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Climate-friendly mobility in cities. Planning for carbon reduction in the long term in four European cities

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ABSTRACT

Many cities have ambitious climate targets, like becoming climate-neutral by 2050, 2040 or 2030, but are uncertain about how mobility and land use should change in order to reduce GHG emissions to levels consistent with the cities' aims. Finding answers on this, and also on the question of how to strike an effective balance between desired fundamental transformation and realistic expectations, was at the heart of the Interreg Europe project 2050 CliMobCity (2050 Climate-friendly Mobility in Cities). The project partners were four medium-sized but otherwise quite different cities (Bydgoszcz, Plymouth, Thessaloniki and Leipzig), along with the Potsdam Institute for Climate Impact Research (PIK) and TU Delft. Each partner city conducted a so-called demonstration study, which required defining ambitious packages of measures (mobility, land use, electrification) and forecasting changes in mobility by macroscopic transport modelling. PIK then analysed GHG emissions using its carbon model. This paper extends the demonstration studies into a case-study approach. This is preceded by an exercise in consistently structuring types of GHG and mobility performances and corresponding measures. The case-study approach is supplemented by a review of the literature on shared and micromobility. A conclusion drawn from the case study is that none of the partner cities is in fact sufficiently reducing GHG emissions. Even if electricity production was completely green, the remaining gap between GHG reduction aims and analysed GHG delivery lies between 30–81 %, dependent on the scenario and city. Shared and micromobility seem not to lead to strongly deviating conclusions. We discuss policies to close the gap. One major option discussed is tackling GHG emissions from urban freight, in forms such as organising public-private cooperation designed to accelerate the electrification of freight vehicles.

1. Framework and introduction

1.1. Subject and background of the paper

This paper is about municipal planning of climate mitigation actions with regard to mobility in, from, to and through cities. It reports on the European project 2050 Climate-friendly Mobility in Cities (2050 CliMobCity)¹ and embeds the work process and findings of the project in a

scientific discussion. The “2050” in the project name was not meant to fix the period of planning, but to indicate that the project focusses on the long term and the big picture. The central thematic area of the project was therefore strategic mobility planning for climate mitigation.

The project took place between 2019 and 2023 in the framework of Interreg Europe. It has been extensively described in the “Project Summary” (110 pages), five background reports, the so-called Appendix-X-reports, and four Newsletters produced by the project (Kreutzberger &

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¹ Project coordinator 2050 CliMobCity

² Niels and Fatemeh are co-authors in Section 5 only and one conclusion in Section 6

¹ For ease of formulation, we in this article will often use the term CliMobCity instead of 2050 CliMobCity, for instance as the name of the more ambitious measure package than the future BAU (business as usual) package.

van Binsbergen, 2023; <https://www.tudelft.nl/en/ceg/about-faculty/departments/transport-planning/labs/smart-public-transport-lab/links/2025climobcityfiles>; <https://www.interregeurope.eu/2050climobcity>, <https://projects2014-2020.interregeurope.eu/2050climobcity/library/>). The project was initiated by TU Delft (CEG, Transport and Planning, The Netherlands). The relevance of the draft content was recognized by what became the other project partners: four European municipalities, namely Bydgoszcz (ca. 350,000 inhabitants, Poland), Plymouth (ca. 260,000, United Kingdom), Thessaloniki (ca. 315,000, Greece) and Leipzig (ca. 600,000, Germany), and the knowledge organisations Potsdam Institute for Climate Impact Research (PIK, Germany) and TU Delft. TU Delft was also the project leader.

1.2. Aim of this paper

The aim of this paper is to strengthen climate mitigation processes by connecting the 2050 CliMobCity project with the scientific community and discussing the project work approach and findings in a scientific context. The connection works in two directions:

- from science to the project, reflecting on the context of approach, methodology and findings;
- from project to research, with contributions to scientific knowledge building.

1.3. Cities in climate mitigation

The starting point for the project was the notion of urgency of climate mitigation. The Paris agreement of 2015 to limit global warming to 2°C and preferably 1.5°C vs. pre-industrial emission levels changed societal and policy perspectives. The European Commission, also referring to IPCC, concluded that GHG emission neutrality would “need to be reduced with far more urgency than previously anticipated” (EC, 2018, p. 5). While in the EU27 the GHG emissions² were declining in most sectors despite of population and GDP growth (EEA, 2023, Fig. 1.2), they in transport were not decreasing but increasing. COVID-19 interrupted this development, but after 2020 carbon emissions increased again (EEA, 2023, Fig. 2.7). Currently, the EU27 transport emits almost one quarter³ of all GHG emissions. Those of road mobility represent about three quarter of total mobility emissions. GHG emissions of cars in 1990–2021 increased by + 15 %, those of trucks by + 28 % and of vans + 49 % (ECA,

² GHG = Greenhouse gases, also referred to as CO₂e = CO₂-equivalents, consist of CO₂ and other warming gases. In mobility the warming emissions mainly consist of CO₂. We in this paper conduct analyses on the GHG level, as this is more complete.

Regarding power trains, we in this paper call vehicles with internal combustion engine (ICEVs) and running on gasoline, diesel and other non-green fuels, **fossil fuel vehicles**. Vehicles that have no GHG emissions at the car exhaust, like electric vehicles or hydrogen vehicles, we call **post-fossil vehicles**, whether the electricity or hydrogen they use, has been produced in a green fashion or not. The electric vehicles can either run on batteries (like battery electric cars = BEVs) or be fed via electric catenaries (like some PT buses and in pilots also long-haul trucks on highways). The term post-fossil fuel vehicles includes ICEVs running on short-cyclic GHG emitting fuels (like bio fuels); these are regarded as post-fossil as the emitted GHG has shortly before also been withdrawn from the atmosphere. As much of the replacement of fossil fuel by post-fossil fuel vehicles refers to electric vehicles, we for formulation ease synonymously use the expressions **shift to post-fossil vehicles** and **electrification etc. of vehicles**.

³ The shares of mobility in urban carbon emissions vary, dependant on the activities in and the infrastructure running through a city. An indication of the range is presented in a study of the regional authority Haaglanden (Leguijt et al., 2014): in municipalities without much greenhouse horticulture (7 municipalities) the share of mobility emissions ranged between 16 % and 25 %. A highway through a municipality can increase the share significantly, as in Wassenaar (43 %).

2024 on the basis of EEA, Data viewer, 2023). Much of these emissions took place in cities.⁴

Cities for several reasons are important actors regarding sustainable mobility and climate mitigation (EC, 2020): 75 % of Europeans live in cities [Statista, 2024]). Correspondingly, a large part of the GDP, energy consumption and carbon emissions relates to cities (Golubchikov, 2011) and much of public expenditure is allocated at the municipal level. Global warming impacts are expected to cause much damage particularly in cities (Kamal-Chaoui & Robert, 2009).

In terms of decision-making, cities function as hinges between policy layers and sectors and between the public and private domain (Harstadt, 2016; Moloney & Horne, 2015; Madsen & Hansen, 2019; Staricco & Vitale Brovarone, 2018). “Cities are the level of government that is closest to the people, therefore the task to plan and provide mobility for its residents lies with them in most European countries” (Rupperecht, 2019, p. 6). For balancing climate mitigation and adaptation measures, “urban systems are critical, interconnected sites for climate resilient development; urban policies that implement multiple interventions can yield adaptation or mitigation gains with equity and human well-being” (IPCC, 2023, p. 114).

The pace of GHG reduction in mobility is insufficient not only on the level of the EU and individual countries but also of cities. In the past this slowness was partly due to a lacking sense of climate urgency; present in a part of the four large Dutch cities, as documented in Kreutzberger & Unsworth, 2018; analysed for European cities in terms of the “ancillary role of CO₂ reduction in Urban Transport Plans” (Nocera & Cavallaro, 2014); accompanied by the fact that within sustainability, air quality rather than carbon emissions temporarily drew the main attention. In general there was less research focussing on carbon reduction on the local level than on higher echelons (Gouldson et al., 2015).

In awareness of the important position of a municipality for climate mitigation while not neglecting the relevance of cooperation between all governance levels the following societal and scientific challenge emerges we observe the following. Many cities have ambitious climate targets, like becoming climate-neutral in 2050, 2040 or 2030 but many of the same cities are uncertain about how the mobility should change and which measures should be involved in order to reduce GHG emissions to the levels of the cities’ aims. As the spatial setting of a city affects the sustainability of mobility, this introduces another spectre of uncertainty, namely: how must the urban structure change to support the development towards climate-friendly mobility?

1.4. Research questions

This leads to the **central research question** in the project and of this paper. What is the potential content of municipal measure packages containing mobility, land use and technical measures, enabling a partner city to sufficiently respond to its GHG reduction aim?

From the central research question we have derived the following concrete research questions, distinguishing between those having been present at the beginning of the project and those added in the run of the project.

Initial research questions, hence present already at the beginning of the project:

- 1) What type of research is suitable or required to appropriately respond to the central research question and which approach and methodology is chosen to answer the research questions 3–10?
- 2) What types of mobility, technological and spatial measures exist, how do they interact, how can they reduce GHG emissions and what magnitudes of GHG reduction can roughly be indicated?
- 3) City by city: What are the strategic business-as-usual (BAU) policies of the partner cities?

⁴ EEA doesn’t present data on the city level.

- 4) City by city: Which type of measures did the partner cities select for their climate-directed measure packages (**CliMobCity measure packages**) and how was this influenced by other city departments and by stakeholders?
- 5) City by city: how much GHG reduction could be achieved by means of the partner cities' BAU and climate-directed measure packages, given different speeds of greening of energy production?
- 6) City by city: if the combination of BAU and climate-directed measure packages and of energy greening does not reduce GHG emissions sufficiently, how must the measures change to after all achieve sufficient GHG reduction?
- 7) City-by-city: what is the direction of future space requirement of moving traffic?

Research questions added in the course of the project were:

- 8) Which conclusions can be drawn from the comparison of the partner cities regarding the mobility and GHG emission changes?
- 9) What about the transferability of all study findings to other cities?
- 10) Which additional GHG reduction may be expected from novel types of mobility (micromobility, shared mobility)?
- 11) Which shortcomings did the project witness and which recommendations can be given from the project and study to future research?

As the questions show, the research presented in this paper concerns non-monetary impacts of urban mobility. We don't monetarise GHG emissions or other impacts and don't calculate costs of measures.

1.5. Structure of the paper

The remainder of the paper is structured as follows. In [Section 2](#) we describe the type of research, research approach and methodology (RQ 1). [Section 3](#) is about how to consistently structure the relation between GHG reduction, mobility performances and measure (package)s (RQ 2). [Section 4](#) describes the demonstration studies and is organised in five blocks. In the first four we city by city analyse the change of mobility and GHG emissions due to the measure packages and other content of scenarios for future development. And we briefly address the space requirement of future traffic (RQ 7). In [Section 4.7](#) we compare the measures, mobility and GHG changes (RQ 8). The section also serves as summary of [Section 4](#). [Section 5](#) contains a literature review about shared mobility and novel types of micromobility (RQ 10). In [Section 6](#) we draw conclusions and discuss the transferability of findings (RQ9). Furthermore, we present recommendations about future research (RQ 11) and summarise the paper's contributions to research and policy-making.

2. Approach and methodology ⁵

2.1. Research approach and methodology

The research providing the basis for answering the research questions is organised in three modules. The centre of the research sequence are the so-called demonstration studies, one per partner city, in which GHG emissions were analysed bottom-up, hence in an activity-based fashion (Box II in [Fig. 1](#)). The demonstration studies in the project have been widened to case studies. This is to case-wise conduct explorations, compare them, also with those of former projects and studies, reflect on the general meaning and the transferability of the case study findings.

In order to have the cities develop relevant measure packages, it was found necessary to discuss the types of measures that could be included and their potential impacts for mobility and GHG emissions. This

process was supported by first – preceding the demonstration studies – developing an overview of types of measures and how these influence mobility and GHG performances. Such overview was the content of the first module (Box I), the result also being referred to as a “checklist”. Methodologically speaking, the checklist was established by consistently and checklist-directed combining own structuring notions with structuring statements/elements from GHG, mobility or behaviour literature.

The measure packages of all partner cities included measures to develop shared mobility and mobility hubs. The macroscopic transport models employed to predict the change of mobility, however, can't yet appropriately deal with these novel types of mobility. This is a problem, as one can imagine the novel mobility types to become game changers substantially influencing GHG emissions. We therefore conducted a literature review to uncover research-based expectations about their mobility and emission changes (Box III); see [Section 5](#).

The steps in each demonstration study were:

- Each city defines one or more CliMobCity (see [Section 2.4](#)) measure packages which expectantly reduce GHG emissions of mobility in magnitudes that sufficiently respond to the city's climate aims (Box B in [Fig. 2](#)).
- Each city then predicts the change of mobility due to the measure packages (Box C).
- PIK analyses the change of GHG emissions (Box D) deriving from the change of mobility and the shift to post-fossil fuel vehicles, also taking account of the greening of electricity production.
- The analysed GHG emissions are then the basis for considering following steps, like reflecting on further measures (Box F), repeating the mobility prediction and GHG analysis, repeating only the GHG analysis on the basis of mobility input assumptions, and deciding whether further modelling should be conducted in the forecasting or backcasting mode.

Methodologically speaking, several models were employed, namely macroscopic transport models to predict mobility, and a carbon model to analyse GHG emissions. The carbon model was developed as a what-if model, its input, like a certain modal shift or change of trip distance,

consisting of expert-based assumptions. The problem of such assumptions is that they are difficult to make, given the complexity of a city and its transport network. Expert-based assumptions can also easily miss the consequences of city-specific granularity. For this reason, the research setup is to let a transport model precede as this can more accurately take account of the city's complexity and fine granularity. ⁶ Its output could then be used to give orientation when defining the input of the carbon model. This combination leads to the main analytical pathway in the demonstration studies, namely along the boxes A+B+C+D+E of [Fig. 2](#). We explain the measure packages, mobility prediction, carbon analyses and different analytical pathways in the subsections 2.4–2.8

The research approach and chosen methodology have two backgrounds.

2.2. Background 1: interregional learning and city demonstration studies

Interreg Europe is no programme to conduct fundamental research for innovation but instead supports initiatives aiming for societal change in innovative, sustainable and region-strengthening directions. In this framework the programme focusses on the “capitalisation” of innovation and other experiences of practitioners in the field of the programmes' “priority axes”, in our case “low-carbon economy”. The main mode of capitalisation is “interregional learning”: the policy

⁵ Responding to RQ 1.

⁶ For similar reasons – a reference from the past – macroscopic transport modelling has become widespread in the planning work of many German ([Schönharting & Schuhman, 2010](#)) and European municipalities.

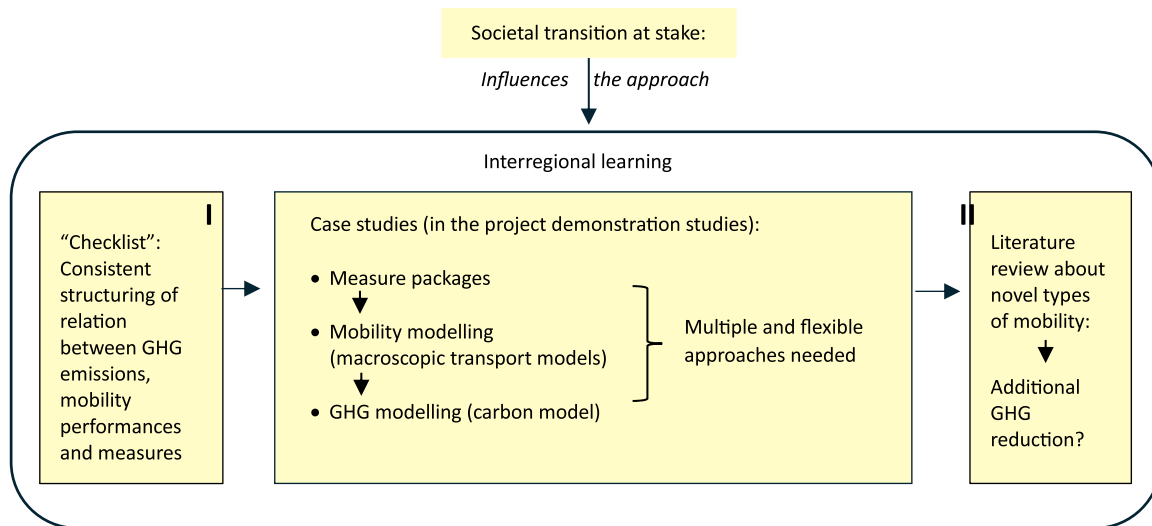


Fig. 1. Research approach.

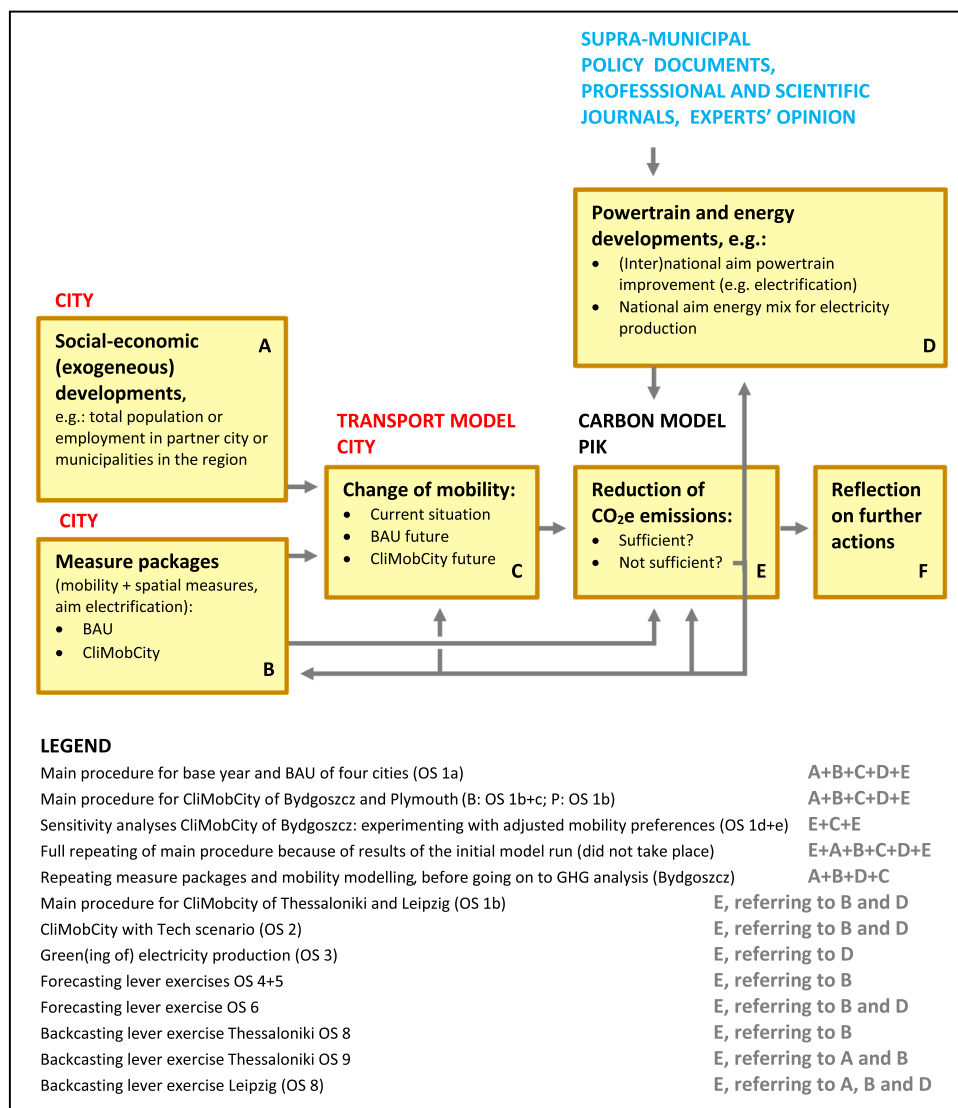


Fig. 2. Structure of the demonstration studies per partner city and overview of analytical pathways.

organisations in the project, in our case four medium-sized cities, mutually learn by exchanging experiences and good practices. This learning is to take place in three circles, first involving the direct project attendees, thereafter their organisations, here the municipalities (like the own and other departments or like politicians) and involved stakeholders, thereafter an external audience like other municipalities and other organisations.

Within the interregional learning demonstration studies were allowed. In our project each partner city conducted a demonstration study to show the GHG impact of explorative climate-friendly mobility policies. They learned from the demonstration studies of the other partner cities and also from their own demonstration study. For real life policy-making the demonstration studies could be seen as a first phase in the cities' strategic planning. Different however, in the project there was more freedom for out-of-the-box thinking and exploration than there typically is in the regular municipal strategic planning business.

2.3. Background 2: societal challenge and impacts for research

Climate mitigation is a development challenge for the next half century. The European Union from the Paris agreement derives the aim to become net climate neutral in 2050 and to reduce GHG emissions from transport by 90 % in the period 1990–2050 (EC, 2020). "Net" includes the policy option to organise artificial negative GHG emissions next to the already expectable natural negative emissions. Together these absorb part of the GHG which have already been emitted, hence part of the positive emissions. Such is illustrated in the European report "A clean planet for all" (EC, 2018). Without such compensation, the remaining global carbon budget would require achieving climate neutrality earlier than 2050, like between 2035 and 2040.⁷

The required GHG reduction can only be achieved on the basis of large changes in the envisaged systems, here the energy and mobility system, and in lifestyle and production. Transition is at stake, transition to climate-neutral mobility. Only optimising the existing systems or regimes lets them run stuck. Therefore, as the EU puts it: "Overall, we must shift the existing paradigm of incremental change to fundamental transformation" (EC, 2020). Or: "The focus needs to shift from stimulation to facilitation and boost of the transition ... in the energy and mobility sector" (Geilenkirchen et al., 2024, p10). The difference in subject and approach can easily be illustrated: one could continue improving the fuel and emission efficiency of the fossil-fuel car, but the achievable GHG-reduction is limited. This would represent an incremental change. Instead, one can substantially reduce the dominance of private fossil-fuel car use by a fan of measures, most likely combinations from the policy triptych "avoid, shift, innovate", hence achieving respectively less travel demand, less private car use and less fossil-fuel car use. These together with adjustments in the urban structure and/or of public space are fundamental changes having the potential to achieve large GHG reductions.

This societal challenge together with the city level addressed mark the type of research involved and approach needed. Key words for this approach are long term, transition, climate urgency, quantification, uncertainty, and – already mentioned – city-specific and fine granularity.

Quantification is an imperative deriving from the urgency of climate mitigation. This demands to provide a relative concrete orientation about to which extent current long-term policies and actions are on track in terms of municipal climate aims. For global warming it makes a difference whether (net) climate neutrality is achieved in 2040 or 2060. Therefore, the Guidebook for Sustainable Energy and Climate Action Plan (SECAP) (Bertoldi, 2018, p23) demands "whenever possible" to "estimate the GHG emission by target year".

⁷ Such conclusion can be drawn on the basis of two IPCC reports (IPCC, 2022 and 2023) and are explained in an upcoming paper.

Long term periods, certainly very long ones like up to 2050, provide uncertainty. This is a challenge for quantification, as some of the assumptions regarding the influence of entities on other ones are likely to become invalid in the run of time. A good example are the mobility preferences of travellers, also referred to as belief (Ajzen, 2006) or attitude (Van Wee & Kroesen, 2022), in macroscopic transport models. When predictions cover long periods, also ones without transition, these deserve attention. A mobility preference describes the probability of choosing a certain transport alternative with certain performances (quality, costs). The preferences change somewhat in the long run. Macroscopic transport models nevertheless assume them to remain constant through time, not because this is appropriate, but because too little is known about their future changes. This can bias the modelling results, like perhaps underestimating the willingness to choose more sustainable mobility options in the future, or the opposite (Van Wee & Kroesen, 2022).

In transitioning processes, the uncertainty is even larger. When quantifying future impacts in the demonstration studies, one cannot fully rely on established perceptions, assumptions or concepts. From here two types of conclusions can be drawn. One is to refrain from complex modelling, use more simple models, or conduct analyses using city typological data instead of city-specific data. One could skip transport demand modelling and instead let experts determine future market shares of alternative modes of travel. Or one could use tools in which GHG reductions are analysed after the customer city chooses from predefined measures and from predefined quantities.⁸

An alternative conclusion is that all modelling should be embedded in what Schön (2016) calls the **reflective conversation with the situation**, identifying problems and exploring solutions iteratively, interactively, progressively and tentatively. The conversation encounters the incapacibilities and incompleteness of models, checks on the validity of assumptions and the appropriateness of (planning) solutions in multiple ways, and explorations of the conditions and impacts of changing attitudes, choices, technical solutions etc. The reflective conversation does not only help to find orientation and answers, but even to discover which societal and research questions first or additionally need to be raised.

The project chose and this paper describes the second approach: design research sequences employing models which together: enable conducting city-specific analyses with a fine granularity; the analyses are flexible allowing to respond to uncertainty, part of which may first be discovered during the analyses; the analyses give space for the mentioned reflective conversation.⁹

Schön (2016) also advocates 'no research for, but with practitioners', as their involvement contributes to the reflective conversation. This was inherent to the setup of the city demonstration studies which was completely together with the municipalities and their stakeholders.

2.4. Measure packages and exogenous modelling input

A measure package (Box B in Fig. 2) describes transport infrastructure, services, their properties (capacity, speed, costs/prices), vehicle powertrains, and optionally also urbanistic structures supporting sustainable mobility, all to change the base year situation. Examples of urbanistic changes are city densification in general or at PT stops or stations, or the increase of functional mix.

We distinguish **business-as-usual** (= BAU) and **CliMobCity**

⁸ An example is the EUCityCalc (PIK and Climact, 2022), a tool to predict the future GHG reduction of European cities in a slightly standardised fashion, in all policy fields of a municipality, one of them being mobility.

⁹ The reasonability of such approach is perhaps and to some extent confirmed by an appraisal recently conducted by the Öko Institute et al. (Timpe et al., 2022) for Munich. This for mobility included similar research sequences towards identifying pathways of GHG reduction.

measure packages. Both focus on future development. A major difference between the two is that the BAU measure package has a policy status, like in the past having been formally decided by the municipality; perhaps it is part of a strategic plan like a sustainable mobility or land use plan or programme. The CliMobCity measure package has no policy status. It is only agreed on in the learning environment for the project. Another main difference between a BAU and CliMobCity measure package is that the latter describes the set of measures which together with the BAU package and according to the city expectantly provide sufficient GHG reduction to meet the city's reduction aim. In three of the cities the CliMobCity package is supplementary to the BAU package, in Bydgoszcz some CliMobCity measures replace some BAU measures while others are supplementary.

Regarding BAU measure packages, the main task was to clarify its content. Then each partner city developed one or more CliMobCity measure packages: Bydgoszcz two, each of the other cities one. For developing CliMobCity packages the civil servant(s) directly participating in the project firstly engaged their departments and then also other departments, and they discussed measures with stakeholders. On the basis of the starting document of the project it was communicated that the partner cities would in this project have the freedom and opportunity to think differently and boldly, heading towards fundamental change; and also think in longer terms, like several decades, than common in municipal strategic planning. All was possible except for including a few technical innovations in the package, namely autonomous driving and freight drones.

CliMobCity packages are expected to increase the GHG reduction, but this is not to say that BAU packages weren't already ambitious. Illustrative in this regard is the sustainable mobility plan for Thessaloniki, representing BAU policies and envisaging a strong modal shift by introducing two metro lines, a regional train line, coastal PT and significantly improving infrastructure for active travel.

The social-economic developments like population and working places are generally considered to be exogeneous (Box A in Fig. 2), meaning that they are not/hardly influenced by municipal actions. However, there are exceptions to such mechanism. A city can strive for a certain population or spatial distribution of population in favour of societal aims, like sufficient demand for amenities or PT services. Corresponding measures (e.g. housing) would then be part of the measure package (Box B) instead of exogeneous. Such was present in the BAU package of Leipzig, the CliMobCity package of Plymouth and in one of the two CliMobCity packages of Bydgoszcz.

Also certain technology measures can either be exogeneous or not. The (inter)national initiatives aiming to change powertrains (e.g. ICEV diesel, ICEV gasoline, BEV, hydrogen) are exogeneous to municipalities and then are part of Box D. Whenever the municipal electrification aims/measures were more ambitious than the national ones, these were used as input for GHG calculations instead of the (inter)national ones. They then are part of the municipal measure package (Box B). The Box-D data are fed from the carbon model's so-called inventory, a collection of city, mobility and technical data found in professional and scientific literature/documents.

The future powertrain shares are next to other technical data described in two scenarios, the **EU reference** and the **Tech scenario** (e.g. Taylor et al., 2019; Capros et al., 2015; Warmuth et al., 2020). The first scenario mirrors policy trends in the future in the EU and its member states, as identified on the basis of a literature review. One could call this a technical BAU scenario. In the Tech scenario the ambition is higher, corresponding with higher EU aims which were varied to the country level, assuming their share developments to converge. For each country base year, EU reference 2050, and Tech 2050 shares were determined. Where the planning periods of the partner cities deviated from these years, PIK calculated the corresponding shares by means of linear interpolation. All values for a country are assumed to apply for any city in that country. This is a pragmatical assumption.

The found shares of post-fossil powertrains in the countries of the

partner cities lie between 0 % and 1 % in the base year,¹⁰ between 1.5 % and 23 % the EU reference future year, between 11 % and 56 % and the Tech future year (Table 1). Shares are also enlisted for other vehicle types (busses, tram metro, rail, HGVs and LGVs). The share of post-fossil fuel HGVs was projected to lie near to zero in the base year, and still to be low in the future year, namely up to 6 %.

2.5. Transport modelling

For the prediction of mobility, each city had a macroscopic transport model to its disposal, but there were differences. The models of Bydgoszcz, Thessaloniki and Leipzig were 4-step multimodal ones on the basis of VISUM software, provided by the German consultancy firm PTV, the included modes being road, PT (both with subdivisions), bicycling and walking. This software was used for the project by Gradiens Sp. (Bydgoszcz), in CERTH/HIT (Thessaloniki), and directly by PTV (Leipzig), to forecast current and future mobility. The firms also validated the modelling outcomes by plausibility and calibration activities.

The transport model of Plymouth was an unimodal road assignment model on the basis of SATURN software. It has no modal demand functions, provides no data about non-road mobility and therefore also no modal shift results. A separate expert-based modal shift estimation was conducted by the municipality in cooperation with its transport consultancy firm, WSP. This means that there is less substantiating about to which extent alternative mobility options would be chosen by travellers. Another problem was that Plymouth's transport model for trips from and to Plymouth couldn't distinguish between vehicle-kms taking place within or outside of the municipal area.

The **mobility changes** in each city are described in different variables, all cumulating in vehicle-kms per mode, vehicle type and network part. The vehicle-kms are essentially (see Section 2.7) the central input for GHG modelling. Especially road vehicle-kms are of interest. These are good first indicators for the direction of total **GHG emission change**; and also of **space demand of all moving mobility**. If road-vehicle-kms increase, so may GHG emissions. And so will the total space demand of moving mobility. We for simplified descriptions of changing space demand focus on car-kms, as the car per pkm has the largest space demand of all passenger modes (Allekotte et al., 2021). The conclusions from passenger mobility about the change of space demand of all mobility will seldomly be contradicted by changing freight transport. This simple relation is used to answer RQ 7.

2.6. GHG emissions envisaged

This study analyses scope 1 (= tank-to-wheel) and 2 (= well-to-tank) GHG emissions of all vehicle-kms driven in the municipal area and due to trips in, from, to and through a city. Scope 2 emissions are included, different to numerous older studies, as this gives a picture of the real instead of potential GHG reductions. The reason is that in many countries the electricity production still is rather fossil fuel based and therefore GHG emitting (Table 2), meaning that a replacement of a fossil fuel by an electric vehicle will not already at that moment unfold all of its potential GHG reduction. Only when all electricity production has become green, this will be the case. The data about the energy mix for electricity production are based on Gyalai-Korpos et al. (2019). For GHG calculations the assumption is that the country data apply for any city in the country. PIK recalculated the data to the time windows of the city demonstration studies by means of linear interpolation.

2.7. Carbon model

The carbon model developed by PIK and adapted for this study from

¹⁰ Current shares of post-fossil fuel cars lie higher than in the base years of Table 2, but this is part of the process projected in the table.

Table 1

Share (%) of battery electric cars (BEVs) and hydrogen cars in the countries of the partner cities in the year of their planning horizon in the 2050 CliMobCity scenarios (EU reference scenario; Tech scenario).

	% BEV cars	% Hydrogen cars	% BEV and hydrogen cars
Bydgoszcz, 2021	0.2	0	0.2
Bydgoszcz, all scenarios for 2050	16; 30	7; 13	23; 43
Plymouth, 2015	1	0	1
Plymouth, all scenarios for 2034	13; 39	5; 17	18; 56
Plymouth, 2050	31; 66	13; 28	44; 94
Thessaloniki, 2018	0.2	0	0.2
Thessaloniki, all scenarios for 2030	1.3; 8	0.2; 3	1.5; 11
Thessaloniki, 2050	25; 52	11; 22	36; 74
Leipzig, 2015	1	0	1
Leipzig, all scenarios for 2030/35	12; 36	5; 15	17; 51
Leipzig, 2050	31; 65	13; 28	44; 93

Source: Appendix-PIK-Report [PIK, 2023] on the basis of Taylor et al., 2019; Capros et al., 2015, Warmuth et al., 2020)

Table 2

Share of fossil electricity production in the countries of the partner cities.

	Share (%) fossil electricity production in base year	Change of the share (%-points) of fossil fuel electricity production between the base and the future year (mix A (future))	Share (%) fossil electricity production in energy mix A (future year = reduction still needed to achieve fully green electricity production) *
Poland (2021–2050)	88	-44	44
UK (2015–2034)	55	-35	20
Greece (2018–2030)	70	-25	45
Germany (2015–2035)	60	-9	51

This is an aggregation of a table distinguishing many types of electricity production, such as coal, gas, wind, sun, and nuclear.

Source: on the basis of Gyalai-Korpos et al., 2019.

the EUCalculator, computes energy demand (GWh) and GHG emissions (Mt), essentially of all vehicle-kms, distinguishing modes vehicle types, powertrain shares (for cars ICE, BEV, FCEV, PHEV¹¹; in %), fuel mix per powertrain,¹² the vehicle fleet characteristics, vehicle efficiency (e.g. fuel per km), network parts per mode, and the degree of traffic flow (congestion). The concrete mobility input, however, was slightly different, due history of the carbon model: vehicle-kms were approached via passenger-kms per mode, this being the product of passengers, time spent and speed per mode (Fig. 3).

The energy demand multiplied by emission factors per unit of energy (Mt/GWh) provides the GHG emissions (Mt). The emission factors differ per time horizon (e.g. 2030 or 2050) and country (UK, Poland, Germany, Greece), depending on the mix of coal, gas, oil, nuclear and renewable in the electricity production. Hydrogen is in the analyses considered to be produced completely green.

The freight emissions are analysed in a similar (from activity -> energy demand -> GHG emissions) but more simple way, corresponding

¹¹ ICE = Internal combustion engine, BEV = Battery electric car, FCEV = Fuel cell electric vehicles (hence hydrogen etc.), PHEV = Plug-in hybrid electric vehicles.

¹² ICEs use gasoline, diesel or gas, BEVs electricity, FCEV hydrogen, and PHEV electricity for the first kilometres, thereafter gasoline, diesel or gas.

with data from the transport model which are less detailed data than for passenger mobility.

The input to the carbon model is inserted by positioning so-called levers of the model. This is choosing certain values of input variables. A lever can be moved to any position, also extreme ones, that can be justified from the exploration angle. The positioning of levers takes place by the modelling PIK researcher. Levers of special relevance for potential municipal actions are the total demand, modal share, average trip distance and technology lever (describing the shift to electric or other post-fossil fuel powertrains/vehicles).

2.8. The overall scenarios and analytical pathways to calculate GHG reduction

The analysis of GHG reduction is conducted along different analytical pathways; different per partner city and different per so-called overall scenario (OS). An OS is the combination of a mobility measure package, a scenario of the shift from fossil fuel to post-fossil fuel vehicles and a scenario of the shift from fossil fuel to post-fossil fuel electricity production. The OSs are (Fig. 2 again):

- OS “base year” (base year composition of powertrains and vehicle fuel mix, base year energy mix A, GHG emission level is 100 %),
- OS 1a (BAU, EU reference scenario, future energy mix A),
- OS 1b (CliMobCity, EU reference scenario, future energy mix A),
- OS 2 (CliMobCity, Tech scenario, future energy mix A), and
- OS 3 (CliMobCity, Tech scenario, completely green electricity production).

For Bydgoszcz having developed two CliMobCity measure packages, W1 and W2, there were more CliMobCity scenarios with EU reference powertrain shares and future energy mix A (OS 1b and 1c). Bydgoszcz in awareness of its long planning period (up to 2050) and also in search for additional GHG reduction perspectives experimented with the change of mobility preferences (term is explained above in this section). In the corresponding measure packages W1 + and W2 + (OS 1c and 1d) the travellers’ mobility choices change despite of an unchanged transport supply and city structure. Not being embedded in an established knowledge environment regarding the interaction between preferences and their causes, the performance analyses OS 1d and 1e rather resemble sensitivity analyses to respectively 1b and 1c than real overall scenarios.

For all partner cities none of these overall scenarios turned out to provide sufficient GHG reduction in the light of their reduction aim. Therefore, so-called forecasting lever exercises were conducted for each city, and also backcasting lever exercises for two cities. In the **fore-casting lever exercises** the additional GHG reduction of a standard set

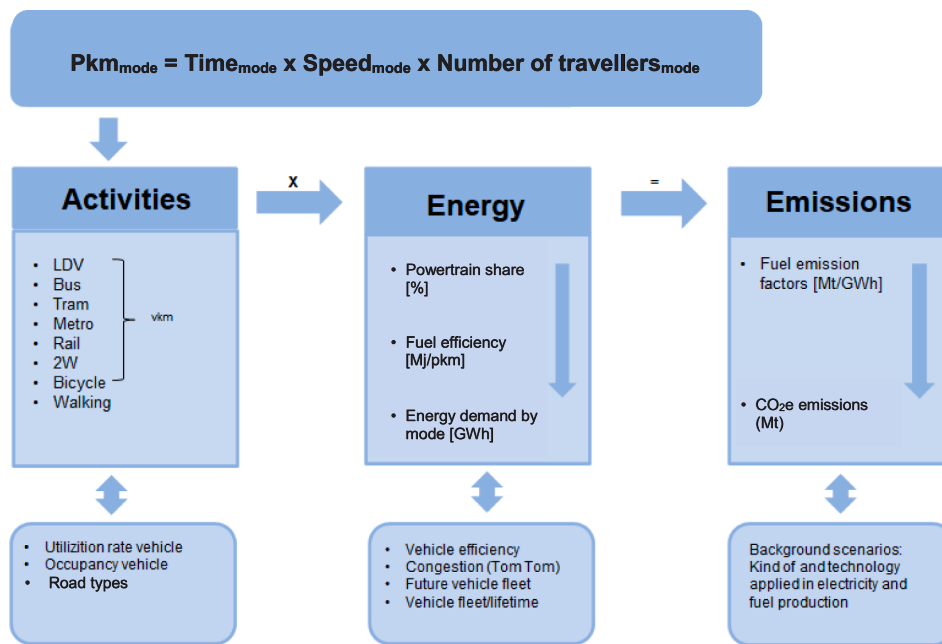


Fig. 3. Main structure of carbon model (Source: Appendix-PIK-report).

of performance changes was explored. Starting from the most ambitious overall scenario, the CliMobCity-tech-green energy scenario (OS 3), the GHG effects of additional performance changes, being determined pragmatically, were explored. These were:

- (OS 4:) an additional modal shift: the share of LDV use is reduced by another –10 %-points in exchange for a higher share of active travel and PT (+ 5 %-points each);
- (OS 5:) –10 % road time spent (road vehicle-kms);
- (OS 6:) + 10 %-points additional share of post-fossil LDVs at the dispense of fossil fuel ones;
- (OS 7:) a combination of these measures (of overall scenarios 3, 4, 5 and 6).

Strictly speaking, the additional content of OS 4–7 consisted of performance changes, and not of measures. The latter would still need to be identified. The additional performances are assumptions, due to skipping preceding transport modelling. This allows to quickly explore GHG impacts, but the measures needed for this change remain unknown or need to be identified afterwards.

As also the forecasting explorations turned out not to provide sufficient GHG reduction, **backcasting lever exercises** were added, in search for additional performance changes which after all do provide sufficient GHG reduction. Again, the starting point were the GHG levels of OS 3. The backcasting exploration was conducted only for Thessaloniki (OS 8 + 9) and Leipzig (OS 8), the two cities not already aiming for climate neutrality in the planning period. These cities still have a prioritisation challenge in the next planning period, like giving more priority to faster electrification or stronger modal shift. In contrast, for Bydgoszcz and Plymouth, which aim for climate neutrality already in the envisaged planning period, such prioritisation is not at stake as they already in the envisaged planning period actually need to fully replace fossil fuel by post-fossil fuel vehicles.

It showed that for the different OS also different analytical pathways are appropriate (Fig. 2). The full analytical pathway A+B+C+D+E was

conducted for the OS 1a (BAU, EU reference) of all four cities and OS 1b (CliMobCity, EU reference) of Bydgoszcz and Plymouth. For the CliMobCity policies of Thessaloniki and Plymouth the pathway with carbon modelling in box E, using varied input from the boxes B and D, was sufficient, as the mobility changes were the same¹³ in BAU and CliMobCity. New transport modelling was not required. Bydgoszcz and Plymouth in CliMobCity also had mobility change in mind, requiring new transport modelling.

For Bydgoszcz' OS 1d and 1e the analytical pathway was E+C+E. For the OS 2 (additional electrification etc.) new calculation work took place within box E, using varied input from the boxes B and D. Also, for OS 3 (additional greening of the electricity production), the new calculation work took place within box E, now with reference only to box D.

The forecasting and backcasting lever exercises took place without preceding mobility modelling, which is within box E, using varied input from box B (OS 4, 5, and for Thessaloniki also 8) or from boxes B and D (OS 6, for Thessaloniki also 9 and for Leipzig also 8). While the exercise aim of the fore- and backcasting is different, the methodology is rather the same. In the forecasting exercises GHG reduction modelling output, in the backcasting the starting point. The backcasting comes down to a trial and error modelling approach, repeating input->analysis->output until the GHG reduction aimed for is achieved.

Summarizing, the larger number of OSs and corresponding analytical pathways is the result of a search tour to identify policies which might after all provide the GHG reduction strived for. All in all, there was a tentative approach, successively establishing an overview of policy options, the total representing a piece of Schön's (2016) reflective conversation with the situation.

2.9. Comprehensive presentation of the combined output of mobility and technical scenarios

The number of scenarios can easily lead to graphs with dot clouds which can't be understood quickly. We avoid such by presenting the GHG reductions as shown in Fig. 4. It on the x-axis distinguishes mobility

¹³ In Thessaloniki almost the same because, as mentioned above, the city had quantified some mobility effects of shared car use. But this merely changed the mobility changes predicted.

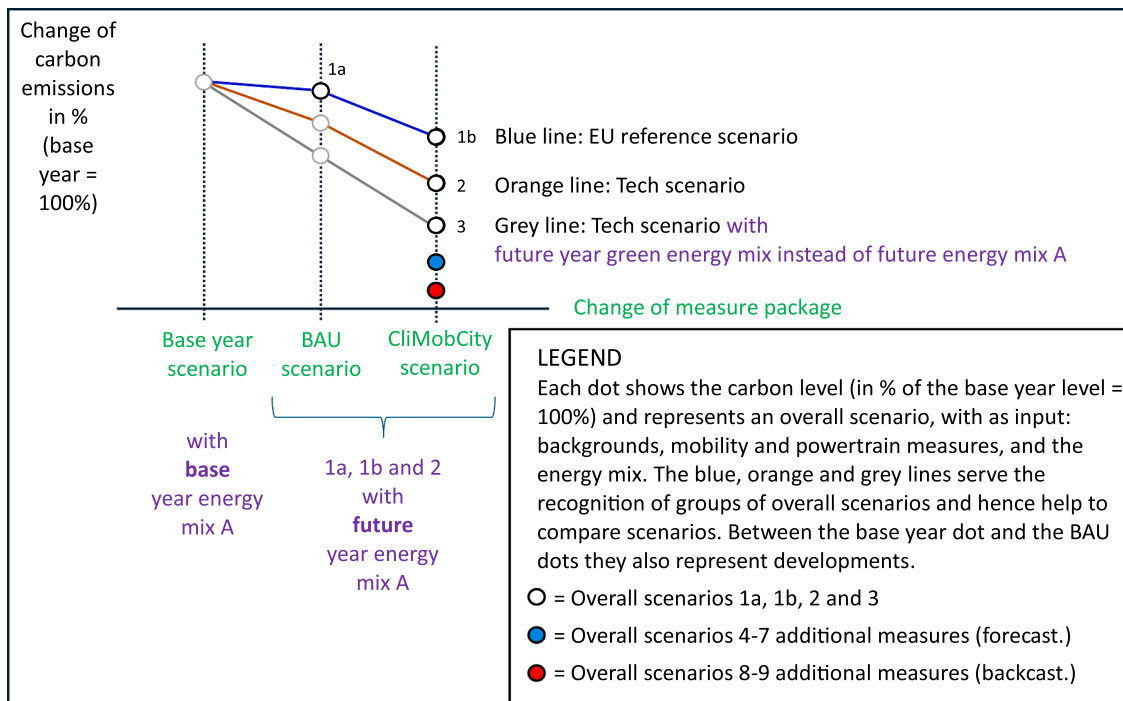


Fig. 4. Way of presenting GHG reductions (%) of overall scenarios.

measure packages and on the y-axis technical scenarios (powertrains and energy mix). **Each dot** represents the emission level of an overall scenario. The GHG level is expressed in % of the base year emission (100 %). The x-axis is no time axis. The lines between the dots primarily serve the recognition of scenarios for comparison. They do not describe a development. Only the lines between the base year and BAU dots can also be read as a development.

3. Performance changes and measures types towards low-carbon urban mobility¹⁴

3.1. Types of performances and measures

There is much confusion about which changes of mobility and powertrain performances effect GHG emissions and how mobility and city measures interact. We therefore developed an overview of measures and mechanisms along which GHG reduction of mobility takes place. For practitioners the overview can be used as a checklist. The columns and lines in the checklist (Table 3) are not new, however the coherence between all is. In former structuring attempts we find the presence of the mentioned core performance changes (in e.g. Litman, 2023) or an overview of main performance changes (in Van Wee et al., 2005). Furthermore, PBL presents the relation between core and main performances (e.g. Wright, 2022; or in Figure 5.3 in Geilenkirchen et al., 2023), but then less complete and mixing main performance changes and main measures.

In the (Check)List of prerequisite performance changes and measure types towards low-carbon urban mobility we distinguish GHG input performances, mobility performances, main and supporting measures. The GHG input performances, namely vehicle-kms and GHG emissions per vehicle-km, are a comprised version of the three factors of mobility GHG emissions described in Section 2.7. The mobility performance changes (column 2 in Table 3) are the centre of the checklist. They influence the GHG input performance changes (column 1) and are induced

by measures. Column 3 enlists a selection of main measures, needed to change mobility performances in column 2. Many main measures are decided on the local level. Examples are the implementation or change of transport infrastructure, of transport services or their properties, like speed, costs or reliability.

The main performance changes towards zero GHG mobility are:

- 1) **Reduce the number of trips;**
- 2) **Reduce the average trip distance;**
- 3) **Achieve modal shift** from the truck, private car or private van to climate-friendly modes;
 - a. Classical: in passenger mobility to walking, bicycling and (averagely well used) public transport. In freight to (well used) trains or barges, for flows from and to the city;
 - b. New: to shared vehicles and new types of micromobility vehicles (e.g. step, freight bicycle);
- 4) **Increase the passenger vehicle occupancy and freight vehicle loading degree;**
- 5) **Reduce vehicle net weight, vehicle air resistance and vehicle frictional resistance;**
- 6) **Improve the vehicle powertrains, especially replace fossil fuel vehicles by post-fossil fuel vehicles;**
- 7) **Smoothen traffic flows.**

The mobility performance changes 1 and 2 correspond with **Avoid** from the policy triptych, 3a to **Shift**, 3b partly to **Avoid** and partly to **Shift**, and the rest to **Improve**. The list may not be exhausting. Nevertheless, if none of the main performance changes occurs, a decline of GHG emissions of mobility in the framework of municipal policies is unlikely to take place.

Examples of municipal main measures supporting modal shift from the private car to other modes

are investments into PT, bicycle or pedestrian infrastructure, the reallocation of road space to other modes or to non-traffic public space, reducing maximal road speed and other traffic management, accelerating PT and increasing PT service frequencies, parking regulations and pricing, and city access limitations by means of regulation or pricing.

¹⁴ Responding to RQ 2.

number of trips and their length decreases and modal shift towards sustainable modes increases with the urban density, functional mix and city size (except for mega-cities), and the more dense city parts are located close to PT. Former comparable paradigm contributions were [Kenworthy and Laube \(1996\)](#), exploring the relation between urban density and declining car-kms, and the PLUME project ([Jopson et al. \(2005\)](#)), drawing conclusions from 12 projects in a land use and transport research cluster, one of them being the Propolis project ([Lautso, 2004](#)). The notion of trip distance led in the 1990s to the target image “city of short distances” ([Wegener, 1999](#)); short distances to work and daily amenities like shops, elementary schools. The X-minute city concepts are more recent concretisations of such thinking. For instance, [Allam et al. \(2022, p1\)](#) sees the 15-minute city as a concept that “can shape a net zero future”. In other recent research the paradigm statements are confirmed and some variables have been added. A confirmation of the impacts of modal shift we find in [Prieto-Curiel and Ospina \(2024\)](#) in their large-scale analysis of almost 800 European and other cities. An EU-study ([Armoogum et al., 2022](#)) concluded that private car ownership (1st, 2nd or 3rd and more private cars per household) in denser European cities is lower than in less dense cities, just as car dependency is then lower ([Quinio & Rodrigues, 2021](#)). Densification of the existing city appears to be of influence not only for number of trips, trip distances, and choice of travel mode, but also reduces private car ownership, and is beneficial for the use of shared scooters ([Badia & Jernelius, 2021](#)). Furthermore, urban density is of influence for the feasibility of amenities, PT and – a new gameplayer – green heat networks in the city. The low density in UK cities in comparison to continental European cities, due to the Anglo-Saxon housing tradition, and the deriving difficulty to provide satisfactory and cost-efficient PT is discussed by e.g. Centre for cities experts ([Rodrigues & Breach, 2021](#)).

The densification’s alternative is suburbanisation, people moving out of the existing city to new locations in the city fringe or – even further – to smaller towns including urban satellites. This all is “a development for which growing car ownership and the modal shift from PT to car act simultaneously as both causes and effects” ([Lautso et al., 2004, p32](#)). Another effect of suburbanisation is the increase of average travel distance ([Tillema & Jorritsma, 2016](#); [Slaev et al., 2018](#)). Connecting growing suburbs to the core city by PT will make mobility more sustainable than if the suburbs are only accessed by car, as shown for Barcelona ([Muñiz & Garcia-López, 2019](#)), but doesn’t necessarily compensate for additional emissions due to the increasing average distance caused by suburbanisation, as observed for Aarhus ([Tennøy et al., 2016p19](#)). There is also the warning from historical examples ([Knowles, 2012](#)) and contemporary studies (e.g. [Lautso et al., 2004](#)) that attractive PT in general can contribute to further suburbanisation.

Different mobility changes and the compactness of the city strengthen each other. Modal shift from the car saves space because the space requirement per passenger-km is the largest for the car and less for other modes (see [Section 2](#)). Modal shift, in this way, provides a double benefit: it reduces energy demand and GHG emissions while increasing or conserving the compactness of the city. This means that average trip distance is shorter, for which reason more people choose to travel by walking, bicycling, perhaps PT and shared car.

Functional mix is about increasing the vicinity of housing, working and amenities, shops, schools, garbage collecting points in residential areas. Mixed land-use allows to reduce private car usage per capita ([Ewing & Cervero, 2017](#)), average travel distance and corresponding emissions. In the location and city discussion special attention is paid to retail. Large shopping concentrations, certainly ones in the urban periphery, increase the use of the car and the average car distance, as analysed for Belgium ([Ronse et al., 2015](#)) or for five Irish cities ([O’Driscoll et al., 2022](#)). The latter authors observe that large retail concentrations in the urban fringe and car-dependency are intertwined. They add that governments should develop “compactly and efficiently before expanding peripheral boundaries” ([O’Driscoll et al., 2022 p. 10](#)).

Continuously new types of measures emerge, all fitting in the check

list of performance changes. Typically, these are new conditions for or new shapes of old measure types, or are new combinations of existing and new measure types, or new combinations of behavioural and technological measures.

New structuring of accessibility has stirred up the hierarchy between performances, main and background measures a little. In the so-called Triple access planning ([Lyons et al., 2024](#)) the accessibility of and in cities (= a performance) can be improved by increasing physical spatial proximity (main measure in the Checklist), improving the transport system (main measure in the Checklist) and/or improving the digital system (background measure in the Checklist). The digital system might reduce travel demand in terms of distance or even number of trips.

[Table 3](#) does not show **background measures**. These support the main measures, but require additional action. Organising legislation to allow innovation in cities is such background measure. ICT/telematic/digitalisation as discussed by [EEA \(2022b\)](#) or for Warsaw heading for climate neutrality [Zawieska and Pieriegud \(2018\)](#) helps to observe mobility, give advice to travellers and increase operational effectiveness and efficiency of transport. [Weber et al. \(2022\)](#) give examples in Germany and Switzerland of which municipal regulations are allowed according to national legislation.

While climate challenge is acknowledged amongst an increasing fraction of Europe’s population and organisations to be present and human made, this doesn’t automatically lead to a corresponding change of mobility behaviour, like a fast take-up of vehicle electrification or shared mobility or more shift to PT and active travel. From here a need for another background measure, namely **awareness raising**, can be derived. This can change mobility behaviour, either by informing people about options they did not know until then, or by changing their preferences (attitudes, beliefs) about (dis)advantages of alternative ways to travel. Scientific literature (e.g. [Van Wee & Kroesen, 2022](#)) explains that preferences can change by cognitive, doing/experiencing, and/or ‘feeling’ processes. Awareness raising can focus on any of these. Regarding doing/experiencing, [Ibraeva et al. \(2022, p4\)](#) give the example “that recent movers to dense urban neighbourhoods not only increase their transit use”, “but also gradually develop favourable attitudes towards it”.

3.2. Indications of the magnitude of GHG reduction of types of measures

Next to understanding the conceptual relation between types of performances and measures ([Table 3](#)), rough orientation regarding the potential magnitude of GHG reductions is a prerequisite for designing effective climate-friendly mobility measure packages. These would be ones finding a good balance between fundamental change, as propagated by climate and transition experts, and realistic change. One might summarise this as ambitious change potentially being realistic under future conditions. Two publications are suitable to illustrate that challenge.

The first is a study ([Leguijt et al., 2013a and 2013b](#)) in charge of the city council of The Hague exploring how climate neutrality in 2040 can be achieved. The study shows GHG reductions following from municipal and non-municipal measures (like road pricing on national motorways passing the city). For the remaining GHG gap (27 %) the required reduction was to be achieved by a goal-oriented measure package of which the content wasn’t yet known.

About five years later, after sharpening its climate aim, now aiming for climate neutrality in 2030 instead of 2040, the city of The Hague commissioned a new climate study ([Schilling et al., 2017 and 2018](#)). Its main measure was the implementation of a city-wide zero emission zone in 6–11 years from then, which would eliminate almost all GHG emissions. Such measure is very ambitious, but also unrealistic in such short time: the required car replacement speed is too high, given car lifetimes and given Dutch replacement support. This will make the city less accessible for some traveller groups, if no convincing alternatives are developed, and may reduce (political) support. A similar warning comes

from the SUMP appraise for Munich (Timpe et al., 2022, p29) regarding areal pricing. The “effectivity of this measure is very high, but one should, if implementation is planned, consider a temporal phasing because on the medium term ... there are no alternatives in sight.”

To sense reduction magnitudes of GHG reduction by measures, column II of Table 4 shows ¹⁵ tank-to-wheel (scope 1) GHG emissions of alternative modes. Switching from fossil fuel to electric cars provides –100 % GHG change. So does the switch to tram and metro. That to a diesel bus provides 22 % . A full **car electrification etc.** is what eventually what needs to take place to achieve zero mobility GHG emissions. But this process takes time. From Table 2 one can derive that in our four cities the share of post-fossil fuel cars is projected to increase by 1–9 %-points per 10 years (EU reference) up to 9–29 %-points (Tech). **Modal shift** is important for climate and space-saving in the city. But also modal shift takes time. And different to the electrification it will only partly take place, as not all situations allow and not all travellers are willing to go by PT.

(Source: on the basis of Leestemaker & Berg, 2023 (STREAM passenger transport); elevation to city levels by own calculations using information from the same source)

Envisaging scope 1 and 2 emissions (column I of Table 4) shows – given the Dutch energy mix for electricity production – that a switch from fossil-fuel to electric car would not provide –100 % GHG change, but only –66 %; the switch to tram has a similar magnitude, that to metro would change emissions by about –80 %.

Scope 2 emissions are declining, visible in terms of changing emission factors. CE Delft (Leestemaker & Berg, 2023) for the period 2020–2030 and the Dutch context analysed smaller reductions of scope 1 emissions due to increasing efficiency, and large reductions of scope 2 emissions due to the greening of e.g. electricity production. For instance, tram scope 1 emissions are zero in 2020 and 2030. Their scope 2 (WTT) emissions per passenger-km are in the period 2020–2030 expected to change by almost –70 %. The greening in the scope 2 sector is also beneficial for GHG emissions of electric cars, PT busses and the metro.

For freight the shift from fossil-fuel to post-fossil fuel vehicles changes scope 1 GHG emissions by –100 %, and scope 1 + 2 emissions by –20 % (hydrogen) and –30 % (electric). Roughly the same goes for all vehicle types (vans, medium sized trucks or light to heavy tractors with semi-trailers; Klein et al., 2021; STREAM freight project). However, the absolute reduction is very different per vehicle type. Shifting from van to small truck would change GHG emissions per ton-km by –50 %; shift to a light tractor/semi-trailer combination would provide –80 %.

Back to the **modal shift** of passengers. Rohs & Flore (2022) analyse

Table 4
GHG emissions of passenger transport (g/pkm; Dutch situation in 2020).

	GHG emission (g/ pkm)		GHG emission (g/ pkm)	
	WTW (scope 1+2)		TTW (scope 1)	
Car gasoline	197,6	*	152,1	*
Car fossile diesel	205,4	*	156	*
Car battery electric	67,1	**	0	
Tram	63		0	
Metro	42		0	
Bus fossile diesel	155	***	118	***
Bus battery electric	66	***	0	

* = average value * 1.3 = city level

** = average value * 1.1 = city level

*** = average value * 1,2 = city level

¹⁵ The emission factors in Table 3 refer to the Netherlands. For other countries they are different, but the rough picture is similar.

the percentual change of passenger-kms per mode in four medium-sized to large cities in Germany, namely Hagen, Magdeburg, Munich, Saarbrücken analyses the percentual change of passenger-kms per mode. These cities are quite different in terms of social-economic characteristics, city structure, transport network and therefore car shares (respectively 83/69/52/76 % in passenger-kms). Table 5 for three measure packages summarises the modal shift. Passenger-kms in cars change by up to –20 %. Package 3 has more measures, but not more reduction, mainly because of city densification: total passenger-kms increase. Would the car occupation not change in time, the –20 % can also be read as change of car-kms.

While the range of car passenger-km decline already indicates differences between these cities, modal shift in reality can be even less impressive, reasons being, for instance, a rather high level of PT in the base year, unfortunate land use patterns, or unattractive PT quality or prices.

In the study Propolis (Lautso et al., 2004) the change of mobility and scope 1 GHG emissions is analysed for seven quite different European metropolitan areas. Three of them, Helsinki, Dortmund and Bilbao, are of interest for the demonstration studies, given the size of the core city. The study includes numerous rather extreme measures, letting the study remain of interest for orientation still today. Table 6 summarises GHG changes of selected measure (combination)s: –2 % to –31 % or more for extreme measures. Combinations of pull and push measures achieve the largest reductions.

The rather low improvement values of Bilbao are hardly explained.

Zooming into road and areal pricing for cities, such schemes can change traffic volumes by up to –35 % (Burrieza, 2019) also when envisaging larger areas as the inner cordon of Stockholm (Ricci et al., 2017; Croci, 2016; Santos & Caranzo, 2022). (Scope 1) GHG can change by around –15 % (Transport for London, 2008; Croci, 2016, for Stockholm). But such changes only refer to the

envisaged flows. Total reduction, hence in relation to all flows, is smaller, but not indicated by the sources. Ricci et al. (2017) show that also urban vehicle access regulations without pricing can be effective. Areal access pricing can sort another effect than less car mobility, namely less private car ownership (Morton & Ali, 2025, p189), as analysed for London.

Increasing car occupation is another policy field potentially leading to GHG reduction. “Although fuel consumption and hence emissions from a car will only marginally differ between having only the driver on board or a fully occupied vehicle, its relative efficiency (in terms of CO2 emission per passenger-km) depends on the number of passengers in the vehicle” (Eurostat, 2021). A municipality could support the increase of occupancy rates by facilitating carpooling. One analysis (Franckx, 2024) found that in Belgium an occupancy increase (from 1.3) to 1.5 could be obtained by a road charge of 4 eurocent per km, and would change GHG by about –13 %.

Background measures. The contribution of ICT and digital solutions to sustainable mobility was estimated for Warsaw (Zawieska & Pieriegud, 2018). The result was a GHG change potential of –5 to –30 %. This estimate, however, is hardly further explained.

Another background measure is awareness raising. Plymouth’s awareness raising and incentivising platform Plymotion is reported to have induced a 4 % decline of car ownership where residents have spoken to a travel advisor, a 9 % decrease in the number of short car trips, 8 % decrease of daily car trips, and a 4 % higher awareness of car sharing (Starr, 2010). Laffond et al. (2020) analysed the GHG impact of choosing one of six pilot travel options instead of the private car. Regarding the pilot “Personal mobility trainers to switch from car to sustainable modes” in Marseille 31 % of the questioned persons stated they will change to cycling. In relation to all mobility the percentage would be small.

Regarding the effectivity of measures there are two issues, potentially reducing GHG reduction, namely rebound and distribution. **Rebound** is about non planned activities diluting achieved performance

Table 5

Measure fields included in three measure packages and the range of passenger-km changes of the four cities.

Measure package	PT	Bi-cycle	Pe-des-trian	Par-king	Freight load. De-grees	Higher costs fossil-fuel cars and trucks	Access central area	More time private motorised	Speed limit road	Den-sification	P-kms in private motorised vehicle *	Total p-kms *
1	x	x	x	x	x			x	x		-17 % to -20 %	-2 % to -3 %
2				x		x	x				-9 % to -15 %	-3 % to -4 %
3	x	x	x	x	x	x	x	x	x	x	+ 12 % to -20 %	+ 4 % to + 6 %

*Values concluded by authors from figures.

Source: [Rohs & Flore, 2022](#) (table by authors)**Table 6**

(Scope 1) GHG change of different measure (package)s.

City and trip share private motor. veh. in base year ↓	Measures → Impacts * ↓	Opera-tional car costs +25% to +100%	Higher par-king costs	Distance based congestion pricing OR cordon pricing	New rail connec-tion	PT fares -60% to -100%	Different measure combi-nations	Different extreme measure combi-nations
Helsinki	GHG emissions (%) **	-7 to -23	-23	-12 to -26	-8%	-12 to -16	-19 to -22	-7 to -31
Dortmund	GHG emissions (%) **	-4 to -14					-18	-52
Bilbao	GHG emissions (%) **	-2 to -8	-6					

*In comparison to the reference situation.

**Scope 1 emissions (TTW).

Source: [Lautso et al., 2004](#) (Propolis project; table by authors)

improvements. Following the demarcation of [Borger et al. \(2021\)](#), a well-known “direct” rebound effect, hence one emerging within the same system, in mobility is how an increase of road capacity reserves, for instance because of modal shift, attracts new traffic again and then also reduces part of the initially expected GHG reduction. Transport research tends to elevate road pricing to a measure suitable to combat traffic rebound effects on roads after capacity reserves increase because of road widening, traffic management, modal shift etc. [Santos and Caranzo \(2022, p5\)](#) referring to former research for London found that “a large number of commuters, especially from outer London boroughs, switched from other modes to the car as a result of the London Congestion Charge.” Hence also road pricing can induce rebound effects. We address rebound at different occasions in this paper.

Distribution is about how costs/efforts and benefits of measures are distributed across different layers/sectors of society, potentially reducing the measure effectivity. For instance, flat pricing measures like parking of cordon pricing tend to have a regressive nature, hurting low incomes while much less affecting high incomes ([Santos & Caranzo, 2022](#)). The transition to climate-friendly mobility potentially brings along financial impacts for travellers, too many to disregard (e.g. higher purchasing costs of electric vehicles, higher parking fees, areal access pricing or cordon pricing, more penalties in case of large scale reduction of maximal speeds, higher housing costs in densifying cities, higher housing costs in densified areas). Eventually (part) of these increases may disappear again or even turn into cost reductions, but up to then they are unfair and reduce effectiveness. A conclusion could be to introduce income-dependent pricing, comparable with the income-dependent traffic penalties introduced in Norway and Finland. In former times the execution of such would have technically been impossible. But that has changed. [Qorbani et al. \(2025, p1\)](#) give a new example of a new distributional issue, namely that half of the households in Norway in 2022 own three or more BEVs, while “lower income, having children are positively linked to owning emitting vehicles.” This signalizes less effectiveness of car electrification to GHG reduction.

We don’t elaborate distribution in this paper, but it is a dimension of many pricing, cost-related or selective access measures to be aware of.

3.3. Rough profile of the measure packages of the partner cities in the demonstration studies

The relation between types of performances and measures and their GHG potential were discussed on project meetings and seminars; in a similar way, as not all references used in this section were then already published.

The partner cities’ final response were CliMobCity measure packages. These were developed in different ways, always involving more municipal sectors than only mobility and also discussing potential measures with stakeholders. Also the content is different. Plymouth’s CliMobCity measure package was defined as one including “all known interventions, both physical measures and policy” ... “that have been applied elsewhere in the UK and go beyond BAU policies”. The city discussed the package content with the *Transport Strategy Working Group (TSWG)* made up of transport officers from Plymouth City Council, neighbouring local authorities and other key transport stakeholders, which meets quarterly. The content of the city’s 2050 CliMobCity measure package is by far more ambitious than the city’s current strategic policies.

Bydgoszcz’ development of its CliMobCity measure packages started with a close cooperation of the municipal mobility and spatial departments, while ideas and proposals were also gathered in a series of stakeholder meetings with regional authorities, PT operators, transportation-related NGOs, university researchers, and private consultancies. The extensive *Appendix-Bydgoszcz-report (MoB, 2023)* describes the measure directions discussed and the considerations for choices. For instance, given the extensions of the PT network already included in the BAU package, a conclusion was: “No major tram extensions have been proposed during the meetings. Stakeholders do not deem them very necessary and observe that the focus should be on the

existing resource utilisation and mobility management”.

Leipzig joined the project in search of orientation for updating its “smart mobility city” policies, as outlined in a report of which the final report was launched during the project time (Leipziger Institute für Energie, 2021) focussing on the acceleration of implementing electric charging points and of shared and micromobility, all supplementing the modal shift directed (BAU) mobility policies. The CliMobCity measures were discussed with municipal departments and stakeholders as part of the new draft policy report in this field (MoL, 2021) and eventually influenced the new charging infrastructure report 2030.

Thessaloniki involved stakeholders mainly on a bilateral basis including two consultancies, namely the Hellenistic Institute for Transport (CERTH/HIT) and LEVER, the writer of the extensive *Appendix-Thessaloniki-report* (MoT & Lever Development Consultants, 2022). The focus of its CliMobCity measure package was vehicle electrification, shared and micromobility because, as in Leipzig, the very ambitious BAU mobility measures (including two metro lines and a regional train line, improvements in the slow traffic network, reassigning road space to slow traffic) led to a complementary policy demand in the demonstration study, namely to focus on electrification and shared mobility.

4. Demonstration studies: measure packages, mobility changes and GHG reduction¹⁶

4.1. Introduction

In this section we analyse the change of GHG emissions of mobility in the municipal area of each partner city, taking account of the change of mobility, the shift to post-fossil fuel vehicles and the greening of the electricity production.¹⁷ We then compare the analysed GHG reduction with the GHG reduction aims of the municipality and discuss deriving perspectives and actions. In addition, we briefly reflect on the change of space requirement of changing mobility. These analyses are grouped in four sub-sections, one per partner city. In the seventh sub-section we compare the finding for the four cities and discuss measure for further GHG reduction.

4.2. GHG reduction aims

The climate aims for the four partner cities at the beginning of the project were achieving climate neutrality by 2050 (Bydgoszcz), 2040 (Leipzig) of 2030 (Plymouth) or a 42 % GHG reduction between 1990 and 2030 (Thessaloniki). The latter was found to be equivalent to 52 % reduction for the planning period 2018–2030. These aims were sharpened in the run of the project,¹⁸ but for the project they remained valid. The corresponding annual GHG change rates aimed for were –3.5 % (Bydgoszcz 2021–2050), –5.3 % (Plymouth 2015–2034), –4.3 % (Thessaloniki 2018–2030) and –4 % (Leipzig 2015–2035). Each city partner interpreted the general reduction aim to also apply for any individual policy sector including the mobility one. There was no net zero emission approach in which an emission overshoot in mobility could be compensated by negative emissions in another sector in the municipal area, let alone outside of it.

The reduction aims of Plymouth and Leipzig for the project were more ambitious than those of their countries, in Bydgoszcz and Thessaloniki they were roughly the same as the national ones.

4.3. Bydgoszcz

4.3.1. Bydgoszcz in general

Bydgoszcz is a regional policy centre and a production city with the spearheads locomotive and rail wagon assembly (passenger and freight trains), tram repair, construction and chemical industry. Industry provides 30 % of the employment. Next there is trade, transport, communication (26 %) and financial, insurance and other services (44 %). The city belongs to the “functional urban area” (FUA) Bydgoszcz-Torun with 0.6 million inhabitants and a relatively rural character between the cities.

Bydgoszcz has a relatively small historical centre and next to that a dense 19th century development belt. Between the otherwise rather green housing settings, larger mass housing areas were built in the socialist period, elongating the spatial development along the east-west axis. One of the new mass-housing areas is located east of the city centre in the formerly independent city part of Fordon. Its urban centre of gravity lies ca. 5 km east of the historical city centre, with major implications for mobility system, e.g. a high transportation demand between the Fordon and Bydgoszcz centres. After the fall of the iron curtain, a network of larger shopping malls was erected along the outer edge of the 19th century belt (Fig. 5).

The main roads in the city are radial ones whose outer ends at three sides of the city are connected by an expressway ring road. Its radius is about 10 km. The fourth (eastern) side is the river Vistula (Wisła). Then there are two dual-carriageway roads, one running north-south, the other east-west, functioning as bypasses around the central city parts. The city has a tram network which serves the mutual connection of the central city parts and connects these with all mass housing areas except for ones in the south-western part of the city, and also with larger production and workplace areas. Most tram routes have dedicated infrastructure. In addition, there are regional trains running on the general train network; at some train stations one can transfer from and to trams. These stations also have larger parking lots facilitating train-car trips.

4.3.2. Bydgoszcz measures

The BAU policy, documented in different strategic plans, a local spatial (MoB, 2009), local transport (MoB, 2022) and regional transport plan (MoB, 2013), projects a population change of –3.5 % between 2021 and 2050 and employment growth of + 3.4 %. Such cornerstones signalise larger suburbanisation and increase of commuter flows on a regional scale, but suburbanisation is also projected within the municipality, as the Fordon area is projected to grow further. A spearhead in the BAU package (“W0”) is the extension of the tram network, now finally accessing the last mass housing area and thereby establishing a tram ring around the city centre. In the future all tram lines will have a track per direction. Furthermore, new main road links are projected including the so-called suburban ring road (see Fig. 8), and different existing main roads are to be widened.

Bydgoszcz has formulated two CliMobCity measure packages: W1 follows the ongoing suburbanisation. The tram network proposed in W0 (BAU) is adopted and two service lines are added implying the need for some additional tram tracks. In W2 the overall city’s population is the same as in W0 (BAU), but 35 % of the future population in the BAU scenario assigned to the Fordon area is now relocated to the central city, attracted by brownfield re-developments (Fig. 6). Exploring such a scenario was considered to be relevant, by both the mobility and the land use department because of uncontrolled (sub)urban sprawl, nowadays taking place in many Polish cities (Śleszyński et al., 2020). In W2 the tram infrastructure is limited to the expansion proposed in W0 (BAU), while tram service frequencies are increased (up to a doubling) in the more central tram city part. Also, in W2 the in BAU projected suburban ring road (the road with the largest decline of traffic intensity) is cancelled, and Jagiellońska street, i.e. the main east-west thoroughfare in city centre, is closed (Fig. 8). Summarising, some of the measures in W2 replace certain BAU measures which would be superfluous or

¹⁶ Responding to RQ 3–8.

¹⁷ We assume hydrogen production to be green from the very beginning.

¹⁸ Like Thessaloniki and Leipzig joining the EU mission of 100 climate neutral cities in 2030.

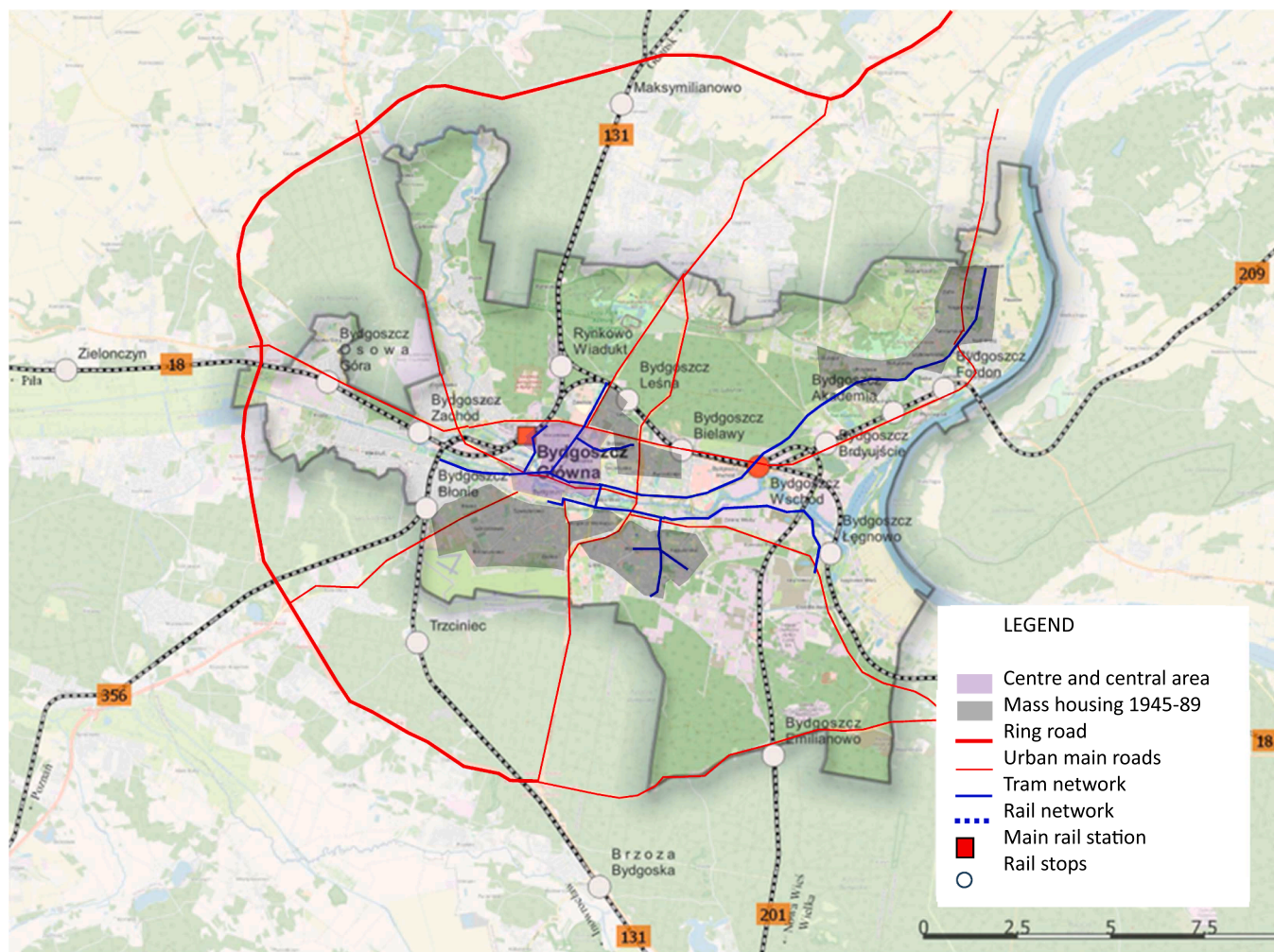


Fig. 5. Existing (base year) spatial structure and main transport networks in Bydgoszcz. Source: Project Summary (Kreutzberger & van Binsbergen, 2023).

requiring substantial investments. This is contrary to W1 and exceptional in the project.

In both CliMobCity scenarios, P + R nodes are implemented at strategic points in the PT network. Also in both CliMobCity scenarios, the main roads in the central city are narrowed for general road traffic (with road space reallocated for bus or cycling lanes etc.) and the central area becomes a tempo 30 zone (W1 and W2). In W2 an east-west road along the centre's edge (Jagiellońska Street; see Fig. 8) is closed for most private road traffic, providing more space at its most narrow part for the tram, bus, bicycle and pedestrian system.

Bydgoszcz at the time of the demonstration study had no vehicle electrification aims. For the analysis of GHG emissions therefore the powertrain composition of the EU reference and Tech scenario for Poland according to Table 2 in Section 2 was adopted. The shares of post-fossil fuel cars are assumed to grow from near to 0 % in the base year to 23 % in 2050 (EU reference scenario) or 43 % (Tech scenario). All bus operations in Bydgoszcz are planned to be zero-emission ones in 2050.

Bydgoszcz developed two further CliMobCity scenarios, W1 + and W2 +. These consist of the same spatial or network measures as W1 and W2 respectively, but assume mobility preferences (see above) of travellers to change towards lower preference for private car mobility and higher preference for sustainable modes. In the transport model, this is simulated by increasing the perceived attractiveness (travel utility) of active travel (walking, cycling), PT and car as passenger by 10 %, and by lowering the perceived attractiveness (travel utility) of car as driver by 10 %. The legitimacy of such modelling intervention is increasingly

acknowledged (e.g. Van Wee & Kroesen, 2022). The direction of preference change could be one in the sustainable direction, facilitated by awareness-raising and promotion campaigns, long-term lifestyle changes and measures aimed at consequent improvement of perceived quality of alternative, sustainable travel modes. However, the conditions leading to a change of mobility preferences and the magnitudes of change are not yet backed up well by research, neither for Bydgoszcz nor in general. In this regard W1 + and W2 + rather represent sensitivity analyses than real scenarios.

4.3.3. Bydgoszcz, mobility effects

In all future scenarios the number of trips increases despite of declining population. Especially car trips increase (Fig. 7), leading to larger modal shares of car. In CliMobCity W2 the car share is smaller than in WO(BAU) (51 % instead of 52 %), but still higher than in the base year. Also travel distances are increasing, especially those of car mobility (from 10 km in the base year to about 12 km in CliMobCity W2). As a consequence, car-kms increase by about + 40 % in WO(BAU) and about + 30 % in CliMobCity W2 (Fig. 7). In W2 + the increase is the smallest, about + 20 %.

At the same time total truck-kms increase by + 30 % in WO(BAU) and – in absence of freight measures – also in the CliMobCity scenarios. LGV-kms (like vans) decline (-10 %).

Interestingly PT trips increase in both CliMobCity packages in almost the same magnitudes, attracted by the – although very different – improved PT performance. But only in CliMobCityW2 there is a decline in car-kms. The difference is largely caused by the other urbanisation in

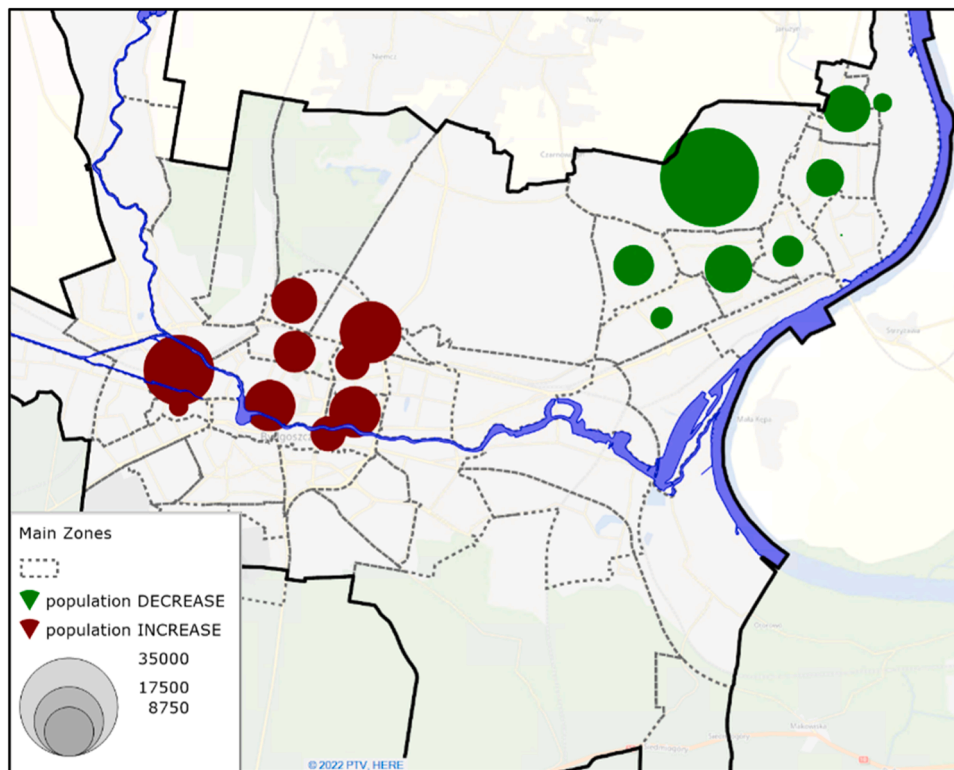


Fig. 6. Population changes in CliMobCity scenario W2 compared to W0 (BAU) scenario Source: Appendix-Bydgoszcz-Report (MoB, 2023).

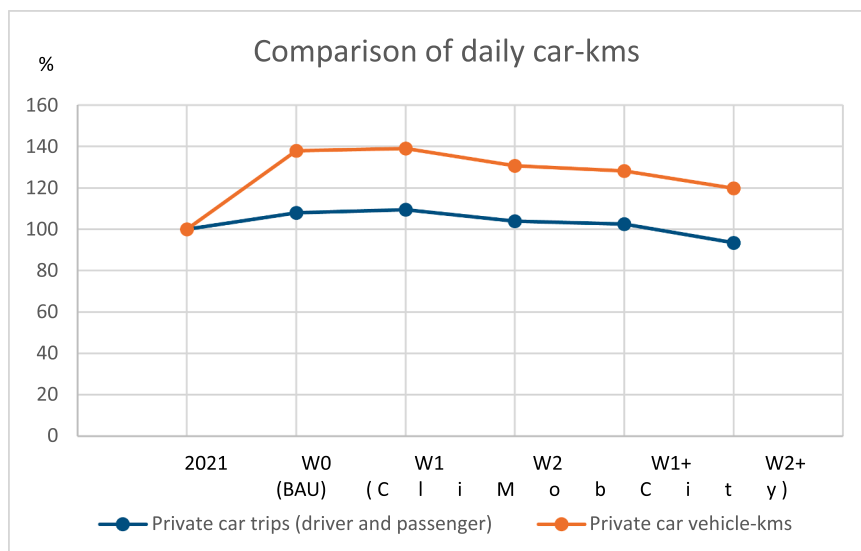


Fig. 7. Bydgoszcz: Comparison of daily trips and car-kms in the different scenarios.

W2, providing shorter car and PT distances than in W1, and by the cancelling of new road links projected in BAU.

4.3.4. Bydgoszcz, spatial impact of moving mobility

The substantial increase of road vehicle-kms in all overall scenarios signals an increasing spatial demand of mobility in the city. Traffic growth is pronounced especially in the central road network. Outside of the city’s central area this effect is also visible albeit to relatively lower extent, given the comparatively low urban density and the layout of the built environment. In CliMobCity measure package W2 the downscaling of BAU road infrastructure expansion, in particular of the Suburban ring road (see Fig. 8) is proposed despite of the increase of road vehicle-kms

also in W2. This together with the closure of Jagiellońska street pressures adjacent routes in the central city area. This increase seems manageable on all links, perhaps with the exception of the centre east-west by-pass parallel to and south of Jagiellońska Street. This may require specific actions to maintain or improve road use of and liveability along that route and the functioning of the city which is compact in the central area.

4.3.5. Bydgoszcz GHG emissions (RQ 5)

The change of input per overall scenario is shown in Table 7, the corresponding GHG reduction in Table 7 and Fig. 9. All changes of GHG emission are calculated in comparison to the base year.

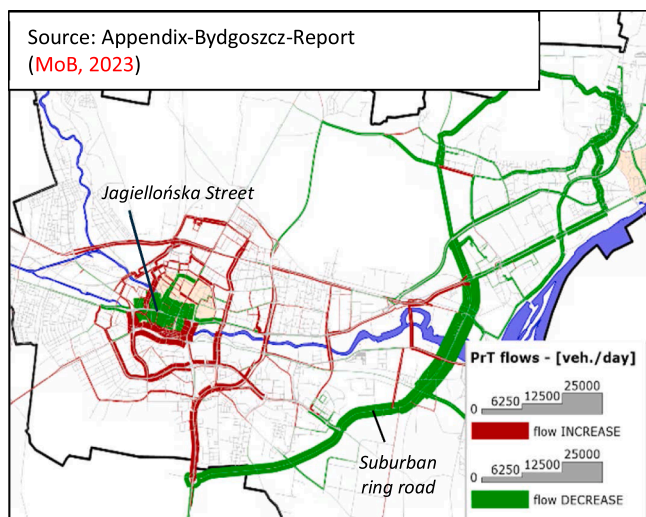


Fig. 8. Change of traffic intensities in W2 (CliMobCity) compared to W0 (BAU).

The general mobility picture is that of increasing vehicle-kms in all future scenarios, although less in CliMobCity. The GHG emissions don't increase correspondingly because of car electrification and some greening of the electricity production. Yet the kilometrage is a main factor why Bydgoszcz' GHG emissions don't decline substantially. The car electrification is important, however according to Table 1 still limited in 2050. We come back to this in Section 4.7. Comparison of changes between OS 1a, 2 and 3 shows that energy greening provides a lot of GHG reduction.

Bydgoszcz' climate aim is to become climate neutral by 2050. After OS 7 – the energy mix for electricity production is completely green – the GHG gap between reduction target and analysed delivery is 68 %. This

for 54 % consists of passenger (car etc.) emissions and for 46 % of freight emissions.

4.3.6. Bydgoszcz, additional measures and performance improvements to cover the gap

The GHG gap of 81 % after OS3 or of 68 % after OS 7 is significant, as it refers to 2050, a time for which different results are anticipated. Gravity points for further reduction are urban freight transport, the reduction of car-kms (also via preventing suburban sprawl), and car-electrification. For urban freight there is a big opportunity emerging. As this opportunity is one for all partner cities, we describe this solution in Section 4.4.

Regarding car-kms the main challenge is, after all, to achieve substantial modal shift and car distance reduction. In addition, the Appendix-Bydgoszcz-report (MoB, 2023) mentions the idea to develop a car-pool network to increase average car occupation, but also states that the contours of such concept would need to be further explored.

Regarding modal shift, the current PT network in combination with new measures makes PT omni-present, except to a few peripheral employment concentrations, for which the development of tailor-made alternatives to private car use deserve consideration. In general, road is still or is becoming too attractive, while the PT service isn't attractive enough. The mentioned document enlists the measures for CliMobCity which can also be read as ideas for even sharper policies than in Cli-MobCity, like reducing the attractiveness of radial roads by narrowing them, reducing maximal (posted) speed limit, and by active traffic management. Other recommendations are to implement "P + R facilities at multiple bus, tram and train interchanges... raising the relative attractiveness of PT connections over private car trips between central Bydgoszcz and outer area." Clean traffic zones can gradually be extended, but this "should be considered carefully ..., especially with regards to feasible pace of car fleet replacement". Regarding "preferential measures for low- (zero-)emission car vehicles" the "municipality of Bydgoszcz may utilise policies such as lower parking fees or

Table 7
Bydgoszcz, input and GHG reduction per overall scenario.

OS	Vehicle-kms	Extra changes	Share of post-fossil fuel vehicles *	Energy mix for electricity production *	GHG emission *
BAU					
1a (blue line) (W0)	Car-kms +38%	/	+23% (EU reference)	88% -> 44%	+0.5%
CliMobCity					
1c (W2, blue line Figure 8)	Car-kms +31%	/	+23% (EU reference) All PT busses electric	Idem	-1.3%
1e (W2+, blue line Figure 8)	Car-kms +20%	/	Idem	Idem	-1.9%
2 (orange line Figure 8)	Idem	/	+43% (Tech) All PT busses electric	Idem	-6%
3 (grey line Figure 8)	Idem	/	Idem	88 -> 0%	-19%
4	Same as OS 3 plus ->	OS 3 plus -10 %-points car/LDV share	Idem	Idem	-25%
5	Same as OS 3 plus ->	OS 3 plus -10% time spent (travel distance)	Idem	Idem	-22%
6	Same as in OS 3	OS 3 plus +10 %-points post-fossil cars smaller share of fossil-fuel cars/LDVs	← Idem plus	Idem	-24%
7	Same as in OS 3 plus changes in OS 4-6	OS 3 plus combination of OS 4-7	Idem	Idem	-32%

*= Change compared to base year.

Red= Input change in comparison to line before.

Idem= Same as line before.

**= Additional to OS 3.

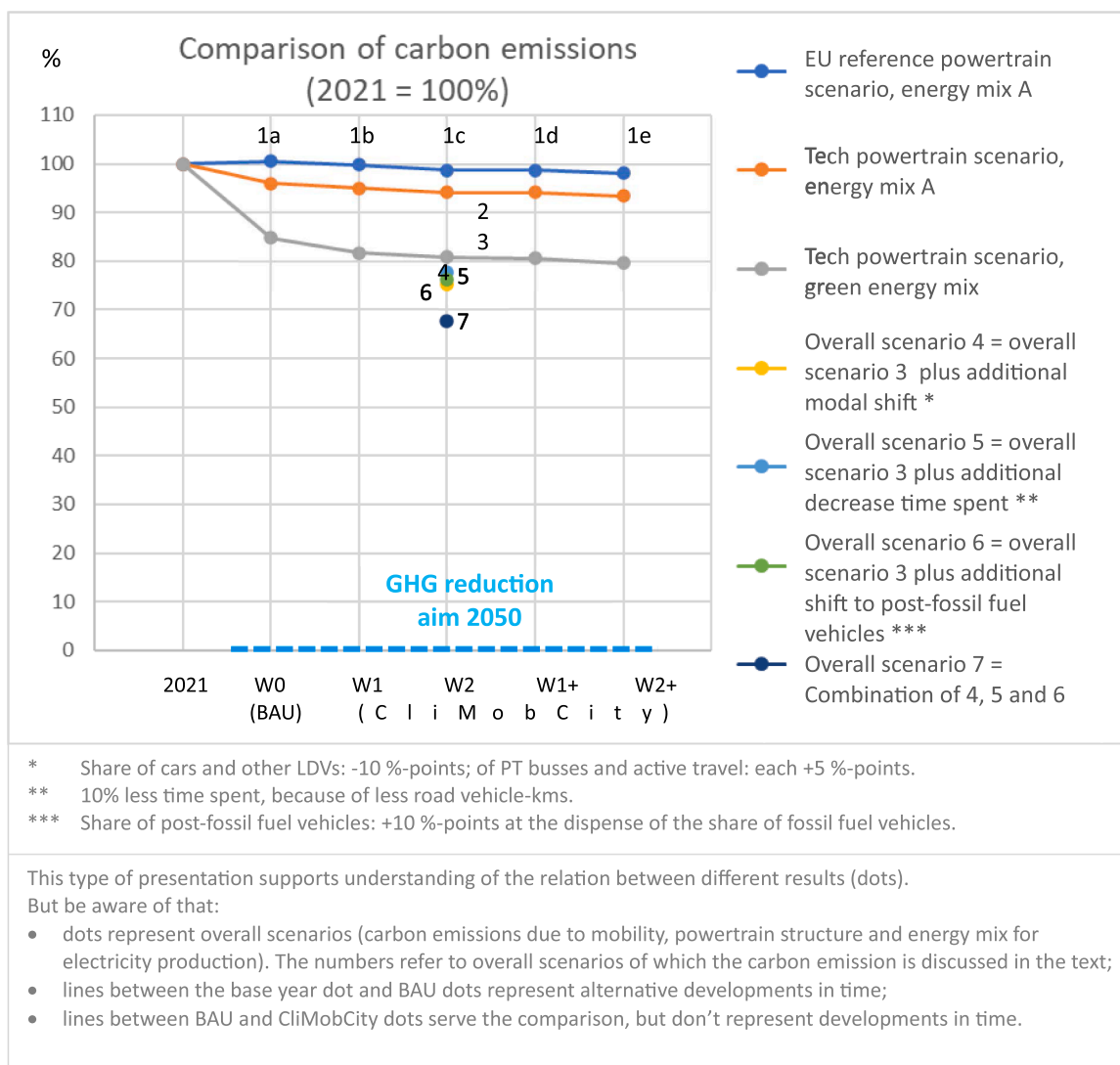


Fig. 9. Bydgoszcz, comparison of GHG emissions of overall scenarios.

designated parking spaces for electric (or hydrogen) vehicles.” Regarding car distance, the suburbanisation is a key issue to address. More housing on brownfield locations in the central city area and transit-oriented development along the PT axes and less new greenfield housing in municipal peripheral areas seem

promising. However, supporting the prosperity of the major peripheral location, Fordon, is also a municipal aim. Next, the relation between local and regional suburbanisation requires more clarity.

Car-electrification is a last straw to reduce GHG emissions. The content of ambitious electrification is actually already answered by the Tech projections. But – and discussion-wise – for planning periods as up to 2050 the more recently announced launch of a new generation of BEVs with substantially extended action radius may change the BEV’s popularity and increase BEV market share, in which case more municipal push and pull measures supporting electric car mobility make sense.

4.4. Plymouth

4.4.1. Not completely comparable

We present the change of GHG emissions for Plymouth, although they – along with the underlying mobility changes – are not comparable with the changes analysed for the other three partner cities. This is because for trips from and to Plymouth the distances outside of municipal area were included. Also, in absence of a multimodal

transport model, the modal shift projected is not the result of demand modelling in the transport model, but of expert’s judgement on the basis of statistical information.

4.4.2. Plymouth in general

Plymouth’s economic columns, largely related to the city’s coastal location, are the royal naval dockyard, fishing, transport and tourism. Plymouth’s distribution of employment sites is distinctive: work places are concentrated in the city centre, in Devonport (the location of the Naval Base) and some employment clusters in the north (including Derriford Hospital) and in the east of the city (including Langage Business Park). The urban density is the lowest of the four partner cities, in the city centre due to a spatially generous rebuilding after its destruction in WW2, around the centre because of the terraced houses structure in prewar residential areas and the green setting of residential areas developed thereafter. The city is accessed (Fig. 10) by rail and a national highway, both running east-west through the city and each having a branch to the north. Two of the city’s main roads run parallel to the highways, the others perpendicular. Most important for PT is the network of bus lines. There is a bicycle network, adapting to the hilly topography of the city and its surrounding. Controlled parking zones prevent non-residential parking in residential areas during critical periods of a day.

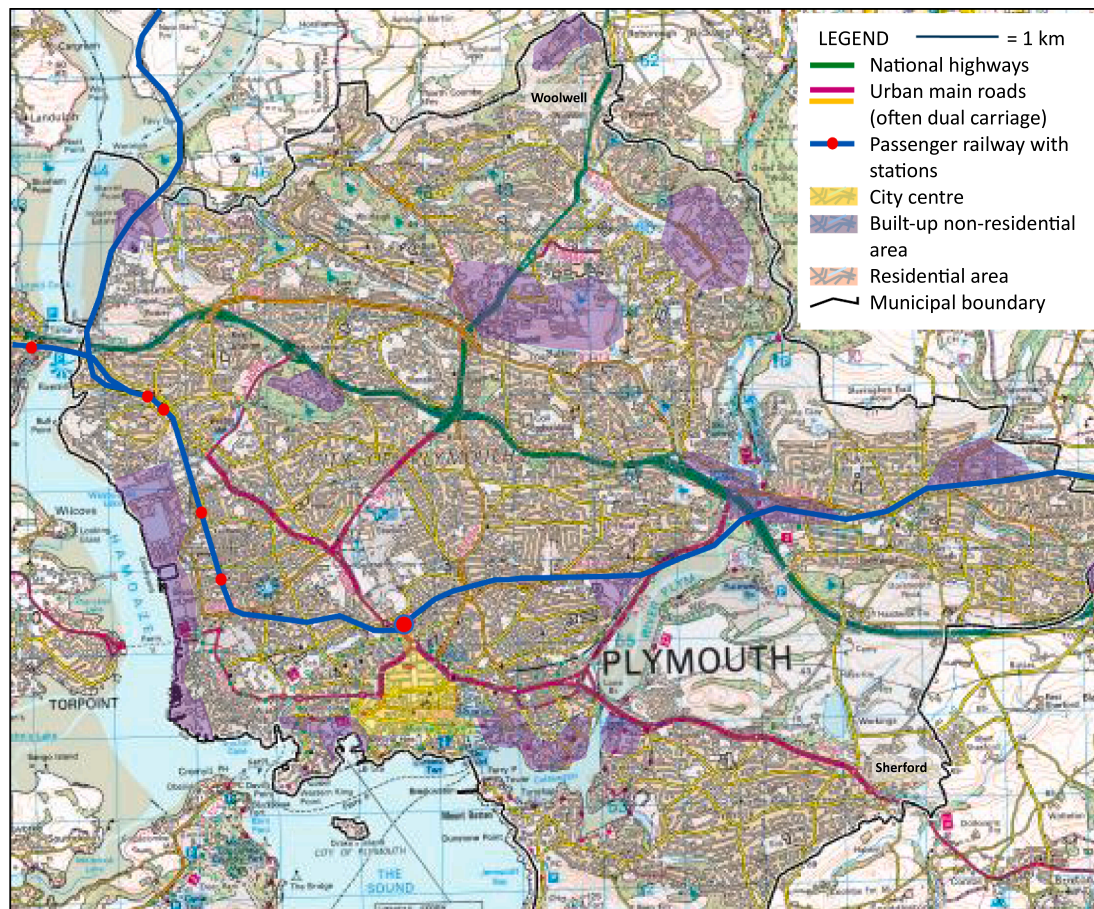


Fig. 10. Existing (base year) spatial structure and main transport networks in Plymouth.

4.4.3. Plymouth, measures

In all scenarios, Plymouth's population is projected to grow by +13% between 2015 and 2034. Plymouth's **BAU policies** in the project were represented by the *Plymouth Plan (PP, MoP, 2019a)* and the *Joint Local Plan of Plymouth (JLP, MoP, 2019b)*. Typical for the planning system, the plans give an outline of **types** of measures relevant to mobility and spatial development, and of **directions** of future performance (e.g. "delivering a healthy city"), rather than identifying specific concrete measures to be developed, financed and implemented.¹⁹ For transport modelling the directions need to be concretised. In BAU the city strives for directing urban development towards three growth areas, city centre/waterfront, the northern and the eastern corridor growth area, to be connected by the High Quality PT Network.²⁰ In addition there is housing development in the surrounding municipalities belonging to the planning area of the Joint local plan 2034. New rail stations along the

existing rail line and new P + R locations in the periphery of the municipality are to be investigated. Other policy areas are bicycle network development, pedestrian area development, parking regulation and pricing for housing or other uses, or more charging infrastructure for

electric cars. The modelling input included:

- 5 measures to support PT (e.g. bus lane or road improvement for train station);
- almost 30 measures referring to road junctions and roundabout infrastructure and their use;
- less than 10 measures referring to road links.

Plymouth is proud of its municipal platform Plymotion supporting sustainable mobility of persons and organisations, by providing information and financial support for individual modal shift and by organising awareness raising campaigns. The platform allows to continuously communicate societal urgencies and municipal policies.

4.4.4. Plymouth, CliMobCity

The city for the demonstration study defined a more ambitious measure package, referred to as the UK Max or Plymouth CliMobCity. This package includes "all known interventions, both physical measures and policy, ... that have been applied elsewhere in the UK and go beyond BAU policies" (WSP, 2021). It is more modal shift oriented, containing 4 bus, 1 rail, 13 walking and cycling, 6 hub, shared mobility and electrification, 4 behavioural, and 3 parking measures (WSP, 2021). The rail measure was about the reinstatement of a rail connection to Tavistock in the framework of Devon metro (see Project Summary; Kreutzberger and Van Binsbergen, 2023), an older plan, incorporated into the CliMobCity scenario. It helps to combat congestion on the main connection, especially in the city area, but its electrification is not projected. The parking measures include clear air zones with charges for non-compliant vehicles and a workplace parking levy based on Nottingham model. Bus measures refer to infrastructure like bus gates and lanes, next to a

¹⁹ Funding for local transport investment in England is very centralised. Municipalities have few opportunities to independently generate significant tax or levy income for transport investment purposes and (other than funding for highway maintenance, which is reliably funded on a formula basis) are typically only able to secure transport investment funding by submitting competitive bids to an evolving array of purpose-specific national funding pots. This makes it challenging for municipalities to develop and successfully implement long term strategic transport delivery plans (Source: Project summary).

²⁰ According to the *Plymouth Plan*.

trend-breaking measure consisting of city-wide bus service improvements. The latter, in itself already a measure package, is in line with the policy outlined in the national trend-breaking report 'Bus Back Better Guidance' (Department for Transport, 2021) and following the Brighton example. The report describes how (outside of London) after the deregulation of municipal bus operations (abolition of Road Service Licensing) in the 1980s private bus companies instead of the public hand decided on which routes to ride and on service frequencies to provide, all on a commercial basis. This led to a substantial decline of the PT share. Without a policy change the municipality would have little or only very expensive influence on the design of the bus service network. The "2017 bus act" powers to introduce bus franchising, as Greater Manchester intends to do. This would give city leaders powers to control bus routes, make them more reliable, bring down costs for passengers through a simpler ticketing and fare system, and clean up the fleet. The Government should also extend these powers to other areas outside mayoral combined authorities" (Quinio & Rodrigues, 2021).

Plymouth had at the time of the demonstration study published neither electrification targets nor pathways to achieve them, but had in August 2023 commissioned consultants to produce a draft *Electric Vehicle Charging Infrastructure Strategy*. In the GHG analysis for Plymouth the electrifications shares shown in Table 2 of Section 2 were adopted, post-fossil fuel cars in 2034 having a share of 18 % in the EU reference and 56 % in the Tech scenario.

4.4.5. Plymouth mobility effects

In BAU the number of car trips increases²¹ and so does the average car distance.

The car trips also increase in CliMobCity, but much less (+4 %), and the average car distance is about the same as in the base year. The car share in CliMobCity changes by -154%-points to the level of 51 %, all other modes, especially bus and bicycling, increasing their shares.

Fig. 11 shows the cumulative result of mobility changes in the Plymouth area. Car-kms increase in BAU (+19 %) and CliMobCity (+4 %). The change of HGV-kms in BAU is + 18 % and in CliMobCity almost the same. LGV-kms in BAU increase by a staggering + 59 % and in CliMobCity "only" by + 35 %.

Note that the vehicle-kms are not comparable with those of the other demonstration studies as the distance of trips outside of the municipal area is included. For trips this fact, however, makes no difference. The flow matrix shows that trips from and to the Plymouth have larger growth rates than the city-internal ones. This indicates that there is some suburbanisation at stake, although less in CliMobCity than in BAU.

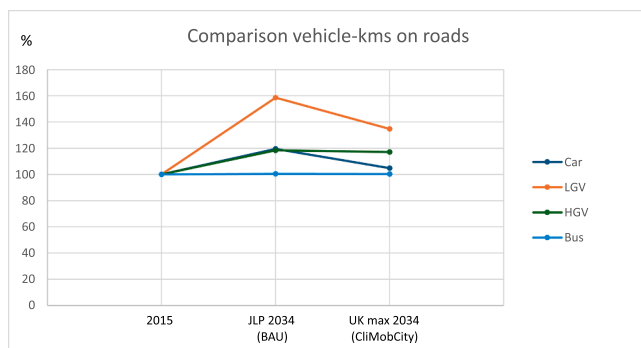


Fig. 11. Comparison of road vehicle-kms in Plymouth and surrounding region.

²¹ + 22 % in BAU, more than population growth (+13 %).

4.4.6. Plymouth, spatial impact of moving mobility

The increase of vehicle-kms means more pressure on the road system and potentially on land use requirement, in BAU more than in CliMobCity. Nevertheless, the general picture is that traffic flow remains relatively stable on all road types. In this city having relative low urban densities the CliMobCity increasing space demand of mobility will hardly threaten the city's compactness. In both scenarios traffic speed is projected to decline a little. Problems at notorious congestion points may become a little worse. On urban roads, junction V/C increases by + 15 % (BAU) or stays the same (CliMobCity).

4.4.7. Plymouth: change of GHG emissions

The change of input per overall scenario is shown in Table 8, the corresponding GHG reduction in Table 8 and Fig. 12. All changes of GHG emission are calculated in comparison to the base year.

The general picture is that road vehicle-kms increase in all future scenarios, although less in CliMobCity because of improved networks. The GHG emissions don't increase correspondingly because of car electrification and some greening of the electricity production. This is sufficient to provide some GHG reduction. The emissions change by -5 % in BAU (OS 1a) and -9 % in CliMobCity (OS1b). Further car electrification etc. and energy greening let GHG reduction jump to respectively -24 % (OS 2) and -32 % (OS3), the changes in OS 4-7 up to -45 %. Plymouth's climate aim climate neutrality by 2030. After OS 7 the GHG gap between reduction target and analysed delivery is 55 %. The gap largely consists of road emissions: 54 % come from cars, 11 % from PT busses, and 35 % from HGVs.

4.4.8. Plymouth, additional measures and performance improvements to cover the gap

The spearheads of measures to cover the GHG gap are firstly to tackle the freight sector. Also limiting suburbanisation deserves consideration, or - if this wakes tensions in regional planning frameworks - organising more modal shift in the flows from and to the city. More than already projected in the CliMobCity package (Tavistock, bus back to better). Discussion-wise, working on more co-development of PT development and urban densification (see proposal for UK cities in Section 3) would make sense, the more that the city's densities are relatively low even in central city parts. And one might consider reducing the attractiveness of radial main roads and organising (more) P + R+PT bus or P + R+carpooling systems there. From an inventory of potential measures for the CliMobCity package, several of them were finally excluded, which would provide additional GHG reduction. The proposals included a consolidation centre for HGVs/LGVs freight, the transfer of x% of last mile delivered to e-cargo bikes, hydrogen traction on local rail lines, local ferries electric, implement V2G networks, replace diesel by post-fossil fuel PT busses, introduce free residents' parking permits for ZEVs, and develop licensing policy to incentivise transition to EV taxis.

For accelerating vehicle electrification and further freight measures see Section 4.7

4.5. Thessaloniki

4.5.1. Thessaloniki in general

Thessaloniki has an industrial fundament, but today's employment is for three quarter related to services, in particular trade, but also tourism, education and transport.

The port, the second largest of Greece, serves the city and the north of Greece and fulfils a gateway function to southeastern Europe. Thessaloniki is the central city of the officially defined "Urban area Thessaloniki" (= municipality of Thessaloniki plus 7 neighbouring municipalities, together having 0.8 million inhabitants) and "Metropolitan area" (1,3 million inhabitants)

The city and also some neighbouring municipalities have high urban densities. The large area of the city centre largely consists of 5-8 stories high building blocks with in between narrow streets. Outside of the

Table 8
Plymouth, Input and GHG reduction per overall scenario.

OS	Vehicle-kms	Extra changes	Share of post-fossil fuel vehicles *	Energie mix for electricity production *	GHG emission *
BAU					
1a (blue line) (W0)	Car-kms +19%	/	+18% (EU reference)	70% → 45%	-5%
CliMobCity					
1b (W2, blue line Figure 8)	Car-kms +4%	/	Idem	Idem	-9%
2 (orange line Figure 8)	Idem	/	+56% (Tech)	Idem	-24%
3 (grey line Figure 8)	Idem	/	Idem	70% → 0%	-32%
4	Same as OS 3 plus →	OS 3 plus -10 %-points car/LDV share	Idem	Idem	-36%
5	Same as OS 3 plus →	OS 3 plus -10% time spent (travel distance)	Idem	Idem	-34%
6	Same as in OS 3	OS 3 plus +10 %-points post-fossil cars smaller share of fossil-fuel cars/LDVs	← Idem plus	Idem	-39%
7	Same as in OS 3 plus changes in OS 4-6	OS 3 plus combination of OS 4-7	Idem	Idem	-45%

*= Change compared to base year.

Red= Input change in comparison to line before.

Idem= Same as line before.

**= Additional to OS 3.

centre, blocks with 4–6 stories dominate.

In the time of the project this all, as far as PT is concerned, was accessed by a bus network. At most places these buses ran in mixed traffic. In the large city centre the main roads run parallel to the coast, connecting the residential areas with the centre. Some of these main roads are broad boulevards on which traffic flow are under pressure over day. To the east and the north of the municipality of Thessaloniki a highway serves as bypass.

4.5.2. Thessaloniki measures

Thessaloniki projects a population growth of + 6 % between 2018 and 2030, reversing past developments. According to the city's General urban plan this growth is to mainly take place in the already dense large city centre area.

The main measure in the BAU package (draft *SUMP Thessaloniki 2030* [MoT, 2018]) is the implementation of new transport system, the metro, consisting of two lines. The metro runs underground and accesses many dense city areas, most of which lie in Thessaloniki, but also some in a neighbour municipality to the south (Fig. 13). Because of the metro the bus network was to be adjusted, cutting bus lines parallel to the metro out of the bus network and organising feeder bus lines to/from the metro. Furthermore, two other new systems were planned, namely the west-suburban railway (one line between the train station and a neighbour municipality in the northwest) and a maritime PT line along the coast. Other measures focussed on the restructuring of public space in favour of active travel. 46 km of bicycling infrastructure are to be built, and park-and-ride locations with 1500 parking lots. Furthermore, urban distribution is to mainly take place in certain time windows of a day.

While the BAU package is largely about physical measures, the CliMobCity-package focusses on electrification, shared mobility and awareness raising: until 2030 17 hubs with electric shared cars are to be installed, of which 13 in Thessaloniki. The municipal *Electric Vehicle Charging Infrastructure Plan* (MoT, 2021) has the target for 2030 of 37 % of cars being electric ones. This target goes beyond that of national documents and of the levels of the Tech scenario according to which

11 % of the cars in 2030 will be post-fossil fuel ones. It was formulated after the start of the project and included in the CliMobCity measure package. Also, part of the PT busses and all other municipal vehicles are to become electric ones by 2030. The streamlining of the PT bus network (BAU) and electrification of the remaining busses (CliMobCity) together imply a change of PT fossil fuel bus-kms by more than –60 %. Furthermore, the CliMobCity package includes the cooperation with and use of the THESSM@LL data and information platform supporting decision-making in sustainable mobility management and planning. The BAU and CliMobCity measure packages are further described in the *Appendix-Thessaloniki-Report (MoT & Lever Development Consultants, 2022)*.

4.5.3. Thessaloniki mobility effects

As the CliMobCity measure package focusses on vehicle electrification and contains only few mobility measures, the mobility changes in BAU and CliMobCity are almost the same; “almost” because the network of shared cars will change mobility, but the change is very small, as is quantified by Thessaloniki.

The number of trips in, from and to the municipality is forecasted to increase, a bit more than the population growth. The new transport systems and other measures generate much modal shift, changing the number of PT trips in/from/to Thessaloniki by + 30 %, while those of cars decline. This effects modal shares (Fig. 14), the share of PT moving up to almost 40 %, and that of car down to around 25 %. In the base year the share of PT was already close to that of cars. In 2030 PT is predicted to have by far the largest share.

With only internal trips (= two ends of a trip are in the municipal area) in picture, PT already had the largest share in the base year. The share of internal car trips expectantly declines from 23 % to 18 %.

The average car trip distance is predicted to decline between 2018 and 2030 from 8.1 to 7.8 km, that of PT increase from 7 to 10 km. Evidently much modal shift takes place on the longer distance.

Modal shift and the change of trip distances leads to a change of passenger-kms in the municipal area of PT (all kinds) by + 13 % and of car-kms by –18 %, which is very large.

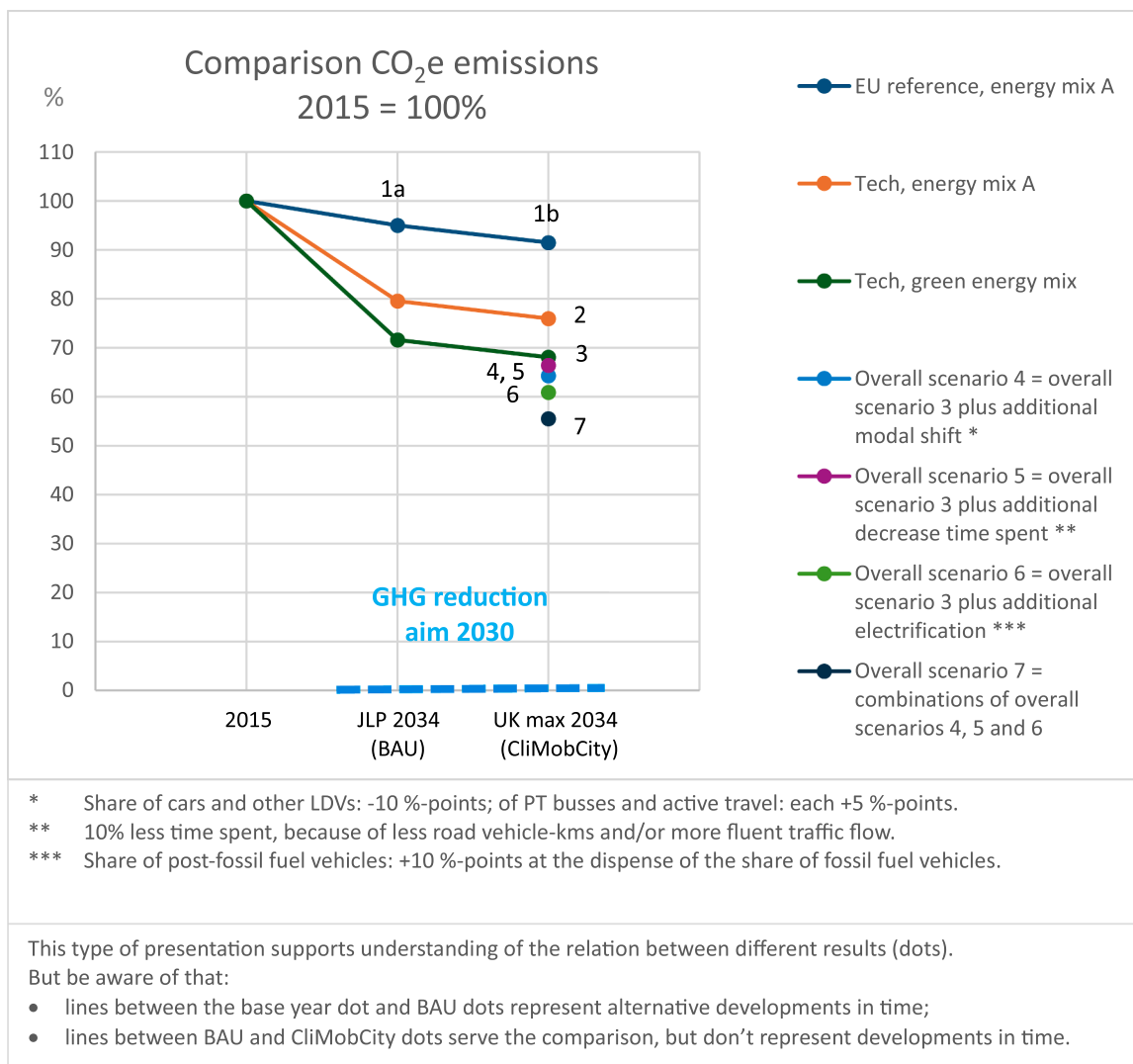


Fig. 12. Plymouth (and surrounding region), comparison of GHG emissions of overall scenarios.

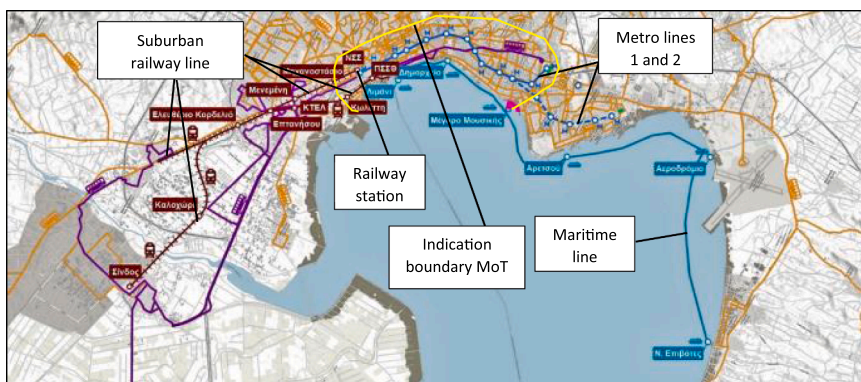


Fig. 13. New transport systems in the BAU measure package of Thessaloniki Source: on the basis of a figure in the draft SUMP 2030 (see Project Summary [Kreutzberger & van Binsbergen, 2023]).

Lever and CERTH/HIT have in the *Appendix-Thessaloniki-Report (MoT & Lever Development Consultants, 2022)* summarised what had been formerly explored about the impacts of shared cars. Assuming 150 shared cars to be in service in 2030, 3 % (peak hour) to 3.5 % (daily) of all intra-municipal car trips would then go by shared car. Taking account of the averagely shorter distance involved, the shared car scheme

contributes to about 1 %-point of car-km reduction.

4.5.4. Thessaloniki, spatial requirement of traffic

The modal shift from car to other modes cumulating in -18 % change of car-kms, and the underground positioning of the metro imply that ground floor space requirement of all mobility is declining. In the

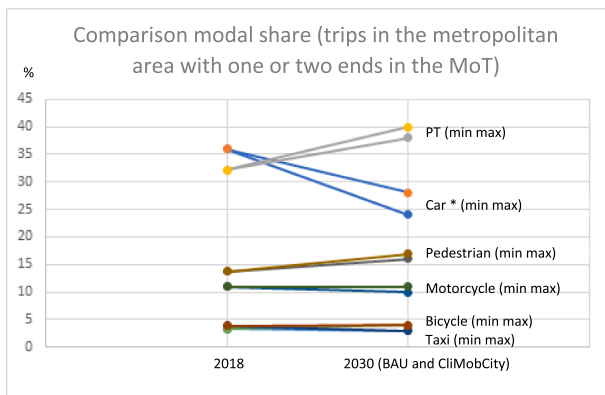


Fig. 14. Comparison modal share of trips in, from or to the municipality (= trips in the metropolitan area with one or two ends in the municipality of Thessaloniki) *Private and – in 2030 – also shared electric car. Source data: Appendix-Thessaloniki-report, Table 7 (MoT & Lever Development Consultants, 2022).

large city centre, public space is redistributed at the expense of road capacity, along boulevards and smaller main roads through the centre. Together this strengthens the functioning of the compact city and contributes to GHG reduction. On the main roads outside of the centre to and from neighbouring municipalities, potentially increasing capacity reserves may induce rebound traffic, unless circumstances/measures in the centre (like limited capacity of main roads and parking; reduced speed limits) or outside (reduced speed limits, perhaps cordon pricing) suppress such.

4.5.5. Thessaloniki GHG emissions

The change of input per overall scenario is shown in Table 9, the corresponding GHG reduction in Table 9 and Fig. 15. All GHG reduction is calculated in comparison to the base year.

All mobility changes in Thessaloniki provide the mentioned change of car-kms of –18 % in 2018–2030. The GHG reduction in BAU (OS 1a) is less than one might expect from this change: –8 %. This is the result of a weighted average of different changes. The travellers of the declining car-kms largely shift to PT, but its GHG effect is only “half” given the “half” (45 %) share of post-fossil fuel electricity production still in operation in 2030. A comparable mechanism is also present for travellers switching from bus to metro. In urban freight there is little progress in GHG reduction. Finally, in BAU (OS 1a) there is no supplementing reduction amongst the remaining car-kms, given the very small electrification etc. in 2030 (share 1.5 %). In CliMobCity (OS1b) there is the municipal aim of 37 % electric cars in 2030. This overrules the EU reference and Tech projection of electric etc. car shares, which on the other side are relative low, compared to other cities. Furthermore, the city strives for the electrification of all municipal vehicles and of about half of the bus-kms remaining after the restructuring of the bus network because of the metro. The complete greening of electricity production and performance improvements in OS 4–7 let GHG emissions change by –24 %. Thessaloniki strives for a GHG change –52 % in 2018–2030.²² The first of two backcasting lever exercises showed that a maximal modal shift of passengers from car does not, given the already very sustainable modal split, provide enough GHG change (–43 % in OS 8). More and sufficient reduction change can be achieved by increasing the share of BEVs by + 61 %. This result shows the tension of mitigating policies, because evidently such share increase will under current conditions hardly be achievable in the period. It is 1.7 times the amount of the ambitious aim of the city.

²² For assumptions of this translation see the Project Summary.

4.5.6. Thessaloniki, additional measures and performance improvements to cover the gap

On the long term there is a very promising development for substantial GHG reduction by changing mobility, which is to add phase 2 and 3 of the metro network (Attiko Metro S.A., 2014 according to Salariara, 2014), by which other dense city parts become metro-accessed and the airport metro-directly metro-connected to the city. The greening of electricity production will by then also sort larger GHG reductions per unit of modal shift than currently. However, this long-term perspective does not contribute to covering the identified GHG gap, but instead to reduce GHG emissions after 2030.

Theoretical short to medium term options for further GHG reduction in this planning phase are – discussion-wise – to electrify the last tranche of PT buses, support car-pooling, partly perhaps coupled to the network of P + R locations, implement zero-emission zones in city areas where the lack of parking possibilities does not already unfold sufficient push power, perhaps reduce PT fares, which are evaluated to be high (Perra et al., 2017) and increase modal shift to PT and active travel by means of focused awareness raising. All despite of the relative low GDP/capita which Perra et al. (2017) bring under attention.

For accelerating vehicle electrification see Section 4.7

4.6. Leipzig

4.6.1. Leipzig in general

Leipzig is the largest city after Berlin in the eastern part of Germany. It was an important trade, production and cultural town already centuries ago. The Leipzig fair dates back to medieval times and today is accommodated in a large complex of exhibition and conference halls. Leipzig until 1945 had a large publishing and editing sector, some of which is still flourishing. Due to the large-scale industrialisation in the 19th century Leipzig has a substantive dense residential belt around the city centre (both, the centre and the belt have about 3500 inhabitants per km²), outside of which the densities gradually decrease, ending in single house areas in the city’s fringes. The fringe, however, also includes a number of suburbs hosting large housing complexes, stomped out of the ground during the GDR-period (1945–1989). These areas have a density comparable with the belt (Fig. 16).

The city is divided by a green corridor, today hosting recreational functions in a forest and along a small river.

The industrial activities of some large parts of the 19th century industrial areas have moved to other places in the world, but their many buildings have been or are being repurposed giving home to young enterprises, housing and culture. After the unification of West and East Germany there have been substantial investments by large employers in transport and logistics (airport, DHL freight hub) and car assembly factories (BMW, Porsche) along the northern edge of the city.

Leipzig’s PT consists of regional train lines, a dense tram network, bus lines and – in residential areas with low densities – an on-demand share taxi network (FLEXA) under management of the PT company. This is reported to support bus use by 6–12 % and tram use by 3–4 % (2050 CliMobCity Newsletter 3 [TU Delft, 2022]). Many tram and bus lines run mixed with other traffic. Some are nevertheless fast, others are clearly bothered by the other traffic. The main station is technically the largest one in Germany. Part of it still accommodates national and regional trains. It is a terminal station, but for regional trains a tunnel has been built more recently running beneath the historical centre and attached to the rail network on the other side of the centre. Quite some Leipzig residential areas including the mass housing on the westside of the city are accessed by regional train. Three (inter)national highways run around the city. The other main roads run radially from/to the city centre, cutting the highways on distances of 7–13 km. Leipzig also has a dense network of bicycle lanes.

4.6.2. Leipzig measures

Leipzig’s BAU mobility policy is documented in the multisectoral

Table 9
Thessaloniki, input and GHG reduction per overall scenario.

OS		Vehicle-kms	Extra changes	Share of post-fossil fuel vehicles *	Energie mix for electricity production *	GHG emission *
BAU						
1a (blue line) (W0)		Car-kms -18%	/	Cars 0.2% → 1.5% (EU reference)	70% → 45%	-8%
CliMobCity						
1b (W2, blue line Figure 8)		Idem	/	Municipal aim: Cars 0.2% → +37%. All municipal vehicles and ca. half of remaining PT bus-kms electric	Idem	-14%
2 (orange line Figure 8)		Idem	/	idem	Idem	-15%
3 (grey line Figure 8)		Idem	/	Idem	70% → 0%	-21%
4		Same as OS 3 plus →	OS 3 plus -10 %-points car/LDV share	Idem	Idem	-22%
5		Same as OS 3 plus →	OS 3 plus -10% time spent (travel distance)	Idem	Idem	-21%
6		Same as in OS 3	OS 3 plus +10 %-points post-fossil cars smaller share of fossil-fuel cars/LDVs	← Idem plus	Idem	+22%
7		Same as in OS 3 plus changes in OS 4-6	OS 3 plus combination of OS 4-7	Idem	Idem	-24%
8		Same as OS 3 plus →	OS 3 plus share of cars and other LDVs, 2-wheelers, bus, metro, rail, walking and bicycle: respectively -25, -5, +8, +8, +3, +3 or +9 %-points	Same as in OS 3	Idem	-42%
9		Same as OS 3 plus →	OS 3 plus BEV +61, diesel -15, gasoline -46 %-points	← Idem plus	Idem	-53%

*= Change compared to base year.

Red= Input change in comparison to line before.

Idem= Same as line before.

**= Additional to OS 3.

planning document *Integrated city development plan Leipzig 2030 (INSEK 2030)* (MoL, 2018a) and *the Mobility Strategy 2030* (MoL, 2018b). After their launch it showed that the projected growth of population needed to be adjusted downwards, namely to + 13 % between 2015 and 2035.

For describing the mobility effects of the BAU measures, given the lower population growth, the project consulted the results of a PTV modelling run called *Planfall 2035*, described in PTV (2020)²³ and consulted by the project in 2022 and 2023.

Then there are specific policy areas relating to mobility which depend much on the cooperation of firms, and which are more the working field of Leipzig's department for economic affairs: vehicle electrification etc, car sharing, micro-mobility, passenger or freight mobility hubs. The implementation frameworks for these areas are the subject of the city's document *Leipzig – City of Smart Mobility* (MoL, 2017).

The BAU measure package contained about 20 road measures like new links and road widening. For PT there are about 10 regional train, 15 tram and 20 bus measures, envisaging new lines, new nodes (also new train stations), extension of some lines and shortening of others, new routes for lines, increase of the service frequency, and refurbishment of train and bus stops. Also the number of FLEXA areas is to be increased. The package included measures for active travel.

²³ It strictly speaking predicts the change of mobility for the period up to 2035 instead of 2030.

Leipzig's CliMobCity package, partly developed in the framework of updating the Smart mobility policies (MoL, 2022a), focussed on the acceleration of vehicle electrification and on the further development of shared mobility. The package included:

- the electrification projections conform the EU reference and Tech scenario (resp. 17 % and 51 % post fossil-fuel cars in 2035). During the demonstration study the outlines of new municipal policies were communicated. The *Charging Infrastructure Concept Leipzig 2030* (MoL, 2022b) describes the infrastructure needed to achieve a near to 30 %-share of post-fossil fuel vehicles by 2030. This communication did in the project not lead to a recalculation of GHG emissions in the demonstration study, but the differences in results are indicated in Fig. 18;
- electrification of all PT vehicles by 2030;
- electrification of all municipal vehicles by 2030, installing fast and normal public charging points in public and private space;
- creating new public mobility stations where one can park and pick up shared vehicles (bikes, cars), charge e-vehicles, shared or not (cars) and park private bicycles;
- expanding private electric car charging and sharing nodes or making such accessible to other users;
- more on-demand transport networks to supplement PT services where the transport demand is too small to provide tram or bus services;

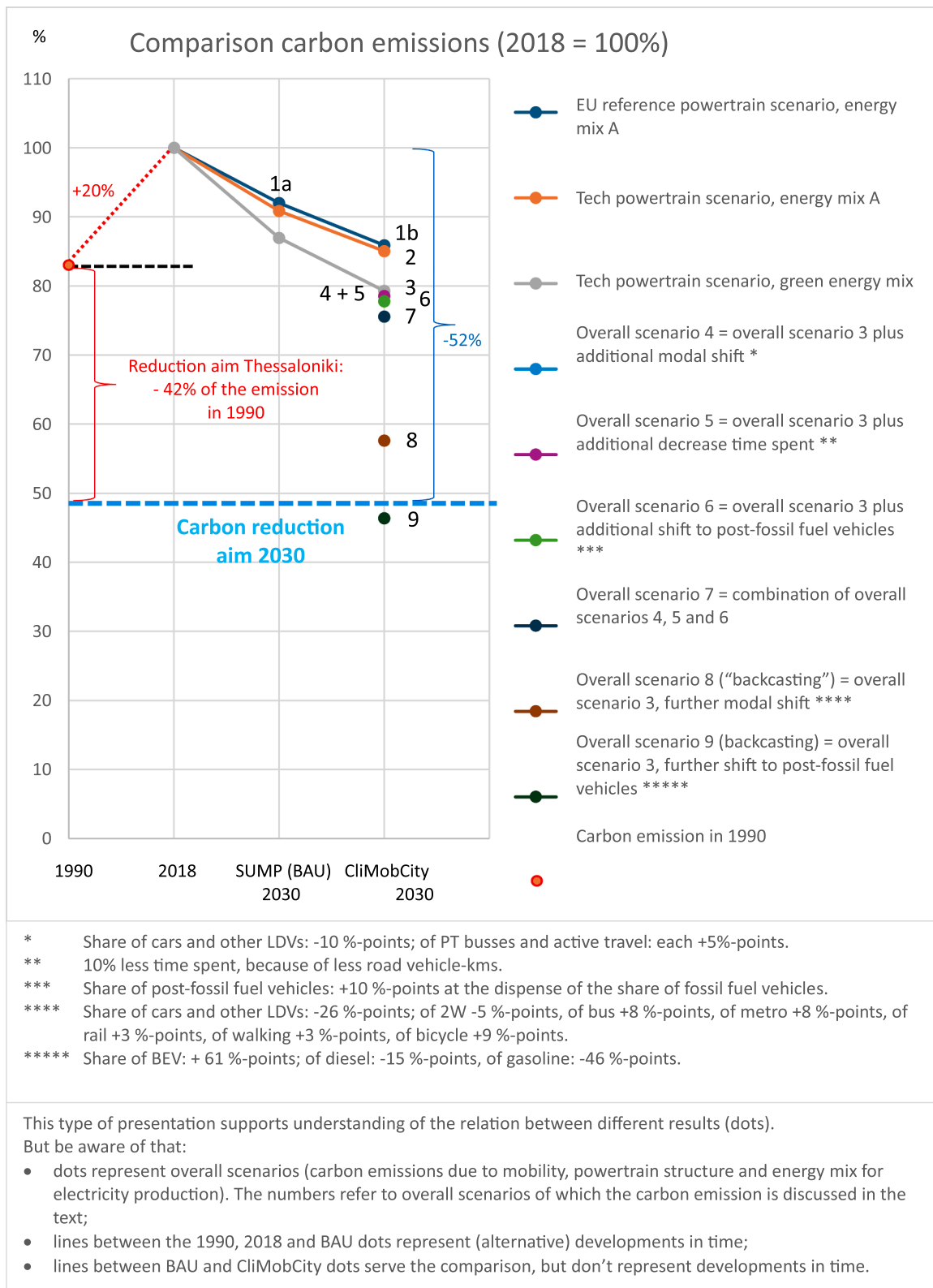


Fig. 15. Thessaloniki, comparison of GHG emission of overall scenarios.

- increasing and improving multimodal services in new business models like ride sharing;
- implementing urban hubs enabling to use larger trucks in parts of the transport chain or and small vehicles including cargo bikes in other parts. There are plans for central hubs (inner cities), hubs in neighbourhoods as well as large hubs at the city borders.

4.6.3. Leipzig mobility effects

Leipzig's CliMobCity scenario focusses on vehicle electrification. For mobility, the CliMobCity scenario is largely the same as the BAU scenario. Therefore the mobility results of transport modelling for the BAU scenario (Planfall 2035) also apply for the CliMobCity scenario.

Cars trips are forecasted to change by -5 %. The total picture is that

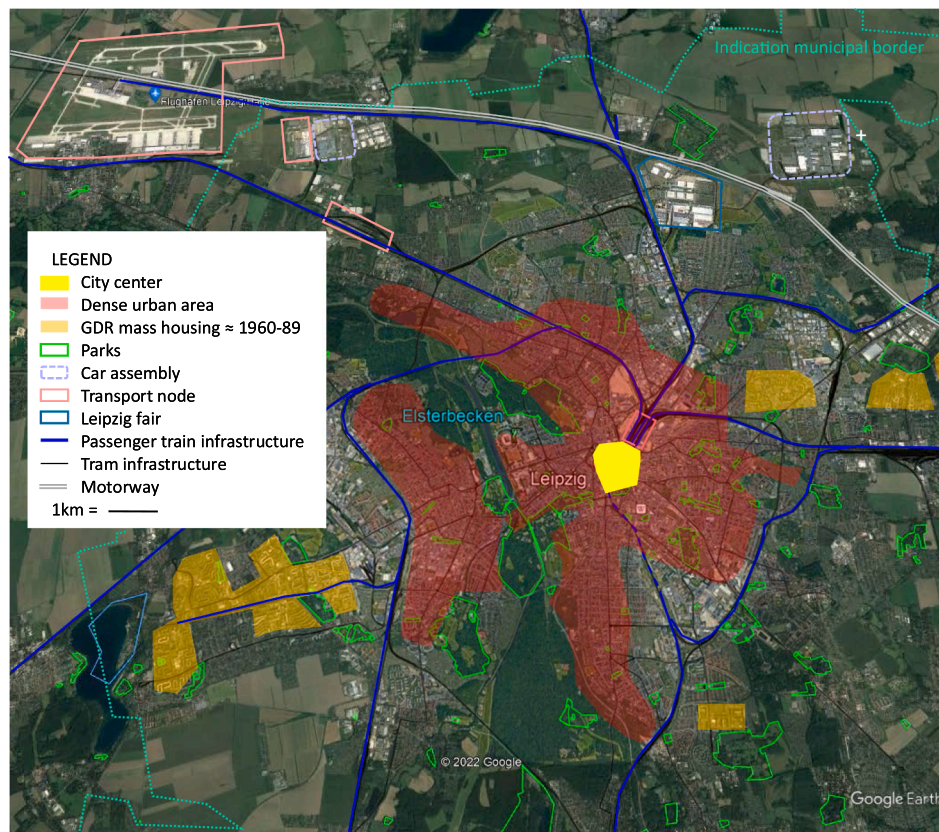


Fig. 16. Existing (base year) spatial structure and main transport networks in Leipzig.

of successful modal shift, car shares declining from 58 % to 50 %. PT and bicycling have smaller, but similar shares and also similar growth rates.²⁴

Regarding the spatial pattern, the decline of car trips refers to Leipzig-internal mobility. From and to the municipality, car trip numbers increase by +8 %. These changes are accompanied by increasing distances in both groups which, however, in their effect for car-kms are overruled by higher vehicle occupancy. This leads to a net change of car-kms of -8 %. Truck-kms are predicted to increase by +12 %.

4.6.4. Leipzig, spatial requirement of traffic

The change of car-kms implies that the space demand of all traffic in Leipzig declines. This is also visible by the decline of traffic intensities (vehicle passing a point per time unit) between 2015 and 2035 on almost all roads in Leipzig (Fig. 17). Major exceptions are the national highways and several roads in the periphery giving access/egress to/from the highways.

4.6.5. Leipzig GHG emission

The change of input per overall scenario is shown in Table 10, the corresponding GHG reduction in Table 10 and Fig. 18. The GHG reduction is calculated in comparison to the base year.

All mobility changes in Leipzig provide the mentioned -8 % of car-kms in . The GHG reduction in BAU (OS 1a) is larger than what one might expect from this change, namely -25 %. This is especially due to the car electrification etc. amongst the remaining car-kms which, however, is only "half" GHG effective given the "half" (51 %) share of fossil fuel electricity production still in operation. This half-mechanism also

applies for the modal shift from car to PT. The GHG reduction emerges despite of the increasing truck-kms (+12 %). In CliMobCity (OS 1b) the municipal aim is a share of electric cars of 30 % (OS 1c), lower than the Tech share of 51 % (OS 2), providing respectively the GHG reduction of the red dot in Fig. 18 and of OS 2.

The complete greening of electricity production and performance improvements in OS 4-7 let GHG change by -50 %. Leipzig's GHG aim is -80 %. The backcasting lever exercise (OS 8) shows that a mix of modal shift and of electrification etc. (share for cars is 86 %, for trucks 22 %) would provide the targeted GHG reduction. However, such level of car electrification in 2035, a 2.9-fold of the ambitious municipal aim, is quite unrealistic under current conditions.

4.6.6. Leipzig, additional measures and performance improvements to cover the gap

The city's local PT plan (MoL, 2019) enlists a large number of short to medium term PT measures, part of which are not already subject of the modelled BAU policies. Examples are PT lines for which land is already being reserved, including some tangential tram lines. Other PT measure, like frequency and capacity increase, acceleration of PT, improvement of interchange between PT lines, preparing on wider tram profiles infrastructure, were partly already subject of the BAU package and partly go beyond that. A new measure mentioned in the document is not to increase PT fares, for which financing has already been organized. The other additional measures would require an increase of financing.

The PT document also suggests building houses and employment buildings mainly near to PT tracks.

And discussion-wise one can imagine abolishing the PT-absence from and to large industrial employers, by either accepting less cost coverage of corresponding PT lines or by embedding the locations in new urbanism in combination with PT network expansion. The latter is, however, rather a measure for the following planning phase than for the one towards 2035.

²⁴ For Leipzig internal trips, the shares of all modes are converging, car shares then being only slightly larger than of PT and bicycle.

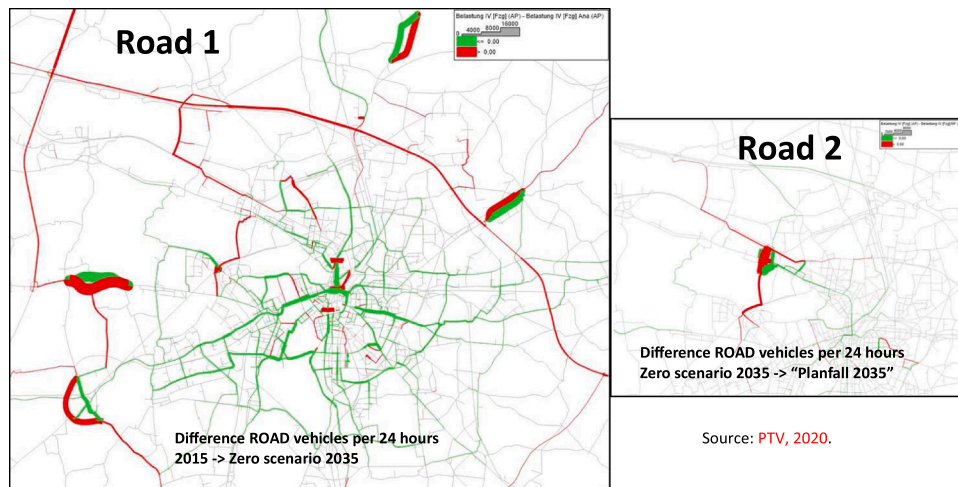


Fig. 17. Change of traffic intensities on the road and PT networks by BAU policies (= sum of “Road 1” and “Road 2”). The change would also apply for the Cli-MobCity scenario.

Table 10
Leipzig, input and GHG reduction per overall scenario.

OS	Vehicle-kms	Extra changes	Share of post-fossil fuel vehicles *	Energie mix for electricity production *	GHG emission *
BAU					
1a (blue line) (W0)	Car-kms -8%	/	Cars 1% → 17% (EU reference) **	60% → 51%	-25%
CliMobCity					
1b (W2, blue line Figure 8)	Idem	/	Idem All PT busses and all municipal vehicles electric	Idem	-26%
1c	Idem	/	Idem Municipal CliMobCity aim: cars 1% → 30%	Idem	Red dot in Figure 17
2 (orange line Figure 8)	Idem	/	1% → 51% 30% of cars electric	Idem	-34%
3 (grey line Figure 8)	Idem	/	Idem	60% → 0%	-41%
4	Same as OS 3 plus →	OS 3 plus -10 %-points car/LDV share	Idem	Idem	-45%
5	Same as OS 3 plus →	OS 3 plus -10% time spent (travel distance)	Idem	Idem	-43%
6	Same as in OS 3	OS 3 plus +10 %-points post-fossil cars smaller share of fossil-fuel cars/LDVs	← Idem plus	Idem	-45%
7	Same as in OS 3 plus changes in OS 4-6	OS 3 plus combination of OS 4-7	Idem	Idem	-50%
8	Same as OS 3 plus →	OS 3 plus ... modal share of cars/LDVs changes by -10 %-points, and share of post-fossil cars and other LDVs increases to the level of 86%, that of post-fossil fuel trucks/ HDVs of 22%	← Same as in OS 3 plus	Idem	-79%

*= Change compared to base year.

**= Municipal reduction aim is smaller.

Red= Input change in comparison to line before.

Idem= Same as line before.

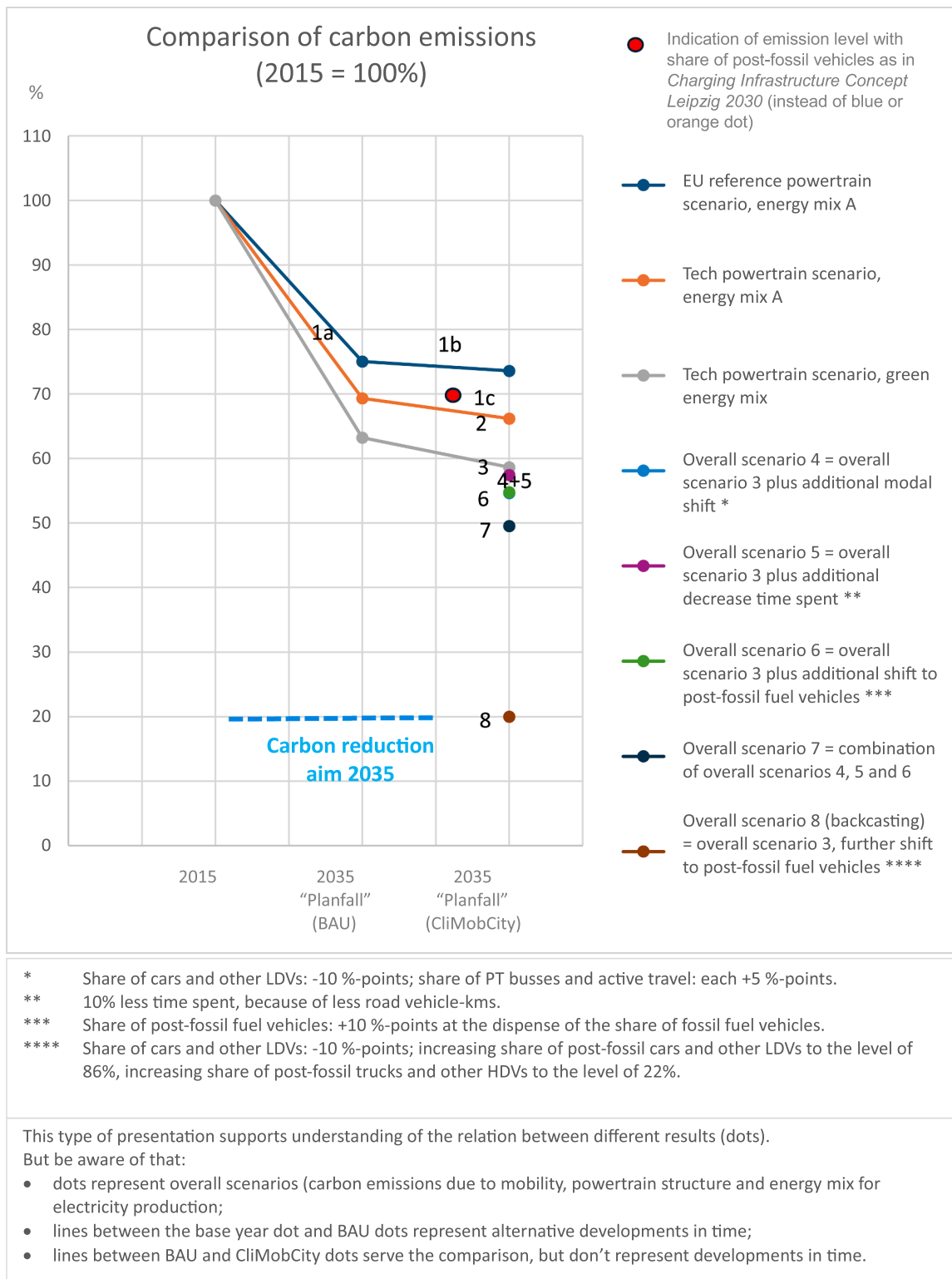


Fig. 18. Leipzig, comparison of GHG emissions of overall scenarios.

For urban freight and accelerating vehicle electrification see [Section 4.7](#).

4.7. Summary: overview and comparison of GHG reductions in the four cities, and their reasons ²⁵

4.7.1. Comparison BAU measure packages

Bydgoszcz, Thessaloniki and Leipzig in the BAU framework plan to extend and improve their PT and active travel networks. Bydgoszcz' measure package could be referred to as "all-round", while Thessaloniki's and Leipzig's BAU policies are clearly modal shift oriented. Plymouth's measure package perhaps has the intention of being all-round focussed, but the city in the BAU framework misses the instruments to effectively develop PT; what remains is rather car and active travel oriented.

4.7.2. Comparison CliMobCity measure packages

The CliMobCity measure packages have a different focus, partly because of the new emphasis on climate-friendly mobility, partly because aims may require other, namely complementary actions to the BAU ones. Thessaloniki and Leipzig for CliMobCity explorations primarily focus on vehicle electrification. The centre of Plymouth's CliMobCity focus is rather modal shift, in particular towards PT. Bydgoszcz CliMobCity package W2 focusses on combating urban sprawl and suburbanisation within the municipality and on corresponding PT development. All cities are devoted to continue supporting shared (micro) mobility and developing mobility hubs.

4.7.3. Comparison input and magnitude of GHG reduction in BAU

[Table 11](#) gives an overview per partner city of the policy focus of BAU and CliMobCity measure packages, the change of road vehicle-kms predicted per city, the assumptions concerning the shares of post-fossil fuel vehicles like electric cars (aims according the EU reference or Tech scenario, or municipal aims), the assumptions regarding the greening of electricity production, and the GHG reductions analysed per overall scenario. We for comparison start with the BAU scenarios of Thessaloniki and Leipzig. In the first city, car-kms change by -18% (line 5 of [Table 11](#)), but the GHG change is "only" -8% (line 9 of [Table 11](#), OS 1a). In Leipzig GHG emissions change by -8% , and GHG by -25% . This difference in GHG reduction is mainly caused by the electrification etc. amongst the remaining car-kms, which in Thessaloniki is near to zero and in Leipzig substantial. The electrification increases the reduction, while all other changes (freight, half green energy mix for electricity production) reduce the reduction.

4.7.4. Comparison input and magnitude of GHG reduction in CliMobCity (EU reference and Tech)

In CliMobCity, still with EU reference shares of post-fossil fuel vehicles, GHG reduction is larger. The changes in the four cities are -1.3% / -9% / -14% / -26% compared to the base year. In Bydgoszcz (OS 1c) the larger reduction is due to the combination of pull and push mobility and land use measures, in Plymouth to mobility measures providing more modal shift, and in Thessaloniki to the municipal electrification aim which overrules the EU reference projection. The latter in principle also applies for Leipzig (red dot). CliMobCity in combination with the Tech scenario (OS 2) provides larger reductions. Interestingly, Leipzig's ambitious electrification aim lies below that of the Tech scenario projection.

4.7.5. Comparison factors (input) and magnitude of GHG reduction in CliMobCity (Tech, 100 % green electricity production)

Assuming also the electricity production to become completely green (OS 3) GHG emissions in Bydgoszcz/Plymouth/Thessaloniki/Leipzig

change respectively by another -13% / -8% / -6% / -8% compared to OS 2, and by -19% / -32% / -21% / -41% , compared to the base year (line 9).²⁶ This is the most far going reduction analysed on the basis of concrete measures and preceding transport modelling. The gap after OS 3 is 81% / 68% / 31% / 39% . The meaning of the reductions may be difficult to understand given the different time windows. [Fig. 19](#) helps to interpret, also by looking to the extrapolated reduction rates to a common year, like 2050. This suggests that Leipzig would have the largest reduction, followed by Thessaloniki (and Plymouth) and finally Bydgoszcz.

4.7.6. Comparison input and magnitude of GHG reduction in CliMobCity forecasting lever exercises

The forecasting exercises show the GHG impact of the following performance improvements: -10% car and other LDV share, -10% time spent (travel distance), $+10\%$ higher share of post-fossil fuel cars, and a combination of these (OS 4-7). They reduce the gap somewhat. We discuss the measures which could lead to these changes in the last subsection of this section.

4.7.7. Comparison input and magnitude of GHG reduction in CliMobCity backcasting lever exercises

Only a few backcasting lever exercises were conducted, their results being very informative. For Thessaloniki one exercise (OS 8) shows that a far-reaching modal shift of passengers from car to other modes (the share of cars/LDVs moves to near to zero) doesn't provide sufficient GHG reduction. The main reasons are that the car share was already small, secondly that the freight emissions remain substantial. The second backcasting exercise (OS 9) shows that an increase of the BEV share by $+61\%$ -points would lead to the reduction aim. However, under current conditions such increase in such short time is unrealistic. The Leipzig backcasting exercise (OS 8) reveals that a combination of modal shift and electrification (LDVs to the level of 86% , HDVs 22%) would lead to the city's GHG aim. However, also here the electrification speed seems to be unrealistic.

4.7.8. Comparison of measures to fill the gap

All four cities have common and specific types of measures to reduce the GHG gap. A common and promising measure field is to address the freight sector. Another common, but under current conditions less promising solution is an acceleration of car electrification. During the demonstration studies, little attention was paid to **urban freight transport**, kind of repeating what is widespread in transport research (Cui et al., 2015) and in municipal mobility planning (Bjorgen & Ryghaug, 2022; Akgün et al., 2019), and deviates from European ideas about sustainable mobility (EC, 2021). The lack of attention also deviates from the conclusions one should draw from the BAU mobility predictions for Bydgoszcz (truck-kms $+30\%$), Plymouth (truck-kms $+18\%$, van-kms $+59\%$) and Leipzig (truck-kms $+12\%$). Typical reasons often articulated are that local freight logistics and hence innovation potentials are not well known, also difficult to get to know, and often challenging in terms of reliable long-term transport forecasts; also, that logistics and freight transport would be mainly subject of corporate and hardly of public planning.

While this all may partially mirror reality correctly, in particular when striving for higher loading degrees by means of bundling, it is also increasingly evident that for freight vehicle electrification there are new opportunities in sight; opportunities because for trips between regional distribution centres and the customers in the city, the distance range of electric freight vehicles hardly provides limitations anymore. In this regard an "immediate" and continuous vehicle replacement process could be organised, as tight as vehicle depreciation periods allow. This process should be synchronised with a gradual expansion of zero-

²⁵ Responding to RQ 8.

²⁶ Again, the Plymouth value is not comparable with the other ones.

Table 11
Factors (input) and magnitude of GHG reduction per partner city.

	Bydgoszcz	Plymouth	Thessaloniki	Leipzig																																																																																																																															
1	GHG reduction aim	-100% in 2050.	-100% in 2030.	-52% in 2018-2030.																																																																																																																															
2	City density	Little dense.	Not dense.	Very dense.																																																																																																																															
3	Measure focus BAU	All round.	Relative car oriented.	Metro, regional train, slow mobility.																																																																																																																															
4	Measure focus CliiMobCity	<ul style="list-style-type: none"> Allround. CliiMobCity W2 (= OS 1c): re-urbanisation + less roads than in BAU. CliiMobCity W2+ (= OS 1e): as W2, but mobility preferences more sustainability oriented. 	Modal shift oriented.	Electrification.																																																																																																																															
5	Mobility change	<ul style="list-style-type: none"> BAU car-kms +38%. CliiMobCity W2 car-kms +31%. CliiMobCity W2+ car-kms +20%. Truck-kms +30%. 	<ul style="list-style-type: none"> BAU car-kms +19%. CliiMobCity car-kms +4%. BAU truck-kms + 18%. CliiMobCity truck-kms +17% BAU LGV-kms +59%. CliiMobCity +35%. 	<ul style="list-style-type: none"> BAU car-kms -18%. Almost same in CliiMobCity. OS 8: share of cars and other LDVs: -26 %-points. 	<ul style="list-style-type: none"> BAU car-kms -8 %. BAU truck-kms +12%. Same in CliiMobCity. OS 8: share of cars and other LDVs: -10 %-points. 																																																																																																																														
6	Share of post-fossil fuel cars	<ul style="list-style-type: none"> OS 1a-1e: 0.2% -> 23% (EU reference). OS 2-5: 0.2% -> 43% (Tech). OS 6+7: 0.2% -> 53%. 	<ul style="list-style-type: none"> OS 1a+1b: 1% -> 18% (EU reference). OS 2-5: 1% -> 56% (Tech). OS 6+7: 1% -> 66%. 	<ul style="list-style-type: none"> OS 1a: 0.2% -> 1.5% (BAU, EU reference). OS 1b-5, 8 : 0.2% -> 37% (municipal CliiMobCity aim overruling lower share value of Tech (11%). OS 6+7: 0.2% -> 47%. OS 9: 0.2% -> 100% 	<ul style="list-style-type: none"> OS 1a+1b: 1% -> 17%. Red dot Figure 17: 1% -> 30% (municipal CliiMobCity aim) OS 2-5: 1% -> 51% (Tech). OS 6+7: 1% -> 61%. OS 8: 1% -> 86% 																																																																																																																														
7	Other electrification	OS 1b-7: All PT buses		OS 1b-9 (CliiMobCity): all municipal vehicles and part of PT buses																																																																																																																															
8	Greening (share of fossil fuel in all) electric production	<ul style="list-style-type: none"> OS 1a-2: 88% -> 44%. OS 3-7: 88% -> 0%. 	<ul style="list-style-type: none"> OS 1a-2: 55% -> 20%. OS 3-7: 55% -> 0%. 	<ul style="list-style-type: none"> OS 1a-2: 70% -> 45%. OS 3-9: 70% -> 0%. 	<ul style="list-style-type: none"> OS 1a-2: 60% -> 51%. OS 3-8: 60% -> 0%. 																																																																																																																														
9	GHG (all OS = CliiMobCity, unless BAU)	<table border="1"> <thead> <tr> <th>OS</th> <th>GHG (%)</th> <th>Diff. (%-p)</th> </tr> </thead> <tbody> <tr><td>1a (BAU)</td><td>0,5</td><td></td></tr> <tr><td>1b (W1)</td><td>-0,2</td><td></td></tr> <tr><td>1c (W2)</td><td>-1,3</td><td>-1,8</td></tr> <tr><td>1d (W1+)</td><td>-1,2</td><td></td></tr> <tr><td>1e (W2+)</td><td>-1,9</td><td></td></tr> <tr><td>2</td><td>-6</td><td>-5</td></tr> <tr><td>3 (EP green)</td><td>-19</td><td>-13</td></tr> <tr><td>4</td><td>-25</td><td></td></tr> <tr><td>5</td><td>-22</td><td></td></tr> <tr><td>6</td><td>-24</td><td></td></tr> <tr><td>7 = comb. 4-6</td><td>-32</td><td>-13</td></tr> </tbody> </table>	OS	GHG (%)	Diff. (%-p)	1a (BAU)	0,5		1b (W1)	-0,2		1c (W2)	-1,3	-1,8	1d (W1+)	-1,2		1e (W2+)	-1,9		2	-6	-5	3 (EP green)	-19	-13	4	-25		5	-22		6	-24		7 = comb. 4-6	-32	-13	<table border="1"> <thead> <tr> <th>OS</th> <th>GHG (%)</th> <th>Diff. (%-p)</th> </tr> </thead> <tbody> <tr><td>1a (BAU)</td><td>-5</td><td></td></tr> <tr><td>1b</td><td>-9</td><td>-4</td></tr> <tr><td>2</td><td>-24</td><td>-16</td></tr> <tr><td>3 (EP green)</td><td>-32</td><td>-8</td></tr> <tr><td>4</td><td>-36</td><td></td></tr> <tr><td>5</td><td>-34</td><td></td></tr> <tr><td>6</td><td>-39</td><td></td></tr> <tr><td>7 = comb. 4-6</td><td>-45</td><td>-13</td></tr> </tbody> </table> <p>Values also refer to mobility across municipal boundaries. Are not comparable with other cities.</p>	OS	GHG (%)	Diff. (%-p)	1a (BAU)	-5		1b	-9	-4	2	-24	-16	3 (EP green)	-32	-8	4	-36		5	-34		6	-39		7 = comb. 4-6	-45	-13	<table border="1"> <thead> <tr> <th>OS</th> <th>GHG (%)</th> <th>Diff. (%-p)</th> </tr> </thead> <tbody> <tr><td>1a (BAU)</td><td>-8</td><td></td></tr> <tr><td>1b</td><td>-14</td><td>-6</td></tr> <tr><td>2</td><td>-15</td><td>-1</td></tr> <tr><td>3 (EP green)</td><td>-21</td><td>-6</td></tr> <tr><td>4</td><td>-22</td><td></td></tr> <tr><td>5</td><td>-21</td><td></td></tr> <tr><td>6</td><td>-22</td><td></td></tr> <tr><td>7 = comb. 4-6</td><td>-24</td><td>-4</td></tr> <tr><td>8 (backc.)</td><td>-42</td><td>-22</td></tr> <tr><td>9 (backc.)</td><td>-54</td><td>-33</td></tr> </tbody> </table>	OS	GHG (%)	Diff. (%-p)	1a (BAU)	-8		1b	-14	-6	2	-15	-1	3 (EP green)	-21	-6	4	-22		5	-21		6	-22		7 = comb. 4-6	-24	-4	8 (backc.)	-42	-22	9 (backc.)	-54	-33	<table border="1"> <thead> <tr> <th>OS</th> <th>GHG (%)</th> <th>Diff. (%-p)</th> </tr> </thead> <tbody> <tr><td>1a (BAU)</td><td>-25</td><td></td></tr> <tr><td>1b</td><td>-26</td><td>-1</td></tr> <tr><td>2</td><td>-34</td><td>-7 *</td></tr> <tr><td>3 (EP green)</td><td>-41</td><td>-8 *</td></tr> <tr><td>4</td><td>-45</td><td></td></tr> <tr><td>5</td><td>-43</td><td></td></tr> <tr><td>6</td><td>-45</td><td></td></tr> <tr><td>7 = comb. 4-6</td><td>-50</td><td>-9</td></tr> <tr><td>8 (backc.)</td><td>-79</td><td>-37</td></tr> </tbody> </table>	OS	GHG (%)	Diff. (%-p)	1a (BAU)	-25		1b	-26	-1	2	-34	-7 *	3 (EP green)	-41	-8 *	4	-45		5	-43		6	-45		7 = comb. 4-6	-50	-9	8 (backc.)	-79	-37
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11	after OS 7	68%	55%	28%																																																																																																																															
12	Specific ** improvement options in the same planning time window *** and not already part of BAU or CliiMobCity measure package	<ul style="list-style-type: none"> Reverses the trend of suburbanisation. Reduce attractiveness of main roads. Establish car-pooling facilities Substantially accelerate electrification of cars (2050!). Electrify freight vehicles and logistic innovation 	<ul style="list-style-type: none"> Selective densification city Probably useful: less suburbanisation Electrify freight vehicles and logistic innovation. After franchising PT bus system, additional performance improvement 	<ul style="list-style-type: none"> Electrify all PT buses Electrify etc. freight vehicles and logistic innovation. Zero-emission zones where parking limitations don't already function as powerful push force. 	<ul style="list-style-type: none"> Improve PT performance by multiple medium to short term measures. Electrify etc. freight vehicles and logistic innovation Find sustainable mobility solutions to large greenfield employers. 																																																																																																																														

OS = Overall scenario.

* = Values seem to deviate from what is visible in the main column. "Deviation" is due to off-rounding.

** = Without general actions which we occasionally mentioned but did not analyse, as awareness raising campaigns, or the provision of real time information, both supporting the choice of low GHG mobility solution

*** = Without options which are rather a subject for the next update of strategic planning, like a new metro branch in Thessaloniki, or building train stations in residential areas in Plymouth.

= Also without road retrofit actions responding to decreasing car-kms and attempting to minimize rebound road traffic.

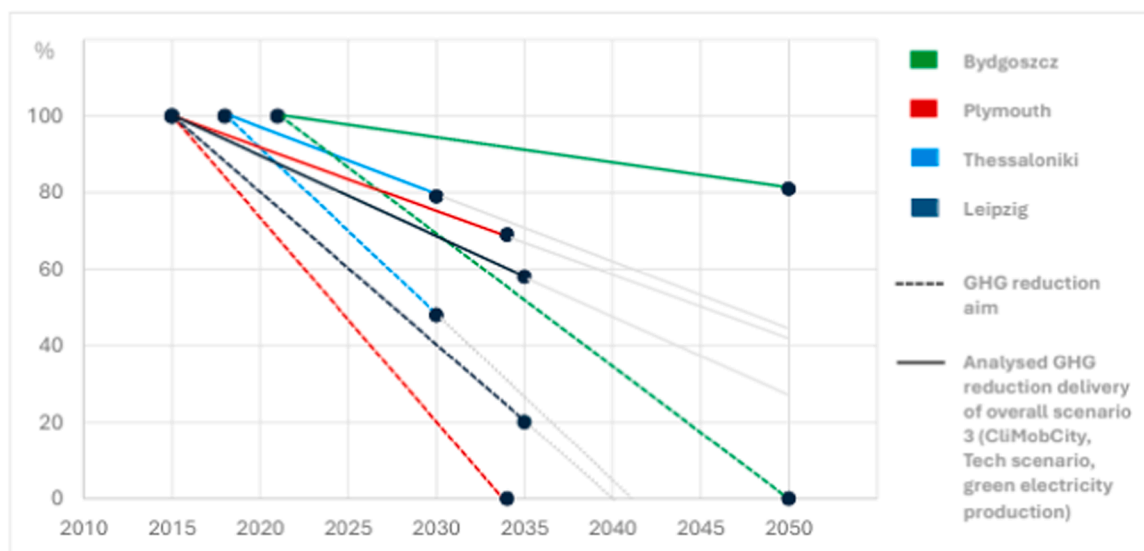


Fig. 19. Overview of GHG reductions of the partner cities in OS 3 (CliiMobCity, Tech, green electricity production).

emission zones by municipalities. Functionally,²⁷ the municipality can initiate such cooperation. The barrier of comparatively high purchasing prices of electric freight vehicles (Müller, 2024)²⁸ is less a problem, if 1) all operators are (obliged to be) involved, and 2) given the fact that electric operations can already be commercially competitive: "...battery electric trucks that ... drive a daily distance of only 200 km are" said to be "cheaper to own and operate than diesel trucks" (Transport and Environment, 2024). The co-development of consistent vehicle replacement and gradual development of city-wide zero-emission zones may result in more commitment from the logistic sector towards GHG reduction than if only zero-emission zones are implemented. The GHG reduction speed would, if started soon, go beyond that of the EC Green deal policies of stronger GHG emissions standards for all new HDVs.

Parallel to the electrification etc., pilots could be organised to test bundling options as proposed in literature.

The share of electric etc. cars in many European countries still is around the 5–10 % in 2023 (Eurostat, 2025). On the other side there is Norway with a share of EVs of almost 30 %. Both percentages tell a story. That of the 5–10 % is about limited action radius of BEVs, an insufficient density of charging points, long charging times, and high purchasing costs of BEVs. The story of the 30 % is a country's policy providing "several types of subsidies and privileges (exemption from VAT and excise tax on cars, free parking, free charging, exemption from tolls, right to use the bus lanes)" (Hagem et al., 2023, p2). The authors report more than 3.000 fast- and superchargers in Norway in 2020, and that the government has subsidised 40 % of the costs of part of the fast chargers outside of the city. A factor partly explaining the difference between Norway, Germany/UK and Poland/Greece is the GDP/capita.

This outline suggests that **car electrification** in the four partner cities can be accelerated if either the national policies adjust towards the Norwegian level of support, or if BEVs themselves become more attractive. The first seems rather unlikely, given the GDP differences and current policy priorities in practice. The second could in the next decade change quickly. This is based on announcements of leading car producers who, as it seems, are about to launch a new generation of BEVs having an extended action radius (like 800 km) (e.g. Demling et al., 2025) which in combination with a denser network of fast charging points (several minutes only) should provide a performance an attractiveness leap.

Other potential common measure types of the four cities to cover the GHG gap are: the implementation of new combinations of P + R, PT, car-pooling shared mobility, active travel, and/or awareness raising measures.

Additional measures to reduce road vehicle-kms and envisaged **only by 1–3 partner cities** include selective urbanisation in favour of shorter trip distances or modal shift, reduce capacity and attractiveness of roads, redistribute public space at the dispense of roads, reduce maximal speed on roads and traffic management, reduce PT fares, introduce on demand PT services in low density areas attached to PT lines, make parking regulation privilege electric etc. vehicles more (e.g. introduce free residents' parking permits for ZEVs), convert local rail lines to post-fossil fuel powered ones, replace local ferries by electric ones, implement V2G networks, replace fossil fuel by post-fossil fuel busses, and develop licensing policy to incentivise transition to EV taxis.

²⁷ Not necessarily also legally, this being different per country, and perhaps demanding background measures on the national legislation.

²⁸ Mentioned as a main barrier by companies busy with road transport (Cartolano et al., 2022).

5. Novel types of mobility ²⁹

5.1. Policy hype with unknown impacts

Novel types of mobility have entered the stage. These are new modes like scooters or electric bicycles, and new services like shared cars or bicycles. Their emergence is partly accompanied by the implementation of new node types like mobility hubs. The novelties have become a spearhead of current (strategic) mobility policies, as witnessed by strategic mobility plans of cities throughout the world, including the four partner cities, although little is known about their adoption and impacts. The expectation of cities is that the novelties will increase the sustainability of mobility. Experts initially expected large market shares, like McKinsey according to CROW (De Kievit et al., 2020) that in Munich in 2030 8–10 % of all passenger trips would go by micromobility, and in a more ambitious scenario even 15 %. The Dutch government expected the number of shared cars to become more than a 6-fold between 2015 and 2018 (Nijland and Meerkerk, 2017). Also optimistic was the outcome of a survey of the Dutch national Knowledge Institute on Mobility KIM (Jorritsma et al., 2015) amongst Dutch residents of 18 years or older and having a driver's license, pointing out that 20 % would be willing to sell a private car in return for becoming users of the novelties. In a follow-up survey (Jorritsma et al., 2021) this was only 2 %. One factor for too optimistic expectations was drawing general conclusions from early adopter behaviour, as already concluded earlier by Nijland et al. (2015).

An analysis of shared car mobility in 80 German cities on the basis of the national mobility panel revealed that in 2013 2 % of respondents were car sharing members. In 2017 this was 4.5 % (Göddeke et al., 2022). The use is of course less than membership suggests.

The general picture is that the hype at the beginning of this policy wave was followed by implementation on niche market level. However, the market is slowly growing.

5.2. New research question in the project

The potential of the novel mobility types is difficult to test by means of the cities' macroscopic transport models. This background in the project led to the **question how much additional GHG reduction the novel mobility types might provide, on the short to long term**. A brief literature review was conducted to answer the question, the findings being presented below. Our review is limited to studies about European cities, as the city characteristics and mobility patterns are quite different on other continents, like between Europe and North America (Fearley et al., 2020). Our review is also limited to private electric bicycles, shared (electric) cars, shared (electric) bicycles, shared e-scooters and shared e-mopeds, and mobility hubs. But also amongst the novel types which we do envisage, there still is quite some uncertainty because "shared e-mobility systems are still in its infancy period in most places" and "research on micromobility is still in its nascent stage" (Liao & Correia, 2022), "... there is a lack of a wide academic literature about shared e-scooters" (Badia & Jenelius, 2021), and "shared micro-mobility services are rapidly expanding yet little is known about travel behaviour" (Reck et al., 2022). Being a nascent mobility type, the technical state and performances are improving quickly (ITF, 2024), which contributes to the instability of findings. In general, the performances of novel mobility types are not yet thoroughly evaluated (D'Almeida et al., 2021) in policy making or research.

5.3. Potential performance improvements

From the viewpoint of environmental sustainability, the **main performance changes** achieved or strived for when developing novel

²⁹ Responding to RQ 10.

mobility types and mobility hubs are the **reduction of private and total car-kms and of the number of private and total cars in circulation**. As for traditional modes, less car-kms implies less GHG emissions and road surface required, and fewer cars in circulation less surface for parking. The reduced space demand supports the concept of the compact city with shorter travel distances and higher shares of sustainable modes. Shared cars next to generating less car-kms emit less GHG than private cars because they are replaced faster, hence averagely are newer and more energy-efficient, and because shared cars accelerating car electrification.

5.4. Replacement of car-kms and other shift to novel types of mobility

Starting with the first performance improvement, the reduction of car-kms was found to take place when travellers start using **shared cars** (Nijland & Meerkerk, 2017 [Netherlands]; Pfortner, 2017 [Würzburg, Germany]), **private electric bicycles** (Kämper et al., 2014 [four German city-regions: München, Frankfurt/Main, Hannover-Braunschweig, Bremen-Oldenburg]; Hiselius & Svensson, 2017 [Sweden, distinguishing cities and rural area]), **shared bicycles** (Fishman et al., 2014 [four city-regions in USA, Australia, one in the UK, namely London]; Munkácsy & Monzón, 2017 [Madrid], Ma et al., 2020 [Delft, Netherlands]; D'Almeida et al., 2021 [Edinburgh, Scotland]), **shared electric bicycles and shared electric scooters** (Liao and Correia, 2020 [cities in Europa, North America and Asia]; Krauss et al., 2022 [Paris, Stockholm, Berlin, Düsseldorf, one in Australia and one in the USA]; Faber, 2021 [shared e-scooters in Rotterdam]; Weschke et al., 2022 [shared e-scooters in Germany]; Fearnley et al., 2020 [shared e-scooters in Oslo]). The shift from **private to shared car** reduces **total car-kms** as the shared car is used less than the private car.

The replacement amounts differ per mode. In many studies, more users of shared vehicles originate from PT, bicycling or walking than from the private car (same authors as above). Given the magnitudes involved, some publications even speak of cannibalisation of PT or conventional bicycling. The shift from PT can eventually lead to a drop of service frequencies or even the abolishment of PT lines. D'Almeida et al. (2021), referring to former research, underlines that the “degree to which any resulting fall in PT demand translates into reduced PT supply is crucial to calculating” GHG emissions of shared bicycle systems, “but there is very little literature on this topic”. The Dutch conventional bicycle sharing system “OV-fiets” (PT bike), introduced by the Dutch railways to improve the mobility from and to trains, led to the following shifts: 34 % of OV-fiets users go less by car, and 60 % less by bus and tram. 17 % use the train more often (Ma et al., 2020). Weschke et al. (2022; p15) conclude that the e-scooter next to reducing car use “substitutes PT trips” but, “when supplied outside city centers with good PT accessibility, it works as a feeder and last mile” for PT use. Shared services in Würzburg on the one side replace PT (18 % of Nextbike users originate from there; 50 % of car sharing customers at the new hubs have been bus and tram users before) while PT is also reported to be used as access and egress mode to Nextbike (18 % egress, 27 % access) and to shared cars (16 %) (Pfortner, 2017). In Dublin the shared bicycle has reduced car use, walking and PT mobility as main mode, but “is playing a very important role in trip chaining between the various forms of public transport” (Murphy & Usher, 2015). Fearnley et al. (2020) conclude that most shared e-scooter users would otherwise use PT, and also that a “considerable share of ... e-scooter trips are in fact made in combination with different PT modes (metro, bus, train and tram).”

5.5. GHG emissions

From the mode substitution patterns in combination with travel distances and GHG emission factors the change of GHG emissions can be derived. As far as the **use** of vehicles is concerned including energy/electricity production (hence envisaging scope 1 and 2 emissions) the main pattern is, that the novel mobility types reduce GHG reductions

because of fewer car-kms and despite of the shift from more sustainable modes, like from PT and active travel to the shared car, or from the conventional bicycle and walking to the private or shared electric bicycle or scooter.

For the shift to private electric bicycles or from the private car to the shared car this is the main line. For the shift to shared micromobility there is more at stake, as shared bicycles and scooters tend to have relative short lifetimes, not because of intensive use, but because of bad treatment by users and loss. This implies that their lifespan mileages are much smaller and therefore lifecycle GHG emissions per passenger-km higher than of many mobility alternatives (Hollingworth et al., 2019; De Bortoli, 2021; D'Almeida et al., 2021; Reck et al., 2022; Weschke et al., 2022). Lifecycle emissions are scope 1 + 2 + 3 GHG emissions and are analysed by means of lifecycle analyses (LCAs). Scope 3 describes the emissions from the production, maintenance and end-of-life processes of vehicles and – optionally – also infrastructure. Most studies regarding (shared) micromobility therefore analyse GHG emissions on the LCA level.

A general observation (on the basis of Kämper et al., 2016; Krauss et al., 2022; De Bortoli, 2021; Reck et al., 2022, ITF, 2024) is that the ranking of modes according to their GHG emissions is largely the same for use (scope 1 +2) or LCA (scope 1 +2 +3) approaches if the comparison refers to private vehicles, but is different for shared micromobility. On the use level the shared e-bike is climate-friendlier than metro/urban rail, on the LCA level the shared e-scooter was analysed to have larger emissions than the private BEV car; and the shared e-bike higher than metro/urban rail.

Regarding specific types of novel mobility, we start with the **shift to private electric bicycles**. In Sweden, each person starting to use one is analysed to change GHG emissions by –14 % in cities and –20 % in the rural area, compared to the average emission of the Swedish mobility system (Hiselius & Svensson, 2017). The authors don't relate the share of this user group to the total of Swedish mobility. The authors only indicate the share of electric bicycles amongst all bicycles bought in a certain period, being 1.3 %. From other sources the share can roughly be sensed: Sweden for e-bikes belongs to the 6 leading countries in Europe, for which the trip share of conventional bicycles for trips below 50 km was almost 30 % and of electric bicycles 1.8 % in 2015, and forecasted to be respectively 35 % or up to 4.5 % in 2050 (Astegiano et al., 2019).³⁰ The same paper shows average GHG emissions for all 28 European countries and found that an increase of the e-bicycle trip share from 1 % (2015) to 2.9 % (2050) changes mobility related GHG emissions by –1.5 %.

For the shift to shared electric micromobility, three of the consulted papers distinguish use from other LCA emissions, i.e. D'Almeida et al. (2021), De Bortoli. (2021), and Krauss et al. (2022). However, only the first paper allows to derive total reductions on the scope 1 and 2 level. The paper of Krauss et al. (2022) allows comparison of scope 1 and 2 emissions *per passenger-km* between modes, but not of all passenger-kms, hence not expressing the consequences of modal shift.

D'Almeida et al. (2021) analysed GHG emissions of a new **shared bicycle** system in Edinburgh. These emitted 195.000 t of GHG (scope 1–3) of which 49 % are “use” (scope 1 and 2) emissions.³¹ The GHG savings due to modal shift were 4.300 t,³² of which about 25 %³³ were use emissions. The change of use emissions was then about –1 % (calculated by authors) and slightly more when optimising the re-balancing of bicycles. Concluding, the shared bike system changed the use emissions per user by –1 % and of the total mobility system in the city by much less.

³⁰ Total is bike, e-bicycle, car and PT.

³¹ Excluding GHG emissions of human activities, which belonged to the centre of the paper's analysis.

³² Again excluding GHG from human activities.

³³ From Fig. 2 of the source.

Krauss et al. (2022) on the way to analysing LCA GHG emissions of changing mobility in Berlin, Düsseldorf, Paris and Stockholm³⁴ also present use, servicing (e.g. repositioning), vehicle, and infrastructure emissions per passenger-km. The first two together represent scope 1 and 2 GHG emissions, the latter two scope 3 ones. The scope 1 and 2 GHG emissions per passenger-km show large differences between the modes. Comparing the emissions per passenger-km, the unweighted averages of the four cities are - with **shared e-bicycle set to 100** - private bicycle 0, private e-bicycle 12, metro/urban rail 52, shared bicycle 88, shared e-scooter 109, bus/shuttle 268, private ICE car 476 and taxi/ride-hailing 740. Although the ratio differs per city (Fig. 20) the rough picture is similar for the four cities.

In a study about the use of **shared cars** in the Netherlands (Nijland & Meerkkerk, 2017) the net change of GHG emissions was analysed to be -5 % **per user** compared to the situation before joining car sharing. This is the net result of -13 % GHG emissions due to fewer car-kms and + 8 % because of shift from PT and active travel to the shared car (percentages by authors). The reduction compared to GHG change of all travellers is a fraction of this because of the low share of car sharing in passenger mobility. Only if **all** travellers in the country would use shared cars and the same conditions apply, would the total GHG emission change by -5 %, or more if the shared cars were electric ones.

In Würzburg, Germany, the 1200 shared car users at the 9 new mobility stations together change GHG emissions by about -1 %. The savings represent about 1 % of local mobility emissions (Pfertner, 2017) being the net result of -97 % GHG due to the reduction of car-kms, -1 % GHG because of a higher efficiency of shared vehicles, and + 5 % GHG deriving from modal shift from PT and active travel to the shared car (percentages by authors).

For shared mobility the **vehicle drop-off models** are relevant for GHG emissions. In principle one can distinguish the so-called station based back-to-one concept, station based back-to-many concept, and the free-floating concept. The last two, in which the user doesn't need to return the vehicle to the starting point, may cause spatial imbalances which eventually require **rebalancing** of the vehicles. All three drop-off concepts exist for any shared vehicle concept. The needed repositioning efforts can be substantial, and if carried out employing fossil-fuel vehicles lead to substantial GHG emissions. These are scope 1 emissions. An extreme example is London where 1 km of shared bicycle use was accompanied by 2.2 km of repositioning by fossil fuel vans (Fishman et al., 2014). The repositioning operations of shared bicycles in Edinburgh "are currently so poorly optimized that they could be improved by 30 %" (D'Almeida et al., 2021). The GHG emissions of servicing in the mentioned study of Krauss et al., 2022, only present in shared vehicle systems, are a fourfold or more of the use emissions (own calculations on the basis of Table 3 in Appendix A.2). Such proportions are confirmed by ITF (2024) for shared micromobility taking place around 2020. The study, however, claims that repositioning emissions have declined substantially, in 2024 hardly exceeding use emissions. The repositioning emissions can be reduced by defining return zones in a city for free-floating vehicles, by bundling repositioning operations, or by pricing policies (e.g. reward for bicycle return on the top of hills) or by using electric vehicles for repositioning (De Bortoli, 2021).

5.6. Discussion and preliminary conclusion

Responding to research question 10, we observe two issues dominating the discussion whether novel types of mobility may significantly reduce GHG emissions beyond the levels analysed in the demonstrations studies. One is the GHG level per passenger-km, the other the share of novel in all mobility. Regarding the first, private e-bikes and e-scooters score positively, having no repositioning emissions and - actually exceeding the scope of this paper - no increased scope 3 emissions

because of bad treatment and therefore short vehicle lifetimes. Their overlap with cars regarding trip distances is promising for GHG reduction. The GHG reduction of shared e-bikes and e-scooters can - dependent on the business model - easily be absorbed by relative high repositioning and scope 3 emissions. The latter - again - lie outside of this paper's scope, but they are present and tend to change the sustainability ranking of modes, contrary to when scope 3 emissions are included in comparisons of private or public transport modes. Imagining that scenarios of improved business models including improved use behaviour supporting GHG reduction yield some truth, research up to now seems to provide little tangible confirmation. Different studies for shared micromobility recommend behavioural and management measures to extend vehicle lifetimes (hence lower scope 3 emissions) and to reduce repositioning (scope 1 and 2) emissions. ITF (2024) claims that operational (repositioning) emissions of micromobility already have declined in the short period of 2020-2024 by 50% or more and that also vehicle improvement has reduced use and scope 3 emissions. But "only improving the lifespan will not make micromobility less emitting than e-public transportation in Paris" (De Bortoli et al. 2021, Section 4.3). Station-based shared bicycles and cars have little repositioning emissions, shared cars, whether station based or not, seem to have less hinder of bad treatment and shorter lifetimes, indicating that these novel mobility types could increase GHG reduction of mobility in cities.

The second issue, namely the market penetration of novel mobility, is perhaps a larger burden. Wherever there are promising indications or potential GHG reduction by shift to novel mobility, the total reduction nevertheless tends to be very small, as the market shares of novel mobility types are small. Change is imaginable, surely for longer time periods as up to 2050. Nansubuga and Kowalkowski (2020) in their literature review about car sharing underline the need to respond better to customer needs, e.g. improving convenience of access and vehicle availability. Liao et al. (2020, p966) argue that "because our study shows that young people are more than average inclined to become users of" car sharing "... systems, such systems may lead to postponed car ownership, or even to an overall reduction of the desirability of owning a car." Göddeke et al. (2022) underline that a density increase of shared car supply in the city (pull) is not sufficient for reducing private car ownership, but that private car costs need to be increased (push). This old argument to support PT and other sustainable modes now also seems to apply for novel types of mobility. Coenegrachts et al. (2024) in their analysis of shared mobility in 300 cities of city clusters with specific operator profiles conclude that the shared mobility market is well established in Europe, but "still a difficult market in which to operate a profitable service" and that the "... most comprehensive provision of shared mobility is found in the largest cities across Europe ...". Adoption "is influenced by population density ..., parking pressure" and PT properties. The presence of more types and schemes of shared services is beneficial, as they would strengthen each other.

We launch the preliminary conclusion that the novel mobility types are an opportunity to make urban mobility more climate-friendly as they appeal to people hesitating or not willing to walk, use the conventional bicycle or move by PT, and because the distance ranges to some extent overlap with the private car. However, up to now the contributions in terms of reduction of car-kms and reduction of car ownership are very limited, rather representing niche than mainstream markets. Novel mobility types are widespread in medium and larger European towns, but still face reservation or barriers towards becoming mainstream configurations. At some places like Paris the dock and shared bicycle investments already have mainstream proportions, the city density is a favourable urbanistic condition, and we have to observe whether the adoption of the offer follows that scale, whether the combination of management and hybrid dock-based leads to improved bicycle lifespans, and to which extent all together including external cost savings justifies the large efforts. For the nearer future, as addressed by Plymouth, Thessaloniki and Leipzig, there seems to be no reason to expect substantial supplements of GHG reduction to the results of the

³⁴ And two non-European cities.

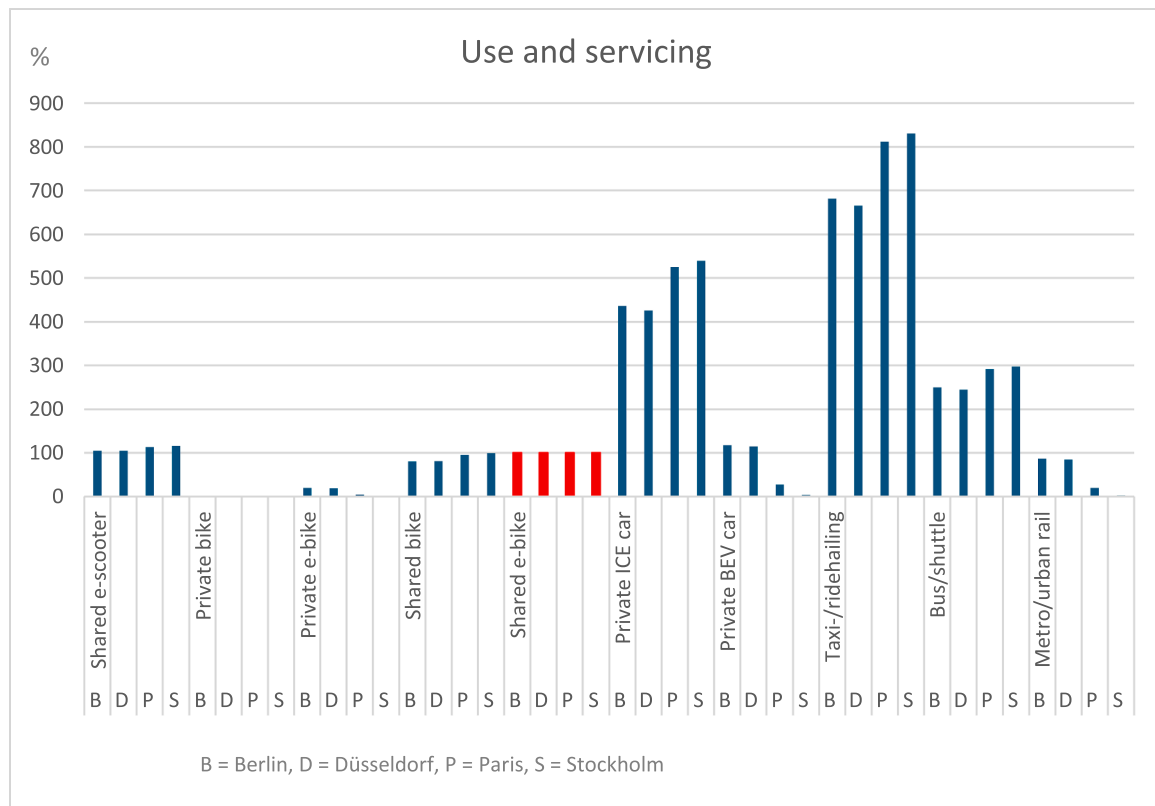


Fig. 20. Relative size (%) of scope 1 and 2 GHG emissions per passenger-km of alternative modes (shared e-bicycle = 100 %) Source: own presentation on the basis of Krauss et al., 2022, Table 3 in Appendix A.2.

demonstration studies because of these novel types of mobility.

6. Main conclusions, transferability, contributions and discussion³⁵

6.1. Main conclusions and transferability

In this subsection we present main conclusions drawn from the findings of the case studies and the literature review, and where appropriate, add a remark about the transferability of the conclusion to other cities. Transferability was already a subject in the project, as this is mainly what the interregional learning is about. We here extend the transferability to other cities. The transferability statements represent expert estimations of the researchers in the project.

GHG conclusions and transferability

- 1) The demonstration studies show that **the partner cities have difficulties to respond to their GHG reduction aims**. Even if electricity production is completely green, there is a gap remaining between aim and analysed delivery of GHG reduction of at least 68 %/55 %/28 %/30 % (resp. Bydgoszcz/Plymouth/Thessaloniki/Leipzig; see line 11 in Table 11), the case of Plymouth not being completely comparable with the other three cities. Closing the gap is very challenging. Given the big differences between the partner cities, this conclusion seems transferable to many other European cities.
- 2) On the basis of current knowledge – this is from Section 5 and from Thessaloniki's quantification of impacts of shared car use – we also conclude that the GHG gap is unlikely to shrink much because of **shared mobility or novel micromobility**, at least not

in Plymouth, Thessaloniki and Leipzig, given their closer planning horizons. With continued technological progress, operational/managerial improvement and supportive policies, these innovations may hold promising potential for greater impact in the longer term. This conclusion will also apply for many other European cities.

- 3) A major medium-term opportunity to achieve further GHG reduction in substantial amounts is to develop effective policies for **urban freight**. The centre of further actions would be coordinated push and pull measures of municipalities together with logistic operators to **accelerate regional freight vehicle electrification**. This is to be accompanied by a consistent gradual development of a city-wide zero-emission zone for freight vehicles. The principal idea is to waste no time in the greening of the vehicle fleet (see last subsection in Section 4.7) which in practice may nevertheless be challenging because of national legislation and the willingness of firms to cooperate. The freight electrification efforts require consistent planning and cooperation work, but seem achievable, and there aren't many valid hindrances for pursuing these efforts. Furthermore, a wider uptake of cargo bicycles in urban last-mile deliveries can also contribute to mitigation of freight traffic carbon footprint, especially in congested city centres. The need to pay more attention to urban freight (Section 4.7) and the idea of coordinated actions to accelerate freight vehicle electrification to substantially reduce GHG within a medium term seem promising, although requiring some challenging preparatory work. This looks transferable to many other European cities.
- 4) As long as the market share of the BEV is small because of unsatisfactory performance (see again last subsection in Section 4.7) an **acceleration of car electrification** etc. by municipal actions is difficult. Whenever the BEV performances become satisfactory, and that could be soon within the coming decade, acceleration

³⁵ Responding to RQ 9 and 11.

comes into reach. Such a development may already provide certain benefits regarding additional GHG reduction in Plymouth, Thessaloniki and Leipzig. Yet, because of the limited length of their planning time windows benefits could be rather limited. The cities could nevertheless prepare the expectable acceleration of car electrification by already expanding the network of fast charging points to avoid these becoming a bottleneck for future electrification. For Bydgoszcz with its longer-term planning period, the increasing attractiveness of the BEV could substantially elevate the post-fossil fuel cars shares to levels (far) beyond current expectations (e.g. Tech scenario). Then, the additional GHG reduction would be substantial as well. The expectation of some additional GHG reduction in shorter planning periods and large ones for longer periods, all in comparison to existing projections for future electrification etc., seems to be transferable also to other European cities.

- 5) Whether acceleration of electrification etc. from the viewpoint of GHG reduction makes sense or not, also depends on the **energy mix of electricity production**. Where the fossil fuel share of electricity production still is high, like in Bydgoszcz/Poland, and hence where electricity production still emits much (scope 2) GHG, an accelerated electrification is likely to first unfold its mitigating potential relatively late, compared to where electricity production already is relatively green, like in Plymouth/UK. In this regard, again only from the GHG viewpoint, acceleration of electrification makes less sense in Bydgoszcz than in Plymouth. A similar argumentation is possible for hydrogen production, which in the study of this paper was pragmatically regarded to be green from the very beginning. This more technical conclusion about physical interactions and their potential meaning for policy making is certainly transferable to other cities.
- 6) In each of the four cities there is a larger number of imaginable **smaller mobility measures** for further reduction of car-kms and GHG emissions, like different PT (pull), car (push or efficiency), and land use measures (see again last subsection in Section 4.7). Together with cooperatively (i.e. municipality and logistic sector) organising the effective GHG reduction of urban freight, and with minor acceleration of car electrification in the cities with short reduction time windows and its larger acceleration in Bydgoszcz with its larger time window, **the GHG gap would shrink far below the levels of OS 7, but – with reference to the few backcasting exercises – probably not close the gap**. This conclusion, already referring to a quite heterogeneous range of cities in this study, could plausibly also refer to many other European cities.
- 7) Furthermore, there are some **large projects** in sight or imaginable which, however, given their long preparation times, are not suitable to reduce the existing GHG gap in Bydgoszcz, Plymouth and Thessaloniki, but rather to reduce GHG emissions in the following strategic planning period. Examples of such measures are the following tranches of the Thessaloniki metro, some tangential PT connections in Leipzig, train station building in residential areas in Plymouth (already envisaged as exploration theme in BAU), or further densification in central brownfield locations and/or around train stations (all four cities).
- 8) To boost GHG reduction, mobility behaviour must change, like more travellers choosing sustainable modes, other times to travel, travelling less or joining carpooling. Behaviour can change due to improved transport performances, but also by changing the mindsets of travellers and lifestyle habits. Both can be mobilised by **awareness raising** including incentivising, and by **real time mobility advising**. Such signals come from Plymouth's awareness raising platform Plymotion and the Thessaloniki Smart Mobility Living Lab (ThessM@LL). It has been shown that awareness raising changes mobility behaviour of those people reached, but the reach is limited and could/should be expanded

by increasing municipal awareness raising efforts. This still rather general conclusion is transferable to other European cities.

Mobility performance conclusions and transferability

- 9) **Car-kms** in Thessaloniki change by -18% , in Leipzig by -8% . Both changes take place in a rather short period (to 2030 and 2030/35 resp.).
 - a. Thessaloniki: the reduction is mainly due to **modal shift to PT and walking**, and also to **shorter travel distance of car** (PT distance becomes longer). The base-year PT share is already high, predominantly comprising bus travel. The reduction of car-kms and decrease of car share represent a top performance in the range of what can be shifted in one strategic planning cycle. We consider the transferability of such magnitude to be small, only to cities with comparable urban density and which also shift directly from bus to metro etc. Notwithstanding, comparable magnitudes have been forecasted to emerge also in less dense cities in case they envisage packages containing powerful push and pull measure combinations (see Section 3.2).
 - b. Leipzig: the reduction is due to **modal shift to PT and bicycle**. The PT share is already high in the base year, although less than in Thessaloniki, and also refers to other PT than bus travel. We consider the magnitude to be transferable to cities with comparable urban, PT and bicycling conditions, of which there are many.
- 10) The big car-km reduction in Thessaloniki and the limitation of car-km increase in Bydgoszcz are also due to convincing combinations of **pull and push measures** present in their packages:
 - c. In both cities there is push in the central city area by narrowing roads and reassigning public space at the dispense of road traffic, suitable to give space to sustainable modes while also combating rebound road traffic.
 - d. In Bydgoszcz there is push in comparison to BAU by cancelling new main road links (package W2), which become superfluous without expansion of sprawl development. And there is pull in comparison to BAU by re-urbanising in central brownfield locations at the dispense of growth of peripheral greenfield locations. Therefore the average trip distance increases less than in BAU.

All of this seems transferable to other European cities.
- 11) Despite of the success of push and pull measures in Bydgoszcz, the city and also Plymouth witness increasing car-kms, although much less in CliMobCity than in BAU, meaning that their GHG reduction depends on car-electrification etc. This from the viewpoint of space demand (bullet 12) and especially of the benefits of parallel mitigation strategies (bullet 13) is suboptimal. Even stronger push and pull city (shorter distances) and mobility (modal shift, higher vehicle occupation) are actually required. Such conclusions apply also for other European cities with increasing car-kms.
- 12) Car-km development has a double effect, as it influences GHG emissions as well as **space requirement of mobility**. In the Thessaloniki and Leipzig analyses both decline, in Bydgoszcz and Plymouth both increase. On the basis of conceptual structuring, in case of declining space demand the city remains or becomes more compact, due to which travel distances are or become shorter and more people opt for active travel and PT, implying further GHG reduction. In case of space demand increase, the amplifying effect works in the opposite direction. This pattern of interaction is transferable to any city, although the quantitative relation between car-km and space requirement will differ per city.

Strategic planning of climate-friendly mobility in cities and transferability

- 1) Cities should develop **parallel strategies** to reduce the GHG instead of focussing mainly on only one: for instance, plan changing mobility parallel to facilitating vehicle electrification parallel to changing land use. The mix is likely to provide faster GHG reduction. The reasoning is that – given financing and technological barriers – the choice is not little of many strategies versus much of one strategy, but much of many strategies versus much of one strategy. A broad focus is also likely to increase political and societal commitment as it appeals to more directions of taste (e.g. mobility preferences) of residents, other stakeholders and politicians. This conclusion seems transferable to all European cities.
- 2) The GHG gap gives reason to question **whether the measure packages could have been more fundamental and powerful**. The reasonable answer is that the measure packages, not neglecting differences between cities, already are quite powerful. The insufficient performance change nevertheless suggests that even more is needed. This leads us to another level of argumentation, namely that of involved planning frameworks. A few examples of framework issues: More ambition solely on the municipal level is difficult because of missing financing (from the [inter]national level) including lack of staff size, lack of readiness of new technology (like batteries), lack of capability to innovate (part of the car producers), lack of willingness to change lifestyle and mobility behaviour (part of the residents and organisations) and/or lack of awareness of stakeholders towards climate mitigation. All barriers may change in multi-level and -sectoral approaches and on the basis of significantly increasing awareness raising efforts. Municipalities can play an important role in these processes, but not be the only actor. For planning and research in search for a good balance between expected fundamental and realistic change, the challenge partly consists of estimating how future conditions might change allowing behavioural, technological, economical or governmental configurations to become realistic, while they under present conditions are not. This conclusion seems transferable to many European cities and to research dealing with climate mitigation or other societal transitions.
- 3) The research in this paper was already at its start structured and then in the run of the research adjusted in ways that respond to initial and later emerging research questions. In a **reflective conversation with the situation** one can benefit from existing theorems about city, mobility and GHG emissions, and from employing existing methods, like our models, while always anticipating on their limitations and searching for other approaches and methods to find answers. This conclusion seems transferable to other research dealing with climate mitigation or other societal transitions.

6.2. Contributions

The **central contribution** to academic research consists of adding **four new cases** to the knowledge building of climate oriented strategic mobility (and city) planning. For none of the four municipalities had there before been analyses of how mobility and GHG might change by means of more ambitious measure packages. These cases yield a wide range of **transferable analytical evidence** for understanding the effectivity and prospects of climate impact mitigation policies related to transport and mobility in European cities.

We consider an **experiment** within the case of Bydgoszcz to be a separate contribution, namely exploring the impact of **changing mobility preferences** on the mode choice of travellers. There is theory development in this field, but without empirical testing. This is a valid analytical contribution, albeit from methodological perspective this represents a sensitivity analysis.

For developing measure packages relevant for GHG reduction of mobility in cities, we structured the relation between the components of GHG reduction, the types of mobility and technical “main performance” changes needed to influence the components, and the main and supporting measures suitable to change main performances. We call this

structuring, which also entails interactions with land use developments, a **checklist**. Some elements of the checklist have been published before. We consider our comprehensive integrative structuring to be a contribution to research and also helpful for practitioners.

Finally, we conducted a limited **literature study** to find out whether substantial additional GHG reduction may be expected from **novel types of mobility**, as shared or electric micromobility, because the macroscopic transport models can't deal with these innovations, while they are often considered to be game changers.

6.3. Conclusions to improve this study and recommendations for further research

Should this type of research be conducted another time, we would introduce the following improvements:

- 1) Show the change of GHG emissions due to changing mobility separately from the change due to electrification etc. and a changing energy mix for electricity production.
- 2) All partner cities dispose over a four-step multimodal macroscopic transport model to capture the granularity of a city structure, and to predict the changing choices of travellers regarding alternative travel options dependent on the comparative attractiveness of alternatives, as well as impacts on transport performance of land-use changes.
- 3) In case of preceding transport modelling, the carbon model should alter one of its central inputs from time spent (i.e. vehicle hours) to distance travelled (i.e. vehicle-kms), as this is easier to interpret.

Recommendations for further research deriving from this study are as follows:

- 1) Conduct systematic overview of magnitudes of climate-relevant performances and how they change by mobility, technical and city measures; performances as car share, passenger-kms by car, car-kms, distance of car trips, comparable information regarding other modes, and GHG emissions (scope 1, 2 and 3 separately), distinguishing the municipal area of a city and the region around it.
- 2) Conduct systematic research on distributional impact of measures in climate (mobility) transition and how to organise – with regard to income and taking account of enlarged managerial possibilities due to ICT – fair and inclusive change.
- 3) Conduct research capturing the land saving benefits of reduced parking demand by shared mobility uptake for GHG reduction.
- 4) Conduct systematic research on national legislation in European countries and municipal competences regarding innovative types of GHG reducing measures, and how legislation could be adjusted.
- 5) Conduct research connecting the conceptual work on mobility preferences with exploring magnitudes of mobility change by changing preference related parameters in macroscopic transport models would expectantly improve understanding about how to improve awareness raising policies.
- 6) Regarding other research needs, is it not time for EEA to start providing separate data for the municipal level?

As the literature basis for these recommendations was limited, we consider the recommendations to be hypotheses.

Abbreviations of municipalities in the References

MoB = Municipality of Bydgoszcz
 MoP = Municipality of Plymouth
 MoT = Municipality of Thessaloniki
 MoL = Municipality of Leipzig

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CRedit authorship contribution statement

Kreutzberger Ekki: Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Van Binsbergen Arjan:** Writing – review & editing, Visualization, Validation, Methodology, Data curation, Conceptualization. **Reitemeyer Fabian:** Software, Methodology, Formal analysis, Data curation. **Torabi Kachousangi Fatemeh:** Writing – review & editing, Investigation. **Van Oort Niels:** Writing – review & editing, Investigation. **Arkadiusz Drabicki:** Writing – review & editing, Validation, Software, Methodology, Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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