Modeling and Analysis

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Unraveling the role of biofuels in road transport under rapid electrification

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Abstract: Biofuels have been the predominant option for climate change mitigation in road transport for decades, but the recent expansion of electric vehicles may bring into question their key role. In this work we model the energy use and life-cycle emissions of road transport activities until 2050 in Norway, a country with a rapid growth in vehicle fleet electrification, to investigate the role that biofuels can play in climate change mitigation, and assess the implications for air pollution and human health. The mitigation benefits from biofuels peak around 2030 at 3.1 ± 0.45 $MtCO_2eq.\ year^{-1}$, approximately 30% of today's road transport emissions. The largest specific emission savings are achieved from biofuels in trucks and vans, for which the penetration of electric vehicles is slower. These results are consistent under different time horizons and climate metrics. The average impacts on human health are also decreased, but the uncertainty ranges for some biofuels options overlap with those of fossil fuels. Complementary and integrated strategies combining high electrification rates of the vehicle fleet with targeted applications of biofuels can increase the mitigation of road transport emissions. © 2022 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Industrial Chemistry and John Wiley & Sons Ltd.

Supporting information may be found in the online version of this article.

Key words: sustainability; LCA; human health; climate metrics; biomass

Introduction

Global greenhouse gas (GHG) emissions from transport have increased about three times since 1970,[1] and they represent about a quarter of total global emissions. Road transport is responsible for about three-quarters of these emissions,[2] and is expected to grow by 20% by 2030 and 50% by 2050 if no major mitigation efforts are taken.[3] In addition to the long-term climate effects from GHGs, road transport has been identified as one of the largest contributors to near-term climate forcing.[4] The combustion of fossil fuels (and biofuels) in different vehicles releases a different mix of so-called near-term climate forcers (NTCFs), such as primary and secondary aerosols and ozone precursors, whose climate impacts are sensitive to emission locations and time horizon.[5,6] At the same time, NTCFs are an important source of air pollution, with potential negative effects on human health.[4,7] Ambient (outdoor) air pollution accounts for an estimated 4.2 million deaths per year globally,[8] and many of the drivers of air pollution are also climate forcers.[9–11]

Since the early 1990s, biofuels have been the predominant options for emission savings in the transport sector, as several countries have established policy instruments to promote

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biofuel use.[12,13] In the recent past, the electrification of road transport has overcome some of its main technical and economic challenges,[14–16] and supported by tax incentives and mandates, the replacement of internal combustion engine (ICE) vehicles with electric vehicles (EVs) is accelerating in many regions of the world, especially Norway, China, US and other European countries.[17,18] In Norway, for example, the deployment of EVs occurs faster than expected (about 50% of new passenger cars sold in 2019 were full electric).[19] By avoiding tail-pipe emissions, EVs are also seen as 'win–win' solutions for both climate and health.[8] In this context, EV mobility is gradually gaining increasing prominence compared with biofuels as a key climate mitigation option for road transport emissions in many regions of the world.[2,20]

Biofuels and EVs are frequently studied independently, but their mitigation potentials are highly interconnected. Future mitigation scenarios show that the amounts of biofuels needed will be strongly dependent on the scale and rate of EV deployment.[21,22] At the same time, the scale of transport electrification will depend on the availability of biofuels combined or not with carbon capture and storage (CCS).[21–24] More specifically, the climate change mitigation potential of biofuels depends on future transport activity and modes, and the scale of deployment, and it is constrained by land competition and the availability of sustainable biomass resources.[25,26] An in-depth quantitative analysis unraveling the complementary role of biofuels in the context of large-scale electrification of the vehicle fleet is missing.

In our analysis, we used the case of Norway, where an unprecedented rapid expansion of electric vehicles is combined with ambitious targets for biofuel use, to investigate this issue. A bottom-up road activity-fleet model based on national transport targets is developed to project road transportation activities and the use of liquid fuels in Norway until 2050. The gradual implementation of biofuels follows existing targets under the concomitant large-scale introduction of electric vehicles. A flow diagram of our methodological approach is shown in Fig. 1. The model integrates real-word historical data about type-specific traffic activities to project vehicle retirement curves and improvements in vehicle energy efficiency (see Section 2). The biofuel conversion technologies produce lignocellulose-based Fischer–Tropsch diesel (FTD) or cellulosic ethanol (2G ethanol) (see Fig. S1). The mitigation potentials are explored considering either domestic or imported biofuels, with or without CCS. The life-cycle emissions of climate forcers (both GHGs and NTCFs) and other pollutants include different combinations of liquid fuels and vehicle types. The climate change effects are assessed through different climate metrics representative of different temporal perspectives. The human health effects account for life-cycle emissions of particulate matters, ozone precursors, heavy metals and climate change effects and are based on a recently developed approach where regionalized characterization factors are derived from global chemical transport models and species-specific exposure and damage risks.[7] The robustness of the results is tested with a Monte Carlo analysis (10 000 repetitions) that considers multiple uncertainty ranges reflecting variability in key emission factors and impact models (see Methods).

Methods

Road traffic activity

Road traffic activity and energy use in the Norwegian road transportation sector are explicitly modeled for different

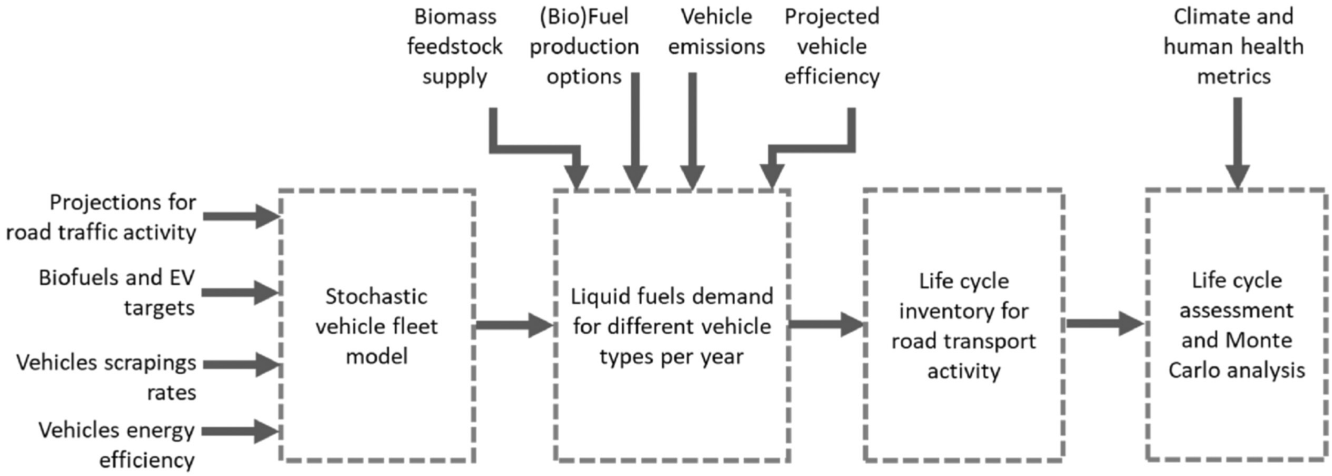

Figure 1. Flow diagram of the main steps and modeling inputs used in this study.

combinations of vehicle types and fuels until 2050. Road traffic activity data for the period 2013–2020 from official national statistics[27] are used to project future road activity. Figures for transport of passengers are assumed constant after 2020, following governmental plans aiming at no increase in traffic.[28] The transportation of goods is assumed to increase at a rate of 1.3% per year, according to Norway-specific projections based on macro-economic modeling.[29] The road traffic activity, expressed as distance (km) traveled with different fuels in light-duty vehicles (LDVs), buses, vans and small and heavy lorries, is converted to energy use using the energy efficiencies of the different types of vehicles.[30] Trends for improvements in vehicle energy efficiency from the period 2005 to 2015[31] are consistently projected up to 2050. For example, LDV energy efficiency using liquid fuels is expected to evolve at 0.6–0.8% increase per year from today's 2.3–2.8 to 1.9–2.2 $\mathrm{MJ\,km^{-1}}$ by 2050.

Projections of biofuels use are based on the targets from the National Transportation Plan.[28] Targets for the use of advanced biofuels were established at 8% in 2020, and are linearly scaled up to 1.7 billion liters in 2030 (about 62% of the total energy from liquid fuels), consistently with the National Transportation Plan.[28] For the period 2030–2050, biofuel use is considered to maintain a constant share of energy use in the total liquid fuels used in the transport sector. The usage mix between petrol and diesel in LDVs is based on extrapolation of the average historical figures for the period 2013–2021.[27]

The introduction of electric vehicles in the transportation sector in Norway follows the targets from the National Transportation Plan.[28] According to these targets, all new passenger cars sold to the market should be electric by 2025, while 75% of new buses and small lorries and 50% of new heavy lorries should be electric by 2030. These trends are implemented in our road transport model and the introduction of electric vehicles is projected to increase linearly from current levels to the proposed targets. After 2030, we assume these targets for the introduction of new electric vehicles in the market will be maintained.

The fraction of the vehicles leaving the current fleet and sent to scrap (vehicle retirement) is 4.9% for LDVs and 3% for the other vehicles.[32] For the new vehicles that are introduced to the fleet, we use the average age of vehicles when scrapped from Williams et al.[33] to model their life span. The introduction of new vehicles in the fleet therefore depends on the number of vehicles leaving the fleet and on the road traffic activity volumes in each specific year according to the developments of the targets for biofuels and electric mobility as described above.

Backcasting biofuel targets to feedstock supply

We connected the given biofuel targets in Norway to the corresponding biofuel demands using the transport activity model described above. We considered that this demand is primarily met with biofuels produced from domestic biomass resource potentials from forest and wood industry residues. The remaining biofuel demand is met from imported biofuels produced from equivalent technologies using lignocellulosic biomass from the international market. This assumption is based on the national ambition to prioritize biofuels from domestically available woody biomass residues from the forestry industry.[28] Forestry residues are currently mostly unused in Norway, contrary to common practices in nearby Sweden and Finland, and represent a potential resource option for climate change mitigation in the country.[34,35] Our estimate of the biomass potential from forest residues in Norway is based on spatially explicit historical harvest volumes of commercial roundwood species like spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) and deciduous species (mostly *Betula pubescens* and *Betula pendula*), considering an average extraction rate of residues of approximately 34% (the fraction of forest residues extracted in relation to the total forest residues available at harvest). This corresponds to about 1.14 $\mathrm{Mton_{db}}$ per year. This volume of forest residues is also complemented by 0.54 $\mathrm{Mton_{db}}$ of industrial wood residues from sawmills and the pulp and paper industries.[36] Overall, we consider a biomass feedstock availability of about 1.7 $\mathrm{Mton_{db}}$ per year.

Imported biofuels are considered to be produced in different potential biomass-producing regions of the world such as other European countries, South America, North America and Asia and a conservative transportation distance of about 10 000 km by transoceanic ship is added to imported biofuels. These regional markets are selected based on the current market shares for wood chips in the international market in the ecoinvent database[37] and biofuel production expansion projections.[38]

Our analysis also considered the direct and indirect land use change (LUC) emissions for imported biofuels as a sensitivity analysis of the mitigation achieved with biofuel deployment under consideration of these factors. The direct and indirect LUC emissions of biofuel production from perennial grasses (switchgrass, miscanthus or unspecified) was summarized by Field et al.,[39] resulting from a review of various literature studies using different global models.

Biofuel conversion technologies

Biofuel conversion technologies are representative of a thermo-chemical process, that is, gasification followed by Fischer–Tropsch synthesis to produce diesel (FTD), and a biochemical process, that is, enzymatic hydrolysis and fermentation to cellulosic ethanol (2G ethanol). These biofuel conversion options produce drop-in biofuels and are among the technologies with the highest readiness level to model conversion of lignocellulosic biomass into biofuels to meet liquid fuel demands in the road transportation sector.[40,41] A simplified process flow diagram of these biofuel conversion technologies is shown in Fig. S1 and their conversion efficiencies are shown in Table S1, the complete life-cycle inventories are shown in Table S2 and the contribution of the individual process stages to the various environmental impacts is presented in Fig. S2.

For the cellulosic ethanol pathway, process inputs and conversion yields are based on Humbird *et al.*[42] This process design involves a dilute acid pre-treatment and enzymatic saccharification, followed by the co-fermentation of C5 and C6 sugars from the lignocellulosic biomass. The severity of the pretreatment process and the type and amount of enzymes are key factors for achieving satisfactory process yields.[43] In this configuration, biogas is obtained from wastewater streams and used to complement the energy demand of the plant together with lignin. Electricity from the excess steam is considered as a co-product of the process using an economic-based allocation approach. This is one of the most widely applied multi-functionality solutions in published LCA studies across sectors,[44] and previous studies from biorefinery systems show that results with economic allocation are similar to the energy allocation as the market prices of products are usually proportional to their energy value.[45] We use relatively long time series for products' market prices (10 years) to minimize the effects of possible price fluctuations.

In the FTD process, lignocellulosic biomass undergoes a gasification process to syngas, which is further converted to biofuels with varied chain lengths through Fischer–Tropsch synthesis. Gasification is the high-temperature partial oxidation of solid material containing carbon with air, steam or oxygen into a gas mixture called synthesis gas or syngas (primarily composed of CO and H_2, but also with varied amounts of CO_2, H_2O and CH_4). Many gasifier configurations have been developed and documented, as well as their advantages and shortcomings.[46] The intermediate gas clean-up and conditioning steps are essential to increase products yields by avoiding catalyst poisoning, remove some of the contaminants and adjust the concentrations of H_2 to CO for suitable process conditions. Syngas can then be converted into synthetic fuels using a catalytic process, where the Fischer–Tropsch synthesis is the most established.[47] The FTD process utilizes a cobalt- or an iron-based catalyst. The catalyst type, the design of the reactor and the process conditions are selected according to the desirable product mix (e.g. gases, naphtha, diesel and waxes), bearing in mind the intrinsic process restrictions. Electricity from excess steam is considered as a co-product of the process, also using an economic-based allocation approach. The process design data of a pressurized fluidized-bed steam/O_2-blown gasification of biomass, followed by hot-filtration and catalytic reforming of hydrocarbons and tars, are taken from the literature,[48,49] considering a process configuration adjusted to a high production of FTD. For the gasification process, air pollutant emissions and the use of inputs are retrieved from the literature.[36,37]

Fossil fuels and tailpipe emissions

Life-cycle emissions of climate forcers and air pollutants [CO_2, CH_4, N_2O, CO, NO_x, SO_x, NH_3, particulate matter (PM), organic carbon (OC), black carbon (BC) and Pb] from the production of fossil diesel and petrol were obtained from the Ecoinvent database, version 3.5. Tail pipe emissions from the use of both biofuels and fossil fuels in different vehicles were modeled according to the Air Pollutant Emission Inventory from the European Environmental Agency using Tier 2 emission factors.[30] These emissions are projected to change in the future according to gradual improvements in vehicle efficiencies.[31] When impacts are presented per passenger.km, as in Fig. 5(a), vehicles are considered with an average occupancy of 1.6 passengers per LDV and 19 passengers for buses.[50]

Carbon capture and storage

Carbon capture and storage based on absorption gas separation with chemical solvents (e.g. monoethanolamine) as a separation agent is considered in this study, as it is the most mature carbon capture technology.[51] The carbon capture unit is considered to capture 90% of the CO_2 of the resulting mixture of flue gases from the combustion of the biogenic carbon from the biofuel production plant. In the cellulosic ethanol conversion process, 28% of the biogenic carbon ends up in the final biofuel. The rest is emitted either in the fermentation processes or in the combustion of biomass residues for energy generation, and therefore available for capture. In the gasification followed by Fischer–Tropsch synthesis, 40% of the biogenic carbon is incorporated in the FTD and co-products and the rest is emitted in the flue gases of the process. The carbon capture unit is modeled as processes that lead to negative CO_2 emissions using additional chemical and energy inputs. The life cycle inventory for the carbon capture unit is based on literature data for a similar CCS application.[51,52] The CO_2 compression, transport and storage stages are also considered.[53] However, the infrastructure of the CO_2 transport network and fugitive emissions during transport and injection phase are not included in our analysis.

Climate metrics

The analysis applied the complementary climate metrics Global Warming Potential (GWP) and Global Temperature Change Potential (GTP) (see Figs S3–S5). While the GWP is a normalized cumulative metric defined as the integrated radiative forcing of a gas between the time of emission and the time horizon, the GTP is an instantaneous normalized metric defined as the change in global mean surface temperature at a chosen time horizon after a pulse emission.[54] Climate metrics are usually sensitive to the time scale of climate forcers, especially for those species with atmospheric lifetimes substantially shorter than that of CO_2. For example, while CO_2 stays in the atmosphere on millennial time scales,[55] many NTCFs, such as CO, NO_x, volatile organic compounds (VOCs), BC and OC, decay from the atmosphere in a few days or months after emissions. This means that NTFCs are not well mixed in the atmosphere and can result in regional impacts that differ from the global average, depending on regions where they are emitted.[5] The GWP is used with two time horizons, 20 (GWP20) and 100 (GWP100) years, to capture short- and medium-term dimensions of the climate system response, while GTP for a time horzon of 100 years (GTP100) is used as a proxy for long-term impacts. Metric values are taken from the latest IPCC Assessment Report.[6] Climate metrics for NTCFs are inherently affected by larger uncertainty than GHGs,[56] which are taken into account in the Monte Carlo Analysis (see Section 2.8 below). In the analysis with GWP20, NTCFs are assessed with globally averaged metrics for the case of imported biofuels, but metrics specifically developed for Europe are used for the case of domestic biofuels to better represent their regional effects (see Table S3).

Human health

Human health impacts are quantified at the end of the environmental cause–effect chain, as they take into account the fate of the pollutants in combination with exposure, effect and damage factors.[57] The characteristics of the emission location determines where and at what concentration a pollutant ends up (environmental fate), and thereby influences the exposure of receptors in the corresponding regions. The exposure factor is used to represent the change in exposure of humans to a given pollutant owing to a change in the emission of its precursor, while the effect factor reflects the change in a disease incidence owing to a change in the exposure to a given pollutant. The damage factor accounts for the years of life lost associated with the health effect per incidence case, which are estimated from World Health Organization statistics.[7] Regional characterization factors for health impacts from PM emission and ozone formation owing to the emission of VOCs, NH_3, SO_2, NO_x and PM are obtained from a recent study using a global chemical transport model to calculate the intake fractions of PM and ozone for 56 world regions covering the whole globe. Region-specific effect and damage factors are derived from mortality rates, background concentrations and years of life lost.[7] Emissions to the atmosphere from the fuel combustion stage and the share of locally produced biofuels are multiplied by the geographically corresponding characterization factors for Norway to quantify location-specific health impacts. For imported biofuels, globally averaged human health metrics are used. Globally averaged characterization factors for human health impacts from heavy metals (e.g. lead) emissions to air were obtained from the literature.[58] We also include human health-induced impacts from climate change effects (e.g. malnutrition, diarrhea, heat stress and natural disasters) based on the factors provided by De Schryver *et al.*[59] (see Table S4).

Uncertainty analysis

A Monte Carlo analysis was used to quantitatively assess the propagation of variability and uncertainty from key factors of the analysis, namely variability in vehicle efficiency, vehicle retirement curves, emission factors for selected vehicles and fuels, future improvements in biofuel production process efficiency, biofuel emission factors and characterization factors for human health and climate impacts. We performed 10 000 repetitions of the analysis by randomly selecting any possible value within the given uncertainty ranges for the different variables. As our sampling was not big enough to establish a normal distribution, we choose a distributions function using the principle of maximum entropy adapted from Mishra and Datta-Gupta[60] and Van der Spek.[61] Using this approach, the triangular distribution was selected as it would better fit when we have the minimum, maximum and mode values of each parameter.

The variability in vehicle efficiency represents the ranges from the present and future energy efficiency targets from the European Environmental Agency (Table S5). The uncertainties in emission factors for selected vehicles represent the ranges from present and future emissions of key pollutants according to the European Environmental Agency (Table S6). The variability in vehicle retirement curves is intended to capture the uncertainty in the rate of different vehicles types leaving the fleet based on Norwegian statistics for the current fleet and the age ranges (Table S7).

Uncertainties also lie in tailpipe emissions of the different fossil fuels and biofuels. For biofuels, emission factors are derived from specific blends of biofuels and fossil fuels reported in the literature.[62] Some of these uncertainties are addressed in the Monte Carlo analysis. Owing the intrinsic chemical composition of biofuels, we also consider some expected reduction in key emission factors from the use of biofuel in comparison with fossil fuels (Table S8). Improved accuracy in tailpipe emissions may be achieved with refined estimates of emission factors for the specific biofuel mixtures in different vehicle applications. Uncertainty in black carbon and organic carbon emission factors from the value chain of liquid fuels is included owing to its importance for climate impacts (they are powerful NTCFs; Table S9). The uncertainties in future vehicle efficiency improvements are captured using the historical trends of improvements for ICEs (Table S10). We selected ranges for biofuel process efficiency to represent the variability in conversion process efficiency found in the literature for the two biofuel conversion options (Table S1).

Climate metrics for NTCFs were assessed with the uncertainty ranges from the latest IPCC report (Tables S3 and S11) to represent their inherent spatial variability and uncertainty. This uncertainty is mainly due to the limitations of climate models and to contemporary understanding of aerosol forcing. Uncertainty ranges used in the characterization of human health impacts are derived from the literature,[7] and are specific to European countries (Table S10).

Results and discussion

Road traffic activity and energy use

The projected road transportation activities according to Norwegian national policies (Fig. 2a) have different patterns than those for energy use (Fig. 2b). The total transportation activity is projected to increase by about 10% in 2050 relative to 2020, mostly as a result of the increased transportation of goods. Passenger transport activity volumes are expected to stabilize in Norway as a result of policies to limit traffic in cities and incentives for alternative mobility.[28] A large and rapid electrification is expected, which will include not only LDVs, but also increasing shares of lorries and buses after 2040. On the other hand, the total energy use is projected to drop by about 65% in 2050. This decrease in energy use is

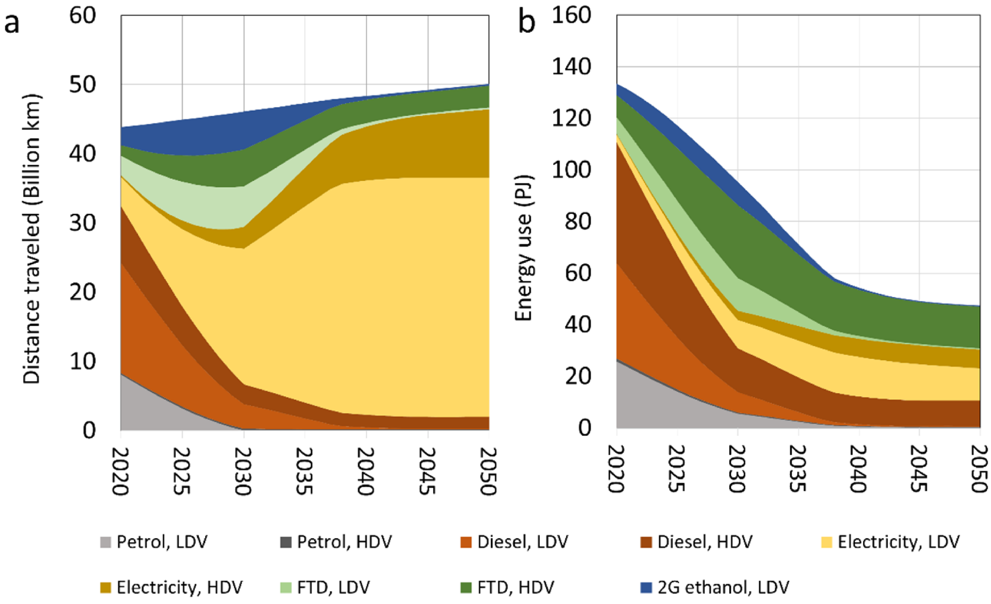

Figure 2. Projections of future road traffic activity (a) and energy use (b) by fuel and vehicle types in Norway until 2050. Note: FTD, Fischer–Tropsch diesel; 2G ethanol, cellulosic ethanol; LDVs, light-duty vehicles (passenger cars); HDVs, heavy-duty vehicles (buses, vans and light and heavy trucks).

largely caused by energy efficiency gains from electrification in relation to correct ICE vehicles, with limited contributions from efficiency improvements over time in ICE vehicles. This decrease in the demand in the road transport sector should not hinder projected new investments in biorefineries, as production processes can be redirected to other sectors than road traffic, such as aviation and shipping, where electrification is more challenging and fewer decarbonization options exist.

The total energy use from fossil diesel and petrol is projected to drop from about 130 PJ in 2020 to <30 PJ in 2050. The contribution of biofuels varies in time, reaching a maximum of 50 PJ in 2030 and stabilizing at about 18 PJ after 2040. Even with a quick and substantial electrification of the road transport system, biofuels are expected to cover a non-negligible share (about 36% in 2050) of the energy use in the future road transport system. This is mostly due to two factors: (i) the current and near future share of the ICE fleet that is driven by liquid fuels, which needs time to be entirely replaced by electric vehicles; and (ii) the continued partial dependency of heavy vehicles (vans, lorries and buses) on liquid fuels. The use of cellulosic ethanol for LDVs tends to fade out after 2035, as a result of a nearly complete phasing out of petrol-driven LDVs. There are larger opportunities for FTD in diesel-fuelled vehicles, mostly heavy lorries and buses.

Climate mitigation of biofuel deployment

Without biofuels, the remaining share of non-electric road transport activities in Norway will be responsible for about

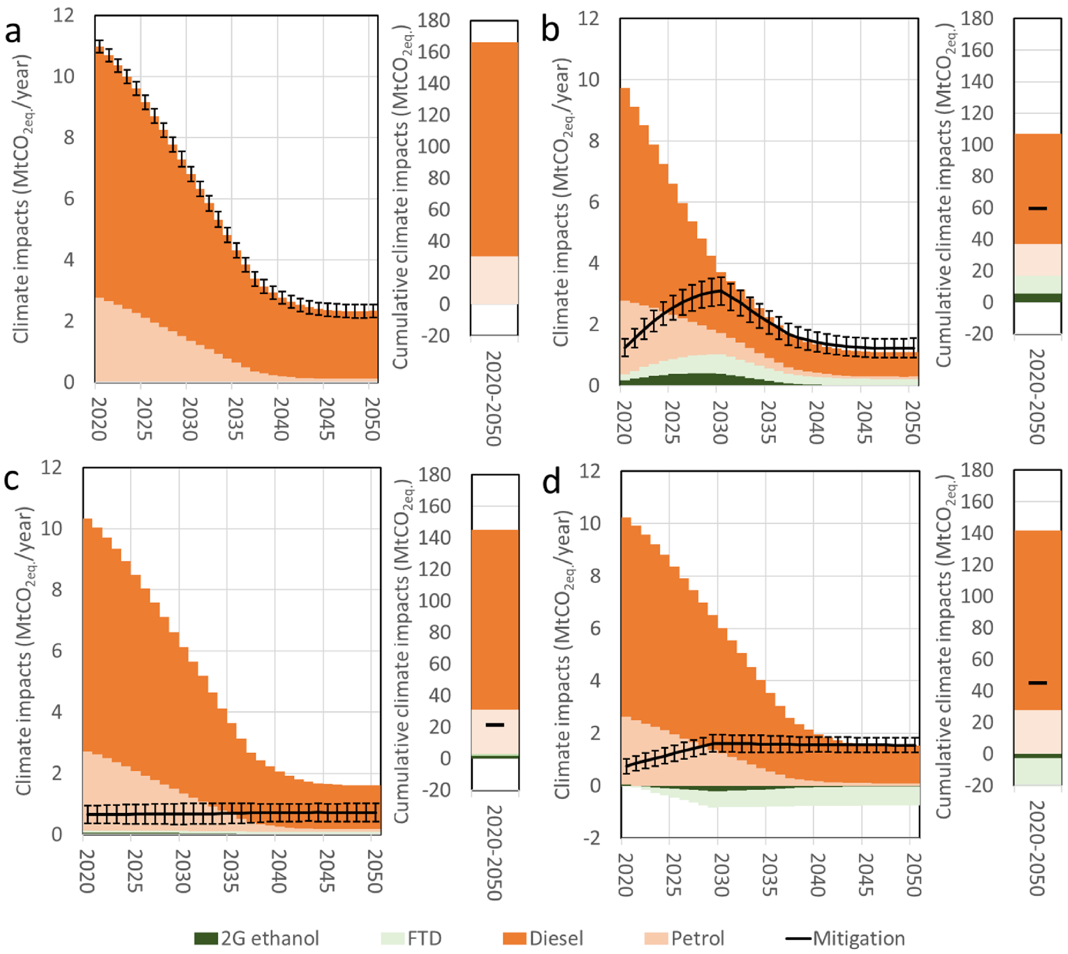

Figure 3. Temporal evolution of climate impacts (GWP100) from liquid fuels used in the road transportation sector in Norway. Panels show results (a) without the introduction of biofuels, (b), considering the introduction of domestic and imported biofuels to fully meet the national targets and (c) the introduction of biofuels limited to domestically available forest residues only, and (d) as (c) but with carbon capture and storage (CCS) (d). Climate impacts are shown both yearly from 2020 to 2050 (left) and as cumulative impacts for the same time period (right column). Both greenhouse gas (GHG) emissions and near-term climate forcers (NTCFs) are included. Uncertainty ranges refer to one standard deviation around the mean.

160 $MtCO_2eq$. of cumulative life-cycle emissions between 2020 and 2050 (Fig. 3a). The cumulative climate change mitigation potential of biofuels ranges from about 20 to 60 $MtCO_2eq$., depending on whether both imported and domestic biofuels are considered to meet national targets (Fig. 3b) or only domestic biofuels are used without (Fig. 4c) or with CCS (Fig. 4d).

There is a clear trend for a reduction of climate impacts from the road transport system even without considering the introduction of biofuels (Fig. 3a), thanks to a rapid and large electrification of the vehicle fleet. For example, climate change impacts without the use of biofuels are projected to reduce by 56 and 74% by 2035 and 2050, respectively. After 2035, climate impacts are mostly related to diesel use in heavy transportation vehicles because nearly all of the LDV fleet will be electrified.

The additional net mitigation from biofuels according to the implementation of national targets peaks around 2030 at 3.1 ± 0.45 $MtCO_2eq$. per year (mean ± standard deviation; Fig. 3b). This corresponds to a reduction of approximately 57% relative to the use of fossil fuels only, and as a benchmark, it is equivalent to 6% of the total emissions in Norway in 2019.[63] The projected national targets need both domestic and imported biofuels to be met (Fig. S6). The national ambition to prioritize biofuels from domestically available biomass resources (mainly woody residues from the forestry industry) as a strategy to stimulate a circular economy perspective; prevent additional pressure on terrestrial ecosystems; and revitalize rural areas has limited potential. Biofuel imports peak when the national biofuel demand is the highest, reaching about four times the domestic production volume in 2030. With the decreased biofuel demand after 2035, the dependency on imported biofuels stabilizes at about the same level as domestic biofuels. The average mitigation for the period 2020–2050 that can be achieved with domestic biofuels is about 0.7 ± 0.31 $MtCO_2eq$. $year^{-1}$ (Fig. 3c), and it could increase up to 1.5 ± 0.30 $MtCO_2eq$. $year^{-1}$ with a gradual implementation of CCS at a rate of 10% per year from 2020 to 2030 (Fig. 3d). The latter is about half of the mitigation per year of the case where both

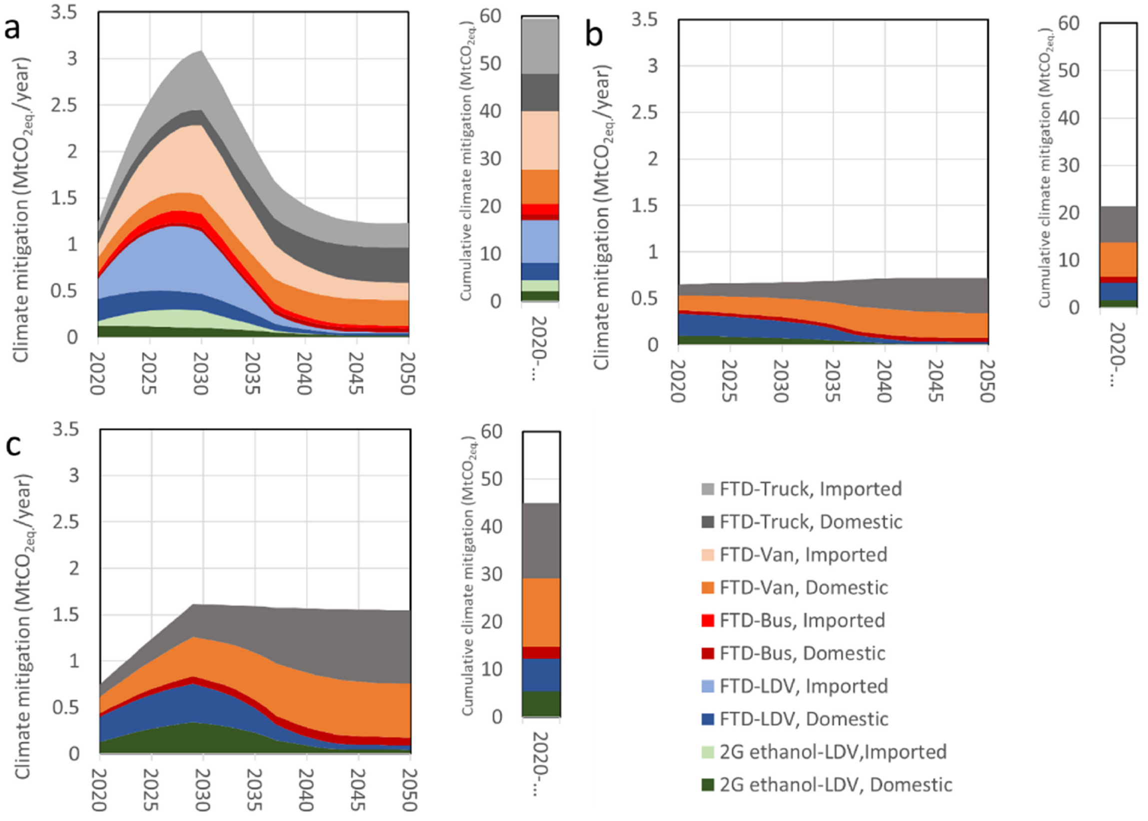

Figure 4. Breakdown of climate mitigation profiles and cumulative mitigation in the period 2020–2050 per type of vehicle and fuel. Results show mitigation potentials (based on GWP100): (a) when both domestic and imported biofuels are considered; (b) when only domestic biofuels are considered; and (c) domestic biofuels are considered with CCS. Note: FTD, Fischer–Tropsch diesel; 2G ethanol, cellulosic ethanol; trucks, vans, buses and LDVs represent the use of biofuels in the different vehicles types; imported and domestic refer to the origin of the biofuel.

domestic and imported biofuels are considered. Biofuels can mitigate cumulative life-cycle emissions relative to fossil fuels by 36% between 2020 and 2050 (Fig. 3b). When only domestic biofuels are considered, the mitigation decreases to 13% (Fig. 3c), but when CCS is implemented, it is about 27% (Fig. 3d). The net life cycle impacts of biofuels turn negative with the implementation of CCS (Fig. S7), meaning that biofuels are produced while delivering negative emissions.

In terms of contributions from individual climate forcers, CO_2 is the dominant component in the mitigation of climate impacts. There are important contributions at the fuel production stages from NTCFs (such as SO_x, NO_x and PM; Figs S8 and S9), some of which show a cooling effect (Figs S10 and S11). Emissions of NTCFs are larger for the cellulosic ethanol production chain than the FTD route, mainly owing to the high use of chemicals such as sulfuric acid and sodium hydroxide during biomass pre-treatment and the need for enzyme production. Even if electric vehicles are introduced at a high rate, biofuels still contribute to the mitigation of emissions from the road transport from the short (mostly LDVs) to the long term. For example, considering one standard deviation around the mean, climate mitigation from biofuels will be in the range of 2.6–3.5 $MtCO_2$eq. in 2030, 1.1–1.7 $MtCO_2$eq. in 2040 and 0.9–1.5 $MtCO_2$eq. in 2050.

The results shown so far considered the GWP with a time horizon of 100 years (GWP100) to assess climate change impacts, as typically done in the majority of life-cycle assessment studies or carbon footprint analyses.[64,65] It is well acknowledged that no single metric can simultaneously assess the impact of different climate forcers on different aspects of climate change, such as the rate of change or long-term temperature increase.[66,67] We therefore tested the sensitivity of our results to alternative metrics as well, like the GTP, and different time horizons, either 20 or 100 years. The GWP20 and GWP100 address short- and medium-term climate change impacts, respectively, targeting effects on the rate of climate change.[65] GWP100 is a proxy for mid-term impacts because, following its numerical similarity with GTP40,[68] it can be interpreted as a metric informing about temperature changes at approximately four decades after emissions.[67] GTP100 is a better proxy for long-term impacts because it targets the potential temperature rise after 100 years, which is more consistent with the temperature stabilization objective stated in the Paris Agreement.[69] The climate mitigation potentials of biofuels measured with the GWP20 and GTP100 are similar to those with the GWP100 (Figs S9–S11). The mitigation potential is slightly larger in the long term (GTP100), where the relative importance of CO_2 is significantly higher than for short- and medium-term impacts, for which non-CO_2 components such as SO_x, NO_x and BC become more relevant.

Climate mitigation by biofuel type and vehicle

The specific mitigation benefits for each combination of biofuel and vehicle type are shown in Fig. 4. In all three biofuel deployment cases, the mitigation trends are largely dominated by FTD in trucks and vans. Climate mitigation from biofuels in LDVs is only remarkable until 2035. About 77% of the total climate mitigation achieved in 2030 is from imported biofuels (Fig. 4a). In the same year, 37% of the mitigation comes from biofuels in LDVs, 31% in vans, 26% in trucks and 6% in buses. In 2050, 41% of the mitigation is from imported biofuels and 52% of it comes from biofuels in trucks, 38% in vans, 6% in buses and 4% in LDVs. When only domestic biofuels are considered (Fig. 4b), FTD use in LDVs in 2030 is 27% of the total mitigation and 56% is from FTD in trucks and vans. After 2030, biofuel use becomes larger in trucks and vans (90% of the total mitigation in 2050) as a result of high shares of LDV electrification. The cumulative climate mitigation from domestic biofuels in the period 2020–2050 is 36% of that achieved with both domestic and imported biofuels. The implementation of CCS (Fig. 4c) increases this share to about 76%, with mitigation from trucks and vans representing 89% of the total mitigation achieved with biofuels use in 2050.

In terms of life-cycle emissions from different fuels and vehicle combinations, the specific climate mitigation from domestic biofuels is larger than that of imported biofuels for all vehicles and biofuel options (Fig. 5). Imported biofuels have higher emissions from the transoceanic transport, and from more energy- and GHG-intensive biofuel production processes from average international markets. Climate mitigation from biofuels in passenger transport (per person. km) is higher for LDVs than buses (Fig. 5a). For LDVs, mitigation is slightly higher for FTD than cellulosic ethanol, although uncertainty ranges largely overlap. Regarding the transportation of goods (Fig. 5b), mitigation is higher when biofuels are used in heavy lorries than in vans and small lorries. In general, the higher the climate impacts of the transport option using fossil fuels, the higher the mitigation when biofuels are used.

Future biofuel carbon impacts per km are expected to decrease with time as a result of continued vehicle efficiency gains (Fig. 5c), and can also be net negative when combined with CCS technologies (Fig. S7). The largest specific climate mitigation potential per km driven is found with FTD in buses and trucks, but when it is combined with activity

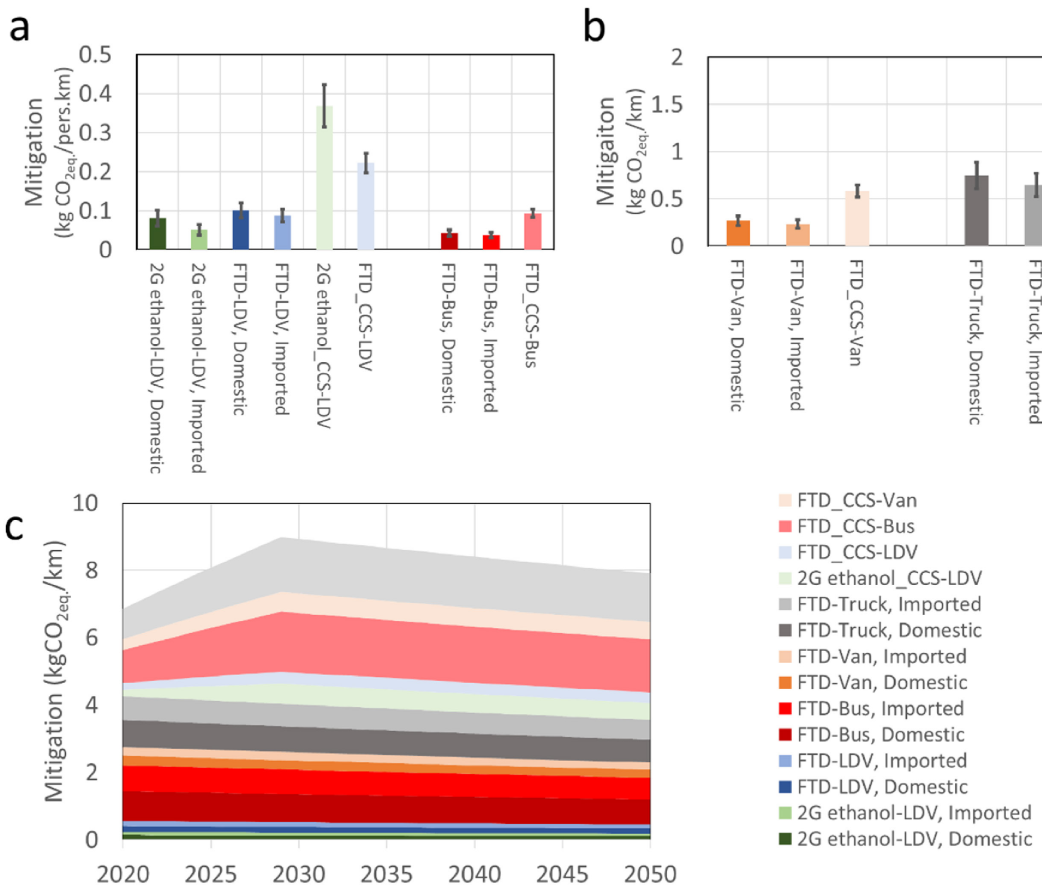

Figure 5. Average climate mitigation (GWP100) from different biofuel–vehicle combinations for the period 2020–2050 in Norway. Uncertainty ranges for biofuels mitigation for (a) passenger vehicles and (b) trucks and vans represent the variations modeled for life-cycle mitigation benefits of biofuels between 2020 and 2050. Uncertainty ranges refer to one standard deviation around the mean. (c) Evolution in time of the total mitigation per km driven and contributions from use of biofuels in different vehicle types. FTD, Fischer–Tropsch diesel; 2G ethanol, cellulosic ethanol; trucks, vans, buses and LDVs represent the use of biofuels in the different vehicles types; imported and domestic refer to the origin of the biofuel.

data (demand of driven km with each vehicle type), the mitigation is much larger for trucks and vans than for buses (e.g. Fig. 5a) owing to the higher demand for the transport of goods. The results of climate impacts per km driven show that prioritizing biofuel use in larger trucks, vans and public transport (buses) can achieve the largest mitigation gains. CCS makes the mitigation per km in 2030 about 2.2 times larger for FTD in all vehicle types, and 4.5 times larger for cellulosic ethanol in LDVs. Differences are due to different shares of carbon sequestration from biofuel production processes.

Human health effects

Spatially explicit characterization factors are used to assess human health damage, measured as disability-adjusted life years (DALY) lost from emissions of toxic compounds (e.g. heavy metals), PM, ozone precursors and climate change effects. The average impacts on human health decrease with increased use of biofuels, but the associated uncertainty ranges are larger. The climate mitigation effects of biofuels might be associated with potential trade-offs in terms of human health impacts relative to the baseline case where only fossil fuels are used (the lower end of the uncertainty bars in Fig. 6). This is particularly due to cellulosic ethanol, which has impacts with uncertainty ranges overlapping those of fossil fuels (Fig. 7). Heath effects are larger for the cellulosic ethanol production chain than the FTD route, mainly owing to the relatively high use of inputs for enzymes production and biomass pre-treatment. The mitigation of the health impacts peaks around 2035, and tends to decline as the demand for liquid fuels, especially cellulosic ethanol, is reduced. Mean human health mitigation is relatively smaller for domestic than imported biofuels (Fig. 6c) and with CCS

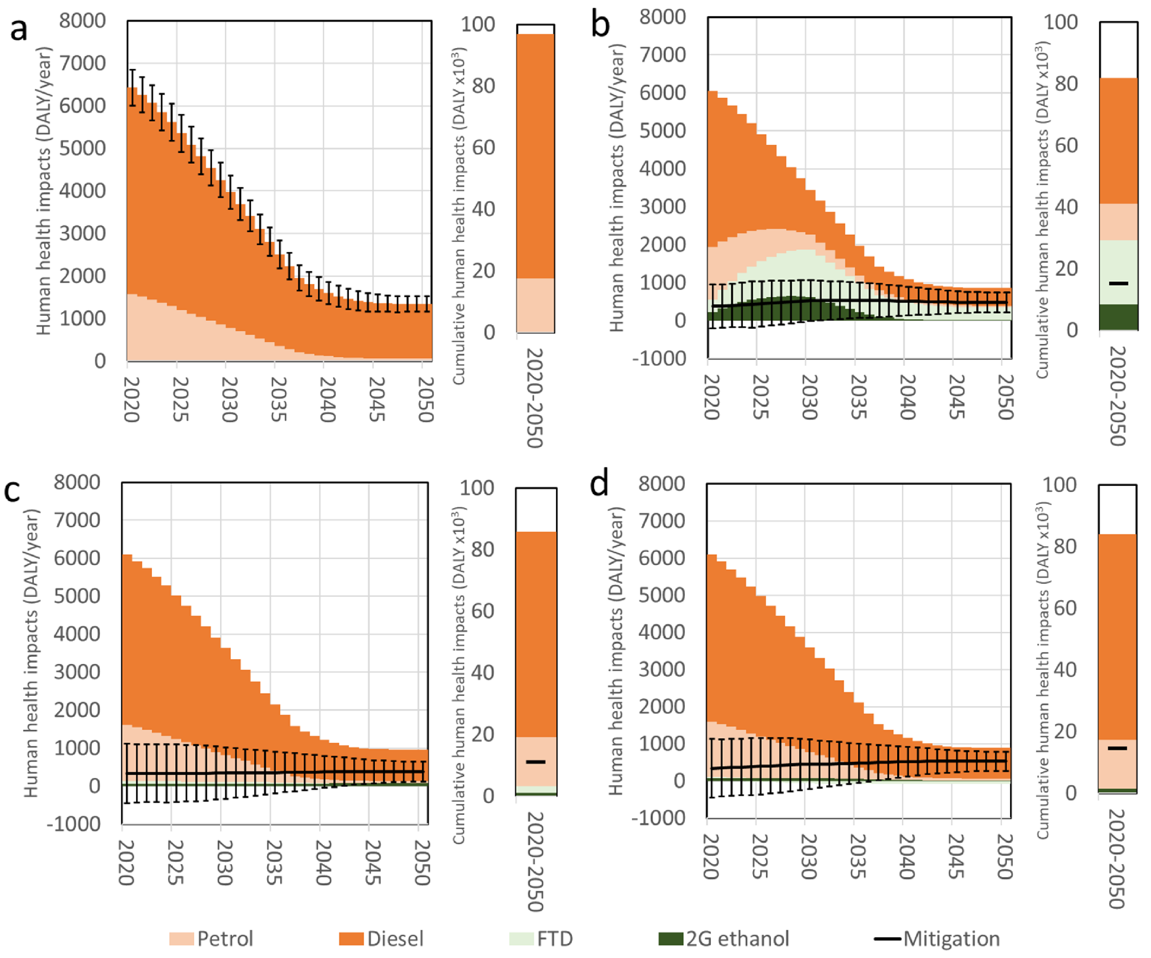

Figure 6. Temporal evolution of human health impacts from liquid fuels used in the road transportation sector in Norway. Results are shown for (a) fossil fuels only, (b) with domestic and imported biofuels to fully meet the national targets, (c) with domestic biofuels only and (d) with domestic biofuels with CCS. Human health impacts are shown as the evolution per year from 2020 to 2050 (left) and cumulative impacts for the period 2020–2050 (right). Uncertainty ranges refer to one standard deviation around the mean.

implementation higher (Fig. 6d). Substantially lower health impacts from biofuels in comparison with fossil fuels are observed from CO_2 emissions, while higher contributions to human health impacts from biofuels are mainly related to higher emissions of lead, PM, NO_x and SO_x (see Fig. 7 and Fig. S12) from the biofuel's life cycle. These emissions are especially high for imported biofuels, which involve shipping, and represent between 8 and 17% of their health impacts.

In general, the Monte Carlo analysis shows that results for effects on human health have lower confidence than those for the climate impacts, preventing the drawing of ultimate conclusions regarding the relative performance of biofuels and fossil reference. Effects on human health are measured towards the end of the environmental cause–effect chain, reflecting the additional uncertainties in exposure risks and damage factors for the characterization of these impacts.[57] Developing more advanced modeling approaches that can combine distributed emissions and the transport of key pollutants at higher temporal and spatial resolution with refined estimates of population density and exposure risks is needed to constrain uncertainties in characterization factors.[4,70,71]

Uncertainties and limitations

The overall climate change mitigation benefits of biofuel deployment remain valid under a large variety of uncertainty ranges explored in a Monte Carlo analysis (see Section 2.8). However, important uncertainties remain. For example, forestry residues are currently mostly unused in Norway and represent a potential biomass resource option (see Section 2.2). However, it is important to

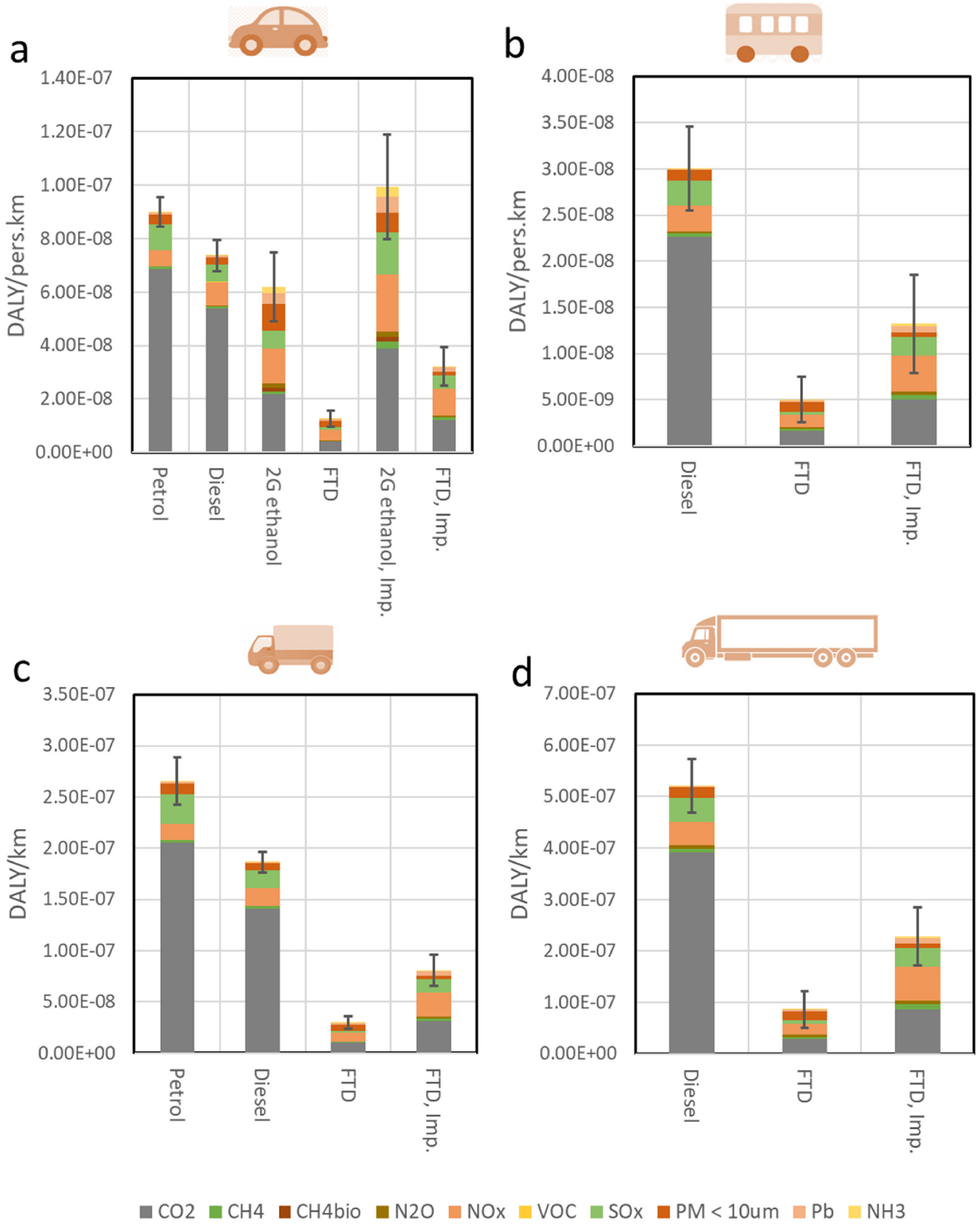

Figure 7. Human health impacts of liquid fuels used in (a) LDVs, (b) buses, (c) vans and small trucks and (d) heavy trucks. Uncertainty ranges refer to one standard deviation around the mean and are derived from a Monte Carlo analysis that considers variability in key factors like vehicle efficiency, vehicle retirement curves, biofuel production efficiency, biofuel emission factors and emission factors for selected vehicles and fuels. FTD, Fischer–Tropsch diesel; 2G ethanol, cellulosic ethanol; imp., imported biofuel.

highlight that there are limitations for its utilization such as procurement and logistics challenges, quality issues (e.g. ash and moisture content, particle size) and, in the absence of market regulations, the actual shares of locally produced and imported biofuels are likely to be driven by their comparative costs and market volume availability. A sustainable supply of biofuels from international markets is thus key to securing high levels of climate change mitigation benefits from biofuel targets in Norway. Major transitions projected for the land use and energy sectors at a global level can significantly increase sustainable biomass resource availability.[26,72] Our analysis assumed no major changes in terrestrial ecosystem carbon stocks from imported biomass, but both positive and negative effects have been widely documented.[39,73,74] These effects have high spatial and temporal variability and largely depend on local climate and soil conditions, the type of biomass feedstock, previous land use, management intensity and the accounting method.[26,39,75] Large-scale deployment of biofuels is frequently associated with increased risks of carbon emissions from direct and indirect LUC,[76] although recent estimates of indirect LUC emissions are remarkably smaller than earlier factors.[39,77,78] For example, the addition of default indirect LUC factors averaged from multiple studies[39] to the imported biofuels would increase climate impacts by 6 and 17% for cellulosic ethanol and FTD, respectively. The net climate change mitigation benefits of biofuel deployment would thus decrease by 4% in 2030. The consideration of these potential indirect LUC effects from suboptimal management of biomass resources thus reduces the overall emission savings, but it does not offset the net emission savings benefits. However, risks are expected to be larger for ecosystem services in the case of unsustainable practices.[79] Our analysis considers that imported biofuels are supplied from an averaged international market of lignocellulosic biomass that is today still under development. As highlighted by the IPCC Special Report on Climate Change and Land, biofuels are an essential component of future climate change mitigation scenarios but their large-scale deployment requires governance and cross-sectoral policies to prevent land competition and environmental degradation and maximize co-benefits.[26]

Our analysis does not include uncertainties associated with other factors of future road transportation systems. For example, the climate change mitigation benefits are based on today's prescribed policies and targets, and the sensitivity to alternative policy objectives is not considered (other than the baseline case of electrification without biofuels). Other renewable transport options than EVs and biofuels are under development and can become widely used by 2050. Some of these technologies are compatible with existing engines (drop-in biofuels), others must be used in low blends with fossil fuels or in dedicated engines, or require large changes in infrastructure. In addition, a techno-economic analysis and the use of more econometric models would also help to understand the many possible interactions and feedback loop mechanisms between EVs and liquid fuels demands, including the dynamics of market competition and their sensitivity to key factors like future changes in oil prices, EV material costs, the availability of metals and electricity potentials and prices. More knowledge on these matters, together with information on environmental aspects of the different technologies, can help to design more efficient policies to support a complementary co-development of biofuels and EV in the transport sector.

Although gradual improvements of biofuel conversion efficiencies are included in the Monte Carlo analysis, we do not consider the possibility of novel conversion routes for advanced biofuels production, including many other potential biomass and biofuels import options. We also do not include potential changes in the driving cycles from real-world usage of vehicles in comparison with standardized driving cycles, especially considering additional behavior driving changes owing to factors such as the autonomy phobia associated with EVs or rebound effects.[19] The life-span of new vehicles is considered constant in our analysis, meaning that future potential improvements in the durability of new vehicles is not considered. In addition, the recent Covid-19 pandemic has caused significant changes in the transport sector activity,[80] and how the sector will develop after the pandemic is unclear.

Concluding remarks

Under a substantial and rapid electrification of the vehicle fleet, biofuels still offer large opportunities for additional mitigation of emissions from the road transport sector both in the shorter and longer terms. In the near term, biofuels mitigate emissions from current and near-future ICE vehicles until they represent a sizeable fraction of transportation activities. In the longer term, biofuels are a key mitigation option in the segments of the transport sector with slower penetration of electric vehicles, such as heavy-duty vehicles (trucks and vans). These climate benefits can have potential trade-offs with human health, but the associated uncertainty ranges prevent the drawing of robust conclusions (especially for cellulosic ethanol).

Domestic biofuels have limited potentials when compared with the national targets. The magnitude of the mitigation is intrinsically connected to the availability of sustainable biomass or biofuel markets, but it also depends on externalities such as the current and near future fleet turnover, EV penetration rate and technological developments (e.g. vehicle efficiencies, and to a larger extent, CCS). Our results are specifically based on a Norwegian context as a prominent example of high penetration of EVs, but similar outcomes can be expected elsewhere under varying rates of electrification (larger mitigation from biofuels if electrification is slower). As Norway has an almost fossil-free electricity supply, domestic biofuel production can have higher impacts in other countries, whereas life-cycle emissions of imported biofuels can be smaller as Norway typically has longer shipping distances.

Overall, integrated strategies that combine increasing shares of EVs with targeted biofuel use in selected segments of the road transport sector can better exploit strengths and synergies of electrification and biofuels in a given local context, with the potential to achieve a larger share of mitigation. However, there is no one-size-fits-all solution to decarbonize transport and no single mitigation option can solve the grand challenge of very low emissions from the road transport sector. The required massive net emission reductions can only be reached with a set of measures including EVs, biofuels and other carbon-free energy carriers, as well as parallel measures to improve ICE efficiency, increased use of public transport and more climate-friendly personal choices such as the reduction of vehicle ownership and usage. A proper consideration of these issues in combination with comprehensive assessment of the environmental aspects of the different available technologies can help to design more efficient policies to support a complementary co-development of biofuels and EVs in the transport sector.

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