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Recoupling Climate Change and Air Quality: Exploring Low-Emission Options in Urban Transportation Using the TIMES-City Model

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Abstract: Fossil fuels in transportation are a significant source of local emissions in and around cities; thus, decarbonising transportation can reduce both greenhouse gases (GHGs) and air pollutants (APs). However, the degree of these reductions depends on what replaces fossil fuels. Today, GHG and AP mitigation strategies are typically 'decoupled' as they have different motivations and responsibilities. This study investigates the ancillary benefits on (a) APs if the transport sector is decarbonised, and (b) GHGs if APs are drastically cut and (c) the possible co-benefits from targeting APs and GHGs in parallel, using an energy-system optimisation model with a detailed and consistent representation of technology and fuel choices. While biofuels are the most cost-efficient option for meeting ambitious climate-change-mitigation targets, they have a very limited effect on reducing APs. Single-handed deep cuts in APs require a shift to zero-emission battery electric and hydrogen fuel cell vehicles (BEVs, HFCVs), which can result in significant upstream GHG emissions from electricity and hydrogen production. BEVs powered by 'green' electricity are identified as the most cost-efficient option for substantially cutting both GHGs and APs. A firm understanding of these empirical relationships is needed to support comprehensive mitigation strategies that tackle the range of sustainability challenges facing cities.

Keywords: climate policy; air pollution policy; ancillary benefits; energy-system optimisation model; urban energy system

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1. Introduction

Radical shifts in the current fossil-based energy system are needed to reduce greenhouse gas (GHG) emissions and improve local air quality. Cities collectively account for more than three quarters of the total global final-energy use and generate three quarters of total global GHG emissions [1]. More than 80% of urban residents (in cities that monitor air pollution) are subject to substandard air quality [2]. In developed countries, where urban economies are typically service-intensive, transportation represents 25–35% of total final energy use [3] (pp. 160–161). Moreover, since most transportation fuels have fossil sources, they generate significant emissions of both carbon dioxide (CO_2) [4] and air pollutants (APs) [5]. With this close connection between CO_2 and APs, there is broad scientific consensus that reducing fossil fuel combustion to mitigate climate change could also improve local air quality [6]. However, some potential trade-offs have been observed. For example, switching from gasoline to diesel improved fuel economy and CO_2 performance, but it resulted in considerably higher emissions of particulate matter (PM) and nitrogen oxides (NO_X) [7,8], while substituting fossil diesel with biodiesel was similarly found to increase emissions of NO_X [9,10]. Furthermore, although battery electric and hydrogen fuel cell vehicles (BEVs and HFCVs, respectively) can completely eliminate local emissions, their total contribution to mitigating climate change is determined by upstream factors such as the feedstock of and specific production pathways for electricity and hydrogen (H_2) [11–13].

Considering significant regional heterogeneity in the power mix, relying on one-size-fits-all subsidies to support the introduction of BEVs may cause negative co-benefits for climate change mitigation, hence, more diversified subsidies may be called for to ensure positive impact from BEV deployment [14]. Meanwhile, very little investigation has been conducted on how deep cuts in local APs from transportation could potentially impact on climate change mitigation. In [15], meeting the 2020 air quality targets for the European Union (EU) induced a 10% cut in total CO_2; however, most of this reduction occurred in power production and agriculture. Thus, a deeper understanding of the positive and negative side-effects of different options is needed to tap into their potential co-benefits [16]; this calls for a holistic view, where multiple objectives are taken into consideration simultaneously [17].

Many cities possess the wealth, willingness to act and the required understanding when it comes to accelerating the transition towards a more sustainable provision, delivery and final use of energy [18]. Within the EU, which is the overarching setting for this study, a growing number of cities are adopting ambitious, strategic energy and climate-change-mitigation plans, and many cities are already engaging in transnational networks to address energy-related GHGs [19]. Cities and regions are also being urged to adopt Air Quality Plans (AQPs) that tackle the health and environmental impact of substandard air quality (prompted by Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe) [20]. To improve accessibility, equity and the overall quality of urban life, while at the same time reducing energy consumption, APs and GHGs from transportation, the European Commission (EC) also strongly recommend employing Sustainable Urban Mobility Plans [21] (p. 32). However, as energy-related emissions from transportation are typically being addressed in several different, locally determined strategies and action plans, this can result in a patchwork of policies that effectively decouple the mitigation of GHGs and APs. Thus, exposing the potential co-benefits and trade-offs from different options can help to highlight the advantages of recoupling (i.e., reverting current decoupling of) CO_2 and AP mitigation strategies [22]. As much of the low-hanging fruit in respect of achieving these measures has already been harvested, further emissions reductions will place even greater pressure on using economic resources more efficiently, which, in turn, calls on policymakers to design stringent and cost-effective win-win strategies [23].

If one wishes to assess the long-term options available in real-world systems, mathematical models can be employed to provide a powerful framework for 'mental experiments' that widen our understanding of how the system may evolve under different circumstances [24]. For example, energy-system optimisation models (ESOMs) are widely used to provide insight into anticipated long-term energy transitions. The analytical strength of such models is linked to their ability to offer a detailed and consistent techno-economic representation of all critical technologies and energy-carriers in the energy system, including emission factors for CO_2 and APs, and their linear programming approach that allows efficient goal-seeking within complex systems [25]. In this way, the ancillary and co-benefits from CO_2 and AP mitigation actions in energy sectors can be explored. Some studies have assessed the effect on national climate change mitigation priorities when also adding air pollution damage costs to the modelling efforts (e.g., by [26,27]), while others have explored some specific ancillary benefits from decarbonising the transport sector (e.g., by [28–30]). However, these earlier researchers focused on the ancillary benefits that decarbonisation had on air pollution: no studies to date have simultaneously explored climate-change-mitigation and air quality targets (as emphasised by [31]). Moreover, while other research [26–30] targets national levels, comprehensive ESOM studies at city-level typically exclude APs when they explore policies aimed at transforming final-energy use in cities [32] or at transitioning to low-carbon options in urban centres under various circumstances [33–35]. Thus, previous energy-system transition studies addressing urban-level co-impacts between CO_2 and AP mitigation options and strategies are rare. This study aims not only to contribute towards filling this gap, but also to identify potential win-win strategies by assessing ancillary and co-benefits from low-emission options in the transport sector. The objective is to explore (i) the benefits to AP from decarbonising the transport sector; (ii) the benefits for CO_2 mitigation from deep cuts in APs; and (iii) the possible additional co-benefits when CO_2 emissions and APs are reduced in parallel. These explorations will be achieved by applying and adapting a generic TIMES-City ESOM to Malmö, a city of around 320,000 inhabitants in south-western Sweden.

The remainder of the paper is structured as follows. Section 2 outlines the analytical approach taken, defines the system studied and introduces the modelling framework adopted, while Section 3 describes key data and scenario assumptions. Section 4 presents the results of the model simulations and outlines the ancillary and co-benefits they may entail. In Section 5, the results and their implications are discussed, whereas Section 6 offers the main conclusions drawn.

2. Analytical Approach, Definition of the System Studied, and Modelling Framework

2.1. Analytical Approach

Determining the potential co-impacts when meeting ambitious CO_2 and AP emission-reduction targets in the transport sector is approached by categorising different types of impacts; by distinguishing between the notions *direct benefit*, *ancillary benefit* and *co-benefit*; and by using the framework laid out in [36] and illustrated in Figure 1. A direct benefit is the intended impact of an implemented policy, e.g., lower CO_2 emissions due to a specific CO_2 mitigation measure when compared with a no-policy reference scenario. An ancillary benefit is a (positive or negative) side-effect which is not the primary intended outcome of the imposed policy, e.g., where a policy primarily targeting CO_2 emissions simultaneously reduces APs. Ancillary benefits are quantified as the relative difference in emissions compared with a no-policy reference scenario. Co-benefits may occur when both CO_2 and AP reduction targets are applied in parallel; such benefits are quantified as any additional emission reduction when compared with the direct benefits found in each respective individual-policy scenario.

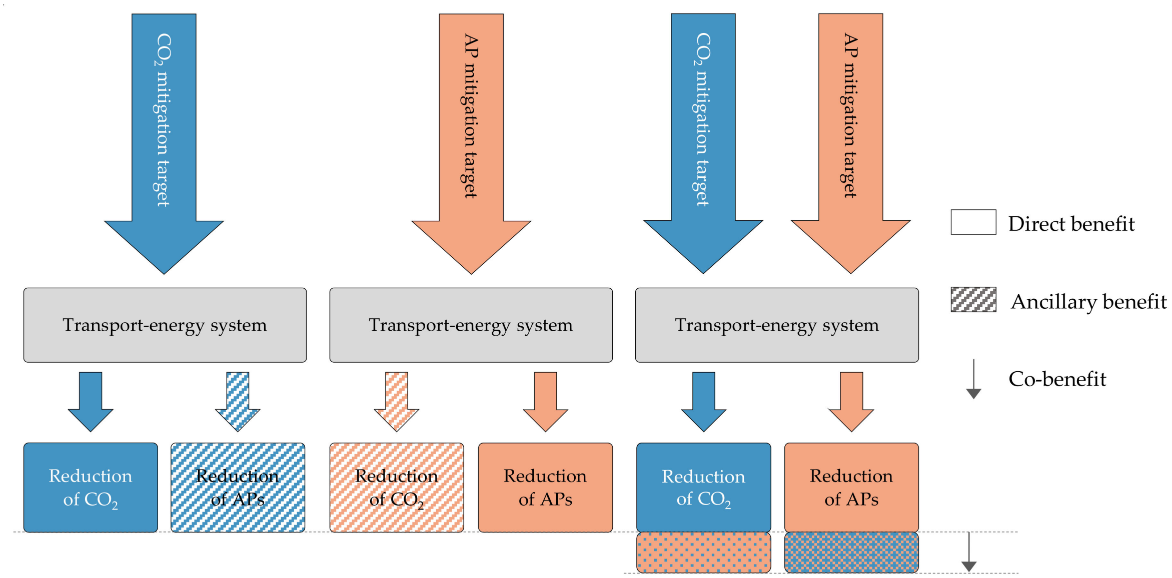

Figure 1. Conceptual framework for assessing the *direct*, *ancillary*, and *co-benefits* of mitigation measures targeting carbon dioxide (CO_2) and air pollutant (AP) emissions.

2.2. Definition of the System

This paper builds on the basic understanding of urban transport-energy system characteristics laid out in [37]. Besides thoroughly considering the technology and fuel options in the specific setting, one also needs to specify the system boundaries for the modelling efforts. These boundaries are key, since cities rely on a continuous flow of people and goods within, into and out of them; thus, only including intra-city transport activities is insufficient. This study therefore employs a so-called geographic plus model representation adopted from [38], which uses daily intra-city as well as long-distance transport activities induced by cities, i.e., by its residents, local businesses, public administration, etc. This approach allows the demand for transportation and the associated use of energy and subsequent emissions to reflect the transport-related 'footprint' of a city (here, Malmö), whereas local energy statistics typically account for fuels and their associated emissions, regardless of users within a city's administrative borders. Also note that transport activities attributed to neighbouring cities or traffic simply passing through are excluded in this study.

2.3. Modelling Framework

The TIMES-City model used in this paper is based on The Integrated MARKAL-EFOM System (TIMES) optimisation model generator, which seeks to satisfy user-defined demand for energy-intensive services (as transportation) and goods at minimum cost under given constraints [39]. The objective function to be minimised by the model optimisation is formulated as:

$$NPV = \sum_{r=1}^{R} \sum_{y \in YEARS} \left(1 + d_{r,y}\right)^{REFYR-y} \cdot ANNCOST(r,y) \tag{1}$$

where NPV is the net present value of the total cost for all regions; $ANNCOST(r,y)$ is the annual cost in region r and for year y; $d_{r,y}$ is the general discount rate; $REFYR$ is the reference year for discounting; $YEARS$ is the set of years for which there are costs; and R is the set of regions in the study area. The TIMES modelling framework is well-suited for analysing long-term energy-environmental policies, which may be accurately represented by explicit and consistent representation of energy carriers, as well as by the extraction, conversion and end-use technologies across all sectors (see e.g., [40]). The model framework is typically characterised as a (multiple) partial equilibrium model, i.e., it has no explicit connection to the rest of the economy and thus cannot be used to analyse the wider social impacts of specific energy-environmental policies. The TIMES-City model was developed from this framework and was adapted to three municipalities—including Malmö—as part of the SureCity project. The underlying scope and rationale are elaborated in [41] and the entire city modelling framework is described in [42]. While the general modelling framework encompasses all sectors, this study only addresses the transportation and energy supply sectors.

2.3.1. Transport Sector Representation

The general TIMES-City model covers conventional road, rail, maritime and aviation transport modes, as well as non-travelling options that represent home-based work, video conferencing, etc. Options that do not apply to Malmö have been excluded. Figure 2 illustrates the specific model representation used in this study, along with the assumed load factors involved, i.e., the average number of passengers or the amount in tons of goods carried by each vehicle or vessel type.

Demands are given separately for each mode of transport and each segment, i.e., a shift in mode is dealt with via exogenous scenario assumptions. All transport activities are divided into either short- (intra-city) or long-distance travel (entering or exiting Malmö). Thus, walking, bicycles and urban buses constitute intra-city modes of transport, while intercity buses, rail transportation and maritime freight meet the long-distance transport demand. Cars, light commercial vehicles (LCV), medium-sized goods vehicles (MGV) and heavy goods vehicles (HGV) service both short- and long-distance transport needs. For the latter representation, individual technology options needed to supply a minimum share of 25% (short- and long-distance) each to prevent unrealistic outcomes, e.g., where one technology option (such as BEVs) only meet intra-city transport demands, while others (such as diesel vehicles) only meet long-distance needs.

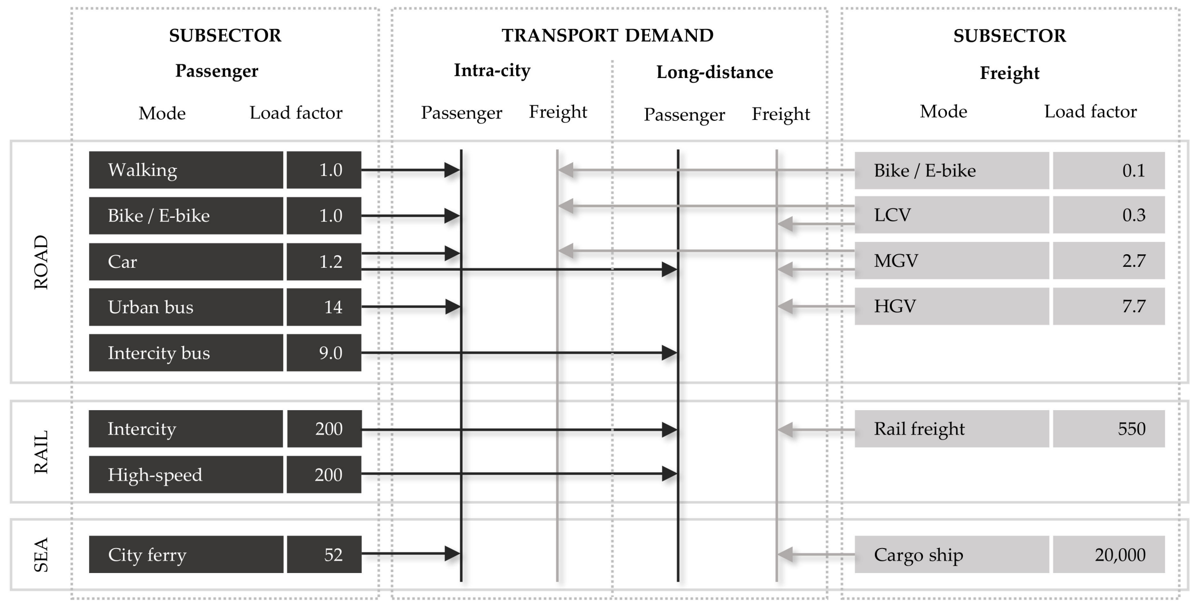

Figure 2. Transport sector representation used in the study, with load factors detailing the as assumed number of passengers or tons of goods for each mode of transportation. *Note*: LCV = light commercial vehicle (<3.5 t); MGV = medium-sized goods vehicle (3.5–18.0 t); HGV = heavy goods vehicle (>18.0 t).

2.3.2. Fuel Portfolio

All the currently available and prospective fuel options applicable to the various transport modes and subsectors are summarised in Table 1. The greatest variety in current and future choices is found in road transportation, while its rail and maritime counterparts have a comparatively limited portfolio of options. Note that not all listed fuel options are available to all vehicle segments. This study also assumes all fuels have been imported, i.e., fuel production is not explicitly modelled. To account for the variety in feedstock and production pathways for the various fuel options, different import commodities are used and assigned specific upstream CO_2 emission factors (see Section 2.3.3).

Table 1. TIMES-City fuel portfolio and current/assumed prospective year of availability per fuel option and transport mode.

Transport Mode	Biodiesel	Biomethane	Bio-Dimethyl Ether	Diesel	Electricity	Bioethanol	Fuel Oils	Gasoline	Hydrogen	Liquefied Petroleum Gas	Biomethanol	Natural Gas
Road	2015	2015	2030	2015	2015	2015	-	2015	2030	2015	2030	2015
Rail	2015	-	-	2015	2015	-	-	-	-	-	-	-
Sea	-	-	-	-	-	-	2015	-	-	-	2030	2030

2.3.3. Emission Factors

The TIMES-City model includes emission factors (given in kg/GJ) for all major GHGs. However, this study only targets CO_2 since it is by far the most significant GHG emitted from transportation. CO_2 emission is associated with the provision and use of energy commodities (fuels). Thus, CO_2 emission factors are divided into *tailpipe* emissions (i.e., emitted directly by combusting fossil fuels) and *upstream* emissions (i.e., from extracting, converting and distributing energy commodities) to account for the global impact of different pathways. By using different upstream emission factors, we can also (implicitly) account for a variety of feedstock options in the production of biofuels, electricity and H_2. All assumed CO_2 emission factors are provided in Appendix A, Table A1. Note that upstream CO_2

emissions exclude emissions from the manufacturing of vehicles and the construction of road, rail or energy supply infrastructures.

For APs, which mainly have a local or regional impact, we only include tailpipe emissions, determined for each combination of technology and fuel. Consequently, non-tailpipe emissions, such as PM from road and break wear and tear or suspended dust particles, are not captured. For road vehicles, anticipated improvements in emission performance following tightened EU standards are captured by improved emission factors. Since there are no similar general standards in place for the rail, aviation or maritime modes, no general improvements are assumed for these modes of transport. All assumed AP emission factors are provided in Appendix A, Table A2.

3. Key Data and Scenario Assumptions

A TIMES model scenario is based on a set of assumptions about the future trajectories of the main drivers of the energy system concerned. These assumptions typically include an exogenously determined projection of future demand (over the entire modelling horizon), energy supply curves with associated costs, a set of technologies with related techno-economic data and the policy settings to be explored [38]. The following sections elaborate on the key considerations and assumptions for the current study, which adopted a modelling horizon spanning from 2015 to 2050.

3.1. Transport Demand

The model is driven by the demand for passenger and freight transportation over the entire period modelled. Such demands are expressed in passenger-kilometres (pkm) and ton-kilometres (tkm), respectively. Since no official projections were available for the future transport demand in Malmö, own estimates needed to be made based on various sources and data. For passenger travel demand, the base-year demand and mode shares were derived from the City of Malmö's travel survey, which included data such as trip purpose, mode share and average trip distance [43]. Future daily travel demand was assumed to grow according to the anticipated population growth (i.e., independent from socio-economic development); this resulted in an 0.8% average annual growth in travel demand, based on the City of Malmö's own short-term projection [44] and long-term projections from [45]. In the *Business-as-usual* (BAU) case, no shift (compared to the base year) in modal preference was assumed. To also analyse the impact on energy-use and emissions from mode shifting, a *Mode Shift* (MS) case was introduced. The assumed shifts from private cars to active travelling (walking or cycling) and public transportation are exogenously determined to reflect the ambitions of the City of Malmö's Sustainable Urban Mobility Plan [46]. In the plan, the City of Malmö provide some examples on how to achieve this, e.g., mobility management measures, improving bicycle infrastructures and the level of service in public transportation, developing intermodal travel points, support car-free living and car-sharing options, shifted parking policies and physical planning priorities. Note that we make no attempt to explore the effects or costs of such policies, nor to assess the likeliness of achieving the assumed shifts. For freight transport demand, where quantifiable data and information was scarce, we first determined the demand for goods attributed to Malmö from a consumption perspective, using per capita 'material footprint' data from [47], population growth projections (the same as for determining future travel demand), and gross domestic product (GDP) per capita projections [48]. This resulted in an average annual growth of 2.3% in the demand for goods over the modelling horizon. Next, the demand for goods in each time-period was combined with the average distances and mode shares for the transportation of different commodity groups within Sweden gathered from [49]. For the BAU case, no mode shifting was assumed, while the MS case included moderate shifts from road to rail for long-haul freight (based on own exogenous assumptions). All demand inputs are given in Appendix A, Table A3.

3.2. Fuel Costs, Fuel Taxes, and Infrastructure Costs

As fuel production is not explicitly modelled, all fuel costs are given as exogenous modelling assumptions. The costs of conventional fossil fuels are related to crude oil and natural gas price projections adopted from the International Energy Agency's '450 ppm' [50] and '2 °C' Sustainable Development scenarios [51]. The pricing of alternative fuels can depend on several factors, including fossil fuel prices, feedstock prices, subsidies, level of technology and market maturity. In the current study, all alternative fuels are priced in relation to their respective fossil fuel counterpart. Short-term price relations are based on data from [52], while the relative cost difference between fossil and alternative fuels in the longer term is assumed to decrease to account for technology learning and economy of scale in the production of alternative fuels. Nonetheless, all alternative fuels are priced higher than conventional fossil fuels in all time periods. All scenarios use the same fuel cost assumptions, which are presented in Appendix A, Table A3. Besides the fuel costs, the model simulations also include fuel taxes; these are based on Sweden's 2015 national fuel taxation principles and tax levels. Fuel taxes are split into energy taxes and CO_2 taxes, where the latter are only applied to tailpipe emissions (i.e., only to fossil fuels). Thus, there is no CO_2 tax assumed on upstream emissions from fuel production. All scenarios use the same fuel tax assumptions, presented in Appendix A, Table A4.

Another critical factor for the uptake of electricity, alternative fuels, or high-blend biofuels in the transport sector is the availability of recharging and refuelling infrastructure. To account for this, an additional fuel-specific cost (set as €2015/GJ·year) was included on all fuel supply technologies deployed after the base year. As far as possible, cost assumptions are based on data from the supporting information in [53], with some additional own assumptions; these costs are presented in Appendix A, Table A5. Note that we do not account for any costs of upgrading local electricity grids to support fast-charging, or for investments in the existing natural gas grid in Malmö to support a potential increase in gas use.

3.3. Technology Database

The set of technology options includes vehicles with conventional internal combustion engines, plug-in hybrid electric vehicles (PHEVs), BEVs and HFCVs, but not all options are assumed to be readily available to all segments. Rail transportation only has the choice of electricity as a source of power, while the maritime subsector is represented in less detail than its counterparts, namely as a generic freight vessel with three different fuel choices. As far as possible, the techno-economic parameter assumptions used in this study were retrieved from the JRC-EU-TIMES model (thoroughly described in [54]), which reflect assumed efficiency improvements and projected cost curves for different vehicle types over the entire modelling horizon. Additional assumptions were needed for bicycles, biomethanol and dimethyl ether road vehicles, bioethanol trucks, all intra- and intercity bus options and city ferries. The technology portfolio and all associated techno-economic data are the same for all scenarios, and all costs are given in €2015. To explore the relative attractiveness of different options under stringent mitigation targets, rather than assessing the likeliness and pace of technology or fuel uptake, no model boundaries were set for potential future market shares or on the rate of technology deployment.

3.4. Policy Setting

3.4.1. Climate-Change-Mitigation Targets

Since 2018, Sweden has had a new and ambitious climate policy framework in place, calling for net-zero domestic GHG emissions by no later than 2045 [55]. The net-zero target is defined as an 85% reduction of direct domestic GHGs by 2045, compared with 1990 levels. Any remaining emissions should be offset by complementary actions, including carbon capture and storage or utilisation. The framework includes an intermediate target for domestic transportation (excluding aviation) to cut GHGs by 70% by 2030, compared with 2010 levels. The official local CO_2 emission data are derived from national aggregate data using a territorial approach [56], which is not in line with the 'footprint' modelling approach used in this study. Instead, therefore, the baseline was generated by running the model for a single year using 2010 input data. Next, the target was applied, starting from 2020 (notably, the same total aggregate CO_2 emissions allowed in 2015 were also allowed in 2020). Thereafter the CO_2 target trajectory progresses in a linear fashion from 2020 to 2030, and then from 2030 to 2045. The net-zero target was implemented by imposing a 100% reduction target on tailpipe emissions (which effectively disqualifies use of fossil fuels), and an 85% reduction target on upstream CO_2 (which allows some remaining upstream emissions). The latter (85%) reduction target was necessary for the model to find a solution as some upstream emissions were assumed for all biofuels, and as zero-emission options (e.g., electric vehicles powered by carbon-neutral electricity) are not available to all subsectors. Note that 2010 is used as baseline also for the 2045 target, though the official national target is set relative to 1990. The reason is that the vehicle statistics from 1990 is less detailed compared with the statistics for year 2010 (from 2006, the vehicle stock statistics is disaggregated by fuel-type). Using 1990 as reference would likely have reduced the 2045 target slightly, however, there are no additional technology or fuel choices in the model which are not already induced by the current targets. Any measures to offset remaining upstream emissions are not analysed or discussed further in this paper. The targets and milestone years are summarised in Table 2.

Table 2. Summary of CO_2 and air-pollutant mitigation targets and milestone years.

	CO_2 Mitigation Targets (Relative to 2010 Levels)			AP Mitigation Targets (Relative to 2015 Levels)		
Year	**Total Emissions**	**Tailpipe Emissions**	**Upstream Emissions**	**Emission of NO_X**	**Emission of PM**	**Emission of NMVOCs**
2020	0%	0%	0%	0%	0%	0%
2030	−70%	-	-	−70%	−70%	−70%
2045	-	−100%	−85%	−85%	−85%	−85%

3.4.2. Air-Pollutant Mitigation Targets

PM, NO_X and ground-level ozone (O_3) are generally considered the most troubling APs, both globally [57] and in Sweden [58]. Ground-level O_3 is not emitted directly but is formed by precursor compounds such as NO_X and non-methane volatile organic compounds (NMVOCs) [59]. Hence, our modelling efforts target PM, NO_X and NMVOCs. Air quality targets expressed as maximum allowed concentrations of pollutants (μg/m^3 of air) cannot be directly applied in a model such as TIMES-City. Instead, as for CO_2, the targets were set as reductions in quantitative emissions relative to a specific reference year, using model-generated emissions as a baseline. The targets for all APs were applied in parallel. Early model runs included targets that reflected the local situation in Malmö (based on the city's own monitoring [60]) with regard to current Swedish air quality standards set for 2020 but with no further strengthening thereafter. However, these model runs did not result in any significant shifts in technology or fuel preferences, nor did they produce any co-benefits for CO_2 mitigation. Instead, progressively stricter AP mitigation targets were used, applying the same levels and milestone years to APs as for CO_2 (completely eliminating all APs was not possible with current model assumptions) (see Table 2). Furthermore, air quality is typically considered an urban issue, yet the long-range dispersion of pollutants necessitates mitigation actions beyond the local scale [61,62]. In Malmö, considering the city's port and its location along a heavily trafficked waterway, the maritime segment is recognised as a significant contributor to local AP concentrations. Hence, in this study, AP mitigation targets were applied to all transportation activities equally.

3.5. Scenario Set-Up

To assess the ancillary benefits of single policies as well as the co-benefits of combining all targets at the same time, eight different scenarios were defined and implemented in the model. Four of these built on the BAU transport demand curves, while the remaining four took mode shifting into account (MS). A summary of the scenario characteristics is provided in Table 3.

Table 3. Summary of scenario characteristics.

Model Assumptions	Scenarios							
	BAU_REF	**BAU_AP**	**BAU_CO2**	**BAU_AP_CO2**	**MS_REF**	**MS_AP**	**MS_CO2**	**MS_AP_CO2**
Business-as-usual demand projections	✓	✓	✓	✓				
Mode-shift demand projections					✓	✓	✓	✓
Air-pollutant mitigation targets		✓		✓		✓		✓
CO_2-emissions mitigation target			✓	✓			✓	✓

4. Results

In this section, we first present the model results for each scenario regarding technology and fuel choices and their respective associated CO_2 and AP emissions, followed by an analysis of the ancillary and co-benefits from each scenario. Road transportation is given special attention as it not only accounts for the bulk of transport-related emissions, but also currently enjoys the largest pool of prospective low-emission options, which is also reflected in the model's level of detail. In the presentation of the results (Section 4.1) road-transport technology preferences are aggregated by key technology type (summarised in Table 4), and all fuels are aggregated in key fuel-categories (summarised in Table 5).

Table 4. Types of road vehicle by drive-train technology and associated fuel.

Vehicle by Drive-Train Type	Abbreviation	Associated Fuel
Conventional + non-plug-in hybrid electric spark ignition (SI) vehicle	SI + HEV	Gasoline, compressed natural gas (CNG; natural gas + biomethane), flex fuel (E85), liquefied petroleum gas (LPG), and biomethanol
Conventional + non-plug-in hybrid electric compression ignition (CI) vehicle	CI + HEV	Diesel, biodiesel, bioethanol (ED95) and bio-dimethyl ether (DME)
Plug-in hybrid electric vehicle	PHEV	Electricity + gasoline or diesel
Battery electric vehicle	BEV	Electricity
Hydrogen fuel cell vehicle	HFCV	Hydrogen

Table 5. Aggregate fuel-categories.

Fuel-Category	Type of Fuel or Production Pathway Included
Fossil fuel—liquid	Gasoline, diesel, and fuel oils
Fossil fuel—gaseous	Natural gas and liquefied petroleum gas (LPG)
Biofuels—liquid	Biodiesel, bioethanol, biomethanol
Biofuels—gaseous	Biomethane and bio-dimethyl ether
Electricity	Nordic electricity mix, average EU mix and CO_2-neutral ('green') mix
Hydrogen (H_2)	H_2 produced from natural gas, without carbon capture and storage (i.e., 'grey' H_2), or by electrolysis, using CO_2-neutral electricity (i.e., 'green' H_2)

4.1. Technology and Fuel Preferences and Associated Emissions

Mode shifting was found to reduce the total final-energy consumption and slightly alter the relative contribution from different fuel options compared with the *BAU* scenarios, but such shifts had no impact on overall technology or fuel preferences. For this reason, only the *BAU* scenario results are displayed here; *MS* scenario results are presented in Appendix B. Similarly, PM proved to be the most constraining of the APs; thus, we only display PM results here, while NO_X and NMVOC results are shown in Appendix B.

In the no-policy *BAU_REF* scenario, the least-cost solution is dominated by conventional road vehicles (see Figures 3 and 4) and fossil fuels (see Figure 5) in all given time periods. Up until 2025, compressed natural gas (CNG) vehicles dominate among new cars and LCVs, while diesel-fueled hybrid electric vehicles (HEVs) take over from 2030. Across all time periods, urban buses run on CNG, while long-distance heavy road transport remains diesel-powered. All rail transportation continues to be powered by electricity, while the maritime subsector continues to rely on fossil fuel oils in all time-periods. Assumed energy efficiency gains in new conventional road vehicles reduce the total final-energy demands up until 2040, despite an increase in transport demand, which also helps to curb upstream and tailpipe CO_2 emissions (see Figure 6), while energy use and emissions increase from 2040 as efficiency improvements can no longer offset the growth in transport demand. The faster growth in freight transport demand compared with passenger transport results in road freight taking over (from cars) as the main contributor of tailpipe CO_2 (from 29% in 2015 to 54% in 2050). Even without AP targets, the no-policy *BAU_REF* scenario generates considerable reductions in all included pollutants. NMVOCs are cut drastically as light duty gasoline vehicles, which represent >80% of base-year NMVOCs, are substituted for diesel HEVs. A NO_X decrease follows anticipated improvements in all road vehicles, and despite an increase in maritime NO_X. Total PM decreases due to significant improvements in heavy road vehicles, representing 65% of reference-year PM. However, this reduction is (partly) countered by an increase in PM from maritime transport and from light duty road vehicles, owing to the dominant role of diesel HEVs from 2030 (see Figure 7).

In *BAU_AP*, the AP targets induce significant shifts in road transportation. Cars and LCVs are initially shifted to CNG (–2025) while transitioning to zero-emission HFCVs and BEVs is needed to reach very low AP levels (2030–). From 2035, MGVs—which operate mainly in intra-city freight distribution—shift to HFCVs, while urban buses and long-distance heavy road vehicles remain CNG- and diesel-powered, respectively, over all time periods. As the fleet of energy-efficient zero-emission road vehicles increases, total fuel demand reduces notably; by 2040–2050, a significant share of fuel demand is covered by 'grey' H_2 (i.e., H_2 produced from natural gas, without carbon capture and storage). The AP targets also induce a shift from fuel oil to natural gas in shipping, which significantly cuts maritime PM emission levels. Altogether, the technology and fuel shifts in *BAU_AP* produces very low levels of APs: while NO_X and NMVOC targets are exceeded, the PM target is precisely met—indicating that it is the most constraining of the AP targets under the assumed conditions.

In the *BAU_CO2* scenario, the progressive CO_2 target induces no shift in technology preferences compared with *BAU_REF*, while the fuel mix is dominated by low-carbon liquid biofuels. In this scenario, biodiesel replaces fossil diesel in all road transport modes except urban buses, which shift from natural gas to biomethane. Maritime freight transport shifts to biomethanol (from 2040), which is the only available biofuel option in this subsector. Electricity is only used for rail transportation; the mix in this case consists of carbon-neutral 'green' electricity and the Nordic electricity mix. The only remaining CO_2 emissions in 2045–2050 are upstream emissions from biofuel and electricity production.

In *BAU_AP_CO2*, the combination of AP and CO_2 targets induce equally substantial yet slightly different shifts, compared with the *BAU_AP* scenario. Beginning in 2030, the car and LCV fleets are dominated by BEVs instead of HFCVs, i.e., BEVs powered by 'green' electricity are the least-cost option for meeting very low levels of local APs and upstream and tailpipe CO_2 emissions. This shift also further reduces the total final-energy demand (see Figure 5). In the MGV segment, a partial shift to BEVs is also found in 2045–2050, while biomethane replaces natural gas in urban buses. Long-distance heavy road vehicles are still dominated by conventional diesel vehicles powered by biodiesel. However, a small share of HGVs shifts to bioethanol (ED95) from 2040; this shift reduces PM from HGVs, which is needed to counter increasing maritime PM following the shift to biomethanol (as an alternative to natural gas as in *BAU_AP*). Also, as in *BAU_AP*, NO_X and NMVOC targets are exceeded in *BAU_AP_CO2* following shifts to zero-emission vehicles and anticipated improvements in heavy road diesel vehicles, while PM and CO_2 targets are met precisely. In other words, the PM and CO_2 targets are the main drivers of the model outcomes.

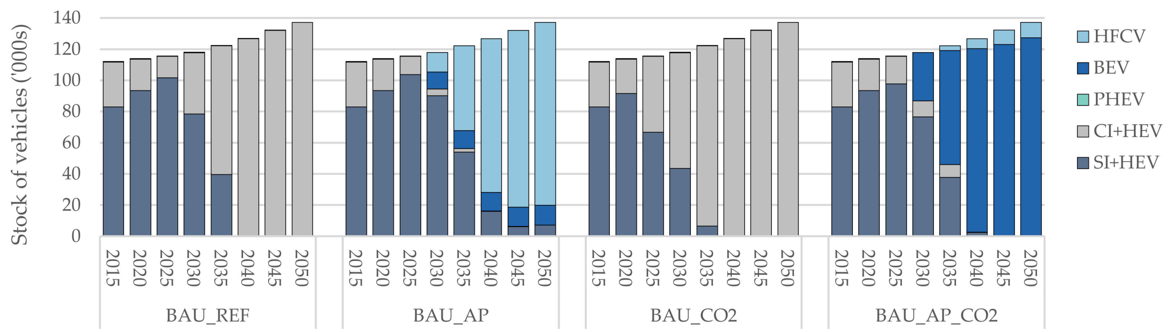

Figure 3. Total stock of cars and light commercial vehicles (LCVs) in the Business-as-usual (BAU) scenarios ('000s). *Note*: HFCV = hydrogen fuel cell vehicle; BEV = battery electric vehicle; PHEV = plug-in hybrid electric vehicle; CI + HEV = Conventional + non-plug-in hybrid electric compression ignition (CI) vehicle; SI + HEV = Conventional + non-plug-in hybrid electric spark ignition (SI) vehicles.

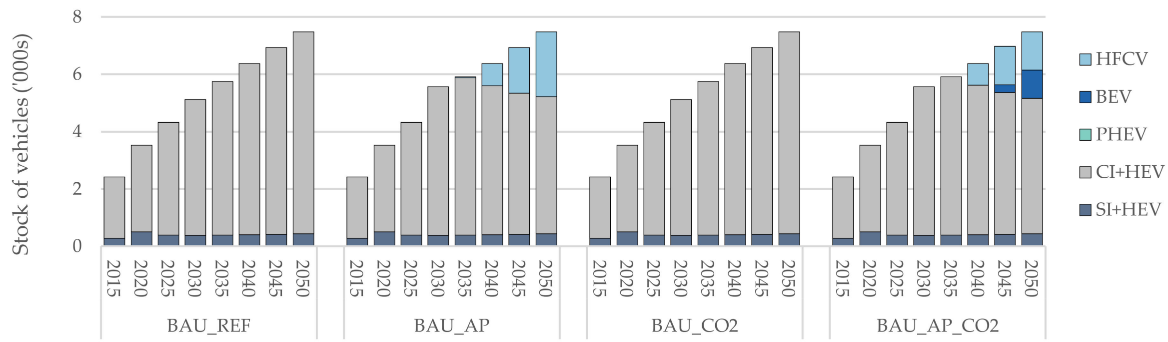

Figure 4. Total stock of buses, medium-sized goods vehicles (MGVs) and heavy goods vehicles (HGVs) in the Business-as-usual (BAU) scenarios ('000s). *Note*: HFCV = hydrogen fuel cell vehicle; BEV = battery electric vehicle; PHEV = plug-in hybrid electric vehicle; CI + HEV = Conventional + non-plug-in hybrid electric compression ignition (CI) vehicle; SI + HEV = Conventional + non-plug-in hybrid electric spark ignition (SI) vehicles.

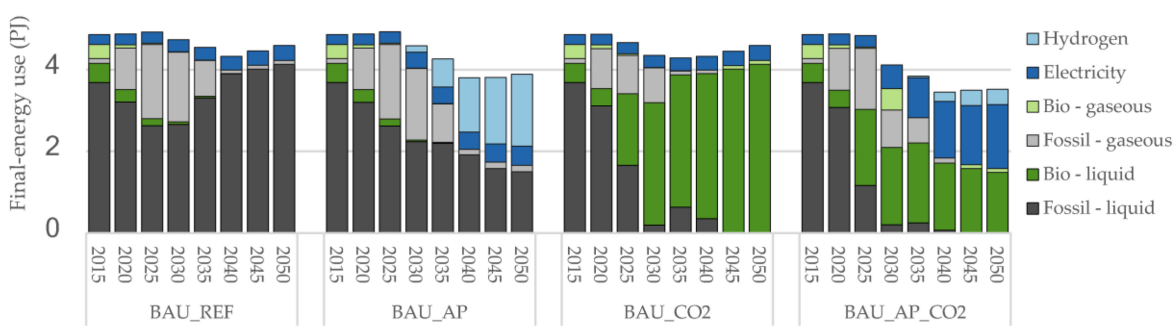

Figure 5. Total final-energy use by fuel type in the Business-as-usual (BAU) scenarios (PJ).

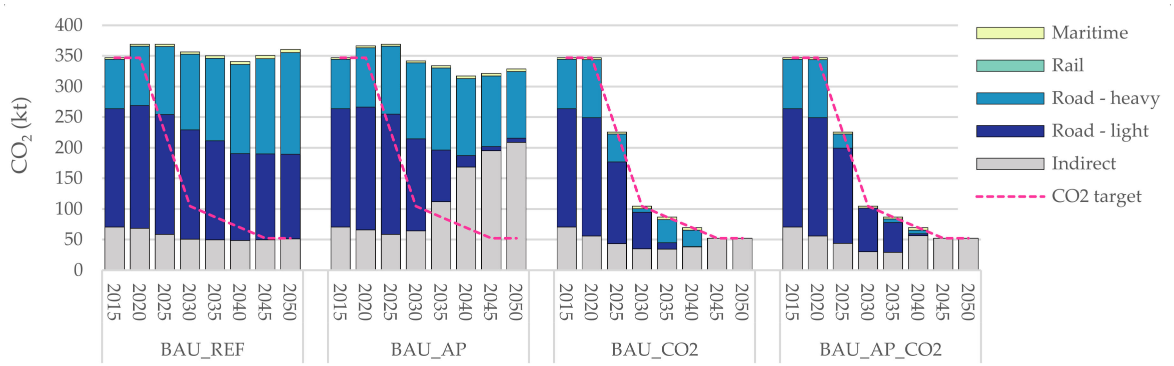

Figure 6. Total upstream and by-mode tailpipe CO_2 emissions in the Business-as-usual (BAU) scenarios (kt). *Note*: Road—heavy = buses, MGVs and HGVs; Road—light = cars and LCVs.

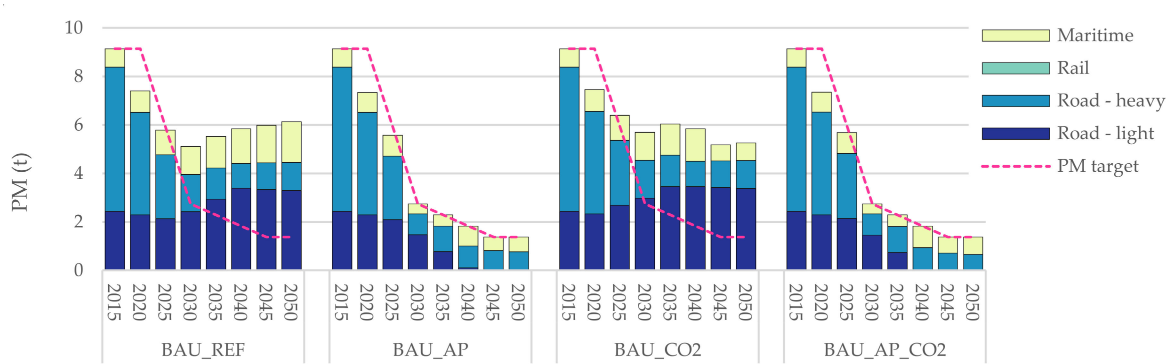

Figure 7. By-mode tailpipe particulate matter (PM) emissions in the Business-as-usual (BAU) scenarios (t). *Note*: Road—heavy = buses, MGVs and HGVs; Road—light = cars and LCVs.

4.2. Ancillary and Co-Benefits from Meeting Ambitious Mitigation Targets

The ancillary and co-benefits were calculated using the no-policy *BAU_REF* scenario as a baseline. Figure 8 displays the relative (positive or negative) impact on each respective AP and CO_2 as a result of different mitigation targets. Comparing *MS* scenarios to *BAU_REF* indicates the additional benefits derived from mode shifting.

Meeting ambitious AP mitigation targets produces limited yet consistently positive ancillary benefits for CO_2 mitigation, as illustrated by the dashed red bars in Figure 8a. In the *BAU* scenario, there is an additional CO_2 reduction of almost 9%, mainly because zero-emission light duty vehicles are deployed, which effectively reduces the total final-energy use and cuts tailpipe emissions. The reduction in tailpipe CO_2 emissions is offset by the dramatic increase in upstream fossil CO_2 emissions from the production of 'grey' H_2 (drawn from natural gas), which is assumed to be the least costly H_2 production pathway. The shift to natural gas in maritime transportation also generates minor ancillary benefits for CO_2 emissions compared with fuel oils, whereas no ancillary benefit for CO_2 mitigation is found in long-distance heavy road transport: it remains diesel-dominated in all time periods.

The CO_2 mitigation target has a diverse impact on the APs included in this study, as illustrated in Figure 8b–d. In *BAU_CO2*, full decarbonisation (by 2050) produces additional reductions of NO_X, PM and NMVOC emissions by up to 25%, 14% and 1%, respectively. However, in road transportation, which accounts for over 90% of all APs in the base year, the ancillary benefits are negligible as this subsector does not undergo any additional technology shifts, unlike those in the *BAU_REF* scenario. In fact, the short-term effect (up to 2030) is even negative, particularly due to the quicker shift—compared with the *BAU_REF* scenario—to biodiesel-powered light-duty diesel HEVs. The shift to biodiesel powered HEVs, which are a cost-efficient decarbonisation option, produces more APs compared with other options. In the long term (2045–2050), more notable ancillary benefits are found for NO_X and PM due to the shift from fuel oils to biomethanol in maritime transportation from 2040 onwards.

Figure 8. Additional (relative) change in emissions of (**a**) carbon dioxide (CO_2), (**b**) particulate matter (PM), (**c**) nitrogen oxides (NO_X), and (**d**) non-methane volatile organic compounds (NMVOCs), compared with the business-as-usual reference scenario (*BAU_REF*) under different mitigation targets. *Note*: Solid blue bars = direct benefit for CO_2 emissions from CO_2 mitigation target; dashed blue bars = ancillary benefits for AP emissions from CO_2 mitigation target; solid red bars = direct benefits for AP emissions from AP targets; dashed red bars = ancillary benefits for CO_2 emissions from AP mitigation targets; green bars = impact of combining all mitigation targets; arrows = positive or negative co-benefits from combined mitigation targets.

Adding all mitigation targets in parallel (green bars in Figure 8) produces no additional co-benefits for CO_2 and PM emissions (these targets are met precisely), while minor co-benefits of up to 5% are found for NO_X emissions. This latter outcome is explained by light duty BEVs being deployed more quickly than the rate at which HFCVs are introduced in the AP scenario (see Figure 3) as well as by a partial shift from biodiesel to bioethanol (ED95) in heavy road freight. Moreover, these minor co-benefits were achieved despite increasing maritime NO_X emissions, being a result of the shift to biomethanol (to meet the CO_2 target) as a substitute for natural gas, as in the individual-policy AP scenarios. In the *MS* scenario, assumed shifts to public transports significantly increase AP emissions from buses, which is offset by a more extensive shift to bioethanol (ED95) in heavy road freight vehicles (compared to the *BAU* scenarios).

The no-policy *BAU_REF* scenario cuts NMVOC emissions below the target level in 2030. This outcome enables negative short-term benefits from the various policy scenarios (while still meeting the target). In the longer term, the AP targets reduce NMVOCs considerably—especially following the introduction of zero-emission vehicles, while combining all targets produces slight co-benefits for NMVOCs because zero-emission vehicles are deployed more quickly and broadly, compared with their deployment in the AP scenario. Overall, the NMVOC targets have no significant impact on model outcomes, which makes the NMVOC results more difficult to interpret.

Mode shifts produce additional ancillary benefits in all scenarios. Combining the AP targets with assumed mode shifts produces additional CO_2 reductions of up to 26% (in 2050). The said benefits are primarily due to shifting from private cars to other modes of transport—a change that significantly reduces H_2 demand for cars and, therefore, the upstream emissions from producing 'grey' H_2. When one combines the CO_2 reduction target with mode shifting, NO_X, PM and NMVOC emissions are reduced by an additional 29%, 34% and 34%, respectively (in 2050). These reductions are specifically due to a drop in demand for travelling by private car, which in turn reduces the total fuel demand and, consequently, tailpipe emissions. Some of the benefits of reduced car travel are offset by increasing emissions from the growth in bus traffic. If one imposes all mitigation targets and includes mode shifting, no additional co-benefits are found for CO_2, PM or NMVOC emission reduction targets, whereas total NO_X emissions are reduced slightly further and the contribution from different modes is altered; buses become the main contributor of NO_X emissions (by 2050), while heavy-road-freight NO_X emissions are reduced significantly; over 50% of the fleet shifts from biodiesel to bioethanol (ED95).

5. Discussion

Malmö's Sustainable Urban Mobility Plan sets out to improve the availability and accessibility of transport options for people and businesses in the city, while mitigating the negative environmental impacts associated with transportation, such as GHG and AP emissions. However, the local government cannot single-handedly decide the outcomes, and nationally determined measures inevitably play a key role as well. For example, Sweden's current national strategy to reduce CO_2 emissions from road transportation rests on two main pillars: blend-in quotas to rapidly scale up the use of biofuels (and biodiesel in particular) in conventional vehicles, and purchase premiums to accelerate the adoption of low-emission vehicles (especially PHEVs and BEVs).

With the technology and fuel options included in this study (and their related techno-economic assumptions), the most cost-efficient way to reduce fossil-fuel-based CO_2 emissions is to replace such fuels with biofuels. Conventional biofuels require no transitional investment in new vehicle types or new fuel distribution or refuelling infrastructure (note that investments in biofuel production were not included). However, the biofuels path retains the existing combustion-engine regime and compared with the reference scenario (dominated by fossil fuels), it produces no additional reduction in APs. Thus, depending on how future traffic levels in and around cities unfold, the biofuel strategy may have a very limited—or even negative—impact on local air quality. This outcome also adds to previous concerns over the implications for air quality from biofuels (see e.g., [9,10]).

The current study also shows that improving local air quality by significantly reducing APs requires a transition to zero-emission vehicles such as BEVs and HFCVs, which in turn need investments in new fuel-supply or recharging infrastructure. Nonetheless, besides cutting APs, zero-emission vehicles also eliminate tailpipe CO_2 emissions. However, since our model distinguishes between tailpipe and upstream CO_2 emissions, our results highlight potential upstream implications from the zero-emission option. For instance, powering a significant portion of the vehicle fleet with 'grey' H_2 would result in very limited ancillary benefits for total CO_2 emissions, as emissions from local tailpipes would simply shift to upstream sources. Similar impacts could be found from electrification, depending on the specific electricity mix used to recharge the BEV fleet (although the low carbon intensity of the Nordic electricity mix ensures Sweden benefits from BEVs in respect of climate change impacts). Thus, and in line with several previous studies as e.g., [11–14], our results further highlight the importance of considering upstream implications when assessing the impact of zero-emission vehicles. Moreover, with the anticipated increase in zero-emission vehicles, upstream considerations are likely to grow in importance, and sustainability criteria for the electricity and H_2 to be used as transportation fuels (similar to the criteria for biofuels) may be called for to ensure their total climate change impacts are minimised. Upstream considerations also have potential policy implications at the local level. A case in point is Malmö, which is among many EU cities enforcing local 'green' zones that only allow certain low-emission vehicles into the city centre to improve inner-city air quality and human health, among other things. However, the specific impacts of these zones on tailpipe and upstream CO_2 emissions have not yet been extensively investigated (as discussed, e.g., in [63]). Our study suggests that careful consideration of upstream implications is needed.

Globally, the most prominent and fastest-growing trend in transportation today is the electrification of road vehicles. However, BEVs are not yet fully cost-competitive, nor are they commercially available to all road segments. Yet BEV fleets are expected to grow, especially considering the pressure being exerted by the current EU CO_2 emission performance standards (with specific benchmarks to incentivise more rapid development and uptake of BEVs), national-level support such as tax exemptions and purchase premiums (as in Sweden, for example), and the AP standards anticipated in the upcoming Euro7/VII pollutant emission regulations, which the European Automobile Manufacturers Association has labelled an effective ban on combustion engine vehicles [64]. This overall direction for future road vehicle development is promising, especially in light of the study results, which indicate that BEVs powered by 'green' electricity are the least-cost option for producing drastic cuts, in parallel, in both total CO_2 emissions and APs. Nevertheless, long-haul heavy road vehicles pose a significant challenge: they are firmly locked into diesel dependence, with few low-emission alternatives readily available to them. An alternative to BEVs in respect of heavy road freight could be HFCVs, for example, especially as regards meeting the need for extended distances and duration of operations. However, as well over 95% of H_2 is currently sourced from fossil fuels [65], the future role and impact of H_2 in the sustainable energy transition hinges on the development of a carbon capture and storage or utilisation system and/or the cost not only of electrolysers to produce 'green' H_2, but also of the low-carbon electricity required in order to do so.

While the lifetime of the most severe local APs is typically counted in hours or days, such pollutants may continue to disperse over large areas, depending on prevailing weather conditions, and their concentrations typically vary over time (both within a single day and between seasons) [66]. Moreover, dense urban structures can 'trap' APs, causing much more elevated AP concentrations in cities. This complex behaviour by APs, e.g., as determined by short-term weather conditions and local built environments, is not captured in an ESOM framework such as TIMES-City, which only provide the total quantitative emissions of each substance from different sources for a specific time period. As a result, this study applied AP targets as cuts in quantitative emissions relative to a baseline year. Moreover, the targets were applied equally to all intra-city and long-distance transport activities—which is, of course, a simplification: at least some of the emissions captured using this approach would not actually have had any impact on air quality in Malmö.

Another aspect not captured in this study is non-tailpipe PM from, for example, road and break wear-and-tear and resuspended dust particles, which entailed omitting a significant source of local PM. As non-tailpipe PM increases with vehicle weight, switching to BEVs—which are heavier than their conventional counterparts due to their batteries—will have a negative impact on non-tailpipe PM [67] and, hence, a less positive impact on reducing total urban PM levels than what our results suggest. Thus, our modelling effort does not fully capture the challenge of reducing urban transport-related PM levels. Nonetheless, the TIMES-City framework has proved useful for shedding light on key technology and fuel options and their potential trade-offs or co-benefits for reducing several harmful APs and CO_2.

The City of Malmö has high ambitions for shifting passenger transport from private cars to active travelling and public transportation. Such a shift, according to our results, produces additional emissions reductions, especially since the reduced fuel demand cuts both tailpipe AP and CO_2 and upstream CO_2 emissions. However, based on the assumptions made in this study, an increased demand for intra-city public transport showed significant growth in the local bus fleet, which in turn increased bus emissions—offsetting some of the emissions reductions from cars. The benefits from mode shifting may be even greater in a city with an extensive subway or light rail system (powered by electricity).

MS scenarios result in significantly lower total system cost, compared with their respective *BAU* counterparts, due to the lower investment in new vehicles (cars in particular) and lower total fuel costs. However, these results are sensitive to exactly how much car travel can be shifted, and whether the existing public transportation capacity can absorb an increased demand for such services. Moreover, an ESOM framework as TIMES-City is not suited to assess the realisation of these shifts by introducing transport policies such as parking policies, congestions charging, investments in bicycle infrastructure or transport and land-use planning practices. Since the costs of achieving and maintaining the assumed shifts are not included, the resulting total system costs of *BAU* and *MS* scenarios respectively are not fully comparable. Still, the relative difference in total system costs can be used as an indication of the opportunity for investments to support and enable shifts away from private car travelling.

Besides encouraging passenger mode shifts, local governments can also help to reduce urban freight movements, e.g., by fostering urban logistics centres where goods are reloaded and consolidated for last-mile deliveries by low-emission freight vehicles. Such measures contribute to reducing congestion, noise levels and APs in settings where these issues are most pressing. Reducing the overall energy intensity of transportation, e.g., by mode shifting and consolidating goods for delivery, is critical—especially considering the limited availability of sustainably sourced material and renewable energy.

Our study does not assess the specific health impacts associated with APs. However, a previous study in this regard, which looked at local NO_X and PM emissions from transportation in Malmö, found that large-scale introduction of BEVs and greater shares of active travelling reduced the adverse health effects of APs, such as premature death, asthma and other respiratory diseases, and dementia [68]. Therefore, the latter and current study on Malmö together underline the complexity and scope of the social and environmental implications—felt both locally and globally—from energy-related emissions from transportation. The two studies also highlight the need for comprehensive mitigation strategies to be devised that explicitly target both APs and total (tailpipe and upstream) CO_2 emissions and take potential trade-offs and co-benefits into account. Such strategies, in turn, require recoupling local and global motivations and responsibilities to facilitate change on all levels and to unlock the technological, structural and social shifts needed to reach transport-efficient, low-emission cities and communities.

6. Conclusions

With the modelling approach and assumptions used in this study, shifting from fossil fuels to biofuels in conventional vehicles is the least-cost pathway for achieving an ambitious CO_2 mitigation target in the transport sector, but this produces very limited, or even negative, ancillary benefits for local APs such as PM and NO_X. While deep cuts in APs require a shift to zero-emission vehicles such as BEVs and HFCVs, which will also reduce tailpipe CO_2 emissions, it may also entail significant upstream CO_2 emissions from electricity or H_2 production. Through our scenario analysis, we found that meeting ambitious climate change mitigation and air quality targets in parallel requires significant investments in zero-emission vehicles and their associated energy supply infrastructure, as well as mechanisms to ensure that the supplied energy is drawn from low-carbon sources to minimise upstream implications. The density of cities generally allows for high shares of public transportation and active travelling, and for reloading and consolidating goods for more efficient last-mile deliveries; our analysis shows that such shifts slow down growth in total fuel demand and associated emissions by reducing overall energy-intensity of the transportation system. Thus, enabling and supporting shifts in passenger and freight transportation are important elements of local mitigation strategies. Meanwhile, our results do not give any further insight into exactly how these shifts are to be achieved. Finally, the urgency of ongoing climate change and significant air quality issues that face many cities calls for recoupling CO_2 and AP mitigation strategies, grounded in comprehensive scientific analyses. This study sheds more light on the potential trade-offs and co-benefits of different options in the transport sector. We have also shown that a technology-rich ESOM, in which AP and CO_2 targets can be added as constraints to the model optimisation, provides a useful framework to support such analyses, but it is critical that the modelling of local transport-energy systems includes both tailpipe and upstream CO_2 emission to capture the global implications of different pathways.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Modelling Assumptions

Table A1. Tailpipe and upstream carbon dioxide (CO_2) emission factors (kg/GJ).

Fuel/Energy Carrier	Feedstock	Tailpipe CO_2 Emission Factors (kg/GJ)	Upstream CO_2 Emission Factors (kg/GJ)
Biodiesel	Palm oil	0	48.64
	Sunflower/rapeseed oil	0	50.81
	Soy	0	55.14
	Waste oils	0	8.08
Bioethanol	Waste wood	0	19.46
	Sugar cane	0	24.76
	Wheat	0	28.33
	Wheat straw	0	9.19
Biomethane	Municipal waste	0	14.12
	Other miscellaneous waste	0	18.82
	Waste wood	0	4.40
Biomethanol	Waste wood	0	5.40
Diesel	Oil	73.32	10.98
Dimethyl ether	Waste wood	0	5.40

Table A1. *Cont.*

Fuel/Energy Carrier	Feedstock	Tailpipe CO_2 Emission Factors (kg/GJ)	Upstream CO_2 Emission Factors (kg/GJ)
Electricity	EU average mix	0	116.32
	'Green' (carbon-neutral)	0	0
	Nordic mix	0	12.40
Gasoline	Oil	72.34	15.47
Heavy fuel oil	Oil	78.00	10.01
Hydrogen	Electricity	0	9.10
	Natural gas	0	104.30
Kerosene (jet fuel)	Oil	71.40	10.57
Light fuel oil	Oil	74.00	11.12
Liquefied petroleum gas	Oil	68.04	11.96
Natural gas	Natural gas	64.96	7.70

Table A2. Assumed emission factors for particulate matter (PM), nitrogen oxides (NO_X) and non-methane volatile organic compounds (NMVOCs), in the reference year (2015) and for new vehicles (2016–), respectively (kg/GJ).

Mode	Type of Vehicle	Fuel	Assumed Emission Factors (kg/GJ)					
			PM		NO_X		NMVOCs	
			Existing Vehicles (2015)	New Vehicles (2016–)	Existing Vehicles (2015)	New Vehicles (2016–)	Existing Vehicles (2015)	New Vehicles (2016–)
ROAD	Cars and light commercial vehicles	Diesel	0.0015	0.0017	0.2281	0.0567	0.0185	0.0216
		Biodiesel	0.0015	0.0017	0.2328	0.0579	0.0189	0.0220
		Electricity	-	-	-	-	-	-
		Bioethanol	0.0005	0.0006	0.0086	0.0086	0.1890	0.1897
		Gasoline	0.0004	0.0005	0.0360	0.0408	0.1854	0.2057
		Biomethane	0.0005	0.0007	0.0204	0.0263	0.0004	0.0005
		Natural gas	0.0005	0.0007	0.0204	0.0263	0.0004	0.0005
		Hydrogen	-	-	-	-	-	-
		Biomethanol	0.0014	0.0017	0.2224	0.0553	0.0180	0.0210
	Bus—urban	Diesel	0.0052	0.0005	0.7050	0.0569	0.0045	0.0039
		Biodiesel	0.0054	0.0006	0.7195	0.0581	0.0046	0.0040
		Dimethyl ether	0.0004	0.0005	0.2515	0.0203	0.0005	0.0005
		Electricity	-	-	-	-	-	-
		Bioethanol	0.0033	0.0005	0.4841	0.0403	0.0002	0.0002
		Biomethane	0.0009	0.0008	0.2461	0.2490	0.0003	0.0002
		Natural gas	0.0009	0.0008	0.2461	0.2490	0.0003	0.0002
		Hydrogen	-	-	-	-	-	-
		Biomethanol	0.0051	0.0005	0.6875	0.0555	0.0044	0.0038
	Bus—intercity	Diesel	0.0047	0.0005	0.6688	0.0677	0.0043	0.0040
		Biodiesel	0.0050	0.0006	0.5839	0.0535	0.0043	0.0039
		Dimethyl ether	0.0004	0.0005	0.2435	0.0243	0.0005	0.0004
		Bioethanol	0.0037	0.0004	0.3892	0.0320	0.0002	0.0002
		Biomethane	0.0008	0.0005	0.2074	0.2503	0.0003	0.0001
		Natural gas	0.0008	0.0005	0.2074	0.2503	0.0003	0.0001
		Hydrogen	-	-	-	-	-	-
		Biomethanol	0.0047	0.0005	0.5580	0.0511	0.0041	0.0037
	Medium-sized goods vehicle	Diesel	0.0050	0.0005	0.5789	0.0581	0.0034	0.0038
		Biodiesel	0.0051	0.0005	0.5908	0.0593	0.0034	0.0039
		Dimethyl ether	0.0004	0.0004	0.3252	0.0424	0.0002	0.0004
		Electricity	-	-	-	-	-	-
		Bioethanol	0.0014	0.0002	0.1988	0.0165	0.0001	0.0001
		Biomethane	0.0009	0.0009	0.2619	0.2649	0.0003	0.0002
		Natural gas	0.0009	0.0009	0.2619	0.2649	0.0003	0.0002
		Hydrogen	-	-	-	-	-	-
		Liquefied petroleum gas	0.0009	0.0009	0.2743	0.2775	0.0003	0.0002
		Biomethanol	0.0049	0.0005	0.5645	0.0566	0.0033	0.0037

Table A2. *Cont.*

Mode	Type of Vehicle	Fuel	Assumed Emission Factors (kg/GJ)					
			PM		NO_X		NMVOCs	
			Existing Vehicles (2015)	New Vehicles (2016–)	Existing Vehicles (2015)	New Vehicles (2016–)	Existing Vehicles (2015)	New Vehicles (2016–)
ROAD	Heavy goods vehicles	Diesel	0.0046	0.0005	0.4685	0.0441	0.0030	0.0034
		Biodiesel	0.0047	0.0005	0.4781	0.0450	0.0031	0.0035
		Dimethyl ether	0.0004	0.0005	0.3066	0.0386	0.0001	0.0005
		Bioethanol	0.0015	0.0002	0.1598	0.0131	0.0001	0.0001
		Biomethane	0.0007	0.0007	0.2114	0.2136	0.0002	0.0002
		Natural gas	0.0007	0.0007	0.2114	0.2136	0.0002	0.0002
		Hydrogen	-	-	-	-	-	-
		Liquefied petroleum gas	0.0008	0.0008	0.2214	0.2237	0.0003	0.0002
		Biomethanol	0.0044	0.0005	0.4568	0.0430	0.0030	0.0034
RAIL	Intercity train	Electricity	-	-	-	-	-	-
	High-speed train	Electricity	-	-	-	-	-	-
	Freight	Electricity	-	-	-	-	-	-
SEA	Cargo ship	Fuel oil	0.0240	0.0240	1.6700	1.6700	0.0220	0.0220
		Natural gas	0.0086	0.0086	0.1100	0.1100	0	0
		Biomethanol	0.0102	0.0102	0.4100	0.4100	0	0

Table A3. Transport demand input data given in pkm or tkm (millions).

Subsector	Type of Vehicle	2015	2030		2050	
			Business-As-Usual	Mode Shift	Business-As-Usual	Mode Shift
Passenger -Intra-city	Walking	48.1	54.4	54.4	64.0	64.0
	Bike	149	169	234	199	367
	E-bike	1.4	1.6	17.9	1.9	39.9
	Bus	186	211	260	248	376
	Car	466	527	396	621	286
Passenger -Long-distance	Bus	124	140	264	165	491
	Car	1088	1230	1020	1449	915
	Train	816	923	1009	1087	1306
Freight -Intra-city	Light commercial vehicle	14.7	20.7	15.3	32.7	18.3
	Medium-sized goods vehicle	79.1	111	117	176	191
	Heavy goods vehicle	4.9	7.0	5.6	11.0	7.3
	E-bike	0.1	0.1	1.4	0.2	3.5
Freight -Long-distance	Heavy goods vehicle	413	582	524	919	764
	Train	306	431	489	680	834
	Navigation	107	151	151	239	239

Table A4. Fuel/energy-carrier cost assumptions (€2015/GJ), excluding all taxes and delivery/infrastructure costs. Crude oil and natural gas cost projections added for reference.

Fuel/Energy-Carrier	Feedstock	2015	2020	2030	2040	2050
Biodiesel	Palm/sunflower/rape seed oil or soy	24.00	33.73	38.54	35.36	32.64
	Waste oils	24.24	34.06	38.92	35.72	32.97
Bioethanol	Waste wood	n.a.	n.a.	39.39	35.76	32.64
	Sugar cane	24.00	34.06	38.54	35.36	32.64
	Wheat/wheat straw	24.00	33.73	38.54	35.36	32.64
Biomethane	Municipal waste	24.00	33.73	38.54	35.36	32.64
	Other miscellaneous waste	24.00	33.73	38.54	35.36	32.64
	Waste wood	n.a.	n.a.	39.39	35.76	32.64
Biomethanol	Waste wood	n.a.	n.a.	39.39	35.76	32.64
Diesel	Crude oil	10.28	14.71	17.13	15.72	14.51
Dimethyl ether	Waste wood	n.a.	n.a.	39.39	35.76	32.64
Electricity	EU average mix	5.89	7.06	7.67	7.78	7.97
	'Green' (carbon-neutral)	7.06	8.48	9.20	9.39	9.57
	Nordic mix	5.83	6.99	7.59	7.74	7.89
Gasoline	Crude oil	10.28	14.71	17.13	15.72	14.51
Heavy fuel oil	Crude oil	5.76	8.25	9.61	8.81	8.14
Hydrogen	Electrolysis (w. 'green' electricity)	n.a.	n.a.	18.07	19.03	19.61
	Natural gas	n.a.	n.a.	16.06	16.92	17.43
Light fuel oil	Crude oil	7.91	11.32	13.18	12.09	11.16
Natural gas	Natural gas	8.97	8.84	12.05	12.69	13.07
Crude oil	-	7.11	10.18	11.86	10.88	10.04
Natural gas	-	5.98	5.89	8.02	8.45	8.71

Table A5. Energy tax and CO_2 tax assumptions for each respective included fuel option.

	Energy Tax (€2015/GJ)			CO_2 Tax (€2015/t)		
Fuel/Energy Carrier	**2015**	**2030**	**2050**	**2015**	**2030**	**2050**
Biodiesel [1]	0	7.36	7.36	0	0	0
Bioethanol (high-blend) [2]	0	12.63	12.63	0	0	0
Bioethanol (low-blend, in gasoline) [1]	4.58	19.71	19.71	0	0	0
Biomethane [2]	0	12.63	12.63	0	0	0
Biomethanol [2]	n.a.	0	12.63	0	0	0
Diesel	7.09	7.09	7.09	120	120	120
Dimethyl ether [2]	n.a.	0	7.36	0	0	0
Electricity	8.73	8.73	8.73	0	0	0
Gasoline	12.63	12.63	12.63	120	120	120
Heavy fuel oil [3]	0	7.09	7.09	120	120	120
Hydrogen [4]	0	0	8.73	0	0	0
Light fuel oil [3]	0	7.09	7.09	120	120	120
Natural gas [5]	0	12.63	12.63	120	120	120

[1] As of 2018, low-blended biofuels are subject to a full energy tax in Sweden, following the introduction of blending quotas for diesel and gasoline intended to reduce emissions by way of the mandatory blending of biofuels (Reduktionsplikten). [2] High-blend biofuels are currently exempt from energy and CO_2 taxes. Here, an energy tax is imposed once the various biofuels are assumed to reach market maturity: biomethane and bioethanol from 2030, and the remaining options from 2040. [3] Fuels in commercial shipping are currently exempt from energy tax in Sweden. From 2030, it is assumed to be subject to the same tax as that for diesel. [4] Hydrogen used as a transport fuel is currently exempt from taxes. From 2040, it is assumed to be subject to the same tax as that for electricity. [5] Natural gas used in vehicles/vessels is currently exempt from energy tax in Sweden. From 2030, it is assumed to be subject to the same tax as that for gasoline.

Table A6. Investment cost assumptions for new recharging and refuelling infrastructure deployed from 2016 (€2015/GJ·year).

Fuel/Energy Commodity	Cost	Comments/Additional Key Assumptions
Bio-dimethyl ether	2.42	Fuel supplied by tanker truck to refuelling station
Bioethanol (E85/ED95)	0.10	Fuel supplied by tanker truck to refuelling station
Biomethanol	0.10	Fuel supplied by tanker truck to refuelling station
Diesel/biodiesel, gasoline/low-blend bioethanol	0.05	Low additional cost of expanding existing refuelling stations
Electricity	3.84	Public fast charging
Hydrogen	1.34	Liquefied hydrogen supplied by tanker truck to refuelling station
Liquefied petroleum gas	2.42	Fuel supplied by tanker truck to refuelling station
Natural gas/biomethane	0.72	Refuelling station supplied by local gas grid

Appendix B. Results

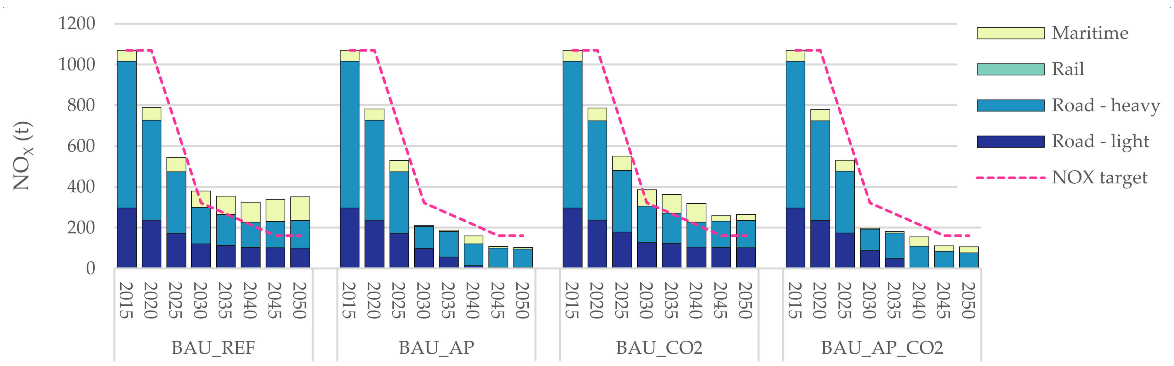

Figure A1. By-mode tailpipe emissions of nitrogen oxides (NO_X) in the Business-as-usual scenarios (t). *Note*: Road—heavy = buses, MGVs and HGVs; Road—light = cars and LCVs.

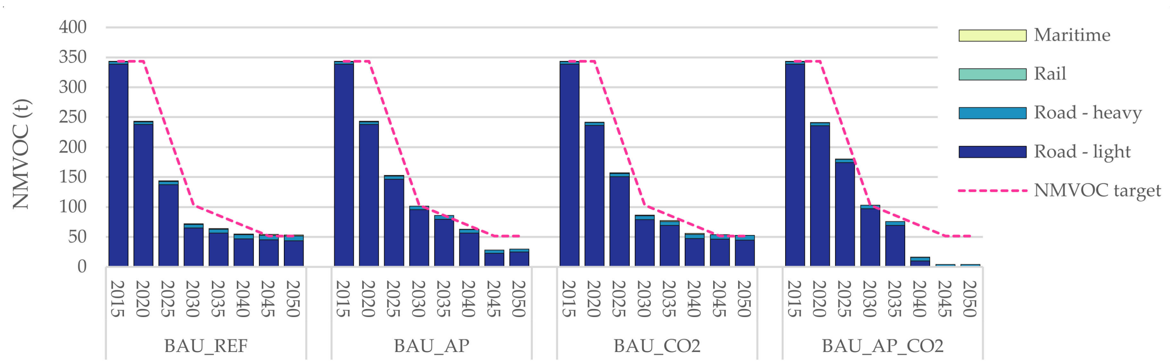

Figure A2. By-mode tailpipe emissions of non-methane volatile organic compounds (NMVOCs) in the Business-as-usual scenarios (t). *Note*: Road—heavy = buses, MGVs and HGVs; Road—light = cars and LCVs.

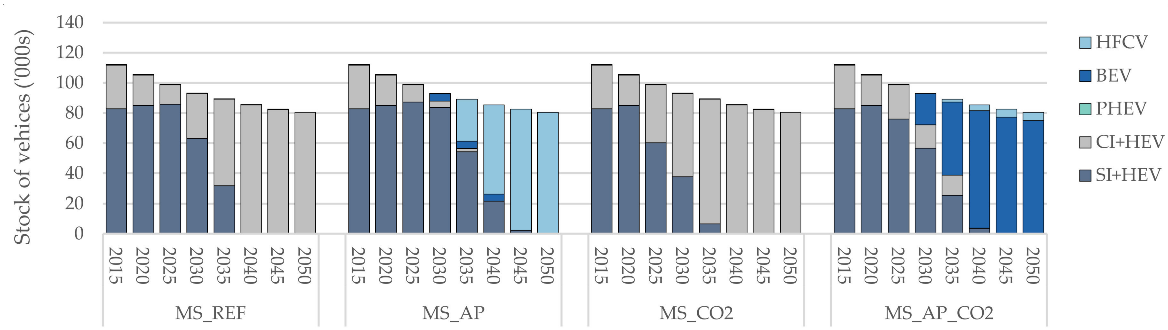

Figure A3. Total stock of cars and light commercial vehicles (LCVs) in the mode shift (MS) scenarios ('000s). *Note*: HFCV = hydrogen fuel cell vehicle; BEV = battery electric vehicle; PHEV = plug-in hybrid electric vehicle; CI + HEV = Conventional + non-plug-in hybrid electric compression ignition (CI) vehicle; SI + HEV = Conventional + non-plug-in hybrid electric spark ignition (SI) vehicle.

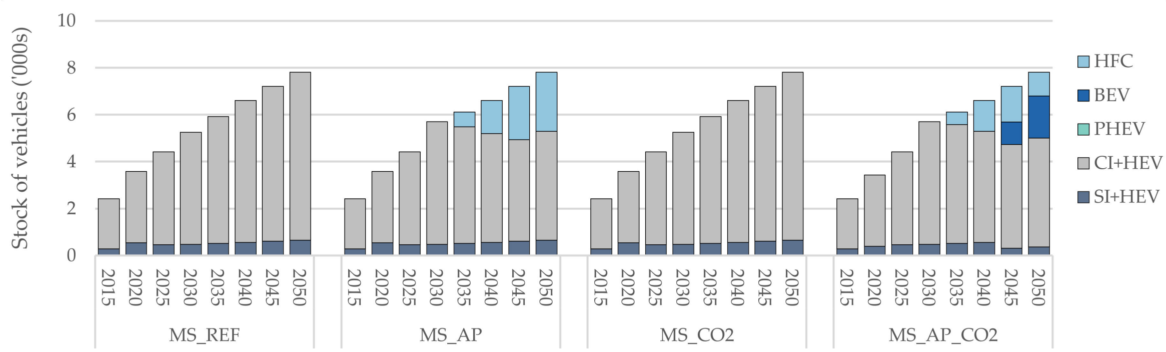

Figure A4. Total stock of buses, medium-sized goods vehicles (MGVs) and heavy goods vehicles (HGVs) in the mode shift (MS) scenarios ('000s). *Note*: HFC = hydrogen fuel cell vehicle; BEV = battery electric vehicle; PHEV = plug-in hybrid electric vehicle; CI + HEV = Conventional + non-plug-in hybrid electric compression ignition (CI) vehicle; SI + HEV = Conventional + non-plug-in hybrid electric spark ignition (SI) vehicle.

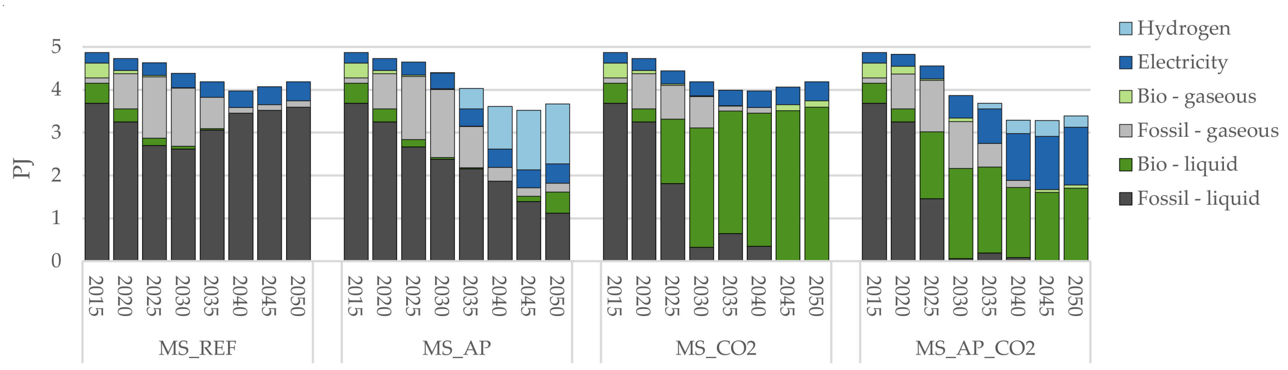

Figure A5. Total final-energy consumption by different fuel types in the mode shift (MS) scenarios (PJ).

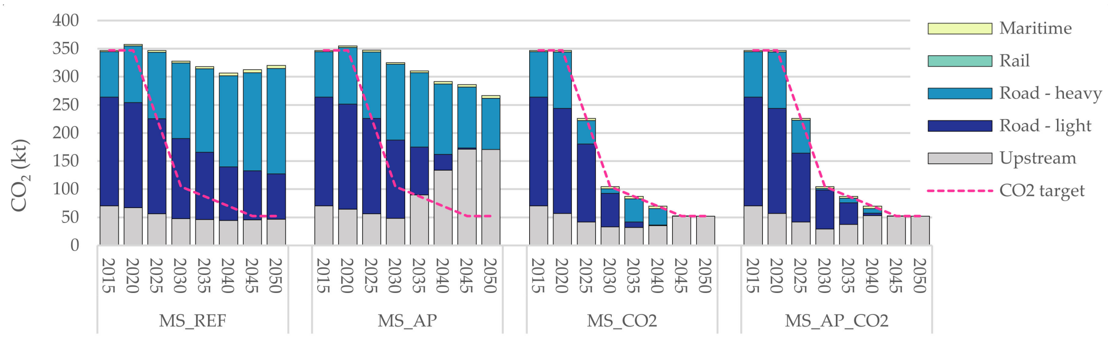

Figure A6. Total upstream and by-mode tailpipe emissions of carbon dioxide (CO_2) in the mode shift (MS) scenarios (kt). *Note*: Road—heavy = buses, MGVs and HGVs; Road—light = cars and LCVs.

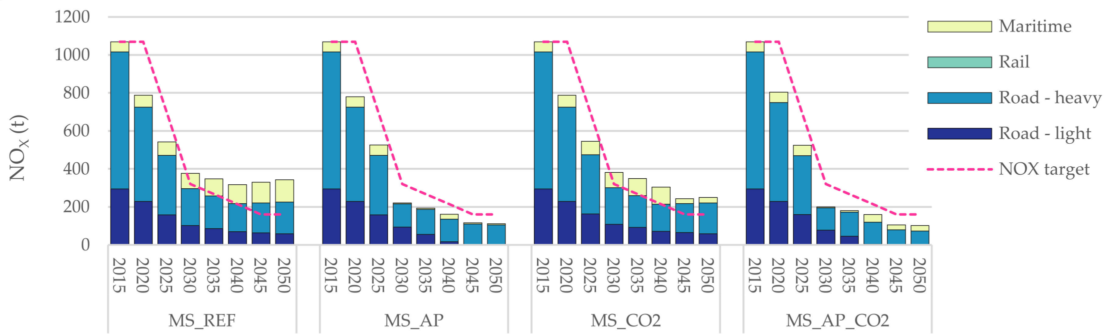

Figure A7. By-mode tailpipe emissions of nitrogen oxides (NO_X) in the mode shift (MS) scenarios (t). *Note*: Road—heavy = buses, MGVs and HGVs; Road—light = cars and LCVs.

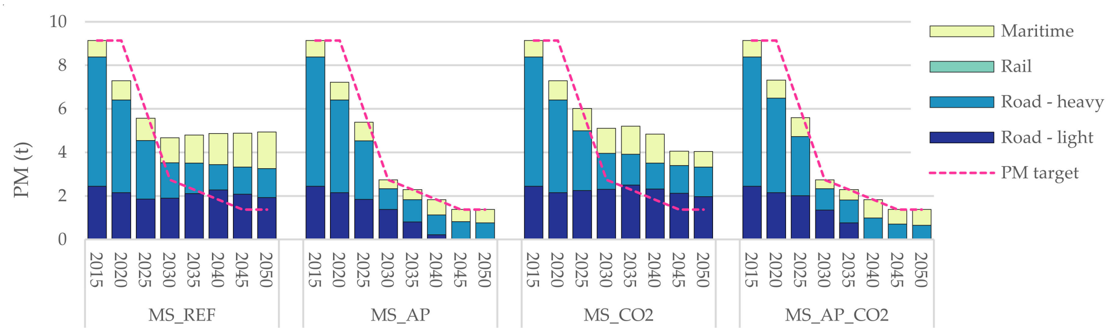

Figure A8. By-mode tailpipe emissions of particulate matter (PM) in the mode shift (MS) scenarios (t). *Note*: Road—heavy = buses, MGVs and HGVs; Road—light = cars and LCVs.

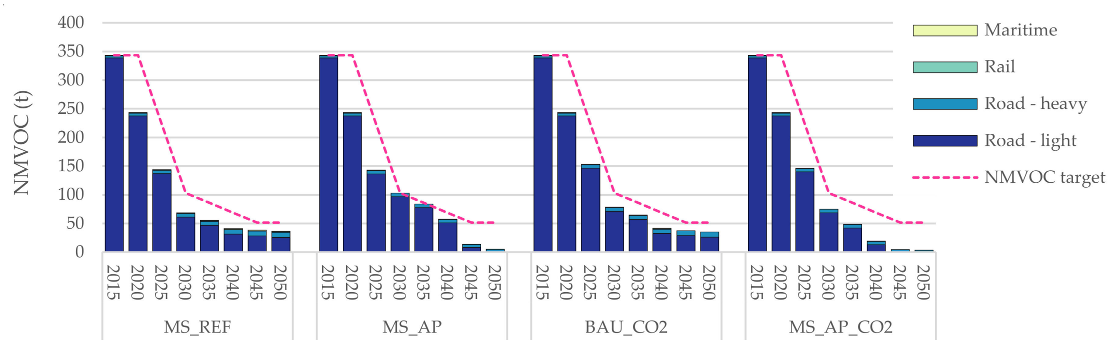

Figure A9. By-mode tailpipe emissions of non-methane volatile organic compounds (NMVOCs) in the mode shift (MS) scenarios (t). *Note*: Road—heavy = buses, MGVs and HGVs; Road—light = cars and LCVs.

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