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Carbon footprint impacts of banning cars with internal combustion engines

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ABSTRACT

Banning sales of passenger cars with internal combustion engines is becoming a common climate change mitigation policy. This study analyzes the effects of such a ban on the carbon footprints of passenger car travel in Sweden using a novel vehicle turnover model and prospective lifecycle assessment, with scenarios for decarbonization of supply chains. A ban on internal combustion engines results in significantly decreased carbon footprints primarily due to reduced tailpipe CO_2 emissions. The full effect of a ban is delayed due to fleet inertia. Increasing the pace of electrification is beneficial for the carbon footprint regardless of global manufacturing decarbonization pathways. A ban in 2030 is not sufficient to reach national policy targets for the transport sector, requiring either an earlier ban (i.e., 2025) or increased biofuel use. Risks of carbon leakage may motivate extending current regulations of vehicle-specific tailpipe emissions to also cover carbon footprints for new cars.

1. Introduction

Decarbonizing road transportation is important for meeting long-term climate change mitigation targets, both for achieving the goal of the Paris agreement and for individual countries such as Sweden (Swedish Government, 2020a; United Nations Environment Programme, 2019). Policies toward decarbonizing road transportation tend to be built around approaches such as a more transport efficient society (incl. transport systems planning), more energy efficient vehicles, larger shares of renewable fuels and faster introduction of chargeable cars (de Coninck et al., 2018; MIT Energy Initiative, 2019).

Many countries, including Canada, France, Japan, Mexico and the UK, have announced targets or plans for phasing out internal combustion engines (ICEs) (United Nations Environment Programme, 2019; Wappelhorst, 2020). Such a phase-out would effectively remove direct fossil fuel use from the passenger car system, transferring decarbonization concerns to activities further up fuel and electricity supply chains. In 2019, the Swedish government followed suit by initiating a public inquiry on possibilities and effects of phasing out fossil fuels and ICEs (Swedish Government, 2019), and later announced that sales of new diesel and gasoline fueled cars should not be allowed from 2030 onwards (Swedish Government, 2020a). In 2018, the Swedish government also imposed an emissions reduction obligation quota in road transportation, which requires fuel suppliers to reduce greenhouse gas (GHG) emissions of gasoline and diesel by blending it with biofuels. The policy has been strengthened to meet the emission reduction target in 2030 of −70% compared to 2010 (Swedish Government, 2020b).

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The discussion on the most suitable substitute for fossil fuels in passenger cars to reduce GHG emissions has been going on for decades (Azar et al., 2003; Connolly et al., 2014; de Coninck et al., 2018; Grahn et al., 2009). The key energy carriers and technologies typically discussed are biofuels used in internal combustion engine vehicles (ICEVs), electricity used in battery electric vehicles (BEVs), and hydrogen used in fuel cell electric vehicles. Prevailing trends indicate a strong growth of BEVs corresponding to 1% of the global fleet in 2019 and are projected to increase to 8–14% by 2030, depending on global climate policies (International Energy Agency (IEA), 2020a). The share of the global road transport demand met by biofuels corresponds to 2.8% in 2019 and is projected to increase to 5.4% by 2025 (IEA, 2020b). Fuel cell electric vehicles show very little growth for passenger cars (IEA, 2020a). Recently, carbon-neutral synthetic fuels have also been discussed (Brynolf et al., 2018; Hannula and Reiner, 2019), which include electro-fuels produced using carbon dioxide (CO_2), water and electricity as feedstock and synthetic biofuels produced using gasification. The cost of producing electro-fuels is higher than producing synthetic biofuels and whether electro-fuels will be competitive against BEVs depends on how fast battery costs will decrease (Hannula and Reiner, 2019). Battery cost per kWh capacity (kWh_c) have decreased by 85% since 2010 and are projected to decrease further following economies-of-scale (IEA, 2020a, 2019a). In such a scenario, electro-fuels would primarily be considered for heavy duty transports that may be hard to electrify using batteries as the only on-board energy storage system due to the large cost and low energy efficiency of the electro-fuel production. Hence, fuel cell electric vehicles and electro-fuels are not further analyzed given this study's focus on the development of passenger cars.

Biofuels, including synthetic biofuels, can have anywhere from a large beneficial climate change mitigation effect, if a reduction in transport system emissions is combined with land carbon increases and low non-CO_2 emissions, to an undesirable effect, if land carbon losses outweigh any reductions in transport system emissions for a relatively long time period (Jia et al., 2019; Smith et al., 2019). There are also many potential co-benefits and adverse side-effects of biofuel systems (Hoegh-Guldberg et al., 2018). Thus, the implications on mitigation and other sustainability criteria are context dependent and influenced by feedstock, management regime, soil and climate conditions, conversion technology, scale of deployment, among others (Ingrao et al., 2019; Jeswani et al., 2020). The potential connection between increasing biofuel production and indirect land use change (ILUC) causing, e.g., biodiversity impacts and GHG emissions, is one concern that have fuelled debate as well as policy development the recent decade (Berndes et al., 2013; Khanna et al., 2017; Sumfleth et al., 2020; Takaes Santos, 2020). For the Swedish case, the climate effects are debated due to the fact that palm oil based hydrogenated vegetable oils (HVO) contributes significantly to the biofuel mix, which could drive further deforestation in the exporting countries with resulting GHG emissions (European Commission, 2019a; Martin et al., 2020; Rulli et al., 2019; Uning et al., 2020). Domestically produced biofuels are expected to contribute with an increasing share, as a consequence of EU legislation (European Council, 2018) limiting so-called high-ILUC risk biofuels, and also due to increasing interest in the forest industry. Studies report contrasting findings concerning the climate effects of forest biofuels, in part due to varying scope and use of different spatial and temporal system boundaries when calculating carbon balances (Cintas et al., 2017, 2016). Hence, there may be limitations to large-scale deployment of biofuels that, together with competition on biofuel use with other sectors, may have led to an increasing focus on electrification of passenger car fleets.

Chargeable cars, including both plug-in hybrid electric vehicles (PHEVs) and BEVs, have other sustainability issues. In addition to the social and environmental issues following mining of materials used in lithium-ion batteries, the production process is also electricity intensive (Davidsson Kurland, 2019; IEA, 2019a) and cause large GHG emissions in the generation of the electricity used, given the prevailing electricity generation system (Emilsson and Dahllöf, 2019). The share of renewables in electricity generation is expected to increase to 44% by 2040 if currently stated polices are kept in place and to contribute to a close-to full decarbonization of the electricity system if countries follow pathways in line with the Paris agreement (de Coninck et al., 2018; IEA, 2019b; Rogelj et al., 2018). Hence, an extrapolation of the current system into the future leads to unreasonably high estimated GHG emissions related to future battery manufacturing (Hoekstra, 2019). The same goes for the electricity used for charging the cars, where the carbon intensity of electricity has very large implications in the use phase of a BEV (Ellingsen et al., 2016; Hoekstra, 2019; Kamiya et al., 2019; Wu et al., 2018). The mitigation potential of fleet electrification using BEVs may become underestimated unless local variations and future decarbonization of electricity generation, e.g., the Swedish case where electricity is already largely decarbonized (Swedish Environmental Protection Agency, 2019), and manufacturing systems are taken into account.

Vehicle fleet turnover models are useful for analyzing the impact of technology trends and different policy instruments on fleet evolution and can be combined with lifecycle assessment (LCA) to estimate energy and environmental impacts. However, recent studies (Fridstrøm et al., 2016; Keith et al., 2019; Milovanoff et al., 2019, 2020; Modaresi et al., 2014; Spangher et al., 2019) do not consider the future development of other production systems than electricity generation nor analyze the impact on fleet-wide carbon footprints of banning ICEs in the context of competing mitigation strategies, such as increasing use of biofuels. This research gap is filled by applying a model called the *Vehicle Turnover model Assessing Future Mobility services* (V-TAFM) to estimate the future carbon footprint of Swedish passenger car travel based on prospective LCA including stock-flow simulations of vehicle fleet turnover coupled with global climate change mitigation scenarios capturing decarbonization of electricity generation and manufacturing systems.

Specifically, this study aims to estimate impacts on the carbon footprint from banning ICEs in sales of new cars in Sweden. V-TAFM provides insight to the future car fleet, fuel use, and CO_2 emissions throughout the cars' lifecycles, aspects crucial to understand for designing future climate and transport policy. While the results are specific to Sweden, the method could easily be applied for other countries based on local data.

2. Methodology

2.1. Analytical framework

The methodology is based on prospective LCA for estimating carbon footprints (i.e., focusing only on climate change impacts) to ensure temporal match between the different systems analyzed. The functional unit for the analysis is defined as Swedish passenger car travel. The purpose of prospective LCA is to assess the environmental impact of an emerging technology, currently in its early phases of market introduction, at a later point in time when the technology has matured. The foreground system captures the market diffusion of the analyzed technology as well as its scale of production while the background systems capture processes that are out of the decisionmakers' reach (Arvidsson et al., 2018; Mendoza Beltran et al., 2020).

Chargeable cars are the chosen emerging technologies in this study and their deployment are analyzed as a foreground system. Material and fuel production as well as vehicle manufacturing processes are considered background systems. Since both BEVs and the processes used in their manufacturing are not yet fully mature, there is a risk of overestimating the emissions occurring in their production and underestimating BEV sales (Hoekstra, 2019; Nordelöf et al., 2014). Hence, scenario approaches are applied for both fore- and background systems, see Fig. 1. The modeling time horizon is year 2020 to 2060. The carbon footprints of Swedish passenger car travel include tailpipe emissions (calculated in the foreground systems, also known as *tank-to-wheel*), fuel cycle emissions (calculated in the background systems, fossil and biofuel production and generation of electricity for charging, also known as *well-to-tank*) and vehicle cycle emissions (calculated in the background systems, vehicle and battery manufacturing, incl. supply chains).

The scenarios in the foreground system capture the effect of introducing a ban on ICEs, see Electrification Scenario in Fig. 1 and Table 1 on scenario assumptions. The ban means that no new ICEVs or PHEVs are sold by a specific year (2030), resulting in BEVs

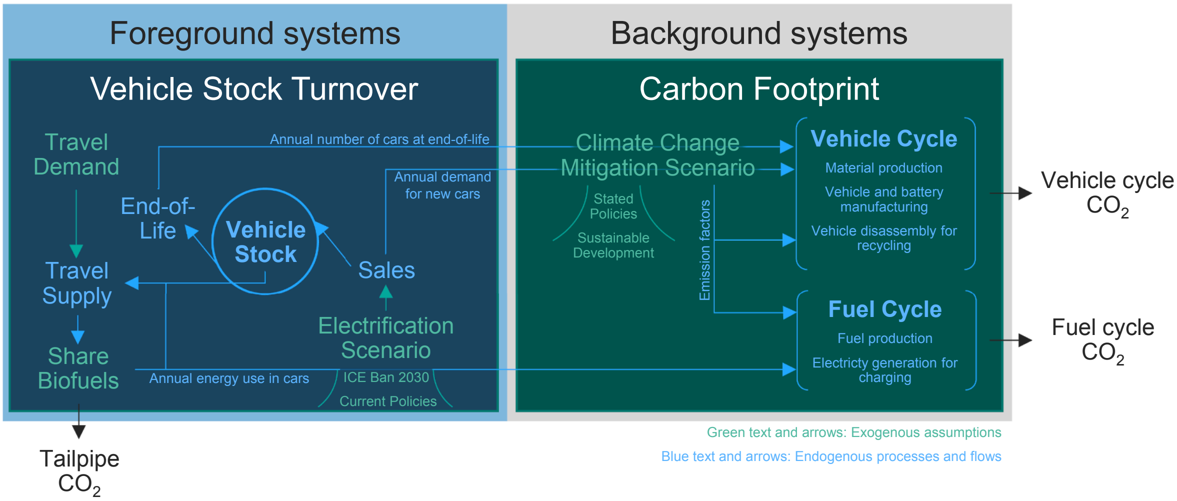

Fig. 1. Graphical representation of modelling framework for the prospective LCA.

Table 1
Main scenarios considered and major assumptions for foreground systems.

	Ban on ICEs in Sweden and high global mitigation ambitions	Ban on ICEs in Sweden and low global mitigation ambitions	No ban on ICEs in Sweden and high global mitigation ambitions	No ban on ICEs in Sweden and low global mitigation ambitions	Common assumptions
Foreground systems	**Year for ICE ban** 2030	**Year for ICE ban** 2030	**No ban**	**No ban**	**Travel demand** Base prognosis by Swedish agencies **Biofuel scenario** Biofuel policy until 2030
Background systems	**Global climate change mitigation** Sustainable Development	**Global climate change mitigation** Stated Policies	**Global climate change mitigation** Sustainable Development	**Global climate change mitigation** Stated Policies	**Location of production** Global average **Electricity used for charging** Swedish average

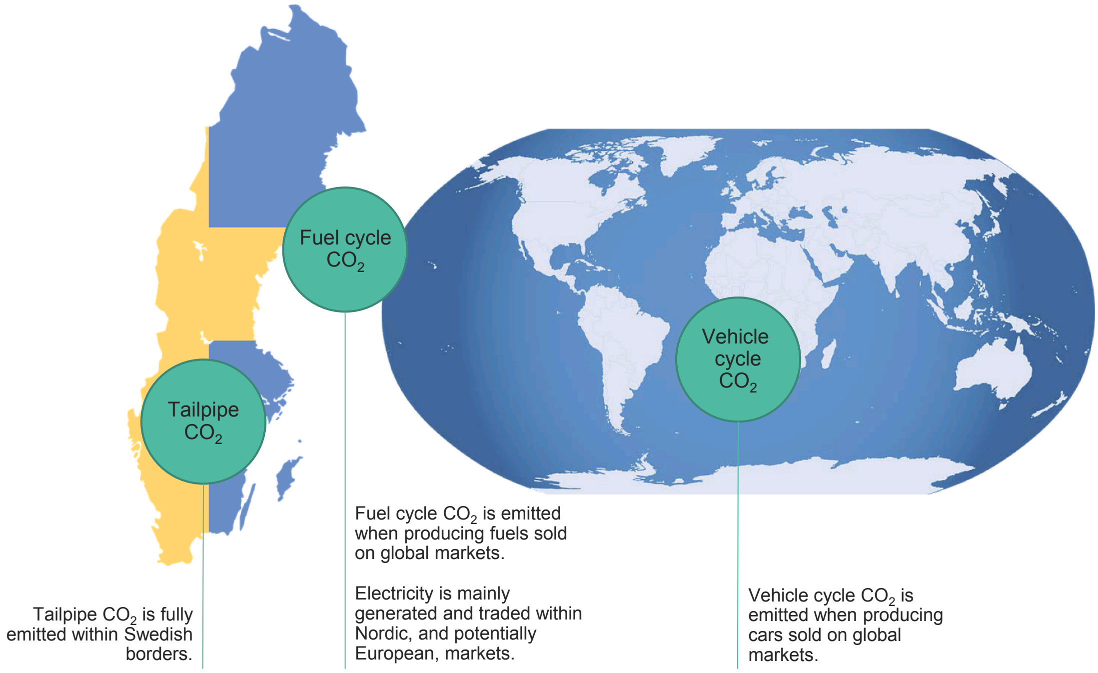

Fig. 2. Assumed geographical location of tailpipe, fuel and vehicle cycle CO_2 emissions.

making up 100% of sales of new cars from that point forward. For the background systems, the scenario approach aims to capture the uncertainty in global climate change mitigation efforts relevant for supplying fuels and vehicles to meet Swedish demands. A range in mitigation efforts is built up by two scenarios: Sustainable Development or Stated Policies, designed to resemble the average global pathways with the same names developed by the IEA (2019b). Note that electricity used for charging is assumed to come from the Swedish grid. There is no need to differentiate between Stated Policies and Sustainable Development scenarios for the Swedish grid since the current emission abatement policy[1] (i.e., the Stated Policies) for Sweden is expected to be in line with the Sustainable Development scenario for the case of electricity generation. Further, average coefficients are applied when assessing the carbon intensity of different aspects of the background systems, for example electricity use, following the attributional nature of the chosen prospective LCA framework (Arvidsson et al., 2018; Yang, 2016).

The carbon footprint comprehends climate impacts of (i) tailpipe CO_2 emissions, fully emitted within Swedish borders and can be directly related to national emission accounting, and (ii) fuel or vehicle cycle CO_2 emissions, which are predominately assumed to be emitted outside Swedish borders, see Fig. 2. This division enables risks of carbon leakage to be identified. Of course, one may miss some territorial emissions with this approach since some cars are manufactured in Sweden and these are partly based on raw materials that have been produced in Sweden (vehicles manufactured abroad can also in part be based on raw materials produced in Sweden). However, the majority of cars sold in Sweden, as for now[2], are manufactured abroad, and for those manufactured in Sweden large shares of the raw materials originate from international markets. Hence, a reasonable assumption is to account vehicle cycle CO_2 emissions as largely occurring abroad. A similar reasoning can be applied to biofuels used in passenger cars since they are primarily imported[3], although this may change in the future depending on how the Swedish biofuel strategy evolves.

Emissions of non-CO_2 GHGs are not considered in the estimations except for the fuel cycle of biofuels since they are of negligible importance in all other parts of the lifecycle (Lane, 2006).

[1] The climate policy action plan on how to reach the net-zero target by 2045 for Sweden include the political interpretations of emissions from electricity generation reaching close-to-zero by the target year (Swedish Government, 2020a).

[2] The only passenger car producer with production in Sweden is Volvo Cars (Bil Sweden, 2020a), but not all Volvo cars are produced at Swedish plants (Volvo Car Group, 2019). Around 20% of the cars sold in Sweden are Volvo cars over the last five year period (2015–2020) (Bil Sweden, 2020b).

[3] The majority of liquid biofuels used in Sweden are imported. For the case of HVO, the majority was imported from the Netherlands and Finland using raw materials from Indonesia, USA, Germany and the UK in 2016 (Swedish Energy Agency, 2018). Statistics for 2019 show that 97% of net-deliveries of liquid biofuels were imported (Statistics Sweden, 2020).

Table 2
Summary of main assumptions for foreground systems.

Travel demand	Base prognosis (Swedish Transportation Administration, 2020a)
Occupancy rate	1.7 (Swedish Transportation Administration, 2020b)
Biofuel use	Biofuel policy (Swedish Government, 2020b)
Annual mileage	17,800 km the first year after registration with declining rate of 4.4% per year (Transport Analysis, 2020a)
Expected vehicle lifetime	Normal distribution with mean of 16.93 years and standard deviation of 0.26 multiplied by the mean of 16.93 years (Transport Analysis, 2020b)

Table 3
Share of chargeable cars in sales of new cars in 2020 and 2030 for the foreground system scenarios.

	2020	2030 No Ban	2030 Ban in 2030
No Ban			
Chargeable cars	31%	39%	100%
of which PHEV	70%	50%	0%
of which BEV	30%	50%	100%

2.2. Foreground systems

2.2.1. Conceptual description of the vehicle fleet turnover simulations

The vehicle fleet turnover captures the inertia of the fleet when new technologies are introduced into the car market. The fleet inertia can be captured in simple stock-flow simulations that account for current fleet of cars, referred to as the stock, and the inward and outward flows represented by sales, and end-of-life (when a car is scrapped), imports, exports and deregistrations (Fridstrøm et al., 2016; Keith et al., 2019; Milovanoff et al., 2020, 2019; Modaresi et al., 2014; Spangher et al., 2019). In this study, a reference travel demand is met by the transport capacity determined by the existing stock and registered new cars, representing the inflow to the stock. Cars that reach their end-of-life are subtracted from the stock and represent the outflow from the stock, see Fig. 1 and Supplementary Materials (SM) 1.1. The inflows and outflows combined with the vehicle characteristics of the stock, summarized in Table 4, provide estimates of total energy use in vehicles and tailpipe CO_2 emissions as well as the necessary inputs for estimating fuel and vehicle cycles emissions in background systems, see Fig. 1.

To form a stock of different drivetrains (ICEV, PHEV and BEV) that matches the current fleet, the model is initiated at year 1950 and then estimates the evolution of the fleet until 2020. The composition of the fleet estimated by the model has then been verified against the current fleet. The fleet is gradually changed depending on scenario assumptions (i.e., share in sales of different drivetrains) as well as assumed characteristics for the Swedish fleet (i.e., annual travel demand, occupancy rate, annual mileage and expected lifetime – all based on currently available statistics, see Table 2). For the scenario introducing a ban on ICEs, the share of chargeable cars in the total is assumed to grow linearly to 100% by 2030 from 31% in 2020 and the share of BEVs in chargeable cars grow to 100% by 2030 from 30% in 2020 (Transport Analysis, 2021). If no ban is introduced and electrification follows current policies, market diffusion of chargeable cars is assumed to be limited to the requirements set out for CO_2 emissions per km in the EU by Regulation 2019/631 (European Commission, 2019b). This implies that 39% of car sales are assumed to be chargeable by 2030, of which 50% are BEVs and 50% are PHEVs (i.e., assuming that the mix of PHEVs and BEVs within chargeable vehicle increase linearly to 50% each), see Table 3 and SM 1.2.

Note that the vehicle stock turnover model does not explicitly consider economic impacts, such as shifts in travel demand, vehicle sales or retirement decisions, in response to the ban. Such impacts of phasing out ICEs from sales of new passenger cars will largely depend on the vehicle prices set by vehicle manufacturers and the package of policies that will be used to implement a strict ban or a phase-out of ICEs. The policy package will also need to be aligned with various policies aimed to limit the use of fossil fuels by vehicles currently in the fleet. Detailed analyses of different policies and economic mechanisms will be crucial for the design of a cost-effective

Table 4
Summary of assumed average vehicle characteristics for the year 2020 and 2030 (in real-world driving conditions).

ICEVs	2020	2030
Vehicle-specific tailpipe CO_2 emissions	173 CO_2 per km	127 g CO_2 per km
Energy use	669 Wh per km	492 Wh per km
PHEVs		
Vehicle-specific tailpipe CO_2 emissions	87 g CO_2 per km	25 g CO_2 per km
Energy use	446 Wh per km	259 Wh per km
Battery size	12 kWh_c	12 kWh_c
Utility factor	0.5	0.8
BEVs		
Energy use	223 Wh per km	201 Wh per km
Battery size	75 kWh_c	75 kWh_c

Table 5
Cases considered in the sensitivity analysis.

	Low	Medium	High
Year for ICE ban	2025	2030	2040
Travel demand	−20% in 2040	Base prognosis	+20% in 2040
Biofuel use	Constant 2020 levels	Biofuel policy until 2030	Biofuel scenario 100% by 2065

transition away from fossil fuels and ICEs. However, such analyses are considered to be beyond the scope of this study, which focuses on the design and results of a prospective LCA framework that captures the overall dynamics of the transition.

2.2.2. Vehicle characteristics

The estimation of vehicle energy use and tailpipe CO_2 emissions in the foreground system is based around the evolution of vehicle-specific tailpipe CO_2 emissions performance per kilometer (km), see SM 1.2. ICEV-specific tailpipe CO_2 emissions per km for new cars are assumed to decrease from 130 g CO_2 per km in 2018 to 91 g CO_2 per km in 2030 onwards (equivalent to a 30% decrease in the new European driving cycle - NEDC, see resulting real-world driving estimates in Table 4). This is comparable with the Swedish Transportation Administration (2020c) assumption of 85 g CO_2 per km by 2030 (NEDC). The assumed decrease is based on more widespread use of hybrid electric vehicles (non-chargeable), engine downsizing, engine friction reductions, aerodynamic improvements, reductions in rolling resistance, smaller transmission losses, and other potential efficiency improvements (Awadallah et al., 2018; Cox et al., 2020; Heywood et al., 2015; Hill et al., 2016; MIT Energy Initiative, 2019). We assume that energy use per km for real-world driving is 40% higher than NEDC procedure (Tietge et al., 2019).

BEVs are assumed to be three times more energy efficient than ICEVs registered the year 2020. The energy use of BEVs is assumed to decrease by 10% from 223 Wh per km in 2020 to 201 Wh per km by 2030 onwards (real-world driving conditions). The decreased energy use in BEVs is based on reductions in transmission losses, weight reductions (e.g. higher energy densities for batteries), aerodynamic improvements, reductions in rolling resistance, and increased overall experience of designing and building BEVs (Cox et al., 2020; MIT Energy Initiative, 2019).

The average battery sizes are assumed to be 75 kWh_c for a BEV and 12 kWh_c for a PHEV, in line with IEA's (2020a) estimates for 2030. This is slightly higher than the range of average battery capacities 48–67 kWh_c in new BEVs in 2019, as presented by the IEA (2020a). Batteries used in BEVs have increased in capacity rapidly and are therefore assumed to be larger than the global average already from 2020 onwards, which may result in a slight overestimation of vehicle cycle emissions for the first few years. Global average battery capacities for PHEVs have been fairly constant around 11 kWh_c for the last five years (IEA, 2020a). The battery chemistry in new cars is assumed to be Nickel-Manganese-Cobalt oxide with respective shares of 0.6, 0.2 and 0.2 (known as NMC-622). While NMC chemistries are becoming increasingly apparent as a market standard, Tesla utilizes a low-cobalt NCA chemistry (Benchmark Mineral Intelligence, 2018). How different chemistries will evolve in the future is highly uncertain, meanwhile this assumption does not have a significant impact on the carbon footprint, see SM 1.4.

PHEVs are assumed to use the ICE for approximately 50% of driven kilometers in 2020, resulting in an electric engine utility factor of 0.5, based on recent real-world estimations (Plötz et al., 2020). The utility factor is assumed to increase linearly to the approximate theoretical level of the worldwide harmonized light vehicles test procedure (WLTP) of 0.8 in 2030 (for the assumed battery size of 12 kWh_c, which yields a WLTP electric range of about 60 km) (Liu et al., 2020; Riemersma and Mock, 2017) since stronger incentives are assumed to increase the share of electricity use in the future. Those incentives include increased availability and use[4] of fast chargers (Gnann et al., 2018) and continuously increasing cost benefits from electric driving since gasoline and diesel prices are foreseen to increasing faster than the electricity price (Swedish Transportation Administration, 2020d).

Imports and exports of used cars are not considered since the main purpose of the analysis is to follow material flows for estimating the carbon footprint, where new cars and the use of the existing stock are the key components. Imports and exports may however influence the explicit results presented for sales, scrappage and stocks.

2.2.3. Sensitivity analysis of ban year, future travel demand and biofuel use

A number of sensitivity cases are considered for the foreground systems, see Table 5.

The main scenario builds on that sales of ICEs should not be allowed after 2030 (Swedish Government, 2020a). A sensitivity analysis is designed to highlight the effect of the timing of the ban. Internationally, the timing of considered ICE bans vary between 2025 and beyond, where Norway represents the most ambitious target (2025) while, e.g., France and Spain aim for 2040 (Wappelhorst, 2020). Each country's specific context has strong implications for the timing and the feasibility of implementing an adopted target. Note that the status of policy implementation varies from announced plans to adopted laws. Nevertheless, the range from 2025 to 2040 is useful for understanding the impact of timing for the Swedish case.

The base prognosis assumed for future travel demand is based on current policies and prognoses on economic development, population growth and fuel price changes developed by different governmental agencies in Sweden. The starting point of the base prognosis is current policies and among them the adopted climate targets are included. Since the targets have not yet been fully turned into climate policy, the Swedish Transportation Administration (2020a) supplement current policy to achieve the targets. This

[4] Note that only few PHEV models support fast charging at present (Nicholas and Hall, 2018).

supplement is in the form of strengthening the policy instruments for increased use of biofuels and investment support for low-emitting cars. However, other climate policies, e.g., increasing taxation (distance-based or fuel-based) or measures that reduce congestion (Gärling and Schuitema, 2007), could contribute with reducing travel demand for passenger cars, thus indirectly reducing emissions. Other factors point towards a more rapid increase in travel demand, e.g., the introduction of connected and autonomous cars that can cause a significant degree of induced travel demand through significantly reducing the costs associated with spending time driving, leading to more frequent and longer trips (Rebalski, 2021). Hence, a sensitivity analysis is designed to highlight the effects that these potential developments of the travel demand could have on the carbon footprint, see Table 5.

The share of biofuels was 23% of total liquid fuels in terms of energy used for Swedish road transportation in 2019 (Swedish Transportation Administration, 2020e). In the main scenario, the share of biofuels is assumed to increase linearly to 59% in 2030, in line with the adopted biofuel policy – the emissions reduction obligation quota (Swedish Energy Agency, 2019a; Swedish Government, 2020b). Two additional sensitivity cases highlight the impact on the carbon footprint if (i) the share of biofuels is assumed to be constant at 2019 levels from 2020 onwards, and (ii) the share of biofuels is assumed to linearly increase from 2030 reaching 71% in 2040 and 100% by 2065, inspired by a biofuel intensive emissions abatement scenario (Swedish Transportation Administration, 2020d). Tailpipe CO_2 emissions from biofuel use are assumed to be zero since the CO_2 subsequently would be sequestrated by vegetation. While this may not be true for all biofuels and also depends on the timing of vegetation regrowth, the guidance from the International Panel on Climate Change (IPCC) on emission inventories and accounting suggests this approach (Goodwin et al., 2019), which is adopted for Swedish emission accounting (Swedish Environmental Protection Agency, 2020).

2.3. Background systems

The two scenarios that make up the range of climate change mitigation outcomes for global average production system are conceptually based on IEA's (2019b) Sustainable Development and Stated Policies scenarios. While the global average carbon intensity of electricity is used directly from the IEA's (2019b) results, all other data is based on other, more detailed sources aiming to resemble the IEA's (2019b). The vehicle cycle emissions are estimated using GREET® 2 – Version 2019 – LCA model (Argonne National Laboratory, 2020), adapted by the authors to enable scenario analyses. The emission factors for the fuel cycle are estimated based on Jing et al. (2020) and Masnadi et al. (2018) for fossil fuels, and the Swedish Energy Agency (2020b) and the European Council (2009) for biofuels.

The Stated Policies scenario is built around current policies and stated targets (IEA, 2019b). For global average material production and manufacturing in the vehicle cycle, current processes are kept in place based on GREET®, see details in SM 1.5. Our reasoning is that this scenario should be conservative since the raw material and manufacturing sectors are considered hard to abate (Davis et al., 2018). Hence, additional incentives beyond current stated policies are expected to be needed when introducing innovations in manufacturing processes (Bataille et al., 2018). The material composition of the car is assumed to be constant, as provided in GREET®. Fuel cycle emission factors are assumed to be constant.

The Sustainable Development scenario illustrates a climate change mitigation pathway that would achieve holding global average temperature increase below 1.8 °C and reaches net-zero emissions by 2070 (IEA, 2019b). Global average production and manufacturing processes in GREET® are assumed to be gradually replaced with innovative technologies when deemed ready for full-scale deployment (IEA, 2020c), see SM 1.5. The gradual introduction of innovative technologies is assumed to follow logistic trajectories from the timing of early adoption (when the technology has less than 1% market share) to fully dominating the market (reaching 99% market share) by 2070. Logistic growth trajectories have been shown to capture diffusion rates of industrial innovations well by simulating the S-curve of markets maturing (Grübler, 1998; Marchetti and Nakicenovic, 1979; Wilson, 2009).

2.3.1. Accounting for future changes to the electricity generation system

The carbon intensity for electricity used in the vehicle cycle is assumed to develop in line with the global average results for the IEA's (2019b) Stated Policies and Sustainable Development scenarios, see SM 1.3. Both scenarios imply a carbon intensity for electricity of 550 g CO_2 per kWh in 2020 (based on estimates for 2018, incl. transmission and distribution losses), decreasing to levels of 350 and 91 CO_2 per kWh by 2040 for the Stated Policies and Sustainable Development scenarios, respectively. The Stated Polices scenario remains at the 2040 level for the remaining period while the Sustainable Development scenario continues to decrease linearly, reaching zero by 2070.

The global average carbon intensity for electricity is not relevant for the fuel cycle emission estimation since electricity used for charging would come from the Swedish grid. Hence, the background scenario for electricity used for charging is based on the Swedish average electricity generation technology mix[5], resulting in a carbon intensity of 29 g CO_2 per kWh in 2020 (Swedish Environmental Protection Agency, 2019; Swedish Energy Agency, 2020b) and decreases linearly to zero by 2045. Assumptions and results for a case using European electricity for charging are available in SM 3.

Electricity generating technologies also incur lifecycle emissions (i.e., construction of production facilities and production of fuels). Such emissions are added to the carbon intensities based on Pehl et al.'s (2017) estimates of global average lifecycle CO_2 emissions for different electricity generation technologies weighted by the future mix of technologies (IEA, 2019; Swedish Energy Agency 2019b).

[5] Swedish electricity is traded on a Nordic market that on average has a slightly higher direct emission intensity of 34 g CO_2 per kWh (Swedenergy, 2019). Average European direct emission intensity could be more reasonable to assume if European electricity markets are further integrated in the future, see SM 3.

2.3.2. Details on estimating emissions in the vehicle cycle

Data extracted from GREET® include vehicle composition (incl. battery), its manufacturing and disposal, and supply chain processes (including production of steel and cast iron, plastics, rubber, wrought and cast aluminum, copper, electronics, fluids, and battery materials), as well as car and battery assembly, see SM 1.5. Emissions related to material production and manufacturing are assumed to occur the same year as the car is sold and emissions related to disposal the same year as the car reaches end-of-life. The mass in running order is based on GREET® with 1507 kg, 1765 kg and 1571 kg for ICEV, PHEV and BEV, respectively. This is comparable to the Swedish average for 2018 of 1530 kg for an ICEV (European Environment Agency, 2020). There is an on-going trend in increased size of cars in Sweden (Swedish Environmental Protection Agency, 2019), meanwhile lightweight materials could contribute to reducing the mass in running order. Hence, the mass in running order is assumed to be constant throughout the modeling time horizon while the material composition of the car is assumed to shift slightly towards larger shares of aluminum and plastics (Modi and Vadhavkar, 2019), counteracting the increased size of cars.

A limitation of GREET® is that electronics only are included for the charging of batteries and use of the electric engine in PHEVs and BEVs. Even though electronics use in cars are expected to increase due to assisted driving, infotainment and future connected and autonomous driving (Tummala et al., 2016), their share in vehicle cycle emissions is expected to be relatively small (Gawron et al., 2018).

The *cut-off* approach is used to account for recycling of materials at the end-of-life (Nordelöf et al., 2019). This means that the potential emissions savings of recycling and replacing of virgin material is not credited as a decrease in emissions. This is considered as appropriate for common materials with established processes for recycling. The cut-off approach also implies that no impact is carried over from previous lifecycles for the scrap used in the production processes. The specific process of vehicle manufacturing can be considered a closed-loop system where potential scrap in the production is reused or recycled internally. Hence, only net material use is accounted when estimating the carbon footprint. The reasoning behind treating material available for recycling at end-of-life differently from leftover material arising in manufacturing is that *old* scrap (from end-of-life) may not have the properties needed in current production (i.e., materials used in a 20-year-old car may not be equivalent to a car being produced today). This is not the case for *new* scrap (arising in manufacturing) if used for producing the same or similar products as where it arose (Morfeldt et al., 2015; Nordelöf et al., 2019).

2.3.3. Details on estimating emissions in the fuel cycle

Fuel cycle emissions from biofuel production are based on weighted average lifecycle emissions for biofuels used in Sweden during 2019 as reported to the Swedish Energy Agency (2020a) by Swedish fuel suppliers (mainly HVO, fatty acid methyl esters (FAME) and ethanol), resulting in 69 g CO_2e per kWh, which is assumed to be constant in the Stated Policies scenario. The design of the emission reduction quota obligation favours biofuels with lower lifecycle GHG emissions, as the required blending volumes decrease with decreasing lifecycle GHG emissions for the biofuel, which can partly explain that the estimated lifecycle emissions reported by Swedish Energy Agency (2020a) are significantly lower than other published estimates (Källmén et al., 2019). Another reason could be assumptions made on allocation of emissions between different products originating from the same process. Note that climate impacts related to ILUC are not considered.

In the Sustainable Development scenario, Fischer-Tropsch diesel is assumed to be gradually introduced following a logistic curve,

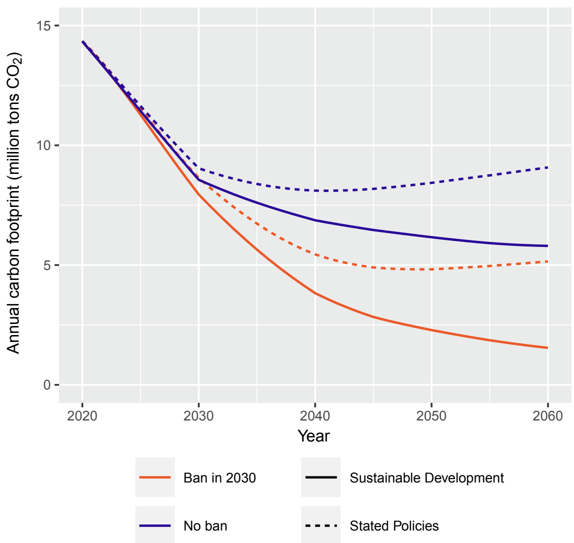

Fig. 3. Annual carbon footprints for passenger car travel in Sweden highlighting the impact of introducing a ban in 2030, see red color for introducing a ban and blue color for no ban, for the two background scenarios, see line type solid for the Sustainable Development pathway and dashed for the Stated Policies pathway. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

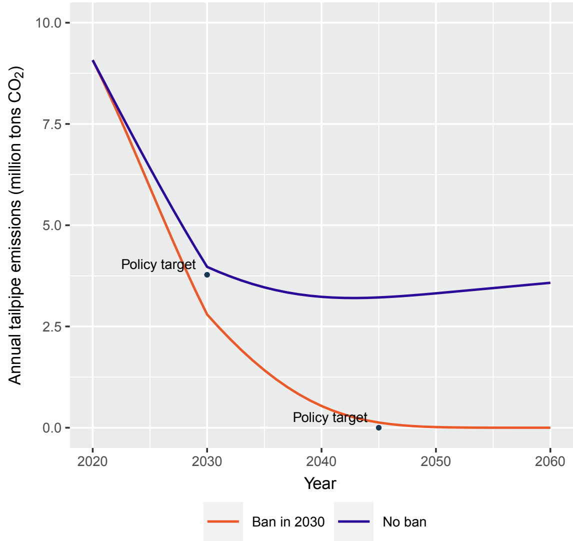

Fig. 4. Annual tailpipe CO_2 emissions for passenger car travel in Sweden. The indicative policy target for 2030 corresponds to a 70% decrease in annual emissions compared to 2010 and the indicative policy target for 2045 corresponds to reaching zero.

resulting in 18 g CO_2e per kWh by 2060 (based on the average between waste wood and farmed wood Fischer-Tropsch diesel, see total lifecycle emissions for Fischer-Tropsch diesel on page 59 in the annex to Directive 2009/28/EC (European Council, 2009) given the focus on forest-based biofuels in Sweden.

Global average lifecycle CO_2 emissions from crude oil extraction used to produce gasoline and diesel are assumed to be 35 g CO_2 per kWh and global average emissions from refining are assumed to be 25 g CO_2 per kWh with a mitigation potential of around 50% on emissions from refining (Jing et al., 2020; Masnadi et al., 2018). The mitigation potential is realized following a logistic curve in the Sustainable Development scenario, starting in 2020 and resulting in halved emissions from refining by 2060.

3. Results and analysis of carbon footprint impacts by introducing a ban on ICEs

Introducing a ban on ICEs results in considerable reductions in annual carbon footprints, see Fig. 3. Annual emissions decrease from 14 million tons of CO_2 ($MtCO_2$) in 2020 to between 1.5 and 5.1 $MtCO_2$ by 2060 depending on the decarbonization of background systems. Without a ban on ICEs, annual emissions drop to between 5.8 and 9.1 $MtCO_2$ by 2060, depending on the decarbonization of background systems where 1.0 $MtCO_2$ of the reduction is the result of lower carbon intensity in biofuel production. Regardless if a ban is introduced or not, emissions start increasing again towards the end of the modelling time horizon in the Stated Policies scenario as a result of the increasing travel demand. This effect is counteracted by the decarbonization of background systems in the Sustainable Development scenario.

Annual stocks and flows of vehicles as well as the vehicle energy use are provided in SM 2.6–2.10. These results clearly show the effect of the ban on sales of new cars with ICEs and the impact on fleet electrification. The stock of cars shows that ICEVs would in principle be fully phased out from the entire fleet by 2050 since the car lifetime is approximately 17 years.

3.1. Foreground system - tailpipe CO_2 emissions

Annual tailpipe emissions from passenger cars drop rapidly from 9.1 $MtCO_2$ in 2020 towards zero between 2045 and 2050 if a ban on ICEs is introduced. Without a ban, emissions decrease significantly until 2030 due to the biofuel policy and then continue decreasing slightly until 2042, due to the assumed energy efficiency improvements, only to increase again reaching a level of 3.6 $MtCO_2$ by 2060, as a result of increased travel demand and a levelling-off of potential energy efficiency improvements, see Fig. 4.

3.2. Background system – The fuel cycle

Annual emissions occurring in the fuel cycle are estimated to 3.0 $MtCO_2$ in 2020 and decrease significantly if a ban on ICEs is introduced, see Fig. 5. The pathways highlight the significant effect on fuel cycle emissions of phasing out liquid fuels (both fossil and

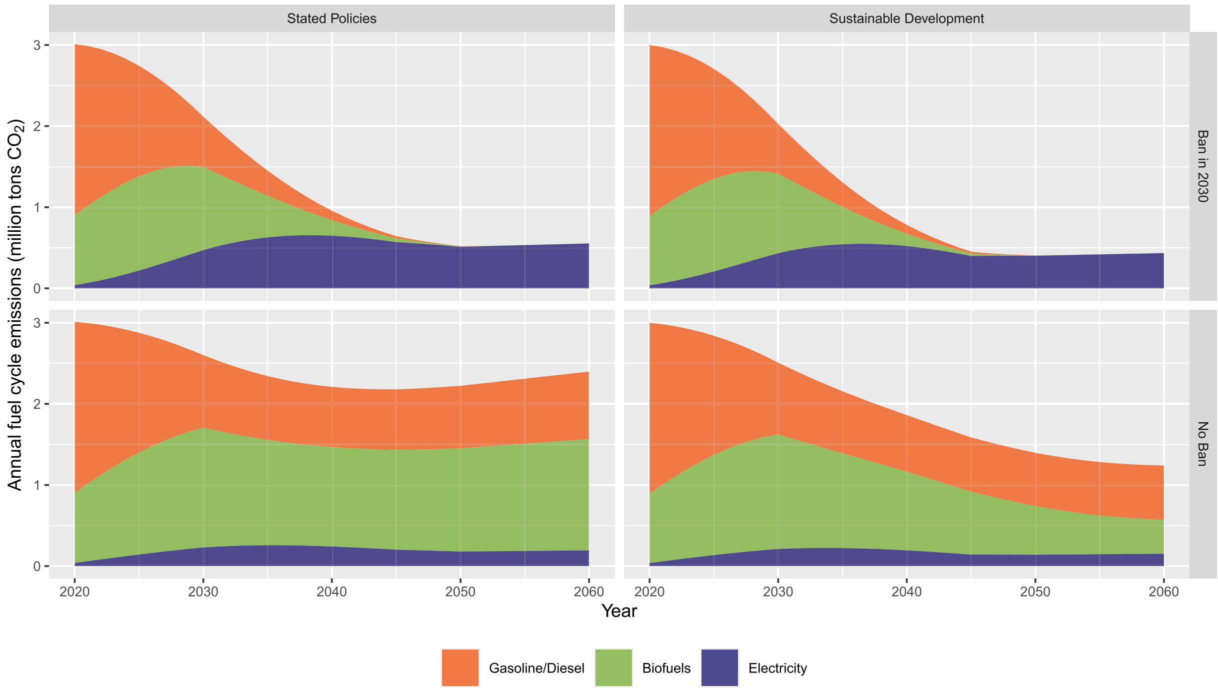

Fig. 5. Annual fuel cycle CO_2 emissions for passenger car travel in Sweden. Labels denote the foreground (i.e., Ban in 2030 or No Ban) and background (i.e., Stated Policies or Sustainable Development) scenarios of each subplot.

bio-based), reaching annual levels of 0.43 to 0.55 $MtCO_2$ by 2060, depending on the decarbonization of background systems.

Decarbonization of background systems does not have a significant impact on the results for the scenario introducing a ban on ICEs. This can be explained by the fast shift in vehicle energy use from liquid fuels to electricity and that the carbon intensity of Swedish electricity is low and assumed to be similar for Stated Policies and Sustainable Development scenarios (see SM 3 for results based on carbon intensity of European electricity instead of Swedish).

For the scenario without a ban on ICEs, annual emissions in the fuel cycle differ more significantly depending on decarbonization of background scenarios. Annual fuel cycle emissions follow a decreasing pathway to a level of 1.2 $MtCO_2$ by 2060 for the Sustainable Development scenario, while the Stated Policies scenario results in increasing emissions from 2043 onwards reaching annual levels of 2.4 $MtCO_2$ by 2060.

3.3. Background system – The vehicle cycle

Annual emissions occurring in the vehicle cycle are estimated to 2.3 $MtCO_2$ in 2020 and initially increase rapidly if a ban on ICEs is introduced, see Fig. 6. This is an effect of the increased manufacturing of batteries needed for the BEVs and PHEVs (see SM 2.1–2.3 for results for individual cars). Annual vehicle cycle emissions start to decrease beyond 2030 in the Sustainable Development scenario as manufacturing and production processes become decarbonized and the annual demand of new batteries becomes more stable. The emissions eventually reach a level of 1.1 $MtCO_2$ by 2060. If background systems instead follow the Stated Policies scenario, annual vehicle cycle emissions continuously increase to a level of 4.6 $MtCO_2$ by 2060 since emissions per individual manufactured BEV remain close to constant. An increase in the carbon intensity of electricity used in manufacturing of 50% would result in annual emissions in the vehicle cycle increasing 0.5 to 0.6–0.8 $MtCO_2$ until 2030, depending on the decarbonization of background systems, and could reach a level of 5.6 $MtCO_2$ by 2060 for the Stated Policies scenario (i.e., 1.0 $MtCO_2$ larger in 2060 as compared to Fig. 6), see SM 3.

The scenario without a ban on ICEs leads to lower emissions in the vehicle cycle compared to the scenarios that include a ban. The annual emissions in 2030 without a ban are between 2.1 and 2.5 $MtCO_2$ (depending on background scenario) which can be compared to between 3.1 and 3.7 $MtCO_2$ (depending on background scenario) in the case with a ban. This difference is largely due the increased need for battery capacity. In the case without the ban, the decarbonization of background systems is crucial for if vehicle cycle emissions increase or decrease over time, resulting in levels of between 1.0 and 3.1 $MtCO_2$ by 2060.

3.4. Sensitivity analysis

In the sensitivity analysis, the impact of varying assumptions in the foreground system with respect to future travel demand, share of biofuels and timing of the ICE ban is tested. Two alternative cases are considered for each assumption, see section 2.2.3 for details and briefly restated here: ±20% difference in travel demand in year 2040, low biofuel case (biofuel share in liquids fuels remains at the

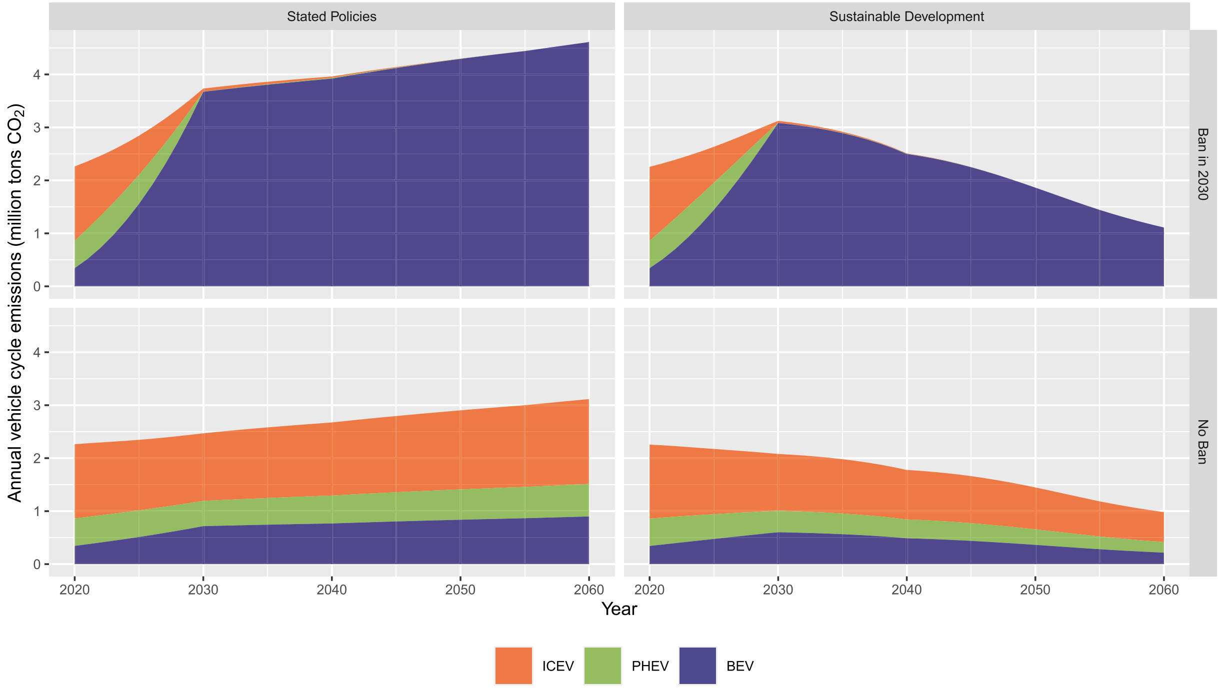

Fig. 6. Annual vehicle cycle CO_2 emissions for passenger car travel in Sweden. Labels denote the foreground (i.e., Ban in 2030 or No Ban) and background (i.e., Stated Policies or Sustainable Development) scenarios of each subplot.

assumed level in 2020) and high biofuel case (biofuel share continues to expand beyond 2030 and reaches 100% by 2065), and two alternative ICE ban years, 2025 and 2040. The impact is analyzed with respect to the cumulative carbon footprint for tailpipe, fuel and vehicle cycle CO_2 emissions over the period 2020 – 2060, Fig. 7, as well as an indicative analysis of emissions occurring within the Swedish territory or abroad, Fig. 8. Annual tailpipe emissions related to the indicative policy targets for 2030 are presented in Fig. 9.

3.4.1. Cumulative emissions – In total, for the Swedish territory and for emissions in other countries

The impact of future travel demand assumptions on the cumulative carbon footprint over the period 2020 – 2060 is about ±10–16% depending on the assumed ban year and biofuel share. The effect is slightly higher for scenarios without a ban on ICEs since it affects future emissions in the long-term to a larger extent than emissions in the near-term and that annual emissions in the long-term tend to be higher in scenarios without a ban.

Varying the assumptions on biofuel use shows a clear impact on tailpipe emissions, which is expected since tailpipe CO_2 emissions for biofuel use are assumed to zero. There is also a net reduction of the cumulative carbon footprint when increasing the share of biofuels despite the increased fuel cycle emissions as compared to fossil fuels. These effects are most significant when no ban is introduced and when global average climate change mitigation efforts follow Stated Policies pathways, see Fig. 7. This can be explained by more liquid fuels being used and the higher carbon intensity in biofuel production. A shift towards biofuels with lower carbon intensity in production, as shown when background systems follow Sustainable Development pathways, results in reduced cumulative emissions but has a relatively small effect on cases that introduce a ban on ICEs, especially if the ban goes into effect early (by 2025 or 2030). This is due to biofuels mainly being used in the beginning of the period in those cases and are phased out before abatement measures have been fully implemented in biofuel production that would reduce its carbon intensity. Note that indirect land-use change in production of biofuels could result in net emissions or net removals of CO_2 for the fuel cycle depending on how land-use is affected by increased biofuel production.

The trade-off when using biofuels as the main mitigation measure is also visible when considering where the emissions occur geographically (i.e., inside or outside Swedish borders[6]), see Fig. 8. The cumulative carbon footprint together with the emissions inside Swedish borders decrease when biofuel use is assumed to increase, while emissions outside Swedish borders stay close to constant. However, a slight increase in emissions outside Swedish borders can be seen for the “No ban” cases following Stated Policies pathways for background systems. For early timing of the ban, the impact of different assumptions on the biofuel shares in 2040 or 2050 is almost negligible since the fleet would be electrified by that point.

An earlier ban year for ICEs would also result in decreases in the cumulative emissions both within Swedish territory and outside

[6] Emissions inside Swedish borders are assumed to be tailpipe emissions and fuel cycle emissions from electricity used for charging. Emissions outside Swedish borders are assumed to be vehicle cycle emissions and fuel cycle emissions for liquid fuels.

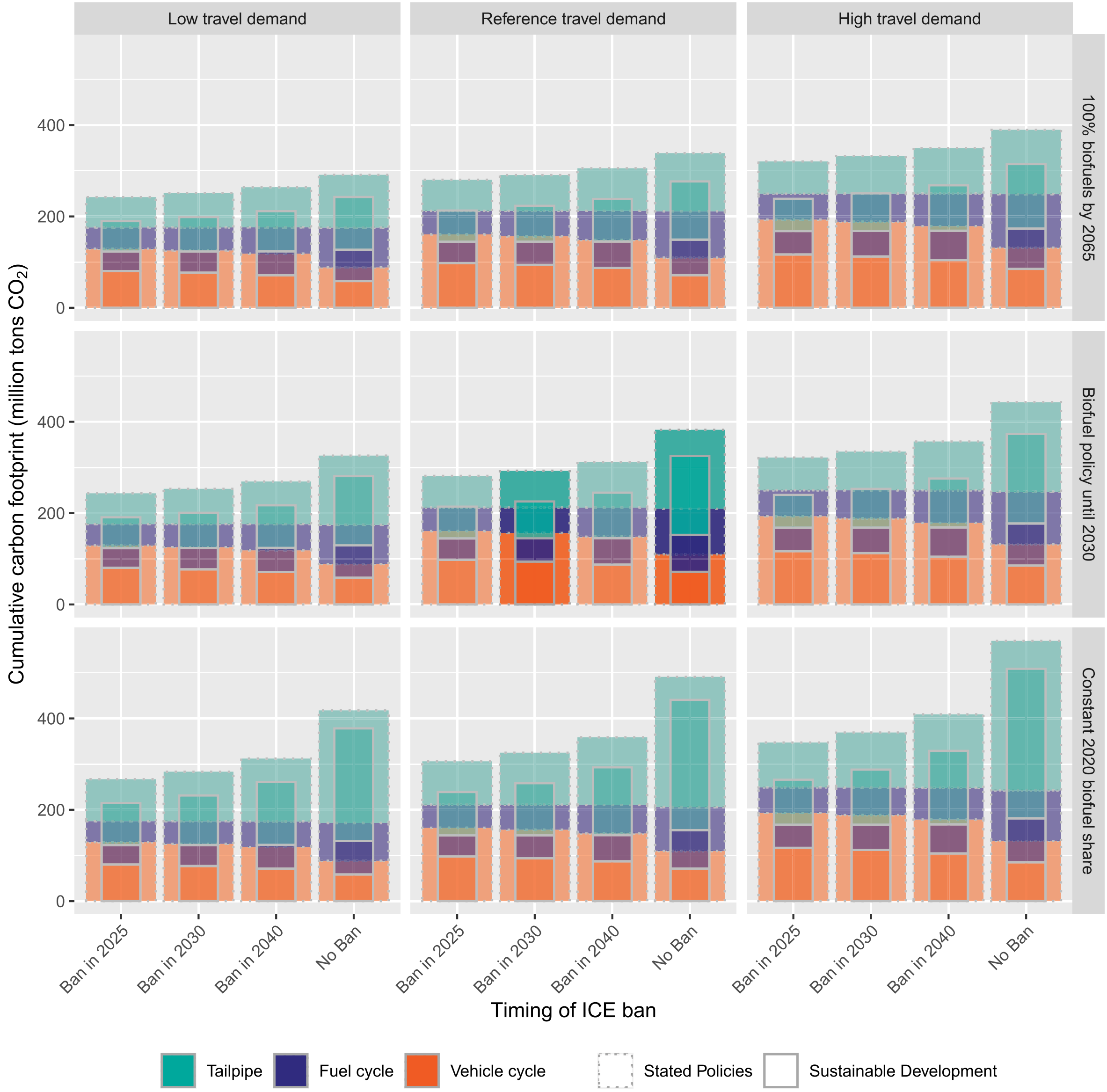

Fig. 7. Cumulative carbon footprint sensitivity for variations in assumptions on travel demand (horizontally in grid), share in biofuel use (vertically in grid) and timing of ICE ban (x-axes of each graph). Decarbonization of background systems are indicated by column width (narrow bars indicate the Sustainable Development scenario and wider bars indicate the Stated Policies scenario). The main scenarios presented in sections 3.1 – 3.3 are highlighted, see bars in middle graph.

Swedish borders in all cases tested, see Fig. 8. Hence, the analysis indicates that the increased emissions that take place due to battery manufacturing occurring at an earlier date (see vehicle cycle emissions in Fig. 7) are smaller than what the emissions would have been if we would continue to use ICEs with liquid fuels, irrespective of the biofuel share scenario assumed.

3.4.2. Relative impact on cumulative carbon footprints and effects on annual carbon footprints

The benefits in terms of reduced cumulative carbon footprints of introducing a ban on ICEs are significantly affected by assumptions such as the share of biofuel use and the future travel demand. In general, earlier timing of the ban, larger share of biofuels or lower traffic demand all result in lower cumulative carbon footprints in isolation, i.e., when other assumptions remain constant. At the same time, the impact on the cumulative carbon footprint of each case is strongly dependent on the assumptions for the others, see Fig. 7. Further, the decarbonization of background systems is less significant than the impact of introducing a ban on ICEs, see SM 2.5. This can be explained by that the reduction of tailpipe and fuel cycle emissions when phasing out fossil fuels from the use phase are larger than the emissions increase following increased battery manufacturing, irrespective of background systems scenario. While this is in part due to the low carbon intensity of Swedish electricity, this conclusion still applies for other assumptions. For example, when using

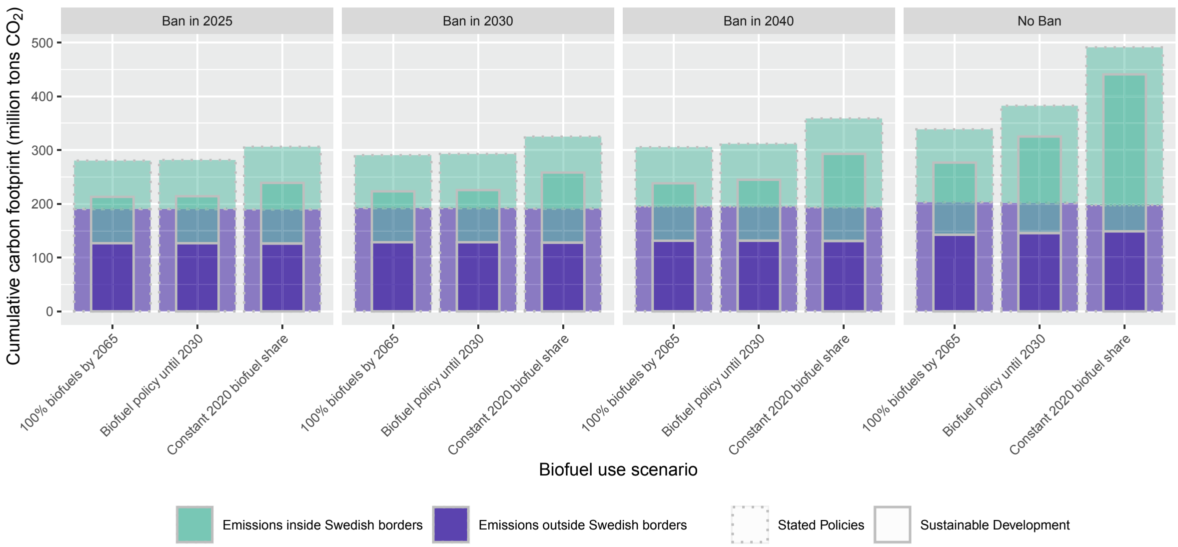

Fig. 8. Cumulative carbon footprints for emissions inside and outside Swedish borders, highlighting the impact of varying the timing of a ban on ICEs as well as the share of biofuel use. The reference travel demand is assumed.

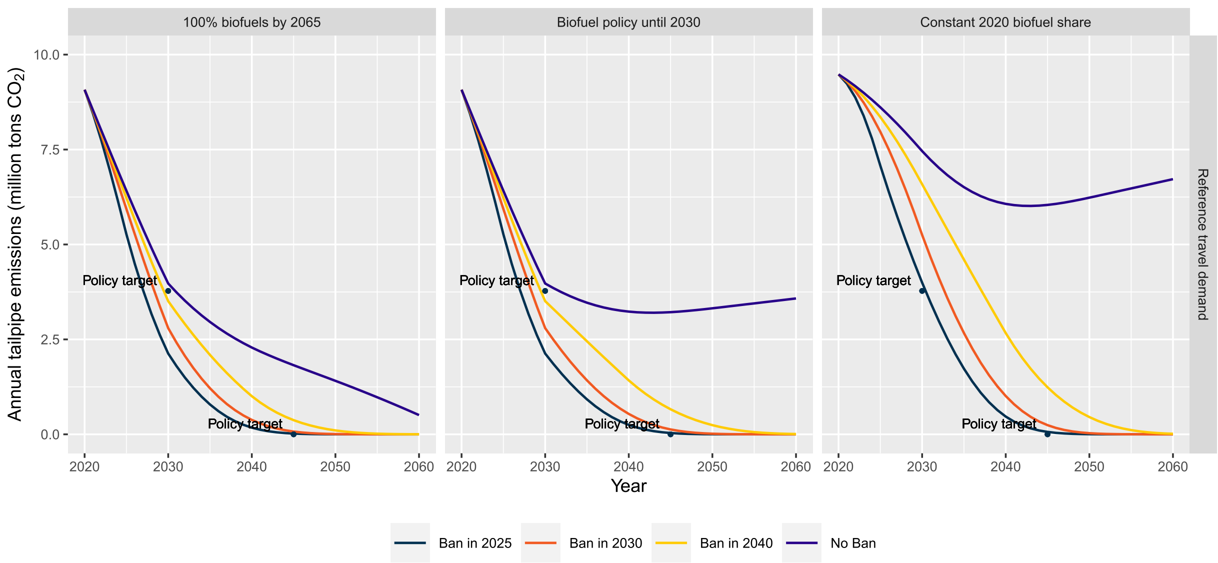

Fig. 9. Annual tailpipe CO_2 emissions highlighting the impact of timing of an ICE ban and the share of biofuel use. The reference travel demand is assumed. The indicative policy target for 2030 corresponds to a 70% decrease in annual emissions compared to 2010 and the indicative policy target for 2045 corresponds to reaching zero.

the carbon intensity for average European electricity and a 50% larger carbon intensity for electricity used in vehicle manufacturing, including the battery, a ban still results in reduced cumulative carbon footprints, see SM 3.

The time between the introduction of a ban on ICEs and the full phase out of those types of vehicles depends on their lifetime. Hence, the timing does not have a long-term effect on the annual carbon footprints beyond the vehicle lifetime (i.e., about 20 years after the ban), but the later the ban is enforced (ceteris paribus), the larger the cumulative carbon footprints will be. If we want to keep global mean surface temperature increase down and minimize the risks for an overshoot in temperature above internationally agreed targets, it is important to keep the cumulative emissions low over the coming decades (Rogelj et al., 2018).

Travel demand assumptions influence the annual carbon footprints throughout the period, resulting in an impact on the cumulative carbon footprint that will continue beyond the modeling time horizon, at least for as long as there are any CO_2 emissions along the supply chains. If a ban is introduced, the main impact of the travel demand assumption is on vehicle cycle emissions since a larger or smaller vehicle fleet would be needed to supply the assumed travel demand and since the electricity production is largely decarbonized in Sweden. Potentially, these emissions could be mitigated by measures that decrease the number of cars needed to meet a certain travel demand, e.g., through car and ride sharing.

3.4.3. Impact on tailpipe CO_2 emissions

As expected, annual tailpipe emissions are significantly influenced both by the timing of the ban on ICEs and by the assumed biofuel use, see Fig. 9. If biofuel use is assumed to be constant at current levels, only a ban in 2025 would be in line with the policy targets of 70% reduction in tailpipe emissions between 2010 and 2030 for the transport sector (shown as an indicative level in Fig. 9 where equivalent reductions are expected for passenger car travel as for the transport sector in general). Without a ban, the biofuel policy until 2030 alone will not be enough for a 70% reduction between 2010 and 2030 (although the target will be missed only with a very small margin). Depending on the timing of the ban, the 70% reduction target is overachieved to various degrees. The indicative level for 2045, which is to reach close to zero, is only achieved by combining an early ban (in effect by 2025 or 2030) with increasing biofuel use until 2030 at least.

Tailpipe emission reductions from increased biofuel use come at a cost of increased fuel cycle emissions. This is not the case for increased use of BEVs in a country such as Sweden, which has a power system that is largely decarbonized. In a broader context, this is likely to hold in other countries as well if the world moves towards the emissions reduction pathways necessary for achieving the climate targets stated in the Paris agreement, considering the growth of renewable electricity generation and the future outlook for the sector (de Coninck et al., 2018).

Tailpipe emissions are also to some extent influenced by the assumed future travel demand, but the effects are only minor in relation to the indicative policy targets, see SM 2.4. Cumulative tailpipe emissions change by ±3–9% for cases introducing a ban and ±10–16% for cases not introducing a ban, where the ranges depend on other foreground assumptions. Nevertheless, the travel demand could have significant impacts on the demand for biofuels in scenarios without a ban (e.g. from 39 TWh per year for the high travel demand case to 24 TWh per year for the low travel demand case in 2060, assuming continuous increase in the share of biofuels, see SM 2.10) and the number of BEVs needed to meet the travel demand in scenarios with a ban (from 10 million cars for the high travel demand case to 6.2 million cars for the low travel demand case in 2060, see SM 2.6). Hence, travel demand aspects are likely to be important given the limitations of bioenergy supply and the supply of critical materials necessary for batteries.

4. Policy implications of implementing a ban on ICEs

One of the motivations for the public inquiry (Swedish Government, 2019) is that emissions from domestic transportation are not declining fast enough to achieve the targets adopted in the Swedish climate policy framework[7]. In the case of domestic transportation, the net-zero target basically means zero emissions to allow for some remaining emissions in other sectors that are harder to abate (Swedish Government, 2020a).

Introducing a ban on ICEs could reduce annual tailpipe emissions as well as the cumulative carbon footprint. However, the full effect of phasing out liquid fuels as a result of introducing a ban is observed roughly 20 years after the ban (i.e., the time it takes for most cars to reach end-of-life). Consequently, only a ban that goes into effect as early as 2025 could in isolation from other policies achieve the annual tailpipe emission reductions needed to meet 70% emissions reduction in 2030 compared to 2010. If the share of biofuels increases until 2030, as a result of implementing the emissions reduction obligation quota policy, in combination with a ban on ICEs in 2025, the indicative policy target could instead be significantly overachieved (reaching a tailpipe CO_2 emissions reduction of 83% by 2030 compared to 2010). Combining a ban in 2030 with the biofuel policy would result in tailpipe emissions reductions of 78%. This is logical since the reduction levels of the policy were set based on a conservative electrification scenario (Swedish Energy Agency, 2019a). For comparison, annual tailpipe emissions would drop by 68% until 2030 compared to 2010 if the biofuel policy would be implemented without any additional policies on electrification of passenger car transport (nor any policies on a transport efficient society beyond the reference travel demand scenario). Hence, an early ban on ICEs could enable slower mitigation in segments of domestic transportation that may be harder to abate since the adopted policy target is binding for domestic transportation as a whole. On the other hand, an early timing of a ban on ICEs may be difficult to implement for a number of reasons, e.g., BEV models not yet spanning the range of cars demanded, limitations in battery supply, negative social and environmental consequences in the battery supply chain, lack of engineering know-how, and high battery manufacturing costs.

Nevertheless, introducing a ban on ICEs presents an important long-term option for emissions abatement since increasing use of biofuels may only be viable in the short-term. Heavy reliance on biofuels post-2030 comes with a number of risks in terms of biofuel supply and use. Apart from potential supply limitations due to competition with other sectors, there are concerns on the potential connection between increasing biofuel production and ILUC causing for example losses in biodiversity and additional GHG emissions (Berndes et al., 2013; Khanna et al., 2017; Sumfleth et al., 2020; Takaes Santos, 2020). In Sweden, some of these concerns may be mitigated through shifting from importing biofuels to domestic production, as a result of policy pressure and interest within the forest industry. Swedish forests consist of a mosaic of stands of different ages. Carbon losses in some stands counteract carbon gains in other stands, so that across the whole forest the carbon stock fluctuates around a trend line that has been increasing for many decades (Berndes et al., 2013). The increasing production of biofuels may influence land carbon stocks both positively or negatively, depending on how forest owners and farmers plan their land use in response to policies and regulations as well as current and anticipated demand for biofuels and other products. Understanding the full climate impact of Swedish biofuel use in relation to different electrification

[7] Adopted targets are that GHG emissions in domestic transportation shall be reduced by 70% by 2030 compared to 2010 and that economy-wide GHG emissions shall reach net-zero by 2045 at the latest.

strategies is an important area for future research. In addition, allocation of impacts between different products could mask emissions from biofuel production systems if they are not adjusted as production evolves to co-producing biofuels with other products rather than just making use of waste (Källmén et al., 2019). If biofuels remain as primarily imported, their use could also result in carbon leakage[8] if they are imported from countries that do not have ambitious enough climate change mitigation targets or do not regulate the production of biofuels throughout its supply chain.

On the other hand, faster fleet electrification also comes with a risk of carbon leakage due to the large demand for batteries following a policy-driven phaseout of ICEs. Battery manufacturing is currently CO_2 intensive. If manufacturing would be located in countries with less ambitious climate change mitigation targets and policies than Sweden, there is a risk that the embedded emissions in the vehicles (incl. batteries) will not decline over time. This risk is especially high for scenarios with a ban on ICEs where background systems (i.e., battery manufacturing) are not decarbonized in line with internationally agreed targets (see results for the Stated Policies scenario in section 3.3). Meanwhile, the mitigation potential in battery manufacturing is significant and could diminish the difference in embedded emission intensity between ICEVs and BEVs over time if fully realized (see results for Sustainable Development scenario in SM 2.2 and 2.3). In addition, the mining of materials used in batteries may result in substantial social and environmental problems abroad, such as negative impacts on water resources, local eco-systems and local communities. These mining operations need to be scaled up significantly if BEVs will become dominating in global passenger car markets. Hence, safeguarding measures need to be considered so that such problems are minimized (IEA, 2019a).

There are ways of handling the risks of carbon leakage and incentivizing emission reductions in manufacturing processes through further policy intervention, e.g., regulating the full carbon footprint of new cars. There are several options for including lifecycle thinking in climate policy for passenger cars, from regulations with more emphasis on data quality to credit systems that incentivize abatement measures in the supply chains (Lehmann et al., 2018). Full carbon footprints are being considered in future passenger car regulations by the European Commission (2019), but so far only developing a common methodology for data reporting has been announced. The European Commission (2020) has also proposed a new regulation on sustainable batteries that could mitigate environmental as well as social concerns in battery manufacturing, if adopted with carbon footprints thresholds in line with the identified mitigation potential in battery supply chains. Note though that such thresholds, irrespective of their ambition level, would not be enforced until 2027.

5. Conclusions

The annual carbon footprints of Swedish passenger car travel as well as annual tailpipe CO_2 emissions are estimated to decrease when introducing a ban on sales of new passenger cars with ICEs by 2030. Annual carbon footprints could be as low as 1.5 to 5.1 $MtCO_2$ by 2060, depending on the decarbonization of background systems (i.e., vehicle and battery manufacturing, and fuel production). This can be compared to 5.8 to 9.1 $MtCO_2$ (assuming increased shares of biofuels until 2030 in line with Swedish biofuel policy) if no ban is introduced. The effect of introducing a ban is delayed because of the lifetime of cars in the fleet of about 17 years.

Electrifying the fleet by introducing a ban on ICEs between 2025 and 2040 is beneficial regardless of the pace of decarbonization in global vehicle and battery manufacturing. Note though that batteries are assumed to be produced under global average conditions, regarding carbon intensity of electricity and the production processes used. Also, the cars are charged with Swedish electricity, which is already largely decarbonized today.

A combination of strategies for achieving tailpipe CO_2 emission reductions in line with adopted climate targets is likely needed. A ban on ICEs is likely to significantly contribute to achieving the policy target for Swedish domestic transportation in 2030 and the economy-wide net-zero target for 2045. However, a strategy based on only banning ICEs would likely not be enough for reducing the tailpipe CO_2 emissions by 70% by 2030 (compared to 2010) unless the ban is in effect already by 2025.

Such an early ban is challenging to implement; hence, the emissions reduction obligation quota policy is likely needed until 2030. The policy together with an early timing of the ban could even overachieve the 70% reduction in tailpipe emissions by 2030, enabling slower abatement in other segments of domestic transportation. The overachievement in 2030 could also be used to reach higher climate change mitigation ambitions in general, which would further contribute to the rapidly decreasing pathway needed to achieve the goal of the Paris agreement without relying on overshoot pathways.

Increasing the share of biofuels further after 2030 comes with risks related to supply, additional climate impacts and carbon leakage. However, also batteries come with potential negative impacts along its supply chain such as potential negative social and environmental consequences of mining operations and risks of carbon leakage. Some of these issues could be handled by considering coupling a ban on ICEs with regulation of vehicle and battery manufacturing, e.g., by regulating the carbon footprint of new vehicles and/or batteries. Nevertheless, supply chain consequences for both biofuels and batteries are important areas for future research aimed at better understanding the consequences of different decarbonization pathways.

Policies that aim to reduce travel demand could be important for mitigating the need for biofuels in a slow transition to BEVs, the need for electricity and batteries in a fast transition to BEVs (including the potentially critical battery materials), and for minimizing emissions along fuel and vehicle supply chains. However, the impact of reduced travel demand on tailpipe emissions is minor in

[8] There are several definitions of carbon leakage, from those that cover all embedded emissions in trade to those that are connected to specific policies, such as the definition in the Kyoto Protocol that only considers the category of country within the agreement (Peters and Hertwich, 2007). The definition used here is based on the Swedish policy target – the Generational goal, stating that environmental problems in Sweden should be solved without increasing environmental problems outside Sweden's borders (Sveriges Miljömål, 2020).

isolation from other mitigation strategies.

CRediT authorship contribution statement

Johannes Morfeldt: Methodology, Formal analysis, Writing - original draft, Visualization. **Simon Davidsson Kurland:** Conceptualization, Methodology, Writing - review & editing. **Daniel J.A. Johansson:** Conceptualization, Methodology, Formal analysis, Writing - review & editing, Funding acquisition.

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Appendix A. Supplementary material

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