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A Report from the Advanced Motor Fuels TCP and IEA Bioenergy TCP

Technology Collaboration Programme on Advanced Motor Fuels

IEA Bioenergy Technology Collaboration Programme




The Role of Renewable Transport Fuels in Decarbonizing Road Transport

Scenarios and Contributions in Selected Countries

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Summary / Abstract

*This report constitutes Part 3 of the report on "**The Role of Renewable Transport Fuels in Decarbonizing Road Transport**". In this report the term decarbonization includes all options to reduce GHG emissions and make road transport cleaner, including low(-fossil)-carbon energy carriers suc*h as biofuels, e-fuels, and renewable electricity. This part of the report covers the core of the project, which is the assessment of the transport sector and its development for a number of selected countries.

In this assessment, the road transport sectors of Finland, Sweden, Germany, USA and Brazil are modeled and scenarios for their development into the future are calculated. This sample of countries is quite diverse and differs largely in land area, population density, number of cars per capita, and average transport work in passenger cars and in trucks, as shown in the table below.

Comparison of some transport-related indicators, taken from https://www.worldometers.info/world-population/population-by-country/.

	2020				
	Finland	Sweden	Germany	USA	Brazil
Population size	5,545,000	10,100,000	83,780,000	331,000,000	212,600,000
Land area, km²	303,890	410,340	348,560	9,147,420	8,358,140
Pop. density	18.2	24.6	240.4	36.2	25.4
Cars/capita	0.501	0.486	0.552	0.717	0.180
Car-km/capita	7,600	5,600	7,800	13,000	3,000
Car-km/km²	138,000	137,000	1,880,000	270,000	76,000
MDT&HDT-km/capita	633	502	496	1,535	374
MDT&HDT-km/km²	11,555	12,344	119,214	55,554	9,514

The transport sector of each of these countries was modeled in the ALIISA model. The model includes 5 vehicle categories, 6 propulsion systems and 12 fuel options. Input data for each country includes assumptions on total sales in each vehicle category for future years, on the distribution between the available powertrain/fuel options in sales, on the fuel consumption (or energy efficiency gain) for future years, and on the annual driven distance, variable between categories, age classes and powertrain/fuel combinations. The model then calculates the fleet composition for each year up to 2050, the total energy demand of this fleet, and the resulting tank-to-wheel (TTW) CO_2 emissions. It should be noted that CO_2 emissions of renewable shares and electricity are

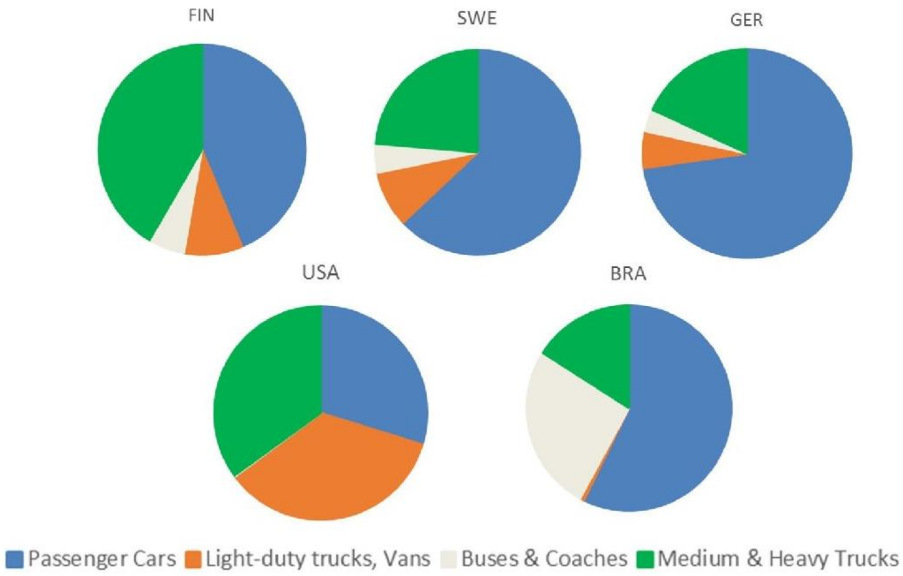
considered to be zero, although in reality both energy carriers cause upstream emissions.

These calculations were performed for four different scenarios:

- Current Policies Scenario
  This is the base case scenario, including input data from each country based on historic data and on current policies.
- MORE EV Scenario
  This scenario reflects higher than anticipated sales of electrified vehicles up to the levels still deemed conceivable by the country experts involved.
- MAX BIO Scenario
  This scenario applies biofuels to the maximum extent possible in the respective country, starting from current deployment level up to the maximum level in 2050.
- E-FUELS Scenario
  This scenario introduces e-fuels in 2030 and increases linearly to reach full displacement of fossil fuels by 2050.

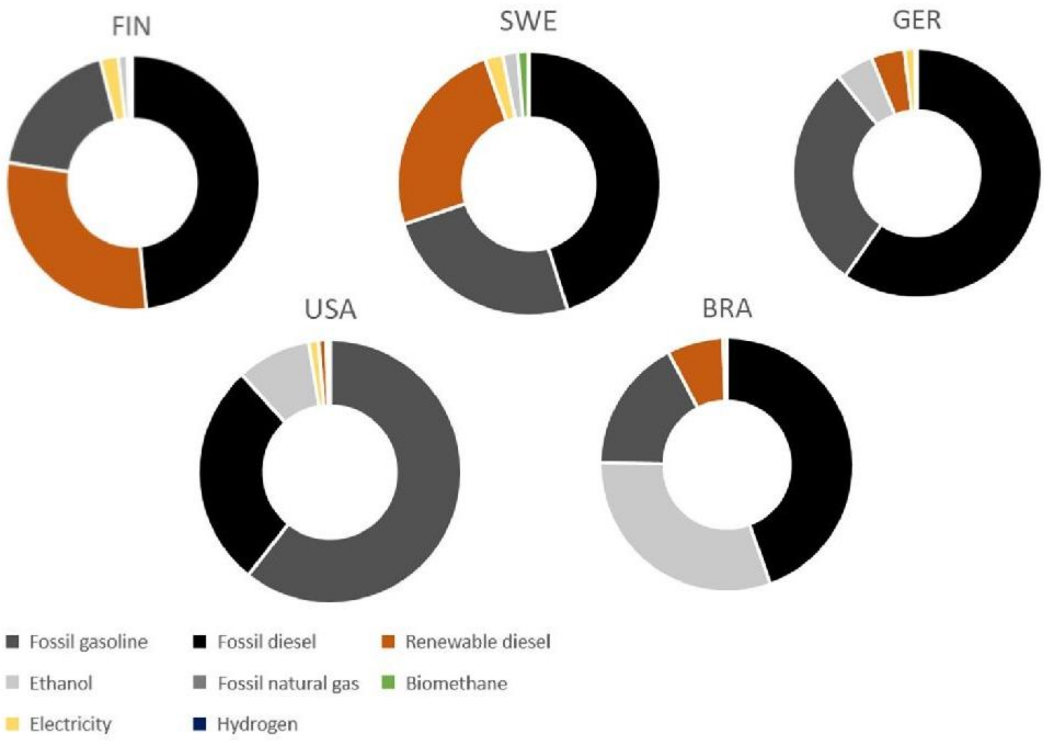
Decarbonization based on current policies

As mentioned before, the transport sectors of the selected countries differ from each other quite a lot. For example, in Finland almost half of the energy in 2030 will be used in trucks, while in Sweden and Germany passenger cars dominate. In the USA the passenger car fleet is complemented by an equally sized fleet of vans, trucks and SUVs used for personal mobility, and Brazil features the largest contribution of buses to the energy use of the transport sector, see the following figures.



Energy use per vehicle category in Current Policies scenarios – 2030.

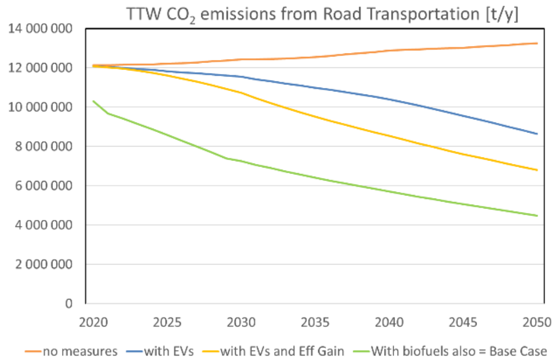
Taking a closer look at the fuels that will be used in the Current Policies scenarios in 2030 in each of the countries, we find different main fuels. In Germany, Sweden and Finland, diesel dominates, and Finland and Sweden will also use significant shares of renewable diesel. In Brazil the share of ethanol will be more than 30%, almost equally large as the share of diesel. In the USA, gasoline dominates over diesel, and ethanol contributes some 10%. The use of electricity is hardly visible, and also biomethane only provides a very minor share.



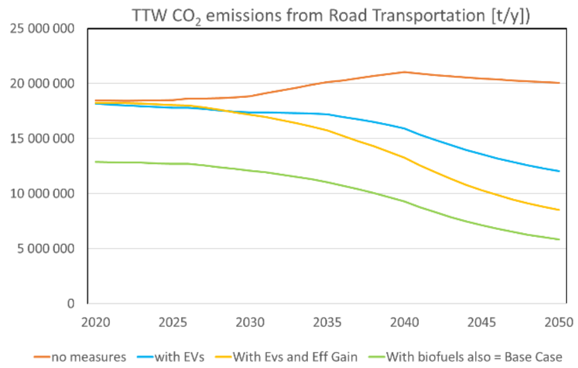
Energy use per carrier in the Current Policies scenarios – 2030.

Based on the projected energy use, the ALIISA model allowed to calculate the effects of several measures separately, namely gains in the energy efficiency of the vehicles in use, use of electric vehicles (with zero TTW CO_2 emissions), and the use of biofuels (also counted with zero TTW CO_2 emissions). In the figure below, the top-most red line is the hypothetical evolution of TTW CO_2 emissions from the road transport sector without any of these measures. The blue line then shows the effect of electrification alone, while the yellow one adds to this the effect of energy efficiency gains. Finally, the green line shows the combined effect of all measures including biofuels.

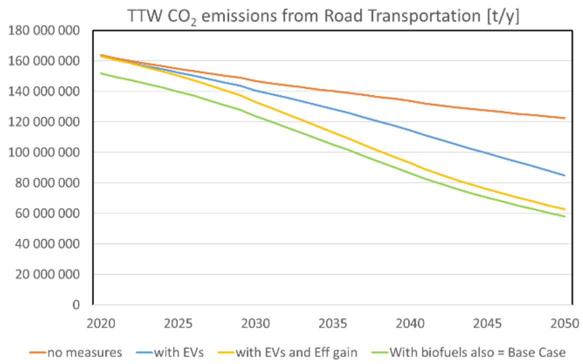
The figure below clearly shows the size of the expected contributions of efficiency gains, electric vehicles and biofuels. Biofuels contribute most to decarbonization now and up to 2030, 2040, or even 2050, depending on the country. In Germany and in the USA, efficiency gains become the main contributor after 2030, and in Finland and Sweden the impact of biofuels remains largest until around 2040 when the use of electric vehicles takes over. In Brazil, biofuels remain the largest contributor until 2050. Biofuels can be implemented in the legacy fleet, whereas electrification and fuel cell vehicles required the introduction of new vehicles and new infrastructure, requiring time to achieve significant impact. The figure also shows the difference in CO_2 emission trends for the selected countries, with CO_2 emissions decreasing in Finland, Sweden and Germany, stabilizing in the USA and still increasing in Brazil. This is due to the projected increase in GDP and the resulting increase in transport work in Brazil.



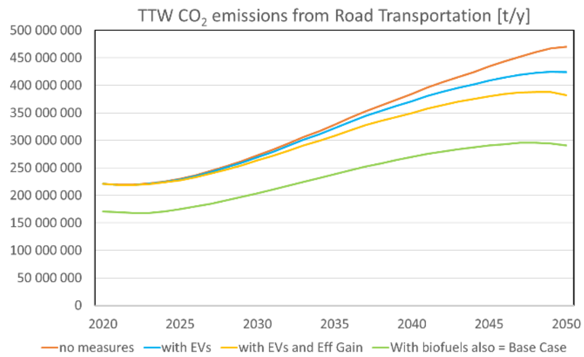
Finland



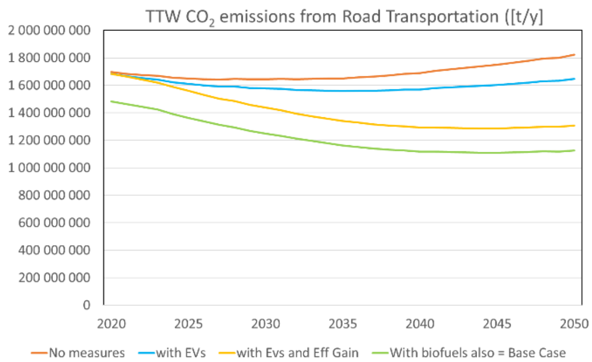
Sweden



Germany



Brazil



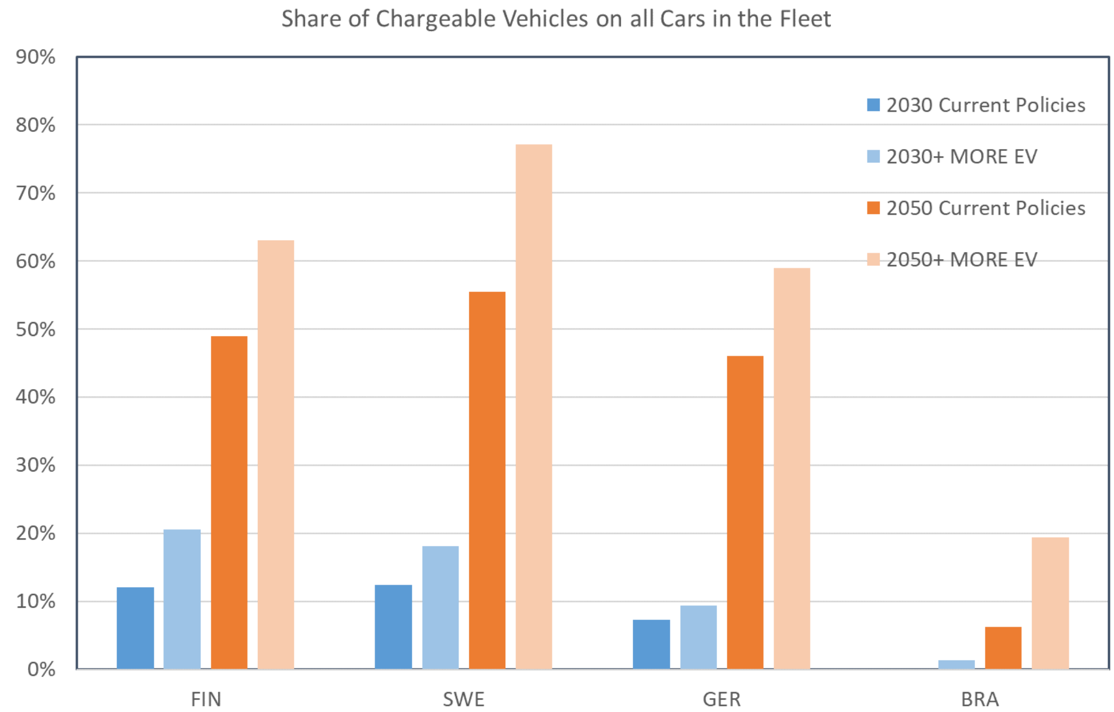
USA

Evolution of TTW CO_2 emissions in road transport by different measures for Finland, Sweden, Germany, USA and Brazil in the Current Policies scenario.

The effect of introducing more electric vehicles

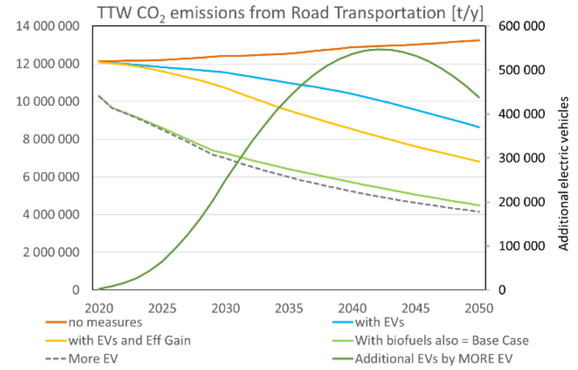
As to check the sensitivity of the results to an accelerated market introduction of electrified vehicles, the MORE EV scenarios were calculated. The assumptions for each country are based on discussions with the country experts involved in this project. For Sweden, Germany and Brazil, 100% of passenger car sales in 2050 were assumed to be various sorts of electric vehicles; only for Finland 25% of passenger car sales were still assumed to be spark ignited ICEs in 2050. The dynamics of this uptake, however, varies strongly between these four countries.

As a result, the share of EVs in the passenger car fleet reaches between 1.3% (Brazil) and 21% (Finland) in 2030, and between 19.4% (Brazil) and 77% (Sweden) by 2050 (see figure below).

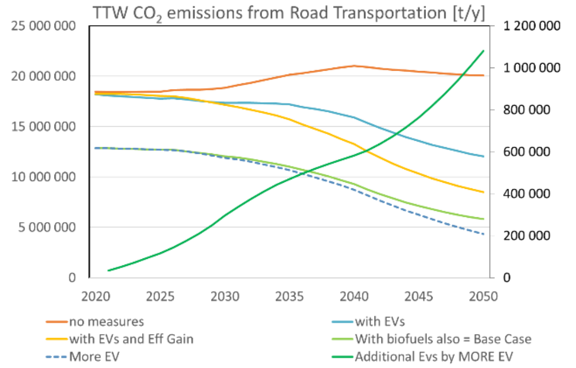


Shares of chargeable vehicles in the national passenger car fleet by 2030 and 2050 for Current Policies and MORE EV (MORE EV marked with +).

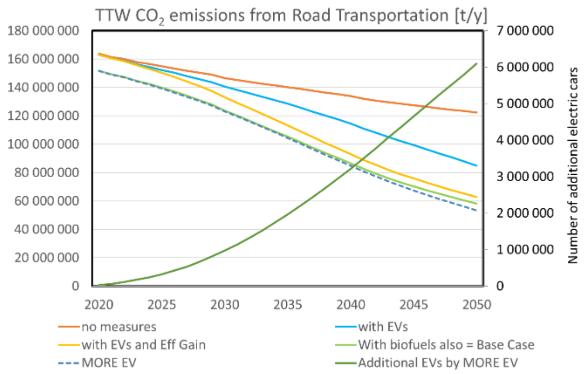
Despite these high shares of EVs in the passenger car fleets, the additional gain in CO_2 emission reductions is rather low, in the range of 0.5% to 4.3% for 2030 and 3.5% to 9.2% for 2050, see figure below, where the dashed line depicts TTW CO_2 emissions for an accelerated uptake of electric vehicles. The dashed blue line shows the number of additional electric vehicles in the fleet as compared to the Current Policies scenario.



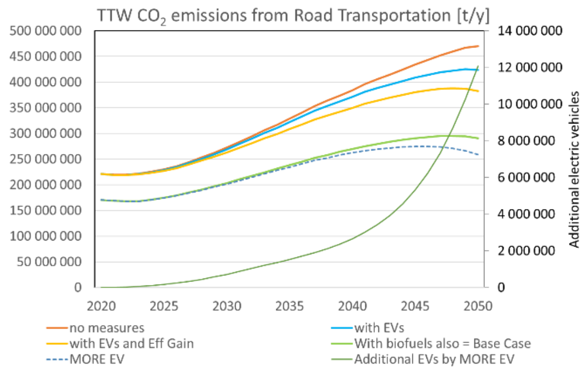
Finland



Sweden



Germany



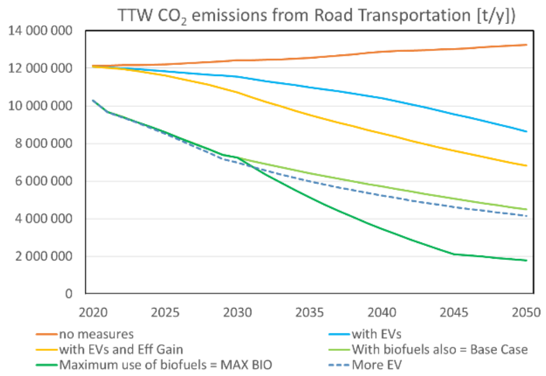
Brazil

Evolution of TTW CO_2 emissions in road transport by different measures for Finland, Sweden, Germany and Brazil in the MORE EV scenario.

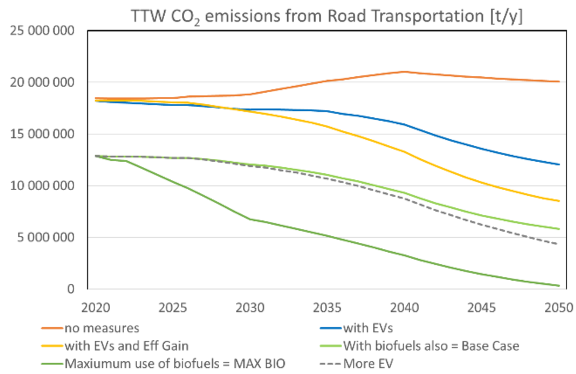
Maximizing biofuels to reach deeper decarbonization

As the level of decarbonization is still by far not sufficient neither in the Current Policies nor in the MORE EV scenario (all transport should be carbon-neutral by 2060 und 2DS scenario, with individual national targets for carbon-neutrality by 2045 and 2050), the MAX BIO scenarios were calculated. These scenarios illustrate the potential impact that biofuels could have, if introduced to the technically maximum in the expected national fleet. This includes maximizing the use of renewable diesel in compression ignited (CI) engines, applying E25 and E30 in all spark ignited (SI) engines as well as utilizing so-called biopetrol in Sweden, and using E100 in Brazilian flex-fuel vehicles.

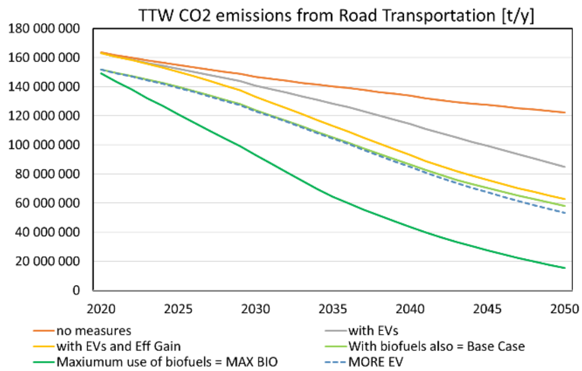
As a result, TTW CO_2 emissions can be decreased significantly by 2050, see figure below. Countries with options to fully substitute both fossil gasoline and fossil diesel can be fully decarbonized by 2050.



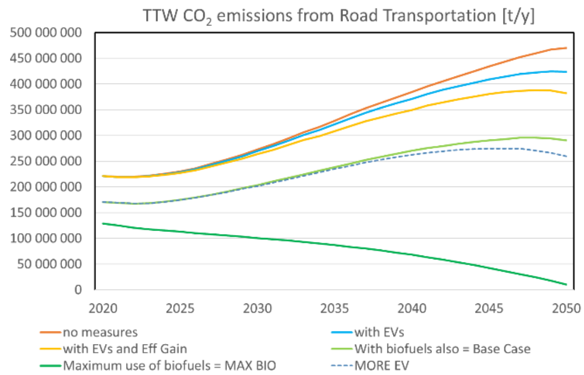
Finland



Sweden



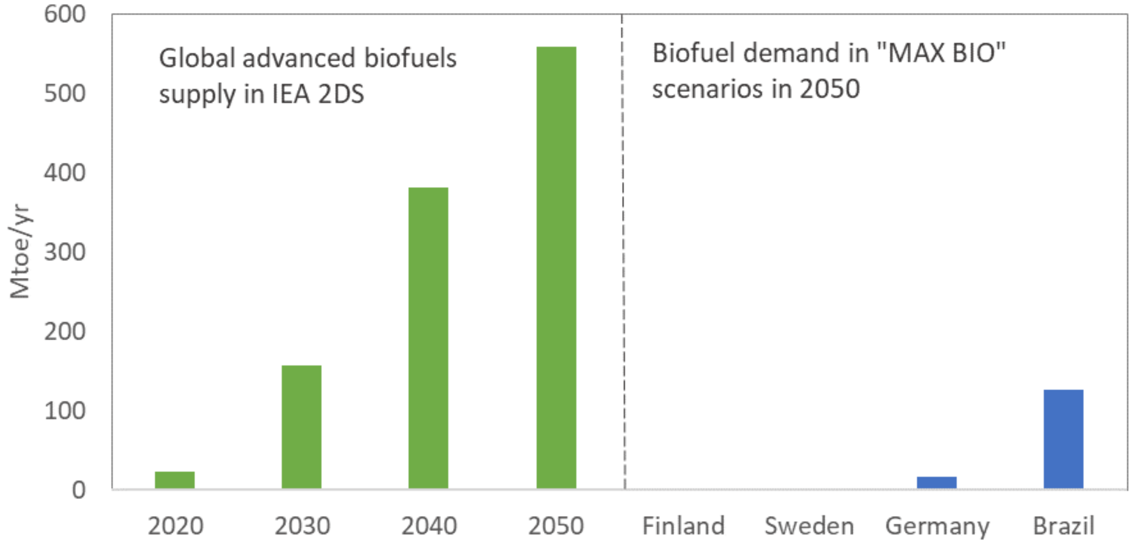
Germany



Brazil

Evolution of TTW CO_2 emissions in road transport by different measures for Finland, Sweden, Germany and Brazil in the MAX BIO scenario.

The total 2050 national demands for drop-in hydrocarbons to replace diesel in the MAX BIO scenarios are illustrated for each country in the following figure. These demand estimates are contrasted with the estimate for global advanced biofuels supply from the IEA's 2DS scenario. Although current production capacities are not sufficient to cover e.g. Brazil´s 2050 demand, if global supply develops in line with the IEA 2DS estimate advanced biofuels could be a realistic option for significantly reducing transport emissions even for the largest countries.

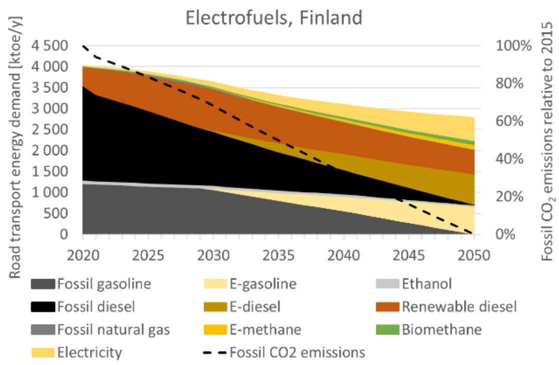


Country specific demand for drop-in hydrocarbons to replace diesel in 2050 relative to IEA global 2DS supply scenario.

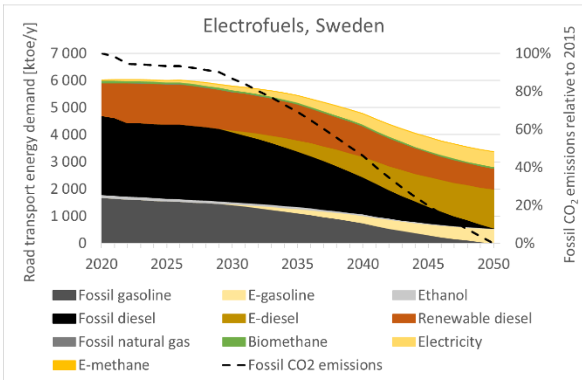
Using e-fuels to fully decarbonize road transport sectors

Another option to fully decarbonize the road transport sectors is to use e-fuels as energy carriers. Substantial reductions in the cost of wind and solar electricity during the past decade have created interest towards the production of sustainable fuels via chemical conversion of CO_2 and water, using renewable energy to drive the process.

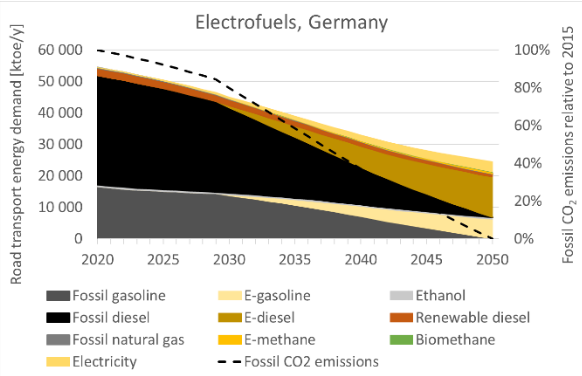
For the purpose of this analysis, synthetic replacements for natural gas, gasoline and diesel, produced from CO_2 and water with electrical energy were considered. In addition, for Germany fuel hydrogen was also considered. The introduction of e-gasoline, e-diesel, e-methane and e-hydrogen to the fuel pools begins in 2030 and increases linearly achieving full displacement of fossil gasoline, diesel, natural gas and hydrogen by 2050, and thus reaching zero TTW CO_2 emissions. The E-FUELS scenarios are based on current policies, taking the remaining fossil fuel pool as a starting point. The figure below shows the resulting energy demand for different fuels along with the resulting TTW CO_2 emissions.



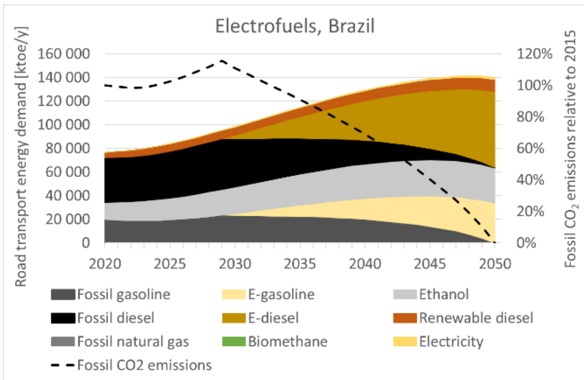
Finland



Sweden



Germany

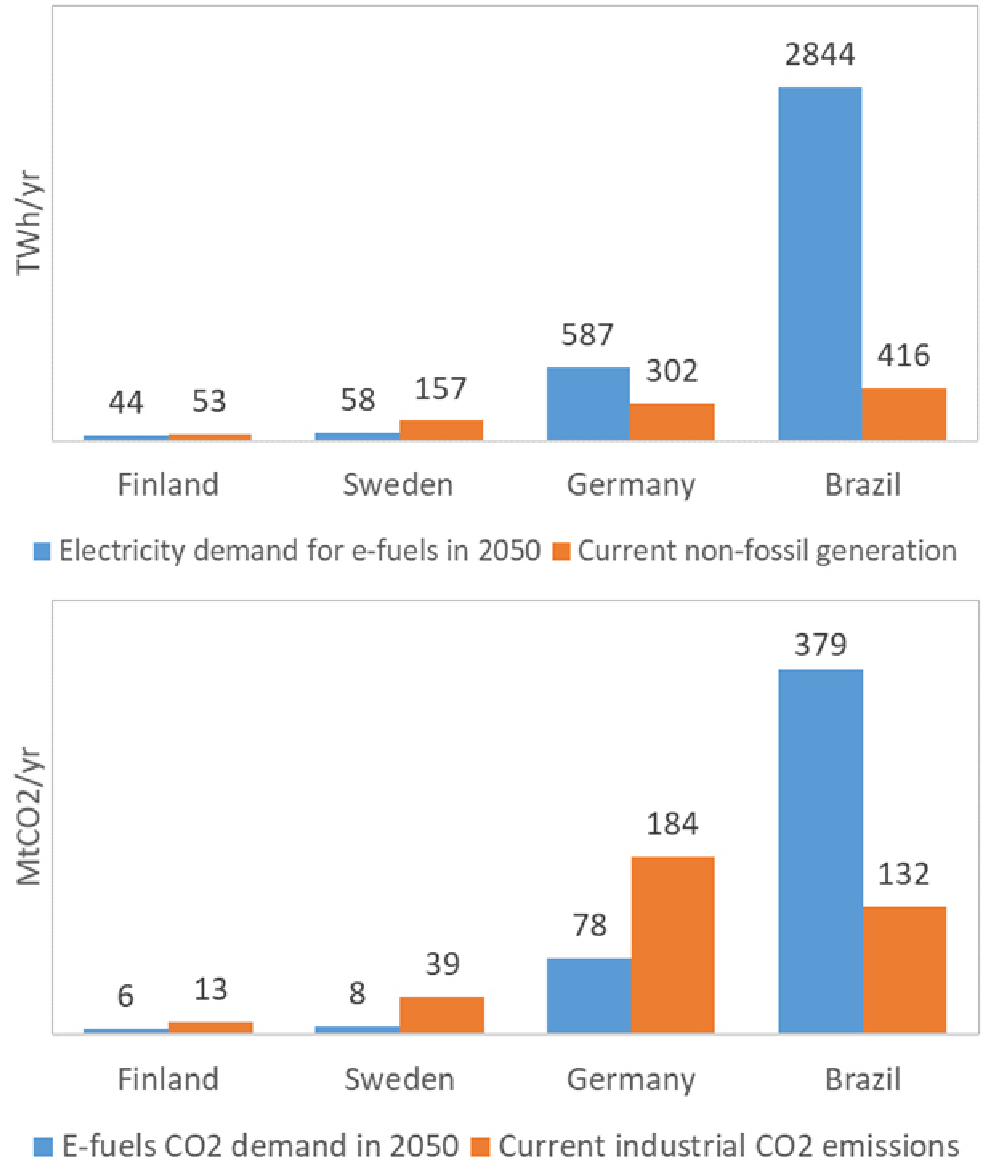


Brazil

Evolution of energy use in road transport by energy carrier for Finland, Sweden, Germany and Brazil in the E-FUELS scenario.

Resources needed for the production of e-fuels are non-fossil electricity and CO_2. The demand for these resources for the production of the e-fuel volumes needed in the E-FUELS scenario is depicted in the next figure. The amount of essentially zero-carbon electricity needed for e-fuels production is comparable to the total non-fossil electricity production in Finland and Sweden today, while in Germany and Brazil the current total non-fossil electricity generation capacity would not be enough to run all the needed e-fuels plants.

However, asking for such substantial amounts of carbon-free electricity dedicated to e-fuels production seems hard to imagine on top of existing requirements for a dramatic expansion of low-carbon electricity generation to meet more traditional electricity demand. With respect to industrial CO_2 emissions, these seem to be sufficient for the required production of e-fuels for Finland, Sweden and Germany, but the Brazilian demand by 2050 would be almost triple the currently available amount. Maximizing the use of other decarbonization measures would therefore be important to decrease the demand for e-fuels and the associated need for non-fossil electricity.



Relative electricity and CO_2 resource requirements related to the national E-FUELS scenarios.

Authors and acknowledgements

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Participants in this project were the Contracting Parties of IEA Bioenergy from Brazil, the European Commission, Finland, and USA, the Contracting Parties of AMF from China, Finland, Germany, Japan, Sweden, and USA, and AMF Annex 28 and AMF Annex 59. All parties provided in-kind contributions, except for the European Commission that also provided 80,000 USD to finance the work of experts. The overall project budget (in-kind plus cash contributions) amounts to 200,000 USD.

Further to this part "Scenarios and Contributions in Selected Countries", the following report parts have been published:

- Key Strategies in Selected Countries
- Production Technologies and Costs
- Deployment Barriers and Policy Recommendations
- Summary Report

This report part was written by Juhani Laurikko, Ilkka Hannula and Nils-Olof Nylund (all VTT Technical Research Centre of Finland Ltd) and edited by Dina Bacovsky (BEST – Bioenergy and Sustainable Technologies). Adaptations to the ALIISA model were made in close cooperation with Rachel Martins Henriques (Energy Research Office of Brazil (EPE)) for Brazil, Franziska Müller-Langer (DBFZ Deutsches Biomasseforschungszentrum gemeinnützige GmbH) for Germany, Helen Lindblom (Swedish Transport Administration) for Sweden, and Alicia Lindauer (US Department of Energy) for USA.

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The IEA Bioenergy TCP is an international platform of cooperation working in the framework of the IEA´s Technology Collaboration Programmes. IEA Bioenergy's vision is to achieve a substantial bioenergy contribution to future global energy demands by accelerating the production and use of environmentally sound, socially accepted and cost-competitive bioenergy on a sustainable basis, thus providing increased security of supply whilst reducing

greenhouse gas emissions from energy use.
www.ieabioenergy.com

The Advanced Motor Fuels (AMF) TCP also is an international platform of cooperation working in the framework of the IEA´s Technology Collaboration Programmes. AMF´s vision is that advanced motor fuels, applicable to all modes of transport, significantly contribute to a sustainable society around the globe. AMF brings stakeholders from different continents together for pooling and leveraging of knowledge and research capabilities in the field of advanced and sustainable transport fuels.
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Introduction

In the light of the global climate crisis there is an urgent need to decarbonize our societies, and transport, and in particular road transport as addressed in this report, must provide its share to this. In this report we understand the term decarbonization to include all options to reduce GHG emissions and make transport cleaner.

There are three major solutions to reducing GHG emissions from transport:

- improving energy efficiency of the transport system, including reducing transport work
- improving energy efficiency at the vehicle level
- introducing renewable energy carriers (biofuels, e-fuels including hydrogen and direct use of electricity)

In order to achieve significant CO_2 emission reductions by 2030 and beyond, a combination of all measures above must be applied. In Sweden, the notion of a **transport efficient society** is used. This encompasses also the reduction of overall transport work by smart placement of the various functions of the society and prioritization of energy efficient ways of moving people and goods. Regulations for better fuel efficiency and lower CO_2 emissions improve the performance of new vehicles, but renewal of the entire fleet takes decades. Therefore, in moving towards zero carbon emissions, carbon neutral energy carriers, renewable fuels as well as electricity are all needed. When heading for electrification, investments are needed in new vehicles and new charging infrastructure, both inducing significant costs and requiring time, as well as technical development for full implementation. However, with the best renewable fuels, we can address not only the new vehicles put on the market today, but the whole existing legacy fleet, as well.

Figure 1 shows schematics of how to decarbonize passenger cars. The example is for Switzerland, but the principle is universal.

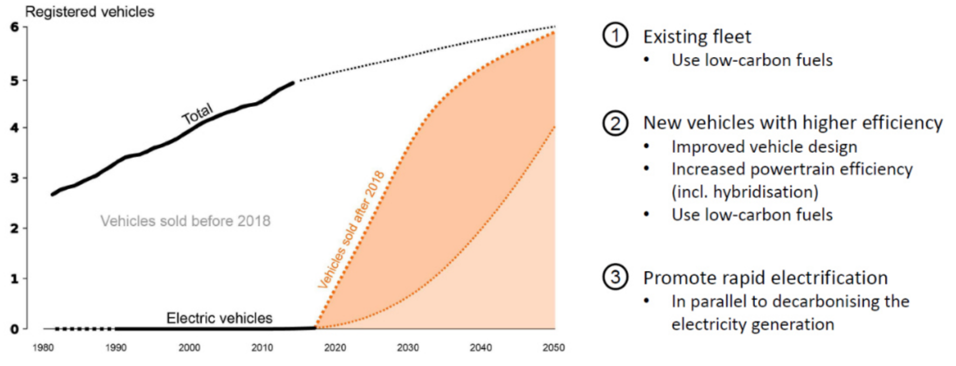

Figure 1: Time horizon in decarbonizing passenger cars. Source: K. Boulouchos 2019.

Figure 1 emphasizes the fact that the share of ICE engine equipped cars in the vehicle fleet will still be substantial in 2030, and that the passenger car fleet is not completely electrified even in 2050. In the case of heavy-duty long-haul vehicles, the transition to electricity will be even slower.

Considering the anticipated pace of electrification of the total fleet, transport decarbonization is bound to rely heavily on sustainable fuels. The question arises, how much sustainable fuels are needed to achieve a certain reduction in road transport CO_2 emissions at a given time for a given country?

In Finland, a number of studies on how to reach a 40 or 50 % reduction in CO_2 emissions by 2030 have been carried out. The 2016 Finnish energy and climate policy confirmed that the reduction target for 2030 is -50% compared to the reference year of 2005. For Finland, biofuels constitute the foundation for emission reductions in transport, and Finland already has a law in place mandating 30 % biofuels share (of energy) in 2030. Appendix 2 summarizes the findings of a Finnish Biofuels 2030 study that assessed the role of biofuels in transport decarbonization in Finland. The study mirrors the amount of biofuels needed against the penetration of electric vehicles and progress in energy efficiency. To be able to make those calculations, a vehicle fleet modelling system called ALIISA was developed to model the development of the future fleet and its use of energy carriers. It is not a heuristic model nor can it predict the future, but it applies a simple "what if" –type approach, where same input data always leads to same output. Yet by varying the input data and some internal parameters, ALIISA made it possible to calculate at a reasonable level of accuracy the outcome of e.g. presence of different amounts of electrified vehicles in the fleet by 2030 and thereafter, and what were the implications regarding the use of different energy carriers, year by year from today to year 2050.

In the study at hand, the same modelling system was applied to four additional countries, namely Sweden, Germany, USA and Brazil. These countries are obviously very different from each other regarding the size and composition of the vehicle fleet, the forecasted amount in transport work, and the availability of raw materials for making biofuels.

Methodology

The ALIISA model was used to calculate future fleet compositions, fuel use, energy use and resulting GHG emissions for several scenarios for Finland, Sweden, Germany, USA and Brazil.

Parameters used in ALIISA model

5 vehicle categories

- passenger cars
- delivery vans & light-duty trucks
- buses & coaches
- medium-duty trucks
- heavy-duty trucks

6 propulsion systems

- spark ignited engine (SI)
- compression ignited engine (CI)
- (plug-in) hybrid electric vehicle with spark ignited engine (PHEV-SI)
- (plug-in) hybrid electric vehicle with compression ignited engine (PHEV-CI)
- battery electric vehicle (BEV)
- fuel cell electric vehicle (FCEV)

12 fuel options

- gasoline
- diesel
- CNG
- E5
- E10
- E27
- E85, E100
- B7, B12
- Drop-in hydrocarbons (FT-liquids, HVO)
- CBG
- electricity
- hydrogen

Main input feed (given for each future year of projection)

- assumption on total sales in each vehicle category for future years
- assumption on the distribution between the available powertrain/fuel options in sales
- assumption on fuel consumption (or energy efficiency gain) for future years
- assumption on annual driven distance ("VMT"), variable between categories, age classes and powertrain/fuel combinations

Calculation

Energy need [l/a] **= driven distance** [km/a] **x consumption rate** [L/100 km] for each vehicle, powertrain, fuel/energy option

TTW CO_2 emissions [t_{CO2}/a] **= energy need** [t_{oe}/a] **x nominal carbon content** [t_{CO2}/t_{oe}] for a given fuel/energy option;

CO_2 emissions of renewable shares and electricity are assumed to be zero

Brazil: special case for ethanol, regular gasoline contains 27 % ethanol (E27), also hydrous ethanol (E100) on the market, special flex-fuel vehicles combining gasoline with any amount of ethanol.

General structure of the model

The model is based on a collection of interlinked MS Excel spreadsheets, and it entails the breakdown of the vehicle fleet according to the propulsion system and fuel/energy that is being used. In the model, vehicles are categorised as passenger cars (PC), vans or light-duty trucks (LDT), buses and coaches, as well as medium (MD) and heavy-duty (HD) trucks. In addition, each of these main categories has a dedicated set of sheets, where each vehicle category has several different options for propulsion and types of fuels they use. The richest number of options is available for passenger cars, as listed in Table 1. Other vehicle categories use a smaller subset of these, as currently all options are not available for all categories in the market place.

Table 1: Options for propulsion system and types of fuels they use for passenger cars.

Engine type	SI	CI	PHEV (SI)*	PHEV (CI)	BEV	FCEV
Fuels	Gasoline (E5, E10, E27)	Diesel (B7, B12) drop-in hydrocarbons	Gasoline (E5, E10, E27)	Diesel (B7, B12) drop-in hydrocarbons		
	E85, E100		E100			
	CNG (CBG)		electricity	electricity	electricity	
						hydrogen

* For Brazil the projections only include HEV flex, not PHEV (SI and CI)

The model takes as input an assumption of total sales for each of the categories and the envisaged distribution between the available powertrain/fuel options for each future year. The evolution and vehicle fleet management is then accomplished by introducing new vehicles to each vehicle category and propulsion/fuel option for the subsequent year (2010 to 2050); according to the input data, and by means of a withdrawal function, the number of “surviving” vehicles for each consequent year batch is determined. Finally, by adding up remaining vehicles for each model year, the total fleet size and composition is computed for each projected year.

This withdrawal function is separate for each vehicle category and propulsion type, can be adjusted so that the fleet size follows the expected trend. Furthermore, the model computes out also an average age of each of the sub-fleets. Like for the calculation of the year 2030, allotments of new vehicles sold in that year are calculated for each vehicle category, propulsion and fuel type, but also remains of the vehicles allotted for previous years (i.e. 2029, 2028, 2027 etc.) are still in the sub-fleet, until all the vehicles for that given option have been withdrawn. The total fleet is then a sum of all these various sub-fleets of different age.

Apart from the share of each propulsion system and fuel, **the needed input also includes fuel/energy consumption values projected for each future year**. These figures also **portray the expected increase in efficiency**, as usually the values are descending for the future.

Furthermore, the **calculation for the use of different fuels requires also annual driven distances** (a.k.a. vehicle miles travelled, VMT). Those are of course different for each main vehicle category, but can also be attributed separately for each powertrain/fuel combination, if necessary. While calculating the VMT, there is a nominal assumed per vehicle average annual distance, but that will be internally modulated for each vehicle age category for that option, as newer vehicles tend to have much higher usage rate than the older ones. The total annual driven distance is then computed from each subsequent model year sub-fleets using available powertrain and energy options, separately for each main vehicle category.

After the quantity of distance travelled (in km) is totaled, the basic function to calculate fuel (or energy use) is of the format:

Driven distance [km/a] **x consumption rate** [L/100 km] **for each vehicle, powertrain, fuel/energy option**

These calculations are performed throughout the arrays of available vehicle categories, powertrain and fuel/energy options, as well as age groups, and then summed up for each subsequent year.

As a separate calculation, the collective use of fuel and energy options in their usual market units (litre, kg, m^3, kWh etc.) is added up, and also converted to different energy units, such as ktoe and PJ.

For the introduction of biofuels, the **calculation also entails the possibility to allocate an annual portion (%) for biofuels**, such as ethanol, renewable diesel and biomethane.

Eventually, **CO_2 emissions are calculated, based on the nominal carbon contents of the given fuel**. Thus, the **emitted amounts of CO_2 are "tank-to-wheel" (TTW), and do not consider the upstream "well-to-tank" (WTT) emissions**. The CO_2 emissions for the renewable shares are assumed to be zero. Furthermore, the amount of electricity used is calculated, but no CO_2 emissions are associated with it. This **complies with the EU emission standards that apply to the automotive industry, but does not include WTT emissions as calculated in accordance with the EU Renewable Energy Directive.**

In essence, the model is "deterministic", i.e. one set of input data will always result in same output.

Adjustments for the study cases

For this exercise, separate **input value sets submitted by the country experts were brought together**. These input value sets also included some historical data and control values that were needed to tune the model parameters, mainly vehicle scrap rates and annual mileages, so that it was **possible to check that the size of the vehicle fleet and total mileages remained within the expected ranges**. These control value sets also included some estimates for the fuel use, and some adjustments were necessary for each country case to get the output of the model to match those figures. Naturally, **a perfect one-to-one fit was not possible to obtain**, but for the sake of this exercise, it was not necessary, because **the goal was to make a comparative analysis using a common methodology,** and address differences between different country cases, and not to replicate the countries own scenario analysis.

After these adjustments, the model was tuned-in for each of the countries and could be used to produce projected vehicle fleet compositions regarding powertrain options, as well as usage estimates for different fuels and energies, as well as the projected CO_2 emissions.

For this study, **the timeframe from year 2020 to year 2050** was portrayed, although most of the projections beyond 2030 are not equally solid.

Scenarios

Following four scenarios were developed for the purpose of our analysis: Current Policies scenario, MORE EV scenario, MAX BIO scenario, and E-FUELS scenario. The relationship between the scenarios is illustrated in Figure 2.

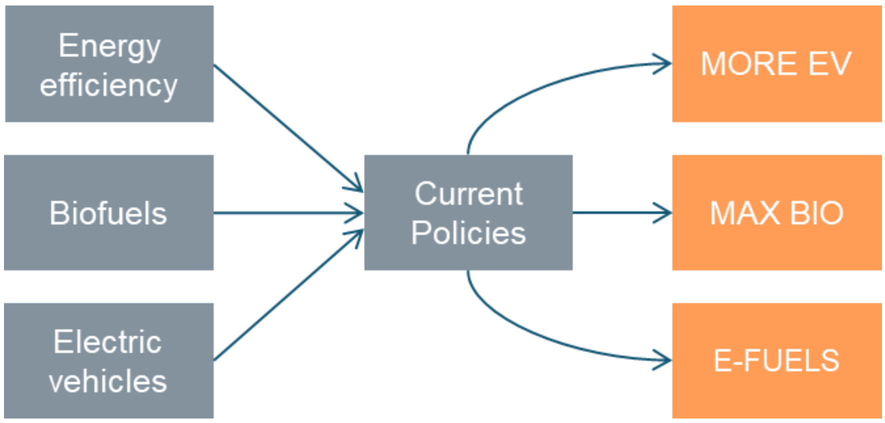

Figure 2: Illustration of the examined scenarios. The Current Policies scenario is composed out of a mix of CO_2 reduction technologies, while the alternative future scenarios (orange boxes) represent pathways where additional emissions reductions are achieved by increasing reliance on one of the main reduction technologies: electric vehicles, biofuels or e-fuels.

Current Policies (Base Case) scenario

For each country, a **base case scenario called Current Policies was developed**, with the aim of matching the model output as closely as possible with country specific input data like fleet size and composition, transport work, use of energy in various forms, and carbon emissions in the form of CO_2. This was accomplished by adjusting internal parameters of the model, such as vehicle retirement age and average annual distance per vehicle, to meet target values of national conditions. The "Current Policies" scenario is therefore unique to each country in relation to its fleet composition, rate of electrification, changes in transport work, and use of biofuels.

The Current Policies scenarios provide a starting point for three future scenarios that adopt a more ambitious approach to emissions reductions. These alternative future scenarios differ from each other based on the adopted technological route, i.e. more electric vehicles (MORE EV), maximum use of biofuels (MAX BIO) or introducing e-fuels (E-FUELS). These scenarios are briefly discussed below.

MORE EV scenarios

MORE EV scenarios are developed by increasing the anticipated sales of electrified vehicles, thereby reaching larger replacement of fuels with electricity in total transport energy use. The level of "EV boosting" varies between countries, and is adjusted in consultation with country experts, to meet their outlooks for such an action. **This scenario intends to reflect what a more aggressive, but still conceivable, electrification could achieve**.

MAX BIO scenarios

MAX BIO scenarios were developed to illustrate the impact of maximal biofuels use. Again, the exact contents of these scenarios differ between countries, but **the common idea is to evaluate how much additional biofuels could technically be implemented**, if available, and what implication this would have on CO_2 emissions. The MAX BIO scenarios are also intended to provide an outlook on how much different biofuel types (ethanol, biodiesel, renewable diesel, biomethane) could be applied, and then to judge, under what conditions it would be possible for each examined country.

In some countries like Sweden, an "advanced biofuels scenario" already exists, and it was used as the basis for the Swedish MAX BIO scenario. This scenario includes also the use of "biopetrol" or "renewable petrol" that would be produced with similar processes as the current pool of renewable diesels. Already now, some 10% of the yield of HVO diesel production contains molecules that can be used as components for gasoline. In the Swedish scenario, biopetrol is expected to reach 25% share of gasoline use in 2030. In the Swedish

MAX BIO scenario, we assumed that this amount (437 ktoe) of “biopetrol” in 2030 would be kept at the same level until 2050 thereby replacing higher and higher shares of fossil gasoline, as the total use of gasoline simultaneously diminishes due to advances in energy efficiency and electrification.

For Finland, Germany and Brazil similar advanced biofuels scenarios were not available. For these countries, the MAX BIO was developed on the simple assumption that the use of biofuels would increase linearly after 2030, reaching 100% of the technically possible level by 2050. Regarding diesel and methane, the highest achievable level was set to 100% for Germany. However, biomethane was not implemented in the scenario for Brazil, as it was not possible to ascertain the size of the fleet using methane.

Furthermore, regarding ethanol in gasoline, the maximum limit (a.k.a. “blend wall”) applied in the calculations was 10%-vol for Germany (E10), 15%-vol for USA (E15) and 27%-vol (E30) for Brazil. It should be noted, however, that higher ethanol contents could possibly be allowed in the future by revising fuel standards to allow more ethanol to be blended in(e.g. E27 that is in use in Brazil, and under some consideration at least in Europe). Similarly, in countries like Finland, Sweden and Brazil that have flex-fuel vehicles in their fleet (flexible to use gasoline or E85/hydrous ethanol), maximal share of ethanol is assumed (E85 in Sweden/Finland, 100% hydrous ethanol in Brazil) in MAX BIO scenarios, whereas in Current Policies scenarios it is lower.

E-FUELS scenarios

E-FUELS scenarios are developed to study the impact of using e-fuels (i.e. fuels produced from CO_2 and water with renewable electricity) for the decarbonization of road transport. The anticipated vehicle fleet development, efficiency improvements and biofuels uptake are based on the Current Policies scenario for each country.

The introduction of e-fuels begins in 2030 for all countries, and increases linearly to reach full displacement of fossil fuels by 2050. Fossil gasoline, diesel and natural gas remaining in the Current Policies scenario after electrification, efficiency improvements, EVs and biofuels are displaced by e-gasoline, e-diesel and e-methane, respectively. For Germany, also displacement of fossil hydrogen with e-hydrogen is considered.

In addition to calculating the needed deployment of e-fuels, the amount of electricity and CO_2 needed to supply the estimated e-fuels demand is also calculated for each country and contrasted against currently available resources.

Comparison of country indicators

To allow characterization and comparison of the five case countries in terms of their vehicle fleet size and composition, vehicle miles travelled (VMT) per vehicle in each category, as well as use of different fuels and fuel components several tables were composed, based on data submitted for the Current Policies cases, and calculated separately for years 2020, 2030 and 2050. The tables are intended to facilitate a comparison of the size and characteristics of the transport sectors in each country, and are presented in Appendix 1. Furthermore, Figure 3 and Figure 4 below are composed from the core data in those tables, presenting both vehicle fleet sizes and total transport work (VMT) per vehicle category.

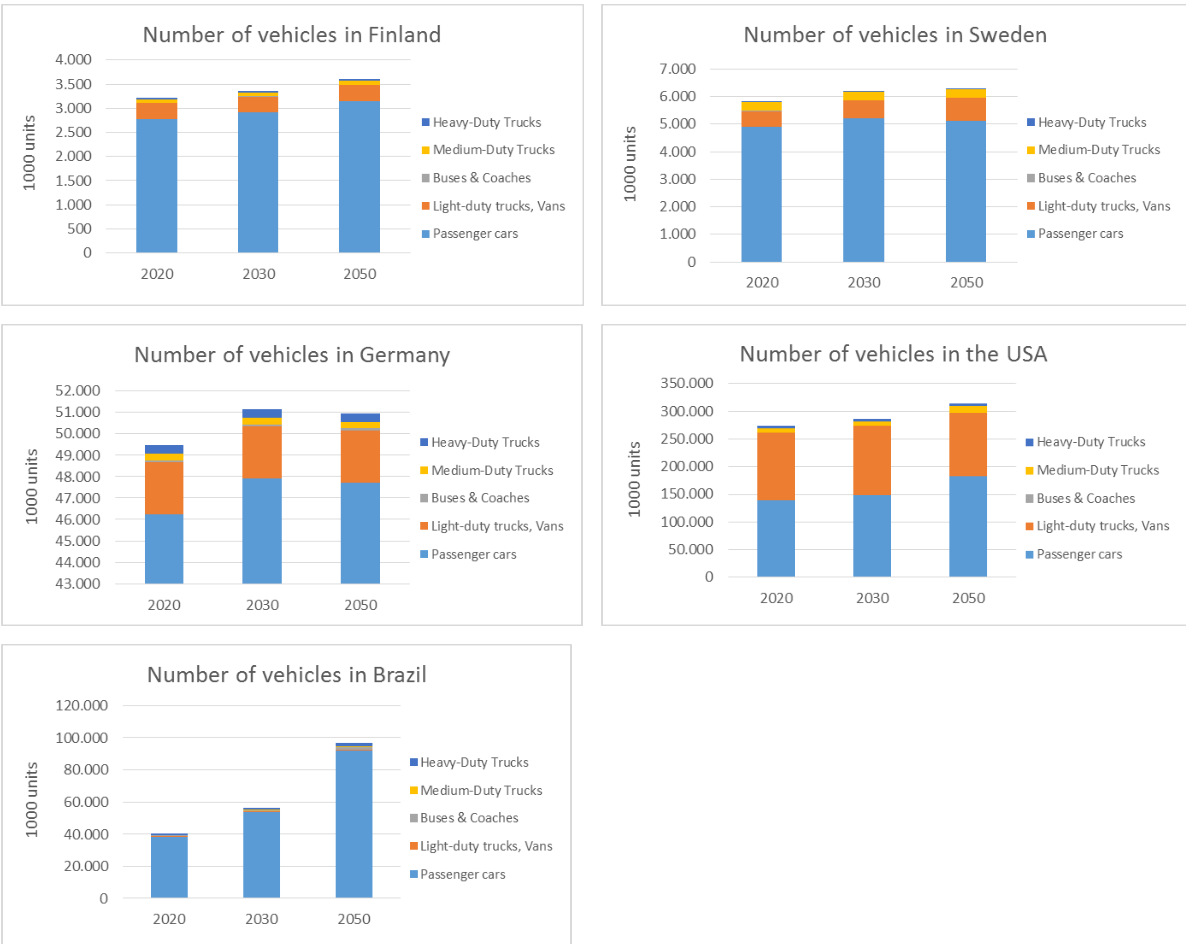

Figure 3: Fleet size and composition for Current Policies scenarios (1000 units).

Figure 4: Total Transport Work (Vehicle Miles Travelled, VMT) for Current Policies scenarios (1 M km/a).

In addition, to enable an easy comparison of the case countries whose geographical size and population differ greatly from each other, some transport-related indicators were calculated as relative to the population and land area, and are presented in Table 2.

Table 2: Comparison of some transport-related indicators.

	2020				
	Finland	**Sweden**	**Germany**	**USA**	**Brazil**
Population size	5,545,000	10,100,000	83,780,000	331,000,000	212,600,000
Land area, km^2	303,890	410,340	348,560	9,147,420	8,358,140
Pop.density	18.2	24.6	240.4	36.2	25.4
Cars/capita	0.501	0.486	0.552	0.717	0.180
Car-km/capita	7,600	5,600	7,800	13,000	3,000
Car-km/km^2	138,000	137,000	1,880,000	270,000	76,000
MDT&HDT-km/capita	633	502	496	1,535	374
MDT&HDT-km/km^2	11,555	12,344	119,214	55,554	9,514

https://www.worldometers.info/world-population/population-by-country

Population-wise, Finland is the smallest of the group, Sweden having about twice the population, Germany about 15, Brazil about 40 and USA about 60 times the population. Finland, Sweden and Germany are about the same size regarding land area, but USA and Brazil are both about 30 times larger. In terms of population density, this means that Finland has the lowest density, while Sweden, Brazil and USA are at about the same level, and Germany has a population density about ten times higher. However, the amount of unpopulated land is much greater for countries other than Germany, therefore population densities at actually habituated areas may not be very different from each other.

If we proportion transport-related activities (presented in Table 2) to population size and land area, the resulting numbers are quite interesting. Starting from the common index of cars per 1000 inhabitants, Finland, Sweden and Germany are about the same level, while US is somewhat higher, because in practice we must account some 70% of the LDT fleet as passenger vehicles. The figure for Brazil is only about a third of that, which is clearly reflected in the large size of the bus and coach fleet, as buses are needed to fulfil passenger transport needs. Likewise, gross kilometers driven with passenger cars (and LDT in US) per capita are roughly at the same level in Finland, Sweden and Germany, while the USA has double the amount, and Brazil less than half of that. If we proportion the number of kilometers driven by these light passenger vehicles to the land area, Finland and Sweden are again on the same level, but Germany has an index that is 14 times higher, while USA is only on about 3 and Brazil even below 1. This clearly underlines the fact that passenger vehicle transport is by far denser in Germany than in the other countries in this study.

Furthermore, regarding freight transport, the figures are again quite telling: Finland, Sweden and Germany are almost on par, with 500 to 600 km of annual heavy-vehicle kilometers per capita, while US has three times as much, and Brazil about a quarter less. As the land area of the country should play a role, an index was also calculated based on land area. This makes Finland and Sweden quite close, not so surprising given the many similarities between these countries. However, Germany has 10 times more HD transport kilometers per land area, while US has less than half of that, and Brazil has the lowest number, being much below Finland and Sweden. This may have something to do with the actual habituated area, but figures for that comparison were not easily obtainable.

The above analysis is not intended for research purposes, but rather to provide additional perspectives to our country analyses, discussed in the following chapters.

Results for the Current Policies scenario

The following figures summarize the energy use per vehicle category for all countries in 2030 and in 2050.

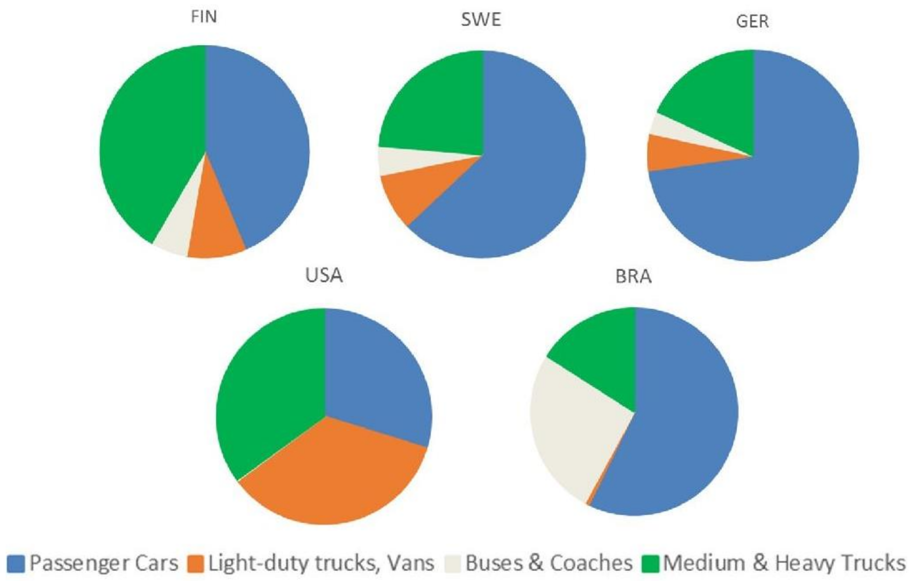

Figure 5: Energy use per vehicle category in Current Policies scenarios – 2030.

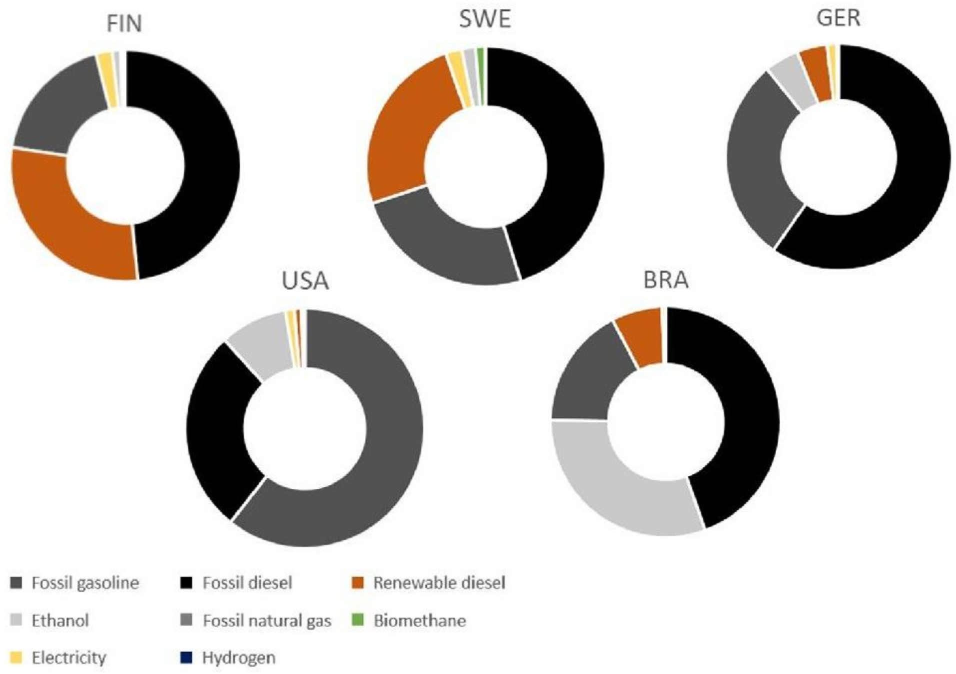

Figure 6: Energy use per energy carrier in the Current Policies scenarios – 2030.

Details of the scenario results for Finland, Sweden, Germany, USA and Brazil are discussed in the following sections, beginning with the Current Policies scenarios. Results for each country are presented between 2020 and 2050 in the following way:

- The allotment of CO_2 emissions reductions between different low-carbon solutions, i.e. adoption of electric vehicles, increased energy efficiency (of vehicles) and use of biofuels is illustrated for each country.
- The evolution of new car registrations per fuel type is calculated.
- The evolution of energy use per main vehicle categories (passenger cars, LDT, busses, medium and heavy-duty trucks).
- The evolution of energy use per energy carrier, both of fossil and renewable origin, is calculated.
- The evolution of Tank-to-Wheel (TTW) CO_2 emissions by vehicle category is calculated.

Next after the Current Policies scenario, results for MAX BIO scenario are presented, followed by results for the E-FUELS scenario and finally for the MORE EV scenario.

Finland

The Current Policies case for Finland is built around the "Base Case" that assumes those measures that are now in place, either by some EU-regulation or by national legislation, such as the 30% biofuels obligation by 2029. However, the expected reduction in CO_2 emissions by 2030 is 38%, compared to the official base year of 2005. Thus, additional measures are needed to reach the targeted 50% reduction.

Of the anticipated 38% reduction, the majority (67%) comes from biofuels, while electrification and energy efficiency gain both add some 16 to 17% shares.

According to part 1 of the overall report ("Key Strategies in Selected Countries), current use of fuels in the road transport sector in Finland is about 4,000 kt, of which 14% is renewable. Furthermore, of the total of 3.2 million motor vehicles, only 65,000 are now alternatively fueled (methane gas or electricity), representing some 2% of the fleet. This combination yields to 10.3 Mt of CO_2 emissions in 2020.

According to Table 3, the Current Policies case for Finland expects the total energy use in road transport to decrease, mainly due to the increase in vehicle energy efficiency overseen as a result of tightening of the CO_2-emissions regulations implemented in the EU. Moreover, the alternatively-fueled vehicle fleet is expected to grow, especially the number of electric cars. Their share in new registrations shall raise from the current level of 1.5% to near 30% by 2030, and represent almost 50% of the passenger car fleet by the year 2050. This will lead to some 20% share for electricity in total transport energy use.

Table 3: Main results of the Current Policies scenario for Finland.

Current Policies, FINLAND	2020	2030	2040	2050
Total energy use in road transport, ktoe	4,020	3,631	3,098	2,788
Share of fossil fuels, %	86 %	67 %	62 %	54 %
EV share in passenger car fleet, %	1.5 %	12 %	29 %	49 %
EV numbers, 1000 units	41	349	851	1,555 000
Share of electricity, % of total transport energy	0.24 %	2.9 %	9.5 %	20 %
Amount of fuels replaced by electricity, ktoe	10	105	295	552
Share of biofuels, %	14 %	30 %	28 %	26 %
Amount of biofuels, ktoe	545	1,087	882	729
CO_2 emissions, Mt	10.3	7.3	5.7	4.5

Concurrently, the use of biofuels shall increase by 2030, due to the legal obligation of the distributors to add up to 30% of bio-contents to the fuels they sell. Even if this 30% obligation is expected to stay after 2030, the better energy efficiency and increased share of electricity will in reality slightly lower that share and the actual amounts afterwards, as seen in Table 3. The maximum expected amount of biofuels equals to some 1,100 kt, and that occurs by the year 2030. Even with this slight reduction in the use of biofuels, they still remain as the largest contributor to the lowering of the CO_2 emissions over the scope of this study, as the share of electricity is not expected to be more than 20% by 2050. With the expected increase in the number of alternatively fueled vehicles, better energy efficiency of new cars and continued use of bio-components according to the Current Policies scenario, the CO_2 emissions are expected to decrease by nearly 40% by 2030, thus falling short of the targeted reduction of 50%, and suggesting that additional measures are still needed.

Figure 7 plots the calculated CO_2 emissions and breaks down the emissions reductions to three major contributors: effects of energy efficiency improvements, introduction of electric vehicles and use of biofuels. In the graph the top-most red line is the hypothetical evolution of TTW CO_2 emissions from the road transport sector without any of these measures. The blue line then shows the effect of electrification alone, while the yellow one adds to this the effect of energy efficiency gains. Finally the green line shows the combined effect of all measures including biofuels. This figure clearly shows how apparent it is that biofuels contribute most to decarbonization up to 2040 and even some years beyond, when the effect of electrification only catches up with biofuels. Expected increase in energy efficiency has also a growing share at least until 2040, if no further regulations are expected after 2030.

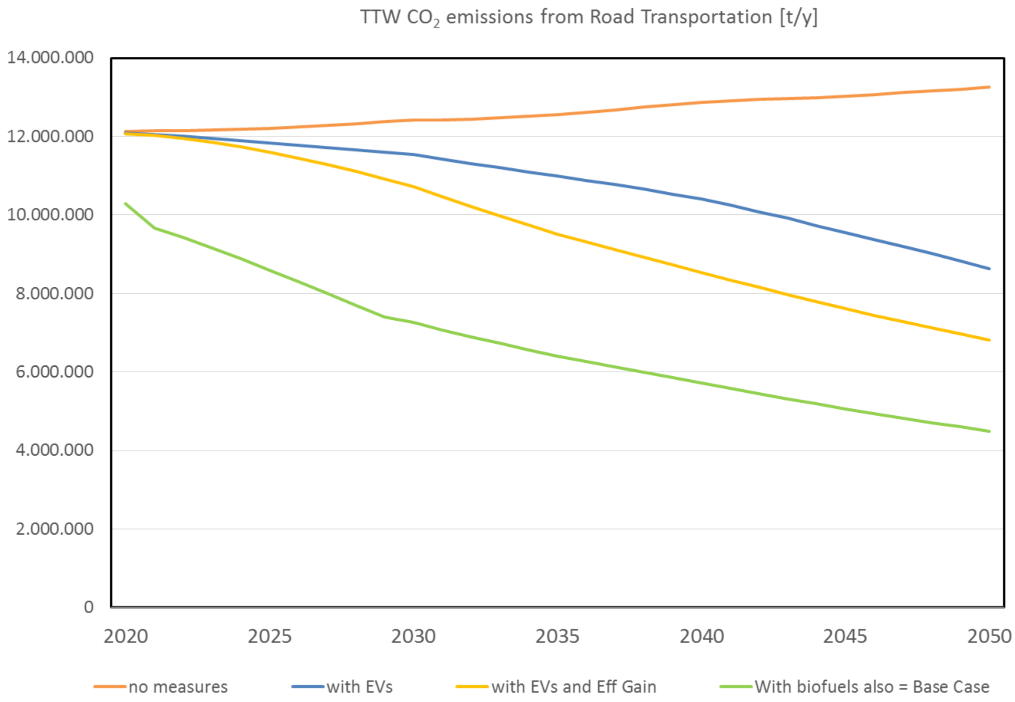

Figure 7: TTW CO_2 emissions in road transport by different measures for Finland in the Current Policies scenario.

According to the Figure 8, the majority of new cars shall be powered by only by an IC-engine until 2040, as by then the combined share of plug-in hybrids (PHEV) or fully-electric vehicles (BEV) slashes over the 50% mark. This Current Policies scenario expects, though, that ICE-only (SI) cars will still retain 25% of the market even by the year 2050, but ICE-only diesels and even PHEVs will be phased away until then.

Hydrogen-fueled FCEV category is not expected to be on the market in Finland. This is mainly due to the large geographical area of the country that makes it difficult and expensive to create a sufficiently dense refilling infrastructure and run it with a profit margin. However, hydrogen fuel cell may yet prove to be a valid option for powering heavier vehicles due to greater energy density it can offer over batteries. It would also be easier to establish a refueling infrastructure to heavy goods vehicles that already now mostly use their dedicated network.

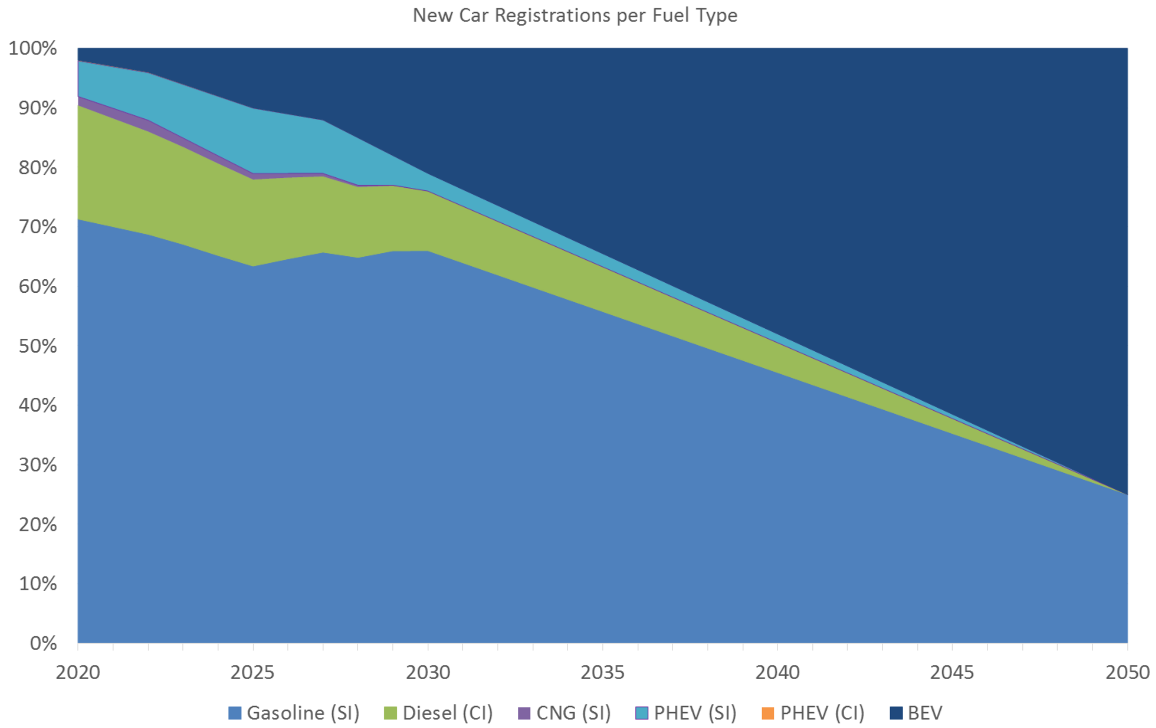

Figure 8: Breakdown of new car sales by powertrain options for Finland in the Current Policies scenario.

Then, if we review Figure 9 that depicts road transport energy use, we can see that the share of light vehicles (cars and vans) is slightly over 60% currently, but due to the expected increase in their fuel efficiency, as well as incoming electrification, their share will gradually decrease close to 50% by the year 2050. Furthermore, overall energy consumption will be down by some 10% by 2030, and 30% by the year 2050 respectively, according to the projections by the Current Policies scenario.

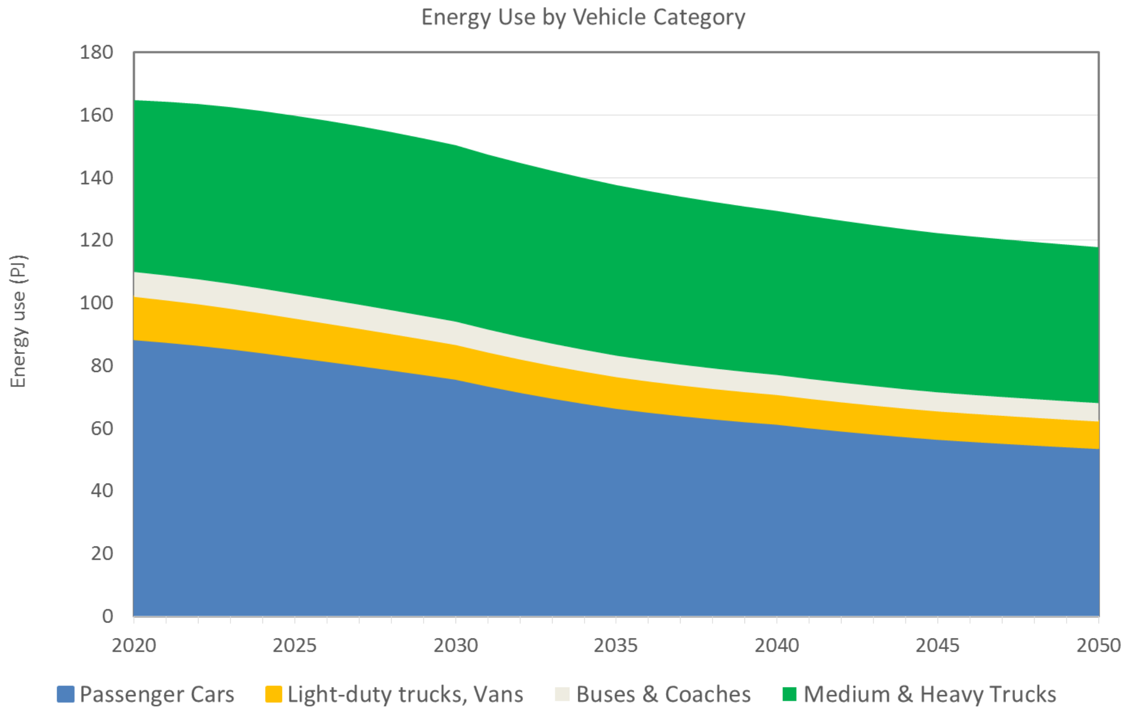

Figure 9: Energy use in road transport by vehicle category for Finland in the Current Policies scenario.

Figure 10 breaks down the use of energy in road transport by type of fuel or energy. It clearly shows the dominance that the diesel pool has, as this pool (fossil or renewable diesel) counts currently some 67% of the total road transport energy use, and even by the year 2045 it is still 55%. Only by 2050 its share is expected to drop below 50%, being 47% by then. Currently, fossil gasoline accounts for 30%, and in this scenario that share remains almost constant until 2045, but slides down to 24% by 2050, due to the expected upturn in electrification and phase-down of ICE & PHEV powerplants.

Use of ethanol remains fairly low, as this scenario does not assume higher than 10% blends (E10) to be on the market. Therefore, the maximum share of the renewable energy in the gasoline pool remains around 7%. Combining this fact with the required 30% share of bioenergy by 2030 and onwards, means that share of renewable diesel must cover the remainder, as in current situation the obligation counts only liquid fuels and use of biomethane is not accounted at all. The share of renewable diesel in the diesel pool is therefore up to 30% already by 2024, and it hits the maximum of 45% by the year 2040, and stays there onwards. Electricity is today highly marginal in road transport, as its share is only 0.25%. However, according to this Current Policies scenario, it shall reach about 3% by 2030, 10% by 2040 and 20% by 2050, being then in energy about the same as renewable diesel. Despite these fairly high shares, fossil fuels accounts still 54% by 2050.

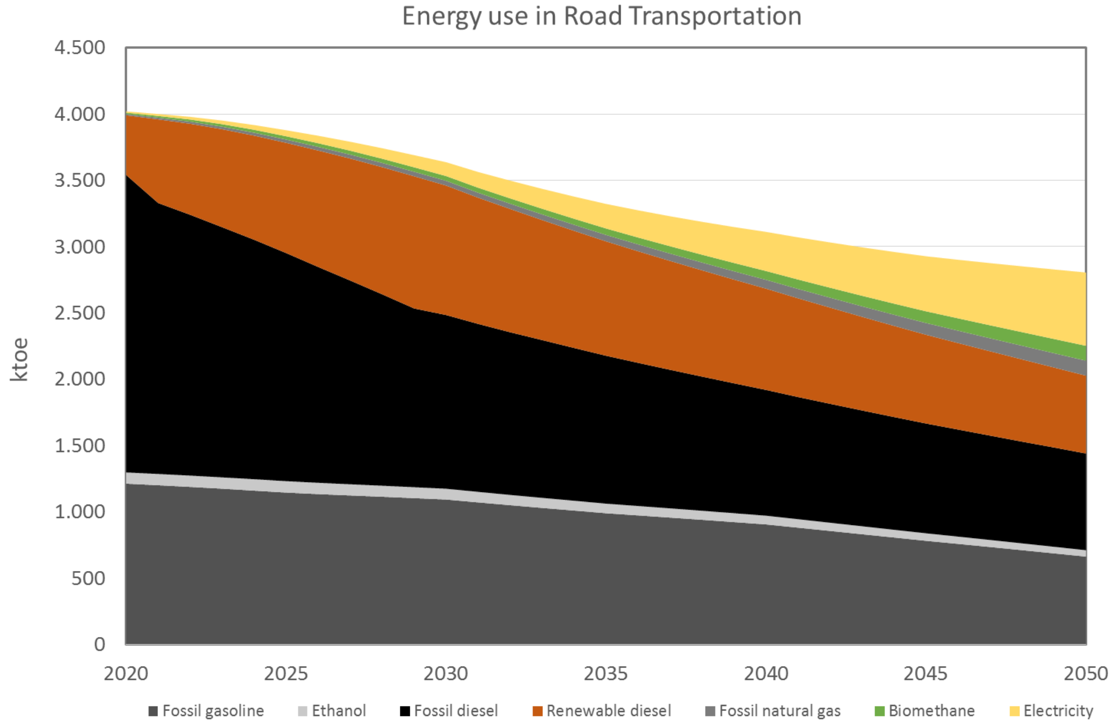

Figure 10: Energy use in road transport by energy carrier for Finland in the Current Policies scenario.

According to Figure 11, that plots the projected evolution of CO_2 emissions per road vehicle category, emissions from passenger cars are expected to be reduced quite effectively: by some 25% until 2030, by 45% until 2040 and over 60% by the year 2050. However, as other vehicle categories cannot show similar performance, the total road vehicle emissions will not be reduced as aggressively.

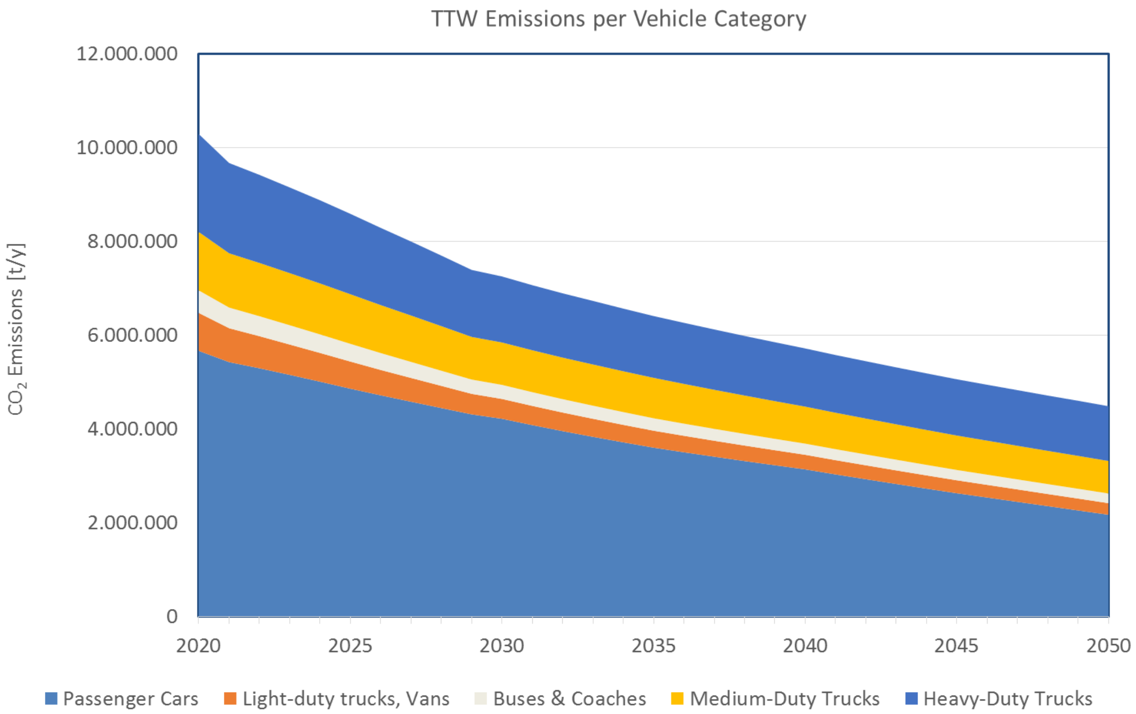

Figure 11: TTW CO_2 emissions in road transport by vehicle category for Finland in the Current Policies scenario.

Sweden

Biofuels already represent 28% of road transport fuels in Sweden. The expected uptake of electric vehicles will result in 56% of the passenger car fleet in 2050, replacing 553 ktoe of fossil fuels. Although this is a significant share (around 16%) of the expected road transport fuel use, it is still only 1/3 of what biofuels already now replace.

Current GHG emissions are about 13 Mt CO_2, and are expected to decrease to below 6 Mt CO_2 by 2050. Up to 2038, biofuels contribute most to reducing CO_2 emissions from the road transport sector. However, the ambitious targets of around 6 Mt CO_2 by 2030 and climate neutrality by 2045 will be missed in the Current Policies scenario.

As mentioned in part 1 of the overall report ("Key Strategies in Selected Countries"), Sweden used 6,700 ktoe of fuel in the transport sector in 2018, of which 1,500 ktoe were renewable. Of the 5.5 million vehicles in use only 0.3 million are alternative fuel vehicles (including electric vehicles). The current GHG emissions from the road transport sector are about 15 Mt CO_{2eq}. The energy consumption of the road transport sector is projected to decrease due to more energy efficient vehicles. The target is to reduce GHG emissions from the transport sector (excluding aviation) by 70% compared to 2010 by 2030. This translates to a maximum of 6 Mt CO_{2eq} emitted by the transport sector by 2030. Measures to achieve this target include a bonus-malus system for CO_2 emissions and a GHG emission reduction obligation on the fuel suppliers. Figure 12 shows the gap between the business as usual scenario and the goals for the Swedish transport sector.

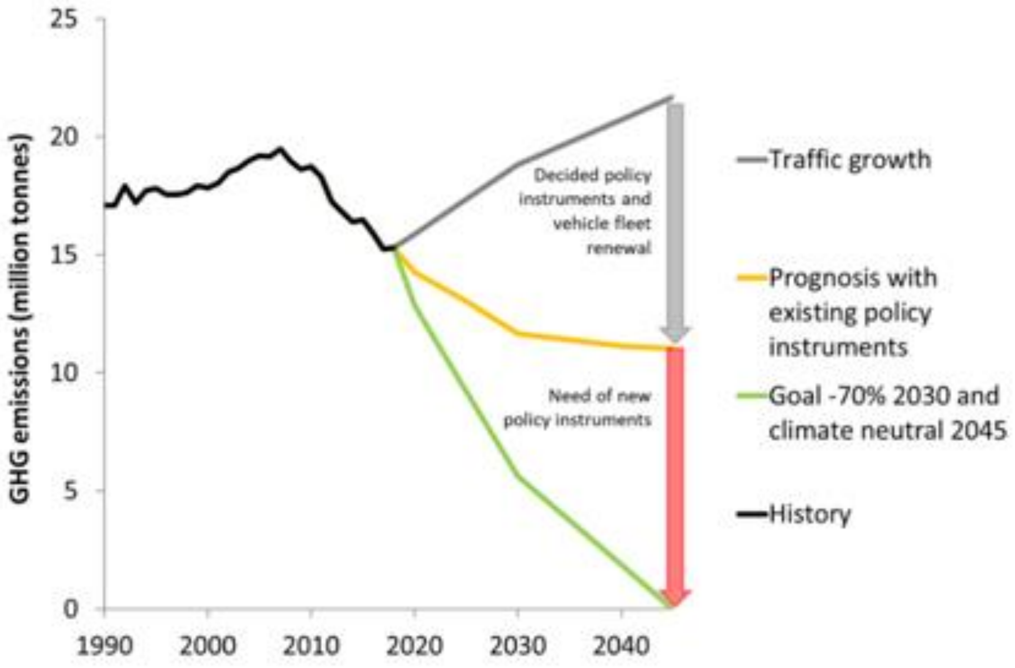

Figure 12: The gap between BAU scenario and the goals for the Swedish transport sector. Source: Swedish Transport Administration

The Current Policies case in Sweden (see Table 4 below) shows that total energy use in road transport is expected to decrease and the share of fossil fuels is also expected to decrease. The electric vehicle fleet is expected to grow from 137,000 in 2020 to more than 2.8 million in 2050, which is more than 50% of the passenger car fleet. The share of biofuels is already one of the highest in the world and is expected to remain rather constant at the current high level of 28%, sliding down to 25% by 2050 due to the decreasing number of vehicles powered by internal combustion engines. The amount of biofuels used is 1,657 ktoe in 2020, which is still more than 3 times the amount of fossil fuels that will be expected to be replaced by electricity in 2050, and some 80 times the current replacement by electricity use. This shows clearly that biofuels are doing most of the job of decarbonization in the coming decades and even turning the entire expected car fleet to electric vehicles will not be able to replace the same amount of fossil fuels as biofuels already do. Total TTW CO_2 emissions in the Current Policies case are expected to be as high as 12.1 $MtCO_2$ by 2030 and will thus by far miss the target of 5.7 $MtCO_{2eq}$.

Table 4: Main results of the Current Policies scenario for Sweden.

Current Policies, SWEDEN	**2020**	**2030**	**2040**	**2050**
Total energy use in road transport, ktoe	6,011	5,794	4,777	3368
Share of fossil fuels, %	72 %	70 %	66 %	58 %
EV share in passenger car fleet, %	2.8 %	12.4 %	36 %	56 %
EV numbers, 1000 units	137	647	1,845 000	2,844 000
Share of electricity, % of total transport energy	0.37 %	2.3 %	8.3 %	16 %
Amount of fuels replaced by electricity, ktoe	22	136	398	553
Share of biofuels, %	28 %	28 %	26 %	25 %
Amount of biofuels, ktoe	1,657	1,595	1,249	852
CO_2 emissions, Mt	12.9	12.1	9.3	5.8

Figure 13 plots the expected progression of CO_2 emissions according to the Current Policies scenario, and disaggregates the effects of energy efficiency improvements, introduction of electric vehicles and awaited biofuels use: The red line on top is the imaginary evolution of TTW CO_2 emissions from the road sector without any of these measures. The blue line shows the effect of electrification alone, the yellow one joins the effect of energy efficiency gains on top of this, and finally the green line shows the combined effect of all measures including biofuels. It is apparent that biofuels contribute most to decarbonization up to 2040, while the effect of electrification catches up with biofuels in 2038.

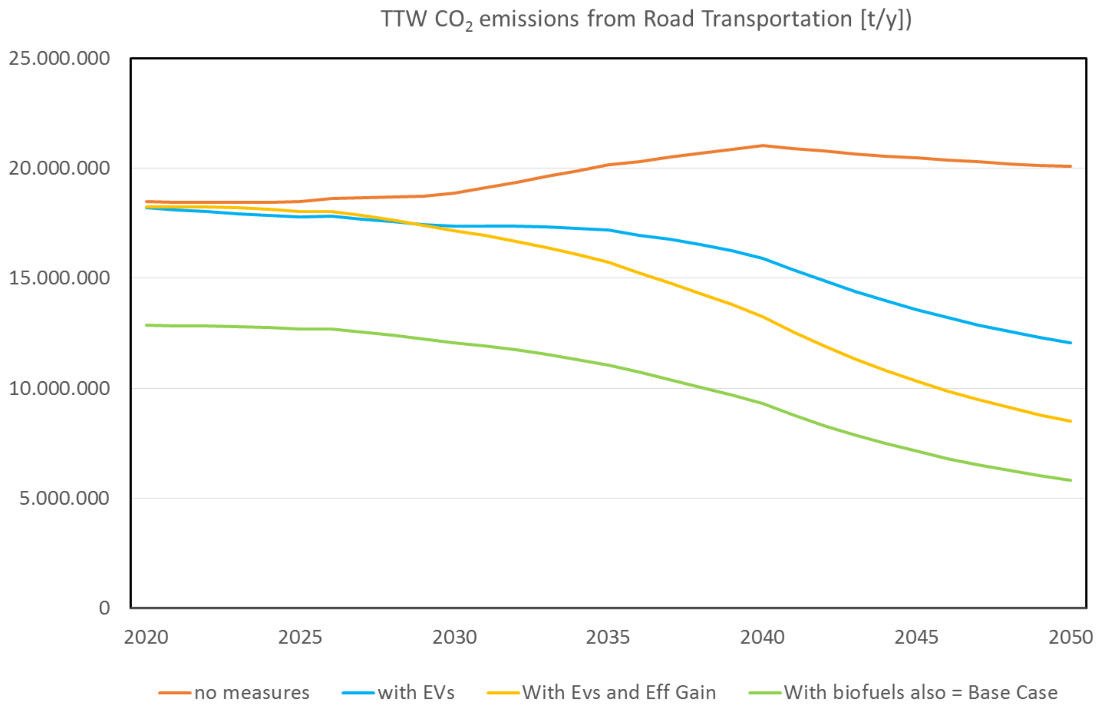

Figure 13: TTW CO_2 emissions in road transport by different measures for Sweden in the Current Policies scenario.

Figure 14 shows the projected split between different engine and fuel/energy options in new car sales from 2020 until 2050 according to the Current Policies scenario. When compared to e.g. that of Finland (Figure 8) we see that current share of diesel is in Sweden much higher, twice as large. Furthermore, it is also expected to increase still for a few years, whereas in Finland it is anticipated to continuously diminish. Even by 2040, when the share in Finland is expected to be only 5%, the corresponding Swedish figure is still 19%, and in 2050, both SI and CI-only cars are expected to be sold at 34% level, whereas in Finland diesel will be completely out-of-picture by then, and only SI cars remain. The Swedish case also assumes higher share of plug-in hybrids between 2025 and 2040 than in Finland, where they are presumed to “fade away” much quicker.

As in Finland, a hydrogen-fueled FCEV category is not expected to be on the market in Sweden. The main reason for this is the same: the large geographical area of the country is making it difficult and expensive to create a sufficient refilling infrastructure and operate it profitably.

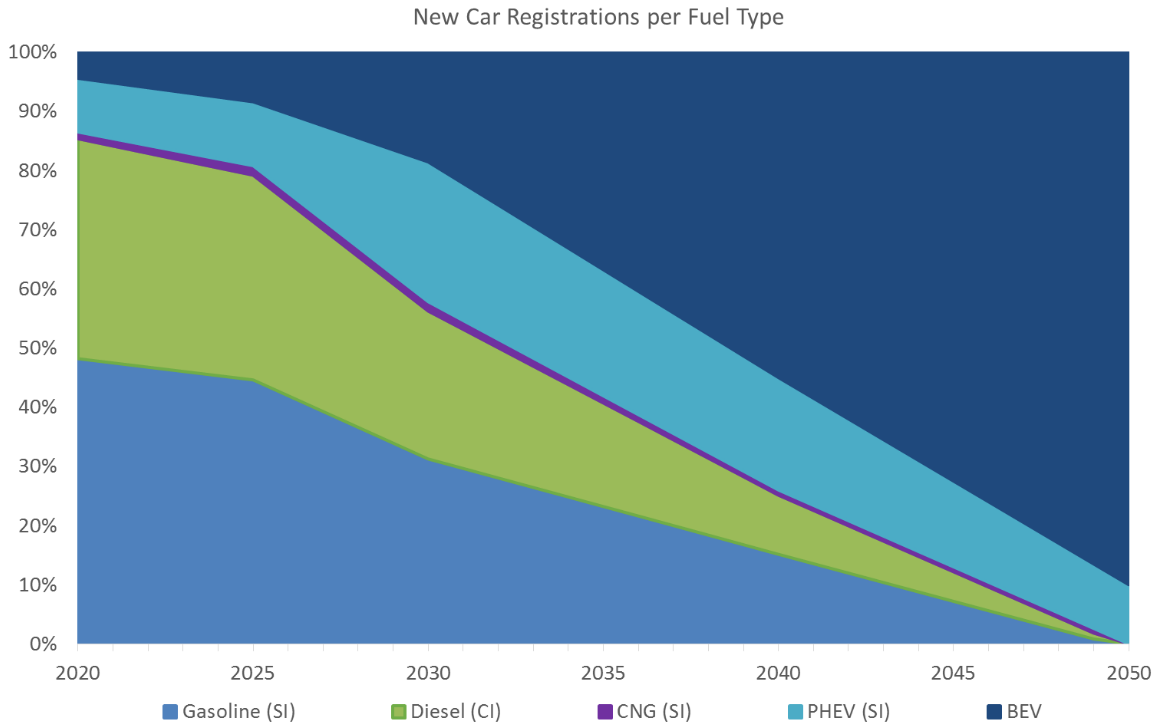

Figure 14: Breakdown of new car sales by powertrain options for Sweden in the Current Policies scenario.

Figure 15 then shows that in the Current Policies case the energy use in the transport sector is expected to decrease, due to increasing energy efficiency of mainly the cars and the increase in electric vehicles. Cars currently use 80% of the overall transport energy, but will only use slightly more than 50% by 2050.

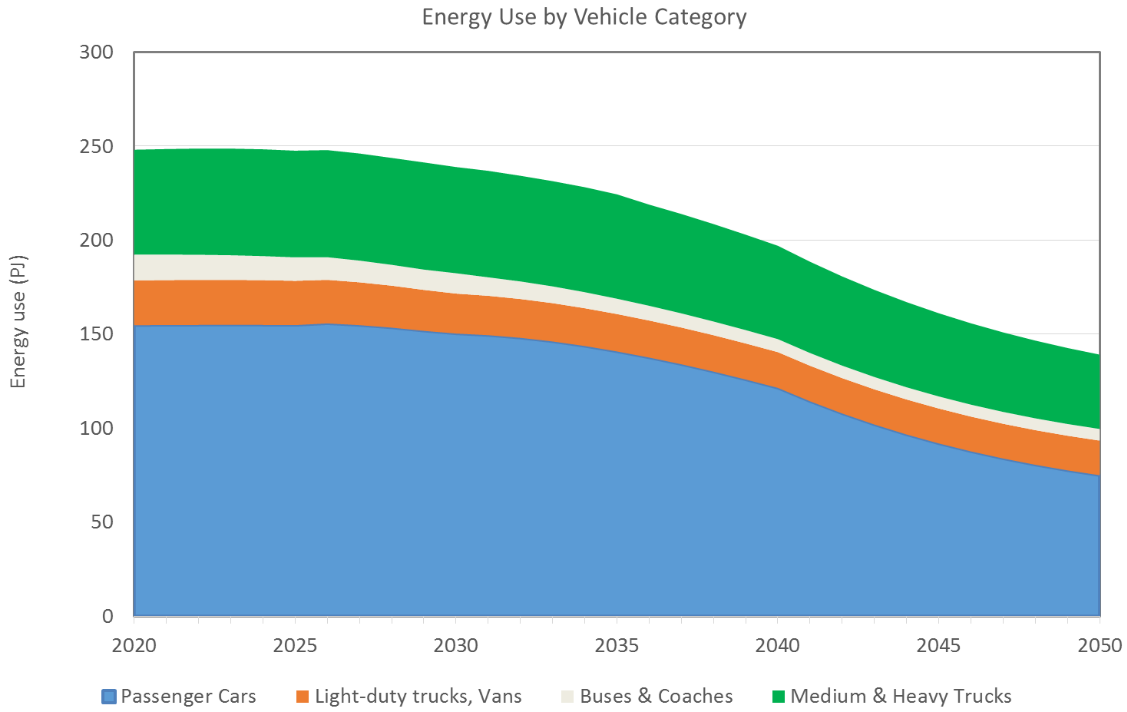

Figure 15: Energy use in road transport by vehicle category for Sweden in the Current Policies scenario.

Almost two thirds of cars in Sweden currently drive on diesel, and a significant portion of this is already substituted by renewable diesel, as can be seen Figure 16. Electric vehicles are more energy efficient than internal combustion engines (4 to 5 times as efficient assumed in this analysis), and thus the proportion of electricity seems to remain small, although they replace almost as much fossil fuel in 2050 as biofuels do.

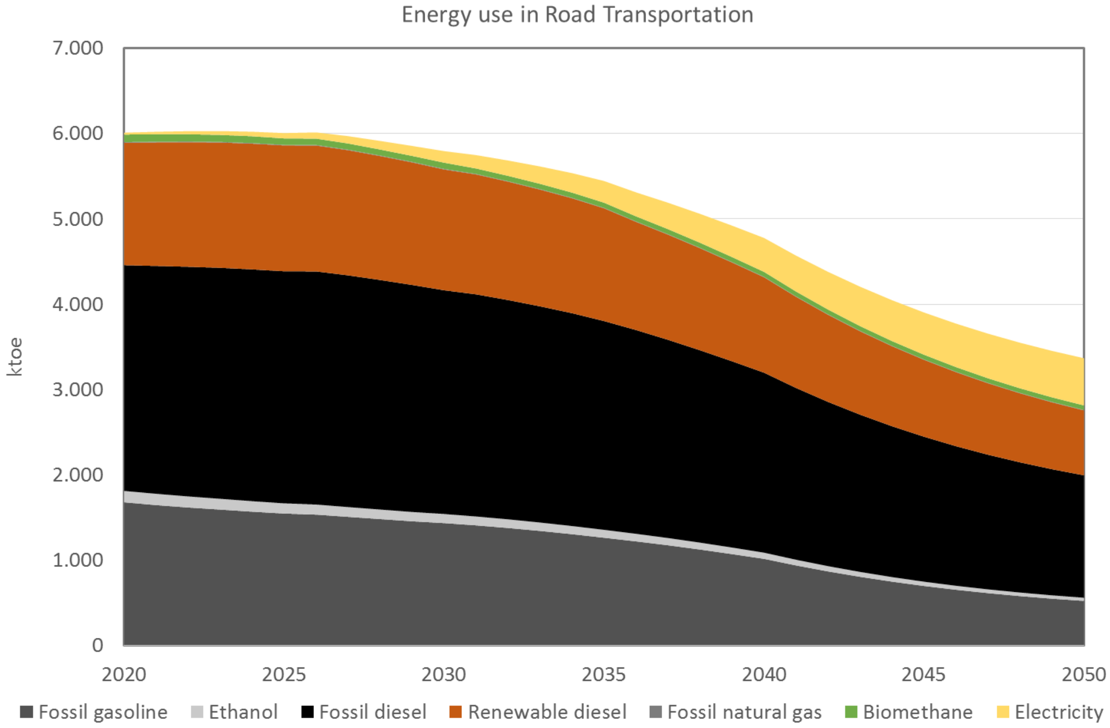

Figure 16: Energy use in road transport by energy carrier for Sweden in the Current Policies scenario.

The TTW CO_2 emissions from the road transport sector in the Current Policies case decrease from 13 $MtCO_2$ in 2020 to 6 $MtCO_2$ in 2050, and by far miss the target of 7 $MtCO_{2eq}$ by 2030. The largest part of CO_2 emissions comes from cars, but their contribution can be halved by 2050, while CO_2 emissions from medium duty and heavy-duty trucks remain more constant, see Figure 17.

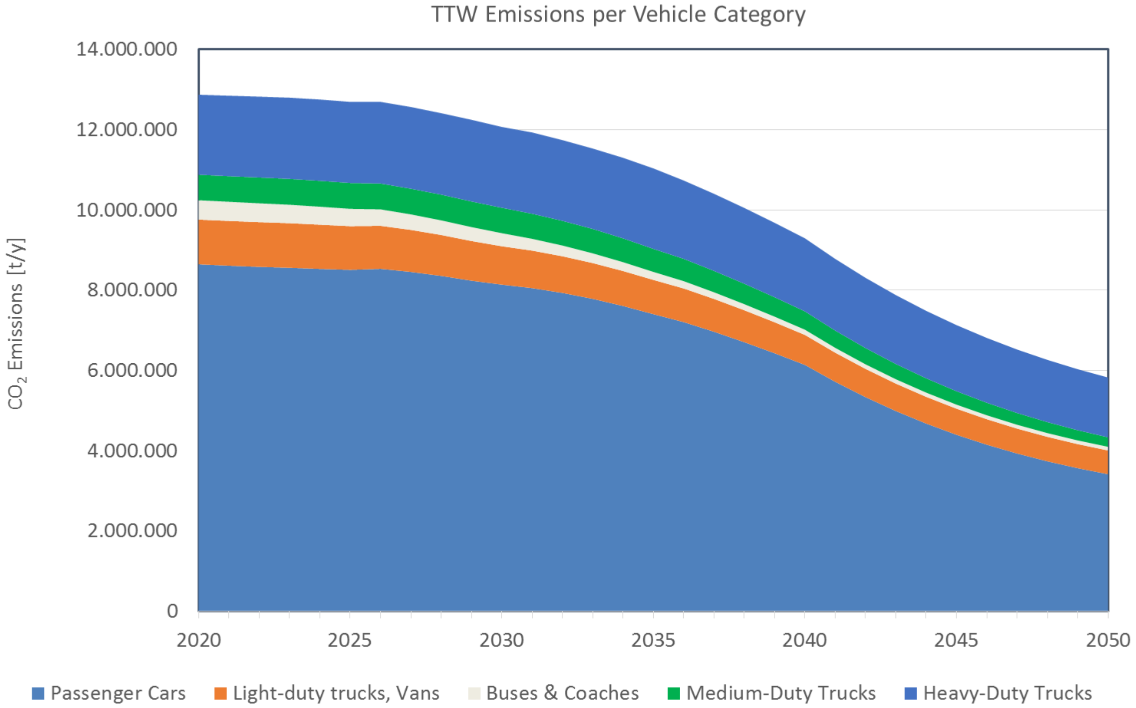

Figure 17: TTW CO_2 emissions in road transport by vehicle category for Sweden in the Current Policies scenario.

Germany

In Germany, biofuels represent currently about 6 % of the total energy use in road transport. Furthermore, according to Current Policies scenario, this share is not expected to increase, and due to the increasing energy efficiency of the fleet, the actual amounts would then actually diminish. However, the electrification rate of the passenger car fleet is projected to grow by a factor of 11 already by 2030, and reach nearly 22 million cars by 2050, representing then 46% of the stock.

Currently, road transport accounts for about 152 Mt of CO_2, and the emissions are estimated to be less than 60 Mt by 2050. At first, the reductions are mostly attributed to the use of biofuels, but after 2030, the increase in energy efficiency takes the lead. However, soon after 2040, increased electrification is the main contributor to the reductions in CO_2 emissions.

Due to the large population in Germany, the size of the road vehicle fleet is much larger than in the Nordic countries Finland and Sweden. Also, the energy consumption of the road transport sector is projected to increase until 2030. Officially, Germany aims to reduce GHG emissions from the transport sector by 42% (as compared to 1990) by 2030. However, as discussed in more detail in Part 1 of the overall report "Key Strategies in Selected Countries", it seems impossible to achieve this target.

In our analysis, the Current Policies scenario starts with 54.5 Mtoe/yr total road transport energy demand in 2020, where the combined contribution of fossil gasoline (16.5 Mtoe/yr) and fossil diesel (34.5 Mtoe/yr) amounts to 94% of the energy use. By 2050, the total energy demand is reduced by 53% to 25 Mtoe/yr with the following main energy carriers: fossil gasoline 6 Mtoe/yr, fossil diesel 13 Mtoe/yr and electricity 3 Mtoe/yr. Fossil CO_2 emissions from road transport in 2050 are down by 38% from 2020 levels, as shown in Table 5.

Table 5: Main results of the Current Policies scenario for Germany.

Current Policies, GERMANY	**2020**	**2030**	**2040**	**2050**
Total energy use in road transport, ktoe	54,465	45,025	33,138	25,088
Share of fossil fuels, %	94 %	93 %	88 %	78 %
EV share in passenger car fleet, %	0.7 %	7.3 %	24 %	46 %
EV numbers, 1000 units	328	3,507	11,560	21,981
Share of electricity, % of total transport energy	0.10 %	1.3 %	5.3 %	12.4 %
Amount of fuels replaced by electricity, ktoe	55	572	1,763	3,121
Share of biofuels, %	6.1 %	6.1 %	6.4 %	7.0 %
Amount of biofuels, ktoe	3,303	2,759	2,104	1,754
CO_2 emissions, Mt	151.7	123.8	86.5	58.1

Figure 18 depicts the anticipated development of CO_2 emissions according to the Current Policies scenario, and separates the effects of foreseen energy efficiency improvements, implementation of electric vehicles and estimated biofuels use. The top-most red line is the hypothetical evolution of TTW CO_2 emissions from the road sector without any measures. The blue line then shows the effect of implementing electric vehicles, whereas the yellow one aggregates also the effect of energy efficiency gains. Lastly, the green line plots aggregated effect of all these measures including also use of biofuels. As the graph shows, in the beginning, biofuels represent the largest contribution to the reduction of CO_2, but soon after 2030 the anticipated gain in energy efficiency will take the lead, and remain the main provider until 2040. This continues even a few years beyond, but then the electrification starts to be the most important measure, and remains so until 2050. However, this is highly dependent on the assumption of the progression in energy efficiency.

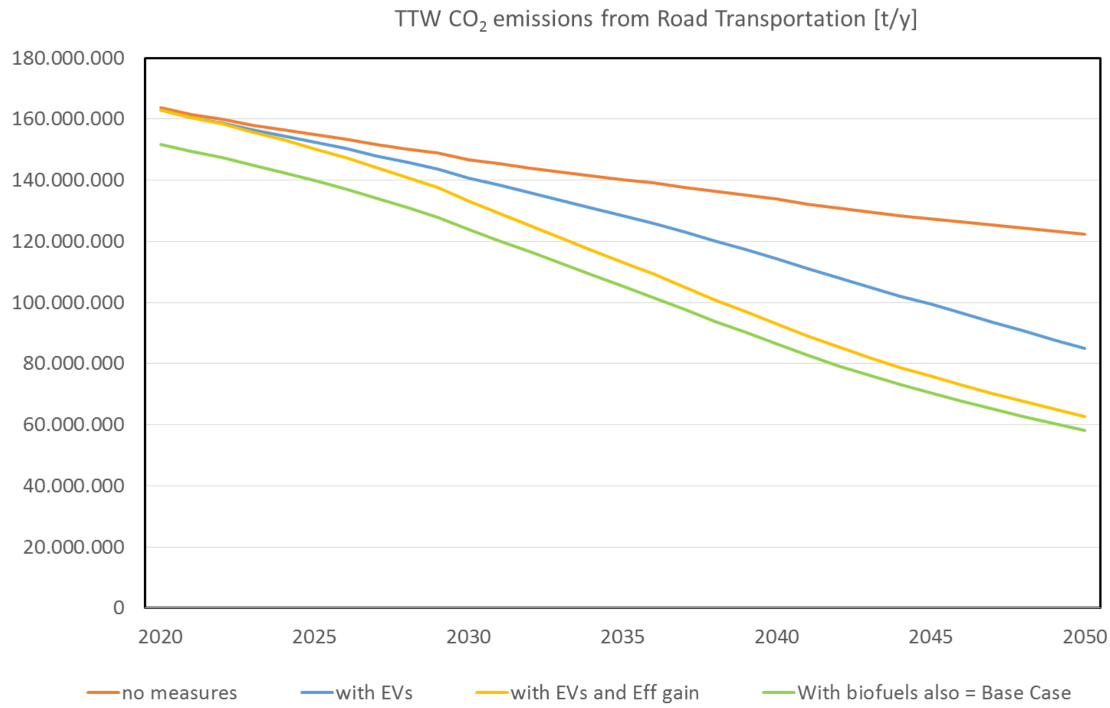

Figure 18: TTW CO_2 emissions in road transport by different measures for Germany in the Current Policies scenario.

Figure 19 shows the projected split between different engine and fuel/energy options in new car sales from 2020 until 2050 according to the Current Policies scenario. When compared to the cases Finland and Sweden, a much wider list of options is considered, as e.g. the share of SI-ICE is accounted separately for “normal” SI-ICE and SI-ICE with electric-hybrid configurations. Furthermore, there is also a hydrogen-fueled FCEV category on top of direct-electric options, which is not expected to be on the market in Finland and Sweden. As opposed to the large geographical area of these countries making it difficult and expensive to create a sufficient refilling infrastructure and run it profitably, Germany has much higher population and road traffic densities that should support the creation and successful upkeep of the hydrogen infrastructure.

Like Sweden, Germany has currently a fairly high share (42%) of diesels (CI-ICE) in new car registrations. However, unlike Sweden but like Finland, in the Current Policies scenario this share is foreseen to quite rapidly narrow down, and drop to about 20% by 2035 and below 10% soon after 2040, becoming almost extinct by 2050. Furthermore, the implementation of electricity is divided between plug-in hybrids with both SI and CI engines (PHEV-SI, PHEV-CI), as well as pure electric vehicles (BEV) and fuel cell electric vehicles (FCEV), which use hydrogen as the energy carrier. The combined share of these shall reach about 20% by

2025, which is about the same as expected in Finland (21%), but more than in Sweden (13%). By 2035 this share is expected to grow to somewhat over 30%, which is lower than what is expected for Finland (37%) or especially Sweden (Sweden expecting a rapid “boom” to reach already a 45% share of chargeable vehicles). By 2045 plug-in cars are foreseen to account for over 60% of new car sales in Germany, of which over 6% is FCEV. For Finland the expectations for xEVs are about on the same level, as well as in Sweden, but neither of these countries account hydrogen-fueled vehicles to be sold. By 2050 the various electrified cars are anticipated to account for nearly 80% of the sales, and of the remaining non-chargeable options the HEV-SI is the largest with 17% share, but the shares of traditional SI and CI cars are both in single-digit figures.

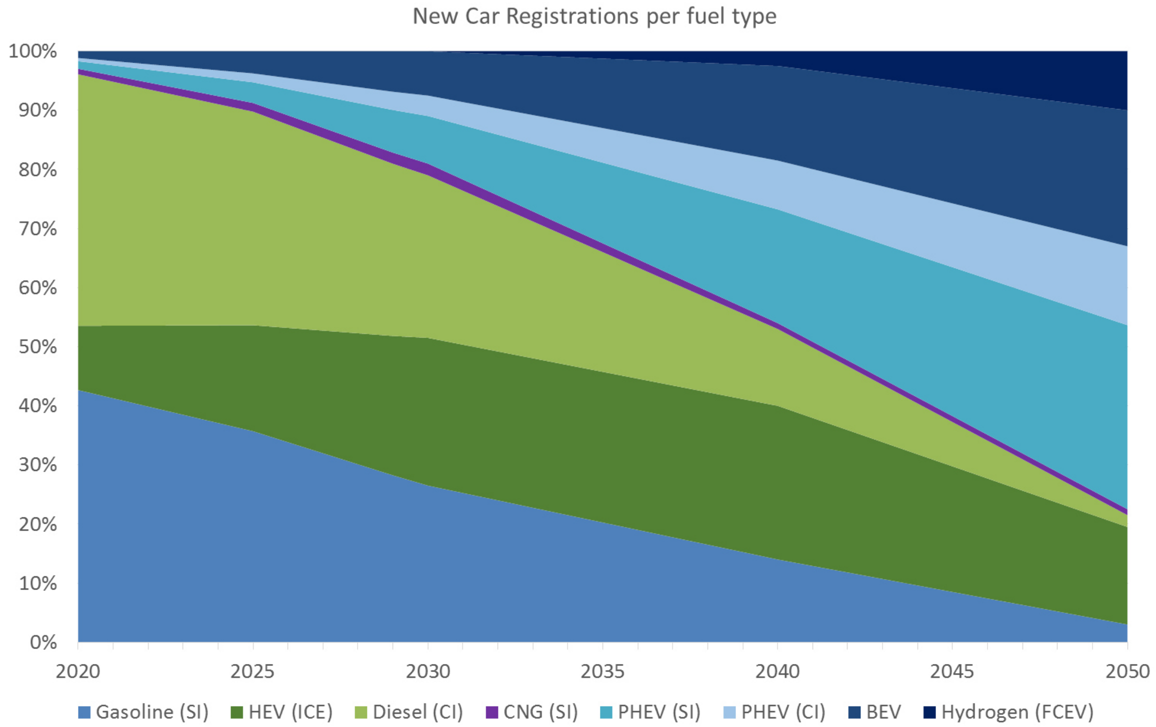

Figure 19: Breakdown of new car sales by powertrain options for Germany in the Current Policies scenario.

If we then view Figure 20 that depicts road transport energy use divided into different road vehicle categories, we can see that light vehicles - especially cars – consume most of the energy, currently almost 80% of the total. In the Current Policies scenario, this scenery is expected to change somewhat, but not drastically, as by 2050 the light vehicles´ share still remains at 66%. However, in absolute numbers the use of energy is expected to drop quite substantially, as by 2040 almost a 40% reduction is expected, and by 2050 the level shall be less than half of the current figures.

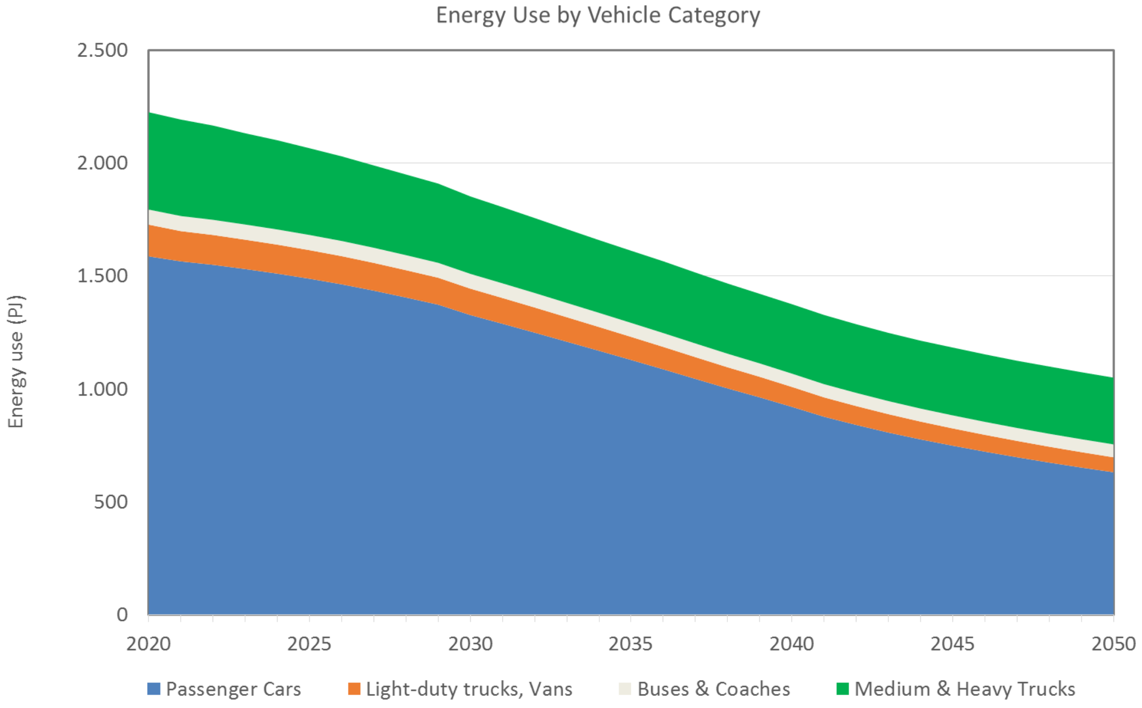

Figure 20: Energy use in road transport by vehicle category for Germany in the Current Policies scenario.

Figure 21 presents the use of energy in road transport by type of fuel or energy. Very distinctly, it shows how dominant the diesel pool is, because of the large diesel passenger car and LDT fleet. The current level is 68%, and by 2050 it is anticipated to lower down to 55%. However, unlike in Finland and Sweden, in Germany the share of renewable diesel remains only at about 8% over the 2020 to 2050 timeframe.

According to Figure 22, the projected aggressive lowering of the passenger cars CO_2 emissions (which is due to electrification (27%), efficiency gains (33%) and the use of biofuels (40%)) reduces the road transport emissions by nearly 20% by 2030. Furthermore, the reduction is over 40% by 2040, and over 60% by 2050, which is the highest reduction rate amongst the case countries of Finland, Sweden and Germany.

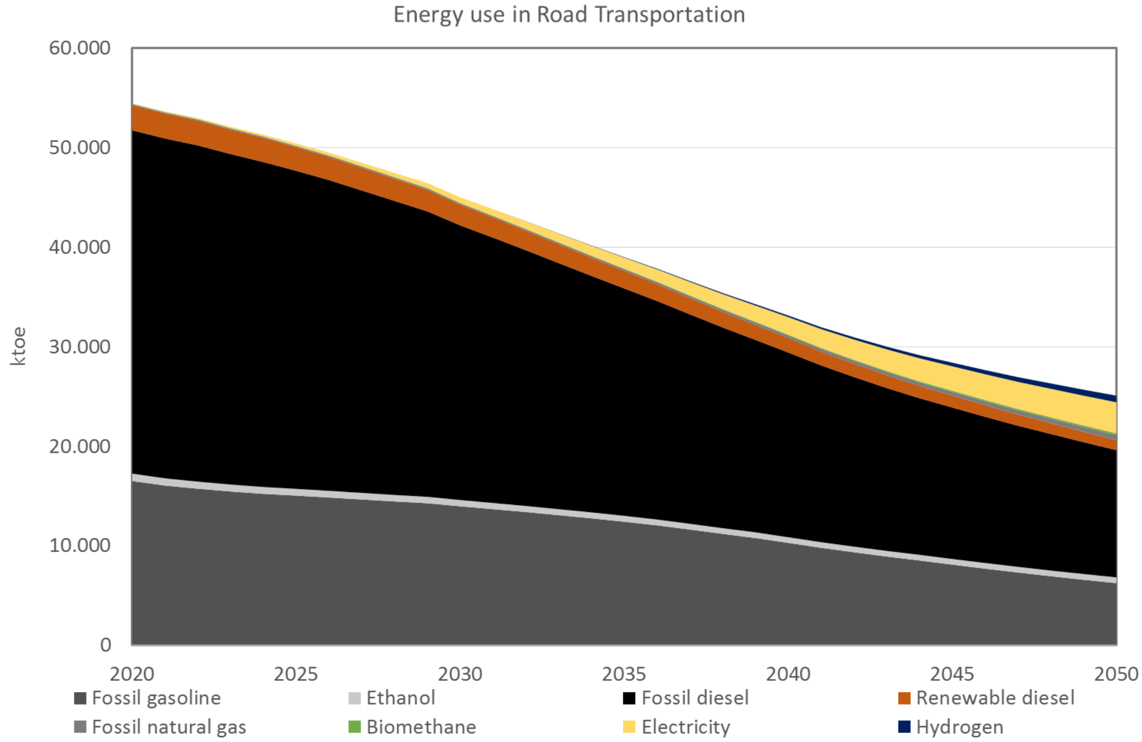

Figure 21: Energy use in road transport by energy carrier for Germany in the Current Policies scenario.

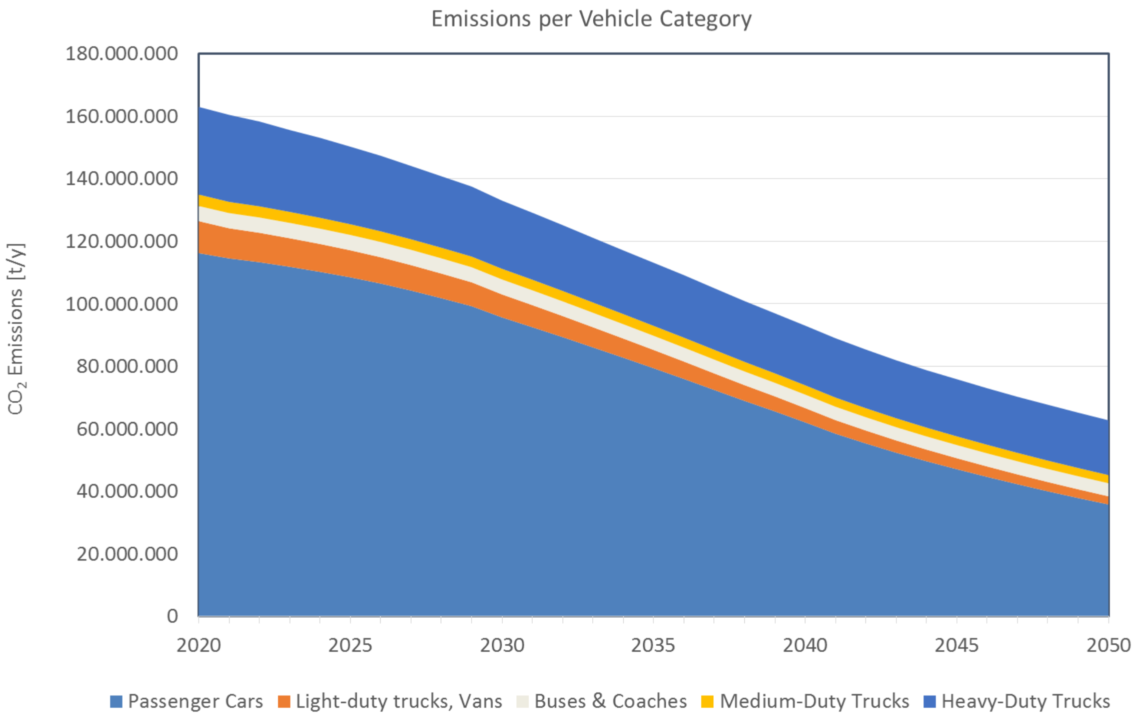

Figure 22: CO_2 Emissions in road transport by vehicle category for Germany in the Current Policies scenario.

USA

In the USA, the use of biofuels currently replaces about 9% of the road transportation energy, and this figure is expected to rise modestly to somewhat over 10% by 2030 and beyond. However, the rate of electrification is expected to increase, and due to the growing numbers of EV's, the share of electricity would be over 1% by 2030, and over 3% by 2050, while the current level is less than 0.3%. By 2050, nearly 33 million EVs are expected to be on the road, nearly 20% of the total light-duty vehicle stock of that time.

For the USA, the Current Policies scenario leads to 1,250 Mt of CO_2 emissions by 2030, followed by 1,117 Mt by 2040 and 1,126 Mt by 2050. These numbers represent a reduction of 16% by 2030, 25% by 2040, and 24% by 2050, compared to current emissions. Thus, unlike in European countries, the US emissions stagnate due to the expected growth in VMT that counterbalances the positive effects of electrification, efficiency gain and the use of biofuels.

Of the reductions in 2030, 17% comes from the EVs, 36% of the expected advances in vehicles' efficiency, and the remaining 47% from the use of biofuels. By 2050 these quotas have changed to 25% by EVs, 49% by efficiency and 26% by biofuels.

The size of the road transport fleet in Unites States is about five times the fleet of Germany. Particularly large is the light vehicle segment, consisting of passenger cars and light-duty trucks (LDT), which nowadays contains a large share of "sport utility vehicles" (SUV) that are essentially large passenger vehicles. Furthermore, traditional pick-up trucks are also still in wide use, but usually more as passenger vehicles rather than in their intended use case as cargo haulers. This particular composition of the fleet also heavily influences the energy spent by the sector, and per vehicle energy need in U.S. is almost twice as large as in Germany.

According to part 1 of the overall report ("Key Strategies in Selected Countries"), the total fuel consumption in road transport is currently about 708 Mtoe (which is ten times that of Germany), even if the total vehicle miles travelled (VMT) in U.S. is only 7 times larger (see Table 25 in Appendix 1). In total, 36.1 Mtoe of this fuel consumption is renewable, and most of it is ethanol. As the prevailing SI-engine fuel in U.S. is E15, the biofuel contents (by energy) would, at maximum, thus be about 11 %, as Table 6 shows.

According to the Current Policies scenario, the projected use of energy in the transportation sector is going to be reduced, but not as strongly as in e.g. Germany. Although the energy use per VMT is reduced, the expectations in the Current Policies scenario are that total VMT in U.S. will grow (up to 20% by 2050, see Figure 4), instead of the reduction presumed for

Germany and the Nordics. Therefore, if the total projected energy expenditure in 2050 will be 440 Mtoe, effectively it means that energy use per VMT is down by over 30% from the current level.

Table 6: Main results of the Current Policies scenario for the USA.

Current Policies, USA	**2020**	**2030**	**2040**	**2050**
Total energy use in road transport, ktoe	545,938	473,466	432,077	439,770
Share of fossil fuels, %	91 %	89 %	87 %	86 %
EV share in passenger car fleet, %	1.6 %	7.6 %	14 %	18 %
EV numbers, 1000 units	2,285	11,220	21,999	32,972
Share of electricity, % of total transport energy	0.20 %	1.2 %	2.3 %	3.2 %
Amount of fuels replaced by electricity, ktoe	1,109	5,565	9,814	14,130
Share of biofuels, %	8.7 %	10.1 %	10.8 %	10.6 %
Amount of biofuels, ktoe	47,326	47,923	46,655	46,827
CO_2 emissions, Mt	1,483	1,250	1,117	1,126

Like in the previous country cases, Figure 23 depicts the estimated development of CO_2 emissions and separates the effects of forecasted energy efficiency gains, anticipated growth of the electric vehicle fleet and projected biofuels use. The red line on top is the imaginary progression of TTW CO_2 emissions from the road sector without any measures. The blue line plots the outcome of the growth of electric vehicle fleets, and the yellow line combines also the consequence of improved energy efficiency. Lastly, the green line shows totaled outcome of all these measures including also use of biofuels. As these plots show, until 2030 and even some years beyond, the use of biofuels accounts for the largest reduction of CO_2 emissions, but soon after 2030 the estimated improvement of energy efficiency shall become more important. It will also keep that role, as the expected effect of electrification is estimated to be so modest that it will not overtake efficiency, but reaches about the same level as the use of biofuels until 2050.

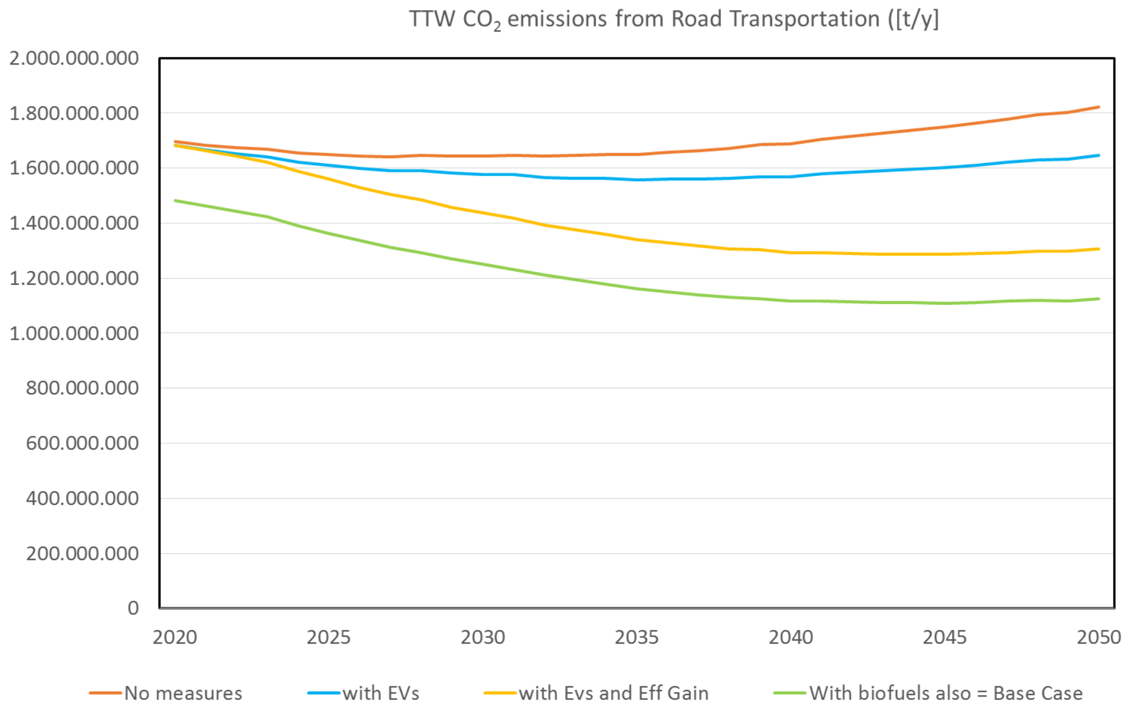

Figure 23: TTW CO_2 emissions in road transport by different measures for the USA in the Current Policies scenario.

Figure 24 shows the anticipated shares between different engine and fuel/energy options in new car sales from 2020 until 2050, as described in the Current Policies scenario. When compared to the other country cases, the image is strikingly different, because traditional SI-ICE overrules the scene completely. Fueled either with gasoline (E15), high-concentration ethanol (E85/FFV) or CNG, the share of this type of primary drivetrain is now over 90%, and shall remain over 80% until 2040, and still yield to about 75% in 2050. On the other hand, diesels (CI-ICE) are a marginal technology regarding passenger cars, as their market share is always projected to remain below 2%. This holds true even if SUV's and other LDT's, not included in this graph, are considered. The rate of electrification in light-duty vehicles is currently below 10%, and it is anticipated to reach about 13% by 2030, nearly 20% in 2040, and subsequently over 20% by the year 2050. The vast majority of chargeable vehicles are expected to be fully electric (BEV), with only 2 to 3% of PHEV(SI), and a fraction (0.2% to 0.3%) of hydrogen fueled fuel cell electric vehicles (FCEV). Even with these fairly modest numbers, due to the large size of the US fleet, the EV fleet shall grow to over 11 million by 2030, over 22 million by 2040 and almost to 33 million by the year 2050 (see Table 6).

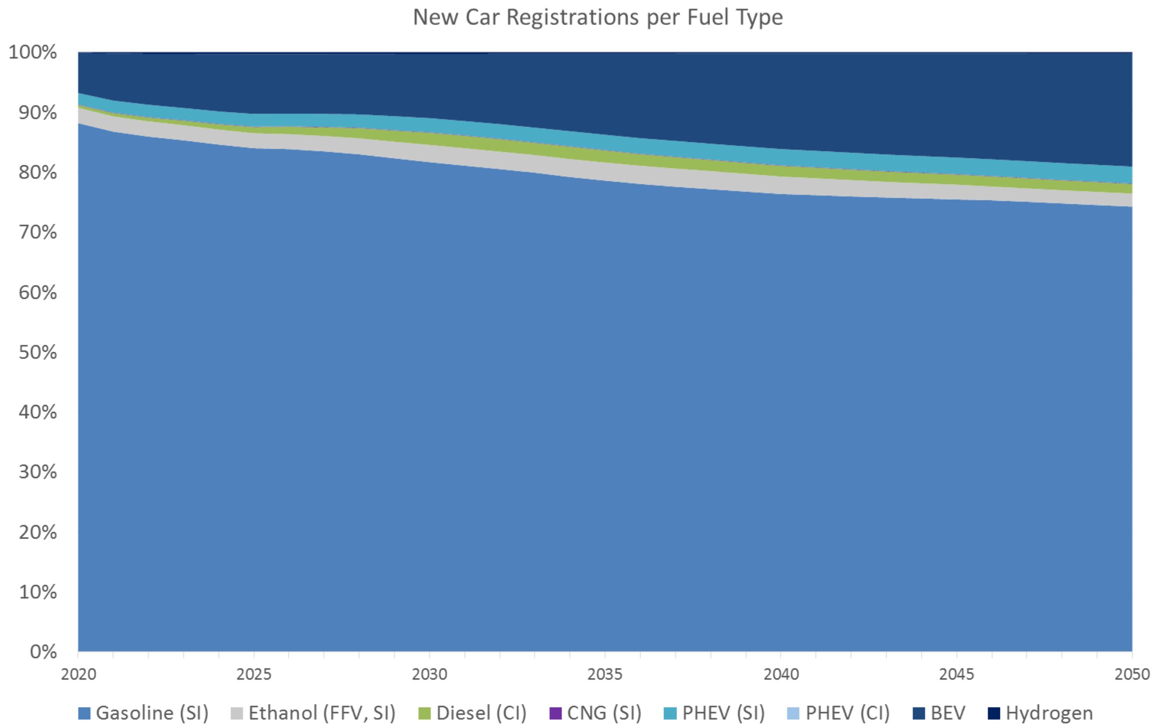

Figure 24: Breakdown of new car sales by powertrain options for the USA in the Current Policies scenario.

Turning then to Figure 25 that illustrates energy use in road transport by vehicle categories, we observe that light vehicles - especially LDTs that include a large number of SUVs – consume most of the energy. Currently at 75% of the total, this share will slide to 67% by 2050 in the Current Policies scenario. Furthermore, in absolute numbers, the combined use of energy in passenger cars and LDT is expected to drop by 20% until 2030, and a further 10% drop is foreseen by 2040, but then levelling until 2050, mainly due to the projected growth in vehicle miles travelled (VMT).

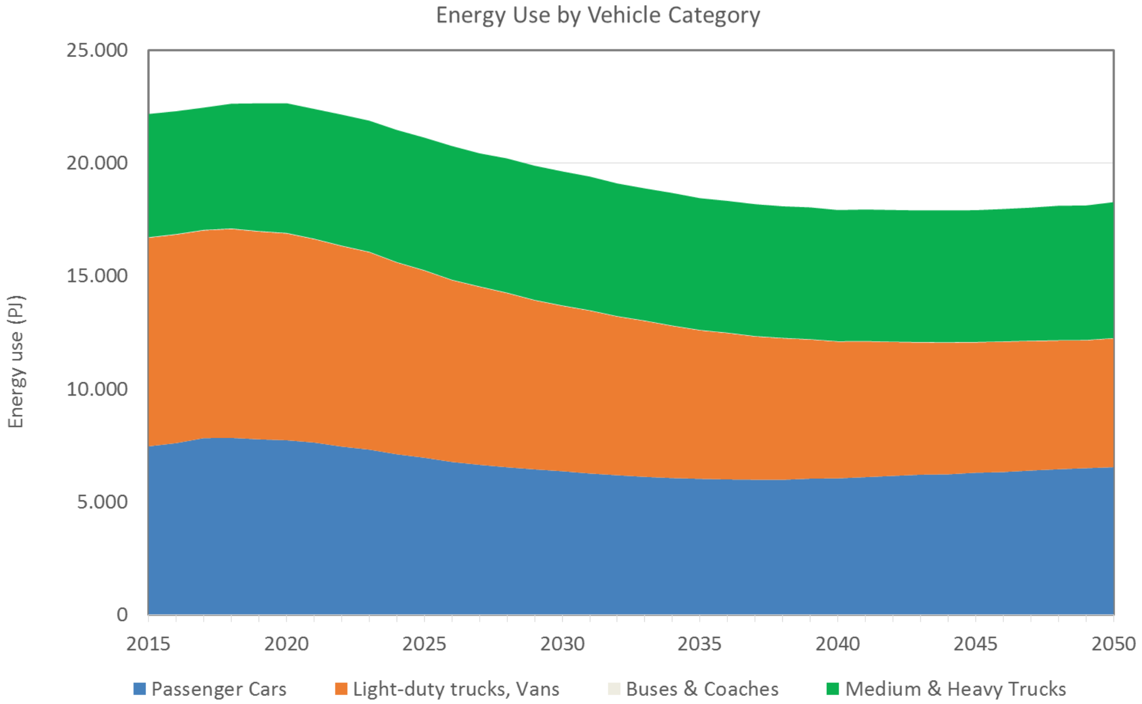

Figure 25: Energy use in road transport by vehicle category for the USA in the Current Policies scenario.

Figure 26 represents the use of energy in road transport by type of energy carrier. Again, compared to the previous country cases the picture is quite different, as fossil fuels – especially gasoline – dominate the scene. Furthermore, over the 30-year period from 2020 to 2050 the share of fossil energy is expected to drop only by 6 percentage points (from 91% to 86%).

Finally, Figure 27, that charts the projected progression of TTW CO_2 emissions, shows how total emissions shall be reduced by some 25% by 2040 from the current level, mainly due to reductions in PC&LDT emissions. However, after 2040 a slight upward trend is anticipated due to increased transport work.

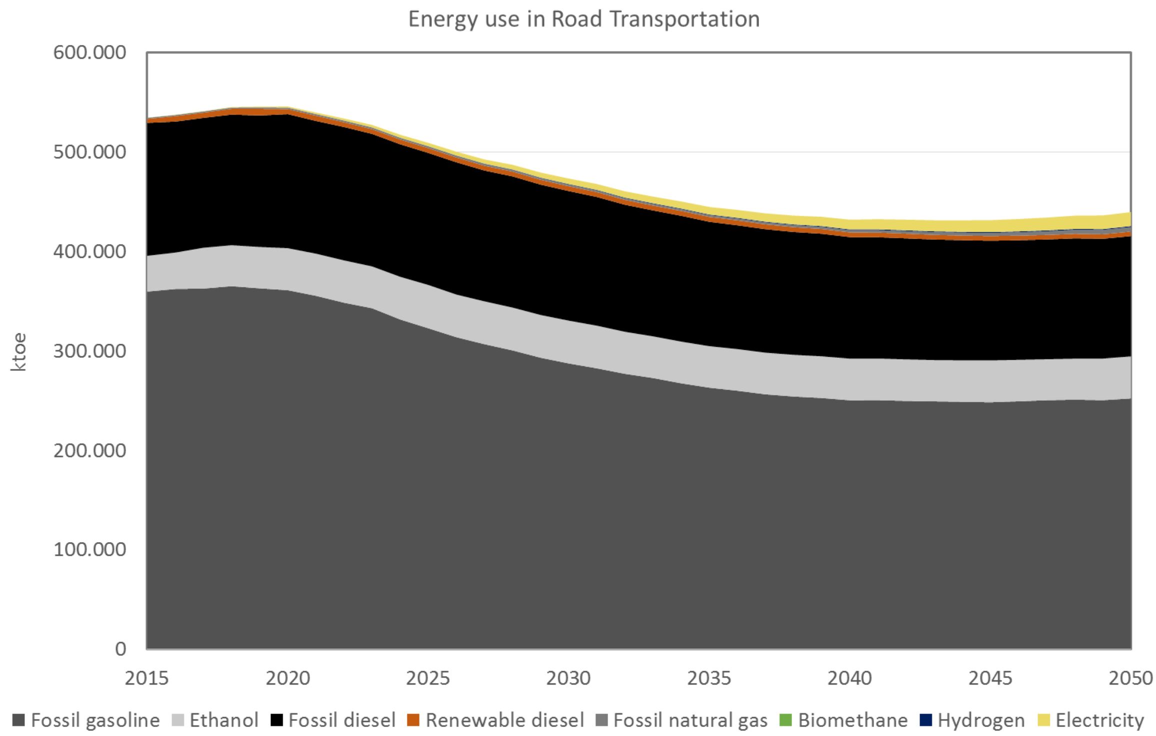

Figure 26: Energy use in road transport by energy carrier for the USA in the Current Policies scenario.

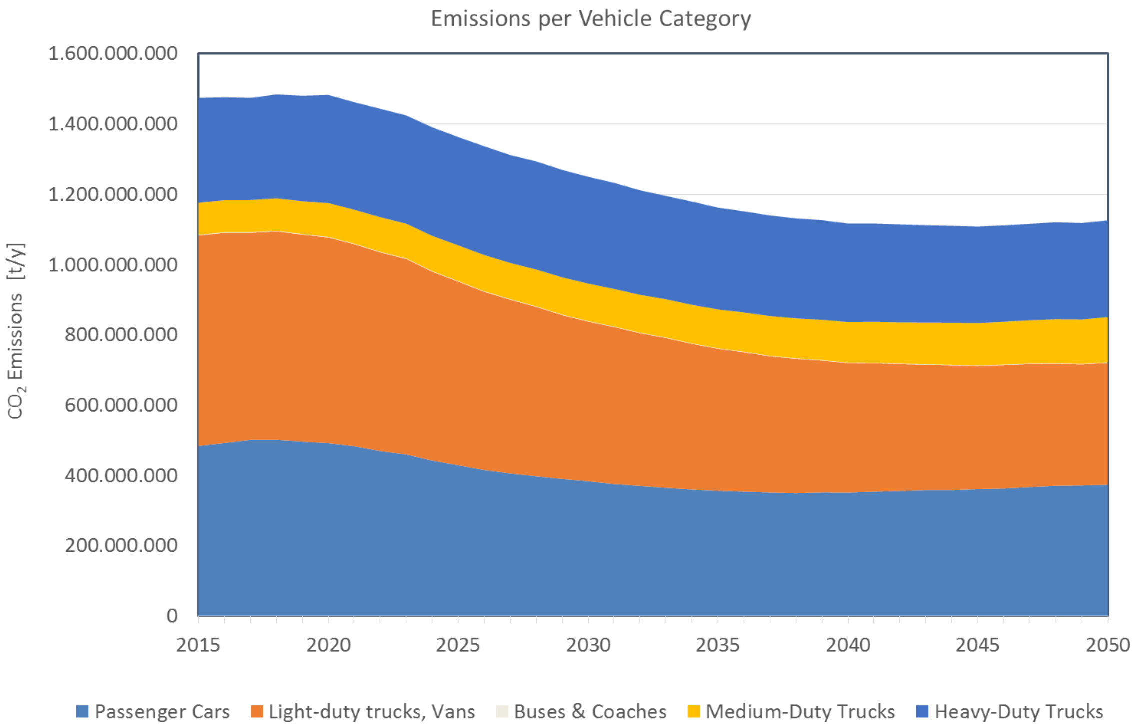

Figure 27: CO_2 emissions in road transport by vehicle category for the USA in the Current Policies scenario.

Brazil

In Brazil, mainly because of the expected growth in economy, the transport work is also expected to increase, leading to a growth in CO_2 emissions. This is in stark contrast to our European case countries, and the stagnating emissions of the US. However, the emissions would grow even more if no reduction measures would have been applied. By 2030, over 25% reduction (69 Mt) is achieved, based on contributions from EVs (5%), increased efficiency (9%), and the use of biofuels (87%). The share of biofuels is currently 25%, and it is expected to grow moderately.

In the Current Policies scenario, in 2020, road transport accounts for 171 Mt of CO_2, and its projected growth to 2030, 2040 and 2050 is 19% (203 $MtCO_2$), 58% (270 $MtCO_2$) and 70% (291 $MtCO_2$), respectively However, the three main measures are projected to reduce CO_2 emissions by nearly 180 Mt by 2050. Of this total reduction electrification accounts for 36%, efficiency gain for 23%, and biofuels for 51% contribution.

Brazil is by population 2/3 of U.S., but mainly due to different status of the economy, their vehicle fleet is much smaller, as Figure 3 showed. A noticeable feature is the large bus fleet that is needed to compensate the lower car/inhabitant ratio. As Figure 4 showed, Brazil is different also due to the fact that the Current Policies scenario suggests total transport work (vehicle miles travelled, VMT) to grow, even quite strongly, as by 2030 total VMT is expected to increase by 40%, and by 70% until the year 2050 from current level. Consequently, this is reflected also in total energy use by the road transport sector, which shows growth from about 80 Mtoe now to about 140 Mtoe in 2050. However, this growth is solely attributed to the growth in VMT, as the energy efficiency is expected to improve, some 10% per 2030 and nearly 20% by the year 2050.
Despite the growing economy, Brazil aims to reduce overall GHG emissions by 37% compared to 2005 by 2025. The RenovaBio policy is the main measure to achieve the required reduction in average GHG intensity in the Brazilian transport sector. Scenarios, which are discussed in more detail in Part 1 of the overall report “Key Strategies in Selected Countries”, show that it seems possible to achieve this target.

The share of fossil fuels of total road transportation energy consumption shows only a modest decline, from the current level of 75% to 70% by the year 2050. In short term, by 2030, by far the largest contributor to this change is the increased use of biofuels, which is considered to be increased from 25% to 30%. However, in the long-term the electrification of the fleet has a stronger growth. Nowadays electricity is nearly nil, and still in 2050 electricity is expected to represent only little over 1% of the total transport energy, whereas the share of biofuels remains at about 25% for the same 30-year period. To support this change, the sales of electric vehicles are projected to grow, and the EV fleet is expected to be nearly 6 million units, which is about 6% of the total passenger car fleet, by the year 2050.

Albeit these advances in electrification and use of biofuels, the road transport-related CO_2 emissions are bound to increase due to the strong growth in total transport work, attributed to the expected growth of the Brazilian economy. Thus, the emissions shall be close to 300 Mt by 2050, which represents a 70% growth from the current level. Already by 2030, the calculated growth in CO_2 is 19%.

Table 7: Main results of the Current Policies scenario for Brazil.

Current Policies, BRAZIL	**2020**	**2030**	**2040**	**2050**
Total energy use in road transport, ktoe	76 764	98 378	129 457	139 991
Share of fossil fuels, %	75 %	70 %	70 %	70 %
EV share in passenger car fleet, %	0.0 %	0.0 %	1.8 %	6.2 %
EV numbers, 1000 units	0	0	1 333	5 696
Share of electricity, % of total transport energy	0.01 %	0.10 %	0.4 %	1.2 %
Amount of fuels replaced by electricity, ktoe	10	103	549	1 744
Share of biofuels, %	25 %	30 %	29 %	29 %
Amount of biofuels, ktoe	19 274	29 777	38 000	40 413
CO_2 emissions, Mt	171	203	270	291

As with the other country cases, Figure 28 plots the computed CO_2 emissions and presents the changes in emissions attributed to three contributors being a) growth of electric vehicle fleet, b) energy efficiency improvements, and c) use of biofuels. As before in this graph, the upper-most red line is the theoretical evolution of TTW CO_2 emissions from the road transport sector without any of these measures. The blue line then shows the effect of growth in the EV fleet, and the yellow line superimposes also the effect of energy efficiency improvements. In conclusion, the green line plots the collective outcome of all these measures including use of biofuels. This figure clearly shows that biofuels are the largest contributor to decarbonization up to 2050, and overshadows even the combined effects of electrification and efficiency gains until about 2048.

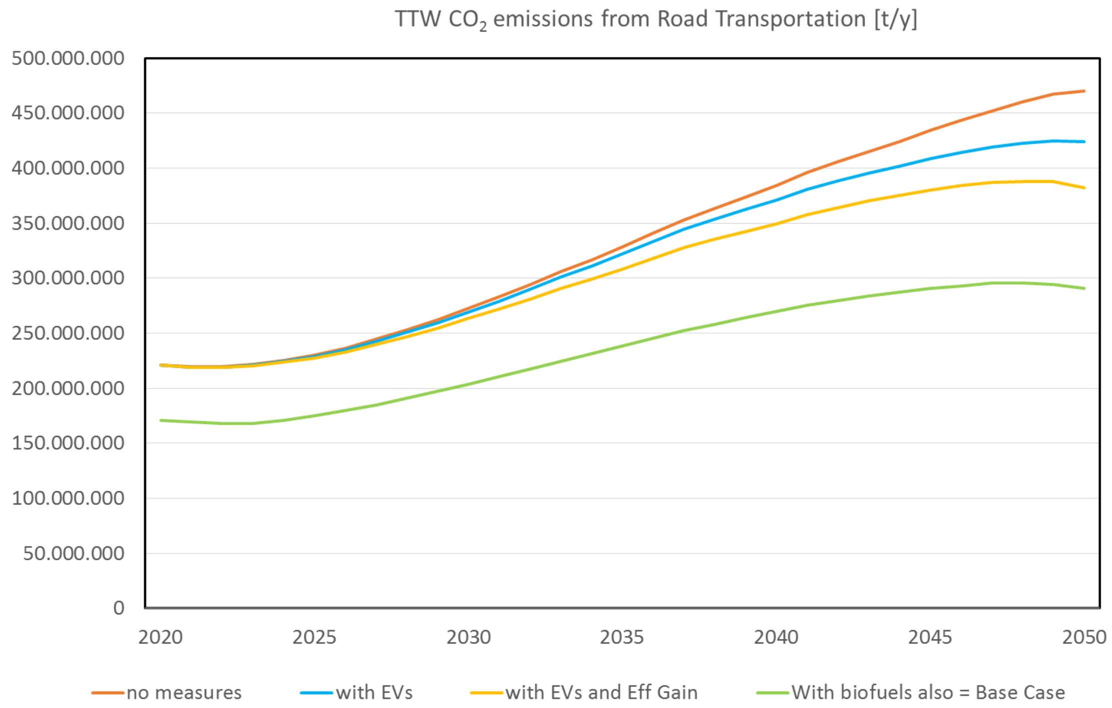

Figure 28: TTW CO_2 emissions in road transport by different measures for Brazil in the Current Policies scenario.

The strong preference of Brazil in using biofuels is clearly seen in Figure 29 that depicts the market shares of different propulsion and energy options in passenger cars. The vast majority of the passenger cars now, and also in coming decades, is expected to be flex-fuel vehicles, a specific type of SI-ICE car that can operate on gasoline or E100 according to the preferences of the consumer (mainly based on fuel prices ratio). Even when the consumer prefers 100% of gasoline C, there is a 27% share of anhydrous ethanol that is a mandatory addition to gasoline.

Both regular SI-ICE and diesel (CI-ICE) are available, but only with single-digit market shares. Both will also slowly fade away, as the hybrid versions of FFV (HEV flex) cars and also pure-electric cars (BEV) will start to become more popular. In the Current Policies scenario this is, however, expected to take quite some time, as by 2040, the market share of electric vehicles (BEV) will be about 5%, and by 2050 the share is estimated to be 10%. Thus, contrary to many other countries, Brazil expects flex-fuel hybrids (HEV flex), based only on a combustion engine, to be the overruling option over electric-only cars.

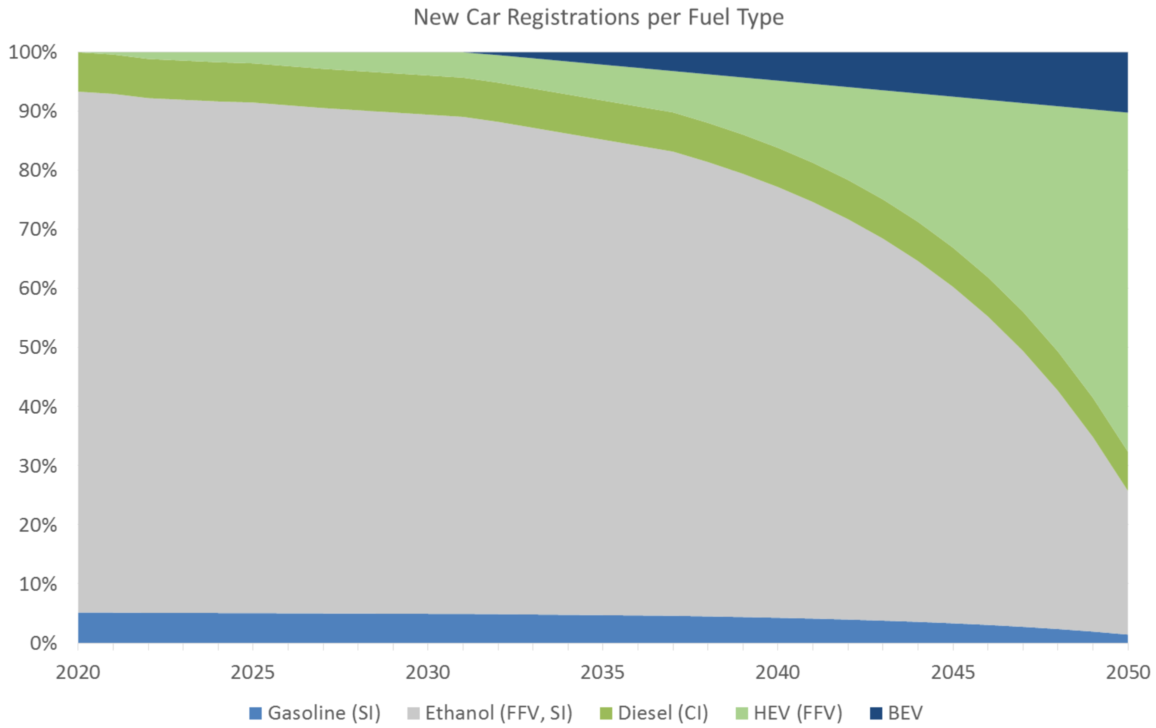

Figure 29: Breakdown of new car sales by powertrain options for Brazil in the Current Policies scenario. For Brazil the projections only include HEV flex, excluding PHEV (SI and CI).

If we review Figure 30 that illustrates energy use in road transport, we can observe that the share of light vehicles (cars and vans) is currently about 50%, and despite changes in VMT, energy efficiency and vehicles fleet composition, it will remain within 50 to 56% over the three-decade period covered in this study.

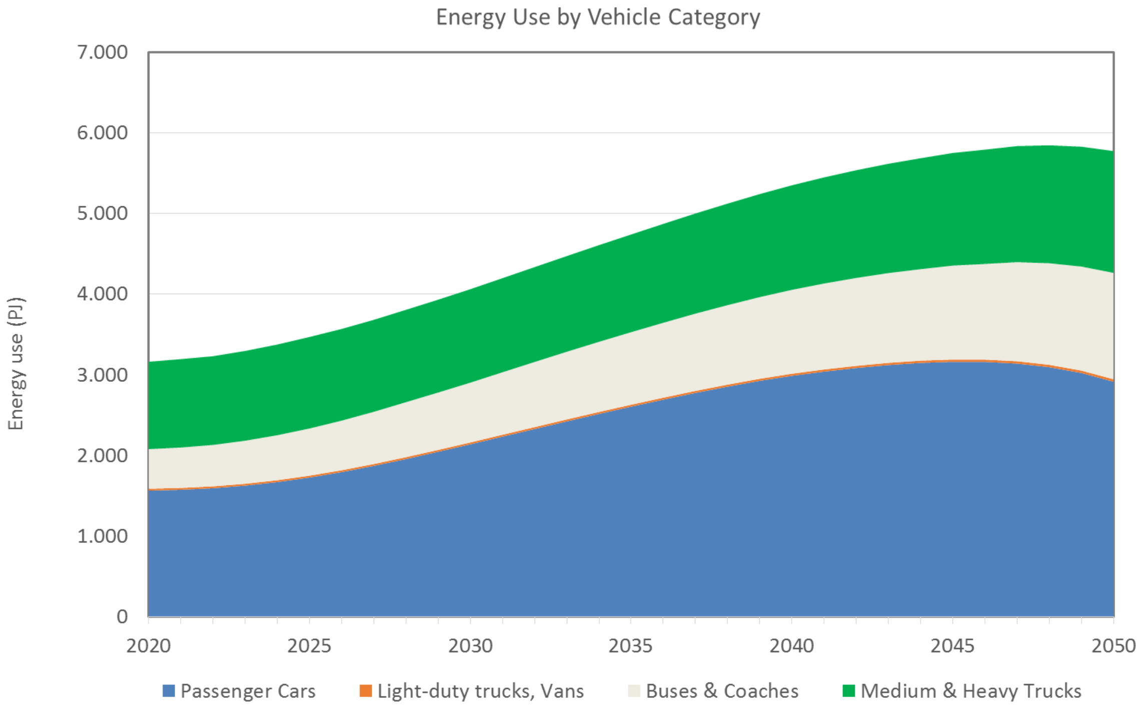

Figure 30: Energy use in road transport by vehicle category for Brazil in the Current Policies scenario.

Figure 31, that charts the use of different fuels in the road transport sector, shows that because approximately half of the energy is consumed in the heavy vehicle category, the diesel pool is the most dominant single fuel with about 50 to 55% share. This graph also clearly depicts the large quantity of ethanol used by the large and growing FFV-fleet. At peak, the amount would be about 27,000 ktoe, occurring around year 2045, and the share of ethanol averages around 18 to 20%. When we add to this the projected use of renewable diesel, the share of biofuels raises to a level of 22 to 27%, being on the maximum level between 2025 to 2036, but remain over 25% over to the year 2050.

Figure 32, depicting the projected CO_2 emissions according to the assumptions in the Current Policies scenario, illustrates what was already commented: the TTW CO_2 emissions from road transport will increase, and due to the fact that most of the biofuels would be ethanol to fuel passenger cars, heavy vehicles dominate as the source of those emissions. Furthermore, unique to Brazil amongst these five case countries is the large bus sector, as buses currently account for 17% of the total road transport emissions. This share will raise steadily, and reach 26% by the year 2050.

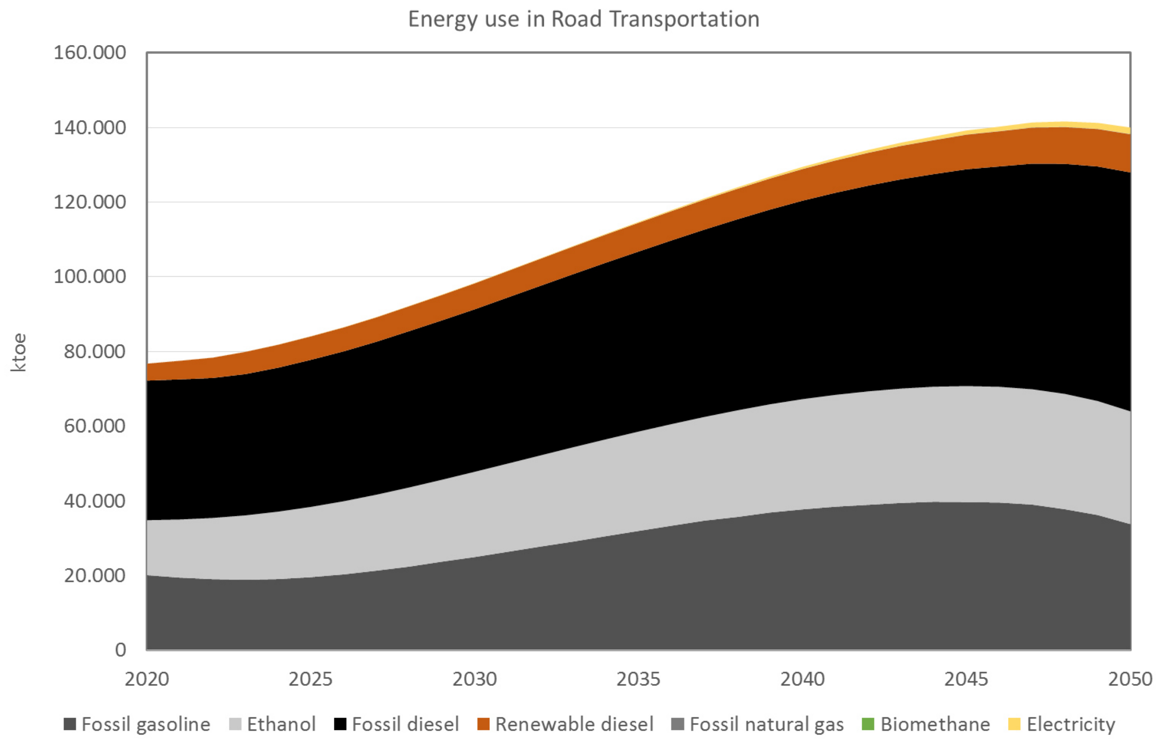

Figure 31: Energy use in road transport by energy carrier for Brazil in the Current Policies scenario.

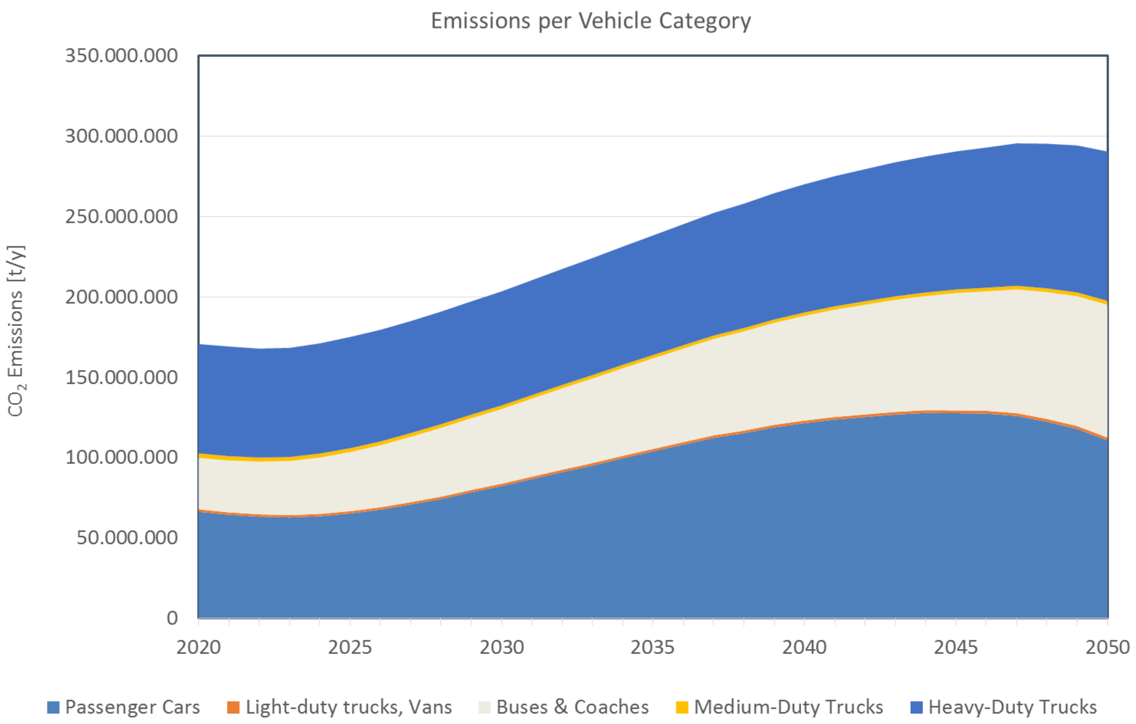

Figure 32: CO_2 emissions in road transport by vehicle category for Brazil in the Current Policies scenario.

Results for the MORE EV scenarios

MORE EV scenarios foresee an accelerated market introduction of electrified vehicles. The details for each country are based on discussions with the country experts involved in the project. For Sweden and Germany, 100% of passenger car sales in 2050 were assumed to be various sorts of electric vehicles. However, for Finland 25% of passenger car sales were still assumed to be spark ignited ICEs in 2050. Furthermore, in Brazil, ethanol-fueled hybrid vehicles would account for 60% and BEV for 40%. The dynamics of this uptake, however, varies strongly between the examined countries.

As a result, the share of EVs in the passenger car fleet reaches between 1.3% (Brazil) and 21% (Finland) in 2030, and between 19.4% (Brazil) and 77% (Sweden) by 2050.

Despite such high shares of EVs in the passenger car fleets, the calculated additional gain in CO_2 emission reductions remains rather low, in the range of 0.5% to 4.3% for 2030 and 3.5% to 9.2% for 2050.

As described under “Methodology”, MORE EV scenarios were created by increasing the anticipated sales of electrified vehicles, thereby reaching larger replacement of fuels with electricity in total transport energy use. The level of this “EV boosting” varies between countries, and was adjusted in consultation with country experts, to meet their outlooks for such an action. These scenarios were meant to reflect what a more aggressive, but still conceivable, electrification rate could achieve.

Figure 33 shows the numbers of electric vehicles that were calculated for each country for the Current Policies scenario and the MORE EV scenario for 2030 and 2050.

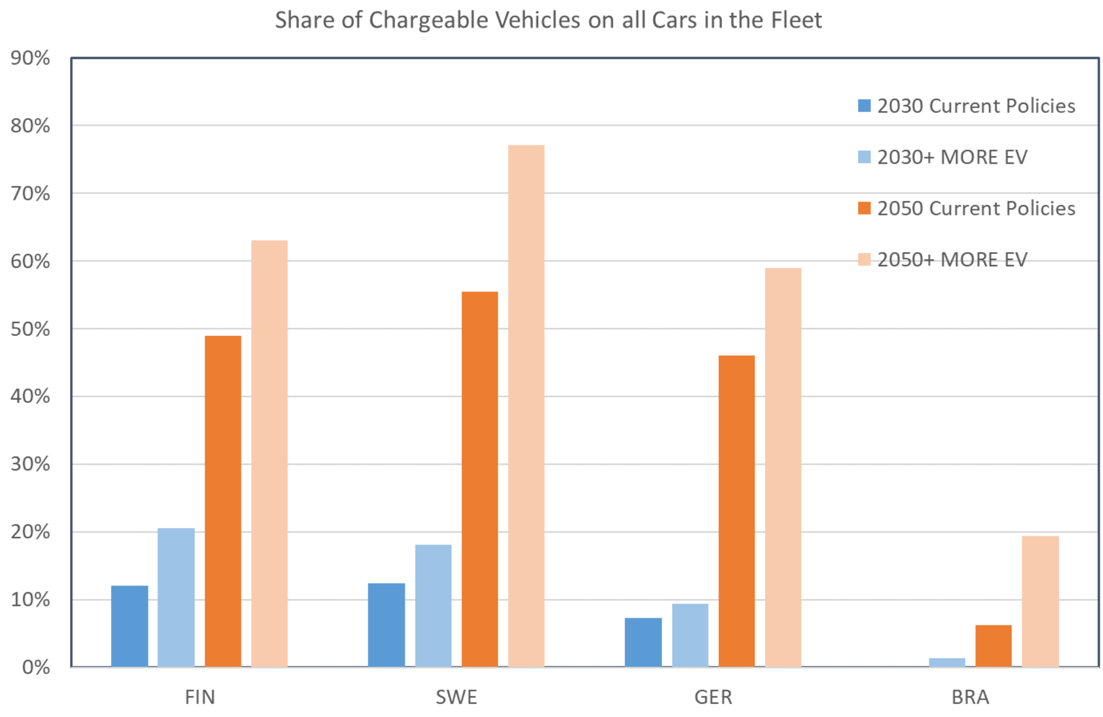

Figure 33: Shares of chargeable vehicles in the national passenger car fleet by 2030 and 2050 for Current Policies and MORE EV (MORE EV marked with +).

Finland

In the MORE EV scenario for Finland the sales of chargeable plug-in vehicles were accelerated already from 2020, but the boosting was most effective between 2030 and 2040, adding over 500,000 xEVs to the fleet, and resulting in nearly 2 million xEVs by 2050, instead of the 1.6 million in the Current Policy case. Figure 34 depicts the break-down of the sales according to this MORE EV scenario. It shows how the sales of diesels were assumed to remain unchanged as sales of diesels is presumed to be more purposefully-oriented, but sales figures of BEVs and especially PHEV (SI) were increased, replacing the normal ICE-only SI cars, because there the performance of the chargeable option is not different. However, the sales figures for the year 2050 were kept the same for both cases, yielding to 75% share of BEV and 25% share for SI-ICE. In both scenarios, diesels (CI-ICE) and plug-in hybrids were faded away by the year 2050. Figure 34 should be compared with Figure 8, which is the corresponding graph for the Current Policies case.

Figure 35 plots TTW CO_2 emissions resulting from applying each of the measures. Starting from the top, the lines represent: a) no measures (imaginary), b) introduction of EV's, c) adding improvements in energy efficiency, d) adding biofuels according to Current Policies scenario, and e) boosting xEV sales from the base case according to this MORE EV scenario. A separate line in the graph shows the number of additional xEVs introduced by the boosted scenario.

According to Table 8 that summarizes the main figures for the Finnish MORE EV scenario, the resulting CO_2 emissions were 7 Mt at 2030, 5.2 Mt at 2040, and 4.2 Mt by 2050, equalling to emissions reductions of 0.3 Mt, 0.5 Mt and 0.3 Mt, respectively, compared to the base case. These equal to some 4 to 8% additional reductions over the base case (Current Policies scenario).

Table 8: Main results of the MORE EV scenario for Finland.

MORE EV, FINLAND	**2020**	**2030**	**2040**	**2050**
Total energy use in road transport, ktoe	4,019	3,562	2,977	2,706
Share of fossil fuels, %	86 %	66 %	59 %	52 %
EV share in passenger car fleet, %	1.6 %	20.6 %	46.7 %	63.3 %
EV numbers, 1000 units	43	600	1,388	1,994
Share of electricity, % of total transportation energy	0.25 %	4.5 %	13.7 %	23.2 %
Amount of fuels replaced by electricity, ktoe	10	161	406	629
Share of biofuels, %	14 %	30 %	27 %	25 %
Amount of biofuels, ktoe	545	1,051	811	681
CO_2 emissions, Mt	10.3	7.0	5.2	4.2

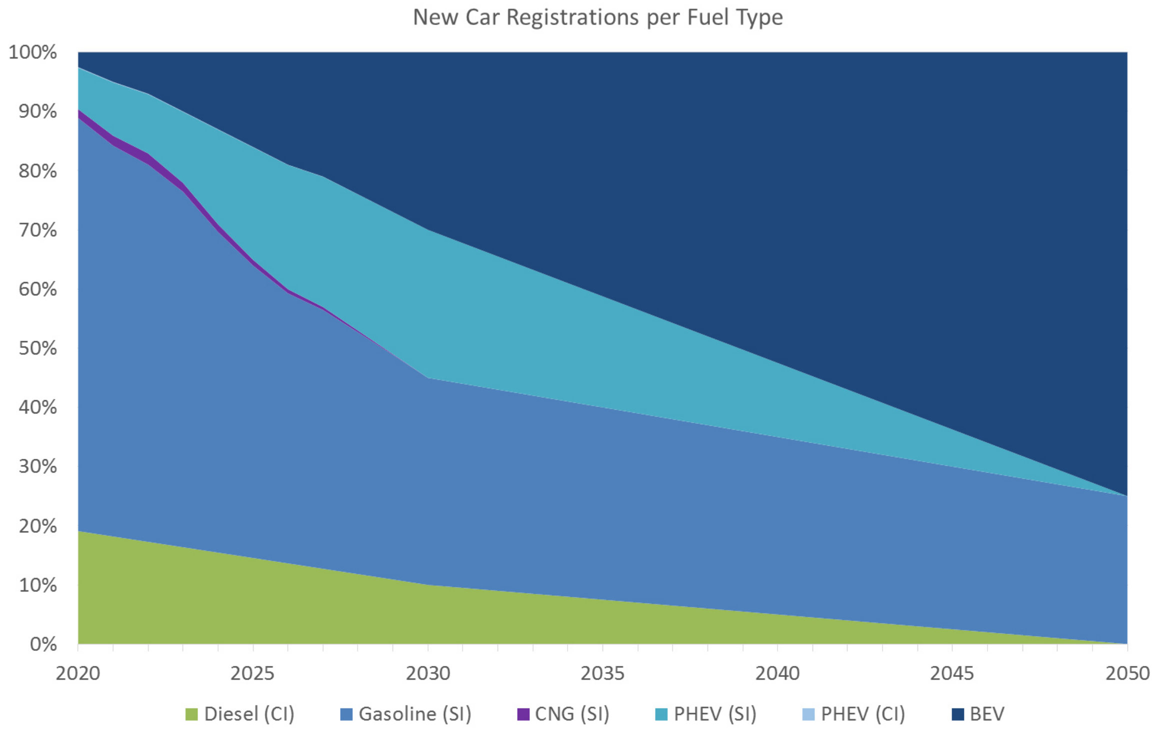

Figure 34: Breakdown of new car sales by powertrain options for Finland in the MORE EV scenario.

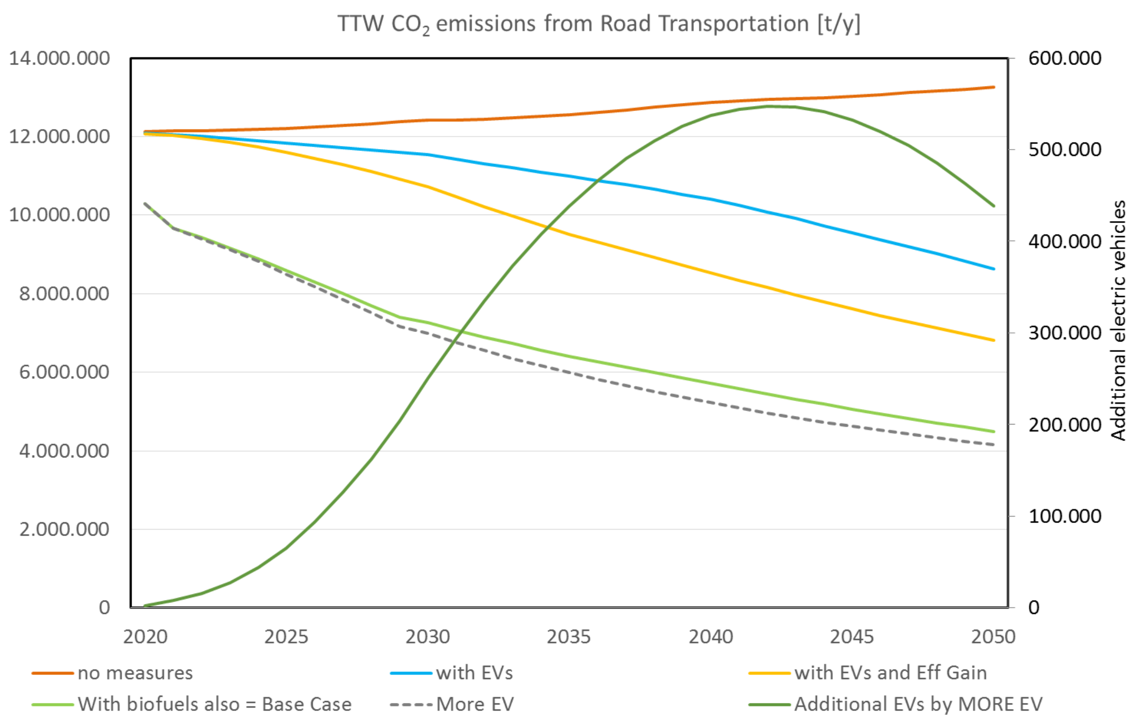

Figure 35: TTW CO_2 emissions in road transport by different measures for Finland in the MORE EV scenario.

Sweden

For Sweden the MORE EV scenario for boosting the sales of electric cars was constructed by first holding back the sales of diesels starting already at 2020, and more aggressively after 2040. Also, the sales of gasoline cars were reduced, but not as much as diesel, and not much before 2030. These reductions were then substituted by increasing the sales of both plug-in hybrids (PHEV) and battery electric cars (BEV). Unlike the Finnish case, the Swedish MORE EV scenario faded out normal SI-ICE and CI-ICE cars completely by the year 2050, whereas in the Current Policies scenario both were still available, and sold by nearly 20% market share each. Total car sales remained the same, but this boosting added more than 1 million xEVs to the fleet until the year 2050. Figure 36 depicts the break-down of the sales according to the MORE EV scenario. It should be compared with Figure 14, which is the corresponding graph for the Current Policies case.

Furthermore, Figure 37 plots TTW CO_2 emissions resulting from applying each of the measures. Starting from the top, the lines represent: a) no measures (imaginary), b) introduction of EV's, c) adding improvements in energy efficiency, d) adding biofuels according to the Current Policies scenario, and finally, e) boosting xEV sales from the base case according to this MORE EV scenario as a dashed line. A separate line in the graph shows the number of additional xEVs introduced by the boosted scenario. It is apparent that the contribution of a more aggressive electric vehicle uptake is rather small, although more than 1 million more EVs would be on the road in 2050 than in the Current Policies case.

According to Table 9 that summarizes the main figures for the Swedish MORE EV scenario, the resulting CO_2 emissions were 11.9 Mt at 2030, 8.7 Mt at 2040, and 4.3 Mt by 2050, equaling to emissions reductions of 0.2 Mt, 0.5 Mt and 1.5 Mt, respectively, compared to the base case (Current Policies scenario). These account for 1%, 6% and 25% reductions.

Table 9: Main results of the MORE EV scenario for Sweden.

MORE EV, SWEDEN	2020	2030	2040	2050
Total energy use in road transport, ktoe	6,005	5,724	4,595	2,848
Share of fossil fuels, %	72 %	70 %	64 %	51 %
EV share in passenger car fleet, %	3.1 %	18.1 %	47.0 %	77.1 %
EV numbers, 1000 units	153	943	2,426	3,925
Share of electricity, % of total transportation energy	0.39 %	3.1 %	11.1 %	26 %
Amount of fuels replaced by electricity, ktoe	23	175	511	734
Share of biofuels, %	28 %	27 %	25 %	23 %
Amount of biofuels, ktoe	1,655	1,537	1,139	651
CO_2 emissions, Mt	12,9	11,9	8,7	4,3

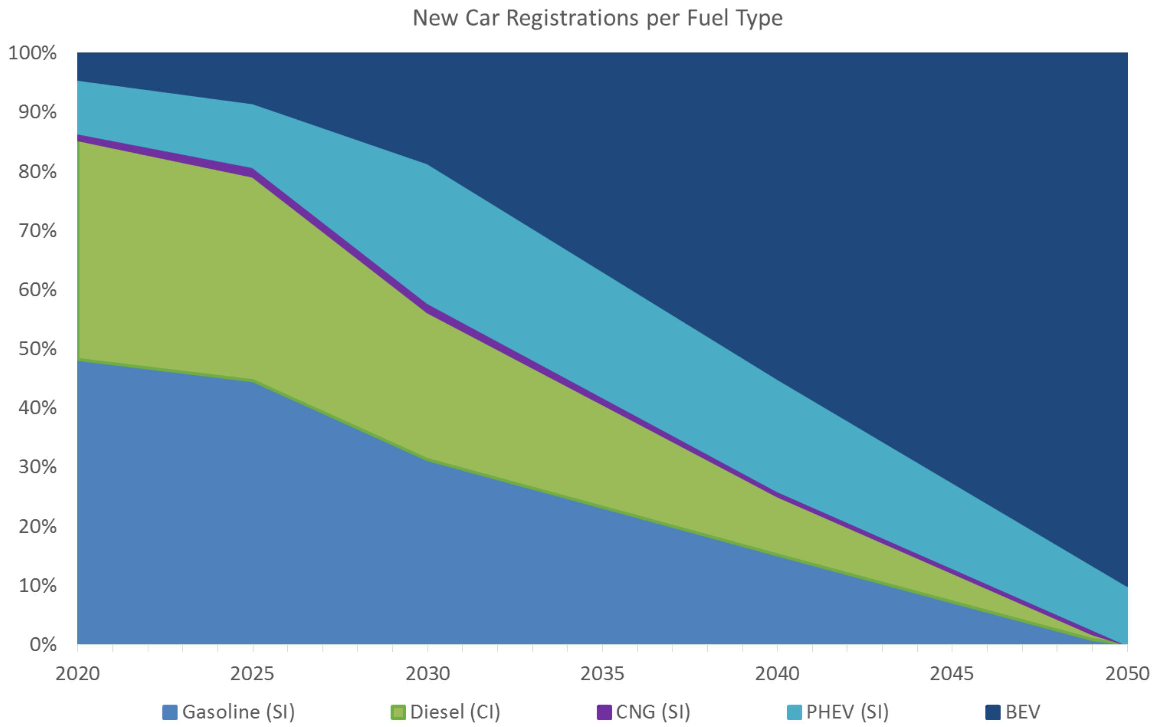

Figure 36: Breakdown of new car sales by powertrain options for Sweden in the MORE EV scenario.

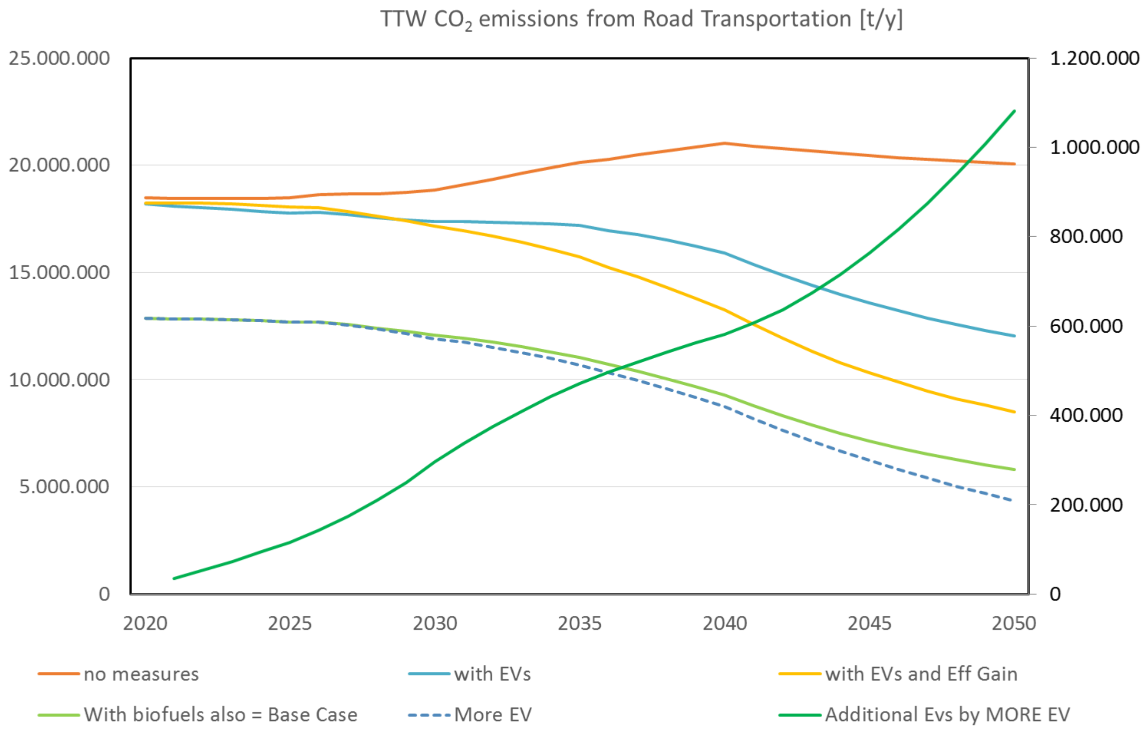

Figure 37: TTW CO_2 emissions in road transport by different measures for Sweden in the MORE EV scenario.

Germany

The MORE EV scenario for Germany was developed mostly by favoring plug-in hybrid (PHEV) cars, mainly with SI engine, over normal, non-chargeable hybrids (HEV) that in the Current Policies scenario were supposed to have a large role. Also, pure electric cars (BEV) were given a larger market share in the MORE EV scenario. Altogether, this boosting added over 6 million xEVs to the fleet by the year 2050, which is nearly 30% more. The primary dimensions of this case are presented in Table 10, and the breakdown of the sales by powerplant and fuel options in Figure 38.

Figure 39 plots TTW CO_2 emissions resulting from applying each of the measures. Starting from the top, the lines represent: a) no measures (imaginary), b) introduction of EV's, c) adding improvements in energy efficiency, d) adding biofuels according to the Current Policies scenario, and finally, e) boosting xEV sales from the base case according to this MORE EV scenario as a dashed line. A separate line in the graph shows the number of additional xEVs introduced by the boosted scenario.

By this increased electrification, 0.7 Mt reduction in CO_2 emissions was achieved by the year 2030, 1.6 Mt by 2040, and 4.9 Mt by the year 2050, representing about 8% further reduction from the Current Policies case on that year.

Table 10: Main results of the MORE EV scenario for Germany.

MORE EV, GERMANY	**2020**	**2030**	**2040**	**2050**
Total energy use in road transport, ktoe	54,435	44,827	32,670	23,237
Share of fossil fuels, %	94 %	92 %	87 %	77 %
EV share in passenger car fleet, %	0.8 %	9.3 %	31 %	59 %
EV numbers, 1000 units	354	4,478	14,776	28,077
Share of electricity, % of total transportation energy	0.10 %	1.5 %	6.4 %	16 %
Amount of fuels replaced by electricity, ktoe	56	1,846	2,084	3,695
Share of biofuels, %	6.1 %	6.0 %	6 %	7 %
Amount of biofuels, ktoe	3,298	2,691	2,018	1,621
CO_2 emissions, Mt	151.7	123.1	84.8	53.2

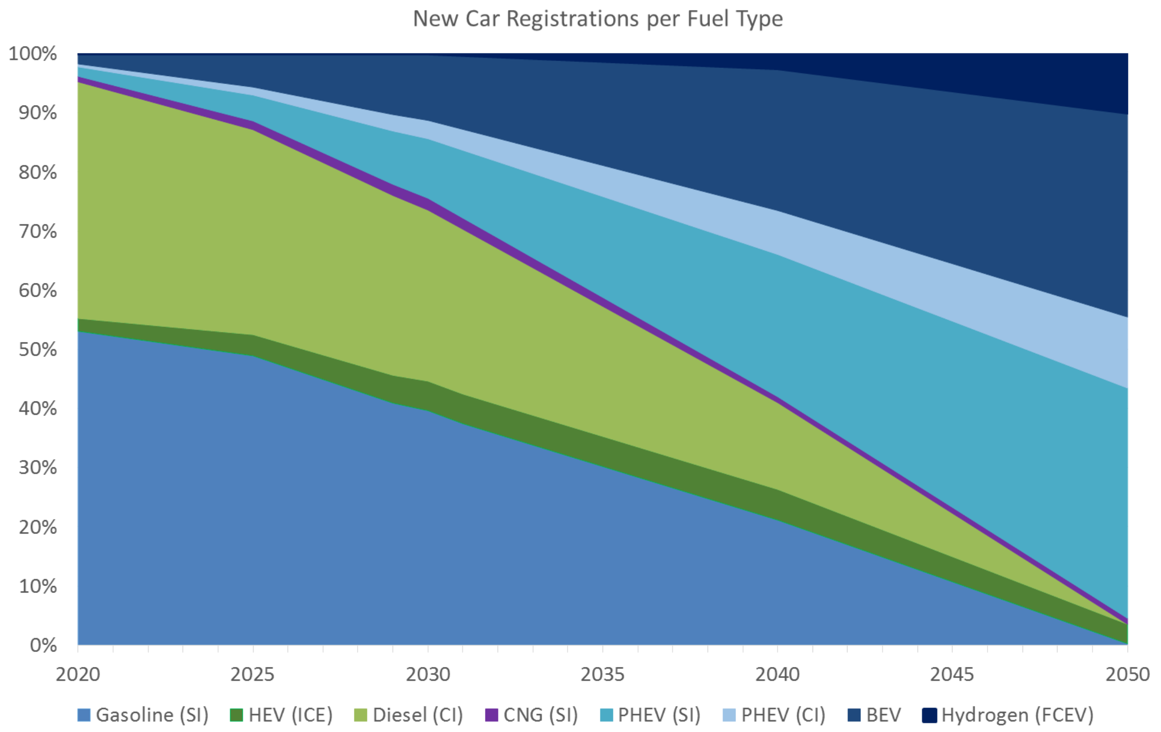

Figure 38: Breakdown of new car sales by powertrain options for Germany in the MORE EV scenario.

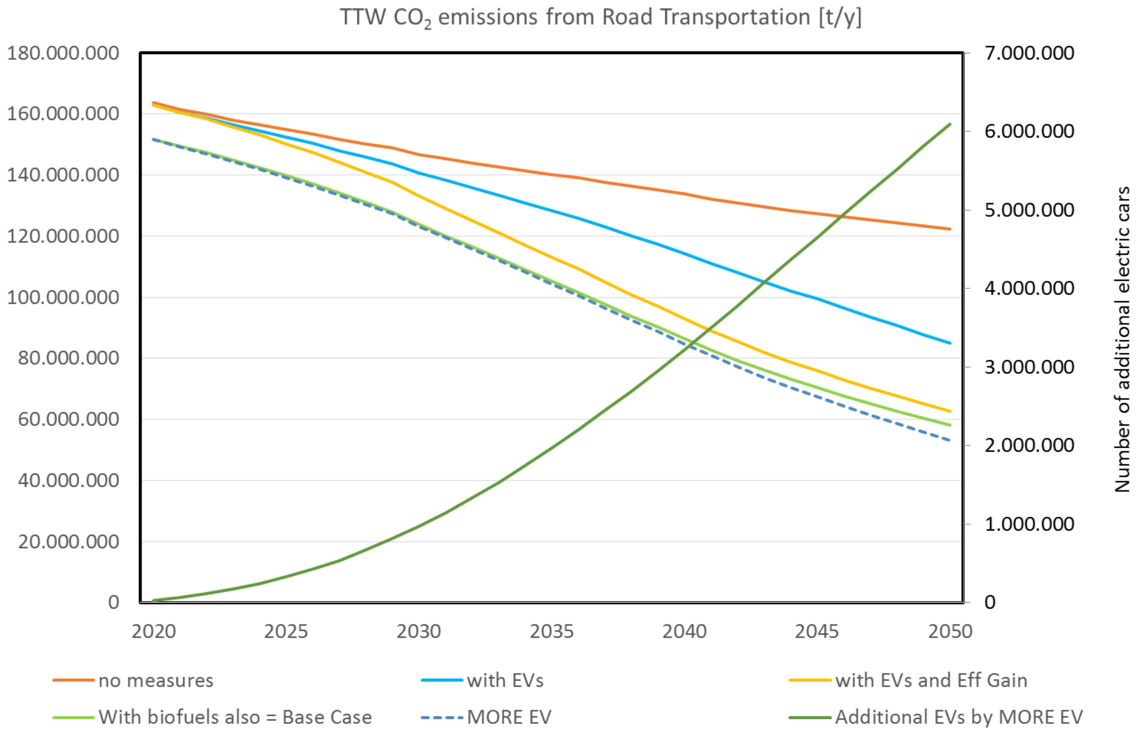

Figure 39: TTW CO_2 emissions in road transport by different measures for Germany in the MORE EV scenario.

Brazil

For Brazil, the boosted MORE EV scenario was constructed by favoring battery-electric vehicles (BEV) over non-chargeable vehicles, and reducing effectively the sales of ICE-powered cars using gasoline, and especially those using diesel. These increased sales brought nearly 18 million BEVs to the fleet by the year 2050, which represents nearly 200% increase. The basic figures of this case are presented in Table 11, and the breakdown of the sales by powerplant and fuel options in Figure 40.

Figure 41 plots TTW CO_2 emissions resulting from applying each of the measures. Starting from the top, the lines represent: a) no measures (imaginary), b) introduction of EV's, c) adding improvements in energy efficiency, d) adding biofuels according to the Current Policies scenario, and finally, e) boosting xEV sales from the base case according to this MORE EV scenario as a dashed line. A separate line in the graph shows the number of additional xEVs introduced by the boosted scenario.

With this boost in electrification, 1.7 Mt reduction in CO_2 emissions was accomplished by the year 2030, 7.5 Mt by 2040, and 31.1 Mt by the year 2050, being about a 5% additional decrease from the Current Policies case on that given year.

Table 11: Main results of the MORE EV scenario for Brazil.

MORE EV, BRAZIL	2020	2030	2040	2050
Total energy use in road transport, ktoe	76 749	98 044	126 520	123 665
Share of fossil fuels, %	75 %	69 %	70 %	71 %
EV share in passenger car fleet, %	0.0 %	1.3 %	5.4 %	19.4 %
EV numbers, 1000 units	0	575	3 988	17 779
Share of electricity, % of total transportation energy	0.01 %	0.11 %	0.4 %	1.4 %
Amount of fuels replaced by electricity, ktoe	10	109	568	1 781
Share of biofuels, %	25 %	30 %	30 %	28 %
Amount of biofuels, ktoe	19 274	28 957	37 565	34 568

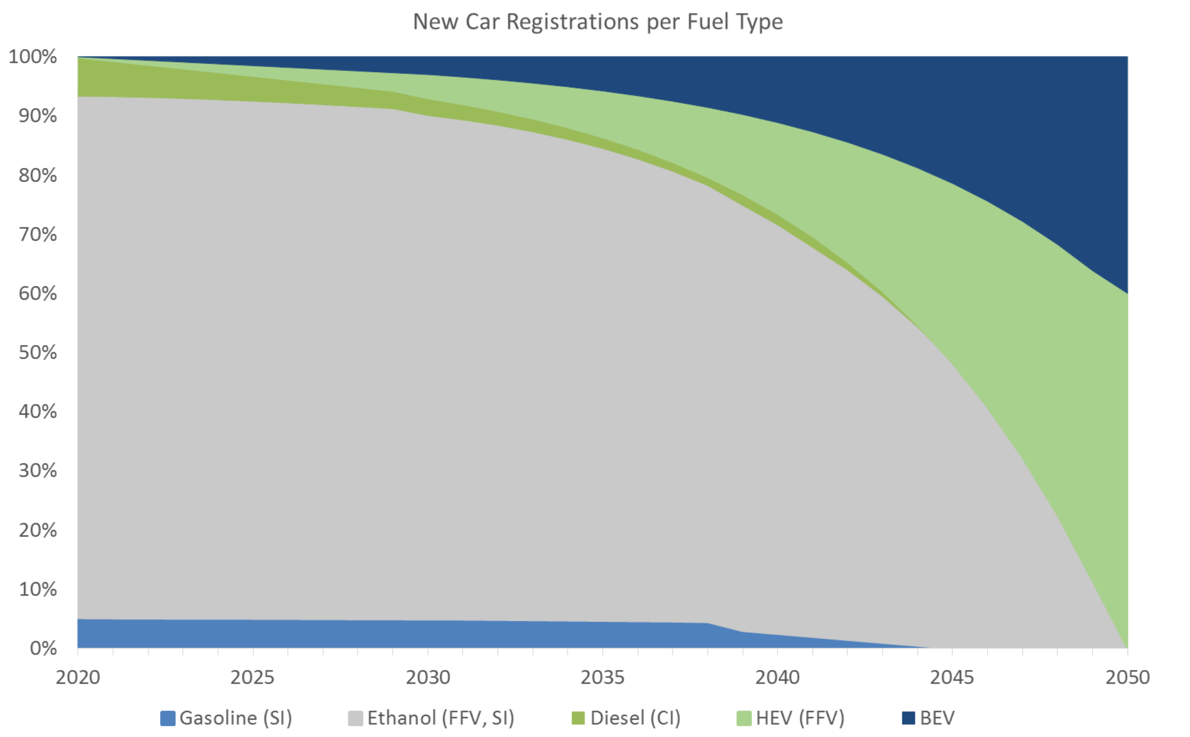

Figure 40: Breakdown of new car sales by powertrain options for Brazil in the MORE EV scenario. For Brazil the projections only include HEV flex, excluding PHEV (SI and CI).

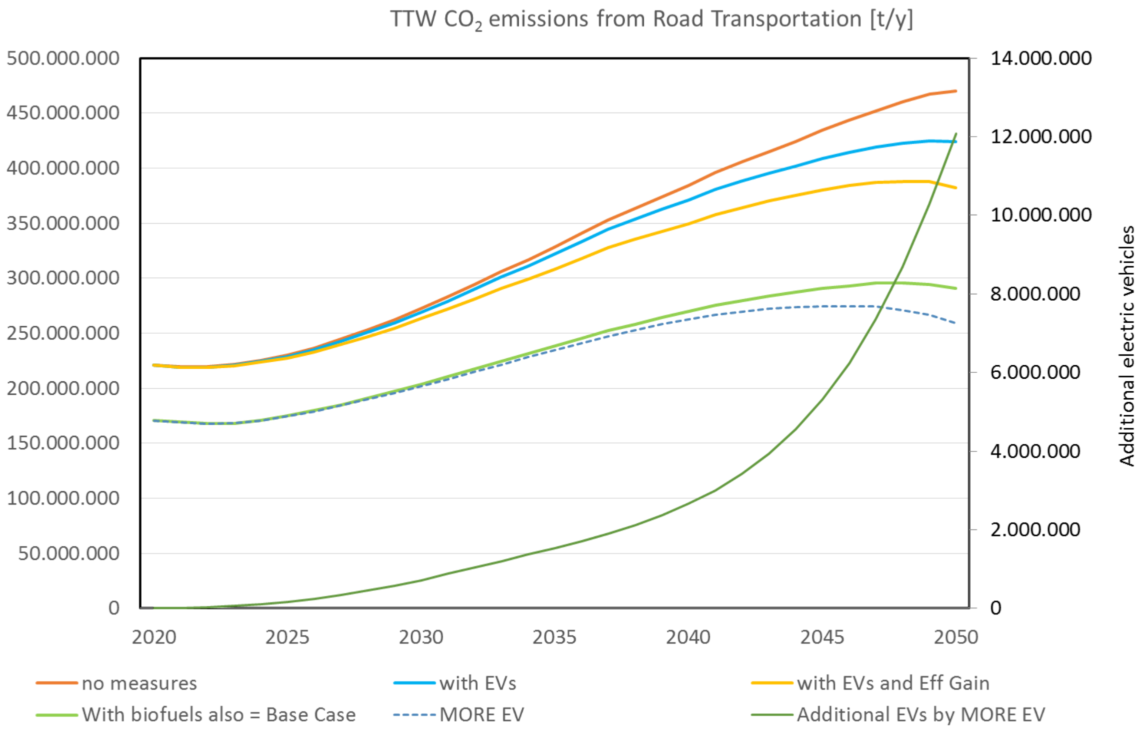

Figure 41: TTW CO_2 emissions in road transport by different measures for Brazil in the MORE EV scenario.

Results for the MAX BIO scenarios

The MAX BIO scenarios illustrate the potential impact that biofuels could have, if introduced up to technical maximum in the projected national fleet. This includes maximizing the use of renewable diesel in compression ignited (CI) engines, applying E25 and E30 in all spark ignited (SI) engines as well as utilizing so-called biopetrol in Sweden, and using E100 in Brazilian flex-fuel vehicles.

As a result, TTW CO_2 emissions can be decreased significantly by 2050. Countries with options to fully substitute both fossil gasoline and fossil diesel can be fully decarbonized by 2050.

The main diesel replacement is renewable diesel, and a comparison with currently produced renewable diesel quantities globally shows that fully displacing fossil diesel with renewable diesel is not possible for Brazil. However, if production capacities rise to the levels required for meeting the IEA´s 2DS scenario, sufficient amount of biofuel could be available.

As already described in the methodology section, to illustrate the impact of additional biofuels use, scenarios called MAX BIO were created. Their common idea was to assess how much additional biofuels the vehicle fleet would technically allow to be implemented, and what implication it would have on CO_2 emissions, if such amounts would be available and could be put in use. The MAX BIO scenarios also intend to provide an outlook on how much different biofuel types (ethanol, biodiesel, renewable diesel, biomethane) could be applied.

Finland

Finland has mandated by law that suppliers of liquid transportation fuels must deliver biofuels (neat or blended in) at a level that raises from the current level (appr. 20%) to 30% by the year 2029, and stays on that level afterwards. This ruling with the expected advances in fleet electrification and expected gain in energy efficiency leads to a situation in which the need for biofuels would be greatest at 2029 to 2030, and then the absolute amount would slowly diminish, as the gain in efficiency and increase in electrification will decrease the need for fuels.

However, there is a strong political ambition to make road transport fossil free by 2045, and MAX BIO is built around that target. Thus, both the shares of renewable diesel as well as biomethane are set to grow from the values of 2030 up to 100% by 2045, and remain at that level. However, the Finnish MAX BIO assumes E25 gasoline (and cars compatible with it) to enter the market, so that after 2040, all SI-ICE could use E25, raising the bio-contents in gasoline to nearly 19%. Therefore, the fleet cannot reach 100% renewable level, as about

50% of the fleet in 2045 are still SI-ICE powered cars that run on gasoline. To make the fleet totally fossil free, about 600 to 700 ktoe of "biopetrol" would be needed.

Table 12 summarizes the main elements and outcomes of the MAX BIO scenario for Finland. It shows that compared to the Current Policies case, this MAX BIO yields to additional lowering of CO_2 emissions, amounting to 2.3 Mt by the year 2040 and 2.7 Mt by the year 2050 compared to Current Policies case. Emissions for 2030 remain unchanged as the current policy is already quite ambitious. Maximizing the use of biofuels would allow Finland to reach a reduction of CO_2 emissions of 38% in 2030, 70% in 2040, and 85% in 2050 compared to the official base year (2005).

Figure 42 portrays the fuel mix and Figure 43 breaks down the corresponding TTW CO_2 emissions per vehicle category, according to this MAX BIO scenario.

Finally, Figure 44 shows the emissions resulting from applying each of the measures. Starting from the top, the lines represent a) no measures (imaginary), b) introduction of EV's, c) adding improvements in energy efficiency, d) adding biofuels according to Current Policies scenario, and e), adding as much biofuels as technically possible according to this MAX BIO scenario.

Table 12: Main results of the MAX BIO scenario for Finland.

MAX BIO, FINLAND	2020	2030	2040	2050
Total energy use in road transport, ktoe/yr	4,020	3,631	3,059	2,747
Share of fossil fuels, %	86 %	67 %	54 %	38 %
EV share in passenger car fleet, %	1.5 %	12 %	29 %	49 %
EV numbers, 1000 units	41	349	851	1,555
Share of electricity, % of total transportation energy	0.24 %	2.9 %	10 %	20 %
Amount of fuels replaced by electricity, ktoe	10	105	295	552
Share of biofuels, %	14 %	30 %	52 %	59 %
Amount of biofuels, ktoe	547	1,099	1,613	1,642
CO_2 emissions, Mt	10.3	7.3	3.5	1.8

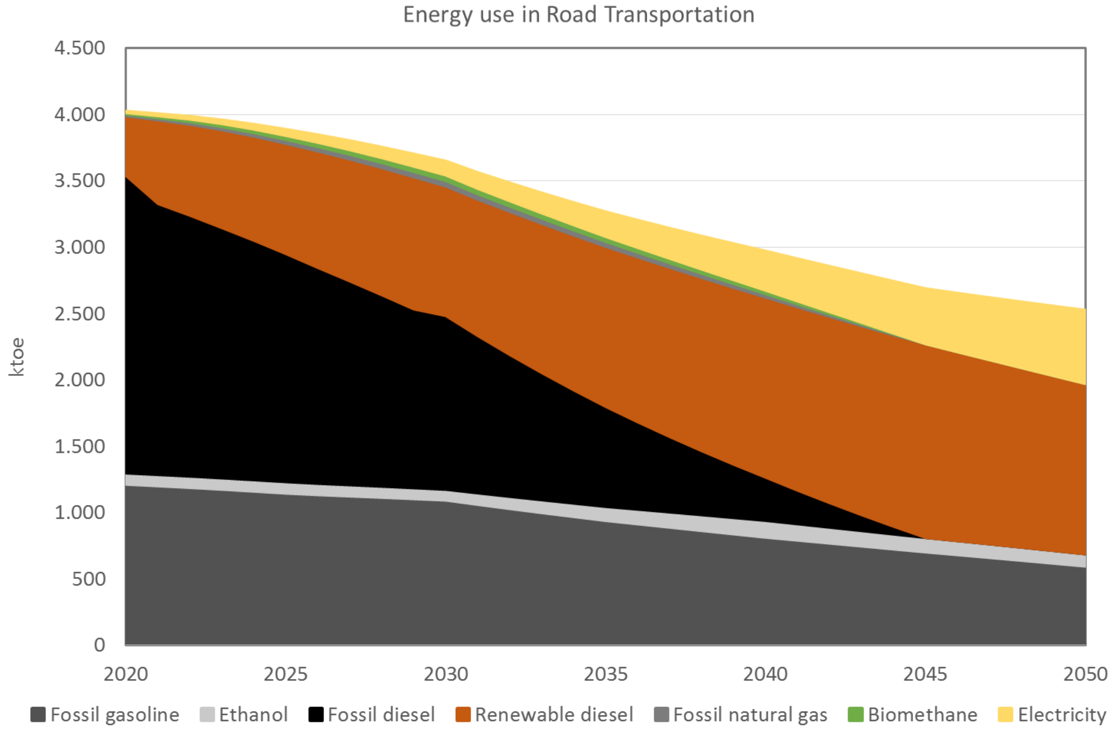

Figure 42: Energy use in road transport by energy carrier for Finland in the MAX BIO scenario.

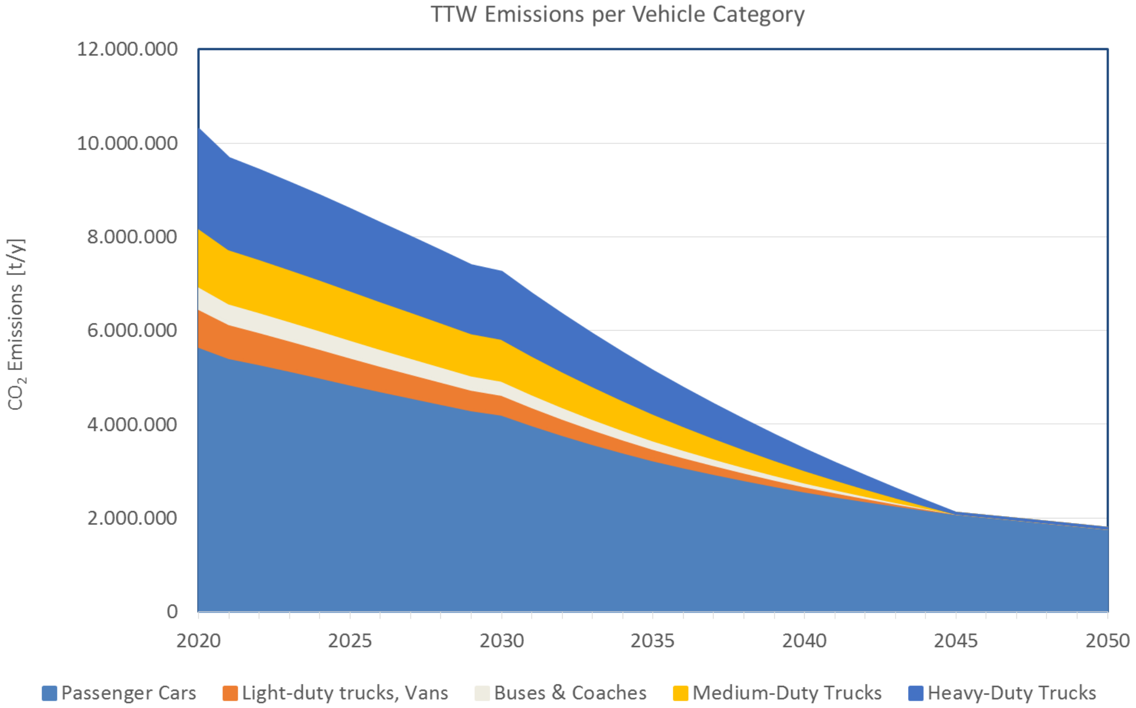

Figure 43: TTW CO_2 Emissions in road transport by vehicle category for Finland in the MAX BIO scenario.

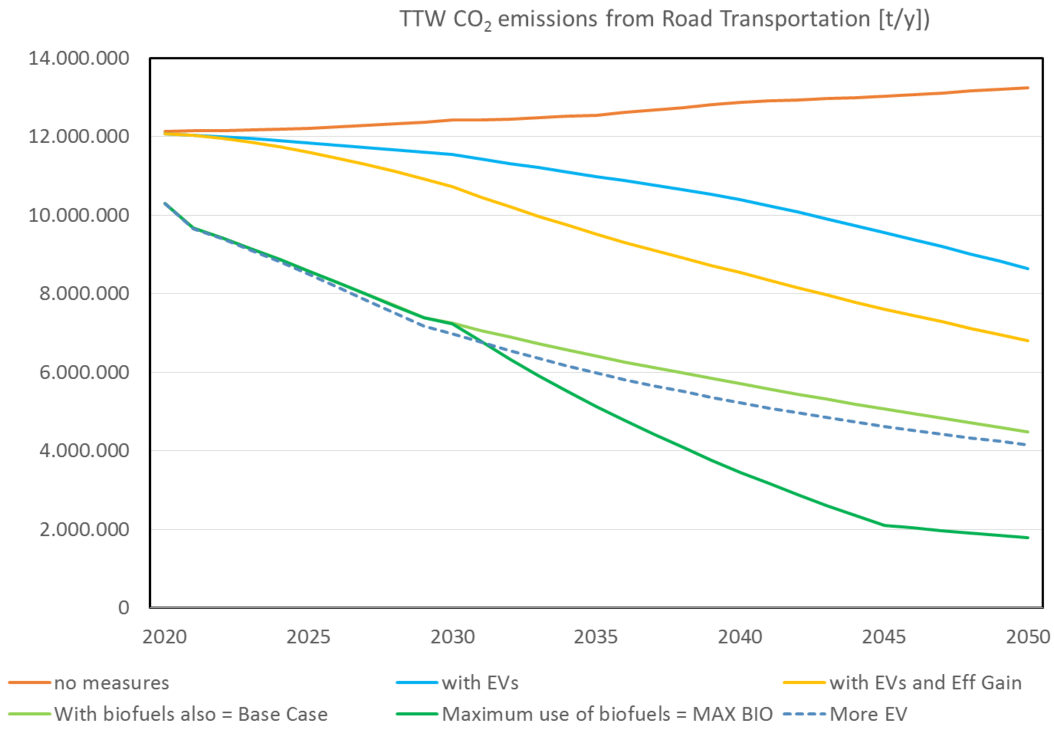

Figure 44: TTW CO_2 emissions evolution by different measures in road transport for Finland in the MAX BIO scenario

Sweden

Sweden had already developed a more ambitious scenario for implementing biofuels over the current policies, and this was used as the basis for the Swedish MAX BIO scenario. This scenario includes also the use of “biopetrol” or “renewable petrol” that would be produced with similar processes as the current pool of renewable diesels. In the Swedish scenario, biopetrol is expected to reach a 25% share of gasoline use in 2030. Technically, this kind of fuel is possible, but currently, there is no targeted production. Only some residuals of the renewable diesel manufacture are of similar molecular structure than those of gasoline are produced, but not used as motor fuels.

In the Swedish MAX BIO scenario, we assumed that this amount (437 ktoe) of “biopetrol” in 2030 would be kept at the same level until 2050, thereby replacing increasingly higher shares of fossil gasoline, as the total use of gasoline simultaneously diminishes due to advances in energy efficiency and electrification.

Table 13 summarizes the main elements and outcomes of the MAX BIO scenario for Sweden. The figures show that compared to the Current Policies case, this MAX BIO results in very effective reductions in CO_2 emissions. By 2030 the reduction is 5.3 Mt, 6.0 Mt by

2040 and 5.5 Mt by 2050, respectively, yielding to almost total elimination of fossil CO_2 emissions, amounting only to 0.3 Mt by the year 2050.

Figure 45 explores the effect of adding as much biofuels as technically possible, which means substituting all fossil diesel with renewable diesel and all fossil gasoline with biopetrol by 2050. This brings GHG emissions down to almost zero by 2050, see Figure 46.

GHG emissions from all vehicle categories decrease to zero, also those from the truck sector that remained rather constant in the Current Policies case. However, the target of 5.7 $MtCO_{2eq}$ by 2030 cannot be met, but full decarbonization by 2050 is possible.

Figure 47 plots the emissions resulting from applying each of the measures. Starting from the top, the lines represent a) no measures (imaginary), b) introduction of EV's, c) adding improvements in energy efficiency, d) adding biofuels according to Current Policies scenario, and e), adding as much biofuels as technically possible according to this MAX BIO scenario.

Table 13: Main results of the MAX BIO scenario for Sweden.

MAX BIO, SWEDEN	**2020**	**2030**	**2040**	**2050**
Total energy use in road transport, ktoe	6,008	5,731	4,705	3,303
Share of fossil fuels, %	72 %	40 %	23 %	3 %
EV share in passenger car fleet, %	2.7 %	12.4 %	36 %	56 %
EV numbers, 1000 units	133	645	1,844	2,844
Share of electricity, % of total transportation energy	0.36 %	2.4 %	8.5 %	17 %
Amount of fuels replaced by electricity, ktoe	21	135	398	553
Share of biofuels, %	28 %	58 %	68 %	81 %
Amount of biofuels, ktoe	1,656	3,325	3,221	2,664
CO_2 emissions, Mt	12.9	6.7	3.3	0.3

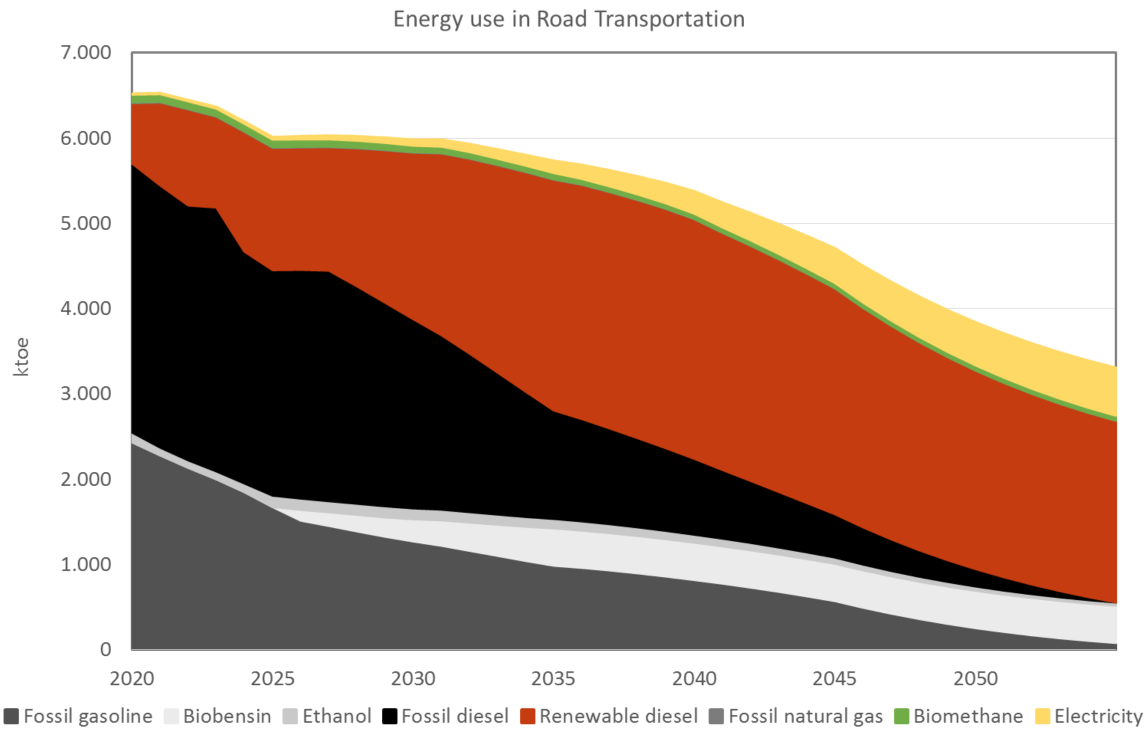

Figure 45: Energy use in road transport by energy carrier for Sweden in the MAX BIO scenario.

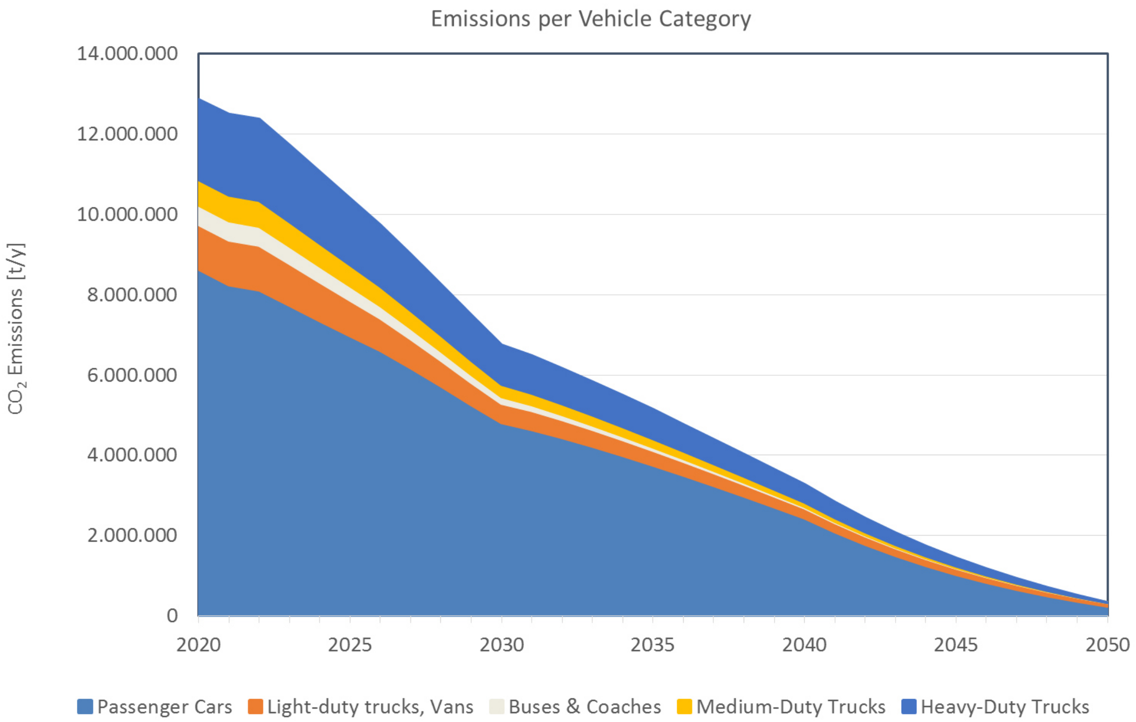

Figure 46: TTW CO_2 emissions in road transport by vehicle category for Sweden in the MAX BIO scenario.

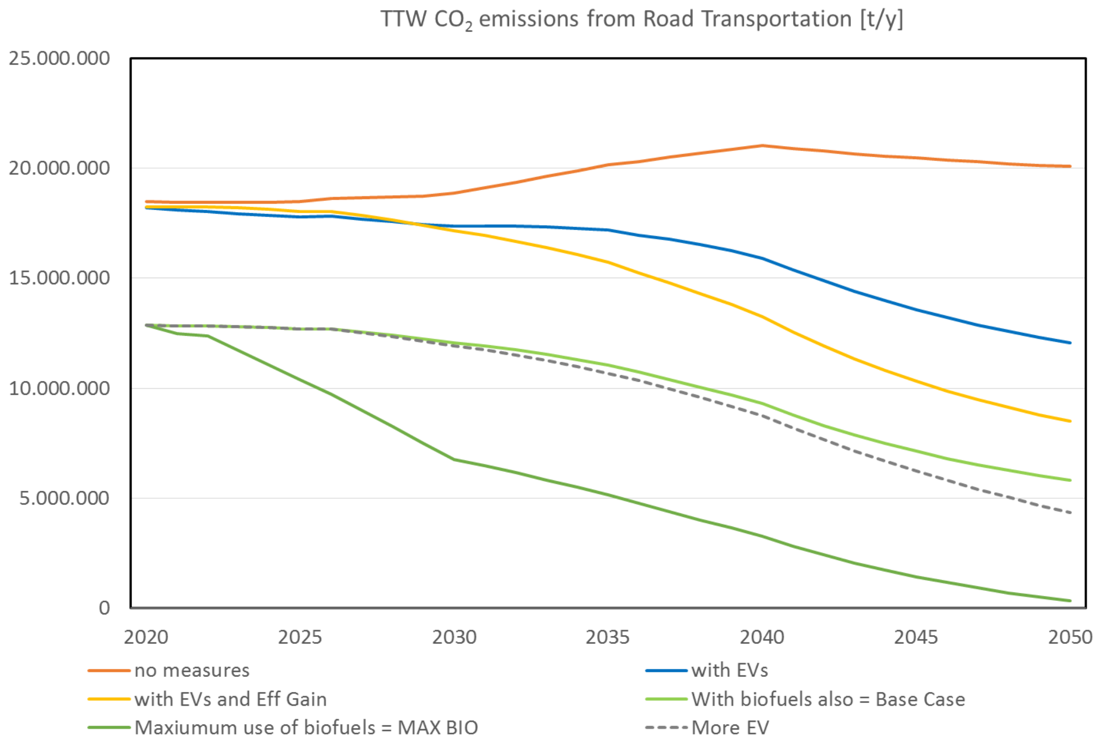

Figure 47: TTW CO_2 emissions evolution by different measures in road transport for Sweden in the MAX BIO scenario.

Germany

For Germany there was no pre-existing scenario for implementing more biofuels than what was expected in the Current Policies case. As the diesel pool is heavily dominant in Germany regarding the energy mix used in road transport, the main scheme in the MAX BIO scenario was to gradually increase the share of renewable diesel, until it reaches 100% by the year 2050. In addition, the use of ethanol was boosted, assuming that E25 and E30 fuels would become available at the marketplace and compatible vehicles should follow.

Table 14 summarizes the main characteristics and outcomes of this this MAX BIO scenario, and Figure 48 presents the breakdown of the total road transport energy use to different carriers. The share of biofuels is increased quite forcefully, as by 2030 the biofuels share is 29%, which is an almost five-fold increase compared to the Current Policies case. Furthermore, in 2040 biofuels are assumed to represent half of the total energy use, which is nearly about eight times the basic assumption (6%). Eventually, by the year 2050 share of biofuels would be 65%, which is over nine times the status of the Current Policies case.

The achieved reductions in CO_2 emissions are also quite apparent. For the year 2030 the calculated CO_2 is 93 Mt, signifying a 25% reduction from the base case, and which is in the range of the target of 95 Mt CO_{2eq}. For 2040 the figure 43.6 Mt indicates a 50% reduction, and subsequently for the year 2050, the estimated emissions of just 15.4 Mt denote a 74% reduction.

The strong effect that this increased use of biofuels has upon CO_2 emissions is clearly illustrated in Figure 50 that plots the CO_2 emissions calculated by the ALIISA model for different cases and combinations of measures. Compared to the plot of the MORE EV scenario, drawn as a dashed blue line, the MAX BIO case achieves stellar reductions. However, we must bear in mind that the amounts of renewable diesel that are needed to fulfil the demand of this case are so large that even the current world-wide supply and refining capacities are not sufficient, given the fact that more countries and other sectors in transportation like aviation are seeking strong upsurge in use of renewable diesel fuel. (See chapter Resource Considerations for further deliberation.)

Table 14: Main results of the MAX BIO scenario for Germany.

MAX BIO, GERMANY	**2020**	**2030**	**2040**	**2050**
Total energy use in road transport, ktoe	54,424	44,778	32,988	25,266
Share of fossil fuels, %	92 %	70 %	44 %	20 %
EV share in passenger car fleet, %	0.7 %	7.3 %	24 %	46 %
EV numbers, 1000 units	328	3,507	11,560	21,981
Share of electricity, % of total transportation energy	0.10 %	1.3 %	5.3 %	12.4 %
Amount of fuels replaced by electricity, ktoe	55	572	1,763	3,121
Share of biofuels, %	7.6 %	29 %	50 %	65 %
Amount of biofuels, ktoe	4,119	12,932	16,408	16,341
CO_2 emissions, Mt	149.2	93.0	43.6	15.4

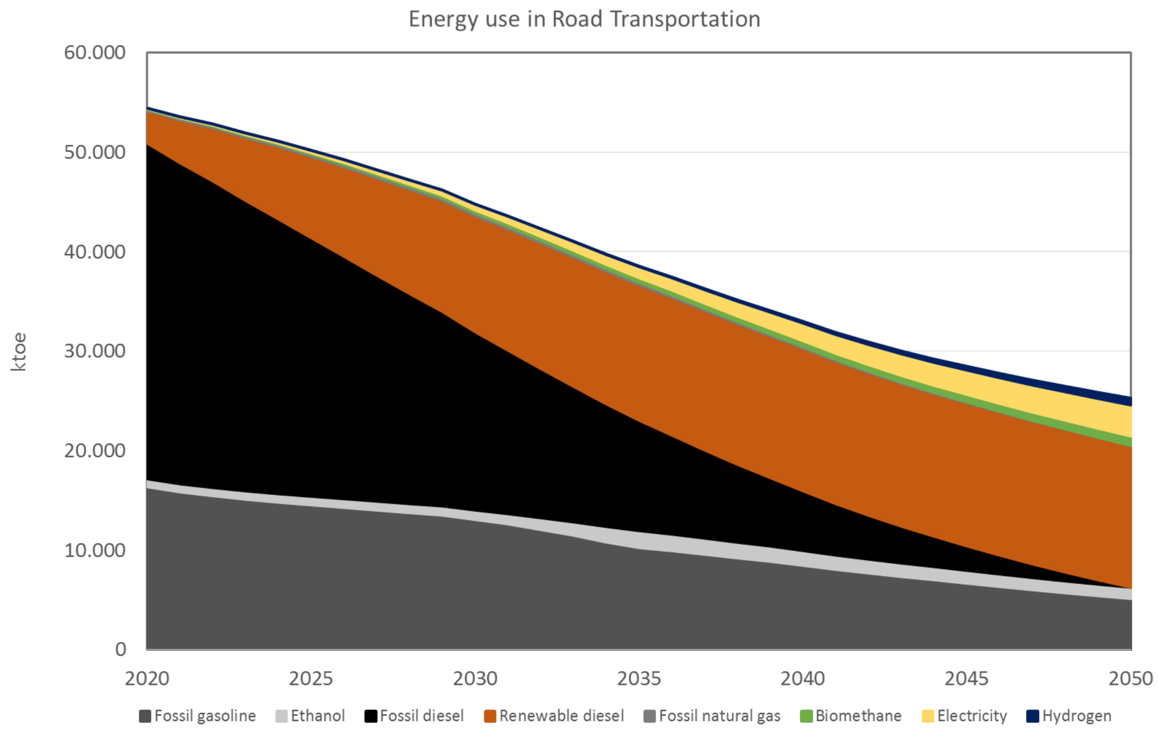

Figure 48: Energy use in road transport by energy carrier for Germany in the MAX BIO scenario.

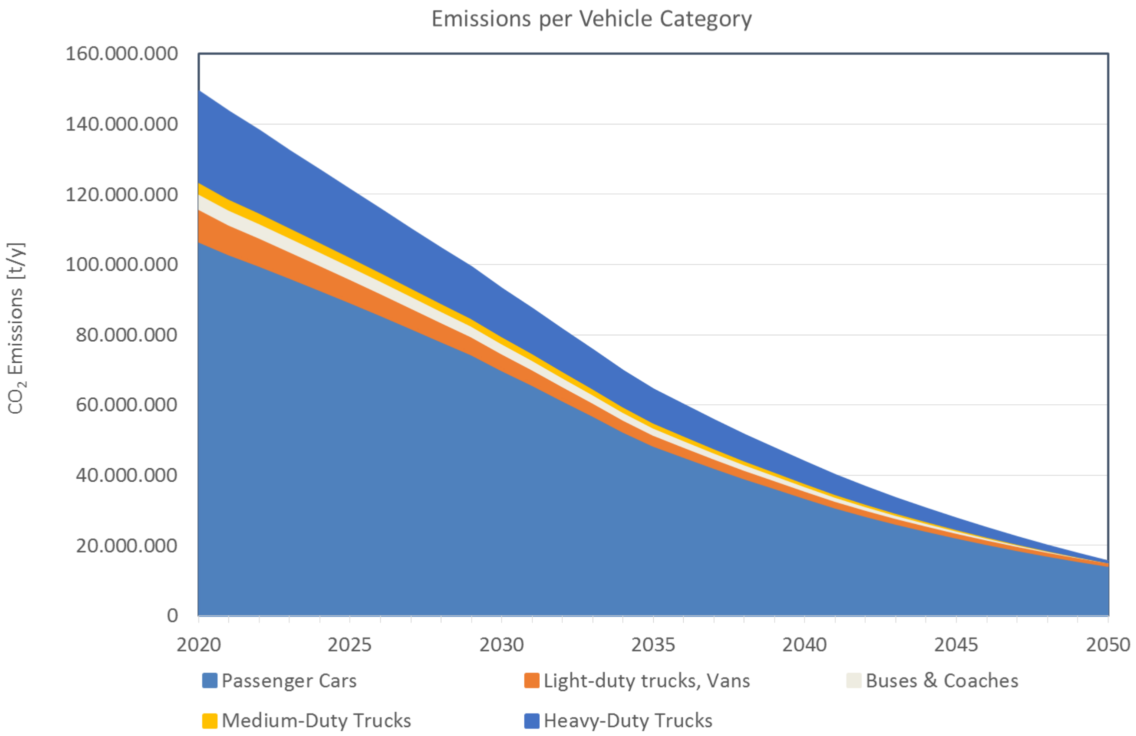

Figure 49: CO_2 emissions in road transport by vehicle category for Germany in the MAX BIO scenario.

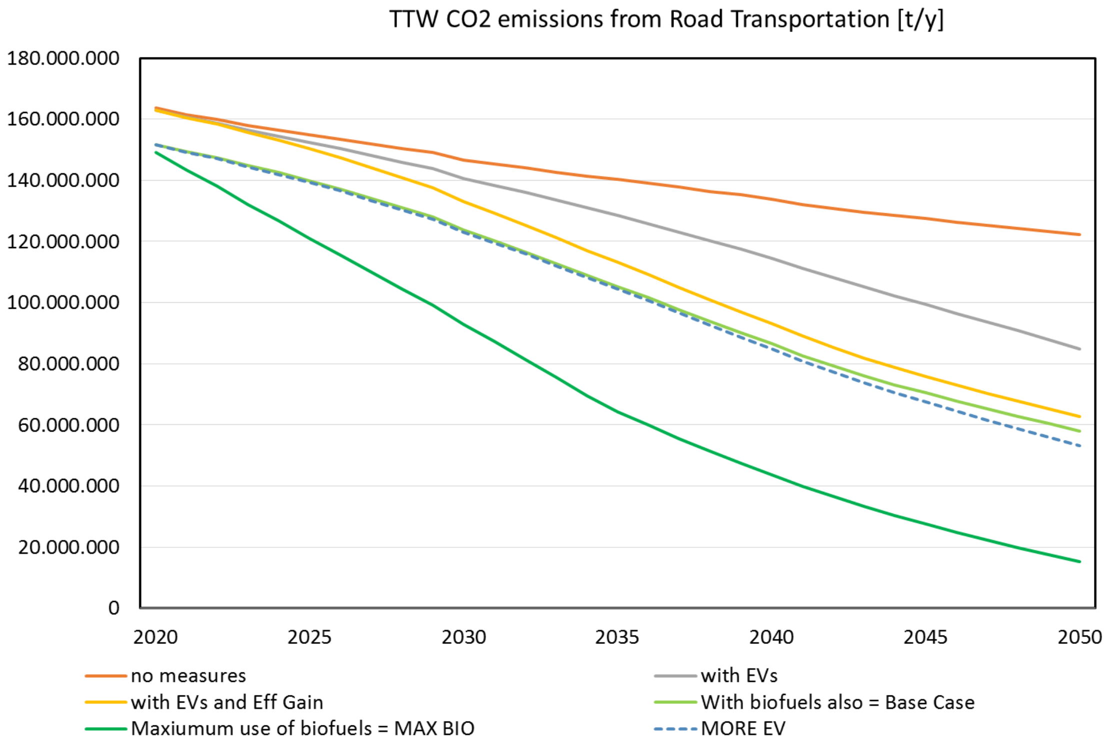

Figure 50: TTW CO_2 emissions evolution by different measures in road transport for Germany in the MAX BIO scenario.

Brazil

Also for Brazil, there was no pre-existing scenario for using more biofuels than what was anticipated in the Current Policies case. For this exercise the scenario for maximum use of biofuels was built upon maximizing the share of ethanol in the SI-powered passenger car fleet (mainly FFVs that could run 100% ethanol, if necessary), and displacing fossil diesel with renewable diesel fuel.

Table 15 condenses the main attributes and results of this this MAX BIO scenario, and Figure 51 portrays the total road transport energy use split to different products. In this scenario, the share of biofuels is increased very effectively, as in the Current Policy case the share of biofuels was assumed to remain at about 25% of the total energy expenditure over the period of 2030 to 2050. However, in the MAX BIO case by 2030 the biofuels share is 54%, almost double the share in the Current Policies case. Furthermore, in 2040, biofuels are assumed to supply 83% of the total energy use, which is more than triple the basic assumption. Finally, by the year 2050 share of biofuels would be 95%, which is over three times the status of the Current Policies case.

Likewise, the calculated reductions in CO_2 emissions are also very evident. For the year

2030 the calculated CO_2 emissions are 128 Mt, signifying a 41% reduction from the base case. For 2040 the figure of 56 Mt designates a vast 80% reduction, and successively for the year 2050, the projected fossil tank-to-wheel (TTW) CO_2 emissions are declined to zero.

The very potent outcome that this multiplied use of biofuels has on CO_2 emissions is distinctly seen in Figure 53 that presents the CO_2 emissions computed for the three study cases. Contrasted to the outline of the MORE EV scenario, presented as a dashed blue line, the MAX BIO case achieves extensive cutbacks. Yet, we need to consider the limited availability of renewable diesel, even if enough ethanol would be available to meet the projected need. (See chapter Resource Considerations for further deliberation.)

Table 15: Main results of the MAX BIO scenario for Brazil.

MAX BIO, BRAZIL	**2020**	**2030**	**2040**	**2050**
Total energy use in road transport, ktoe	76 377	99 300	134 583	173 634
Share of fossil fuels, %	57 %	34 %	17 %	2 %
EV share in passenger car fleet, %	0.0 %	0.0 %	1.8 %	6.2 %
EV numbers, 1000 units	0	0	1 333	5 696
Share of electricity, % of total transportation energy	0.02 %	0.10 %	0.4 %	1.0 %
Amount of fuels replaced by electricity, ktoe	15	107	568	1 804
Share of biofuels, %	43 %	66 %	82 %	97 %
Amount of biofuels, ktoe	33 009	65 173	111 025	168 309
CO_2 emissions, Mt	128	101	68	11

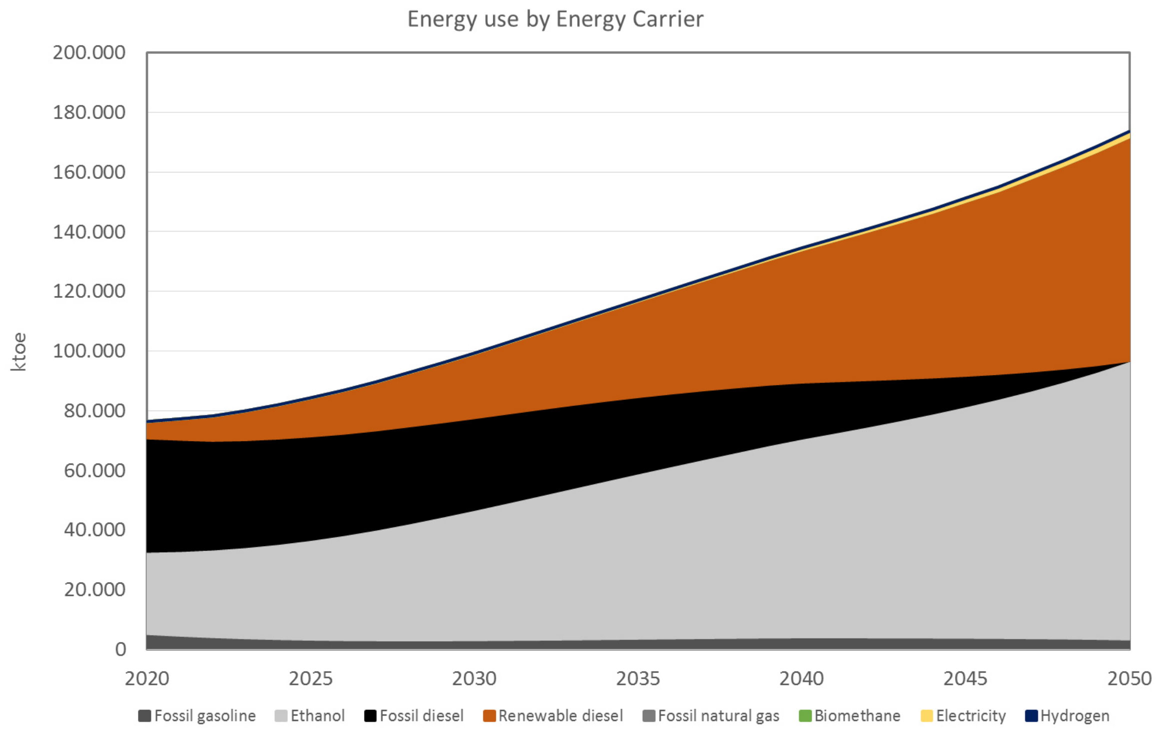

Figure 51: Energy use in road transport by energy carrier for Brazil in the MAX BIO scenario.

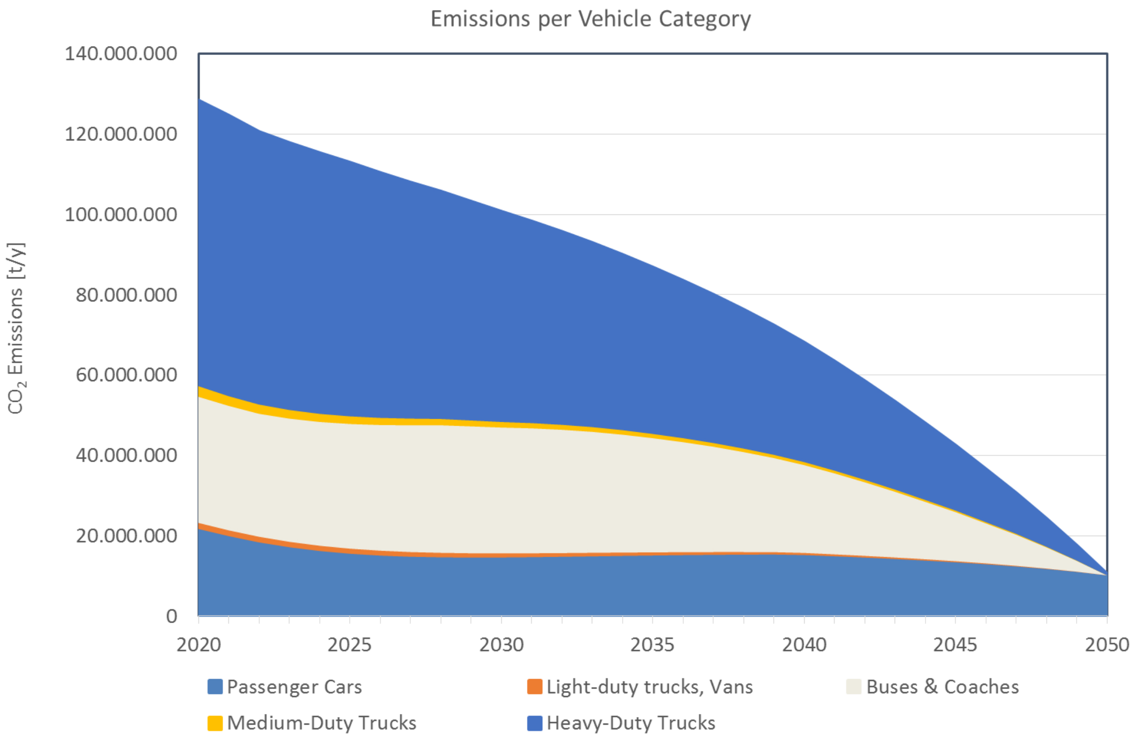

Figure 52: CO_2 Emissions in road transport by vehicle category for Brazil in the MAX BIO scenario.

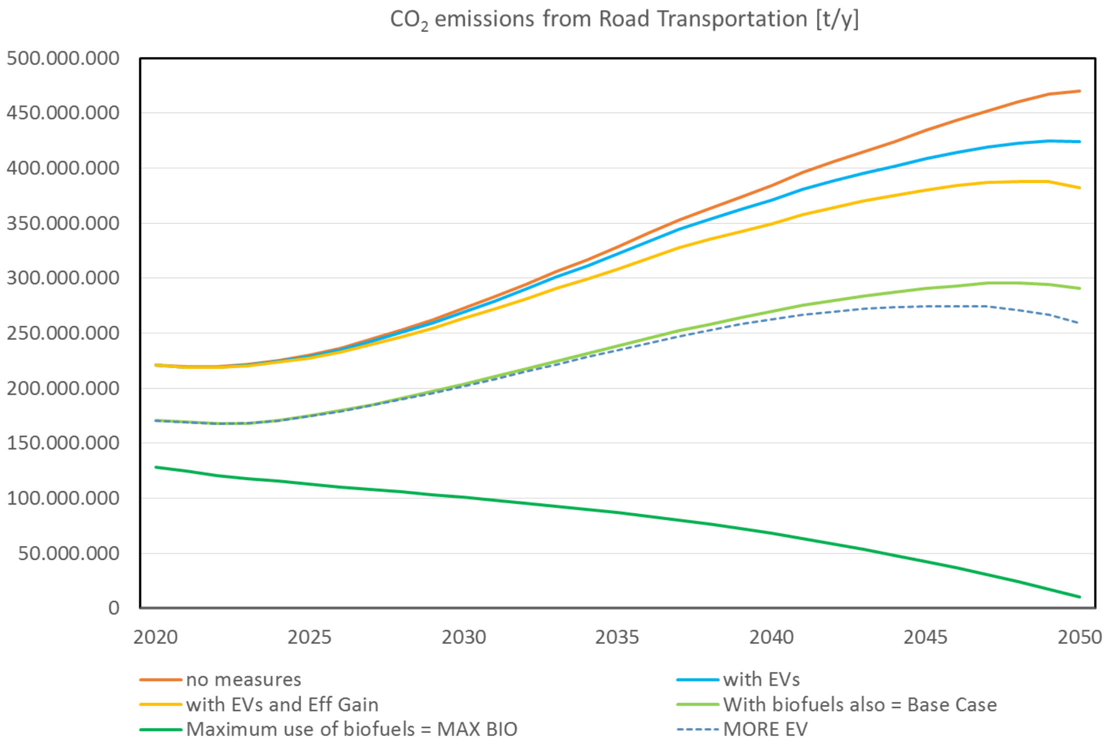

Figure 53: TTW CO_2 emissions evolution by different measures in road transport for Brazil in the MAX BIO scenario.

Resource considerations

The total 2050 national demands for drop-in hydrocarbons to replace diesel in the MAX BIO scenarios are illustrated for each country in Figure 54. These demand estimates are contrasted with the estimate for global advanced biofuels supply from the IEA's 2DS scenario.

The combined 2050 demand of drop-in hydrocarbons to replace diesel in the MAX BIO scenarios for Finland, Sweden and Germany could be supplied from the advanced biofuels production capacity available already today. However, the current total global supply of advanced biofuels is currently only 30% of Brazil's 2050 demand for drop-in hydrocarbons to replace diesel in the MAX BIO scenario. It should be noted that if the supply of advanced biofuels will develop in line with the IEA 2DS estimate, the global supply will surpass 100 Mtoe/yr before 2030 and 500 Mtoe/yr before 2050. It is important to emphasize that Brazil has very favorable conditions for agricultural production and, therefore, it is estimated that a large amount of fossil fuels could be replaced by biofuels. This would make advanced biofuels a realistic option for significantly reducing transport emissions even for the largest countries.

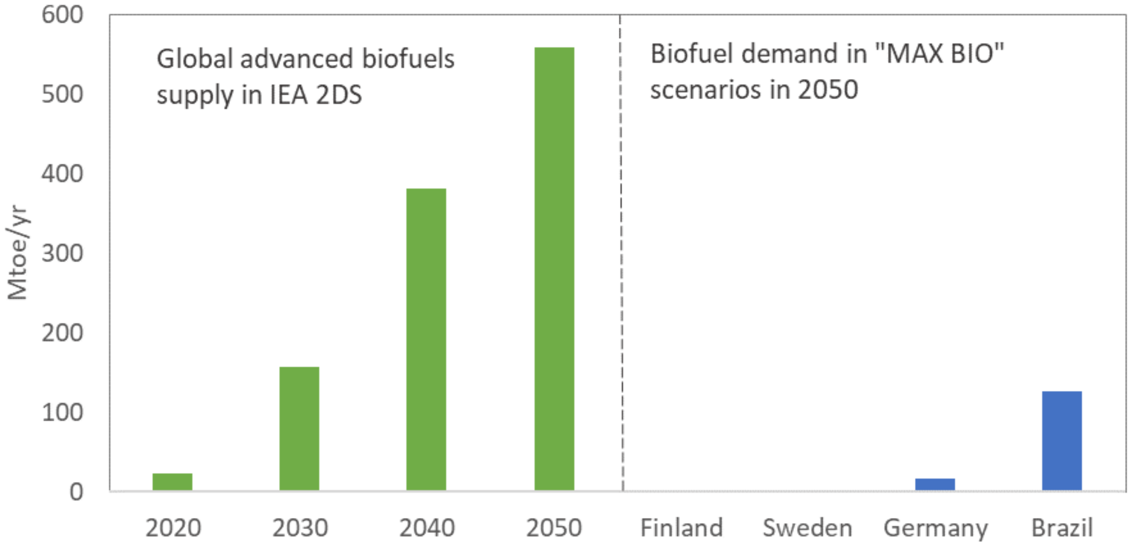

Figure 54: Country specific demand for drop-in hydrocarbons to replace diesel in 2050 relative to IEA global 2DS supply scenario.

Results for the E-FUELS scenarios

E-FUELS scenarios are based on the Current Policies scenarios, sharing the same energy efficiency gains, amount of electric vehicles, and supply of biofuels, but adding e-gasoline, e-diesel, e-methane, and for the Germany case also e-hydrogen. The introduction of e-fuels begins in 2030 and increases linearly to reach 100% substitution of fossil fuels by 2050.

The WTW CO_2 emissions of e-fuels depend strongly on the carbon intensity of electricity used in their production. Fuels produced using today's average grid electricity have lower WTW CO_2 emissions than fossil fuels in Sweden and Finland, are similar to fossil fuels in Brazil, but remain significantly higher in Germany. Problems imposed by high-carbon electricity grids can be circumvented by connecting the production plants directly to low-carbon electricity generators (e.g. wind turbines or PV panels), but this ties fuel production to the capacity factor of the power source, leading to higher costs.

Similar to biofuels, available resources for the supply of significant quantities of e-fuels are currently being debated. While current industrial CO_2 emissions seem to be sufficient for the required production of e-fuels for Finland, Sweden and Germany, the Brazilian 2050 demand in the E-FUELS scenario would surpass the current availability of CO_2 from industrial point sources by almost three times. If the industrial sector will be successfully decarbonized towards mid-century, the availability of CO_2 might become a constraint for the widespread production of e-fuels. With respect to non-fossil electricity production, Finland and Sweden seem to have sufficient generation capacity already today to support the 2050 demand, but Germany and Brazil would face severe constraints in the supply of essentially carbon-free electricity. In addition, asking such substantial amounts of carbon-free electricity dedicated to fuel production seem difficult to satisfy, as they come on top of existing requirements for a dramatic expansion of low-carbon generation to meet more traditional electricity demand. Maximizing the use of other decarbonization measures would therefore be an important way to decrease the demand for e-fuels and the associated need for non-fossil electricity.

Substantial reductions in the cost of wind and solar electricity during the past decade have created interest towards the production of sustainable fuels via chemical conversion of CO_2 and water, using renewable energy to drive the process.[1,2,3,4,5] A number of techno-economic studies are already available in the literature and 128 R&D projects have been realized or already finished in Europe as of May 2018.[6,7] The main application for these projects has been the injection of hydrogen or methane into the natural gas grid for storing electricity from variable renewable energy sources. Producing sustainable fuels for transport is another important application where the focus has been on synthetic methane or methanol, and both applications have already seen a megawatt-scale demonstration. A plant in Iceland produces methanol using CO_2 and electricity that are both derived from geothermal sources.[8] The production began in 2011, but in 2015 the capacity was expanded from 1.3 to 5 million liters of methanol per year. A similarly sized plant in Germany converts CO_2 from a co-located biogas facility to methane with electricity from the grid. The plant began production in 2014, and uses roughly 6 MW of electricity to produce 3.2 MW of synthetic methane.[9]

Although hydrogen, methane and methanol are all globally used commodities, their use in transport is impeded by distribution and vehicle-related barriers. Such barriers could be

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[1] Steinberg, M. Synthetic carbonaceous fuels and feedstocks from oxides of carbon and nuclear power. *Fuel* **57**, 460–468 (1978).

[2] Zeman, F.S. and Keith, D.W. Carbon neutral hydrocarbons. *Phil. Trans. R. Soc. A* **366**, 3901–3918 (2008). DOI: 10.1098/rsta.2008.0143.

[3] Dimitriou, I., Garcia-Gutiérrez, P., Elder, R.H., Cuéllar-Franca, R.M., Azapagic, A., and Allen, R.W.K.. Carbon dioxide utilisation for production of transport fuels: process and economic analysis. *Energy Environ. Sci.* **8**, 1775–1789 (2015).

[4] Abanades, J.C., Rubin, E.S., Mazzotti, M. and Herzog, H.J. On the climate change mitigation potential of CO_2 conversion to fuels. *Energy Environ. Sci.* **10**, 2491-2499 (2017).

[5] Hannula, I.; Kaisalo, N. and Simell, P. Fuels and chemicals from CO_2 via catalytic partial oxidation and Fischer-Tropsch synthesis: a conceptual and experimental study. *Carbon* **6**(3), (2020). DOI: 10.3390/c6030055.

6 Brynolf, S., Taljegard, M., Grahn, M., Hansson, J. Electrofuels for the transport sector: A review of production costs. *Renewable and Sustainable Energy Reviews* **81**(2), 1887-1905 (2018). DOI: 10.1016/j.rser.2017.05.288.

7 Wulf, C., Linßen, J. and Zapp, P., Review of Power-to-Gas Projects in Europe, *Energy Procedia* **155**, 367-378 (2018) DOI: 10.1016/j.egypro.2018.11.041.

8 http://www.carbonrecycling.is/george-olah/

9 Otten, R. (2014). The first industrial PtG plant – Audi e-gas as driver for the energy turnaround. CEDEC Gas Day Verona Italy. http://bit.ly/2zTg5kW..

overcome by focusing on the production of “drop-in” transport fuels, i.e. synthetic fuel replacements to fossil diesel, kerosene and gasoline. These fuels can be produced by post-processing methanol with a methanol-to-gasoline (MTG) process or via the well-known Fischer-Tropsch (FT) reaction.

For the purpose of this analysis, synthetic drop-in replacements for natural gas, gasoline and diesel, produced from CO_2 and water with electrical energy were investigated. In addition, fuel hydrogen was also considered in the case of Germany. The introduction of e-gasoline, e-diesel, e-methane and e-hydrogen to the national fuel pools begins in 2030 and increases from there linearly, achieving full displacement of fossil gasoline, diesel, natural gas and hydrogen by 2050. The E-FUELS scenarios are based on Current Policies, taking the remaining fossil fuel pool as a starting point. In addition to analyzing the needed scale-up in the production of e-fuels, the resulting need for electricity and feedstock CO_2 in 2050 is also calculated for each country and contrasted against currently available resources.

Finland

For Finland, the Current Policies scenario starts with 4 Mtoe/yr total road transport energy demand in 2020. Fossil gasoline, fossil diesel and natural gas account for 86% of the sector’s energy use, resulting in 10 $MtCO_2$ annual direct fossil carbon emissions. By 2050, the total energy demand is reduced by 31% to 2.8 Mtoe/yr of which biofuels account for 26% and electricity for EVs 20%.

The introduction of e-fuels begins in 2030, and the total supply increases by 66 ktoe each year until full displacement of fossil fuels is reached in 2050. The final e-fuels supply is 1.5 Mtoe/yr, representing 54% of the sector’s energy use. The corresponding electricity demand for producing the required amount of e-fuels is 43 TWh/yr and CO_2 feedstock demand is 6 Mt/yr.

Table 16: Main results of the E-FUELS scenario for Finland.

E-FUELS, FINLAND	**2020**	**2030**	**2040**	**2050**
Total energy use in road transport, ktoe/yr	4,020	3,631	3,098	2,788
Share of fossil fuels, %	86 %	65 %	37 %	0 %
Share of EV energy use, %	0 %	3 %	10 %	20 %
Share of biofuels, %	14 %	30 %	28 %	26 %
Share of e-fuels, %	0 %	2 %	25 %	54 %
Amount of e-fuels, ktoe/yr	0	66	730	1,393
CO_2 emissions, Mt	10	7	3	0
E-fuel electricity demand, TWh/yr	0	2	23	43
E-fuel CO_2 feedstock demand, MtCO2/yr	0	0	3	6

Figure 55 shows the amount of fuels and the resulting reduction in TTW CO_2 emissions.

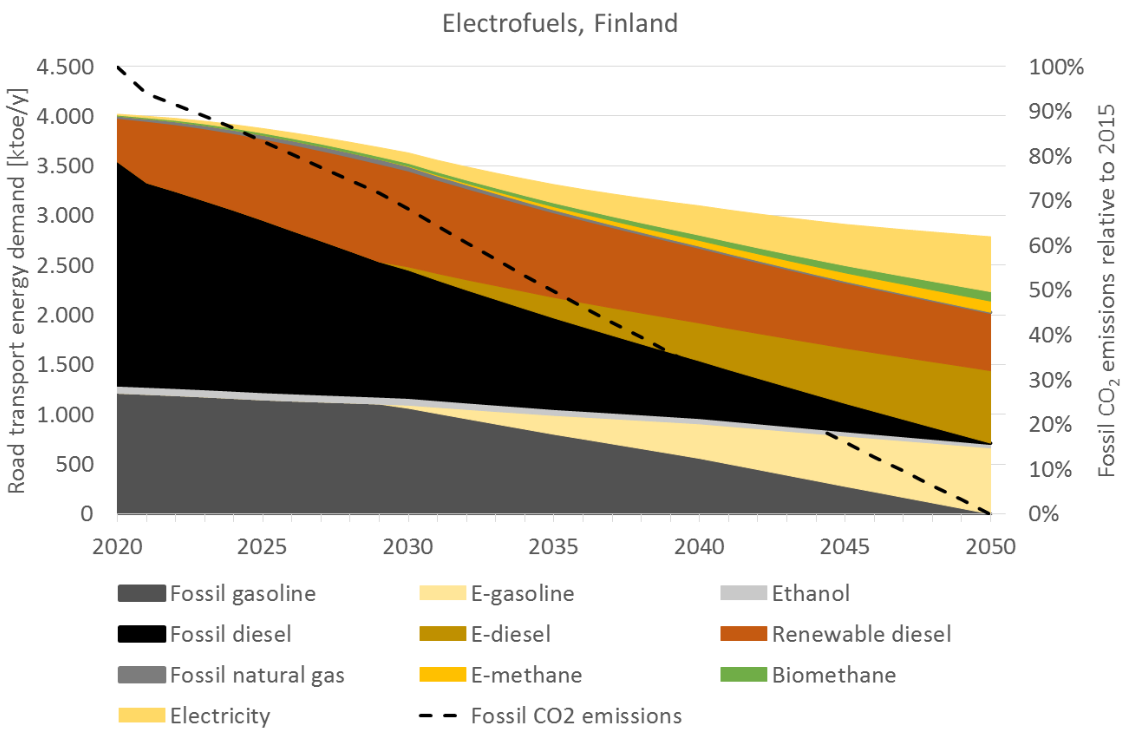

Figure 55. Energy use in road transport by energy carrier for Finland in the E-FUELS scenario.

Sweden

For Sweden, the Current Policies scenario starts with 6 Mtoe/yr total road transport energy demand in 2020. Fossil gasoline, fossil diesel and natural gas account for 76% of the sector's energy use, resulting in 14 $MtCO_2$ annual direct fossil carbon emissions. By 2050, the total energy demand is reduced by 44% to 3.4 Mtoe/yr of which biofuels account for 25% and electricity for EVs 16%.

The introduction of e-fuels begins in 2030, and the total supply increases by 93 ktoe each year until full displacement of fossil fuels is reached in 2050. The final e-fuels supply is 2.0 Mtoe/yr, representing 58% of the sector's energy use. The corresponding electricity demand for producing the required amount of e-fuels is 57 TWh/yr and CO_2 feedstock demand is 8 Mt/yr.

Table 17: Main results of the E-FUELS scenario for Sweden.

E-FUELS, SWEDEN	2020	2030	2040	2050
Total energy use in road transport, ktoe/yr	6,019	5,793	4,777	3,368
Share of fossil fuels, %	76 %	69 %	44 %	0 %
Share of EV energy use, %	0 %	2 %	8 %	16 %
Share of biofuels, %	24 %	28 %	26 %	25 %
Share of e-fuels, %	0 %	2 %	21 %	58 %
Amount of e-fuels, ktoe/yr	0	93	1,026	1,958
CO_2 emissions, $MtCO_2$/yr	14	12	6	0
E-fuel electricity demand, TWh/yr	0	3	30	57
E-fuel CO_2 feedstock demand, MtCO2/yr	0	0	4	8

Figure 56 shows the amount of fuels and the resulting reduction in TTW CO_2 emissions.

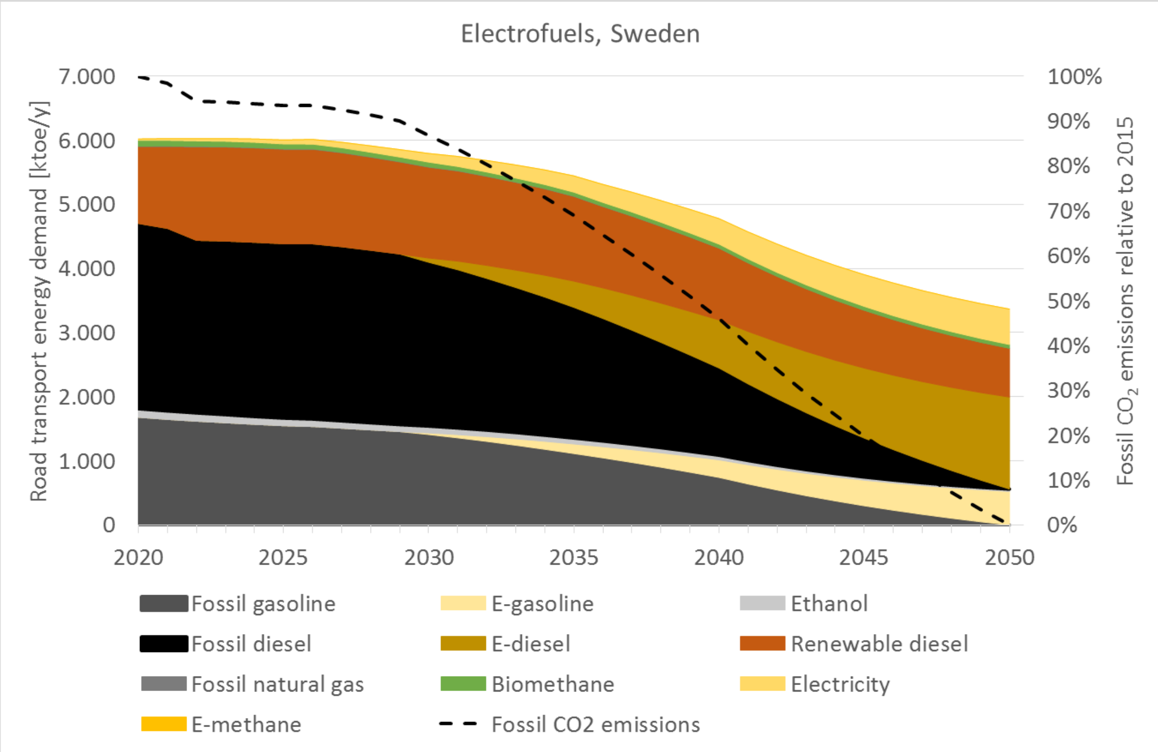

Figure 56. Energy use in road transport by energy carrier for Sweden in the E-FUELS scenario.

Germany

For Germany, the Current Policies scenario starts with 54 Mtoe/yr total road transport energy demand in 2020. Fossil gasoline, fossil diesel and natural gas account for 94% of the sector's energy use, resulting in 153 $MtCO_2$ annual direct fossil carbon emissions. By 2050, the total energy demand is reduced by 54% to 25 Mtoe/yr of which biofuels account for 7% and electricity for EVs 12%.

The introduction of e-fuels begins in 2030, and the total supply increases by 930 ktoe each year until full displacement of fossil fuels is reached in 2050. The final e-fuels supply is 19.5 Mtoe/yr, representing 81% of the sector's energy use. The corresponding electricity demand for producing the required amount of e-fuels is 565 TWh/yr and CO_2 feedstock demand is 76 Mt/yr.

Table 18: Main results of the E-FUELS scenario for Germany.

E-FUELS, GERMANY	**2020**	**2030**	**2040**	**2050**
Total energy use in road transport, ktoe/yr	54,465	45,025	33,138	25,088
Share of fossil fuels, %	94 %	91 %	57 %	0 %
Share of EV energy use, %	0 %	1 %	5 %	12 %
Share of biofuels, %	6 %	6 %	6 %	7 %
Share of e-fuels, %	0 %	2 %	31 %	81 %
Amount of e-fuels, ktoe/yr	0	930	10,228	19,547
CO_2 emissions, $MtCO_2$/yr	153	122	56	0
E-fuel electricity demand, TWh/yr	0	27	296	565
E-fuel CO_2 feedstock demand, MtCO2/yr	0	4	40	76

Figure 57 shows the amount of fuels and the resulting reduction in TTW CO_2 emissions.

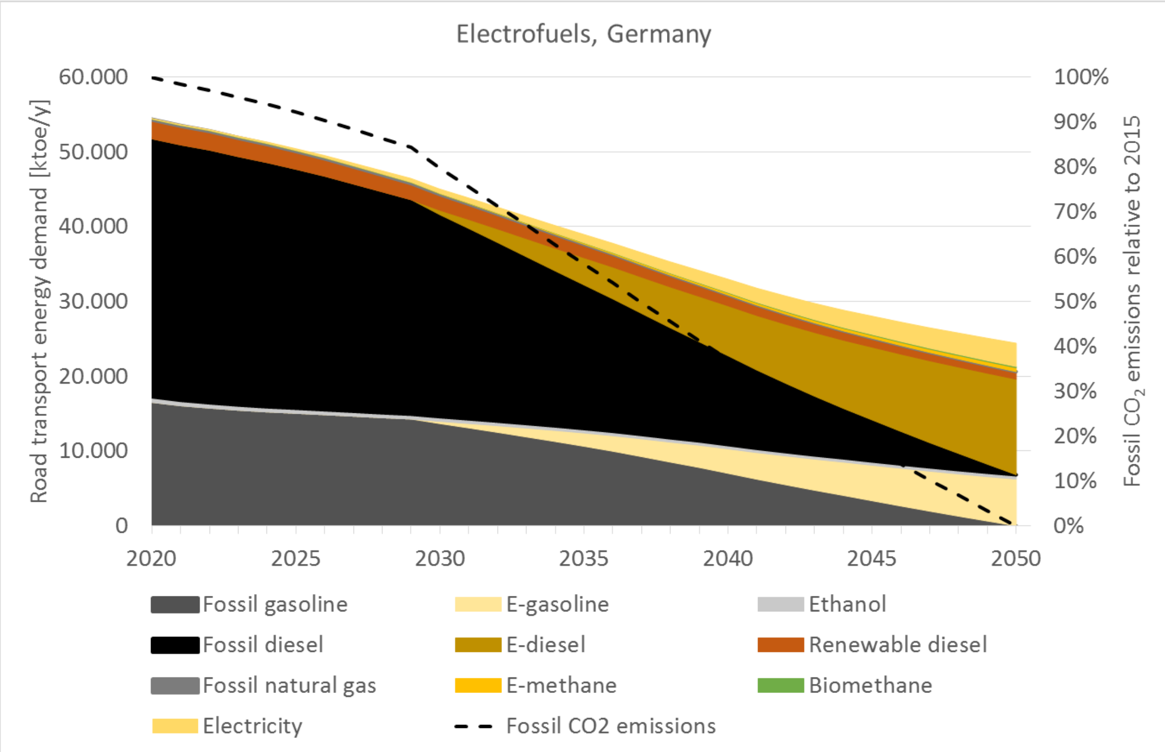

Figure 57. Energy use in road transport by energy carrier for Germany in the E-FUELS scenario.

Brazil

For Brazil, the Current Policies scenario starts with 77 Mtoe/yr total road transport energy demand in 2020. Fossil gasoline, fossil diesel and natural gas account for 75% of the sector's energy use, resulting in 172 $MtCO_2$ annual direct fossil carbon emissions. By 2050, the total energy demand is increased by 82% to 140 Mtoe/yr of which biofuels account for 29% and electricity for EVs 1%.

In the E-FUELS scenario, the introduction of e-fuels begins in 2030, and the total supply increases by about 5 Mtoe each year until full displacement of fossil fuels is reached in 2050. The final e-fuels supply is 98 Mtoe/yr, representing 70% of the sector's energy use. The corresponding electricity demand for producing the required amount of e-fuels is 2800 TWh/yr and CO_2 feedstock demand is 379 Mt/yr.

Table 19: Main results of the E-FUELS scenario for Brazil.

E-FUELS, BRAZIL	2020	2030	2040	2050
Total energy use in road transport, ktoe/yr	76 764	98 378	129 457	139 991
Share of fossil fuels, %	75 %	65 %	31 %	0 %
Share of EV energy use, %	0 %	0 %	0 %	1 %
Share of biofuels, %	25 %	30 %	29 %	29 %
Share of e-fuels, %	0 %	5 %	40 %	70 %
Amount of e-fuels, ktoe/yr	0	4 659	51 246	97 834
CO_2 emissions, $MtCO_2$/yr	172	191	118	0
E-fuel electricity demand, TWh/yr	0	135	1490	2844
E-fuel CO_2 feedstock demand, MtCO2/yr	0	18	199	379

Figure 58 shows the amount of fuels and the resulting reduction in TTW CO_2 emissions.

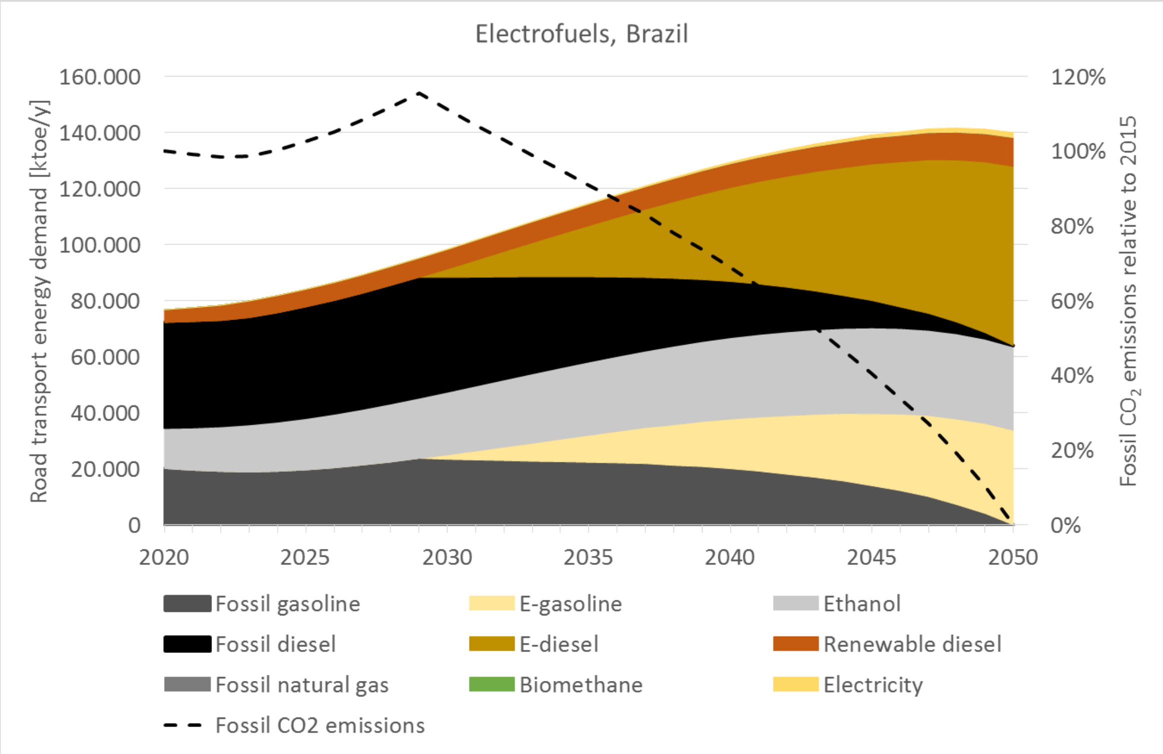

Figure 58. Energy use in road transport by energy carrier for Brazil in the E-FUELS scenario.

Resource considerations

The sustainability of e-fuels is governed by emissions associated with the electricity used in the production process.[10] If an e-fuel production plant is connected directly to a carbon-free electric generator, then overall e-fuels emissions can be very close to zero. However, if the e-fuels plant is connected to an electrical grid, average grid emissions should be used as a basis for calculating e-fuel emissions. Table 20 summarizes scenarios for the evolution of average power system emissions from 2020 to 2050 for the examined countries. For example, average electrical emission for Germany are 455 gCO2/kWh in 2020 and are expected to decline to 151 gCO2/kWh by 2050. In contrast, Swedish emissions are already at very low 47 gCO2/kWh level owing to a large share of hydro and nuclear generation in the national mix. Swedish specific power system emissions are expected to drop to zero by 2040.

[10] Koponen, K. and Hannula, I. GHG emission balances and prospects of hydrogen enhanced synthetic biofuels from solid biomass in the European context, Applied Energy 200, 106-118 (2017). DOI: 10.1016/j.apenergy.2017.05.014

Table 20: Scenarios for specific power system emissions evolution by 2050

Emissions in gCO_2/kWh	2020	2030	2040	2050
FINLAND	140	60	30	0
SWEDEN	47	24	0	0
GERMANY	455	345	236	151
BRAZIL	119	117	N/A	N/A

If average electricity from the power grid would be used to produce e-fuels, the resulting fuel emissions (gCO_2/MJ (LHV)) are shown for different countries in Figure 59. These are illustrated together with emissions from petroleum fuels that are around 90 gCO_2/MJ depending on the feedstock and refining technology.[11] According to the results, e-fuels produced using average Brazilian electricity mix are associated with carbon emissions very close to emissions from petroleum fuels. With Swedish electricity generation mix, e-fuels emissions would be very low already now and be close to zero after 2040. For Germany, e-fuels produced using average national electricity mix are associated with higher emission than petroleum fuels even in 2050.

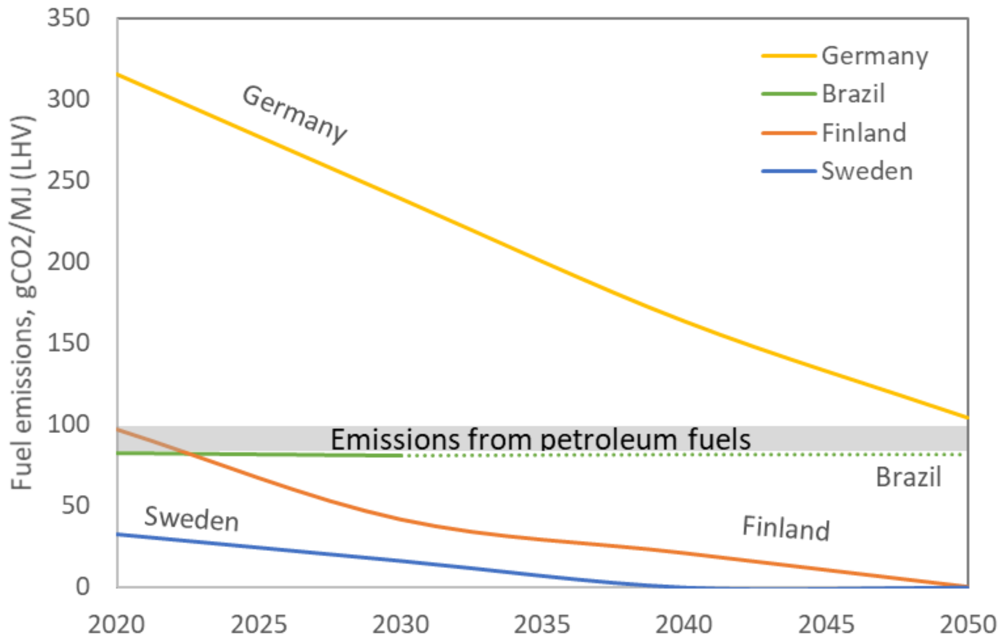

Figure 59: Calculated e-fuel emissions based on national scenarios on the development of average grid emissions. Calculations are made assuming average 40% efficiency from electricity to fuel (LHV).

[11] Edwards, R Definition of input data to assess GHG default emissions from biofuels in EU legislation. (2019) JRC115952, DOI: 10.2760/69179

We also analyzed resource demands associated with the production of e-fuels needed to cover national demands in our non-fossil transport scenarios. Figure 60 contrasts these resource requirements with the current availability of suitable resources in each country. The electricity demand is contrasted with the current scale of non-fossil electricity generation, and the CO_2 demand with current CO_2 emission from industrial point sources.

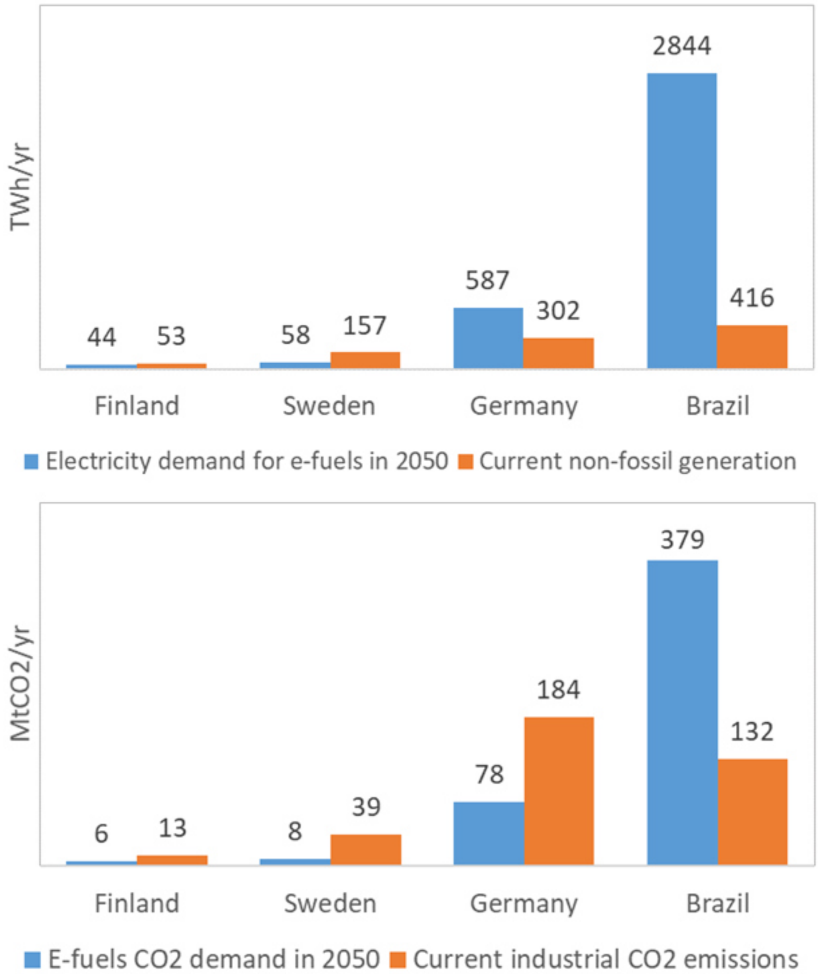

Figure 60: Relative electricity and CO_2 resource requirements related to the national E-FUELS scenarios.

In all cases, except Brazil, current levels of industrial emissions would be large enough to provide carbonaceous feedstock for e-fuels, but the levels of non-fossil electricity generation are likely to impose a serious bottleneck for ramping up a material level of e-fuels production domestically. Without important contributions from biofuels (that underpin all non-fossil transport scenarios), the need for e-fuels would be much higher than shown in Figure 60, and the need for electricity would be much higher than current total electricity generation from non-fossil sources in each country.

Analysis and Conclusions

The implementations of the Current Policies scenarios show that some countries like Finland are expected to see effective reductions of road transport-related CO_2 emissions (30%) already by 2030, whereas Germany and USA are expecting only half of that pace at about 16 to 18% reduction, while Sweden remains at single-digit figures (-6%), according to Table 21. However, Brazil is entirely different, as their road transport emissions are expected to grow, and not reduce, due to the growth of the economy and thus also the amount of transport work. In this timeframe, the strongest contributor for the reductions in all cases is the use of biofuels, and even in Brazil, despite the growth in VMT, biofuels cut down CO_2 emissions by about 20%.

By 2040, Germany starts to catch up with Finland, both reaching about 43…44% reductions, while Sweden and USA yield to 25 to 28% reductions. Simultaneously, Brazil's emissions are up by over 50% from the 2020 levels, but without biofuels, they would be over 25% higher. At this stage for Finland as well as for Brazil, biofuels are still the strongest contributor, but for Sweden, the electrification of cars has taken over, while for Germany, expected increase in vehicles' energy efficiency has the leading role.

In 2050, the Current Policies case for Germany leads to the strongest reductions in CO_2 emissions, as the emissions are calculated to be reduced by over 60%, while Finland and Sweden remain a notch behind at 55 to 56% reductions. On the contrary, Brazil is expecting a 70% increase, but as said, the use of biofuels still brings the emissions down by over 50%. However, for Finland, Sweden and Germany the electrification is the main contributor for these reductions, while in USA, gain in energy efficiency of the vehicle fleet brings the largest share of the calculated emissions reductions.

Table 21: Comparison of the CO_2 emissions according to the Current Policies cases.

		2020	2030	2040	2050
FIN	CO_2 emissions, Mt	10.3	7.3	5.7	4.5
	compared to 2020		-30 %	-44 %	-56 %
SWE	CO_2 emissions, Mt	12.9	12.1	9.3	5.8
	compared to 2020		-6 %	-28 %	-55 %
GER	CO_2 emissions, Mt	151.7	123.8	86.5	58.1
	compared to 2020		-18 %	-43 %	-62 %
USA	CO_2 emissions, Mt	1 483	1 250	1 117	1 126
	compared to 2020		-16 %	-25 %	-24 %
BRA	CO_2 emissions, Mt	171	203	170	291
	compared to 2020		19 %	58 %	70 %

Introducing electric vehicles more rapidly (as in MORE EV) does add to the reduction of GHG emissions. In Table 22, CO_2 emissions for MORE EV scenarios are presented, as well as the additional (relative) reductions from the Current Policies to MORE EV scenarios. However, according to our study the effect is rather marginal for 2030, and even for 2040. This is especially true in countries like Finland and Germany, where the presence of a large heavy transport vehicle fleet effectively dilutes the advances made in the light-duty sector. However, for Sweden, the projected boost in electrification could bring the emissions down by 25% by the year 2050, according to this study.

Table 22: Comparisons of the effects of advanced electrification in MORE EV scenarios on further CO_2 reductions, compared to Current Policies case.

		2020	2030	2040	2050
FIN	CO_2 emissions, Mt	10.3	7.0	5.2	4.2
	reduction, %		-4 %	-8 %	-7 %
SWE	CO_2 emissions, Mt	12.9	11.9	8.7	4.3
	reduction, %		-1 %	-6 %	-25 %
GER	CO_2 emissions, Mt	151.7	123.1	84.8	53.2
	reduction, %		-1 %	-2 %	-8 %
BRA	CO_2 emissions, Mt	171	202	263	259
	reduction, %		0 %	-3 %	-11 %

Furthermore, adding more biofuels up to the technically permissible level of the projected vehicles fleet gives more robust results. Table 23 compares those reductions for each of the case countries. In Table 23, CO_2 emissions for MAX BIO scenarios are presented, along with the additional (relative) reductions from the Current Policies to MAX BIO scenarios.

Table 23: Comparisons of the effects of biofuels in MAX BIO scenarios on further CO_2 reductions compared to Current Policies case.

		2020	2030	2040	2050
FIN	CO_2 emissions, Mt	10.3	7.2	3.5	1.8
	reduction, %		0 %	-40 %	-60 %
SWE	CO_2 emissions, Mt	12.9	6.7	3.3	0.3
	reduction, %		-44 %	-65 %	-94 %
GER	CO_2 emissions, Mt	149.2	93.0	43.6	15.4
	reduction, %		-25 %	-50 %	-74 %
BRA	CO_2 emissions, Mt	128.5	100.8	68.2	10.5
	reduction, %		-50 %	-75 %	-96 %

According to the figures in Table 23, by far the greatest achievement of the MAX BIO scenarios is predicted for Brazil, as according to our assumptions, it would be possible to reach nearly 100% fossil-free road transport by maximizing the use of biofuels. Furthermore, Sweden yields to an almost as good result with a 94% reduction, while Germany stays at about -74%, and Finland only reaches -60%. For these two countries, the “deal-breaker” is the assumption of a larger SI-ICE powered passenger car fleet that is supposed to tolerate a maximum of E25/E30 gasoline, limiting the substitution rate. However, Sweden is supposing the presence of “biopetrol” that effectively closes the gap, and yields to very high reductions in fossil CO_2 emissions. Furthermore, we must bear in mind that the amounts of biofuels necessary to fulfil the demand of these scenarios is exceeding multiple times present and near-future projected production volumes, so they remain highly hypothetical.

In addition, at least in theory, the use of e-fuels basically allows all countries to achieve their transport decarbonization targets. However, an aggressive deployment of e-fuels leads to substantial increase in low-carbon electricity demand on top of existing requirements to expand low-carbon generation to meet more traditional electricity uses. Therefore the viability of E-FUELS scenarios ultimately depend on access to low-cost, ultra-low-carbon power systems or sources of zero-carbon electricity with high annual availability. It is also important to deploy other decarbonization measures like efficiency improvements, electric drivetrains and biofuels to reduce the overall need for CO_2-based fuels in the system.

Abbreviations

ALIISA	Model used by VTT to calculate the future composition of vehicle fleets in this study
AMF	Advanced Motor Fuels
B5, B7,…	Diesel blends with x% FAME
BEV	Battery electric vehicle
BTL	Biomass to Liquid
CBG	Compressed biogas
CI engine	Compression ignited engine
CI-ICE	Compression ignited internal combustion engine
CNG	Compressed natural gas
CNG (SI)	Vehicle with a spark ignited engine running on compressed natural gas
DBFZ	Deutsches Biomasseforschungszentrum gemeinnützige GmbH
Diesel (CI)	Diesel vehicle with a compression ignited engine
E5, E10,…	Gasoline blends with x% ethanol
EPE	Brazilian Energy Research Office
Ethanol (FFV, SI)	Flex-fuel vehicle with a spark ignited engine with the ability to use high-blend ethanol (or pure hydrous ethanol in the case of Brazil)
EU	European Union
EUR	Euro
EV	Electric vehicle
FAME	Fatty acid methyl ester
FCEV	Fuel cell electric vehicle
FFV	Flex-fuel vehicle, capable of using either gasoline or high-blend ethanol (or pure hydrous ethanol in the case of Brazil)
FT	Fischer Tropsch
Gasoline (SI)	Gasoline vehicle with a spark ignited engine
GDP	Gross domestic product
GHG	greenhouse gases
HDT	Heavy duty truck
HDV	Heavy duty vehicles
HEFA	Hydrotreated esters and fatty acids
HEV	Hybrid electric vehicle
HEV (FFV)	Hybrid electric vehicle with a flex-fuel internal combustion engine
HEV (ICE)	Hybrid electric vehicle with an internal combustion engine
HEV-SI	Hybrid electric vehicle with a spark ignited engine

HVO	Hydrotreated vegetable oils
Hydrogen (FCEV)	Fuel cell electric vehicle running on hydrogen
ICE	Internal combustion engine
IEA	International Energy Agency
IEA 2DS	IEA 2 Degree Scenario, compatible with the goal of limiting global heating to 2°C by 2100
LDT	Light duty truck
LDV	Light duty vehicles
LHV	Lower heating value
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas (auto gas)
MDT	Medium duty truck
MTG	Methanol-to-gasoline, process for the production of gasoline based on methanol
PC	Passenger cars
PHEV	Plug-in hybrid electric vehicle
PHEV (CI)	Plug-in hybrid electric vehicle with a compression ignited engine
PHEV (FFV)	Plug-in hybrid electric vehicle with a flex-fuel internal combustion engine
PHEV (SI)	Plug-in hybrid electric vehicle with a spark ignited engine
PHEV-CI	Plug-in hybrid electric vehicle with a compression ignited engine
PHEV-SI	Plug-in hybrid electric vehicle with a spark ignited engine
PTG	Power to Gas
PTL	Power to Liquids
PTX	Power to X (X for different products), usual German definition for e-fuels
RED	Renewable Energy Directive, EU regulation
RED-II	Recast of the Renewable Energy Directive, EU regulation
RenovaBio	Renova Bio, Brazilian regulation
RFS	Renewable Fuel Standard, US regulation
SI engine	Spark ignited engine
SI-ICE	Spark ignited internal combustion engine
SUV	Sports and utility vehicle
TCP	Technology Collaboration Programme (of the IEA)
TTW CO_2 emissions	Tank-to-wheel CO_2 emissions, i.e. tailpipe emissions
UCO	used cooking oil
USD	United States (of America) Dollar

VMT	Vehicle miles travelled
WTT CO_2 emissions	Well-to-tank CO_2 emissions, i.e. upstream emissions from fuel or electricity production
WTW CO_2 emissions	Well-to-wheel CO_2 emissions, i.e. WTT and TTW combined
xEV	all types of electric vehicles

Appendix

The following tables are intended to characterize the analyzed countries in terms of their vehicle fleet size and composition, vehicle miles travelled (VMT) per vehicle in each category, and total use of different fuels and components. The data in these tables is based for Current Policies case, and presented separately for years 2020, 2030 and 2050. The tables are intended to facilitate a comparison of transport sectors in each country.

Table 24: Fleet Size and Composition (Current Policies scenario)

			2020		
Fleet Composition	**Finland**	**Sweden**	**Germany**	**USA**	**Brazil**
Passenger cars	2,776,716	4,905,230	46,224,773	139,060,924	38,360,012
Vans & LDT	325,757	558,974	2,425,898	122,913,804	505,516
Buses & Coaches	12,822	16,116	82,449	12,808	448,004
Medium-Duty Trucks	70,043	79,235	320,107	7,078,121	212,039
Heavy-Duty Trucks	27,230	9,526	405,136	5,238,165	1,042,130
in total	**3,212,569**	**5,569,081**	**49,458,363**	**274,303,22**	**40,567,700**
			2030		
Passenger cars	2,917,450	5,200,261	47,909,627	148,352,562	53,400,439
Vans & LDT	317,015	643,866	2,409,786	124,981,137	604,069
Buses & Coaches	14,125	16,777	89,502	13,042	773,144
Medium-Duty Trucks	76,214	91,244	320,398	8,447,310	213,034
Heavy-Duty Trucks	29,593	10,891	410,669	5,238,043	1,341,263
in total	**3,354,397**	**5,963,038**	**51,139,982**	**287,032,095**	**56,331,949**
			2050		
Passenger cars	3,149,784	5,123,900	47,698,454	183,061,600	91,630,114
Vans & LDT	324,094	820,697	2,452,165	113,703,134	963,656
Buses & Coaches	14,865	16,570	90,574	13,097	1,593,590
Medium-Duty Trucks	88,058	104,281	306,268	12,391,108	313,090
Heavy-Duty Trucks	33,839	12,310	395,502	5,394,439	2,169,067
in total	**3,610,639**	**6,077,757**	**50,942,963**	**314,563,379**	**96,669,517**

Table 25: Total transport work per vehicle category [km] (Current Policies scenario)

Total transport work per category	Finland	Sweden	Germany	USA	Brazil
			2020		
Passenger cars	42,079,656,816	56,377,067,124	654,917,630,384	2,506,199,455,692	637,779,831,93
Vans & LDT	5,717,755,995	8,079,271,039	47,823,214,304	2,261,844,344,858	10,131,181,23
Buses & Coaches	630,150,327	881,809,375	4,629,733,497	1,025,961,840	22,917,968,66
Medium-Duty Trucks	1,617,228,678	1,625,445,903	5,667,018,970	189,121,692,875	4,966,229,42
Heavy-Duty Trucks	1,894,154,912	3,439,908,497	35,886,236,309	319,050,597,226	74,556,046,99
			2030		
Passenger cars	45,543,658,125	66,247,209,897	649,522,603,418	2,720,943,522,791	897,266,104,88
Vans & LDT	5,697,039,404	8,674,905,289	44,897,445,477	2,293,155,656,846	12,062,261,96
Buses & Coaches	665,505,356	917,077,429	5,023,927,802	1,013,478,713	39,291,934,80
Medium-Duty Trucks	1,882,240,621	1,869,774,817	5,759,445,670	235,286,720,589	4,881,447,83
Heavy-Duty Trucks	2,094,027,558	3,961,754,885	31,701,228,884	346,273,993,457	93,253,327,52
			2050		
Passenger cars	50,547,016,571	56,377,067,124	529,103,816,203	3,427,138,995,735	1,521,516,154,64
Vans & LDT	6,011,347,858	8,079,271,039	43,112,428,361	2,161,197,892,369	19,358,861,77
Buses & Coaches	689,662,958	881,809,375	5,060,658,077	1,025,414,928	81,121,945,17
Medium-Duty Trucks	1,773,812,467	1,625,445,903	5,714,110,918	374,303,561,802	7,208,597,90
Heavy-Duty Trucks	2,303,652,554	3,439,908,497	31,221,199,377	392,885,987,201	152,156,783,69

Table 26: Average transport work per vehicle in each category (Current Policies scenario)

Average VMT per vehicle	Finland	Sweden	Germany	USA	Brazil
2020					
Passenger cars	15,200	11,500	14,200	18,000	16,600
Vans & LDT	17,600	14,500	19,700	18,400	20,000
Buses & Coaches	49,100	54,700	56,200	80,100	51,200
Medium-Duty Trucks	23,100	20,500	17,700	26,700	23,400
Heavy-Duty Trucks	69,600	361,100	88,600	60,900	71,500
2030					
Passenger cars	15,600	10,800	13,600	18,300	16,800
Vans & LDT	18,000	12,500	18,600	18,300	20,000
Buses & Coaches	47,100	52,600	56,100	77,700	50,800
Medium-Duty Trucks	24,700	17,800	18,000	27,900	22,900
Heavy-Duty Trucks	70,800	315,900	77,200	66,100	69,500
2050					
Passenger cars	16,000	11,000	11,100	18,700	16,600
Vans & LDT	18,500	9,800	17,600	19,000	20,100
Buses & Coaches	46,400	53,200	55,900	78,300	50,900
Medium-Duty Trucks	20,100	15,600	18,700	30,200	23,000
Heavy-Duty Trucks	68,100	279,400	78,900	72,800	70,100

Table 27: Total fuel use in each category (Current Policies scenario)

Use of fuels	Finland	Sweden	Germany	USA	Brazil
			2020		
Fossil gasoline l/a	1 579 336 310	2 185 356 937	21 479 636 836	469 969 119 149	26 146 297 297
Fossil diesel l/a	2 615 995 263	3 086 771 979	40 263 173 379	157 291 365 368	43 630 986 176
Renewable diesel l/a	550 782 407	1 752 209 234	3 082 597 961	6 189 360 502	5 537 898 864
Ethanol l/a	166 845 003	262 783 324	1 468 693 120	83 124 721 827	28 994 264 978
Fossil methane kg/a	10 655 000	8 401 154	108 889 773	1 625 339 974	788 195
Biomethane kg/a	9 775 867	96 613 270	35 931 890	n/r	0
Electricity kWh/a	113 693 761	258 359 222	634 891 288	12 899 567 103	119 521 530
Hydrogen kg/a	n/r	<100	<100	18 002 093	0
			2030		
Fossil gasoline l/a	1 423 822 648	1 868 181 891	18 174 734 720	374 117 813 741	32 483 126 330
Fossil diesel l/a	1 528 095 677	3 059 410 928	32 211 833 371	152 043 138 060	50 796 649 062
Renewable diesel l/a	1 192 439 497	1 729 142 594	2 548 502 477	5 940 116 598	8 479 974 609
Ethanol l/a	159 801 139	210 136 425	1 242 716 931	84 701 452 738	44 916 631 663
Fossil methane kg/a	38 895 394	6 923 469	136 919 307	1 838 964 577	10 602 019
Biomethane kg/a	31 793 429	79 619 896	44 924 346	n/r	0
Electricity kWh/a	1 217 917 171	1 576 028 331	6 653 343 808	64 709 606 932	1 196 419 170
Hydrogen kg/a	n/r	<100	<100	171 865 196	0
			2050		
Fossil gasoline l/a	864 177 647	681 656 439	8 126 837 030	328 359 092 190	43 938 184 035
Fossil diesel l/a	850 772 026	1 673 643 933	14 920 647 031	141 159 768 048	74 691 093 874
Renewable diesel l/a	717 003 719	929 562 956	1 232 343 739	5 552 265 801	12 477 128 235
Ethanol l/a	94 154 860	73 658 565	1 148 663 510	83 168 836 786	59 402 281 097
Fossil methane kg/a	122 816 229	5 054 471	563 770 782	4 987 673 068	73 865 510
Biomethane kg/a	103 111 577	58 126 416	176 012 972	n/r	0
Electricity kWh/a	6 423 488 150	6 432 627 579	36 290 539 540	164 306 947 161	20 277 580 334
Hydrogen kg/a	n/r	<100	232 188 399	325 424 485	0

<100: limited use n/r=not reported