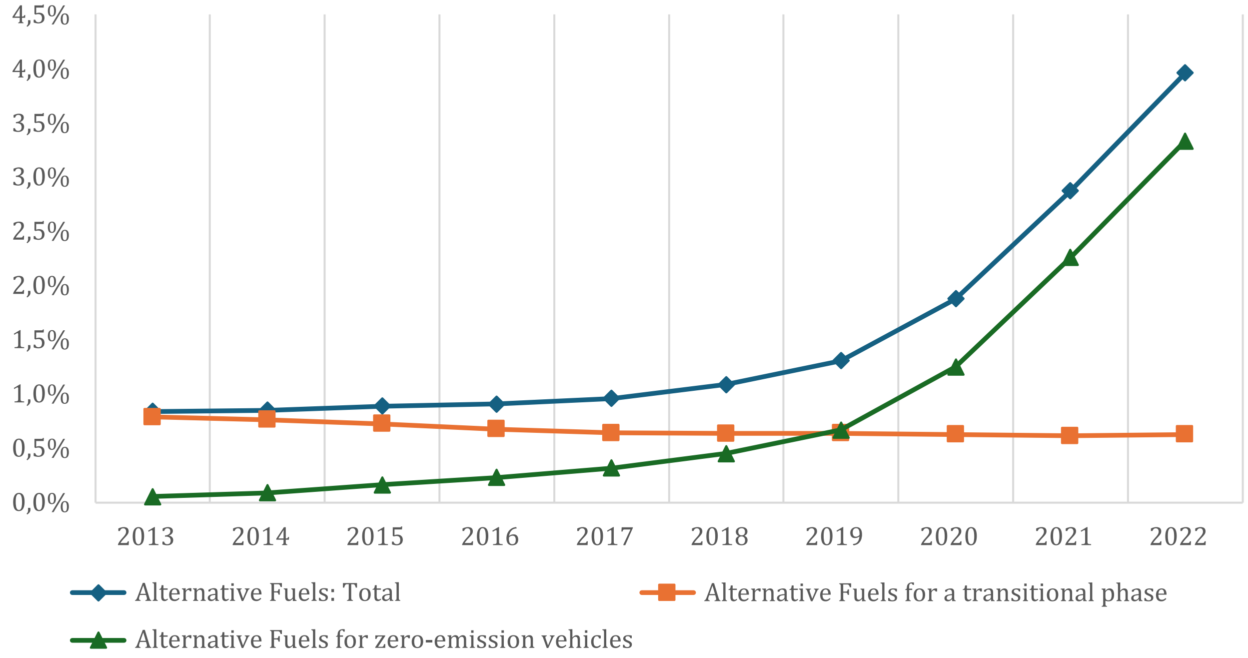

Figure 3. Visual presentation of growth in the alternatively fueled passenger car fleet within Group 1's M1 vehicle stock, 2013–2022

Source: own calculations based on EAFO Database (European Alternative Fuels Observatory 2023).

Lastly, a small fraction of the Nordics' impressive AF fleet growth rate can be attributed to a parallel increase in gas-powered car fleets (CNG), which shows that "transitional" and clean-energy solutions do not have to be mutually substitutable. Among the three countries in question, it was most evident in Finland, where the share of CNG passenger cars in the total M1 stock increased by 1305.75% (from 0.03% in 2012 to 0.42% in 2022), which contributed 8.69% to the total AF fleet growth.

In Sweden, the percentage of CNG cars has almost doubled since 2009 (from 0.46% to 0.90%), but the growth stalled permanently in 2012 with the introduction of the previously discussed price subsidies for clean-energy passenger cars. Outside of the region, even more evident parallel growth was observed in Spain and Malta, where the expansion of transitional (predominantly LPG) vehicle stock constituted 28.29% and 25.97% of the total AF growth rate within the respective periods (Table 2). The opposite scenario took place in the Netherlands and Hungary, where the shrinking fleet of LPG passenger cars reduced the EV-driven growth of the AF fleet by as much as 43.08% and 33.37%, respectively.

A detailed, individual structure of the alternatively fueled passenger car fleet in 2022 is presented in Table 4.

Table 4. Detailed structure of Group 1's alternatively fueled passenger car fleet, 2022

2022	BEV (%)	PHEV (%)	H2 (%)	LPG (%)	CNG (%)	LNG (%)	AF fleet (Total, % of M1)	AF fleet growth (pp.) †	Share (%)‡
DK	3.460	3.481	0.008	0.000	0.004	–	6.954	6.901	99.934
IE	1.510	1.070	–	0.023	0.008	–	2.611	2.601	98.824
LU	3.260	2.859	0.001	0.059	0.033	–	6.212	6.082	98.525
AT	2.140	0.821	0.001	0.006	0.101	–	3.069	2.987	96.513
SE	4.179	5.500	0.001	0.000	0.901	–	10.582	10.109	91.482
FI	1.285	2.840	0.000	0.000	0.422	–	4.547	4.508	90.718
BE	1.560	3.080	0.002	0.286	0.317	–	5.245	4.424	88.498
FR	1.730	1.046	0.001	0.439	0.007	–	3.224	2.668	86.156
CY	0.093	0.110	–	0.036	–	–	0.238	0.237	85.077
NL	3.690	2.101	0.007	1.180	0.085	0.000	7.062	4.052	82.098
DE	2.000	1.911	0.004	0.695	0.173	–	4.783	3.724	81.857
MT	0.820	0.856	–	0.581	–	–	2.257	2.237	74.260
ES	0.420	0.543	0.000	0.312	0.068	–	1.343	1.329	71.703
PT	1.160	1.014	0.000	0.944	0.003	–	3.121	2.309	69.673
HU	0.387	0.353	–	0.560	0.055	–	1.354	0.554	54.588
TOTAL Group 1	1.759	1.571	0.002	0.501	0.126	0.000	3.959	3.119	84.160

Explanation of abbreviations: DK – Denmark; IE – Ireland; LU – Luxembourg; AT – Austria; SE – Sweden; FI – Finland; BE – Belgium; FR – France; CY – Cyprus; NL – Netherlands; DE – Germany; MT – Malta; ES – Spain; PT – Portugal; HU – Hungary.

Explanatory notes:

† The percentage-point change in the AF fleet share within M1 stock during the research period (see Table 2).

‡ The share of passenger cars utilizing the "alternative fuels for zero-emission vehicles" in the AF vehicle stock (BEV, PHEV, H2).

Source: own calculations based on EAFO Database (European Alternative Fuels Observatory 2023).

Group 2 – the EU countries with the predominant role of transitional alternative fuels (LPG, CNG, LNG)

Changes pertaining to passenger cars utilizing gaseous fuels had incomparably more significance in the case of countries experiencing earlier stages of the electrification process, which relied on LPG as the main alternative to gasoline and diesel vehicles (Group 2). Like Group 1, Group 2 is largely geographically homogenous, as it almost exclusively comprises Central and Eastern European (CEE) countries, apart from Italy and Greece. Due to the prominent cases of established use of LPG in said countries, the group achieved in 2022 a higher share of AF passenger cars (with Poland being the EU's leader) but also a considerably lower growth rate. From 2018, the increase in the size of the EV fleet – although exponential – was sufficient only to offset the parallel decline in gas car usage, which has resulted in maintaining the general level and structure of the AF M1 vehicle stock (see Figures 4 and 5).

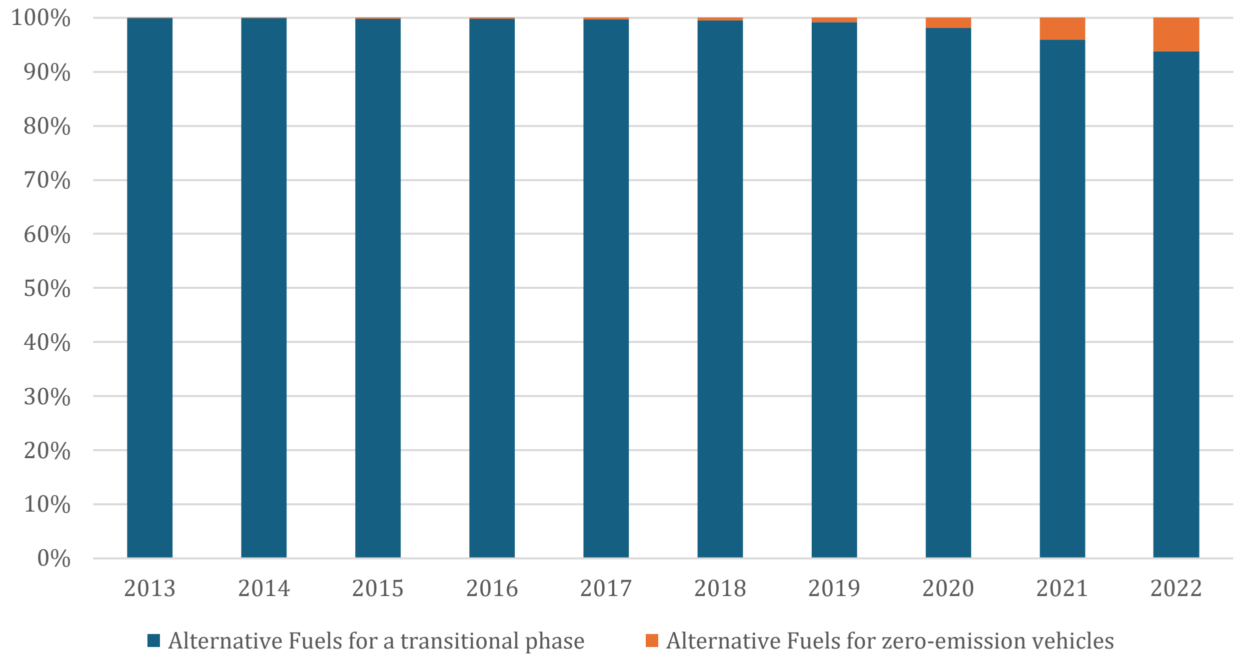

Figure 4. The progression of the structure of Group 2's passenger car fleet powered by alternative fuels

Source: own calculations based on EAFO Database (European Alternative Fuels Observatory 2023).

The individual level and trajectory of the AF fleet's growth is much more diverse than reported in the previous group. The most important feature is the presence of four countries experiencing an overall decline in the relative share of AF fleet: Lithuania (–4.86 p.p.), Czechia (–1.51 p.p.), Poland (–1.31 p.p.), and Romania (–1.16 p.p.). In all the cases, the decline was led by a substantial decrease in the market share of LPG-powered vehicles, which has not been compensated for by a parallel growth of CNG, LNG, or EV fleets (including hybrids). Instead, almost all of the group's passenger car markets (except for Italy) experienced an increasing demand for diesel vehicles. They have been gradually replacing petrol vehicles, and in 2021, constituted almost half (45.71%) of the group's ICE passenger cars fleet. The trend was most noticeable in Lithuania, where the diesel market share growth of 62.79% increased the relative size of the ICE fleet by 9.80% (Eurostat 2023)[5].

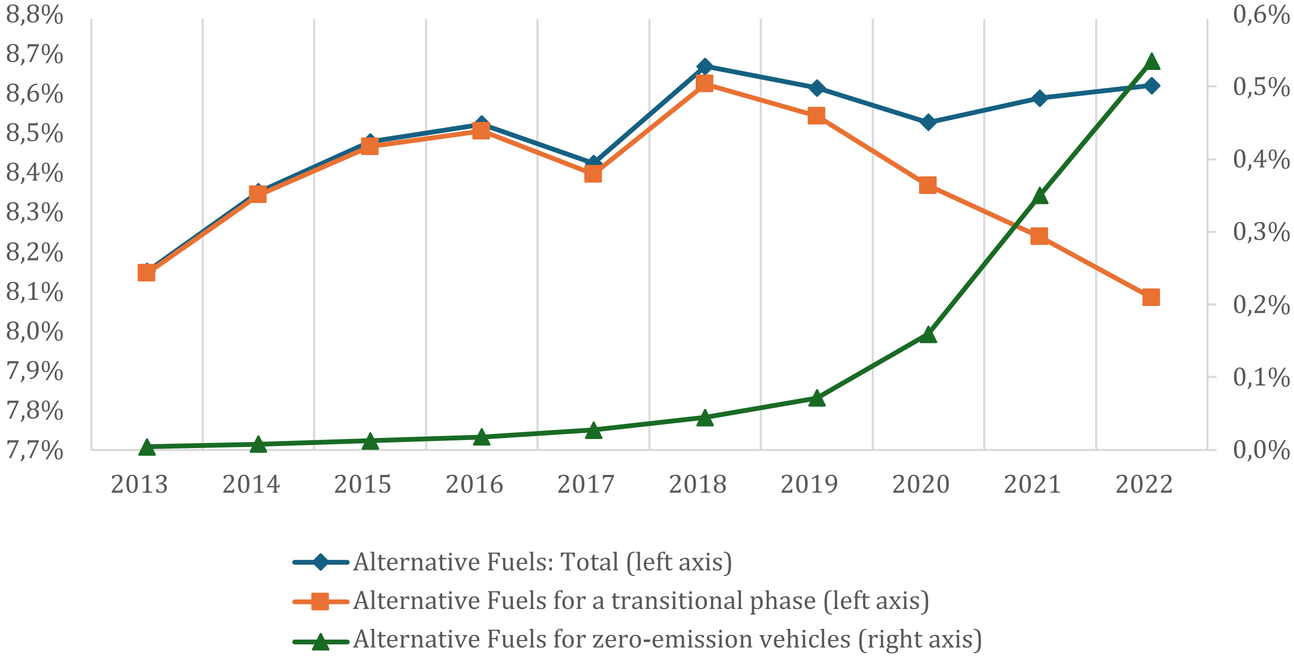

Figure 5. Visual presentation of growth in the alternatively fueled passenger car fleet within Group 2's M1 vehicle stock, 2013–2022

Source: own calculations based on EAFO Database (European Alternative Fuels Observatory 2023).

As indicated by a positive aggregated AF fleet growth rate (0.47 p.p.), the predominant scenario within Group 2 was the increase in the share of the AF fleet, which resulted almost entirely from an expansion of the LPG-fueled passenger car fleet. The biggest and most consistent growth of this kind was observed in Italy (3.99 p.p.), and it is largely attributable to favorable taxation, vehicle acquisition and conversion incentives, as well as local measures to encourage the purchase of clean vehicles (World LPG Association (WLPGA) and Liquid Gas Europe 2022). The LPG stock also grew considerably in Latvia and Greece, but the upward trend was more unstable, with the AF share peaking in the middle of the research period (in 2014 and 2016, respectively) and decreasing afterward.

The demand for "autogas" vehicles was generally driven by cost factors. Over the years, LPG has enjoyed a substantial excise-tax advantage, which translated into a significant, favorable price gap compared to diesel and gasoline. For example, in 2021, the pump price of LPG in Italy was equal to 43.48% of that of petrol and 47.55% of that

5 Own calculations based on Eurostat's Passenger cars, by type of motor energy [ROAD_EQS_CARPDA] dataset (Eurostat 2023). Scope of the data: years 2013–2021; countries: Poland, Latvia, Croatia, Italy, Lithuania, Czechia, Romania, Estonia, Slovenia.

of diesel. Since 2014, the demand has additionally been boosted in Italy by a government scheme that partially covers the conversion purchase costs of an LPG vehicle, with a refund amount conditional on CO_2 emissions. In 2019, the scheme was abolished in favor of a new eco-bonus program that promotes the purchase of a new electric, hybrid, or methane gas-powered car (World LPG Association (WLPGA) and Liquid Gas Europe 2022).

Table 5. Detailed structure of Group 2's alternatively fueled passenger car fleet, 2022

2022	BEV (%)	PHEV (%)	H2 (%)	LPG (%)	CNG (%)	LNG (%)	AF fleet (Total, % of M1)	AF fleet growth (pp.)†	Share (%)‡
PL	0.096	0.099	0.000	12.580	0.019	–	12.794	–1.306	98.471
BG	0.107	0.067	–	5.980	0.739	–	6.893	1.053	97.478
LV	0.366	0.073	–	6.200	0.031	–	6.670	3.362	93.421
EL	0.101	0.197	–	3.624	0.078	–	4.000	3.610	92.560
HR	0.209	0.089	–	3.070	0.007	–	3.375	0.385	91.165
IT	0.431	0.459	0.000	6.380	2.452	–	9.722	3.991	90.845
LT	0.439	0.295	0.000	6.150	0.051	0.003	6.939	–4.861	89.424
CZ	0.221	0.139	0.000	2.500	0.363	–	3.225	–1.505	88.824
RO	0.295	0.105	–	2.790	0.003	–	3.193	–1.161	87.493
SK	0.178	0.165	0.000	1.840	0.109	–	2.292	2.202	85.023
EE	0.350	0.075	0.000	0.728	0.252	–	1.405	1.035	69.703
SI	0.635	0.129	–	0.940	0.019	–	1.723	1.443	55.659
TOTAL group 2	0.277	0.257	0.000	7.032	1.051	0.000	8.619	0.469	93.797

Explanation of abbreviations: PL – Poland; BG – Bulgaria; LV – Latvia; EL – Greece; HR – Croatia; IT – Italy; LT – Lithuania; CZ – Czechia; RO – Romania; SK – Slovakia; EE – Estonia; SI – Slovenia.

Explanatory notes:

† The percentage-point change in the AF fleet share within M1 stock during the research period (see Table 2).

‡ The share of passenger cars utilizing the "alternative fuels for a transitional phase" in the AF vehicle stock (LPG, CNG, LNG).

Source: own calculations, based on the EAFO Database (European Alternative Fuels Observatory 2023).

Conclusion

The deployment of alternative fuel vehicles, defined as vehicles powered by sources that serve as a substitute for fossil oil sources, is an important measure in achieving the EU's objective of reducing greenhouse gas emissions from transport by 90% by 2050 compared to 1990 levels. The study characterized this process on a sample of EU–27 countries based on the developments observed between 2009 and 2022.

The results indicate that the speed of diffusion of electric and hybrid vehicles is largely heterogeneous across the EU–27, with an evident two-speed pattern. At the end of the research period (2022), the largest group, which comprised 15 out of the 27 EU member states, represented the countries with a predominant share (84.16%) of electric (BEV) and hybrid (PHEV) vehicles in their AF passenger car fleet (Group 1). The group, comprised mainly of Nordic and highly developed Western European countries, was characterized by a share of AF vehicles within the total M1 vehicle stock that was lower than the EU average (3.96% in 2022) yet exceptionally dynamic and rapidly growing. Although almost all the growth can be attributed to the exponential expansion of BEV/PHEV vehicles, some of the countries experienced a parallel increase in the gas-powered fleet (LNG/LPG). This was most evident in Spain and Malta, where the expansion of the LPG vehicle stock constituted 28.29% and 25.97% of the total AF growth rate within the respective periods (Table 2). The opposite scenario took place in the Netherlands and Hungary, where the shrinking fleet of LPG passenger cars reduced the EV-driven growth of the AF fleet by as much as 43.08% and 33.37%, respectively.

"Transitional" gaseous fuels (mainly LPG) were the leading alternative fuel in Group 2, which consists of CEE countries, Italy, and Greece, with an even more one-sided ratio of 93.80% to 6.20%. Over the last decade, the relative size of the group's AF M1 stock grew significantly slower than in Group 1 – from 8.15% in 2013 to 8.62% in 2022, with a peak of 8.67% in 2018. The lack of growth from 2018 onwards stems from the fact that the dynamic expansion of electric and hybrid vehicle M1 stock has been fully offset by the parallel decline in LPG usage. In four CEE countries (Lithuania, Czechia, Poland, and Romania), the recent contraction of LPG-fueled vehicle stock exceeded the EV growth, which led to an overall decline in the relative share of the AF fleet.

The results emphasize the need to diversify alternative fuels, which should be introduced gradually, as outlined by their classification proposed by Directive 2014/94/EU of the European Parliament and the Council, depending on the socio-economic development and infrastructural readiness of the country. In this context, the main focus is LPG, which remained the EU's most widespread alternative fuel in 2022, utilized in 52.37% of its AF passenger car fleet. Given the current circumstances, such as a shrinking LPG fleet and rising demand for diesel vehicles, exclusively focusing on battery-electric vehicles in LPG-dominated countries is likely to lead to a temporary increase in the market share of ICE cars (assuming the current pace of electrification remains unchanged). Consequently, this may result in higher greenhouse gas emissions from transport. Statistical verification of this scenario could be the subject of further research.

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Paliwa alternatywne jako zrównoważona innowacja we flocie pojazdów UE–27: diagnoza i perspektywy rozwoju

Rozszerzenie floty pojazdów napędzanych paliwami alternatywnymi stanowi ważny instrument realizacji celów klimatycznych Unii Europejskiej. Celem badania jest scharakteryzowanie i ocena, w sposób porównawczy, obecnego etapu popularyzacji samochodów osobowych napędzanych paliwami alternatywnymi w państwach członkowskich UE. Punktem centralnym badania jest eksploracja podobieństw i różnic obserwowanych pomiędzy krajami unijnymi w odniesieniu do aktualnej struktury floty pojazdów napędzanych paliwami alternatywnymi oraz tendencji rozwojowych w tym zakresie. W tym kontekście zaobserwować można wyraźny schemat „dwóch prędkości" – równolegle do szybkiego rozpowszechniania pojazdów elektrycznych w krajach skandynawskich i zachodnioeuropejskich wielkość i struktura floty pojazdów napędzanych alternatywnie pozostała w dużej mierze niezmieniona w krajach Europy Środkowej, z wciąż dominującą rolą utrwalonego na tych rynkach skroplonego gazu płynnego (LPG). Wyniki badania podkreślają potrzebę dywersyfikacji paliw alternatywnych, które należy wprowadzać stopniowo, zgodnie z klasyfikacją zaproponowaną w dyrektywie 2014/94/UE Parlamentu Europejskiego i Rady.

Słowa kluczowe: paliwa alternatywne, zrównoważone innowacje, zrównoważony rozwój, flota samochodów osobowych, UE–27, środowisko