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Decarbonising transport in Europe: Trends, goals, policies and passenger car scenarios

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A B S T R A C T

The paper has two main goals: to draw a summary picture of the progress made towards transport decarbonisation in Europe, and to identify future developments concerning the 2020–2030 decade. The analysis is based on the 4th and 5th reports prepared by the Member States under the obligation Renewable Energy Directive (2009/28/EC) and on the National Energy and Climate Plans (NECPs) for the 2020–2030 decade, paying specific attention to the use of renewables in the transport sector. We find that the Member States rely on two strategies: increasing the production and use of biofuels, especially those produced by advanced materials, and supporting the diffusion of electric vehicles. Performing a scenario analysis capturing the planned policies and goals indicated in the NECPs, we estimate that the biofuel strategy can deliver a GHG reduction of up to 19 MtCO2eq (−3.6%), while the electrification strategy can deliver a GHG reduction up to 45 MtCO2eq (−8.3%). Jointly used, the GHG reduction could reach up to 64 MtCO2eq (−11.9%).

1. Introduction

In 2017, the transport sector generated 27% of total EU-28 greenhouse gas (GHG) emissions (22% if international aviation and maritime emissions are excluded),[1] equal to 1104 million tonnes CO2-equivalents (MtCO2eq) and 28% above the 1990 levels. International aviation was responsible for the largest percentage increase in GHG emissions over 1990 levels (+129%), followed by international shipping (+32%) and road transport (+23%). GHG emissions need to fall by around two thirds by 2050, compared with 1990 levels, in order to meet the long-term 60% reduction target set out in the 2011 Transport White Paper. Road transport was responsible for 71.7% of the total GHG emissions, maritime transport for 13.3%, aviation for 13.9%, railways for 0.5%, and the other transport modes for the remaining 0.6%. Of the 71.7% road transport share, cars were responsible for 43.2%, heavy-duty trucks and buses for 18.7%, light duty trucks for 8.5% and motorcycles for 0.9%. Most countries, but Sweden and Lithuania, increased the GHG emissions from transport in the 1990–2017 period, some of them (e.g. Poland) by a very large margin (Fig. 1).

The increase of transport's GHG emissions took place while other sectors succeeded decreasing their share (Table 1). The data, available at aggregate level also for the year 2018, indicate that the overall GHG emissions decreased by 21%. Transport is the only sector increasing in absolute terms.

In order to contribute to reduce GHG emissions and limit the average temperature growth, transport is, hence, a key sector. In this paper, we will not discuss the causes of the growth of transport's GHG emissions but rather on the efforts and procedures set up at European level to contain and possibly reduce them. The EU has enacted several pieces of legislation trying to curb GHG emissions. Since the energy sector is responsible for more than 50% of the EU's GHG emissions, increasing the share of renewable energy has been considered a key building block to achieving climate neutrality. A major first piece of legislation has been the Renewable Energy Directive (2009/28/EC). It set the target to generate at least 20% of the total energy needs with renewable energy by 2020 to be achieved through the attainment of individual national

Abbreviations: BEV, Battery Electric Vehicle; ETS, emissions trading system; GHG, Greenhouse Gas; HEV, Hybrid Electric Vehicle; ICE, Internal Combustion Engine; LCA, life cycle analysis; MS, Member State; NECP, National Energy and Climate Plan; PHEV, Plug-In Hybrid Electric Vehicle; RES-E, renewable energy sources used in electricity production; RES-O, renewable energy sources used overall; RES-T, renewable energy sources used in transport; TTW, Tank-To-Well; WTW, Well-To-Wheel.

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[1] Source: https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-greenhouse-gases/transport-emissions-of-greenhouse-gases-12#:~:text=In%202017%2C%2027%20%25%20of%20total,by%202.2%20%25%20compared%20with%202016. Accessed on October 26th, 2020.

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targets. With specific regards to transport, the goal was for all EU countries to ensure that at least 10% of their transport fuels came from renewable sources by 2020. Every two years, EU countries were required to report on their progress. So far, 5 out of 6 reports have been published in the EU directive website.[2] In December 2018, the EU enacted the recast Renewable Energy Directive (2018/2001/EU) to reinforce the goals and obligations, in accordance with the Paris agreement. The Directive sets the following binding targets to be achieved by 2030:

- reduce GHG emissions by at least 40% compared with 1990;
- increase energy efficiency to at least 32.5%;
- increase the share of energy from renewable sources in gross final energy consumption in the EU to at least 32%;
- ensure a level of electricity interconnection between Member States equivalent to at least 15%.

The Directive includes new provisions for enabling self-consumption of renewable energy, an increased 14% target for the share of renewable fuels in transport by 2030 and strengthened criteria for ensuring bio-energy sustainability. Only biofuels complying with the sustainability criteria set in the Renewable Energy Directive and the Fuel Quality Directive (2009/30/EC) are considered for this target. In order to ensure a coordinated approach across the Union, each Member State (MS) was required to submit by December 31, 2018 a draft of a National Energy and Climate Plan (NECP) for the 2021–2030 period. The NECPs outline how the EU countries intend to address energy efficiency, renewables, GHG emissions reductions, interconnections, research and innovation. On September 2020, the Commission published a detailed EU-wide assessment of the final NECPs with guidance on their implementation. Other major pieces of legislation of the EU's policy to combat climate change are the 2005 EU emissions trading system (EU ETS), operating on the 'cap and trade' principle which generated the world's first and largest major carbon market, the Regulation (EU) 2019/631 setting new CO2 emission standards for cars and vans and Regulation (EU) 2019/1242 setting CO2 emission standards for heavy-duty vehicles.

Table 1
Greenhouse gas emissions, analysis by source sector, EU27, 1990 and 2018 (Million tonnes of CO2 equivalents).

	1990	2018	2018/1990	Share 1990	Share 2018
Energy-related fuel combustion and fugitive emissions from fuels (without transport)	3062	2079	68%	62.3%	53.4%
Transport (including international aviation)	726	957	132%	14.8%	24.6%
Industrial processes and product use	448	344	77%	9.1%	8.8%
Agriculture	497	394	79%	10.1%	10.1%
Waste management	174	117	67%	3.5%	3.0%
Other sectors	0	0	–	0.0%	0.0%
Total (without LULUCF, with int. aviation)	4912	3893	79%	100.0%	100.0%

This paper has two main goals: draw a summary picture of the progress made towards transport decarbonisation in Europe based on the national reports for the years 2015 and 2018, and identify future developments on the basis of the NECPs concerning the 2020–2030 decade. To achieve the first goal, we have analyzed the 4th and 5th reports prepared by the MSs under the obligation of the Renewable Energy Directive (2009/28/EC), paying specific attention to the use of renewable resources in the transport sector. The national reports provided us with information on the total share of renewable energy used in transport (RES-T), on the amount of biofuels' consumption and renewable electricity used in transport, and on the implemented and planned transport policies in the period 2015–2018. To achieve the second goal, we have compared the NECPs prepared by the MSs, with special attention to their goals concerning the RES-T and RES-E (share of electricity produced using renewable sources), and the planned transport policies for the decade 2020–2030. Based on such goals and policies, we estimated their potential to reduce GHG emissions. We developed a probabilistic model that accounts for uncertainty in GHG emission factor

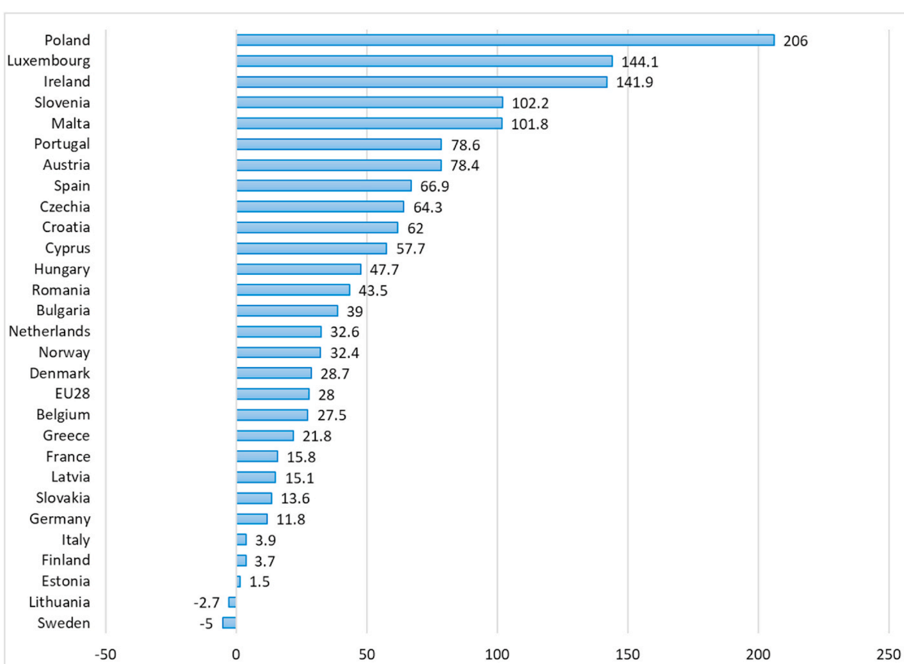

Fig. 1. Change 1990–2017 — Percentage change in total greenhouse gas emissions from transport.

[2] https://ec.europa.eu/info/energy-climate-change-environment/overall-targets/national-energy-and-climate-plans-necps_en.

parameters and performed scenario analyses based on a set of possible developments. The scenarios capture the two main strategies illustrated in the NECPs: the introduction of higher blending levels of biofuels (biodiesel, bioethanol, biomethane) for the combustion engine cars and the electrification of the car fleet. We obtained results at country level, aggregated them at European level, and compared the relative effectiveness of the two strategies as well as their combined impact. The results indicate that significant (up to 11%) GHG emissions reductions are possible. Specific features of our study compared to the previous ones are the probabilistic approach, the joint analysis of both strategies (biofuels and electrification), the level of disaggregation, and the joint use of RES-T and RES-E goals to estimate the gains from electrification. The pros and cons of our estimates are further discussed in Section 5.3.4.

The paper is structured as follows. Section 2 reviews the literature on decarbonising transport in the EU; Section 3 analyses the achievements and policies enacted in the period 2015–2018; Section 4 compares the NECPs in terms of goals and strategies; and Section 5 presents the GHG emission model, illustrates the scenarios and discusses the results. Section 6 summarizes the main findings.

2. Literature review on decarbonising transport in the European Union

As pointed out in the pioneering work by Skinner et al. (2010), decarbonising transport in the EU is challenging, given that transport's GHG emissions have continued to increase despite advances in low-carbon technology and goals setting by at EU and national level. Since the literature on transport decarbonisation is abundant and rapidly growing, we will focus our attention only on the recent studies aiming at shaping EU policies, stemming from EU funded research centers, consulting firms, environmental associations or lobbying groups. We will also limit our discussion to the two main decarbonisation strategies discussed in this paper: the development of biofuels and the electrification of the light vehicle fleet.

Miller (2016) authored a study for the International Council on Clean Transportation comparing potential low-carbon road transport policies for achieving the 2030 target for the transport sector. The focus is on light-duty vehicles (LDV) including passenger cars and vans, and heavy-duty vehicles (HDV) including medium trucks, heavy trucks, and buses. With the existing policies Miller (2016) forecasted for the year 2030 a 7.6% increase of direct CO2 emissions from LDVs and HDVs over the period 2005 to 2030. The inclusion of road transport in the EU ETS, effectively putting a price on GHG emissions from the combustion of fuels for road transport, is judged to be entirely insufficient considering the magnitude of GHG reductions targeted and the minimal fuel price impact of including road transport in the ETS. The adoption of LDV and HDV CO2 standards is valued positively. When stronger targets are introduced, they could avoid 144 Mt in 2030 – equivalent to a more than 50% increase in emission benefits. The electrification strategy, transitioning the LDV fleet to electric-drive vehicles, could avoid 19 Mt in 2030 against the 2030 baseline, even after assuming internal combustion and hybrid vehicles meet stringent CO2 targets. Efforts to decarbonize the grid could further limit the indirect emissions from electricity supplied to electric vehicles. On the contrary, Miller (2016) valued critically the biofuels strategy. He deemed the new biofuel policies not an attractive option if only aiming to reduce direct transport emissions, since biofuels and conventional fuels have similar direct combustion emission factors. Considering fuel lifecycle impacts, however, Miller (2016) argued that expanded deployment of second generation biofuels would have significant benefits compared to first generation biofuels (26 Mt in 2030), since they have lower indirect emissions. Combining the above policies could reduce direct emissions by 282 Mt compared to the baseline in 2030, equivalent to 24% below the 2005 baseline.

A different opinion on biofuels' potential to reduce GHG emissions was proposed in 2016 by the European Renewable Ethanol Association (ePURE). They presented a document (ePURE, 2016) in which they argued that the Fuel Quality Directive must be extended and strengthened by introducing an ambitious and binding ramping up target to reduce the carbon intensity of transport fuels by at least 12% (against the 2010 baseline) by 2030, of which at least a quarter should come from advanced biofuels. They claimed that transport fuel emissions reductions by at least 3% could be achieved solely from advanced biofuels by 2030. The inclusion of 5% in volume in the petrol protection grade of E5, the full roll-out of E10 (petrol containing 10% ethanol in volume), and the introduction (at the latest by 2023) of a higher-octane petrol ethanol blend (min. E20) could achieve reductions in both CO2 and other air pollutants even further. Instead, they argued against the introduction of an accounting cap on conventional biofuels. They underlined that switching to low-indirect land use change (ILUC) risk feedstocks has the potential to have a major impact on achieving the Fuel Quality Directive and RED targets but is expected to be limited by feedstock availability. Finally, they claimed that potential exists for higher biodiesel blends to be used in non-road transport modes to meet the regulatory targets but this will require time, testing and investment.

Another positive opinion on the potential of biomethane to contribute to meet the climate goals is expressed by Rajendran et al. (2019). They argued that biomethane as a transport fuel offers similar rewards as electric vehicles in terms of decarbonised transport and clean air along with energy security, renewable energy, indigenous jobs and greening of agriculture. However, they underlined that biomethane requires a very significant change in infrastructure, including the provision of compressed natural gas service stations and natural gas vehicles. They also stressed the need, at least initially, of large incentives to allow initiation of the industry, but these subsidies can be reduced over time. A further favorable opinion is expressed by Hamelinck et al. (2019) on the basis of a study region comprising 9 MSs in Central and Eastern Europe: Bulgaria, Czech Republic, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia and Austria. They concluded that crop-based biofuels can contribute to the decarbonisation of transport, at scale and with attractive carbon abatement costs. They found that the study region has a large potential to produce additional feedstock, with benefits for the rural economy and agricultural development. The additional feedstock can be produced with low ILUC impacts by increasing the yields in existing crop systems, and by re-developing abandoned agricultural land. They asked for support policies that could help to drive the carbon performance of biofuels by combining mandates with strict requirements or financial rewards for better performing biofuels.

The different views on the role of biofuels derive also from the difficulty of assessing their lifecycle GHG emissions. The recent publication of the JEC Well-To-Wheels report v5 (Prussi et al., 2020), updating previous studies with new available data, provided considerable help to improve the assessment. On the basis of the new data, JRC published in 2020 a document titled "State of the Art on Alternative Fuels Transport Systems in the European Union" (Joint Research Centre, 2020), which contains a thorough review of the main alternative fuels (electricity, hydrogen, biofuels, natural gas and biomethane, synthetic fuels and paraffinic fuels, and liquefied petroleum gas). For each fuel, they analyzed the Well-To-Wheel (WTW) GHG emissions and energy performance, the maturity of fuel production, the Well-To-Tank (WTT) cost and the potential capacity and actual production. They reported on the market development for transport systems and infrastructure for each of the alternative fuels considered. With reference to biofuels, they concluded that they could technically substitute oil in all transport modes, using the existing powertrain technologies and refueling infrastructure up to certain limits in concentration. However, they underlined that the finite resources and sustainability considerations limit the potential production of biofuels. They expressed some hope also for their use in aviation. They advised that a further barrier is the cost of the production of advanced biofuels and claimed that policy measures are needed to better drive the establishment of a market at EU scale, including competition between a diversity of players.

A second decarbonisation strategy proposed at EU level is the electrification of the light vehicle fleet, as discussed by Krause et al. (2020), summarising the results of a research group including the JRC and other academic and research institutes. They analyzed technology and operation options for European road transport CO2 emissions reduction by 2050, focusing on measures improving tank to wheel vehicle efficiency and upstream emissions of electric vehicles. Several measures for vehicle efficiency improvement, transport smoothing, and transport reduction, as well as possible 2050 road vehicle fleet compositions, are proposed combining expert opinions with fleet impact modelling to develop realistic scenarios. They found that WTW road transport CO2 emissions could be reduced up to 90% versus 1990 by 2050 through strong fleet electrification and the proposed policy measures. They also stressed that such a drastic technological change would cause substantial additional demand for low-carbon electricity.

The challenging issue of transport decarbonisation has been tackled at length and with significant insights by scholars of various backgrounds. Lah et al. (2019), for instance, stressed the need of an integrated approach. They argued that there is substantial potential in both technical and behavioral mitigation measures for all transport modes and that, in some cases, the mitigation potential could be realized at very low or even negative net costs from a societal perspective, although with generating substantial sustainable development benefits. Consequently, they argued in favor of an integrated policy approach that combines all intervention areas for transport policy and involves all levels of government. They underlined that a package that achieves low-carbon transport and fosters sustainable development includes avoided journeys, improved vehicle and engine performance technologies, low-carbon fuels, investments in related infrastructures, and changes in the built environment. de Blas et al. (2020) warned that a massive replacement of oil-fueled individual vehicles with electric ones could result in the scarcity of some key minerals, such as lithium and magnesium. In addition, energy-economy feedbacks within an economic growth system may create a rebound effect that counters the benefits of substitution. They argued in favor of a Degrowth strategy, combining a quick and radical shift to lighter electric vehicles and non-motorized modes with a drastic reduction in total transportation demand. Lefèvre et al. (2020) proposed a specific Deep Decarbonisation pathway framework consisting in an iterative method combining detailed qualitative storylines, full scenario quantification and standardized dashboard reporting, adapted from the general Pathways (DDP) framework. From a political science perspective, Haas and Sander (2020) analyzed the controversy surrounding the emission performance standards for cars adopted in spring 2019. They claimed that without a major shift in the balance of power, extensive decarbonisation and a departure from car-centered transport development will not be possible. Therefore, they deemed it crucial for mobility research to critically engage with lobbying powers in the EU and with concepts such as environmental leadership, which often underexpose the structural power of incumbent actors and existing path dependencies. Finally, Figueroa and Lah (2020) underlined the human dimension aspects of the decarbonisation challenge. They stated that nothing short than an unprecedented transformation of the systems supporting the movement of goods and people worldwide will deliver the transport sector's contribution of GHG emissions reduction necessary to limit the increase in global average temperature to 1.5 °C above preindustrial levels by 2050. They argued that a focus on energy use in transport takes care only partially of the more comprehensive goals of sustainable transport concerning equity, accessibility, and contributions to a better quality of life. They maintained that the task requires a deeper understanding of the role of the human dimension to help managing transport energy demand.

Having touched upon the many dimensions of the transport decarbonisation challenge, this paper deals with two topics. The first one concerns the planned policies, analyzing how they evolved in the period 2015–2018, the results they achieved, and how they have been confirmed or adjusted in the recently proposed NECPs. The second topic is the likely impact of the proposed goals presented in the NECPs on the EU27 GHG emissions in 2030, with a specific focus on the two main strategies concerning the development of biofuels and the electrification of the car fleet.

3. Transport decarbonisation up to the year 2018 in EU29

3.1. Renewable energy sources in transport in the period 2015–2018

Article 22 of Directive 2009/28/EC required MSs to submit a report on progress in the promotion and use of energy from renewable sources by 31 December 2011, and every two years thereafter. The sixth report, to be submitted by 31 December 2021, will be the last required report. We have carefully analyzed the available fourth and fifth reports submitted by each MS and containing information up to 2018[3] and summarized some of the information in Table 2 and Table 3. The fourth and the fifth reports were also prepared by the UK and Norway, hence our tables concern 29 countries.

An interesting summary of the achievements of each MS is summarized in Table 2. It reports the percentage of renewable energy sources used overall, in transport and in electricity production. It can be seen that most countries are still below the 10% goal to be reached by 2020. Only the three Scandinavian countries, i.e. Sweden, Norway and Finland, are well above that goal. The difference between the 2018 and the 2015 RES-T share, reported in the last column of Table 2, indicates that in most countries the improvements over the 4-years period is rather small. There is a 0% to 3% improvement in 16 countries. Only 6 countries (Norway, Spain, Sweden, Netherlands, Malta, Slovenia) succeeded in increasing their share by more than 3%: Norway improved by an extremely high amount (11.2%), and Spain and Sweden by a 5.7%. Instead, Denmark, Lithuania, Austria, Slovakia and Finland reported a decrease in the RES-T share. Finland presents a striking 7.3% decrease, although its RES-T share remains well above the 10% goal.

Table 2 complements the information on the percentage of renewables in transport with the percentage in electricity production (RES-E), and with the overall percentage (RES-O) (including also RES-E and RES-H&C[7] (heating and cooling)). In general, the countries with a high RES-T tend to have also a high RES-E (correlation index = 0.55), and consequently a high RES-O (correlation index = 0.64). Such a result might indicate that each country has its own general ability to make use of renewable energy sources irrespective of the sector. The relationships among sectors, for instance transport and electricity generation, is discussed in the sections below.

A further summary table (Table 3) provides the details of the

[3] Some countries limit their reports to the years 2015 and 2016, while others include a longer data series.

[4] Share of renewable energy in transport: final energy from renewable sources consumed in transport (see Articles 5(1)(c) and 5(5) of Directive 2009/28/EC) divided by the consumption in transport of: 1) petrol; 2) diesel; 3) biofuels used in road and rail transport; and 4) electricity in land transport (as reflected in row 3 of Table 1).

[5] Share of renewable energy in electricity: gross final consumption of electricity from renewable sources for electricity (as defined in Articles 5(1)(a) and 5(3) of Directive 2009/28/EC divided by total gross final consumption of electricity).

[6] Share of renewable energy in gross final energy consumption.

[7] Share of renewable energy in heating and cooling: gross final consumption of energy from renewable sources for heating and cooling (as defined in Articles 5(1)(b) and 5(4) of Directive 2009/28/EC) divided by gross final consumption of energy for heating and cooling.

Table 2
The sectoral renewable energy sources (RES) in EU29: transport[4] (RES-T), electricity[5] (RES-E), and overall share of renewable energy sources[6] (RES-O).

		RES-T		RES-E		RES-O		RES-T
		2015	2018	2015	2018	2015	2018	Var.2015-18
Austria	AT	10.1%	9.8%	69.3%	73.1%	33.0%	33.4%	−0.3%
Belgium	BE	3.8%	6.7%	15.5%	18.9%	7.9%	9.4%	2.8%
Bulgaria	BG	6.5%	8.1%	19.1%	22.2%	18.2%	20.5%	1.6%
Cyprus	CY	2.5%	2.6%	8.5%	9.4%	9.3%	13.8%	0.2%
Czech Republic	CZ	6.5%	6.5%	14.1%	13.7%	15.0%	15.2%	0.1%
Germany	D	6.6%	7.9%	30.8%	38.0%	14.6%	16.5%	1.3%
Denmark	DK	6.7%	6.6%	51.3%	62.9%	31.0%	36.7%	−0.1%
Estonia	EE	0.4%	3.3%	15.1%	20.5%	28.6%	30.4%	2.9%
Greece	EL	1.1%	4.1%	22.1%	26.0%	15.3%	18.1%	3.0%
Spain	ES	1.2%	6.9%	37.0%	35.2%	16.2%	17.4%	5.7%
Finland	FI	22.0%	14.7%	32.5%	36.7%	39.2%	41.1%	−7.3%
France	FR	8.3%	9.0%	18.8%	21.2%	15.1%	16.6%	0.7%
Croatia	HR		3.9%		48.1%		28.2%	
Hungary	HU	7.0%	7.7%	7.3%	8.3%	14.4%	12.5%	0.7%
Ireland	IE	5.7%	7.2%	25.3%	33.2%	9.2%	11.0%	1.5%
Italy	IT	6.4%	7.7%	33.5%	33.9%	17.5%	17.8%	1.2%
Lithuania	LT	4.6%	4.3%	15.6%	18.4%	25.8%	25.0%	−0.2%
Luxembourg	LU	6.5%	6.5%	6.2%	9.1%	5.0%	9.1%	0.1%
Latvia	LV	3.9%	4.7%	52.2%	53.5%	37.6%	40.3%	0.8%
Malta	MT	5.0%	8.4%	4.3%	7.7%	5.0%	8.0%	3.4%
Netherlands	NL	5.3%	9.6%	11.1%	15.1%	5.8%	7.4%	4.3%
Norway	NO	8.8%	20.0%	106.0%	106.8%	68.4%	72.8%	11.2%
Poland	PL	5.6%	5.6%	13.4%	13.0%	11.7%	11.3%	0.0%
Portugal	PT	7.4%	9.0%	52.6%	52.2%	28.0%	30.3%	1.7%
Romania	RO	5.5%	6.3%	43.2%	41.8%	24.8%	23.9%	0.9%
Sweden	SE	24.0%	29.7%	65.8%	66.2%	53.8%	54.6%	5.7%
Slovenia	SI	2.2%	5.5%	32.7%	32.3%	21.9%	22.2%	3.3%
Slovakia	SK	8.5%	7.0%	22.7%	22.2%	12.9%	12.3%	−1.5%
United Kingdom	UK	4.5%	6.5%	22.3%	30.4%	8.5%	11.0%	2.0%

Table 3
Total actual contribution from each renewable energy technology in the transport sector in EU29 (ktoe).

Country	Bioethanol/bio-ETBE	Biodiesel	Hydro-gen	Renewable electricity	Of which road transport	Of which non-road transport	Others (biogas, vegetable oils, …)	Row total
AT	58	362	–	204	17	187	40	664
BE	41	391	–	39	1	38	–	470
BG	29	114	–	8	1	7	–	151
CY	–	9	–	–	–	–	–	9
CZ	61	247	–	45	2	43	–	353
D	735	1892	–	335	6	329	59	3021
DK	43	170	–	19	–	19	5	237
EE	5	12	–	1	0	1	3	22
ES	159	1310	–	127	4	124	270	1866
FI	84	281	–	24	1	23	5	394
FR	586	2556	–	264	7	235	22	3428
GR	–	159	–	5	1	5	–	164
HR	0	27	–	11	0	10	–	38
HU	49	141	–	31	1	30	–	221
IE	27	127	–	1	0	1	–	156
IT	33	1143	–	338	3	335	75	1587
LT	8	70	–	2	1	1	–	80
LU	10	123	–	3	0	3	–	136
LV	8	29	–	9	2	6	–	47
MT	–	3	–	0	0	–	6	9
NL	171	320	–	54	13	41	9	554
NO	38	333	–	91	41	51	19	481
PL	173	740	–	88	1	88	–	1001
PT	6	257	–	23	0	22	0	285
RO	90	207	–	39	1	37	–	336
SE	91	1267	–	144	–	144	110	1612
SI	7	66	–	6	0	6	–	79
SK	24	128	–	15	1	14	–	166
UK	381	908	–	127	6	121	0	1416
Column Total (2018)	2917	13,389	–	2054	110	1920	623	18,982
% (2018)	15%	71%	0%	11%	1%	10%	3%	100%
Column Total (2015)	2739	10,164	–	1637	46	1590	920	15,460
Var. 2018/2015	6%	32%	0%	25%	139%	21%	−32%	23%

renewable energy sources used in the transport sector by each country.[8] Data refer to the year 2018. It can be observed that RES-T is mostly due to biofuels. They represent 89% of the total contribution, while the remaining 11% is due to the use of transport electricity generated using RES. Among biofuels, the lion's share belongs to biodiesel (71%). Bioethanol/bio-ETBE represent 15% and other biofuels (hydrogenated vegetable oil and pure plant oil) 3%. Concerning the 11% due to renewable RES-E, 10% is used by rail transport and only 1% for road transport. Hydrogen from renewables play no role.

The last two rows report the column total for each renewable energy source with reference to the year 2015. The values for each country have been not reported for the sake of brevity, although they are available from the authors. We report only the 2015 column totals and the percentage change between 2018 and 2015. It can be observed that in the period 2015–2018 the overall RES-T increased in quantity from 15,460 ktep to 18,982 ktep, which is a 23% increase over three years. An average 7% annual increase is relevant but probably too slow to reach the goals set in the Paris agreements. Among the biofuels, the largest increase concerned biodiesel (+32%), while bioethanol/bio-ETBE increased by only 6% and the others (biogas, vegetable oils, …) decreased by 32%. Renewable energy increased by 25%, with the largest gains taking place in the use of electricity for road transport, which, although marginal in absolute terms, showed a strong upward trend.

3.2. Policy measures up in the years 2015–18 in EU28

Since the main renewable energy sources for transport are biofuels, the EU enacted several directives to regulate them. The Renewable Energy Directive 2009/28/EC contains Article 25 "Mainstreaming renewable energy in the transport sector" that is specifically devoted to mandate the use of biofuels. It prescribes that "each MS shall set an obligation on fuel suppliers to ensure that the share of renewable energy within the final consumption of energy in the transport sector is at least 14% by 2030 (minimum share)." Article 29 sets the "Sustainability and greenhouse gas emissions saving criteria for biofuels, bioliquids and biomass fuels". The Directive indicates that the Commission shall monitor the origin of biofuels, bioliquids and biomass fuels consumed in the Union and the impact of their production, including the impact of displacement, on land use in the Union and in the main third countries of supply. Following the Renewable Energy Directive 2009/28/EC, the MSs are requested to indicate the measures taken in the previous 2 years and/or planned at national level to promote the growth of energy from renewable sources in the sectors of electricity, transport and heating&cooling.

We reviewed the measures implemented by each MS in the period 2015–18, with a specific focus on transport. Not surprisingly, it results that the focus of the policies enacted by the MSs has been on biofuels. All countries adopted and transposed the European directives. Different countries set different blending requirements/targets according to their specificities.[9] The highest blending obligation value has been set in Finland (20%), while other countries chose a more gradual approach mandating levels for 2020 well below the 14% goal indicated in the Directive by 2030. For instance, the Slovak Republic set the blending obligation to 5.8%, Denmark to 5.75%, Hungary to 4.9%, and Cyprus to a very modest 2.4%. In the case of Cyprus, it is claimed that very hot climate combined with the volatile nature of bioethanol does not allow for using petrol mixed with bioethanol, as the petrol specifications laid down in standard EN 228, the steam pressure specifications in particular, are not met. Together with the Scandinavian countries, Italy, Austria, Spain, and Germany were very active and successful in enhancing the use of biofuels in transport. An analysis of their experiences based on their national reports indicates that there are both benefits and limitations in promoting biofuels. The main benefit is the development of the biofuel industry, comprising innovative firms introducing new technologies, integrating the agricultural, energy and transport sectors and reusing waste and residuals in line with the circular economy principles. The main limitation is the dependence from import. Spain, for instance, reports that the origin of the feedstock used in the manufacture of biodiesel is 9.4% Spain itself, 5.8% the rest of EU and 84.8% outside the EU. For the manufacture of HVO there is no national production of raw materials, 3.8% comes from the rest of EU and 96.2% from outside the EU. In the case of bioethanol, 16.2% of the raw materials are produced in Spain, 27.6% in the rest of EU and 56.2% outside the EU. A second limitation is the competition between the use of agricultural crops for food and animal feeding and biofuel production. For this reason, the Renewable Energy Directive 2009/28/EC in its Article 26 has set "Specific rules for biofuels, bioliquids and biomass fuels produced from food and feed crops". It has been decided that biofuels produced from food and feed crops should be maximum 7% of final consumption of energy in the road and rail transport sectors.

Besides introducing blending obligations, the EU Directive has also clarified and promoted the use of advanced raw materials. In essence, biofuels produced with advanced raw materials can be double-counted, thus helping a country to reach the goal of 10% RES in the transport sector. Such allowance is motivated by their higher value in terms CO2 emissions reduction. In their biannual reports, MSs have reported on the progress made and documented the fiscal and regulatory policies enacted to encourage manufacturers to favor advanced fuel production and consumption.

During the 2015–2018 period, various countries have also devised measures to spur electromobility. Among the most active ones, there have been Sweden, Norway, Austria, Germany, Belgium, the Netherlands and Italy. Financing the charging infrastructure, either for public usage, at home or at work, has been a concern of all countries. Some countries have provided for direct subsidies to facilitate electric vehicles' acquisition (Austria, Germany, Italy, and Ireland). Three countries (France, Norway, and Sweden) have introduced a bonus-malus system, subsidized electric vehicles and imposed a tax on conventional ones based on CO2 emissions. Quite common have been also discounts on the car registration tax and green ownership tax (Denmark, Belgium, Italy, Ireland, Norway, and Sweden). Some other countries (Germany, Norway) have allowed cities to set up regulatory advantages regarding parking and access restrictions for electric vehicles. Austria enacted a measure to promote e-carsharing. Yet, as one can see from Table 2, the use of renewable electricity for road transport is, apart from the case of Norway, still very limited and much lower than its use for non-road transport. Only one country, Denmark, reports to have put in place policies to promote the hydrogen infrastructure.

Overall, in the period 2015–2018, most countries have enacted policies promoting biofuels as a tool to increase their RES-T and reach the 10% goal. In the last reported two years (2017–2018), however, there is an increasing interest to promoting the diffusion of electric vehicles.

4. A comparative analysis of the goals and strategies set by the NECPs for the next decade

Regulation (EU) 2018/1999 of the European Parliament and of the Council of December 11, 2018 on the Governance of the Energy Union

[8] Unfortunately, the national reports use two different formats to report the details of the renewable sources used in transport (in a table with the following caption "Table 1d: Total actual contribution from each renewable energy technology to meet the binding 2020 targets and the indicative trajectories for the share of energy from renewable sources in the transport sector"). Hence, we could aggregate only some of the listings.

[9] Sweden (13%), Finland (20%), Italy (9%), Austria (10%), Belgium (8.5%), Cyprus (2.4%), Denmark (5.75%), Greece (7%), Spain (8.5%), France (7.7%), Germany (CO2 reduction goals), Croatia (6.92%), Hungary (4.9%), Ireland (11%), Luxembourg (5.70%), Latvia (4.5–7%), Portugal (7.5%), Romania (8%), Slovak Republic (5.8%), UK (9.75%).

and Climate Action requires that each MS must report in the integrated NECP information on the estimated trajectory for the share of renewable energy in final energy consumption from 2021 to 2030 in the transport sector, also specifying the measures in place to increase such a share. Most of the countries indicated their exact goal in their NECPs, with the exception of the Netherlands who stated that no prediction was available. Some countries indicated only that they expect the goal to be achieved. Some others (IE, ES) made two different predictions: under the WEM and WAM scenarios (with existing measures and with additional measures). In Table 4, we have summarized the national goals and compared them with the actual RES-T in 2018. The NECP has been so far prepared by the 27 MSs.

It can be observed that most countries plan to achieve the suggested 14% goal, with the exception of LV, HU, HR and IE. A quite large group of countries (SE, FI, ES, D, LU, BE, IT, SI, PT, DK, EL) expects to make substantial progresses, with SE and FI anticipating to reach a RES-T share in 2030 as high as 48% and 45%, respectively. The remaining countries plan to overcome the goal by a small margin. On average, if the goals were achieved, the EU27 RES-T share would increase from the 2018 8.1% value to 19.1%. It represents a doubling of the share, but still quite far from the complete decarbonisation goal.

Finally, we have reviewed the strategies and policies planned by the MSs to reduce CO2 emissions from transport, finding several similarities and differences. In order to increase the RES-T share two main strategies are commonly considered: a) stimulate the production and use of biofuels; b) promote the adoption of electric vehicles. Compared to the previous years discussed in the above sections, the latter tends to receive more importance than the former. It comprises several measures including fiscal policies, public procurement of electric vehicles for the public administration fleets, the acquisition of electric buses and support in the deployment of the charging infrastructure. There are, however, differences in emphasis. Some countries (Italy, Czech Republic, Cyprus, Croatia, Lithuania, and Poland) tend to consider electric vehicles with the same level of attention to other alternative fuels (natural gas in the form of LNG and CNG, LPG, liquid biofuels, hydrogen, as well as synthetic and paraffinic fuels). Other countries are more focused exclusively on electric vehicles. Some (for instance, Germany and the Netherlands) envisage also the development of more futuristic fuels (synthetic fuels or hydrogen). Fewer countries have stated a precise date for the phasing out of combustion engine vehicles for passenger transport. Denmark has announced plans to stop sales of all new diesel and petrol cars as of 2030 and to require that all new taxis must be zero-emissions vehicles from 2025. Ireland strives for achieving 100% electric vehicle sales by 2030. Germany, Greece and Spain have set specific goals in the number of electric vehicles on the road for specific dates. The Netherlands aims at 100% emissions-free new sales of passenger cars in 2030 together with a specific goal on the additional number of bicycle commuters.

As expected, accession countries pay also attention to the modernization of their transport infrastructure, especially concerning electrification of the railway lines and ferries (Estonia, Lithuania, Poland, Slovakia), and to the promotion of intermodality (Croatia). All countries list both fiscal policies and regulatory norms as tools to stimulate transport decarbonisation. The former encompass tax exemptions, tax increases and direct subsidies (Cavallaro et al., 2018). The latter include blending obligations, regulations concerning charging on construction requirements for new buildings, and mandatory procurement quotas. The balance among the economic and the regulatory approaches is, however, different among countries. Some countries have a strong tradition in making use of the price stimuli and envision continuous improvements to their fiscal packages. Sweden, Denmark, Austria and France, for instance, have implemented a bonus-malus system. Belgium plans to include the ‘climate change’ dimension in financial, budgetary and investment decision-making and Austria will attempt the gradual phasing out of counterproductive incentives and subsidies. Sweden is quite advanced in the application of an energy taxation system that combines a carbon tax with a fuel tax and an electricity tax. Most countries tend to rely on regulations such as increasing blending requirements, obligation to use advanced biofuels and other renewables, mandate on filling stations to carry a renewable fuel, etc.

Planning and infrastructural investments are also important ingredients of the toolbox. The main areas of public planning are: the electric vehicle charging infrastructure, low-emission zones, spatial and land use planning. Informative campaigns are also often envisaged as a tool to promote more environmentally friendly transport choices (Greece, Germany, Spain, and Croatia).

Some measures and goals are country specific. For instance, Austria and Portugal quote very detailed programs to promote vehicle sharing and active mobility (cycling and walking), while Germany pays special attention to the industrial impacts of the proposed policies on the automotive industry, on the production of mobile and stationary energy storage (battery cell production) and on the port industry. Germany also envisions support for hydrogen production and, similarly to the Netherlands, synthetic fuels. Some countries (Denmark, Sweden) extend their attention to sustainability of the transport modes other than land transport, such as air and the maritime transport, in the case of Sweden already implementing carbon-charging fees.

Table 4
Actual vs planned RES-T in 2018 and 2030 in EU27.

	2018	2030	Var. 2030/2018
AT	9.8%	14.0%	4%
BE	6.7%	23.7%	17%
BG	8.1%	14.2%	6%
CY	2.6%	14.8%	12%
CZ	6.5%	14.0%	7%
D	7.9%	27.0%	19%
DK	6.6%	19.0%	12%
EE	3.3%	14.0%	11%
EL	4.1%	19.0%	15%
ES	6.9%	28.0%	21%
FI	14.7%	45.0%	30%
FR	9.0%	15.0%	6%
HR	3.9%	13.2%	9%
HU	7.7%	12.6%	5%
IE	7.2%	13.4%	6%
IT	7.7%	22.0%	14%
LT	4.3%	15.0%	11%
LU	6.5%	25.6%	19%
LV	4.7%	7.0%	2%
MT	8.4%	15.0%	7%
NL	9.6%	13.6%	4%
PL	5.6%	14.0%	8%
PT	9.0%	20.0%	11%
RO	6.3%	14.2%	8%
SE	29.7%	48.0%	18%
SI	5.5%	20.8%	15%
SK	7.0%	14.0%	7%
Average	7.8%	19.1%	11%

5. Scenario analysis of the GHG emitted by passenger cars

Having reviewed and summarized the goals and strategies set by the NECPs for the next decade, we attempted to evaluate their impact on GHG emissions. We started by translating them into scenarios and then developed a probabilistic model to estimate the GHG reduction relative to a baseline scenario. We applied the model to the car passenger segment only. It however causes almost half of the GHG emissions generated by road transport, as documented in the introduction. The estimate for motorcycles, light- and heavy-duty trucks, buses and other non-road modes of transport (such as railways, air and maritime transport) was outside the scope of this paper. We aimed at estimating the GHG reduction potential of the two main strategies planned by the MSs: widening the use of biofuels and promoting the uptake of electric cars.

5.1. A probabilistic model to estimate the Well-To-Wheel GHG emissions

The Well-To-Wheel (WTW) GHG emissions, GHGic, in a given year from cars with a specific fuel type *i* in country *c* are computed according to the following equation:

$$GHG_i^c = Fleet_i^c \cdot ADT_i^c \cdot WtW\_GHG_i^c \tag{1}$$

where:

- $Fleet_i^c$ represents the passenger cars in use in country *c* with propulsion system *i* (*i* = *petrol, diesel, Battery Electric Vehicle (BEV), Hybrid Electric Vehicle (HEV), Plug-in Hybrid Electric Vehicle (PHEV), LPG, other*) in a given year;
- ADT_i^c (km) is the average annual distance travelled in country *c* by cars of the fuel type *i*;
- $WtW\_GHG_i^c$ is the GHG emission factor. It indicates the CO2 equivalent emissions per kilometer of a car operating with fuel *i* in country *c*.

The sum of the GHG_i^c across all propulsion systems for all 27 MSs provides an estimate for the EU27. With reference to the year 2018, we have reliable data on both $Fleet_i^c$ and ADT_i^c. Consequently, $Fleet_i^c$ and ADT_i^c are treated as deterministic variables. On the contrary, $WtW\_GHG_i^c$ is treated as a normally distributed stochastic variable to account for the many sources of uncertainty[10]. The mean value of $WtW\_GHG_i^c$ for each fuel type and for each country is estimated as explained in the Supplementary Material. The standard deviation is assumed to be equal to 10% of the mean value. A Monte Carlo simulation with 10,000 draws is used to evaluate the interval estimates. The model is implemented with the MATLAB software.

5.2. Definition of the baseline scenario

The baseline scenario is estimated with data on passenger fleet and average annual distance referring to the year 2018 (Table 5). The data available for the GHG emission factor, however, refer to the year 2015 and 2025 (see details in the Supplementary Material).

The baseline WTW GHG median estimate for the year 2015 for the 27 European MSs is equal to 540.9 MtCO2eq, with a 25-percentile value of 532.2 and a 75-percentile value of 549.5. In order to check the validity of the model we compared our estimates with the ones available at European and national level although they refer to different road transport subsets or assume different specifications. The European Environment Agency (EEA) point estimate for the total GHG emissions by EU27 (including international aviation, excluding LULUCF) for the year 2018 is equal to 3893.1 MtCO2eq, of which 957.3 MtCO2eq attributable to the transport sector. Since we know that 43% of the latter is caused by passenger cars (in 2017), GHG emissions from cars are equivalent to 411 MtCO2eq. The EEA estimate is reasonably lower than our estimate, since it considers only the TTW Tank-To-Well (TTW) emissions while we have included also the Well-to-Tank components for all propulsion systems.[11] A similar check has been made with the Italian estimates provided by Italian Institute for Environmental Protection and Research (ISPRA) obtaining a similar order of magnitude. Consequently, we feel reasonably assured that the model provides a sufficient estimation consistency for the purpose of this paper.

Table 5
Summary of model variables.

Variable	Variable type	Description	Year
$Fleet_i^c$	Deterministic	Passenger cars in use (fleet) in country *c* (c = 1, …, 27) with fuel type *i (i = petrol, diesel, BEV, HEV, PHEV, LPG, other)*	2018
ADT_i^c	Deterministic	Average annual distance travelled in country *c* by cars with fuel type *i*	2018
$WtW\_GHG_i^c$	Stochastic	WTW CO2 equivalent emissions per kilometer of a car operating with fuel *i*	2015

5.3. Definition of 2030 scenarios

In this section, we present the 2030 scenarios concerning the biofuel development and the electrification strategy. In all scenarios developed below, we assume that the annual distance travelled and the total number of passenger cars in the national fleets will not change compared to 2018 values.

5.3.1. Biofuel development

Concerning the biofuel strategy, we developed the scenarios illustrated in Table 6.

Scenario B1 investigates the impact of the vehicles' technological improvements in the period 2018–2030 as estimated by Prussi et al. (2020). Prussi et al. (2020) explains that the WTW values for each propulsion system for the year 2015 considered technologies in the market in the years 2013 up to 2017 to represent the current state-of-the-art in the automotive industry. The WTW estimates for 2025+ aim at providing an outlook on the future technical development of passenger cars based upon the likely market-average technology development expected by the European council for Automotive Research and development (EUCAR) and AVL experts.

Scenarios B2 and B3 should be considered with caution since they face at least the following issues: technological barriers concerning vehicles and production; challenges in the development of an efficient production and supply chain; feedstock availability; and cost competitiveness with the fossil fuels. Given the complexity of these issues, we refer the reader to the existing literature (Hamelinck et al., 2019; Joint Research Centre, 2020; IEA, 2020; ePURE, 2016; EEB, 2019). In short,

Table 6
Scenarios concerning biofuels development.

Scenario	Scenario definition
B1: Vehicle technology improvements	Improvements of vehicle technology and consequently in WTW GHG emission factors for each propulsion system in the period 2018–2030
B2: Full adoption of B7 and E10	All MSs sell diesel with 7% biodiesel and petrol with 10% ethanol
B3: Doubling the current blending at country level	The NECPs have described the current biofuel blending for biodiesel or ethanol and the planned introduction of higher levels to be obtained via regulatory or fiscal measures. The B3 scenario assumes doubling the current levels for biodiesel and ethanol while biomethane's level is assumed constant
B4: B1 + B2	Vehicle technology improvements + Full adoption of B7 and E10
B5: B1 + B3	Vehicle technology improvements + Doubling the current blending at country level

[10] For a thorough discussion of the many sources of uncertainty and their tentative quantification see Nocera et al. (2018). They distinguished between technical, economic and decisional uncertainty, considering both the epistemological and the ontological point of view, and provide a set of methodological solutions

[11] For a discussion of the pros and cons of the Well-To-Wheel vs the Tank-To-Well methodology applied to estimate the CO2 emissions of the transport policy, see Nocera and Cavallaro (2017) and Ito and Managi (2015).

with regards to the technological barriers, within certain limits, the existing ICE cars are able to use biofuels almost without modifications. Ethanol is a well-established substitute for petrol in spark-ignition engines and the European EN228 petrol specification allows blending of ethanol up to 10 vol%. FAME biodiesel can be used in standard diesel engines in blends up to 7% with conventional diesel fuel as allowed by the EN590 diesel fuel specification (Prussi et al., 2020). Instead, higher blends such as B20 or B30 are possible only in tightly controlled (captive) fleets. It is estimated that in 2020 about 95% of the (petrol) passenger cars and vans will be compatible with E10, and all diesel vehicles will be compatible with B7 since model year 2000 (Joint Research Centre, 2020). Biomethane from biomass and wastes can be injected into the general gas grid. Methane in liquefied form as LNG is an attractive option for trucks and ships due to its high energy density and low sulphur emissions. The technology is mature for vehicles and to a lesser extent for vessels. There seem to be also very few technological barriers concerning biofuel production.

The development of a competitive production and supply chain remains, however, a challenge in many European countries requiring supportive policies. As illustrated in the previous sections, all NECPs presented by the MSs strive for an increase in biofuel production. The main challenges, however, are the finite resources and sustainability considerations that might limit the potential production of biofuels. Most (64%) biodiesel consumed in the EU in 2016 was produced from EU feedstocks, derived mainly from rapeseed, used cooking oil, animal fat and tall oil. Palm oil from Indonesia and Malaysia is also used for biodiesel production. Ethanol consumed in the EU is made mainly from EU feedstocks (65%), including wheat, maize, sugar beet and a minor amount from cellulosic ethanol. Ethanol-based feedstocks from outside the EU include corn, wheat and sugar cane. As regards biomethane, Joint Research Centre (2020) states that it is not clear how much biomethane would be available for the transport sector in the long term, given limited available feedstocks and strong expected competing demands from other sectors such as heating and industry. Biodiesel production in the EU increased from over 1,000,000 tonnes/year in 2004 to more than 12,000,000 tonnes/year in 2016 (EEB, 2019). With a production capacity of about 18.7 million tonnes for FAME, the industry is operating at about 52% capacity, indicating that there exists room for greater levels of production, if enough sustainable feedstock could be sourced. However, concerns over the indirect effects of the use of large amounts of food and feed materials for biofuels led the EU to limit the amount of these feedstocks which can be used to make biofuels in the EU (2018/2001, RED II). In the long term, the availability of sustainable feedstocks may represent a limiting factor to production expansion. In addition, another main barrier is the cost of the production of advanced biofuels.

The results, illustrated in Fig. 2, indicate that, provided B3 is technically and economically feasible, it would obtain the largest GHG reduction: from 540.9 (490–590) MtCO2eq to 523.5 (480–575) MtCO2eq, equivalent to a 3.2% GHG emissions reduction over the 2018–2030 period. Vehicle technology improvements only (scenario B1) obtain a marginal improvement (−0.8 MtCO2eq, i.e. −0.15%). Scenario B2, which foresees that each MS succeeds in implementing the B7 and E10 quota in diesel and petrol, reduces GHG emissions by 2.1%, equivalent to 11 MtCO2eq. Combining the technical improvements with higher blending goals generates slightly higher GHG emissions reductions, equal to 19.3 MtCO2eq (−3.6%) in the best-case scenario B5, which represents a positive but moderate contribution. It should be

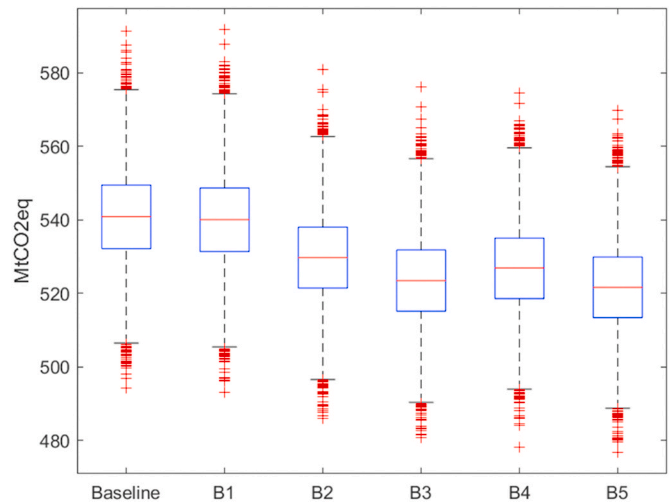

Fig. 2. Biofuel scenarios.

remembered, however, that the positive contribution of biofuels to transport decarbonisation might be much higher and more essential for larger vehicles such as heavy-duty trucks, buses, airplanes and ships. Although the use of biofuels in larger vehicles is still in the experimental phase, it might be technologically and economically possible to make use of biofuels in much larger blends (E20/25, E85, B20)[12] in dedicated and tightly controlled (captive) vehicle fleets.

5.3.2. *Electrification of the car fleet*

Concerning the electrification strategy, we developed the scenarios illustrated in Table 7.

Since in most countries electric vehicles (EVs, i.e. BEVs or PHEVs) are in the initial phase of their uptake (e.g. Italy, see Danielis et al. (2020); Giansoldati et al. (2020)), predicting their uptake in the next decade is quite difficult. The complex interaction of vehicle technology improvements (especially with regards to battery developments), supply factors such as car manufacturers commitments to the new technology and the deployment of the charging infrastructure, demand factors with special regards to consumers' reaction in the new technology, and policy factors (subsidies, taxes and regulation) are known to play a relevant role. Car electrification represents a drastic innovation for the entire car market, thus extrapolating the past year's data might not lead to reliable results. Consequently, we have opted for formulating two scenarios

Table 7
Scenarios concerning the electrification strategy.

Scenario	Scenario definition
EV1: Slow uptake	All MSs will have a fleet composition equal to the Norwegian one in 2017
EV2: Fast uptake	All MSs will have a fleet composition equal to the Norwegian one in 2019
EV3: EV1 + RES-E NECP 2030	EV1 + Share of RES in electricity production set as goal in the NECPs 2030
EV4: EV2 + RES-E NECP 2030	EV2 + Share of RES in electricity production set as goal in the NECPs 2030

[12] See, for instance, the CEN/TC 19 'Gaseous and liquid fuels, lubricants and related products of petroleum, synthetic and biological origin' that studied the overall sensitivity of future (Euro 6c technology) vehicles and the fuel logistics' system towards mid-blend oxygenate ("E20/25") petrol; https://www.cen.eu/work/Sectors/Energy/Pages/Biofuels.aspx. Joint Research Centre (2020) discusses the potential use HVO (or HEFA) in aviation.

based on the most advanced country in the world in terms of EV new registration: Norway.

Fig. 3 (left hand side) depicts the evolution of the new registrations and fleet composition in Norway. EVs entered the Norwegian car market a decade ago and, starting from 2012, thanks to very favorable policies (Scorrano et al., 2019), gained rapidly market share reaching in 2019 almost 60% of the car market with an almost 10% increase each year. Their share on the overall car fleet in circulation (right hand side) is gradually becoming significant. In the years 2017 and 2019, the Norwegian fleet composition was the one reported in Table 8. In the year 2017, EVs made up 7.8% of the fleet. In the year 2019, their share increased to 13.4%, with a significant reduction of both petrol and diesel cars. We will use such a fleet composition as a base for scenarios EV1 and EV2.

Adopting a "copy the leader approach", Scenario EV1 assumes the all MSs will have a fleet composition equal to the Norwegian one in 2017 and Scenario EV2 assumes that they will have a fleet composition equal to the Norwegian one in 2019. It is likely that some EU countries might be slow movers (e.g. the south Mediterranean, the Eastern European countries) or might not reach the Norwegian EV uptake due to differences in income, fiscal systems, and resources to deploy for the needed charging infrastructures. On the other hand, some other countries (Netherlands, Sweden, Germany, France, and Finland) might reach the Norwegian level in a faster tempo, thanks to the growing EV models availability, declining battery costs and consequently list prices, better knowledge and information on the new technology.

There is a high level of uncertainty also regarding the relative share of BEVs and PHEVs within the EV aggregate in 2030. The issue is still openly discussed among the car manufacturers and the results of the discussion are likely to influence the structure of the incentives that each MS will adopt. Furthermore, there is uncertainty on the role of HEVs, which based on recent tends seem to rapidly prevail over conventional ICE cars.

Scenarios EV3 and EV4 incorporate the interaction between EVs and the share of electricity generated using renewable resources (RES-E). In both scenarios, based on the RES-E goals stated in the NECPs, we have adjusted the WTW GHG emission factor for EVs as explained in the Supplementary Material. There is great heterogeneity in the way MSs choose to meet their climate obligations to 2030, with shares of RES-E varying from 11% (Malta) to 100% (Austria, Denmark, Sweden). The impact on GHG emissions is illustrated in Fig. 4.

In the EV1 "Slow EV uptake" scenario, GHG emissions decrease by 3.4% to 522.7 MtCO2eq (477.1-565.8) compared to the 2018 baseline scenario. In EV2 "Fast EV uptake" scenario, GHG emissions decline by 6.4% to 506.4 MtCO2eq (464.8-546.4). If in addition the MSs reached their goals in terms of RES-E, the overall GHG emissions would decrease to 516.9 (470.7-560.5) and 496.2 (453.5-536.0), respectively, or in percentage terms by 4.4% and 8.3%.

Compared to the biofuel development strategy, the electrification strategy is thus estimated to be more effective in reducing GHG emissions, especially if coupled with the greening of the electricity mix.

Table 8
Norwegian fleet composition in 2017 and 2019 (ACEA, 2019), in absolute and percentage values.

	2017		2019	
Petrol	1,139,796	42.0%	1,031,033	36.9%
Diesel	1,289,067	47.6%	1,276,337	45.7%
Hybrid	69,794	2.6%	109,757	3.9%
BEV	138,929	5.1%	260,524	9.3%
PHEV	72,985	2.7%	114,776	4.1%
LPG + natural gas	167	0.0%	239	0.0%
Other	120	0.0%	189	0.0%
Total	2,710,858	100.0%	2,792,855	100.0%

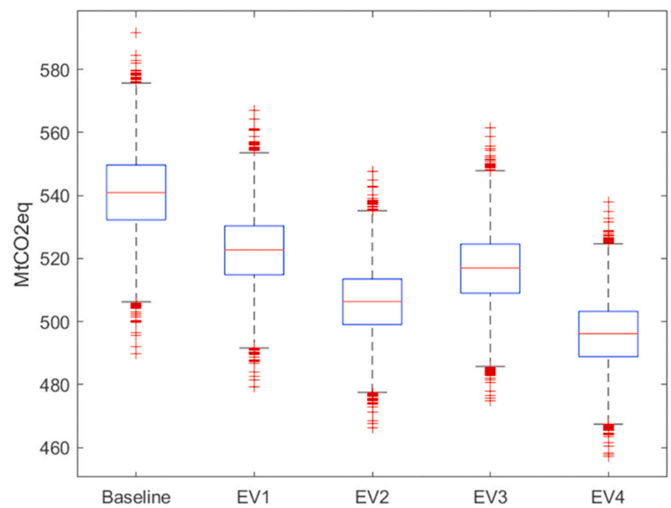

Fig. 4. Fleet electrification scenarios.

Moreover, we underline that in the electrification strategy, differently from the biofuel one, we have opted not to consider the likely technological improvements in the EVs. Prussi et al. (2020) discuss the issue and argue that some WTW reductions in the EV emission factors are likely thanks to the improvement in the battery technology that might become lighter thus reducing the overall energy consumption notwithstanding the increase in the battery energy capacity needed to increase the EV driving range. Because of the many uncertainties associated to these developments in the coming decade, we have opted not to include them in the model. Our estimates should be thus considered as conservative.

5.3.3. Combined scenarios for the year 2030

Let us now combine some of the above-developed scenarios to capture the overall impact of the strategies envisioned in the NECPs. Among the various possibilities, we decided to focus on the following two joint

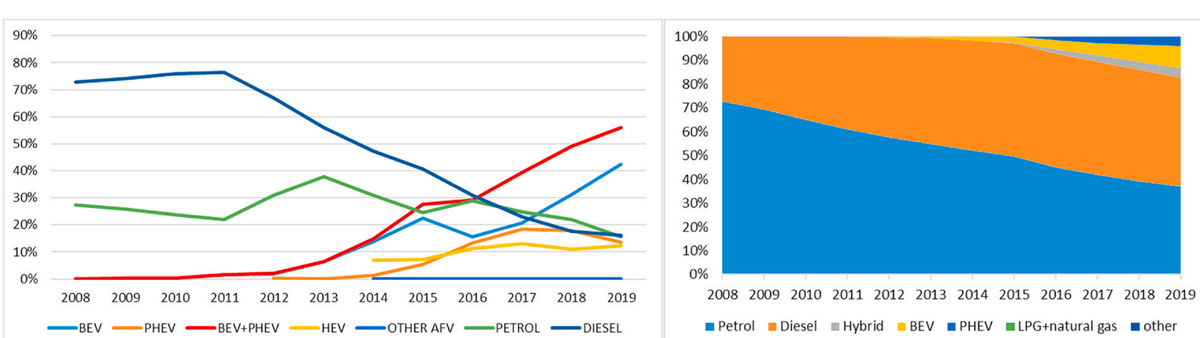

Fig. 3. New registrations and fleet composition in Norway.

scenarios:

- B4+EV3: moderate uptake of biofuels and EVs
- B5+EV4: fast uptake of biofuels and EVs

The results are illustrated in Fig. 5 and Fig. 6, at the EU27 level and MS level, respectively.

Compared with the baseline 2018 GHG emissions, the B4+EV3 scenario depicting a moderate uptake of both biofuels and EVs realized a 6.4% reduction with estimated 2030 GHG emissions equal to 506.1 (464–556) MtCO2eq, while the B5+EV4 "fast uptake of biofuels and EVs" generates a 11.9% reduction, equal to 476.6 (438–522) MtCO2eq.

At country level, our model estimated quite diversified reductions depending on the different levels of biofuel production and on the planned RES-E goals. All countries present a decline in GHG emissions, with the current front-runners reaching the highest levels of reductions.

5.3.4. Strengths and weaknesses of the performed scenario analysis

Compared with previous studies, our study has the following features. In terms of geographical coverage, it is based on national data on fleet composition, annual travel distance, carbon intensity for electricity production, actual and planned biofuel blending. The national estimates are then aggregated to obtain results at European level. A higher level of disaggregation could be considered a plus, but, of course, it introduces higher levels of uncertainty. In terms of transport modes considered, we focused on passenger cars only, while most studies (Miller, 2016; Krause et al., 2020; ePURE, 2016) considered also LDVs and HDVs. Consequently, the scope of our study is more limited and is not directly comparable with other studies. Concerning our modelling approach, differently from many previous studies we applied a probabilistic CO2 emissions model to account explicitly for uncertainty, reporting intervallic predictions rather than point estimates. However, a weakness of our approach is that we did not model the car fleet composition at country level and, differently from Krause et al. (2020), we did not differentiate fuel\energy consumption by traffic conditions (urban, interurban, highway travel). Concerning the channels and pathways considered, we estimated separately and jointly the impact of two main strategies: the introduction of higher blending levels of biofuels and the electrification of the passenger car fleet. As for the GHG analysis, we used WTW emission factors for all propulsion systems, improving on Krause et al. (2020) who used TTW emission factors for conventional cars. We took into account GHG emissions factor reductions deriving from technological improvements to the combustion engine for conventional cars but we opted not to make assumptions on the possible technological improvements of EVs given the higher level of uncertainty. Another limitation of our study, compared for instance with Krause et al. (2020) is that we did not incorporate in the model traffic reductions (spatial planning) and\or traffic improvement measures (smoothing, platooning). Consequently, our model does not consider all transport policies envisaged in the NECPs. As regards the interaction with sectors other than transport, we took into account the planned "greening" of electricity production for each MS. However, we disregarded the impact of increased demand for electricity and the needed improvements in the electric grid as consequence of the electrification strategy. Neither did we discussed issues related to the availability of lithium and rare materials. Other disregarded issues are the economic and employment impacts from supply chain development of biofuel and renewable energy production that, however, will play a relevant for the political acceptability of the planned strategies. Moreover, we did not discuss local air pollution impacts, the implications of the two strategies for the economic and energy independence and their political acceptability. Finally, we considered hydrogen outside the scope of the paper, although we acknowledge that it represents an interesting energy carrier that might play a role for transport modes other than the passenger cars segment.

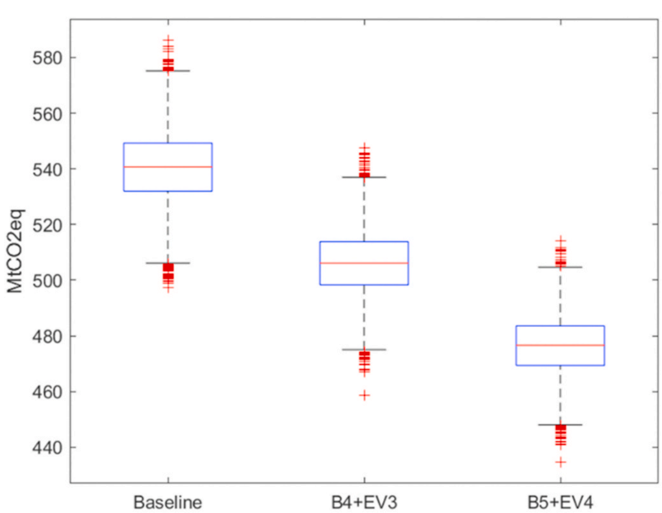

Fig. 5. Joint impact of the biofuel development and fleet electrification strategies at EU27 level.

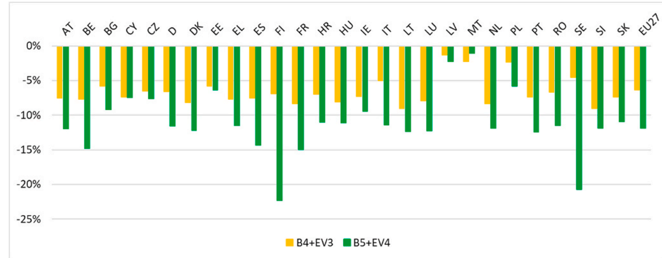

Fig. 6. Joint impact of the biofuel development and fleet electrification strategies at national level.

6. Conclusions

Transport is probably the most difficult sector to decarbonize. In the period 1990–2019, the overall CO2 emissions have increased, while other sectors have succeeded in reducing them. The national reports, compiled every two years by the MSs, allowed us to trace the gains in the use of RES in the transport sector. By the year 2018, only three countries, i.e. Sweden, Norway (strictly not part of the EU, although it compiled the national report) and Finland, succeeded in overcoming by a large margin the 10% RES-T goal set by the EU well before the 2020 deadline (with Austria also marginally achieving that goal). Many countries were well below the goal. Most of the CO2 reductions were due to the use of biofuels, mostly to biodiesel and to a minor extent to ethanol blended in the conventional fuel, and to biogas. Electricity, with the exception of Norway, was used only for rail transport.

Reviewing the policies implemented up to the year 2018 and planned for the decade 2020–30 as illustrated in the NECPs, we found that there has been a shift of focus from internal combustion engine vehicles running on biofuels to EVs. However, all countries still purse both strategies: a) increasing the production and use of biofuels, especially those produced by advanced materials, and b) supporting the diffusion of EVs. Performing a scenario analysis capturing the planned policies and goals indicated in the NECPs, we found that the biofuel strategy can deliver a GHG reduction of up to 19 MtCO2eq (−3.6%), while the electrification strategy can deliver a GHG reduction up to 45 MtCO2eq (−8.3%). Jointly used, the GHG reduction could reach up to 64

MtCO2eq (−11.9%).[13]

However, such strategies require improvements also in areas other than the transport sector. The environmentally sound production of biofuels requires the development of the biofuel industry, well integrated with its supply chain including national and international raw materials' procurement, the waste disposal processing industry and the agricultural sector. Moreover, it requires coordination with the fuel distribution industry and the deployment of a suitable infrastructure, especially in the case of liquid fuel or hydrogen. The successful and rapid implementation of the electrification strategy, in turn, requires the restructuring of the automotive industry and of its supply chain, including firms that manufacture and dispose vehicles' batteries and those extracting the raw materials (lithium and other rare materials). Moreover, the benefits of substituting ICE vehicles with electric ones are strictly dependent on the ability of a country to produce "clean" electricity. Consequently, establishing synergies with other sectoral EU policies is paramount. Because of the complex linkages between various sectors, it is evident that the goal of decarbonising transport cannot be achieved via transport policies alone but requires proper fiscal and normative regulations in various sectors, framed within a coherent holistic vision.

CRediT authorship contribution statement

Romeo Danielis: Conceptualization, Investigation, Methodology, Supervision, Writing – review & editing. **Mariangela Scorrano:** Investigation, Data curation, Methodology, Formal analysis, Software, Writing – original draft, Writing – review & editing. **Marco Giansoldati:** Writing – review & editing.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.retrec.2021.101068.

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[13] The cost savings connected with such reduction are not easy to estimate. As stated by Nocera et al. (2018), the economic valuation of the impact of climate change caused by transport is fraught with difficulties, resulting in large variations across methodologies. Consequently, we leave such a difficult task to an *ad hoc* research paper.