# Report on energy efficiency potentials in the transport sector

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sEEnergies

QUANTIFICATION OF SYNERGIES BETWEEN ENERGY EFFICIENCY FIRST
PRINCIPLE AND RENEWABLE ENERGY SYSTEMS

# **D2.1** Report on energy efficiency potentials in the transport sector

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# Project

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# Executive Summary

The purpose of this report is to illuminate potentials for energy saving within the transportation sector in the EU/EFTA area through energy efficiency measures for bringing about a modal shift from energy-demanding to more energy-efficient modes of transportation and reducing the movement of persons and goods. Here, energy efficiency improvement denotes using less energy while maintaining the activities in society, i.e. 'producing the same level of welfare with less energy use'. Reduced transport volumes and a shift to less energy-requiring transportation modes can therefore be consistent with an efficiency approach, provided that the same level of welfare is maintained. The measures for energy efficiency improvements discussed in this report are urban spatial development, transport infrastructure development, and economic instruments for transportation demand management.

More than for many other sectors, the energy use within the transportation sector and the potentials for improved energy efficiency depend crucially on human motivations, attitudes, social networks or other conditions enabling or constraining their actions. The actual energy use and the potential energy efficiency improvements also vary substantially with geographical contexts, and for many of the measures for increased energy efficiency, the magnitude of potential savings is difficult to measure accurately. Add to this that the effects of relevant measures are unlikely to remain constant over time. The baseline trajectory against which an energy efficiency scenario is compared is also encumbered with great uncertainties.

Bearing these considerable uncertainties in mind, this report represents an attempt to estimate the energy efficiency potentials in the EU/EFTA area within the transportation sector through urban spatial development, transport infrastructure development, and economic instruments for transportation demand management, with 2050 as the time horizon. As discussed in Chapter 2, a scenario approach has been used for this purpose, where a consistent use of energy-efficient measures over the period 2020-2050 has been compared with a continuation of trends observed over the last couple of decades. In Chapter 3, we have reviewed the literature on energy efficient urban spatial development, transport infrastructure development and transportation demand measures and estimated present and future effect sizes of the most relevant ones, taking into consideration the different contexts of Northern Europe, Western and Central Europe, Southern Europe and Eastern Europe. The most promising measures for reducing transportation energy use while maintaining the activities in society are dense and concentrated urban development, replacement of motorway construction and airport expansions with surface transit improvements, and road pricing and flight taxes. Reflecting differences in the available knowledge, the report goes more in detail into the energy impacts of urban spatial development and a halt in motorway construction than for the other measures.

An analysis of past spatial development of urban regions in Europe is presented in Chapter 4. This insight has been used to produce a future baseline trajectory against which energy-efficient urban spatial development will be compared, as part of the comparison of an energy efficiency scenario with a business as usual scenario (Chapter 6). In addition, the actual urban spatial development trajectory over past decades has been used as a background for assessing hypothetical energy gains if a counterfactual, energy-efficient urban spatial development trajectory had instead been followed (Chapter 5).

In chapter 6, energy gains from a consistent pursuit of energy-efficient solutions within urban spatial development, transport infrastructure development, and economic instruments for transportation demand management have been estimated. Keeping vehicle technology improvements aside, our estimations suggest an average annual energy-saving potential of nearly 3000 PJ from applying energy-efficiency measures within these fields, corresponding to 22% of the total annual energy use for transportation in the EU/EFTA area in 2020. The uncertain nature of the estimate must be underlined, cf. above. Around 45% of the estimated energy efficiency potential (excluding vehicle technology improvements) is due to replacement of growth in air travel with growth in other public transport modes and replacement of corporeal business travel with virtual communication. About 25% of the energy efficiency potential is attributable to abstaining from construction of new and expanded motorways, which would otherwise induce a substantial amount of additional traffic resulting in increased energy consumption. Energy-efficient urban spatial development and economic transportation demand measures are estimated to contribute with around 15% each to the average annual energy efficiency potential.

Examples from seven major European cities where some of the envisaged energy efficiency measures have been implemented are show in Chapter 7. In addition, an appendix (A) provides a literature review of various technological options for more energy-efficiency vehicles.

# Contents

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# 1 Introduction

The title of this deliverable D2.1 is “Report on energy efficiency potentials in the transport sector” and provides in the sEEnergies project a key input for the upcoming work that will result in the deliverable D2.3 – “Report on energy efficiency potentials in the transport sector and conclusions from the developed scenarios”.

Norwegian University of Life Sciences (NMBU), work package leader of Work Package 2 and lead beneficiary of the deliverable, is responsible for submitting the deliverable, which has been produced in cooperation with Aalborg University (AAU). Petter Næss (NMBU) has written Chapters 1, 2, 3, 5, 6 and 8 and edited the report. Fitwi Wolday (NMBU) has written most of Chapter 4 and has compiled Appendices B, C and D. Morten Elle (AAU) has written Chapter 7. Hamza Abid, Mikkel Strunge Kany and Brian Vad Mathiesen (all AAU) have written Appendix A.

## 1.1 Objective

The original objective of this deliverable was to assess energy efficiency potentials in the transportation sector by analyzing three main strategies for lowering energy use within this sector: (1) making each separate mode of transportation more energy-efficient; (2) modal shift from energy-demanding to more energy-efficient modes of transportation; and (3) reducing the movement of persons and goods (Grant Agreement of the sEEnergies project, Annex 1, pp. 15-16). This objective is identical to the main objective of the sEEnergies project Work Package 2, which also has two additional objectives not addressed in this deliverable (Grant Agreement of the sEEnergies project, Annex 1, p. 14). The strategies correspond to three of the four main measures to promote sustainable mobility emphasized by Banister (2008) in his seminal article on the sustainable mobility paradigm.

During the first year of work on the sEEnergies project, it turned out that an estimation of the energy efficiency potential by making each separate mode of transportation more energy-efficient could not be done within the deadline of the present deliverable report. The objective regarding assessment of energy efficiency potentials has therefore been adjusted to encompass only the above-mentioned strategies (2) and (3), whereas the objective regarding each separate mode of transportation has been changed to the provision of a literature review of various technological options for such energy efficiency improvements.

## 1.2 Scope

Figure 1.1 shows the main measures and effects addressed in this report. Energy use for transportation is determined by the transport volume (i.e. the distance that persons and goods is transported) and the energy used to transport persons and goods a given distance. The latter depends on the modes of transportation chosen (for example, metros use less energy to transport a person a kilometer than private cars do) and the energy efficiency of each mode of transportation. Transport volumes and the proportions of transport carried out by different modes of transportation are influenced by several causes, but urban spatial development, transport infrastructure development and economic instruments affecting transportation activities have all been identified in the research literature as important. In this report, the energy efficiency potentials through these measures are the ones that will be estimated. There are also some interdependencies between these three groups of measures as well as between transportation distances and modes (cf. Section 1.3). In this report, we examine the effects of the mechanisms shown by bold arrows but not those shown with thin arrows.

Vehicle technology improvements can of course also make a significant contribution to reducing energy use for transportation, but the energy efficiency potentials of such improvements are not estimated in this report. Therefore, the link between vehicle technology improvements and energy use per km of transportation is shown only with a dotted and thin arrow.

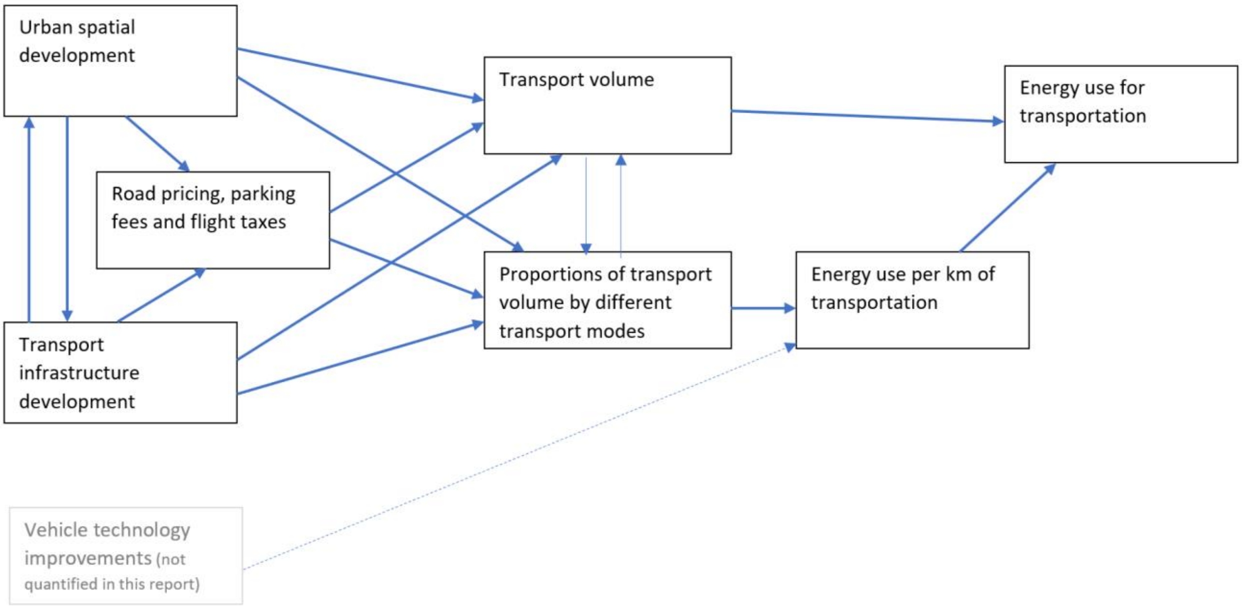

Figure 1.1: Main measures and effects discussed in this report.

This deliverable thus assesses energy efficiency potentials of two of the three above-mentioned main strategies for lowering energy use within the transportation sector, namely strategies 2 and 3. For each of these two strategies, the deliverable identifies policy measures affecting the amount of energy use, current trends in the use of such policy measures, and assesses the effects of a consistent use of relevant policy measures to improve energy efficiency. In addition, the deliverable includes an appendix where a technological improvements for making each mode of transport more energy-efficient are presented. The scope of the deliverable thus encompasses mainly Tasks 2.2 and 2.3 of the sEEnergies project as described in the project description (Grant Agreement of the sEEnergies project, Annex 1, pp. 14-15)[1]. The deliverable will provide inputs to the fourth task of the WP, where current and future (2030 and 2050) scenarios will be developed using the TransportPLAN tool

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[1] The title of the Work Package 2 of the sEEnergies project is “Comprehensive energy efficiency potentials in transport and mobility”. It includes the following five Tasks: Task 2.1: Assessment of vehicle technologies and how to make each mode of transport more energy-efficient; Task 2.2: Assessment of energy efficiency potentials in transport modal shift, from energy demand to more efficient modes of transport; Task 2.3: Assessment of energy efficiency potentials from reducing transport volumes, by reducing the movement of persons and goods; Task 2.4: Scenario development and analysis of the impact of the three main energy efficiency strategies in the transport sector; and Task 2.5: Additional economic, social, ecological, policy impacts and best practices.

developed by Aalborg University, including one, two or all three strategies and compared to a reference scenario where none of the strategies is pursued.

Policy measures to improve energy efficiency within the transportation through modal shift from energy-demanding to more energy-efficient modes of transportation and by reducing the movement of persons and goods will be envisaged in an energy efficiency scenario based on 'best practice' examples from Europe and available evidence about the effects of each measure. Energy efficiency potentials of the following categories of measures will be analyzed: urban spatial development, transportation infrastructure development, and economic transportation demand measures. The effects of these policy measures will be compared to a 'business as usual' scenario based on a continuation of trends observed over the last decades. In line with the overall assumptions of the sEEnergies project, this report is based on the assumption that the trajectories of the business-as-usual scenario will be not be much affected by the current Covid-19 pandemic. In other words, it is assumed that economic and social trends as well as mobility trends will quickly be re-established to the pre-Corona trajectories.

**Strategy 1: Making each transport mode more energy efficient.** This strategy corresponds to Task 2.1 of the sEEnergies project. Each mode of transport can be made more energy efficient and less carbon-intensive by improved vehicle technology, a shift to alternative fuels but also by improving the capacity utilization of each mode, e.g. through carpooling and better-planned public transport provision and goods distribution. In the present report, only technological measures for improving the energy efficiency will be presented (Appendix A). The measures will be discussed separately for different technologies and means of transportation, with no assessment of their overall energy efficiency potentials. The vehicle categories for which such assessments will be made are cars and vans, buses, trucks, trains, airplanes and vessels. Estimates for total energy efficiency gains through improved vehicle technologies will be given in a forthcoming deliverable report from the sEEnergies project.

**Strategy 2: Modal shift from energy-demanding to more energy-efficient modes of transportation.** This strategy corresponds to Task 2.2 of the sEEnergies project. The analysis of energy efficiency potentials through this strategy will focus mainly on the effects of land use solutions in urban regions (in terms of concentration and density), transportation infrastructure development priorities, and economic measures to influence people's travel behavior (e.g. road tolls, road pricing and parking fees). The main policy measures assessed under this strategy are land use planning policies, transportation infrastructure development, and economic instruments to influence travel behavior. Counterfactual historical scenarios ('best practice') and future scenarios with a consistent use of such policy measures to improve energy efficiency (included in an energy efficiency scenario) will be compared to the actual development in European regions and a continuation of current trends (business as usual scenario). In illustrative case examples of selected cities, policy measures to promote the *implementation* of land use and infrastructure policies favorable to promote energy-efficient travel modes will also be discussed. In these illustrative cases, supplementary policy measures (such as facilitation of non-motorized transportation and restrictions on car use in defined zones of the city) will also be discussed in addition to the above-mentioned three main policy measures.

**Strategy 3: Reducing the movement of persons and goods.** This strategy corresponds to Task 2.3 of the sEEnergies project. The analysis of energy efficiency potentials through limiting or reducing per capita transport volumes will focus mainly on the effects of land use solutions in urban regions (in terms of concentration and density), transportation infrastructure development priorities, and economic measures to influence people's travel behavior (e.g. road tolls, road pricing and parking fees). The main policy measures assessed under this strategy are land use planning policies, transportation infrastructure development, and economic instruments to influence travel behavior. Counterfactual historical scenarios ('best practice') and future scenarios with a consistent use of such policy measures to improve energy efficiency in different parts of Europe (included in an energy efficiency scenario) will be compared to the actual development and a continuation of current trends (business as usual scenario). The future scenarios will also briefly discuss potentials for substitution of corporeal air travel by information and communication technologies. In illustrative case examples of selected cities, policy measures to promote the *implementation* of land use and infrastructure policies favorable to promote energy-efficient travel modes will also be discussed, along with the likely effects of the policies in the local contexts.

As can be seen, the analyses of potentials through strategies 2 and 3 are to a great extent overlapping. Although these energy efficiency strategies are conceptually different, the measures to obtain such changes are often similar, and the empirical evidence often does not distinguish between these two components of transport energy efficiency, for example in investigating of impacts of policy measures on car driving distance.

**The energy efficiency concept applied to the transportation sector.** A final remark is needed on the way of conceiving the concept of energy efficiency within the transportation sector. Improving energy efficiency is not the same as simply reducing energy use. The latter can be obtained by reducing the level of activities in society, e.g. by rolling back levels of production and consumption to how they were fifty or a hundred years ago or, as witnessed more recently, by the closing down of economic activities due to the Corona crisis. Distinct from such reductions in energy use, energy efficiency improvement denotes using less energy while maintaining the activities in society, i.e. 'producing the same level of welfare with less energy use'. In the transportation sector, the underlying good to be reached is *accessibility*, understood here as the ease by which an activity opportunity can be reached, depending on its proximity, the transport infrastructure leading to it, and the visitors' individual mobility resources. Providing accessibility implies, for example, to ensure for the inhabitants good possibilities to reach jobs, schools, service facilities and leisure activity opportunities, and ensure for the enterprises good possibilities for recruiting a large number of potential employees. Accessibility can be provided through *mobility* (movements of persons and goods, which is the traditional focus of the transportation sector) as well as by *proximity* (nearness in space). The latter can be promoted through compact, distance-reducing urban development.

Reduced transport volumes can therefore be consistent with an efficiency approach where the same level of welfare is maintained. The same applies to a shift of modes of transportation from energy-demanding (e.g. car driving) to less energy-requiring modes (e.g. public transit, cycling and walking). However, the distinction between energy efficiency improvement (where welfare levels are not negatively affected) and merely energy saving is not always clear-cut. For example, some people may consider it a welfare loss to replace car driving by train, metro or bus trips, let alone using non-motorized modes instead of the car. Shifting travel modes from car to alternative modes can often also entail longer travel times, except in inner-city locations where other modes are often faster than the car. Some people may also consider it a welfare loss to live in a centrally located apartment instead of a single-family house in a car-dependent suburb. On the other hand, the high prices for centrally located apartments in many European cities show that many people are willing to pay more for a moderate-sized centrally located apartment than for a large suburban or exurban single-family house. This suggests that they after all consider the welfare gains of living centrally to be at least as large as those of living in a suburban neighborhood. Recent studies of neighborhood satisfaction in central and suburban parts of urban regions supports this (Mouratidis, 2017). As regards quality differences between travel modes, studies of travel satisfaction (Mouratidis et al., 2019) and public health effects (Oja et al., 2011; Rabi & de Nazelle, 2012) point at important aspects that can balance perceived quality benefits of car travel in terms of travel time, comfort and weather protection.

The issue of possible perceived quality differences between energy-favorable and traditional solutions also applies to strategy 1, particularly for measures such as carpooling but possibly also for vehicle technologies. Some might for example consider electric cars as less useful because of lower driving distance between each recharging than the distance that gasoline cars can drive between each tanking, especially during wintertime. (This difference may still diminish as technologies are developed further.)

Taking the above-mentioned circumstances into consideration, this report will nevertheless consider energy efficiency improvement within the transportation sector to include the measures mentioned above under strategies 1, 2 as well as 3. However, energy efficiency potentials will only be estimated for the two latter categories of measures.

## 1.3 Synergies between different measures to improve transportation energy efficiency

There are important interdependencies between the above-mention policy measures to promote transportation energy efficiency, both between urban spatial development, transport infrastructure development and economic instruments to influence transportation demand. If the urban spatial development results in a low-density, sprawling urban structure, motorized transportation will be necessary to reach most destinations, and the population base will be too low in most neighborhoods to make a high-frequency and fine-grained public transit service viable. In such a car-dependent spatial structure, economic measures to reduce car driving (such as road tolls, road pricing and parking fees) will be politically difficult to implement, since it will be very inconvenient and time-consuming for many people to reach their destinations by other travel modes than the private car. Moreover, transport infrastructure development that makes it easy to travel longer distances within the same amount of time facilitates more dispersed locations of dwellings, workplaces and service facilities and thus contributes to urban sprawl. This is particularly the case for highway development in urban regions. In such a situation, it becomes a very tough challenge for politicians to maintain a compact urban land use policy, since the market forces in favor of dispersal will be strong. Conversely, in a situation with improved walking and cycling facilities, parking restrictions, improved intra-urban transit, no road capacity increase but instead road pricing/road tolls making driving less attractive especially in the inner parts of the urban region, then urban densification will be much easier to implement.

There are also interrelationships between different urban spatial development measures. For several economic (Alonso, 1960) and cultural (Fishman, 1996) reasons, higher densities are more likely to be accepted at central areas than at peripheral locations. Deciding whether to densify or expand the city outward also largely determines whether to build apartments or single-family houses. The location of new residential areas thus influences their density. The same goes for workplaces. Empirically, the influence of location on density has been demonstrated in the form of a strong center-periphery density gradient in many cities and urban regions. At the same time, the average distance to the city center will be shorter in a high-density than in a low-density city, and in order to keep the density high for the city as a whole, is neighborhoods must also have on average a high density. If each neighborhood is built at a low density, the city will occupy more space, and a larger proportion of the dwellings, workplaces etc. will be at a long distance from the center.

Dense and concentrated urban development can also facilitate more positive attitudes toward energy-efficient transport modes by influencing what is considered ‘normal’ travel behavior. Such ‘normalities’ do not emerge out of the blue but are influenced by what is facilitated or made difficult in different urban contexts (Næss, 2015). Dense, concentrated and transit-rich cities and urban regions are therefore likely to create less car-oriented transport attitudes than in sprawling cities and regions.

There are thus important interdependencies between various measures that can promote higher energy efficiency within the transportation sector. According to several authors, these interrelationships also create synergies where the combination of several measures creates larger effects than the sum of the effects of the separate measures. This has been argued to be the case for different urban spatial development measures (Ewing & Cervero, 2010) as well as for the combination of such measures with other measures for improving transportation energy efficiency (Owens, 1986; Ding et al., 2018).

## 1.4 Structure of the report

The structure of the report is as follows: Chapter 2 presents the methods of the study. In Chapter 3, effects of land use, transport infrastructure development and demand management on travel and transport energy will be estimated.  Chapter 4 presents spatial development trends in European urban regions over recent decades. Chapter 5 discusses hypothetical reduced car-driving distances and energy use for intra-metropolitan transportation 1990-2015 if ‘best energy-efficiency practice’ urban spatial development had been pursued instead of the actual spatial development in this period. In Chapter 6, estimates will be made of potential energy use reduction in 2050 with ‘best practice’ urban spatial development, transport infrastructure development and transportation demand management (the energy efficiency scenario), compared to a continuation of trends observed over the recent decades (the Business as usual scenario). Chapter 7 shows examples from selected urban regions of how land use, infrastructure development and transportation demand management measures could be applied in a business as usual and an energy efficiency scenario Finally, Chapter 8 summarizes the conclusions of the work.

Appendix A presents various technological improvements for making each mode of transport more energy efficient. In addition, Appendices B, C and D provide detailed information pertaining to the effect estimates of land use measures dealt with in Chapter 3 and spatial development trends presented in Chapter 4.

## 1.5 Transfer and submission

The submission of this deliverable to the portal of the European Commission happens by uploading of the documentation report at hand.

# 2 Methods

## 2.1 Introduction

This chapter presents methods used in this report at an overall level. More detailed descriptions of the ways in which this research has been conducted are presented in the following chapters, since the specific assumptions and estimation techniques are closely interwoven with the analytical contexts of each chapter and sub-chapter. The general approach of this work is document study, where the documents examined include scientific literature, statistical reports and registries, policy documents as well as professional magazines and consultancy reports.

The main research tasks on which this report is based (Tasks 2.2 and 2.3 of the sEEnergies project) are very different from the rest of the sEEnergies project (including also the Task 2.1 of the WP2 Transport and mobility Work Package) in terms of context-dependency, possibilities for quantification and prospects for prediction of future effects. Whereas Task 2.1 as well as the sEEnergies Work Packages addressing energy efficiency in buildings (WP1), industry (WP3) and energy grids (WP4) deal with technological development where effects of new solutions have been and can be measured relatively accurately, differ little with geographical contexts and do not depend crucially on human motivations, attitudes, social networks or other conditions enabling or constraining their actions (although individual driving styles matter to fuel efficiency), the influences of the measures addressed in Tasks 2.2 and 2.3 depend on precisely such human factors and are likely to vary considerably with geographic contexts and over time. The possibilities for precise quantification of effects are also very different: Whereas research findings on which WPs 1, 2, 4 and Task 2.1 stem largely from the ‘hard’ technological sciences, the evidence on which Tasks 2.2 and 2.3 stems from the much more ‘soft’ social sciences. Moreover, although the energy efficiency strategies addressed in Task 2.2 (changing towards more energy-efficient transport modes) and Task 2.3 (reducing transport volumes) are conceptually different, the measures to obtain such changes will often be similar, and much of the empirical evidence does not distinguish sharply between these two components of transport energy efficiency. In our analyses, we have therefore largely dealt with Tasks 2.2 and 2.3 jointly, without any clear separation.

## 2.2 A scenario approach

In order to estimate the potential energy savings through energy-efficient urban spatial development, transport infrastructure development and economic transportation demand measures, we have used a scenario approach where a consistent use of energy-efficient measures over the period 2020-2050 (the energy efficiency scenario) has been compared with a continuation of trends observed over the last couple of decades (the business as usual scenario). For urban spatial development, we have in addition compared the hypothetical energy savings from a counterfactual ‘best energy-efficiency practice’ scenario with the actual trajectory over the period 1990-2015. In order to calculate energy efficiency potentials, statistics on population development, urban spatial development, transportation infrastructure construction, energy use development and traffic development since 1990 as well as population forecasts for the period until 2050 have been combined with effect estimates of energy-efficient measures within urban spatial development, transport infrastructure development and transportation demand management.

Neither the energy efficiency nor the business as usual scenario aims to predict how the future situation will be. According to Børjesson et al.'s (2006) categorization of scenarios into predictive, explorative and normative scenarios, both the energy efficiency and the business as usual scenario could best be characterized as explorative scenarios, i.e. scenarios that attempt to illuminate 'what if' questions. One might think that the business as usual scenario fits with the predictive category of scenarios, but in a rapidly changing world facing great challenges there is little reason to believe that the development over the next 30 years will follow the same trajectory as in the past two decades. On the other hand, although the energy efficiency scenario depicts what might be desirable from a purely energy efficiency point of view, such a future would obviously conflict with several other interests and values, maybe also some that not even energy efficiency proponents would like to violate[2]. We therefore think the energy efficiency scenario too could be characterized as an explorative scenario rather than a normative (=desirable) scenario. Both scenarios should thus be understood as 'what if' scenarios, where the business as usual scenario depicts urban spatial development, transport infrastructure development and use of economic traffic-regulating measures as if past trends were to continue, while the energy efficiency scenario depicts how the development within these three domains might occur if energy efficiency concern were to take priority over other concerns.

It should also be noted that the scope of the scenarios includes only urban spatial development, transport infrastructure development, economic transportation demand measures and the ensuing differentials in energy use resulting from different trajectories within this domain. Compared to more 'full-fledged' scenarios that situate such trajectories within wider social, political, economic and cultural contexts that might enable the realization of each scenario, the scenarios of this report thus have a narrow scope. The scenarios also do not include any discussion of the steps and decisions that could lead to the realization of each depicted future – such an analysis would typically be the topic of a 'backcasting' scenario approach (Dreborg, 1996).

## 2.3 Estimating energy efficiency potentials

The empirical evidence about the impacts of built environment (i.e. land use, buildings and transport infrastructure) characteristics on transport volumes and modal split stem from studies in different cities of different size and in different countries, thus representing different geographical, social, political and cultural contexts. The same applies to the few studies about the travel behavioral effects of economic instruments to regulate traffic, such as road tolls and parking fees, where most studies are from the USA. The existing studies on built environment impacts on transportation are of varying methodological quality and focus on different aspects within each of the two main outcome variables focused on in Tasks 2.2 and 2.3 of the sEEnergies project. For example, some studies focus only on commuting, others on non-work travel (e.g. shopping); some studies include only residents of the morphological city (or parts of it), some include residents from all over the metropolitan area; and some focus only on local or intra-metropolitan transport while other studies also include travel outside the metropolitan area (such as holiday trips). Upscaling these different pieces of evidence to estimates of the potentials at a European or European-region scale for energy efficiency through lower transport volumes and higher shares of energy-efficient transport modes than in a business-as-usual scenario is therefore a challenging exercise. The complexity of the task is further amplified by the lack of clarity of

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[2] On the other hand, energy efficiency concerns within the three domains addressed in this report may also be synergetic to many other societal concerns, for example protection of farmland and natural areas against urban development and infrastructure construction, or the promotion of a vibrant urban life in cities.

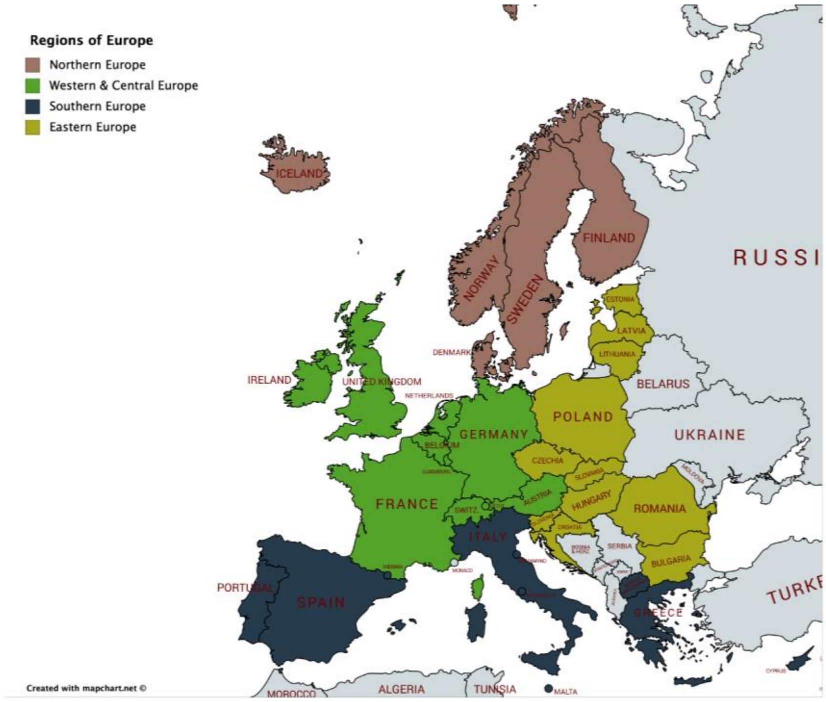
how to define the baseline, or business-as-usual, trajectory of urban development against which energy efficiency policies are to be compared. Some cities experience high population growth and a high pace of construction, others grow only slowly, and others again are shrinking. Moreover, some cities are already dense and may have a limited potential for further densification, whereas other cities have considerable vacant space within their urban area demarcations.

Given this strong context-dependency of empirical findings as well as in the possibilities for cities to pursue a more energy-efficient urban development than in the past years, we consider it impossible to provide the level of detailed information ideally desired as inputs to comprehensive simulation tools such as Aalborg University's TransportPLAN model.

Instead, we have pursued the following, more pragmatic approach:

First, we have compiled an overview of the findings of all studies from Europe published in peer-reviewed journals since 2000 on the effects of selected built environment characteristics on relevant travel behavior and transportation variables (Appendix B). This has been compiled in a way similar to an approach recommended by Næss (2019). Studies investigating variables other than the prioritized ones but still relevant to the purpose of the project have also been reviewed (Appendix B). These studies make up supplementary and background information but do not form the base for synthesizing effect estimates to be used in the present study. For all selected built environment variables, the elasticity with relevant transportation variables are shown, either taken directly from the reviewed publications or calculated by us based on parameter estimates displayed in the publications.

Secondly (Chapter 3), based on the above-mentioned knowledge base, estimates of the likely effects on built environment characteristics on relevant transportation variables have been made for urban regions with main city populations in three different size categories: large urban regions (1 million inhabitants or more within the main continuous urbanized area, i.e. the main morphological city); medium-size urban regions (between 100,000 and 1 million inhabitants within the main continuous urbanized area); and small urban regions (between 10,000 and 100,000 inhabitants within continuous urbanized area of the main city). We have also cautiously tried to differentiate, when relevant, the estimates between four geographical regions of Europe, based on assumed sociocultural, political and urban-geographical differences between the regions: 1) Northern Europe; 2) Western & Central Europe; 3) Southern Europe; and 4) Eastern Europe (see Figure 1). Similar effect estimates have been made for and transport infrastructure development and transportation demand management measures, differentiated between geographical regions of Europe and urban regions of different main city population size classes.



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|---|---|
| **Northern Europe**<br>Denmark<br>Finland<br>Iceland<br>Norway<br>Sweden | **Western and Central Europe**<br>Austria<br>Belgium<br>France<br>Germany<br>Ireland<br>Liechtenstein<br>Luxemburg<br>Netherlands<br>Switzerland<br>UK |
| **Southern Europe**<br>Andorra<br>Cyprus<br>Greece<br>Italy<br>Macedonia<br>Malta<br>Portugal<br>Spain | **Eastern Europe**<br>Bulgaria<br>Check Republic<br>Croatia<br>Estonia<br>Hungary<br>Latvia<br>Lithuania<br>Poland<br>Romania<br>Slovakia<br>Slovenia |

Figure 2.1: Distribution of EU and EFTA countries between the four defined sub-regions of Europe.

Third, current trends of urban spatial development, transport infrastructure development and the use of transportation demand management measures have been identified for cities in each of the four above-mentioned regions of Europe, based on available statistics and relevant national, cross-national and EU documents. Here, we have put particular efforts into investigating trends of urban spatial development (Chapter 4), based on input from Flensburg University (cf. Deliverable D5.2). Our empirical base for assuming trends in the development of transport infrastructure and transportation demand management measures (integrated into the respective sections of Chapters 3 and 6) is much less comprehensive, but we have tried to formulate assumptions for these aspects too, based on our professional judgment.

Fourth, a particular, counterfactual analysis has been carried out in order to illuminate how much energy could have been saved if urban spatial development in the period 1990-2015 in all parts of Europe had followed the ‘best practice’ trajectories identified at steps 1 and 2. This assessment is based on a combination of the effect estimates of steps 1 and 2 and the differences in spatial development identified in step 3 (Chapter 5).

Fifth, we have applied the effect estimates from the two first steps concerning urban spatial development, transport infrastructure development as well as economic measures for transportation demand management to compare the energy use differentials between an energy efficiency scenario and a business as usual scenario for the period 2020-2050 (Chapter 6). By combining estimates of potentials for future energy-efficient urban spatial development, transport infrastructure development, and transportation demand management with a prolongation of current trends, rough estimates of the differentials between energy-efficient development and business-as-usual urban development have been calculated for each of the urban region size classes and each of the four geographical regions of Europe as well as for the EU/EFTA area as a whole.

Finally, in order to illustrate what the energy efficiency scenario might imply in different urban and urban-regional contexts, we have shown a few illustrative examples from selected urban regions of how land use, infrastructure development and transportation demand management measures have already been applied in ways that point forward in the direction of an energy efficiency transportation future.

As can be seen from the above, energy efficiency potentials through vehicle technology improvements have not been calculated in this report. However, a number of possible technological approaches for improving the energy efficiency of different modes of transportation (i.e. energy use per person km or ton km with the specific mode) have been reviewed, based on document studies of scientific and professional literature (Appendix A).

# 3 Effects of land use, infrastructure and demand management on travel and transport energy

The purpose of this chapter is to give an account of the estimated effects of key urban structural characteristics and transportation demand measures on selected transport variables to be used in calculations of energy efficiency potentials of scenarios for energy-conscious spatial development strategies for different sub-regions of Europe. The chapter presents our proposed quantitative effect estimates pertaining to the present-day situation, our empirical and theoretical reasons for proposing these elasticities, and our assumptions about possible future changes, leading to an adjusted set of estimates for the 2050 situation.

## 3.1 Effects of urban built environment characteristics

Based on state-of-the-art research into influences of built environment characteristics on travel and transportation energy use[3], we consider the following spatial characteristics to be the most important ones for maintaining accessibility while reducing transport volumes and promoting a shift from energy-demanding travel modes to modes requiring less energy per person kilometer traveled or ton kilometer of freight:

- High population density for the city as a whole (the continuous urbanized area, i.e. the morphological city)[4]
- Residential location close to the main center of the city/the metropolitan area[5]
- Location of specialized, labor-intensive or visitor-intensive jobs close to the main center of the city/the metropolitan area[6]

The direct effects of neighborhood-scale densities are generally smaller than those of the above-mentioned metropolitan-scale and city-scale characteristics. However, for the overall population density of a city to be high and the average distances of dwellings and jobs to the city center to be low, each neighborhood must also have a sufficiently high density.

The empirical evidence about the impacts of built environment (i.e. land use, buildings and transport infrastructure) characteristics on transport volumes and modal split stem from studies in different cities of different size and in different countries, thus representing different geographical, social, political and cultural contexts. The existing studies are of varying methodological quality and focus on different aspects within each of the two main outcome variables focused on in Tasks 2.2 and 2.3 of the sEEnergies project description. For example, some studies focus only on commuting, others on non-work travel (e.g. shopping); some studies include only residents of the morphological city (or parts of it), some include residents from all over the metropolitan area; and some focus only on local or intra-metropolitan transport while other studies also include travel outside the metropolitan area (such as holiday trips). Upscaling these different pieces of evidence to estimates at an EU scale of the potentials

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[3] For reviews, see Handy et al. (2002); Cao et al. (2009); Saelens & Handy (2008); Ewing & Cervero (2010); Næss (2012).

[4] See, for example, Newman & Kenworthy (1989); Næss (1993); Næss et al. (1996); Kenworthy (2003).

[5] For recent European studies, see, for example, Næss et al. (2017), Næss et al. (2019); Elldér (2014) Engebretsen et al. (2018).

[6] For recent European studies, see, for example, Wolday al. (2019), Engebretsen et al. (2018).

for energy efficiency through lower transport volumes and higher shares of energy-efficient transport modes than in a business-as-usual scenario is therefore a challenging exercise.

In order to assess how built environment characteristics in cities in different size categories and different corners of Europe influence travel and transportation, we have collected as many scientific journal articles as possible about studies conducted on the topic in European cities and city regions since 2000. Since the purpose of this collection of published material is to arrive at quantitative effect estimates that can subsequently be used as a base for calculation of energy efficiency gain potentials of energy-smart urban spatial development, our sample does not include qualitative or purely theoretical papers on the topic. The latter kind of articles makes up, however, an important foundation when evaluating the soundness of the statistical analyses on which the conclusions of the quantitative papers are based. Our information base therefore includes qualitative and theoretical articles as well as the quantitative articles from which we have elicited elasticities between variables.

Our collection of quantitative literature (some of which mixed quantitative and qualitative) includes 30 articles and one research report. Many of the articles cover influences of several built environment characteristics on travel, and they also vary in terms of geographical scale. Among the reviewed publications, 19 address the influence of residential built environment characteristics on travel, 4 focus on the influence of the overall urban density on energy use for transportation, and 10 are about the influence of other built environment characteristics on travel. Apart from two older articles (from 1993 and 1996, respectively) on effects of overall urban population density on transportation energy use, all these publications are from the present century. To our knowledge, our sample of publications includes all articles scientific peer-reviewed journals published on these topics since 2000 that include some sort of quantification of the effects of the urban structural characteristics in question. However, not all these articles include effect estimates suitable as a base for calculating potentials for more transport energy-efficient spatial development of European urban regions. The sample of articles from which we have derived effect estimates to be used in this project was therefore narrowed down to 12 articles (plus one research report). Appendix B shows an overview of the articles used for arriving at effect estimates, the urban structural characteristics and aspects of travel/transportation investigated, and the effects estimated of the relevant urban structural characteristics investigated in each article. Appendix C shows the ‘gross’ sample of publications reviewed, including studies of workplace location as well as many studies of residential built environment characteristics that do not include effect estimates suitable for the present study[7].

We have used *elasticities* as a measure of the influences of urban spatial structural characteristics on aspects of travel behavior. Elasticities refer to the ratio of the percentage change in one variable associated with the percentage change in another variable. For example, if a 1% increase in the independent variable results in a 0.3% increase in the dependent variable, the elasticity is 0.3. Elasticities are widely used measures of effect sizes, particularly in economic research, but also within some fields of planning. One advantage of comparing elasticities instead of regression coefficients is that elasticities do not depend on the measurement units chosen for the variables, for example whether the driving distance is measured in miles or kilometers. Elasticities are therefore the effect

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[7] In addition to the publications shown in Appendix C, we also reviewed four Eastern European studies. However, none of these studies included relevant evidence about effects of urban built environment characteristics on travel.

size measure used in the most cited literature reviews (in the form of meta-analyses) on effects of built environment characteristics on travel (e.g. Ewing & Cervero, 2001 and 2010; Stevens, 2017). However, only a relatively small part of the individual articles we have examined have shown their effect estimates in terms of elasticities. For those publications where elasticities were not shown, we have, similar to what Ewing & Cervero (2010) did, either derived them from data sets already available to us, or calculated elasticities based on unstandardized or standardized regression coefficients displayed in the articles, combined with mean values and standard deviations of the urban structural and transportation variables[8]. When necessary, we have contacted the authors of the articles to get the latter information.

As we had expected, the studies conducted in European cities and urban regions are highly unevenly distributed across Europe. The majority of studies have been carried out in northwestern Europe, and with a particularly high proportion of studies from the Nordic countries. There are also some studies from Western and Central Europe (notably the Netherlands, UK, Germany and France), some from Southern Europe (Portugal and Greece), but almost none from Eastern Europe. We have, however, been able to identify four articles from Eastern Europe that touch upon relationships between urban structures and travel, but without any relevant effect estimates. We have used these articles as supplementary background material along with a number of studies from other European countries without effect estimates of relevant variables. These supplementary studies have particularly been used to judge whether there are particular circumstances in the under-represented countries indicating that the relationships between urban structures and travel would be substantially different in the contexts of these countries.

The aspect of the urban built environment most extensively researched for its travel behavior impacts is the location and neighborhood characteristics of residences. This applies to Europe as well as in a wider international context. Fewer studies have investigated transportation impacts of workplace location, and only a very few have investigated how the location of retail affects travel behavior. How the amount freight traffic is influenced by urban built environment characteristics has, to our knowledge, not at all been addressed in empirical research in Europe, although a few model simulation studies exist. However, two rather old studies (in the 1990s) have investigated relationships between overall urban characteristics and the total energy use for transportation, including private cars, transit as well as freight. Based on these studies, it might be possible to make rough estimates of how large energy use public transit and freight account for in urban areas, compared to the energy used for car driving, and how the proportions of the overall energy use spent on transit and freight, respectively, varies between cities of different population size.

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[8] Ewing & Cervero (2010:273) show formulas for calculation of elasticities from different kinds of regression coefficients (linear, logistic, Poisson, negative binomial and Tobit) and with the built environment variable (x) and/or the transportation outcome variable (y) measured either both linearly, both logarithmically, or one of them linearly and the other one logarithmically. Here, we will only show the formulas used in the present report when calculating elasticities from regression coefficients published in the articles included in Appendix B. With the regression coefficient denoted as B, the elasticity E of the relationship between x and y can be calculated as follows:

Both x and y linearly measured: E = B*(mean of x/mean of y)

Both x and y logarithmically measured: E = B

x linearly measured and y logarithmically measured: E = B*(mean of x)

x logarithmically measured and y linearly measured: E = B/(mean of y)

Above, the different topographical, economic, political and cultural contexts of cities was mentioned as an important reason why studies show heterogeneous effects of a given built environment variable on a given aspect of travel behavior. Another main reason is that studies differ in their inclusion of control variables. The vast majority of studies are based solely on quantitative research methods. They rarely capture the complex ways in which the built environment influences travel behavior in interplay with time-geographical constraints and the backgrounds, motivations and justifications that individuals draw on when making transport-relevant decisions about their participation in activities, location of these activities and modes of transportation (Næss et al. 2018). Due to lack of such qualitative insight, many studies have included and omitted control variables in theoretically unsatisfactory ways. Partly, this involves the inclusion of socioeconomic and attitudinal control variables that are themselves influenced by built environment characteristics, such as car ownership (Cao et al., 2019a; Van Acker & Witlox, 2010). In addition, many studies ignore important causal influences between different built environment characteristics. For economic (Alonso 1960) and cultural (Fishman 1996) reasons, higher densities are more accepted at central than at peripheral locations. However, many studies have ignored the above causal relationships between built environment characteristics, failing to control for location at the city/metropolitan scale when estimating the effects of local variables. Other studies have made such control. The estimates are then not comparable.

For example, many studies investigating the impact of street design (e.g. intersection or street density) have failed to control for the location of the investigated neighborhoods relative to the city center. Or, if they have included the distance to the city center among the independent variables, they have failed to take the indirect effect of the distance to the city center via neighborhood-scale variables such as street design into consideration. Merely calculating averages of the effect estimates of a given urban structural variable found in different studies will therefore be misleading (see Næss, 2019 for an elaborate discussion). Instead, it is necessary to judge the credibility of each study, taking into consideration any omission of relevant control variables, inclusion of irrelevant control variables and how any indirect effects have been dealt with. Needless to say, this makes it additionally difficult to arrive at general estimates of the effects of urban built environment characteristics on travel, even when differentiating between different regions of Europe or city size classes. Moreover, if only the estimates derived from studies where relevant variables have been included and inappropriate control variables excluded from the analyses, the sample of European studies from which general elasticities might be assessed will be diminished. Add to this that some studies are based on comparisons that do not at all lend themselves to the calculation of elasticities, for example studies comparing travel behavior in “traditional” and “suburban” neighborhoods.

The important point here is that state-of-the-art research has shown that the most important urban spatial structural characteristics are the distance of residences and workplaces to the main city center, along with the overall urban density. There are also some effects of the specific design of a suburb – but the most important is to avoid urban sprawl. In this context, the relatively limited number of European studies addressing the most important urban characteristics is a problem. Another problem is that several studies have investigated travel behavior variables that cover only a small part of urbanites’ energy use for transportation, or variables that do not easily lend themselves to upscaling to total transport energy use.

For the purpose of analyzing energy efficiency potentials through energy-conscious urban development, we also need to take into consideration what data are available about the spatial urban development in European cities and city regions. In the European-scale databases available for the sEEnergies project (cf. D5.2), information about average residential distance to the city center of each city is included, as well as the distance of each city to the closest larger city within specified city size categories. The databases also include information about population density within each urban settlement, small as well as large. However, although studies on effects of workplace location on commuting distances and modes otherwise suitable for the sEEnergies estimations exist, no spatial dataset on jobs distribution within urban regions was possible to identify during this project, despite several efforts. We have therefore not been able in this project to utilize research findings about effects of workplace location on travel.

Among the studies that have, based on the above considerations, been found suitable for inclusion as sources of quantitative synthetizing of effect estimates, we have therefore, taking the availability of data on European urban settlements into consideration, chosen to focus on the following urban built environment characteristics:

- Residential distance to the main city center
- Population density within the overall urbanized area (the morphological city), measured by its inverse value (urban area per capita).

The travel and transport variables associated with the built environment characteristics focused on as a base for subsequent energy efficiency assessments are:

- Car-driving distance (in total for all purposes), alternatively travel distance by car (which can be transformed into car-driving distances based on assumptions about average occupancy rates of each car)
- Energy use for transport

The impact of residential distance to the city center as well as that of overall urban population density depends on whether the city is a relatively ‘independent’ city or a satellite of a larger city. In the latter case, the elasticities will take into consideration the small city’s distance to the metropolitan center as well as the mean residential distance of the small city’s inhabitants to the center of the small city. The elasticities are thus applied within the contexts of urban regions, defined as follows[9]:

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[9] No commonly agreed upon definition exists for how to demarcate a functional urban region. Often, demarcations based on the proportion of workforce participants commuting to the main regional center are used (Davoudi, 2008). Another way of demarcating it is to include the municipalities from which the core city center can be reached within a given commuting time by car. For municipalities that cover a large area, this gives rise to inaccuracies. A simplified way of demarcation is to define the functional urban region as the area covered by a circle with a chosen radius around the center of the core city. This is the approach used in the present study. Since the commuting hinterlands of large cities are normally larger than those of smaller cities, we have, based on sporadic evidence about the sizes of commuting areas for cities of different sizes, roughly assumed the radius of functional urban regions to be 50 km, 25 km and 10 km, respectively, for urban regions with main city population of above one million, between 100,000 and one million, and between 10,000 and 100,00. Apart from the crudeness of this way of demarcating, which neglects social, economic, political and cultural conditions specific to each urban region, a general disclaimer here also concerns the way our definition of urban regions disregards local topographic conditions – we are not able to take specific geographical barriers into consideration, such as fjords, sounds, mountains, etc.

- Cities with a population of one million or more include in their urban region all urban areas within a 50 km straight line distance[10].
- Remaining cities with a population between 100.000 and one million include in their urban region all urban areas within a 25 km straight line distance.
- Remaining cities with a population of between 10.000 and 100.000 include in their urban region all smaller cities within a 10 km straight line distance.

Assessment of the extent to which impacts of built environment characteristics on travel are similar or different in other parts of Europe than the regions in which empirical studies of the above-mentioned relationships have been conducted will be based on qualitative judgment (Næss, 2004), addressing questions such as:

- To what extent do the investigated cities or city regions, deviate from the cities and city regions in the rest of Europe with respect to characteristics relevant to our research questions?
- Does it appear likely and reasonable to assume that differences between the contexts of the investigated cities/city regions and the cities/city regions in other parts of Europe have exerted decisive influence on the relationships found between built environment characteristics and travel behavior?
- In what ways would any important contextual differences between investigated and non-investigated parts of Europe be likely to affect the effect sizes of relationships between built environment characteristics and travel found in empirical studies – what differences would likely diminish the effects, and what differences could be expected to increase them?

For older studies, we also needed to assess whether the present context is sufficiently similar to the context when the study was carried out that the effect can be assumed to be the same today, and how much the estimates should be modified if necessary (see below about prediction of how effects will be in the future).

We do not have many clues for making meaningful assumptions about differences between different corners of Europe in the ways in which urban built environment characteristics influence travel and transportation. Our initial assumption was that we might find evidence of such differences, but even though around 35 articles were analyzed, and despite reaching out to the different corners of Europe in order to find grey literature, we did not find much. Coevering & Schwanen (2006) found evidence of such differences between cities in Europe, Canada and the United States, but they did not address differences between different parts of Europe. However, one possible reason for such differences is that people in countries where car travel is associated with higher social status might be less inclined to travel by transit or non-motorized modes despite living at locations facilitating travel by these modes. In Europe, this is arguably the case in Eastern Europe to a greater extent than in other European countries, and maybe to somewhat lesser extent in Northern Europe than in the remaining countries. Another possible mechanism is that people in countries with lower income levels may be somewhat less inclined to travel long distances to find the best facility for carrying out their regular activities, and that they may therefore be more locally oriented in their activity locations. The influence of residential distance to the city center on travel distances would then be weaker than in countries with higher

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[10] See Tiitu et al. (2020), where some justification for the 50 km limit is given.

income levels. In Europe, this would imply somewhat weaker elasticities in south and Eastern Europe than in north and west/central Europe.

### 3.1.1 Present-day elasticities

Based on the evidence presented in Appendix B and the above considerations, our estimates of present-day effects (measured as elasticities) of built environment characteristics on travel and transport variables are as follows (Table 3.1). Estimates for regions where no relevant studies are available are shown in gray instead of black font.

Table 3.1: Present-day effect estimates of built environment characteristics on travel and transport variables in different parts of Europe and for different city sizes (city population sizes in thousands).

| Built environment characteristics | Travel and transport variables | Northern Europe | | | W & central Europe | | | Southern Europe | | | Eastern Europe | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | > 1000 | 100-1000 | 10-100 | > 1000 | 100-1000 | 10-100 | > 1000 | 100-1000 | 10-100 | > 1000 | 100-1000 | 10-100 |
| Residential distance to the main city center | Car-driving distance | 0.29 | 0.38 | 0,50 | 0.27 | 0.36 | 0.48 | 0.25 | 0.34 | 0.45 | 0.22 | 0.30 | 0.40 |
| Urban area per capita | Energy use for transport | 0.42 | | | 0.41 | | | 0.39 | | | 0.35 | | |

To our knowledge, none of the European studies of the impacts of built environment characteristics on travel have investigated the relative importance of the effects of residential location on energy use for transport through its influences on overall travel distance and the modal shares of the distances traveled[11]. Our calculations of energy-efficiency potentials of urban built environment and infrastructure strategies aiming to minimize transport energy consumption will therefore be based on data for car-driving distances, supplemented with data for effects of overall urban density on transportation energy use and about the proportions of this energy attributable to car driving.

However, based on our own data from a recent study (Næss et al.,2019) of residential location and travel in Oslo metropolitan area (population of the main morphological city: 1.02 mill. in 2019), we have made estimates of the effects of residential distance to the city center of Oslo on energy use for intra-metropolitan travel via weekly traveling distance and the proportions of this distance traveled by

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[11] Several studies do report effects of built environment characteristics on overall travel distances as well as on the shares of different travel modes. However, the ways in which these variables are measured vary. Traveling distances may refer to separate trip purposes (such as commuting, grocery shopping or in total for all travel purposes), and in the latter case the travel distance may refer to intra-metropolitan travel only, all domestic travel, or even travel across national borders. There is also much variation in the ways in which modal shares have been measured: some studies measure the percentages of trips carried out by different modes, other studies measure modal shares from the percentages of total travel distance traveled by different modes, and may studies report modal shares only for a particular trip purpose (typically commuting).

car and transit, respectively[12]. Based on these calculations, 70 % of the effect of residential distance to the city center is through its influence on weekly travel distance, 29 % through the proportion of distance traveled by car, and 1 % through the proportion traveled by transit. Data from the same study on Stavanger metropolitan area (population of the main morphological city: 0.225 mill. in 2019) show very similar proportions: 70 % of the effect of residential distance to the city center on energy use is via weekly travel distance, 29 % through the proportion of distance traveled by car, and no impact at all via the proportion traveled by transit[13]. Data from a methodologically similar study of the Icelandic capital of Reykjavik (Næss et al., 2020), with 0.223 million inhabitants in 2019, also show results in the same vein, with 62%, 38% and 0%, respectively, of the effect of residential distance to the city center on intra-metropolitan energy use for transportation taking place via weekly travel distance, the share of distance traveled by car, and the share of distance traveled by transit[14].

The material from these three Nordic cities thus indicates that the lower energy use for intra-metropolitan travel among inner-city dwellers than among suburbanites is first and foremost due to their shorter weekly travel distances, and to a lesser (but still non-trivial) extent due to their lower proportion of distance traveled by car. The share of public transport plays a negligible role in the relationship between residential distance to the city center and energy use for intra-metropolitan travel.

For commuting trips, we also calculated elasticities between residential distance to the main city center of each of the three above-mentioned metropolitan areas and the likelihood of traveling four or more of the days of the week by car, transit and non-motorized modes, respectively. For the likelihood of being a regular car commuter, the elasticity of residential distance to the city center is 0.43 in Oslo, 0,49 in Stavanger and 1,07 in Reykjavik. For the likelihood of being a regular transit commuter, the elasticity of residential distance to the city center is 0.40 in Oslo, 0,95 in Stavanger and insignificant in Reykjavik. For the likelihood of being a regular non-motorized commuter, the elasticity of residential distance to the city center is -1.04 in Oslo, -1.03 in Stavanger and -1.33 in Reykjavik. The diverging results across the three metropolitan areas for the modal shares of car and transit partly reflect the different city sizes (the morphological city of Oslo has four and a half times as many inhabitants as in Stavanger and Reykjavik), where elasticities generally tend to be higher in smaller cities since the change from dense inner-city to rural occurs over a shorter distance in small than in large cities. The higher elasticities in Reykjavik than in Stavanger reflect that Stavanger is a

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[12] These calculations show the following elasticities of residential distance to the city center of Oslo: 0.55 on weekly total travel distance, 0.55 on the proportion of distance traveled by car, -0.15 on the proportion of distance traveled by transit, and 0.76 on energy use for transportation. The calculations show the following elasticities of the transportation variables on energy use: 1.02 from weekly travel distance, 0.42 from the proportion of distance traveled by car, and -0.04 from the proportion of distance traveled by transit.

[13] These calculations show the following elasticities of residential distance to the city center of Stavanger: 0.32 on weekly total travel distance, 0.19 on the proportion of distance traveled by car, 0.04 on the proportion of distance traveled by transit, and 0.49 on energy use for transportation. The calculations show the following elasticities of the transportation variables on energy use: 0.97 from weekly travel distance, 0.73 from the proportion of distance traveled by car, and -0.01 from the proportion of distance traveled by transit.

[14] These calculations show the following elasticities of residential distance to the city center of Reykjavik: 0.56 on weekly total travel distance, 0.22 on the proportion of distance traveled by car, 0.06 on the proportion of distance traveled by transit, and 0.59 on energy use for transportation. The calculations show the following elasticities of the transportation variables on energy use: 1.09 from weekly travel distance, 0.40 from the proportion of distance traveled by car, and -0.015 from the proportion of distance traveled by transit.

predominantly polycentric cityone whereas Reykjavik is relatively more monocentric. Anyway, these differences between three cities in the same sub-region of Europe illustrate the context-dependency of the magnitudes of the influences of urban spatial structural characteristics on travel behavior. Whereas the nature of the causal mechanisms is much the same (see, for example, Næss, 2013; Næss et al., 2018), the effect sizes depend much on the specific city context, for example regarding center structure (notably employment centers), transport infrastructure, neighborhood to other large cities, etc. Consequently, the elasticity estimates and the resulting estimations of energy efficiency potentials must necessarily be very crude.

It should still be noted that the elasticities between residential distance to the city center and car-driving distances show smaller divergences than the elasticities between residential distance to the city center and the shares of different travel modes.

### 3.1.2 Future effects

As mentioned above, present-day effects will not necessarily remain the same in the future. Since the world is constantly changing, important social, political, cultural, economic and geographical conditions may change in ways affecting present relationships between built environment and transportation more or less strongly. Again, a number of questions must be assessed qualitatively:

- Does it seem reasonable to assume that the situation in the future will be different in ways that are likely to substantially change the present relationships between built environment characteristics and travel?
- If so, which traits of development might be expected to diminish or amplify the present relationships, in which ways and to what extent?

Since changes in the mentality and culture of a population usually take place very slowly (Lundmark, 1987), the underlying main rationales influencing people’s locations of their activities and choices of travel modes could be expected not to be radically altered within the foreseeable future. However, a possible future introduction of road pricing schemes making car driving substantially more expensive would likely reduce much of the ‘optional’ traveling, e.g., leisure trips. The remaining trips, such as those between residences and workplaces, schools and stores, depend to a greater extent on urban structural conditions. In such a scenario, the relative importance of urban structure to travel behavior is therefore likely to increase (and the negative social and welfare consequences of living in an area far from relevant facilities will be more serious). On the other hand, if the general mobility continues to increase, trips within the urban region are likely to account for a lower share of the total amount of travel. The relative importance of the location of activities within the urban region to the amount of transport will then decrease. (Measured in absolute figures, the influence of residential location on energy use may still increase, as a rising level of mobility probably implies that people will transport themselves more within the urban area as well.) For the overall elasticities between urban built environment characteristics and inhabitant’s travel and transportation, we think the effect of generally rising mobility levels (in a business-as-usual scenario) will be larger than the effect of road pricing schemes.

However, the concentrated and dense urban development strategy whose effects the elasticities are used to estimate, applies to scenarios that are precisely not business-as-usual. The general mobility levels in European countries will not increase as much as in the business-as-usual, if at all. And road pricing schemes will most likely be implemented to a much greater extent in the energy efficiency scenarios than in the business-as-usual scenario. Combined, these conditions suggest that larger elasticities should be assumed for the future than for the present situation.

Based on such considerations, we assume the following effect estimates for the future situation to which the scenarios refer (Table 3.2):

Table 3.2: Estimates of future (2050) effects of built environment characteristics on travel and transport variables in different parts of Europe and for different city sizes.

| Built environment characteristics | Travel and transport variables | Northern Europe | | | W & central Europe | | | Southern Europe | | | Eastern Europe | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | > 1000 | 100-1000 | 10-100 | > 1000 | 100-1000 | 10-100 | > 1000 | 100-1000 | 10-100 | > 1000 | 100-1000 | 10-100 |
| Residential distance to the main city center | Car-driving distance | 0.35 | 0.45 | 0.60 | 0.32 | 0.43 | 0.57 | 0.30 | 0.41 | 0.54 | 0.26 | 0.36 | 0.48 |
| Urban area per capita | Energy use for transport | 0.50 | | | 0.49 | | | 0.46 | | | 0.42 | | |

## 3.2 Effects of transport infrastructure expansion

Obviously, transport infrastructure development will affect travel behavior by influencing travel and freight distances, modes of transportation and (probably to a lesser extent) the frequency of trips. Investments in rail transport can make trains, metros and streetcars more attractive, compared to other modes of transportation and thus contribute positively to energy efficiency if they are able to attract travelers and freight that would otherwise have chosen more energy-demanding modes. However, improved rail transport is also likely to induce an increase in the overall mobility of the population, and the resulting higher volumes of person kilometers and ton kilometers imply a higher demand for energy. In urban regions, new high-speed rail can even lead to more car driving, since the resulting reduced travel times make it easier for people to commute over longer distances, for example by moving to smaller settlements further away while continuing to have their workplace in the main city. Due to the generally poorer public transport provision in the outer areas and the easier conditions for local car driving (e.g. in terms of uncongested local roads and ample parking possibilities), such region enlargement contributes to increased car traffic to local destinations such as stores for daily necessities purchases, pre-schools, and schools to which children are escorted (Dovre & TØI, 2012). Moreover, and often ignored in debates on sustainable mobility strategies, the construction of new rail lines demands substantial amounts of energy, especially if large proportions of the lines have to been built in tunnels. The extent of induced rail transport, the proportion of new passengers and tons of goods taken from more energy-demanding modes (notably car, truck and airplane), and the specific energy demand for constructing new rail lines are all heavily context-dependent, and few studies of such effects have been carried out.

Since the different effects described above work in opposite direction, it may be reasonable to assume that the net effect of rail investments on energy consumption for transport will be relatively modest.

Even if the new rail lines are able to attract a substantial number of passengers that would otherwise have traveled by car or airplane and/or can replace a considerable proportion of freight now carried on trucks, these gains are likely to be counterweighed to a great extent by induced additional mobility and the high energy requirement during the construction stage. For the purpose of the present study, we have therefore chosen to consider rail investments as 'neutral' in terms of its impacts on future energy demand for transportation. We will instead focus on the impacts of road development on car and truck traffic.

Road construction that increases the standard or capacity of the road network normally results in induced traffic. Induced traffic is here defined as 'the added component of traffic volume which did not previously exist in any form, but which results when new or improved transport facilities are provided' (Schmidt & Campbell, 1956). This includes vehicle traffic resulting from increased distances between origins and destinations, changes in travel routes, changes in travel modes, and changes in trip frequencies (Hills, 1996). The amount of traffic induced from a given road development depends heavily on the context, and the long-term effect (e.g. after more than four years) is generally considerably larger (typically at least twice as large) than the short term (e.g. one year after the opening) effect (Litman, 2019a; Twitchett & Nicolaisen, 2013). In the context of the present study, the long-term effect is the relevant one.

Most studies aiming to measure the size of induced traffic have been conducted in the USA, and only a few European examples exist. According to Litman (2019a, p. 10), a ten percent increase in highway capacity typically results in long-term induced traffic of five to ten percent, but some studies presented in Litman's literature review have shown effects as small as 3 % and as high as 11 %. All the studies included in this overview were from the USA and published between 1993 and 2002, and the validity of the elasticities to a contemporary European context must therefore be interpreted with care. Anyway, it seems reasonable to assume that the variation in elasticities found in the studies (from 0.3 to 1.1) to a great extent reflects different geographical contexts of the road capacity increases. According to a study of Danish road projects (Twitchett & Nicolaisen, 2013), induced traffic was nearly twice as large for motorways as for ordinary highways, with particularly strong effects for motorway bridges across sounds or fjords. For rural bypass roads, induced traffic was very small (close to zero). Moreover, according to Strand et al. (2009), growth in traffic and greenhouse gas emissions due to road capacity increase tends to be considerably greater in large cities and metropolitan areas than for small cities and intercity travel.

Like for rail construction, road development entails considerable energy use and greenhouse gas emissions during the construction period, particularly when the roads go through tunnels. According to Strand et al. (2009), the greenhouse gas emissions due the construction activities would typically be 6 – 12% of those resulting from induced traffic when extending an urban motorway in a large city or metropolitan area from four to six lanes, whereas the corresponding figures for a smaller town would be 22% and 52%, respectively, when building a four-lane and a two-lane road. Since the greenhouse gas emissions from road traffic were, at the time of the publication of the Strand et al. (2009) report, practically proportional to the energy use, the above figures could be taken as indicators of the magnitude of energy use for road construction in the situations described, compared to the increased energy use due to induced traffic.

According to Litman (2019a), induced traffic due to road construction tends to be higher in cities where the congestion level is high than in cities with more moderate congestion levels. According to TomTom (2019), Eastern European cities are the most congested ones, while Southern European cities also are overrepresented among the cities with high levels of congestion. In contrast, Nordic cities have generally low congestion levels. There is therefore reason to assume that induced traffic due to a given percentage of road capacity increase will normally be higher in Eastern Europe, somewhat higher in Southern Europe and lower in Northern Europe than the European average, whereas Western and Central Europe would show effects similar to the European average.

Based on the above considerations, our estimates of present-day effects (measured as elasticities) of highway capacity increase (measured in percentages of lane kilometers) on increases in traffic levels (measured in percentages of vehicle miles traveled) are as follows (Table 3.3). Since most quantitative studies showing elasticities of such effects are from the USA, the table does not distinguish in terms of availability of empirical evidence from the between different parts of Europe.

Table 3.3: Present-day effect estimates of highway capacity[15] increases (% increase in lane kilometers) on long-term traffic levels (% increase in vehicle kilometers) in different parts of Europe, for different city sizes and intercity traffic.

| Geographical context | Northern Europe | W & central Europe | Southern Europe | Eastern Europe |
|---|---|---|---|---|
| Large cities and metropolitan areas | 0.8 | 0.9 | 1.0 | 1.1 |
| Smaller cities and towns | 0.4 | 0.5 | 0.6 | 0.7 |
| Intercity traffic | 0.4 | 0.5 | 0.6 | 0.7 |

As for the impacts of built environment characteristics on travel, present-day effects of highway capacity increases will not necessarily remain the same in the future. Again, a number of qualitative judgments had to be made concerning conditions that might in the future increase or reduce the present effects of highway capacity expansions.

Since the road capacity expansions in question apply to the business-as-usual scenarios, not the energy efficiency scenarios, it is reasonable to assume a general mobility growth in the European countries. In the absence of road capacity increase, there will then be a greater suppressed demand for road space that will be released when additional capacity is constructed, compared to a situation with no growth in the general mobility levels. In the business-as-usual alternatives for the future, somewhat larger induced traffic could thus be expected than in the present situation. At the same time, the present differences between countries with a long and a shorter history of mass automobility could be expected to be gradually diminishing.

Based on such considerations, we assume the following effect estimates for the future situation to which the scenarios refer (Table 3.4):

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[15] In this term, we also include standard improvements often taking place when increasing highway capacity. Such standard improvements may, for example, reduce travel time by reducing the number of crossings, straightening up bends and by allowing for higher speed limits, and thus make road traffic more attractive.

Table 3.4: Estimates of future (2050) effects of highway capacity increases (% increase in lane kilometers) on long-term traffic levels (% increase in vehicle kilometers) in different parts of Europe, for different city sizes and intercity traffic.

| Geographical context | Northern Europe | W & central Europe | Southern Europe | Eastern Europe |
|---|---|---|---|---|
| Large cities and metropolitan areas | 0.9 | 0.95 | 1.0 | 1.05 |
| Smaller cities and towns | 0.5 | 0.55 | 0.6 | 0.65 |
| Intercity traffic | 0.5 | 0.55 | 0.6 | 0.65 |

The energy use associated with the construction period will probably not vary systematically between the four geographical regions of Europe (North, West/Central, South and East), but instead between mountainous regions and regions with smaller altitude differences. Based on Strand et al. (2009:39), we estimate the following energy consumption per lane kilometer for road constructions on average, and with specific rough estimates for mountainous and non-mountainous parts of Europe (Table 3.5). The figures given by Strand et al. refer to a mountainous country, Norway, and we have assumed lower figures for non-mountainous countries as well as for the overall European average figures[16].

Table 3.5: Energy consumption factors pertaining to the period of highway construction.

| Geographical context | GJ per lane kilometer and lifetime year |
|---|---|
| Overall average, four-lane or more | 820 |
| Overall average, two-lane | 530 |
| Non-mountainous regions, four-lane or more | 660 |
| Non-mountainous regions, two-lane | 420 |
| Mountainous regions, four-lane or more | 1310 |
| Mountainous regions, two-lane | 850 |

In addition to the energy spent on the construction of roads, maintenance and operation during their lifetime also requires energy. Such energy use can be substantial, and based on several sources, they might amount to twice as much over the lifetime of a road scheme as the energy consumption during the construction period (Strand et al., 2009; Secretariat of the National Transport Plan, 2010). We will discuss this in more detail in Chapter 6.3.

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[16] We have very roughly assumed energy consumption per km to be on average twice as high in mountainous as in non-mountainous countries. Moreover, we have roughly classified one fourth of Europe as mountainous and the rest as non-mountainous.

Regarding *air traffic*, long-time trends until the recent Covid-19 outbreak[17] imply a sharp increase in decades to come. Keeping air traffic at present or reduced levels would obviously yield large energy-saving benefits. If volumes of passenger transport and freight are still presupposed to increase, the growth in freight and travel would instead have to take place by other modes, primarily train. This would require substantial extension and improvement of the rail network. As mentioned above, we have chosen to treat such rail investments at 'energy neutral' due to their counteracting effects (but also due to the very limited knowledge base, large context-dependency and uncertainty about effect sizes). Curbing or reducing air traffic could take place by a combination of economic-administrative (e.g. high carbon taxes) and physical (e.g. ceasing to increase runway capacity) measures. In our energy-efficiency scenario we therefore assume a halt in future airport capacity development combined with carbon taxes sufficiently high to stop further growth in air traffic.

## 3.3 Road pricing and parking fee effects

In addition to land use and transport infrastructure policies, the energy efficiency of transportation can be influenced by economic instruments such as road tolls[18], parking fees, road pricing[19] and fuel taxes. The impacts of these measures are difficult to estimate, since relatively few studies have been carried out. The contexts of these studies also vary substantially. Moreover, some of the solutions (such as urban toll cordons) have been applied in only a few cases, and some hardly at all (schemes for general road pricing within an urban area). However, for the latter type of instruments, model simulations have in some cases (such as in Oslo) been made, based on experiences from the effects of toll cordons.

Since sEEnergies addresses energy efficiency measures and not reductions in energy use that are obtained at the cost of reduced need satisfaction, economic instruments relevant in this context should contribute to reduce energy use while maintaining accessibility to relevant facilities. Some economic instruments are already in use in some countries to promote more energy-efficient vehicles, for example reduced road tolls and privileged access for electric cars to highway lanes otherwise reserved for buses and taxis, and fuel taxes encouraging a transfer to cars requiring less gasoline or diesel. These effects are, however, already included in the analysis of energy efficiency potentials through improved vehicle technology (cf. Task 2.1). Fuel taxes, road tolls, road pricing and parking fees can, however, also influence travel distances and the shares of different modes of transportation (cf. Tasks 2.2 and 2.3). They can thus supplement the influences of land use policies and transport infrastructure development in promoting energy-efficient modal shares and shorter travel distances. However, if accessibility is to be maintained, economic instruments discouraging, for example, car travel must only be used where alternative modes of travel (transit, and for shorter trips appropriate infrastructure for biking and walking) are available. This is the case mainly in cities and urban regions,

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[17] As mentioned in Chapter 1, this report is based, in line with the overall sEEnergies project, on the assumption that mobility trends will quickly be re-established to the pre-Corona trajectories, and that the business-as-usual scenario will be not be much affected by the current Covid-19 pandemic.

[18] Based on payment at specific toll points, often located as one or more cordons around the inner parts of the city.

[19] Based on payment per kilometer driven, registered through electronically recording the movement of vehicles.

whereas alternative modes are much less available in rural areas for travel beyond acceptable walking and biking distance.

Economic instruments such as road pricing, road tolls and parking fees can also encourage people to choose relevant local facilities rather than facilities further away from home. Such limiting of the radius of action can, however, imply lower accessibility to specialized facilities, for example many kinds of workplaces, specialized stores and cultural facilities. For some kinds of activities, such as grocery shopping, the use of local stores rather than distant shopping malls would probably not cause any important accessibility loss, but for many other activities, reducing trip lengths to relevant facilities below what is enabled through proximity-generating land use development will represent a disbenefit, since people will then more often have to choose a less satisfactory facility than the one they would have preferred. Reducing mobility below a level compensated by higher proximity provided through compact urban development would thus belong to a 'degrowth' scenario rather than to an efficiency scenario. On the other hand, road pricing and urban road tolls could counteract any tendency of utilizing the increased proximity to facilities provided by compact urban development to increase the number of facilities among which to choose, rather than reducing traveling distances. This might increase the effect of densification policies on travel behavior, compared to a situation where no economic instruments to limit mobility were in place.

For rural and intercity travel, economic instruments rarely aim at managing transportation demand but are rather used to provide revenues to be spent on transport infrastructure construction and maintenance. Fuel taxes and road tolls outside the urban regions mainly belong to these categories. In our analyses, we will therefore not include these instruments. Instead, our focus will be on road pricing, road tolls and parking fees applied specifically in urban areas.

As mentioned above, only a few studies have investigated the effects on overall traffic in a city or metropolitan area of urban road tolls or urban road toll cordons. The effects of toll cordons depend on, among others, the number and location of payment points, and the number of cordons. For individual toll roads, any traffic reducing effect depends on the availability of alterative driving routes in the same transport corridor. There do exist a number of studies showing elasticities for road tolls on the traffic on individual roads and in some cases also for the transport corridor as a whole (Olszewski & Xie, 2002; Odeck & Bråthen, 2008; Dunkerley et al., 2014; Litman, 2019b). According to Odeck & Bråthen (2008), elasticities at 19 Norwegian toll roads were on average -0.54 in the short run and -0.82 in the long run. In Oslo, an increase in road tolls from 33 NOK to 43 and 53 NOK, respectively, for non-rush and peak period, while keeping the existing fee level of heavy fossil vehicles at 100-190 NOK (depending on vehicle type), was forecasted to reduce overall road traffic in 2036 by 4 percentage points, compared to a business-as-usual scenario (Litman, 2019b). In the Puget Sound in northwestern USA, an overall elasticity of 0.12 was found between road toll taxes and car driving, but a much lower elasticity for journeys to work. For commuters with good transit accessibility between home and workplace, the elasticity was, however, four times as high as the average elasticity for commuting (Litman, 2019b). The different contexts of the urban regions in which studies have been carried out make it problematic to draw general conclusions about the sizes of the effects of road pricing on travel behavior. For example, the 'car culture' is more ingrained in the USA than in most European countries, and opportunities for using travel modes other than the car are also often less developed in American cities.

Moreover, it appears very difficult to upscale findings for individual toll roads to the scale of a city or a city region. In addition, most transport researchers recommend that transportation demand management in urban areas should rather be conducted through road pricing covering the whole road network (typically GPS-based) than through tolls on individual roads or toll cordons. Such general road pricing schemes are also said to be more efficient and can obtain a given traffic reduction at lower expenses for the drivers than toll cordons can (Norconsult and Municipality of Oslo, 2020). We will therefore use road pricing instead of toll cordon or road tolls as an instrument to be use in the energy efficiency scenario. In addition to road pricing, parking fees in downtown areas and other main workplace concentrations will be included in this scenario.

Distinct from land use and transport infrastructure development, where elasticities for changes in residential location, urban density and road capacity have been applied, elasticities are less relevant when the instruments in questions have hardly been used at all (schemes for general road pricing in a city or city region) or in some cities/city districts, but not all (parking fees). For road pricing and parking fees, we will therefore use results from the most recent, state-of-the-art modeling of likely effects (road pricing) and studies of percentage traffic reductions from introducing the measure (parking fees).

### 3.3.1 Effects of introducing road pricing

The study we have come across from a European country that seems to offer the best indication of the effect of introducing a city-scale road pricing scheme in terms of reducing car traffic is a recent model simulation conducted by Norconsult (2020) for the Municipality of Oslo. Oslo and its city region is an area with a long history or road tolls, and since 1990 a toll cordon system has been in place, consisting of a set of toll cordon rings gradually expanded from only one cordon of manually operated toll stations when the system was introduced to currently a more fine-grained system of several rings including 86 automatically operating toll spots. The model simulations by Norconsult therefore draw on a rich empirical material from studies of the effects of the changes that the tolling system has undergone during its three decades of operation. Taxes are differentiated, for example, there is a discount of more than 50% for electric cars. Driving outside the peak periods is also less expensive than peak-period driving. With these time- and vehicle-differentiated taxes, it is rather complicated to calculate an average reduction in car traffic from a given tax level. Moreover, at the time horizon of the energy-efficiency scenario, the entire car fleet is supposed to be electrical. Fortunately, one of the model simulations by Norconsult (2020) deals with precisely the effect of a road pricing scheme in a situation where the entire vehicle stock of is electric. We have therefore chosen to apply the traffic-reducing effect of a given price per km of car-driving as the effect of road pricing in a Northern European city of around 1 million inhabitants.

According to the model simulations by Norconsult (2020), a tax of 2.87 Euro per kilometer for light vehicles (i.e. less than 3.5 tons) will reduce the car share of motorized trips starting from residences within the municipality of Oslo from 50% to 39% in 2030. This reduction of 11 percentage points implies a reduction of 22 % from the 50% car share in the business-as-usual scenario, or 7.7% per Euro. In the simulation, a much lower tax per km (0.11 Euro) was assumed for the county of Akershus surrounding the municipality of Oslo. This was predicted to reduce the proportion of car trips from 85% to 82%, i.e. by 3.5%, which implies a reduction of 33% per Euro (Norconsult, 2020). The larger reduction per Euro in Akershus reflects that a higher proportion of current trips in this predominantly suburban and exurban county are ‘non-essential’ and can thus be replaced with other solutions, compared to Oslo where existing toll cordons, parking scarcity, parking fees and dense built environments have contributed to a situation where fewer car trips belong to the ‘non-essential’ category.

Based on the above reasoning, the energy-efficiency scenario should apply higher road pricing per kilometer in the central parts of each metropolitan area than in its outer parts. The tolls should also be higher in large cities than in small cities. Using Oslo as an example, the morphological city also includes some parts situated in the county of Akershus. These parts account for one third of the population of the morphological city. The above-mentioned taxes per kilometer therefore translate into approximately 2 Euro per km for car driving within the morphological city. For simplicity, we assume that the percentage reduction in car traffic will then be the same as for the municipality of Oslo in the example above.

In the energy efficiency scenario, we will thus apply the following road pricing taxes[20] per km and corresponding traffic-reducing effects of road pricing in different parts of metropolitan areas and for different city sizes (Table 3.6). The fees apply to the 2020 situation and should be adjusted for income growth during the period up to the 2050 horizon.

Table 3.6: Road pricing taxes per km and travel mode effects assumed in the energy efficiency scenario. The sizes of the fees apply to the 2020 situation and should be adjusted for income growth during the period up to the 2050 horizon.

| Population of morphological city | Within the morphological city | Within the rest of the metropolitan area | Average for the whole metropolitan area | Percent reduction in car share per Euro | Percent reduction in car share with presupposed taxes |
|---|---|---|---|---|---|
| 1 million and above | 2 Euro | 0.1 Euro | Approx. 1.5 Euro | 8.5% | 13% |
| Between 100,000 and 1 million | 1 Euro | 0.1 Euro | Approx. 0.8 Euro | 10% | 8% |
| Between 10,000 and 100,000 | 0.5 Euro | 0 | Approx. 0.3 Euro | 15% | 4% |
| Below 10,000 | 0 | 0 | 0 | 0 | 0 |

### 3.3.2 Effects of increasing or introducing parking fees

According to Christiansen et al. (2017), parking restrictions can contribute substantially to reduce car driving in urban areas, especially when combined with compact spatial urban development. Using national-scale travel survey data, they found that particularly scarcity of parking at the workplace and residence was associated with lower car use, but parking fees at the workplace also had effects. For workplace parking fees, the study indicated that the effect on the share of workers commuting by car was twice as high if workers had to pay daily instead of per month, which was the most commonly used payment scheme. However, Christiansen et al. distinguished only between charged and non-charged parking without taking into consideration the size of the parking fee.

Apart from parking fees, parking policies to reduce car driving in cities can also include a reduction of the space set aside for parking. The effect of this policy measure is partly already included in the effect

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[20] The prices apply to the 2020 situation. The fees should be adjusted for income growth during the period up to the 2050 horizon.

estimates of urban density and residential location, since dense cities and inner-city areas have on average lower availability of parking spaces than low-density cities and suburban areas. Some of the presupposed future urban densification in the energy efficiency scenario may also take place on previous parking areas. Still, even for high-density cities and downtown or inner-city districts it is possible to reduce the present availability of parking opportunities (and of course also to avoid future increases in the availability of parking space). The effects of reduced parking availability would then come in addition to those of parking fees. We have, however, not been able to quantify the travel behavioral and energy consumption effects of systematically converting parking space in cities to other kinds of land use.

The number of studies that have investigated effects on car driving from a given size of parking charge appears to be rather low. Litman (2019b) has reviewed such studies internationally and shows only a few examples. Very few are from Europe, whereas American studies dominate. One of the US studies is a study by Frank et al (2011), using data from Seattle, USA and its surrounding county. They found that increasing parking fees from $0.28 to $1.19 per hour was associated with a reduction in car-driving distance of 11.5%. Another study reviewed by Litman (Hess, 2001) assessed the effect of free parking on commuter mode choice and parking demand in Portland's (Oregon) CBD. According to this study, compared to a situation where parking is free, a parking charge of $6.00 was associated with 21 fewer cars driven for every 100 commuters, and an annual reduction of 39,000 vehicle miles traveled per 100 commuters (Hess, 2001, quoted from Litman, 2019b).

Another study, conducted in the Vancouver area in Canada (Washbrook et al., 2006), found that a parking fee of one Canadian dollar would typically reduce the proportion of drive-alone commuters by 3-4 percentage points, regardless of whether parking fees were combined with road tolls and the levels of such tolls (up to CA$9). If the parking fees were 9 Canadian dollars, the proportion of drive-alone commuters would typically be reduced by around 35 percentage points. The reductions associated with intermediate levels of parking fees (CA$ 3 and 6) were 12-13 and 21-24 percentage points, respectively (Washbrook et al., 2006). On average, the reduction in the share of drive-alone commuters was thus approximately 4 percentage points per Canadian dollar of parking fees.

According to Kuzmyak, Weinberger and Levinson (2003, quoted from Litman, 2019b) the elasticity of vehicle trips with regard to parking prices is typically –0.1 to –0.3, but with substantial variation depending on demographic, geographic, travel choice and trip characteristics. Based on a review of 9 studies conducted in the United States (six studies) as well as in Canada, Australia and Europe (one each), Spears et al. (2014) conclude that there appears to be general agreement that each 10% increase in parking price is associated with approximately 3% reduction in the demand for parking spaces, i.e. an elasticity of -0.3. This also applies to the only European study included in their review, where Kelly & Clinch (2009) found an elasticity of -0.29. However, as noted by Litman (2019b), parking price elasticities can be confusing since in many countries, including the USA, most parking is currently free, and it will then not make sense to measure percentage increases from a price of zero.

In the absence of evidence from European studies, we will cautiously apply the traffic-reducing effect found in the Canadian study by Washbrook et al. (2006), where one Canadian dollar of parking fees was typically associated with 4 percentage points reduction in the number of car commuters. We assume that this applies to a European context as well, and that it applies to all kinds of trip purposes, not only commuting. Measured in Euro, this implies a reduction of approximately 2.5 percentage points per Euro in the proportion of car travelers to destination with charged parking.

In a report on the evolution of European parking policies, Kodransky & Hermann (2011) highlighted ten European cities as examples of parking policies aiming at reduced car traffic. The cities were Amsterdam, Antwerp, Barcelona, Copenhagen, London, Munich, Paris, Stockholm, Strasbourg and Zurich (cf. Chapter 7, where land use and transport policies in some of these cities are discussed). Among these cities, the first-hour parking fee in the city center was highest in Amsterdam (5 Euro) and lowest in Vienna (1.20 Euro). The prices reported in 2011 are higher than those reported a decade earlier (Bannerman, 2002), although it is uncertain whether the latter figures applid to the same spatial demarcations as those in the report from Kodransky & Hermann (2011). Parking fees have also increased since 2011 in some cities, such as Vienna, where motorists currently have to pay 2.20 Euro per hour in the city center (Municipality of Vienna, 2020), compared to 1.20 in 2011. On the other hand, parking fees have remained constant at 5 Euro per hour in Amsterdam (Municipality of Amsterdam, 2020). In Copenhagen too, there has been little change over the last decade, with a current parking price in the most central part of the downtown area of 5 Euro per hour and 3 Euro in the rest of the downtown area (Municipality of Copenhagen, 2020), compared to a reported downtown parking price in 2011 of 3.86 Euro per hour. The European city currently at the top end of parking fees appears to be Oslo, where the current parking fee in the downtown area is 7-8 Euro per hour for gasoline, diesel and hybrid cars, but with 80% discount for electric cars. In the rest of the inner city, parking for non-residents of the local neighborhood costs approx. 3 Euro per hour, whereas local residents have to pay approx. 350 Euro annually for parking in these neighborhoods (Municipality of Oslo, 2020).

According to COST Action 342 (2005), there is a clear correlation between city size and the level of parking fees, with maximum tariffs about twice as high in cities of more than 100,000 inhabitants than in cities of less than 20,000 inhabitants, and with a similar doubling tendency when the population increases from 100,000 to one million.

Based on the above, we propose parking fees similar to those currently used in Oslo for non-electric vehicles to be applied in all European cities of one million or more inhabitants in the energy efficiency scenario. The fees should be adjusted for income growth during the period up to the 2050 horizon. Since parking fees in the energy efficiency scenario are used to influence travel behavior (and not as an encouragement for motorists to buy electric vehicles – this would be unnecessary since all vehicles in the energy efficiency scenario are supposed to be electric), the Oslo taxes for fossil propulsion cars are the ones that should be adopted, not the hugely discounted fees for electric vehicles. This implies an 8 Euro fee per hour in the downtown area and a 3 Euro fee in the rest of the inner city.

Reflecting the above-mentioned differentiation in parking fees according to city size, the fees for a city of 100,000 inhabitants should be 4 Euro and 1.5 euro, respectively, for the downtown and the rest of the inner city, and for a city of 20,000 inhabitants it should be 2 Euro and 0.75 Euro, respectively. However, since we are operating with population size intervals of 10,000 to 99,999 inhabitants and 100,000 to 999,999 inhabitants, we propose fee levels corresponding to the midpoints between the values at the ends of each interval. We thus propose for the city class with population between 100,000 and one million an hourly parking fee of 6 Euro in the downtown area and 2.25 Euro in the rest of the inner city, and for cities with a population of 10,000 to 999,999 inhabitants a fee, only for the downtown area, of 3 Euro per hour.

We do not have available statistics of current parking fees in European cities, but based on the moderate changes since 2011 in several cities and an internet check of current prices in a handful of cities, we roughly assume that current parking fees in downtown areas to be on average around 2 Euro per hour, with somewhat higher rates in North, West/Central and Southern Europe and lower rates in Eastern Europe. In the business as usual scenario, we thus assume the following parking fees for cities of 1 million inhabitants or more: 2.5 Euro per hour in downtown areas of North, West/Central and Southern European cities and 1 Euro per hour in the rest of the inner cities in that population size class in these regions of Europe, and 0.75 Euro and 0.25 Euro, respectively, in Eastern European cities. For cities between 100,000 and 1 million inhabitants, we assume fees of 2 Euro and 0.75 Euro, respectively, for downtown areas and other inner-city areas in cities of North, West/Central and Southern Europe, and 0.5 Euro, only for the downtown area, in Eastern European cities. For the smallest city class (between 10,000 and 100,000 inhabitants), we assume current fees of 1 Euro in the downtown areas of North, West/Central and Southern European cities, and no fees at all in Eastern European cities.

The parking fees assumed above for the energy efficiency and business as usual scenarios apply only to the downtown and inner areas of the cities. This means that only a limited proportion of all trips will be affected by the fees. However, in most cities, a considerable proportion of workplaces, stores, service facilities cultural and entertainment arenas and restaurants/cafes are concentrated in the most central districts. For example, in a study of Copenhagen metropolitan area residents, more than one sixth of the respondents' workplaces were located less than 2 km from the city center (i.e. in the downtown area), and one half of the workplaces were located less than 10 km from the city center (Næss & Jensen, 2005:135). Given that the inner city of Copenhagen is commonly considered to consist of the districts up to some 6 km from the city center, the data show that the proportion of workplaces located within the whole inner city thus defined was 38%, with 21% of the workplaces in the inner city outside the downtown area in addition to the 17% in the downtown area. The concentration of stores, restaurants/cafes and cultural and entertainment facilities in the downtown area and the inner city is even more pronounced than for the workplaces. In addition, there is a steep population density gradient, which means that a high proportion of trips to visit friends and relatives will also have their destinations in the central and inner parts of the city. It may therefore be reasonable to assume that one fifth of the trips of Copenhagen metropolitan area residents have destinations in the downtown area and another fifth in the remaining part of the inner city. However, as shown in several studies, many of these trips would anyway be carried out by travel modes other than the car, since non-motorized modes and transit are competitive with car travel in inner-city areas for several reasons apart from just the parking conditions. Therefore, the number of potential car trips affected by inner-city parking fees is considerably lower than the number of trips with destination in these areas. A reasonable assumption might be that 50 % of the trips to the inner city outside the downtown area and 25% of the trips to the downtown area would be carried out by car if there were no parking fees. Here, the *availability* of parking also plays a role apart from the effect of parking pricing, but inner-city scarcity of parking is largely included as part of the already calculated effect of urban densification.

For predominantly monocentric metropolitan areas such as Copenhagen, Oslo and many other large European city regions, we therefore assume that about 6% of the trips will be affected by downtown area parking fees and about 13% by parking fees in the rest of the inner city. For polycentric metropolitan areas (such as the Randstad area in the Netherlands and the Ruhrgebiet in Germany), the above-mentioned considerations apply to each individual large city in the polycentric metropolitan area instead of the metropolitan center.

In the energy efficiency scenario, we will, based on the above, apply the following parking prices per hour in downtown areas and other inner-city areas, and corresponding traffic-reducing effects based on assumptions about existing average parking prices in different parts of Europe and different city sizes (Table 3.7):

Table 3.7: Hourly parking prices and travel mode effects assumed in the energy efficiency scenario. The sizes of the fees apply to the 2020 situation and should be adjusted for income growth during the period up to the 2050 horizon.

| Population of morphological city | Within the downtown area | Within the rest of the inner city | Price increase compared to business-as-usual, North, Central/West and Southern Europe | Price increase compared to business-as-usual, Eastern Europe | Percentage points reduction in share of car travelers per Euro parking fee | Percentage points reduction in car share, in North, Central/West and Southern Europe | Percentage points reduction in car share in Eastern Europe |
|---|---|---|---|---|---|---|---|
| 1 million and above | 8 Euro | 3 Euro | 5.5 Euro (downtown), 2 Euro (other inner-city) | 7.25 Euro (downtown), 2.75 Euro (other inner-city) | 2.5 | 1.5 | 2.0 |
| Between 100,000 and 1 million | 6 Euro | 2.25 Euro | 4 Euro (downtown), 1.5 Euro (other inner-city) | 5.5 Euro (downtown), 2.25 Euro (other inner-city) | 2.5 | 1.1 | 1,6 |
| Between 10,000 and 100,000 | 3 Euro | 0 | 2 Euro (downtown | 3 Euro (downtown | 2.5 | 0.3 | 0.5 |
| Below 10,000 | 0 | 0 | 0 | 0 | --- | 0 | 0 |

# 4 Spatial development in European urban regions over recent decades

## 4.1 Introduction

In this chapter, we will investigate the spatial urban development of European cities and city regions over the period since 1990. The purpose of this analysis is twofold: First, by analyzing the typical spatial development in European cities and regions in the period and contrasting this with the spatial development of the cities and city regions that have pursued the most favorable spatial development, seen from a transportation energy saving perspective, an assessment can be made, drawing on the elasticities identified in chapter 3.1, of hypothetical reduced car-driving distances and energy use for intra-metropolitan transportation if all urban regions in Europe had pursued 'best practice' spatial urban development. This comparison will be done in Chapter 5. Secondly, the historical spatial urban development over the decades since 1990 will provide a basis for the construction of a 'business as usual' trajectory for future spatial urban development from the present to the scenario horizon in 2050. This trend-based scenario will then be compared to an energy efficiency scenario where spatial urban development is supposed to principles favorable to reducing car-driving distances and energy use for transportation (Chapter 6).

The impact of residential distance to the city center as well as that of overall urban population density depends on whether the city is a relatively 'independent' city or a satellite of a larger city. In the latter case, the elasticities will take into consideration the small city's distance to the metropolitan center as well as the mean residential distance of the small city's inhabitants to the center of the small city. As mentioned in Chapter 3.1, the elasticities will thus be applied within the contexts of urban regions, defined as follows:

- Cities with a population of one million or more will include in their urban region all urban areas within a 50 km straight line distance.
- Cities with a population above 100,000 and not included in the regions of the cities with more than 1 million inhabitants will include all urban areas within a 25 km straight line distance.
- Cities with a population above 10,000 and not included in any of the above-mentioned two groups will include all smaller cities within a 10 km straight line distance.

## 4.2 The data material

Time series data on spatial distribution of European populations for 1990, 2000 and 2015 is obtained from the Global Human Settlement (GHS) population raster data in a 250 m resolution world-wide tiled dataset in Mollweide projection. This was transformed to a merged population raster of 100 m resolution. Cells with a population of zero were set to NoData values. The population value of the 250 m cells was divided by 6.25 ($250^2/100^2$) to maintain the approximate overall population count.

Afterwards, population calculation and populated areas count was applied using the 2018 Urban Areas and the population grids created for 1990, 2000 and 2015. One important caveat that needs mentioning here is that, as the global GHS population data has been developed using a different method and hence is not comparable to the native 100m population raster for the year 2016 by the

JRC (GHS 2016R). This is because both the basis for the population count (Gridded population of the World versus Eurostat 2011 Census), and the distribution of population to a grid (simple distribution versus machine-learning approach) were different. Therefore, the population values of the time series dataset cannot be directly compared. The spatial distribution of European population is based on the 2016 Global Human Settlement population grid (100x100 grid cells) and presented by the European Commission's Joint Research Center (JRC 2016).

To illustrate, based on the world-wide tiled dataset (utilized in this report), the total European population estimate for 2015 was about 387 million. The data that is based on 2011 Eurostat census and reported by the European Commission's Joint Research Center (JRC 2016) reports it at 449 million.

Despite a 16 percent divergence between the two sources, this difference is expected to be of little consequence to the spatial and temporal population distribution.

Tables 4.1 to 4.3 below present summary tables based on population distribution for the last year in the time series, 2015. The city classes indicate urban areas (UA) hierarchy bases on population size (2011 Eurostat census). All three tables underline that middle-sized cities, those with population sizes between 100 000 and 1million accommodate the highest share of the Europeans populations.

Table 4.1: City class aggregates for all European countries taken together.

| Variables | Population size by city classes | | | | | Total |
|---|---|---|---|---|---|---|
| | >= 1 mill. | 100 000 – 999 999 | 10 000 – 99 999 | 1 000 – 9 999 | < 1 000 | |
| Urban areas | 37 | 523 | 4 944 | 35 887 | 105 532 | 146 923 |
| Population | 49 537 514 | 119 983 917 | 111 394 814 | 76 802 999 | 28 914 695 | 386 633 939 |
| Population share | 13% | 31% | 29% | 20% | 7% | 100% |

Table 4.2: Population size in urban areas (2015) by city classes aggregated to European regions.

| European region | Population size by city classes | | | | | Total |
|---|---|---|---|---|---|---|
| | >= 1 000 000 | 100 000 – 999 999 | 10 000 – 99 999 | 1 000 – 9 999 | < 1 000 | |
| Northern Europe | 3 492 084 | 3 695 664 | 5 826 540 | 3 691 375 | 1 208 063 | 17 913 726 |
| Western & Central Europe | 17 982 224 | 74 096 143 | 56 694 865 | 37 014 364 | 12 585 529 | 198 373 125 |
| Southern Europe | 20 134 213 | 24 742 432 | 25 896 292 | 17 550 774 | 4 932 449 | 93 256 160 |
| Eastern Europe | 7 928 993 | 17 449 678 | 22 977 117 | 18 546 486 | 10 188 654 | 77 090 928 |
| Total | 49 537 514 | 119 983 917 | 111 394 814 | 76 802 999 | 28 914 695 | 386 633 939 |

Table 4.3 shows populations aggregated at urban regional scale for different European regions. The city classes refer to the highest-order urban urea in a given urban region. As shown in the above two tables, a significantly higher proportion of the European population resides in middle-sized urban regions, followed by larger cities.

Table 4.3: Population size (2015) by urban regions, aggregated to European regions.

| European region | Population distribution in urban region | | | Total | Population share |
|---|---|---|---|---|---|
| | >= 1 000 000 | 100 000 – 999 999 | 10 000 – 99 999 | | |
| Northern Europe | 5 697 772 | 4 429 196 | 5 145 052 | 15 272 020 | 4% |
| Western & Central Europe | 58 917 645 | 89 755 192 | 30 624 311 | 179 297 148 | 52% |
| Southern Europe | 36 433 129 | 28 129 471 | 19 708 968 | 84 271 568 | 25% |
| Eastern Europe | 13 958 326 | 24 710 627 | 24 017 856 | 62 686 809 | 18% |
| Total | 115 006 872 | 147 024 486 | 79 496 187 | 341 527 545 | 100% |
| Population share | 34% | 43% | 23% | 100% | |

Since urban area units in the Global Human Settlement dataset used in this report are defined as NUTS3 subregions [21], the morphological city (i.e. the continuous urbanized area) is in many cases divided into separate urban area units. Such cases include London, Birmingham, Riga, Copenhagen, Paris, Lisbon, Oslo, Katowice, Dortmund, Amsterdam, Manchester, Leads, Liverpool and Nuremberg, among the prominent ones. The challenge of such subdivisions is evident when measuring intra-urban and inter-urban distances, as each subdivision is treated as an independent city. Cities that are split into several urban area units present a challenge because:

i. Intra-urban and inter-urban distances are not measured from a unitary/common center in the city.
ii. When a large city such, e.g. London, is subdivided into many NUTS3 subregions, the regions may individually have less than a 1 million residents. In such cases, the nearest higher order city is likely to be another city. As a result, the various urban area units in greater London are linked to Birmingham as their nearest higher-order city.
iii. Even when some of the urban area units in a city have a population of more than 1million, aggregation still becomes difficult if there are more than one large urban area unit in the same population class (e.g. in Paris).

Cities that are split into many urban area units where one of the urban areas belongs to a higher population class, would not have the above problem since the inter-urban distance would be measured with respect to the higher-order urban area unit (i.e. the urban area unit of the city belonging highest population class).

**Conclusion**:

After grappling with how to aggregate the urban area units in a manner that reflects spatial interaction between and within them, the following solutions are adopted:

a) Aggregation across urban area units to create urban regions. Here, urban hierarchy as indicated by population size and the corresponding distances to centers of satellite cities and the center of the main morphological city of the region, described in Chapter 3.1 and in 4.1 above, is used.

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[21] The NUTS classification (Nomenclature of territorial units for statistics) is a hierarchical system for dividing up the economic territory of the EU and the UK. For the purpose of socio-economic analyses of the regions, the NUTS3 classification defines ‘small regions for specific diagnoses’ (Eurostat, 2020a).

b) Cities that are fragmented into several urban area units belonging to the same population size class, are aggregated around the central urban area unit to create a unified spatial unit for the entire morphological city.

## 4.3 Calculating mean, population-weighted residential distance to the main city center of an urban region

As mentioned in Chapter 3.1, the urban spatial characteristics for which we have developed effect estimates on travel and transportation energy use are the distance from residences to the main center of the urban region, and the population density of morphological cities. In order to calculate how the first of these variables has developed over the decades since 1990, we have for each year for which data are available (1990, 2010 and 2015) calculated the inhabitants' mean distance to the city center, following a two-step procedure. First, we have calculated the mean, population-weighted distance from the inhabitants' residential areas to the city center of each morphological city (termed 'urban area' in the GHS database terminology). For urban area units outside the main city of the urban region to which they belong (termed 'satellite cities' below), we have in addition measured the distance from the center of each such urban area to the center of the main urban area of the region and added this to residential mean distance to the center of the local urban area, again weighted by population. Finally, we have calculated the mean distance to the center of the main urban area for all inhabitants of the urban region by combining the mean residential distance to the center of the main urban area for the inhabitants of this urban area and the mean distance for the inhabitants of the other urban area units of the urban region, once again weighted by population.[22] The calculation method is described in detail below.

i. Step1: Grid cell distance to the center of an UA.; $\boldsymbol{D_i = P_{ij} D_{ij}}$; where $P_{ij}$ is grid *i* 's population size in UA *j,* and $D_{ij}$ is distance from a grid *i* to the center of $UA_j$.
ii. Step2: population weighted average intra-urban distance (km): $\boldsymbol{D_j = \frac{\sum P_{ij} D_{ij}}{P_j}}$; where $D_j$ is population weighted intra-urban distance for $UA_j$; $P_j$ is population in $UA_j$.
iii. Step3: integration of a satellite city into a wider urban region (UR): $\boldsymbol{D_j + D_{ur}}$ where $D_j$ is as defined in point ii); $D_{ur}$ refers to inter-urban distance, i.e. the satellite city's distance to the center of the urban region.
iv. Step4: Average intra-urban region population weighted distance: $\boldsymbol{D = \frac{\sum (D_j + D_{ur}) P_j}{P_{ur}}}$; where $D_j$ , $D_{ur}$ and $P_j$ as previously defined; $P_{ur}$ is total population for the urban region. Inter-urban

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[22] One might object that this way of calculating mean residential distance to the center of the region's main urban area tends to overestimate the distance, since residents of an urban area outside the main one do not necessarily travel to the main urban area via the center of the local urban area where they live. Many of the inhabitants of such an urban area (on average around a half) will likely have to make a detour if they travel to the main urban area via the local center. Arguably, those with a distance to the main urban area living closer and further than that of the local center may balance each other. It would then be sufficient to calculate the mean, population-weighted distance from the center of each urban area unit outside the main urban area to the center of the main urban area. On the other hand, the transport infrastructure network (especially for public transport, but to some extent also roads) is often more or less radial, also in smaller urban areas, and travelers may then have to go inward towards the local center before turning towards the main urban area. We have therefore chosen to keep the described calculation method, although we are aware that another approach might be equally appropriate. We anyway believe that the tendency of overestimated distances resulting from our method will not affect the calculated changes over the period 1990-200-2015, since the distances are calculated in the same way at all three points in time.

distance, $D_{ur}$, assumes value only for satellite cities. For the main city in the urban region, $D_{ur}$ assumes a unitary value.

## 4.4 Calculation of urban population densities

Urban population densities are calculated in a very straightforward way by dividing the number of inhabitants of each urban area unit by its area size. Density is calculated at each level of aggregation (Urban regions, country, European regions and for the whole EU/EFTA area). Aggregation within an urban region, a country, a sub-region of Europe or for the entire EU/EFTA area is always population-weighted, i.e. the total population of the urban areas within the relevant demarcation is divided by the total area size of the urban areas within this demarcation. The calculations of urban population densities are limited to urban regions where the main urban area has a population size of at least 10,000. Small settlements within an urban region are excluded from the density calculations if their population size is below 50 and/or their populations density is 100 inhabitants or less per km$^2$ (see below).

## 4.5 Data cleaning

Below, some steps to counteract potential sources of error in the data material are described

**Exclusion of small urban area units with few inhabitants and unreliable density figures**

An inspection of the data material showed that a large number of small settlements were recorded with a population density of exactly 100 persons per km$^2$. This gave rise to suspicion that the area size of these settlements was just set to 0.01 km$^2$ per person, without any real area measurement. Prior to aggregations, urban areas with density of <=100 persons per km$^2$ were therefore excluded. Also, very small urban areas with less than 50 inhabitants were excluded.

**Larger urban areas not included**

**Urban areas with a population of 1 million or more.** Urban areas linked to four higher order cities in neighboring countries have been removed. This was because inter-urban distance measurements in the database were not constrained by country boundaries, i.e. an urban area could be associated to the nearest higher order urban area irrespective of state boundaries. This disregarded the fact that national borders are often (and increasingly, it seems) a barrier against spatial interaction. The urban areas in question were therefore not included in the calculations.

**Urban Areas with population between 100,000 and 1 million.** 75 such urban areas were removed as they were linked to higher-order cities in neighboring country. These urban areas are often located close to state borders and are spatially (but not administratively and politically) seamless extensions in the urban conurbation associated with a larger city on the opposite side of country borders. The excluded UA account for a total of 2.7 mill. residents.

**Urban Areas with population between 10,000 and 100,000.** 105 such urban area (with a total population of 290,000) were excluded because they were associated with urban regions in neighboring countries.

## 4.6 Summarized results

Below, the spatio-temporal distribution of relevant indicators (population, density and settlement) will be presented. The presentation here will focus on the level of European sub-regions (Northern Europe, Western & Central Europe, Southern Europe and Eastern Europe). The data for individual countries show some anomalies compared to other sources, particularly regarding mean residential distance to the main center of the urban region[23]. This may be due to the way these distances have been calculated in our data set, cf. the discussion in Chapter 4.4. Among the urban regions in the medium and the smallest population size classes there are also some peculiar density figures[24]. As mentioned earlier, we believe that such anomalies will largely cancel out each other at an aggregate level, which is why we have chosen to present only calculations at the level of European regions in this chapter. Tables and figures for individual countries are shown in Appendix D.

### 4.6.1 Europe-region aggregation of urban regions with core urban areas in different population size classes

Below, we will first present results from the analysis of how urban population densities and residential distance to the main city center have developed over the period 1990-2015 for urban regions in the highest population size class (one million or above). Thereupon, similar results for urban regions in the medium population (100,000 to 999,999) and lowest (10,000 to 99,999) size classes will be presented.

#### Urban regions in the highest population size class

For the urban regions in the highest population size class, urban population densities have increased in North, West & Central and Southern Europe but decreased in Eastern Europe (Table 4.4). The density increase has been particularly strong in Northern Europe, where the urban regions with main cities of a million inhabitants or more have on average increased their population densities by 22.5%. Iceland does not have any city in this size category and the remaining four Nordic countries have only one each, the above-mentioned density increase refers to the urban regions of Oslo, Stockholm, Copenhagen and Helsinki. In particular, the densification has been strong in the Oslo region, where the national-scale data show a density increase of 33%. The density increase in the West & Central and Southern European urban regions in this population size class has been more moderate (9.5% and 6.3%, respectively, whereas Eastern European urban regions with main cities of a million inhabitants or more have on average reduced their urban population densities by 5.7%.

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[23] For example, for urban regions with a population in the main urban area of more than one million inhabitants, our data show a decrease of 4.6% in the mean residential distance to the center of the urban region in Norway and a decrease of 5.8% in Finland for the same category of urban regions. Since there is only one urban region belonging to this class in each country, the data refer to the Oslo region and the Helsinki region, respectively. However, according to data from Statistics Norway (2019) and Finnish Environment Institute and Statistics Finland (2019), reported in Tiitu et al. (2020), the mean residential distance to the city center remained constant from 2000 to 2017 in the Oslo region whereas it increased by 15% in the Helsinki region in the same period. There was hardly any concentration of Helsinki region population toward the center of Helsinki in the period 1990-2000 – there was rather a decentralization trend in that period as well. The average residential distance to the city center therefore likely increased also between 1990 and 2000, which makes the 5.8% overall reduction over the period 1990-2015 recorded in our data implausible.

[24] For example, in Estonia, the data for the medium population size class show a tremendous 60% increase in urban population density increase combined with a 21% increase in the mean residential distance to the center of the main city of the urban region – a combination that appears highly unlikely, as does the very recorded urban population increase.

In urban regions of this population class in North and Western & Central Europe, increasing urban population density has been accompanied with reduced average residential distance. Again, the reduction is strongest in the Northern European urban regions. In Southern European urban regions, there has been a moderate increase in the residents' average distance to the center of the main urban area, whereas this distance has on average remained virtually constant in Eastern European urban regions.

For the urban regions in the highest population size class, Northern European urban regions have thus undergone the most favorable spatial development, seen in a transport energy efficiency perspective, with both a strong densification tendency and with the inhabitants living on average closer to the center of the region. To some extent, Western & Central European urban regions show similar trends, but much more weakly. Eastern European urban regions stand out with the least favorable spatial development, with reduced average population densities.

Table 4.4: Percentage change in urban population density and residential distance to the center of the urban region between 1990 and 2015 at Europe-regional scale for urban regions with a population of >=1mill in the core urban area.

| European region | Urban population density, %Δ 1990-2015 | Mean residential distance to the center of the urban region, %Δ 1990-2015 |
|---|---|---|
| Northern Europe | 22.47 | -7.96 |
| Western & Central Europe | 9.47 | -2.29 |
| Southern Europe | 6.33 | 3.20 |
| Eastern Europe | -5.69 | 0.23 |

### Urban regions in the medium population size class

For the urban regions with a population of 100,000 – 999,999 in the core urban area, urban population densities have increased considerably in Northern Europe and decreased even more in Eastern Europe (Table 4.5). The urban population density increase in the Northern European urban regions has not been as strong as for the urban regions in the highest population class but is still considerable (13.1%). On the other hand, the urban population density decrease in the Eastern European urban regions is more than twice as strong (15.9%) as for urban regions in this part of Europe belonging to the highest population size class. Among the Nordic countries, Norwegian urban regions again stand out with the highest urban population density increase (24%).

For urban regions in this population size class, changes in mean residential distance to the center of the main city of the region appear to have been moderate in all four parts of Europe. The data show slightly higher residential proximity to the centers of the urban regions in North and Western & Central Europe, and moderately increased residential mean distance to the centers of the urban regions in East and particularly in Southern Europe.

Table 4.5: Percentage change urban population density and residential distance to the center of the urban region between 1990 and 2015 at Europe-regional scale for urban regions with a population of 100,000 – 999,999 in the core urban area.

| European region | Urban population density, %Δ 1990-2015 | Mean residential distance to the center of the urban region, %Δ 1990-2015 |
|---|---|---|
| Northern Europe | 13.11 | -0.61 |
| Western & Central Europe | 2.33 | -0.73 |
| Southern Europe | 1.27 | 2.49 |
| Eastern Europe | -15.86 | 1.17 |

### Urban regions in the lowest population size class

For the urban regions with a population of 10,000 – 99,999 in the core urban area, urban population densities have decreased in all four parts of Europe, although the reduction is very slight in Southern European regions belonging to this population size class (Table 4.6). In Western and Central Europe as well as in Northern Europe, the urban population density decrease in the small-city urban regions is 7.5% and 5.9%, respectively. In Eastern Europe, there is a substantial urban population density decrease (22.2%) in the small-city urban regions. Keeping micro-states such as Cyprus and Malta aside, Portugal is the Southern European country where our data show the strongest increase in urban population density. The situation in Northern Europe varies considerably between the five countries, with a very substantial urban population density increase in the single Icelandic urban region in this category (the Akureyri region), a slight urban population density increase in Norwegian small-city urban regions, moderate decrease in Sweden and Denmark, and a rather substantial urban population density decrease in small-city Finish regions.

In all the four parts of Europe, the mean residential distance to the center of the main city of the urban region shows a slight increase among the urban regions in the lowest population size class, varying between 2.1% and 3.6% (Table 4.6).

Table 4.6: Percentage change in urban population density and residential distance to the center of the urban region between 1990 and 2015 at Europe-regional scale for urban regions with a population of 10,000-99,999 in the core urban area.

| European region | Urban population density, %Δ 1990-2015 | Mean residential distance to the center of the urban region, %Δ 1990-2015 |
|---|---|---|
| Northern Europe | -5.90 | 3.63 |
| Western & Central Europe | -7.54 | 2.12 |
| Southern Europe | -0.52 | 3.44 |
| Eastern Europe | -22.24 | 2.86 |

### 4.6.2 Comparison between different sized urban regions at Europe-regional scale

Below, graphs comparing urban population density development (Figure 4.1) and the development of mean residential distance to the center of the urban region (Figure 4.2) for urban regions of different population size and in different parts of Europe. In terms of urban population density development, Northern European urban regions stand out as those with the clearly most favourable development and Eastern European as those with the least favourable trajectories, seen in a transportation energy efficiency perspective. Western & Central Europe and Southern Europe show more mixed patterns. However, even in Northern Europe, the density development in the smallest urban development is on average unfavourable, although with considerable variation across countries.

In terms of residential distance to the center of the main city of the urban region, Northern Europe again shows the most favourable trajectory, especially for regions in the highest population size class. For medium-size population and small-population regions, there is little difference between Northern Europe and Western & Central Europe – the development has actually been slightly more positive in the latter part of Europe. South and Eastern Europe show the least favourable trajectories in terms of residential distance to the main city center of the region. It should be noted that for all four parts of Europe, the mean distance to the regional center has increased somewhat in the region class with the lowest city population, which is unfavourable in terms of transportation energy efficiency.

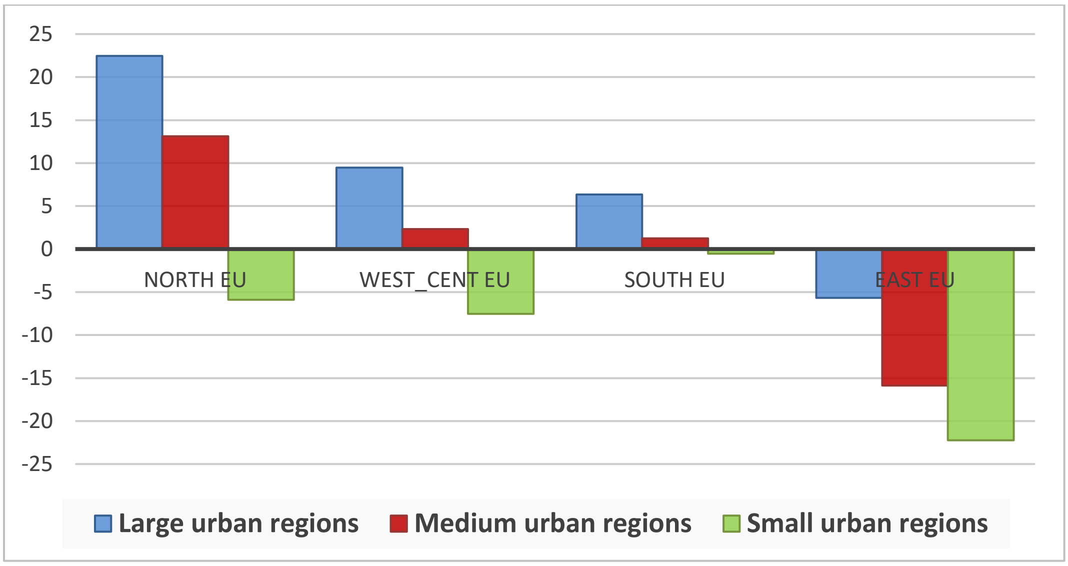

Figure 4.1: Percentage change in urban population density between 1990 and 2015, at Europe-regional scale for urban regions of different sizes.

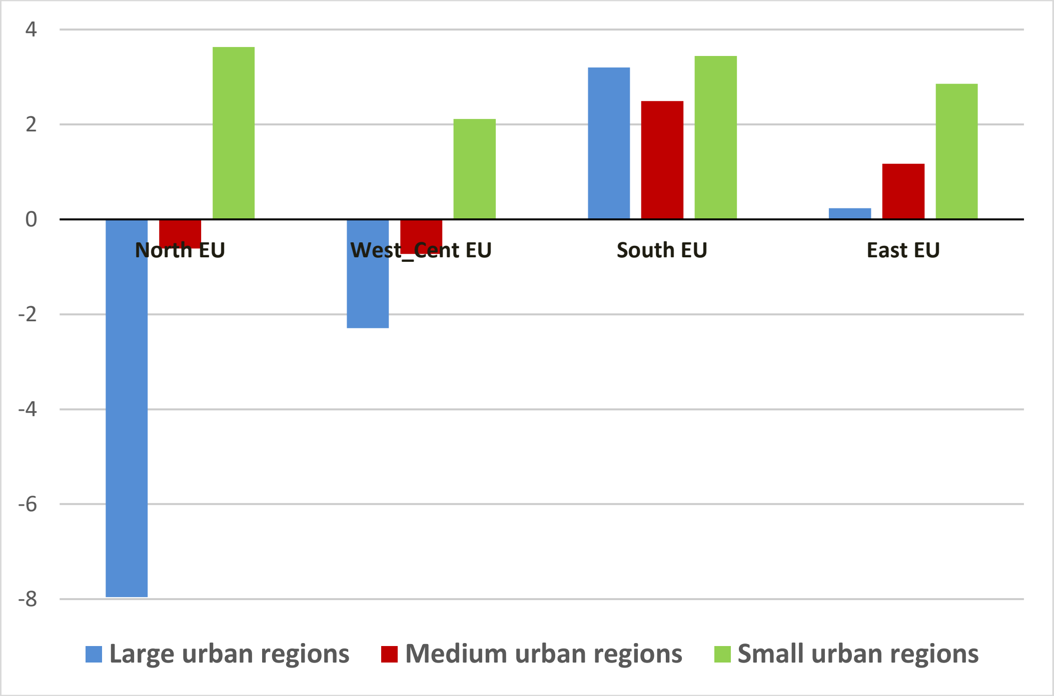

Figure 4.2: Percentage change in mean residential distance to the center of the urban region between 1990 and 2015, at Europe-regional scale for urban regions of different sizes.

# 5 Hypothetical transportation energy saving with ‘best practice’ urban spatial development over past decades

## 5.1 Introduction

In this chapter, we will illuminate how much car-driving distances and energy use for intra-metropolitan transportation could have been reduced in 2015 if all urban regions had pursued ‘best practice’ spatial urban development over the period 1990-2015 instead of the actual urban development that took place during these years. The purpose of this is not to be afterwards wise, but to indicate roughly what might hypothetically have been saved of energy if the measures on which the energy efficiency scenario of Chapter 6 is based had been implemented in the period since 1990. Some of the uncertainties pertaining to the many assumptions about future development within the 2050 horizon will be reduced when applying a retrospective and counterfactual approach based on the actual development of relevant parameters apart from the energy-efficiency measures. The policy measure illuminated in this chapter will be restricted to the spatial development of cities and urban regions, since this is the aspect for which we have data available for the actual development during the 1990-2015 period (cf. the previous chapter).

What, then, should be considered as ‘best practice’? Here, we will limit the analysis to the two aspects of spatial urban development for which we have identified effect estimates and obtained data for actual development, namely residential distance to the center of the main city of the urban region and overall urban population density.

### 5.1.1 The scope for change

The possibility of changing urban population densities and the average distance from the inhabitants’ residences to the main city center depends on the population development and the amount of new building construction that takes place. If there is high population growth, it is possible to increase the density considerably by locating new dwellings within the existing urbanized area (i.e. morphological city). If the population growth is low, the urban population density will not increase much even if all development takes place within the existing urbanized area. And if the urban population is declining, as has been witnessed in many urban regions in East Germany and some other parts of Eastern Europe, the urban population density will inevitably be reduced unless existing buildings at the urban fringe are demolished at a pace similar to or higher than the reduction in population.

#### Population development

According to Eurostat (2020c), population grew by 14.2% from 1990 to 2015 in the Northern European EU and EFTA countries, by 10.7% in the Western & Central European countries and by 11.2 in the Southern European countries. In the Eastern European EU countries, the population decreased by 6.8% in this period. We will apply these Europe-regional figures in the following calculations.

#### Replacement of old buildings

Another factor that affects the scope for urban population density changes is the pace of replacement of old buildings, which is determined by the average lifetime of the building stock. In some countries, such as China, the replacement pace has been very high, whereas in many European cities most buildings reach a high age, reflecting an increased emphasis on the built heritage since the 1970s and a shift from demolition to upgrading of old buildings. We have not found many studies on the pace of demolition of building stock in European countries, According to one of the few such studies, residential buildings in Finland demolished in the period 2000-2012 reached on average an age of 58 years before being demolished, with somewhat longer lifetime for apartment blocks and detached single-family houses than for row houses (Huuhka & Lahdensivu, 2016). For non-residential buildings, the average age at the time of demolition was 43 years. If these figures are stable over time, they correspond to an annual replacement percentage of 1.72% for dwellings and 2.33% for non-residential buildings. The number of demolished buildings was equal to 22% of the new buildings constructed in the period, but only 12% of the new floor area since the new buildings were on average larger than the demolished ones (Huuhka & Lahdensivu, ibid.). The lifetime before demolition of Finish buildings reported by Huuhka & Lahdensivu is considerably higher than the average age at the time of demolition found in a study in Japan, where dwellings had an average lifetime before demolition of only 30 years in 2010 (Daigoa et al., 2017).

Since we do not have any data enabling us to differentiate between different European countries, we cautiously assume an annual replacement percentage of 1.7% for dwellings and 2.3% for non-residential buildings. According to Huuhka & Lahdensivu (2016), non-residential buildings accounted for 51% of the number of buildings demolished in Finland between 2000 and 2012, 76% of the floor area and 83% of the building volume. Since non-residential buildings were probably on average taller than residential buildings, the demolished non-residential buildings probably covered a somewhat lower proportion of ground area than their proportions of demolished floor area and volume. We therefore assume that non-residential buildings might account for around two thirds and residential buildings for around one third of the proportion of ground area released due to demolition. Based on the above considerations, we assume an annual replacement percentage of 2.1% for the building stock as a whole. This means that on average 52.5 % of the building stock existing in 1990 had been replaced by 2015. For dwellings, the percentage of replacement would then be 42.5% and for non-residential buildings 57.5%.

### Growth in floor area per person

A third factor that influences the number of new dwellings constructed is growth in floor area per capita, which results partly from a tendency towards smaller households (more single persons and fewer children in each household) and partly from increasing affluence levels enabling higher housing consumption.

According to available EU statistics, very little updated information exists about the development in floor area per capita in European countries (Eurostat, 2020c). The World Bank previously used to provide data on floor area per capita, but such data are not included in recent statistics from the World Bank. Based on available statistics from selected European countries, there has been a modest growth in residential floor space per capita over the last 10-15 years. In the countries for which Eurostat (2020d) provides national-scale data, residential floor space increased over the period 2011-2018 by 4.6% in Finland, 5,8% in Slovenia and 7.5% in Estonia, whereas the growth was only 0.6% over the period 2014-2016 in Switzerland.[25] Among the Scandinavian countries, Statistics Sweden (2020) reports constant residential floor area per person over the years 2012-2019, whereas Statistics Denmark (2020) reports an 1.4% increase from 2010 to 2018. In Norway, residential floor area per capita increased by only 0.5% from 2012 to 2018 (Statistics Norway, 2020a), and in the municipality of Oslo, it decreased by 7% over the period 2007-2019 (Municipality of Oslo, 2020). The slow growth in residential floor area pe capita in several European countries and even reduction in some cities might indicate a saturation tendency. However, since there are still considerable national differences, a more plausible explanation is the combination of austerity policies since the 2007 financial crisis and skyrocketing housing prices in many European cities. A third explanation is the densification that has taken place in many European cities, since dwellings are normally smaller in inner and central city districts (where high land values lead to high prices per square meter) than at the urban fringe. The quite substantial decrease in residential floor area per capita in Oslo, which has experienced strong densification, high population growth and rapidly increasing housing prices over the last 15 years, is consistent with this explanation.

The stagnating tendencies of residential floor area per capita experienced since the early 2000s stands in contrast with the trajectories of earlier decades. Whereas growth in residential floor area per capita was particularly strong in the 1960s, 1970s and 1980s, floor area per capita also increased in the 1990s. In Denmark, where residential floor area per capita increased by 10% from 1980 to 1990, the increase was 4.7% from 1990 to 2000 as well as in the decade e from 2000 to 2010. Over the whole period 1990-2018, the increase was 11%. Since there was only very low decrease in the2010s, the increase from 1990 to 2015 could be estimated to slightly below 11%. In Norway, residential floor area per capita increased by 15% from 1990 to 1997 (Bartlett, 1993; Statistics Norway, 2008a, b). Considering the very slow growth in the recent decade (cf. above), this suggests a growth over the whole period 1990-2015 of some 16-17%. In Sweden, residential floor area per capita increased by 16% from 1982 to 1993 (Swedish Housing Directorate, 2001, personal communication).

For non-residential buildings, the growth in floor area per capita does not show similar stagnation as for residences. In Norway, for example, the per capita annual construction of floor area in non-residential buildings increased by 13.5% from 2000 to 2019. During this period, non-residential buildings accounted for 54% and residential buildings 44% of the total floor area constructed in Norway (Statistics Norway, 2020b, c). At least in countries where the economy has not been substantially set back due to the recession in the wake of the 2007 financial crisis, growth in non-residential buildings seems to have substituted during the recent decades some of the earlier growth in residential buildings.

In the absence of more comprehensive statistics from European countries, we cautiously estimate the growth per capita in total floor area over the period 1990-2015 to be approximately 15%. For residences, we estimate the growth to be approximately 10%, taking into account the tendency of stagnated growth for this part of the building stock in the later part of the period. We do not have data

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[25] For a couple of other countries, Eurostat (2020c) offers data for individual cities. These data are rather heterogeneous, showing nearly constant floor area per capita in Croatia but considerable decrease in Hungary, especially in Budapest with an astonishing 10% reduction from 2011 to 2016. One might question the reliability of these data.

enabling us to differentiate this figure between different regions of Europe. This percentage will therefore be applied for North, West &Central, South as well as Eastern Europe.

### Estimated total building stock growth 1990-2015

Based on the above considerations, the total building stock constructed between 1990 and 2015 in the four parts of Europe, measured as percentages of the floor area in 1990, could be estimated as shown in Table 5.1:

Table 5.1: Estimated size of building stock constructed between 1990 and 2015 in the four parts of Europe, measured as percentages of the floor area in 1990.

| | Northern Europe | Western & Central Europe | Southern Europe | Eastern Europe | EU/EFTA area |
|---|---|---|---|---|---|
| Change in population | 14.2% | 10.7% | 11.1% | -6.8% | 6.3% |
| Replacement of demolished buildings | 52.5% | 52.5% | 52.5% | 52.5% | 52.5% |
| Change in floor area per capita | 15% | 15% | 15% | 15% | 15% |
| Sum | 100 % | 94 % | 95 % | 63 % | 86 % |

Considering the housing stock only, the total floor area of dwellings constructed between 1990 and 2015 in the four parts of Europe, measured as percentages of the floor area in 1990, could, based on the assumptions mentioned above, be estimated as follows (Table 5.2):

Table 5.2: Estimated floor area of new dwellings constructed between 1990 and 2015 in the four parts of Europe, measured as percentages of the floor area in 1990.

| | Northern Europe | Western & Central Europe | Southern Europe | Eastern Europe | EU/EFTA area |
|---|---|---|---|---|---|
| Change in population | 14.2 % | 10.7 % | 11.1 % | -6.8 % | 6.3 % |
| Replacement of demolished buildings | 42.5 % | 42.5 % | 42.5 % | 42.5 % | 42.5 % |
| Change in floor area per capita | 10 % | 10 % | 10 % | 10 % | 10 % |
| Sum | 79 % | 74 % | 74 % | 46 % | 67 % |

## 5.2 'Best-practice' urban spatial development

As discussed in Chapters 3 and 4, residential distance to the center of the main city of the urban region and population density of the morphological city are the two urban spatial development parameters of high importance to transportation energy use for which data on the historical development in European countries are available. From a transportation energy efficiency point of view, a high urban population density and short residential distance to the main city center of the urban region are favorable.

As shown in Chapter 4, Northern European urban regions have undergone the transportation energy-wise most favorable spatial development over the period 1990-2015, particularly in terms of urban population density but largely also regarding residential distance to the main city center. As mentioned in Chapter 4, we consider our data on how the latter variable has developed over time as more uncertain than the population density figures, at least for the cities in the highest population size classes.

Regarding population density, the national-scale data for the countries with the highest density increases are consistent with the results of more thorough case studies of cities and city regions in these countries. We therefore consider it reasonable to point at the Oslo region in Norway as the urban region that has undergone the most favorable urban spatial development over the period 1990-2015, with a population density increase of 33%. This urban region belongs to the largest population size category, but Norwegian cities in the medium population size category have also undergone quite substantial densification in this period, albeit not as strong as in the Oslo region. In total for the Nordic countries too, the densification in the urban regions of the medium population size category has been fairly high, although lower than among the urban regions of the largest cities. However, for the urban regions in the smallest population size category, densities have on average decreased in the Nordic countries as well as in the other parts of Europe.

Does the latter mean that a modest reduction in urban population density, as observed for the group of Southern European countries, should be considered as ‘best practice’ for urban regions with main cities in the population size category below 100,000 inhabitants? In our opinion, this would not be reasonable. Small cities are on average less dense than larger cities, and the physical potential for densification is therefore arguably higher among the smaller than among the larger cities (although culturally based resistance against densification maybe higher). With a given population growth rate, we therefore consider the densification potential to be equally high in the small and medium population size categories of urban regions as in the highest population size class. There are also some national examples showing high densification in small-city urban regions, although these examples refer mainly to population-wise very small countries such as Cyprus and Iceland, with only a few cities in the class 10,000-99,999 inhabitants.

However, as mentioned in Chapter 6.1, the percentage of densification considered as ‘best practice’ should be adjusted according to the scope for change in the urban built environment, which depends partly on the rate of population growth or decline. We will therefore adjust the percentage of densification considered as ‘best practice’ in line with the different rates of new construction compared to existing building stock size in the four regions of Europe.

Moreover, for density, it also seems reasonable to take the density level at the beginning of the period into consideration, since the potential for further densification tends to be higher when the density is at the outset low than in an already dense city. In 1990, the average urban population density levels for the urban regions in the highest city population class were 22.1 persons per hectare in Northern Europe, 30.6 in Western & Central Europe, 42.6 in Southern Europe and 29.6 in Eastern Europe. In our definitions of ‘best practice’ urban population density increase, we will adjust for these differences as well as for the above-mentioned differences in the scope for change in the built environment[26].

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[26] The adjustment is made by multiplying the unadjusted ‘best practice’ density increase percentage with the scope for built environment change in the European region in question, relative to the Europe-region with the highest scope for change, and multiplying again with the inverse of the density level in 1990 in the European region in question relative to the density level in the European region with the highest unadjusted density increase in the period. For Western & Central Europe, with an estimated building stock construction of 94% of

Regarding residential distance to the main city center of the urban region, our data on earlier urban spatial development are, as mentioned in Chapter 4, somewhat uncertain, especially for individual countries. We will therefore define 'best practice' not based on data for any individual country or city region, but instead consider the European region with the most favorable development over the period 1990-2015 in terms of residential distance to the main city center of the urban region as representing the 'best practice'. For the urban regions in the largest city population class, the Nordic countries showed the energy efficiency-wise most favorable development for this variable, with an 8% reduction on average in distance to the main city center of the urban region over the period 1990-2015. Similar to the above arguments regarding urban population density, we consider it equally possible for cities and urban regions in the lower population classes as for the urban regions with the highest city populations to concentrate new residential development on average closer to the city center than the housing stock at the beginning of the period. We will therefore consider the potential for residential development close to the center of the urban region to be equally high in the small and medium population size categories of urban regions as in the highest population size class. Like for population density increase, we will adjust the percentage of reduced residential distance to the main center of the urban region considered as 'best practice' in line with the different rates of new housing construction compared to existing housing stock size in the four regions of Europe. However, distinct from density development, we do not consider the potential for residential development close to the center of the urban region to depend on the population density level in the beginning of the period. Therefore, no such adjustment will be made regarding 'best practice' development of the residential distance to the main city center of the urban region.

Our defined 'best practice' levels and the differentials between 'best practice' and the actual urban spatial development over the period 1990-2015 in the four European regions are shown in Tables 5.3 - 5.5 for density development and Tables 5.6 – 5.8 for the development of residential distance to the main city center.

Table 5.3: Defined 'best practice' urban population density change and the differentials between 'best practice' and the actual urban spatial development over the period 1990-2015 for urban regions with main cities of one million inhabitants or more in the four parts of Europe.

| | Northern Europe | Western & Central Europe | Southern Europe | Eastern Europe |
|---|---|---|---|---|
| 'Best practice' change in population density, unadjusted for amount of construction | 33 % | 33 % | 33 % | 33 % |
| 'Best practice' change in population density, adjusted for amount of construction 1990-2015 and density level in 1990 | 33 % | 22 % | 16 % | 16 % |
| Actual change in urban population density | 22.5 % | 9.5 % | 6.3 % | -5.7 % |
| Differential between 'best practice' and actual urban population density development | 10.7 % | 13.0 % | 10.0 % | 21.3 % |

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the level in the European region with the highest construction (Northern Europe), and a density level in 1990 of 139% of that of the European region to which the urban region with highest unadjusted density increase belongs (Northern Europe), the adjusted 'best practice' density increase percentage is thus 33% * 94% * (1/139%) = 22%.

Table 5.4: Defined ‘best practice’ urban population density change and the differentials between ‘best practice’ and the actual urban spatial development over the period 1990-2015 for urban regions with main cities of 100,000 – 999,999 inhabitants in the four parts of Europe.

| | Northern Europe | Western & Central Europe | Southern Europe | Eastern Europe |
|---|---|---|---|---|
| ‘Best practice’ change in population density, unadjusted for amount of construction | 33 % | 33 % | 33 % | 33 % |
| ‘Best practice’ change in population density, adjusted for amount of construction 1990-2015 and density level in 1990 | 33 % | 22 % | 16 % | 16 % |
| Actual change in urban population density | 13.1 % | 2.3 % | 1.3 % | -15.9 % |
| Differential between ‘best practice’ and actual urban population density development | 20.1 % | 20.1 % | 15.1 % | 31.5 % |

Table 5.5: Defined ‘best practice’ urban population density change and the differentials between ‘best practice’ and the actual urban spatial development over the period 1990-2015 for urban regions with main cities of 10,000 – 99,999 inhabitants in the four parts of Europe.

| | Northern Europe | Western & Central Europe | Southern Europe | Eastern Europe |
|---|---|---|---|---|
| ‘Best practice’ change in population density, unadjusted for amount of construction | 33 % | 33 % | 33 % | 33 % |
| ‘Best practice’ change in population density, adjusted for amount of construction 1990-2015 and density level in 1990 | 33 % | 22 % | 16 % | 16 % |
| Actual change in urban population density | -5.9 % | -7.5 % | -0.5 % | -22.2 % |
| Differential between ‘best practice’ and actual urban population density development | 39.1 % | 30.0 % | 16.9 % | 37.9 % |

Table 5.6: Defined 'best practice' development of the residential distance to the main city center of the urban region and the differentials between 'best practice' and the actual urban spatial development over the period 1990-2015 for urban regions with main cities of one million inhabitants or more in the four parts of Europe.

| | Northern Europe | Western & Central Europe | Southern Europe | Eastern Europe |
|---|---|---|---|---|
| 'Best practice' change in residential distance to the main city center, unadjusted for amount of construction | -8 % | -8 % | -8 % | -8 % |
| 'Best practice' change in residential distance to the main city center, adjusted for amount of construction 1990-2015 | -8 % | -7 % | -8 % | -5 % |
| Actual change in residential distance to the main city center | -8.0 % | -2.3 % | 3.2 % | 0.2 % |
| Differential between 'best practice' and actual development of residential distance to the main city center | 0.0 % | 5.2 % | 10.8 % | 5.2 % |

Table 5.7: Defined 'best practice' development of the residential distance to the main city center of the urban region and the differentials between 'best practice' and the actual urban spatial development over the period 1990-2015 for urban regions with main cities of 100,000 – 999,999 inhabitants in the four parts of Europe.

| | Northern Europe | Western & Central Europe | Southern Europe | Eastern Europe |
|---|---|---|---|---|
| 'Best practice' change in residential distance to the main city center, unadjusted for amount of construction | -8 % | -8 % | -8 % | -8 % |
| 'Best practice' change in residential distance to the main city center, adjusted for amount of construction 1990-2015 | -8 % | -7 % | -8 % | -5 % |
| Actual change in residential distance to the main city center | -0.6 % | -0.7 % | 2.5 % | 1.2 % |
| Differential between 'best practice' and actual development of residential distance to the main city center | 7.4 % | 6.8 % | 10.1 % | 6.2 % |

Table 5.8: Defined 'best practice' development of the residential distance to the main city center of the urban region and the differentials between 'best practice' and the actual urban spatial development over the period 1990-2015 for urban regions with main cities of 10,000 – 99,999 inhabitants in the four parts of Europe.

| | Northern Europe | Western & Central Europe | Southern Europe | Eastern Europe |
|---|---|---|---|---|
| 'Best practice' change in residential distance to the main city center, unadjusted for amount of construction | -8 % | -8 % | -8 % | -8 % |
| 'Best practice' change in residential distance to the main city center, adjusted for amount of construction 1990-2015 | -8 % | -7 % | -8 % | -5 % |
| Actual change in residential distance to the main city center | 3.6 % | 2.1 % | 3.4 % | 2.9 % |
| Differential between 'best practice' and actual development of residential distance to the main city center | 11.6 % | 9.6 % | 11.0 % | 7.9 % |

### Interdependency between the two urban spatial development variables

When calculating energy efficiency potentials, it is important to be aware that there is an interdependency between the two urban spatial development indicators used in this work (cf. Chapter 1). If a city authority decides to pursue a high degree of densification, the future urban population density will be higher than if instead a strategy of urban spatial expansion is followed. However, densification instead of sprawl also implies that new buildings (including residences) will be located closer to the city center than if urban development takes place as outward expansion. Conversely, the higher the share of new dwellings located close to the city center, the lower will be the number of dwellings (if any at all) constructed outside the existing urban area demarcation. This implies less urban outward expansion, and hence higher urban population density than if more dwellings are constructed at the urban fringe.

In order to avoid double-counting, this interrelationship must be taken into account. Among the 12 countries where there is only one city over 1 million inhabitants[27], there is a correlation of -0.42 between the population density of the morphological cities and their mean residential distance to the city center ($p = 0.001$), controlling for the cities' number of inhabitants. In line with the above discussion, this indicates that residential distance to the city center tends to become shorter, the higher is the urban population density. According to this analysis, around 18% of the variance in residential distance to the main city center of the urban region among this sample of large-city urban regions can be attributed to differences in population density. When calculating energy efficiency potentials, we will therefore subtract 18% from the sum of the separate effect of residential distance to the main city center of the urban region[28].

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[27] I.e. Austria, Bulgaria, Czechia, Denmark, Finland, Greece, Hungary, Ireland, Latvia, Norway, Romania and Sweden.

[28] Within an urban region, the influence of residential distance to the city center on urban population density is arguably stronger and more basic than the influence in the opposite direction. For economic (cf. Alonso, 1960)

We have not made similar analyses of correlations between urban population density and residential distance to the center for urban regions in the lower city population classes, mainly because of the many anomalies found in these data (which is also why we have generally chosen to focus on the four parts of Europe instead of individual countries or city regions in our analyses in this report). In the absence of specific correlation figures for urban regions in the lower city population size classes, we will therefore apply the same reduction factor for urban regions with main city population of 100,000 - 999,999 and 10,000 - 99,999 as well, i.e. 18%.

## 5.3 Hypothetical energy saving 1990-2015 with 'best practice' urban spatial development

Based on the above estimated differentials between actual and 'best practice' spatial urban development and the elasticities for, respectively, the influence of residential distance to the main city center of the urban region on car driving distance and the influence of urban population density on transportation energy use, we will now cautiously estimate energy saving potentials from each of the two urban spatial characteristics. In order to combine the effects of these two variables, we must rely on assumptions about:

- The overall level of energy use for intra-metropolitan transportation in 1990 in each of the four parts of Europe
- Average reduction in energy use per km jointly for all modes of urban-regional transportation over the period 1990-2015 due to more energy-efficient vehicles
- How large share of the total intra-metropolitan energy use car driving accounts for
- Energy use per kilometer of car driving on average for the period 1990-2015

Regarding the first and third of these points, we fortunately have some available information that can help us in making a rough estimate. The data are from a study of energy use for transportation in 22 Nordic cities, where data for 1990/1991 were collected about the sales of gasoline and diesel within geographical areas encompassing each morphological city plus a buffer zone (Næss et al., 1996). Among these cities, the average per capita energy use for transportation was 22.5 GJ annually[29]. Of this, gasoline accounted for on average 74%, auto diesel for 18% and electricity (used for local trains, metros and trams in the larger cities) for 7%. At that time, gasoline was overwhelmingly dominating as fuel for cars, whereas auto diesel was mainly used for trucks and buses. Another study (Næss, 1993), encompassing all Swedish cities of more than 10,000 inhabitants and based on municipality-level fuel sales statistics for 1989, showed a gasoline proportion of 71%[30].

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as well as cultural (Fishman, 1996) reasons, the distance of a satellite town or a residential neighborhood from the city center influences the local population density, but not the other way around. You can increase the density of future residential development by locating new housing construction in the inner city instead of at the fringe of the urban region, but you cannot reduce a suburban neighborhood's or exurban town's distance to the city center by increasing its density. The above calculation is thus merely a technical correction for double-counting and does not reflect the order of causality between location and population density.

[29] 22.5 GJ corresponds to the energy content of 660 liters of gasoline, or 585 liters of autodiesel.

[30] The somewhat lower proportion of gasoline in the latter study may reflect that tanking for long-distance truck traffic accounts for higher proportion of the fuel sales in small towns than in the largest cities. The proportion of diesel cars might also be higher in the smaller cities. Bunker oil in a few cities with oil storage facilities might also

Based on the above, and acknowledging that some of the cars, although a small proportion[31], were diesel cars, it seems reasonable to estimate the share of the intra-metropolitan energy use accounted for by car driving to be around 75% in 1990 in a Nordic context. In the absence of other data, we assume this proportion to apply also in the wider European context.

According to the European Environment Agency (2019b), energy use for road and rail transportation[32] in the EU increased by 22% from 1990 to 2015[33]. At the same time, there were large differences between different European countries in their energy use for transportation at the beginning of the period as well as in how the level of energy used developed over time. In the Nordic countries, to which our data on per capita energy use for intra-metropolitan transportation in 1990 apply, transportation energy remained nearly constant over the period 1990-2015. We will therefore assume the 1990 level for intra-metropolitan transportation (22.5 GJ per capita) to be the annual average in these countries also for the whole 25-year period. This amounts to 563 GJ per capita in the Nordic countries over the 25-year period 1990-2015.

On average for the period 1990-2015, energy use per capita for transportation was 9% higher in Western & Central Europe than in Northern Europe, 7% lower in Southern Europe, 45% lower in Eastern Europe, and 7% lower for the EU as a whole (European Commission, 2019a).

Given the mean number of inhabitants in four parts of Europe during the period from 1990 to 2015 and differences in per capita energy use for transportation between these areas, the energy use per capita and in total per Europe-region for intra-metropolitan transportation can be estimated as shown in Table 5.9:

Table 5.9: Estimated annual energy use for intra-metropolitan transportation (per capita and in total for each region) in four regions of Europe, and in total for each region over the 1990-2015 period.

| | Northern Europe | Western & Central Europe | Southern Europe | Eastern Europe | Whole EU/EFTA |
|---|---|---|---|---|---|
| Annual energy use per capita for intra-metropolitan transportation (GJ) | 22.5 | 24.4 | 21.0 | 12.4 | 21.0 |
| Annual total energy use for intra-metropolitan transportation (PJ) | 560 | 6100 | 2600 | 1300 | 10,600 |
| Total energy use for intra-metropolitan transportation over the period 1990-2015 (PJ) | 14,000 | 153,000 | 66,000 | 33,000 | 266,000 |

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be a source of error, although cities with extreme per capita values for diesel sales have been excluded from the calculations shown here.

[31] In Norway, diesel cars accounted for 3% of the car fleet by the end of 1990 (Norwegian Pollution Control Authority, 2008).

[32] Of this, road transport accounted for more than 97% both in 1990 and 2015.

[33] This was despite vehicle energy improvements in this period. For passenger cars, there was an average 20% reduction in energy use per vehicle km, but virtually no reduction for heavy-duty vehicles. (Norwegian Environment Agency, 2017; Dünnebeil & Lambrecht, 2012).

As mentioned above, we estimate the share of intra-metropolitan transportation energy use accounted for by car driving to be 75% in 1990. Due to the improvement in energy use per km for cars but not for heavy-duty vehicles between 1990 and 2015, the proportion of energy used for car driving has decreased somewhat and could be estimated to be 71% in 2015, yielding an average percentage of 73% for the 25-year period. For the Nordic countries, this implies per capita energy use for intra-metropolitan car transportation of 16.4 GJ, or 410 GJ per capita for the whole period 1990-2015.

Similar to the calculations of total transport energy use, Table 5.10 shows estimated annual energy use for intra-metropolitan transportation by car (per capita and in total for each region) in the four parts of Europe, and in total for each region over the 25-year period.

Table 5.10: Estimated annual energy use for intra-metropolitan car driving (per capita and in total for each region) in four regions of Europe, and in total for each region over the 1990-2015 period.

| | Northern Europe | Western & Central Europe | Southern Europe | Eastern Europe | Whole EU/EFTA |
|---|---|---|---|---|---|
| Annual energy use per capita for intra-metropolitan car driving (GJ) | 16.4 | 17.8 | 15.3 | 9.0 | 15.3 |
| Annual total energy use for intra-metropolitan car driving (PJ) | 410 | 4500 | 1900 | 970 | 7800 |
| Total energy use for intra-metropolitan car driving over the period 1990-2015 (PJ) | 10,000 | 112,000 | 48,000 | 24,000 | 194,000 |

Finally, before we can apply the elasticities established in Chapter 3.1 to the urban spatial development and energy figures estimated in Chapter 4 and in this chapter, it is necessary to take into regard how large share urban regions in each of our three population size classes makes up of the total population of urban regions with at least 10,000 inhabitants in the main city. For the different parts of Europe, these shares are shown in Table 5.11.

Table 5.11: Percentages of the total population of urban regions with at least 10,000 inhabitants in the main city living in urban regions with main city population above 1 million, 100,000-999,999 and 10,000-99,999 in different parts of Europe. Population sizes calculated as the mean between 1990 and 2015 population.

| | Northern Europe | Western & Central Europe | Southern Europe | Eastern Europe | Whole EU/EFTA |
|---|---|---|---|---|---|
| Urban regions with at least 1 million inhabitants in the main city (%) | 35.3 | 32.0 | 42.7 | 20.7 | 32.5 |
| Urban regions with 100,000 – 999,999 inhabitants in the main city (%) | 28.4 | 50.2 | 33.5 | 39.1 | 43.0 |
| Urban regions with 10,000 – 99,999 inhabitants in the main city (%) | 36.2 | 17.9 | 23.8 | 40.2 | 24.5 |
| Total for urban regions with at least 10,000 inhabitants (%) | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |

Given the elasticities, data and assumptions presented in Chapter 3, Chapter 4 and this chapter, we have calculated the hypothetical energy savings over the years 1990-2015 if urban regions had pursued ‘best practice’ urban spatial development as identified in Chapter 3. First, shown in Table 5.12, we have calculated the hypothetical saving in annual energy use in 2015 resulting from ‘best practice’ spatial urban development, compared to the estimated actual transportation energy use in 2015. Thereupon, we have calculated the difference between the hypothetical and actual trajectory in accumulated energy use over the period 1990-2015. Here, we have taken into consideration that the difference between the actual and the ‘best practice’ scenario builds up gradually from zero in 1990 to the whole differential in 2015. Assuming a linear increase in this differential, the average annual potential energy saving in the ‘best practice’ scenario will therefore be only a half of the difference between the scenarios in energy use in the year 2015.The results of the calculations of the difference in accumulated energy use over the 25-year period are shown in Table 5.13.

Table 5.12: Hypothetical annual energy saving in the year 2015 if urban regions in different parts of Europe had pursued ‘best practice’ urban spatial development.

| | Northern Europe | Western & Central Europe | Southern Europe | Eastern Europe | Whole EU/EFTA |
|---|---|---|---|---|---|
| Hypothetical annual transportation energy saving in 2015 (PJ) | 65 | 580 | 190 | 170 | 1000 |
| Energy saving in percent of total energy use for intra-metropolitan transportation in 2015 | 12 | 10 | 7 | 13 | 9.5 |

Table 5.13: Hypothetical energy savings over the years 1990-2015 if urban regions in different parts of Europe had pursued ‘best practice’ urban spatial development.

| | Northern Europe | Western & Central Europe | Southern Europe | Eastern Europe | Whole EU/EFTA |
|---|---|---|---|---|---|
| Hypothetical transportation energy saving 1990 – 2015 (GJ) | 810 | 7300 | 2400 | 2100 | 12,600 |
| Energy saving in percent of actual energy use for intra-metropolitan transportation in the period 1990-2015 | 5.8 | 4.8 | 3.6 | 6.3 | 4.7 |

As can be seen in Table 5.12, pursuing ‘best practice’ urban spatial development in European countries could have reduced the annual energy use for intra-metropolitan transportation in 2015 by around 10% for the EU/EFTA area as a whole, compared to the actual development 1990-2015, with somewhat higher hypothetical savings than the European average in East and Northern Europe and somewhat lower in Southern Europe. It might seem surprising that the gap between ‘best practice’ and actual spatial development in the level of energy use is wider than the European average in the Nordic countries, where urban densification has been more pronounced than in the rest of Europe. However, whereas especially Oslo, but also Stockholm and Copenhagen have increased their urban population density considerably over the 25-year period, average densities among cities with less than 100,000 inhabitants have decreased in Sweden, Denmark and Finland, and residential distance to the city center shows more unfavorable development in the Nordic countries than in Southern Europe for urban regions with main cities between 100,000 and 1 million inhabitants, and less favorable than all the three other parts of Europe for the smallest population size class of regions. In addition, as mentioned in Chapter 6.1, the defined ’best practices’ of urban population density development and residential location relative to the city center have been differentiated to take into consideration the varying possibilities for changing the spatial urban structure and for densification in the four different parts of Europe. Because of the varying volumes of building stock construction 1990-2015 and urban population densities at the beginning of this period, the ‘energy-favorability’ standards against which the actual spatial development has been compared were higher in Northern Europe than in South and especially Eastern Europe.

For the period 1990-2015 as a whole (Table 5.13), the percentage of energy savings in the hypothetical ‘best practice’ scenario is half as high as for the end year of the period, since the difference between the actual and hypothetical urban spatial development evolves gradually from zero difference in 1990 to the difference of close to 10% in 2015.

The average hypothetical annual energy saving of around 10 % after 25 years may appear modest. However, as already noted, several countries had already started a process of urban spatial development in a more transportation energy efficient way, and in some countries, such as Norway, this process started already in the late 1980s in the largest cities (Næss et al., 2011). For these countries and city regions, there was no gap, or only a small gap, between ‘best practice’ and actual development that could hypothetically have been filled by more energy-efficient density development, and thus the calculated hypothetical gain from energy-efficient spatial development was moderate, at least for the high and medium population size urban regions.

In addition to the direct effects of urban spatial development on energy use for transportation, its indirect effects on the feasibility of other measures to improve transportation energy efficiency should be borne in mind. As mentioned in Chapter 1, a relatively compact and concentrated urban structure can be a precondition for implementing restrictions on urban motoring such as road pricing, road tolls and high parking fees, since such a spatial structure facilitates non-motorized and public transportation modes as alternatives to the private car. By laying the ground for a higher-quality mass transit system, compact urban development also reduces the need for highway development and may thus avoid the traffic-inducing effects of road capacity expansion.

# 6 Future energy efficiency potentials from urban spatial development, transport infrastructure development and transportation demand management

## 6.1 Introduction

While the preceding chapter took a backward view on the historical development and hypothetical alternative, energy-efficient use of one kind of policy measure, namely urban spatial development, we will now investigate future possibilities for improved energy efficiency within the transportation sector, considering the broad range of policy measures discussed in Chapters 3 and 4. We will apply the effect estimates presented in these chapters to compare the energy use differentials between an energy efficiency scenario and a business as usual scenario for the period 2020-2050. Like in Chapter 6, the energy efficiency potentials will be assessed separately for four regions of Europe before arriving at a rough total estimate for the EU/EFTA area. Whereas the sEEnergies project as a whole operates with both 2030 and 2050 as scenario years, the analyses of the present report apply only the latter horizon. A forthcoming report (Deliverable D2.3) will show results from scenarios for 2030 as well as for 2050 and present more detailed and sophisticated quantifications than in the present report.

The assumed number of inhabitants in 2020 and 2050 in each of the four parts of Europe are taken from Eurostat (2020d). We have not been able to find official population forecasts differentiating between different parts of each country. Instead, we will assume that the relative growth or decline in the number of inhabitants in large, medium-sized and small urban regions will follow the same pattern as during the period 2000 – 2015. During this period and for Europe as a whole, the population increased by 7.7% in urban regions with main cities of more than one million inhabitants, increased by 2.5% in urban regions with 100,000 to 999,999 inhabitants in the main city and decreased by 3.5% in urban regions with main city population below 100,000. There were also considerable differences between different parts of Europe, with on average high growth in Northern Europe, moderate growth in West & Central and Southern Europe and decreased population in Eastern Europe.

Table 6.1 shows the percentages of population change from 2000 to 2015 in the three urban region categories for each of the four parts of Europe, and the projected percentages of change over the period 2020 – 2050.

Table 6.1: Observed and projected population change in large-city, medium-city and small-city urban regions in different parts of Europe.

| | Observed population change 2000-2015 | Projected population change 2020-2050 |
|---|---|---|
| Northern Europe | 11.7 % | 11.3 % |
| • Large-city urban regions | 19.9 % | 19.5 % |
| • Medium-city urban regions | 14.4 % | 14.0 % |
| • Small-city urban regions | 1.9 % | 1.5 % |
| Western & Central Europe | 4.4 % | 3.4 % |
| • Large-city urban regions | 8.5 % | 7.5 % |
| • Medium-city urban regions | 3.9 % | 3.0 % |
| • Small-city urban regions | -1.6 % | -2.5 % |
| Southern Europe | 5.9 % | -0.8 % |
| • Large-city urban regions | 7.1 % | 0.3 % |
| • Medium-city urban regions | 5.8 % | -0.9 % |
| • Small-city urban regions | 3.9 % | -2.7 % |
| Eastern Europe | -7.1 % | -11.6 % |
| • Large-city urban regions | 2.2 % | -2.8 % |
| • Medium-city urban regions | -7.0 % | -11.5 % |
| • Small-city urban regions | -11.9 % | -16.2 % |
| Whole Europe | 2.7 % | -0.6 % |
| • Large-city urban regions | 7.7 % | 4.3 % |
| • Medium-city urban regions | 2.5 % | -0.8 % |
| • Small-city urban regions | -3.5 % | -6.6 % |

The pace of replacement of old buildings is assumed to be the same as for the period 1990-2015 and common for all parts of Europe[34], i.e. 2.1% annually for the whole building stock, differentiated into 1.7% for dwellings and 2.3% for non-residential buildings. These assumptions will be common for the energy efficiency and the business as usual scenario. However, the development in residential floor area per capita will differ between the scenarios, since the spaciousness of dwellings tends to depend on housing types and the location within an urban region. In the energy efficiency scenario, we will therefore assume constant residential floor area per capita in all parts of Europe except Eastern Europe, where present floor area per capita is considerably lower than in the rest of Europe and therefore could be expected to increase also in the energy efficiency scenario. For Eastern Europe, we therefore assume a 50% increase on average in residential floor area per capita over the period 2020-2050. In the business as usual scenario, we assume 20% increase in North, West & Central and Southern Europe and 70% increase in Eastern Europe. For non-residential buildings, we assume smaller differences between the scenarios as well as between Eastern Europe and the other parts of Europe. Taking into consideration existing trends toward more frequent home-office work and less pace per employee in office buildings, but also possible reindustrialization trends due to higher preparedness

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[34] The estimated replacement rate for 1990-2015 is based on Finnish data estimated by Huuhka & Lahdensivu (2016), cf. Chapter 5.1.1. Their replacement rate refers to demolished buildings, which means that heavy renovations of existing buildings (which would have little or no effect on transportation) are not included. The assumption of the same replacement in all parts of Europe as in Finland is of course uncertain, like many other assumptions in this report. The assumption of similar replacement rates 2020-2050 as 1990-2015 is also highly uncertain. The 2018 Energy Performance of Buildings Directive implies that renovation of buildings should increase considerably (Janssen, 2020), and since in a lifecycle analysis perspective demolishing and replacement is the more durable option for some buildings, the demolishing and replacement rate may increase as well. On the other hand, an increased emphasis on cultural heritage concerns might indicate the opposite.

efforts to face international supply crises, we assume a floor area growth per capita of 10% in both the business as usual and energy efficiency scenario in all parts of Europe except Eastern Europe, where we assume a 20% increase for such buildings. This leaves us with overall 5% increase in the building stock floor area per capita in the energy efficiency scenario for North, West & Central and Southern Europe and a 35% increase in Eastern Europe, with corresponding business as usual percentages of 15% and 45%, respectively.

## 6.2 Main characteristics of the energy efficiency and business as usual scenarios

**Urban spatial development.** In the energy efficiency scenario, urban spatial development is characterized by strong densification, especially in areas close to the center of each urban region. In morphological cities where the overall density is today not very high (defined here as below 50 persons per hectare in 2015) all new buildings in this scenario are constructed within existing urban area demarcations, i.e. with no urban spatial expansion. However, for cities that are already very dense, the possibilities for further densification are limited. For very high-density cities (defined here as above 150 persons per hectare[35] in 2015), the energy efficiency scenario implies that the existing density is to be maintained during the period 2020-2050. This opens for some combination of moderate densification in lower-density parts of the existing city and some limited amount of outward expansion at medium-high densities in areas adjacent to the existing urban fabric. For cities with densities between 50 and 150 persons per hectare in 2015, the proportion of new construction taking place as densification increases linearly from the share in the highest-density cities to the 100% share in cities with less than 50 persons per hectare in 2015.

Since most of the development in the energy efficiency scenario will take place in areas close to the main center of the urban region, average residential distance to the city center will decrease. Within each city, old buildings demolished near the urban fringe will not be replaced with new buildings at the same location but will instead be replaced with new, taller buildings in the inner and central areas.

In some parts of Europe, population is forecasted to decrease over the period 2020-2050 (cf. Table 6.1), resulting in the phenomenon of ‘shrinking cities’ that was also evident in the preceding decades. For cities in these parts of Europe, the energy efficiency scenario assumes that buildings at the outskirts of the cities will be demolished at the same rate as the population decline, resulting in zero reduction in population density despite shrinking population size.

Because the very high-density cities are supposed to expand slightly outwards, residential mean distance to the city center will be reduced less in urban regions with more than 150 persons per hectare in the main city than in regions where the main city has less than 50 persons per hectare. We assume a reduction of 5% in the energy efficiency scenario in the former urban regions and 10% in the latter,

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[35] For comparison, the population density of a high-density inner-city district of a North European capital, Nørrebro in Copenhagen, is 197 persons per hectare. For whole morpohological cities, densities are still normally much lower than for specific inner-city districts. For example, the population density of the whole morphological city of Copenhagen was only 30.5 persons per hectare in 2015, and for the NUTS3 unit of Copenhagen, the population density was 88 persons per hectare. Among the densest European cities, the NUTS3 units of Paris and Athens had 222 and 157 inhabitants per hectare, respectively, but for the whole morphological cities of Paris and Athens, the population densities were considerably lower (101 and 106 persons per hectare, respectively).

with a linearly define percentage in-between for cities with urban population densities of 50 to 150 persons per hectare.

In the business as usual scenario, we presuppose a continuation of the trends from the last fifteen years of the historical period for which we have data, i.e. the years from 2000 to 2015. Percentages of change in urban population density and residential distance to the main center of the urban region will be calculated for regions belonging to different population size classes and corners of Europe in the same way as for the historical development presented in Chapter 4, including an adjustment for the population growth or decline in the 2020-2050 period, compared to the 2000 to 2015 period.

For both population density and residential distance to the main city center, we assume linear increase or decrease, not exponential.

**Transport infrastructure development.** We assume considerable highway development in the business as usual scenario, in line with the EU Trans-European Road Network (TEN-T) comprehensive program (INEA, 2020) and with continued motorway construction in contexts not included in the TEN-T program. In the energy efficiency scenario, no such construction will take place. Similarly, the energy efficiency scenario includes no capacity-increasing airport development, whereas the business as usual scenario includes airport development deemed necessary to accommodate (pre-Corona) projections for air traffic to and from European destinations. Railroad construction in the business as usual scenario will take place according to INEA (2020) plans, while additional rail construction will take place to accommodate increased intra-metropolitan rail transport to facilitate modal shifts from car to transit in the energy efficiency scenario.

**Economic instruments.** In the business as usual scenario, no urban road tolling or road pricing schemes and no substantial parking fee increases are presupposed, whereas all these measures are included in the energy efficiency scenario as outlined in Chapter 4.3.

Based on the above assumptions, Table 6.2 shows key characteristics of the business as usual and the energy efficiency scenario.

Table 6.2: Key characteristics of the business as usual (BAU) and energy efficiency (EE) scenarios.

| Changes over the period 2020-2050 | Northern Europe | | Western & Central Europe | | Southern Europe | | Eastern Europe | |
|---|---|---|---|---|---|---|---|---|
| | BAU | EE | BAU | EE | BAU | EE | BAU | EE |
| Population size | +11% | +11% | +3% | +3% | -1% | -1% | -12% | -12% |
| Annual replacement of building stock | 2.1% | 2.1% | 2.1% | 2.1% | 2.1% | 2.1% | 2.1% | 2.1% |
| Residential floor area per capita | +20% | Constant | +20% | Constant | +20% | Constant | +70% | +50% |
| Floor area per capita for the whole building stock | +15% | +5% | +15% | +5% | +15% | +5% | +45% | +35% |
| Urbans spatial development | Continuation of trends 2000-2015 | Strong densification<br>Reduced residential distance to center | Continuation of trends 2000-2015 | Strong densification<br>Reduced residential distance to center | Continuation of trends 2000-2015 | Strong densification<br>Reduced residential distance to center | Continuation of trends 2000-2015 | Strong densification<br>Reduced residential distance to center |
| Highway capacity increase | According to TEN-T + other motorway construction | None | According to TEN-T + other motorway construction | None | According to TEN-T + other motorway construction | None | According to TEN-T + other motorway construction | None |
| Airport construction | To accomodate growth | None | To accomodate growth | None | To accomodate growth | None | To accomodate growth | None |
| Railroad construction | According to INEA | Intensified in urban regions | According to INEA | Intensified in urban regions | According to INEA | Intensified in urban regions | According to INEA | Intensified in urban regions |
| Road pricing and parking fees | Very limited | Extensive urban schemes | Very limited | Extensive urban schemes | Very limited | Extensive urban schemes | Very limited | Extensive urban schemes |

## 6.3 Calculating differentials between the energy efficiency and the business as usual scenario

### 6.3.1 Urban spatial development

**Population density development.** In the energy efficiency scenario, nearly all new buildings (apart from place-bound non-urban buildings such as farmhouses, buildings for local resource processing e.g. in quarries, mining or aquaculture, tourist facilities, etc.) are constructed within existing urban area demarcations, i.e. no spatial expansion of the morphological cities takes place except in cities with very high population density in 2015 and projected future population growth, where some urban spatial expansion is allowed. This means that the population density will increase at the same rate as the growth in population, except in cities where the population density is already high. For urban regions with such cities, we made some downward adjustment of the density increase, cf. Section 6.2. As also mentioned in Section 6.2, in several urban regions, particularly in Eastern Europe and in urban regions where the main city has less than 100,000 inhabitants, the population is projected to decrease, not to grow. In these regions of shrinking cities, we still presuppose that the population density will be maintained at present level in the energy efficiency scenario as old buildings at the urban fringe will be demolished at a higher rate than for the city as a whole, and will not be replaced with new buildings at these peripheral locations. This also means that the average residential distance to the city center will be reduced in the shrinking cities although there is no increase in their overall population density.

Based on the above considerations, Table 6.3 shows the presupposed changes in urban population densities and mean residential distances to the region centers in the energy efficiency scenario[36].

Table 6.3: Presupposed changes in urban population density at Europe-regional scale for urban regions of different sizes between 2020 and 2050 in the energy efficiency scenario.

| European region | Large urban regions | Medium urban regions | Small urban regions |
|---|---|---|---|
| Northern Europe | 18.8% | 14.0% | 1.5% |
| Western & Central Europe | 6.8% | 3.0% | 0 |
| Southern Europe | 0.3% | 0 | 0 |
| Eastern Europe | 0 | 0 | 0 |

As mentioned in Section 6.2, the business as usual scenario for spatial urban development presupposes a continuation of the trends observed over the period 2000-2015 in different parts of Europe and for urban regions belonging to different main city population size classes. Based on the information from the Global Human Settlement dataset (cf. Chapter 4) used in this report, we first calculated the percentage of change from 2000 to 2015 in urban population density for each of the three population size classes in each of the four parts of Europe. We thereupon calculated for each of these twelve geographical contexts how the population density would have developed if there had been no spatial expansion of the urban areas, given the actual changes in the number of inhabitants. We could thus identify the differential between the actual density development from 2000 to 2015 and a hypothetical trajectory of no urban spatial expansion (as in the energy efficiency scenario for the 2020 – 2050 period. Taking the duration of each of these two periods into account, we could calculate the density changes in the business as usual scenario by subtracting these differentials form the densities calculated for the energy efficiency scenario.

The resulting projected changes in urban population densities in the business as usual scenario can be seen in Table 6.4. Table 6.5 shows the differentials between the energy efficiency and business as usual scenarios in density levels for each urban region class and each of the four parts of Europe.

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[36] The presupposed density development, particularly in urban regions with small population growth, may underestimate the potential for density increase, since we apply population development assumptions at aggregate level for each of the four parts of Europe. Since there is actually a considerable variation between different urban regions within the same size category and part of Europe, a mean population growth of, for example, 1.5% may cover actual population change rates ranging from, say, -10& to 13%. Since we have assumed that the present density levels will not decrease in the regions with decreasing city populations, this means that the density changes will vary between zero and a positive percentage instead of between a negative and a positive percentage. It would, however, be too complicated to take this into account in our estimates.

Table 6.4: Percentage changes in urban population density at Europe-regional scale for urban regions of different sizes between 2020 and 2050 in the business as usual scenario.

| European region | Large urban regions | Medium urban regions | Small urban regions |
|---|---|---|---|
| Northern Europe | 13.1 % | 6.0% | -5.6 % |
| Western & Central Europe | 4.2 % | -0.1% | -4.3 % |
| Southern Europe | -2.2 % | -3.5% | -3.1 % |
| Eastern Europe | -7.8 % | -6.1% | -3.9 % |

Table 6.5: Differentials between the energy efficiency and business as usual scenarios in the percentage changes in urban population density at Europe-regional scale for urban regions of different sizes between 2020 and 2050.

| European region | Large urban regions | Medium urban regions | Small urban regions |
|---|---|---|---|
| Northern Europe | 5.7 % | 8.0 % | 7.1 % |
| Western & Central Europe | 2.6 % | 3.1 % | 4.3 % |
| Southern Europe | 2.5 % | 3.5 % | 3.1 % |
| Eastern Europe | 7.8 % | 6.1 % | 3.9 % |

**Residential distance to the center of the urban region.** Based on the assumptions mentioned in Section 6.2, the mean residential distance to the center of the main city of the region will be reduced by 10% in the energy efficiency scenario, except a slight adjustment for cities with very high population density in 2015. The resulting changes in residential distance to the center of the urban region for the different urban region classes and different parts of Europe can be seen in Table 6.6.

Table 6.6: Presupposed changes in in mean residential distance to the center of the urban region between 2020 and 2050 in the energy efficiency scenario, at Europe-regional scale for urban regions of different sizes.

| European region | Large urban regions | Medium urban regions | Small urban regions |
|---|---|---|---|
| Northern Europe | -9.8% | -10.0 % | -10.0 % |
| Western & Central Europe | -9.6% | -10.0 % | -10.0 % |
| Southern Europe | -9.5 % | -9.7 % | -10.0 % |
| Eastern Europe | -9.7 % | -9.9 % | -10.0 % |

In the business as usual scenario, the annual changes in residential distance to the urban region center over the period 2020-2050 are assumed to be the same as in the period 2000-2015. We calculated the percentages of change in the 2020-2050 period as twice changes over the years 2000-2015 for the countries within each part of Europe, weighted by the number of inhabitants in each country. The resulting projected changes in mean residential distance to the center of the main city of the urban region in the business as usual scenario can be seen in Table 6.7. Table 6.8 shows the differentials between the energy efficiency and business as usual scenarios in residential distance to the region center for each urban region class and each of the four parts of Europe.

Table 6.7: Percentage changes in mean residential distance to the center of the urban region between 2020 and 2050 in the business as usual scenario, at Europe-regional scale for urban regions of different sizes.

| European region | Large urban regions | Medium urban regions | Small urban regions |
|---|---|---|---|
| Northern Europe | -8.9 % | -1.4 % | 4.6 % |
| Western & Central Europe | -2.6 % | -2.7 % | 3.0 % |
| Southern Europe | 4.3 % | 5.1 % | 3.6 % |
| Eastern Europe | 3.2 % | 0.8 % | 2.9 % |

Table 6.8: Differentials between the energy efficiency and business as usual scenarios in the percentage changes in mean residential distance to the center of the urban region at Europe-regional scale for urban regions of different sizes between 2020 and 2050.

| European region | Large urban regions | Medium urban regions | Small urban regions |
|---|---|---|---|
| Northern Europe | 0.9 % | 8.6 % | 14.6 % |
| Western & Central Europe | 7.0 % | 7.3 % | 13.0 % |
| Southern Europe | 13.8 % | 14.8 % | 13.6 % |
| Eastern Europe | 12.9 % | 10.8 % | 12.9 % |

**Energy saving potentials from urban spatial development in the energy efficiency scenario, compared to Business as usual.** Based on the above estimated differentials between Energy efficiency and Business as usual spatial urban development and the elasticities for, respectively, the influence of residential distance to the main city center of the urban region on car driving distance and the influence of urban population density on transportation energy use, we will now cautiously estimate energy saving potentials from each of the two urban spatial characteristics. Like the calculations in Chapter 6 of hypothetical energy-saving gains from upscaling 'best practice' urban spatial development over the period 1990 to 2015, we must rely on assumptions about:

- The overall level of energy use for intra-metropolitan transportation in 2020 in each of the four parts of Europe
- How large share of the total intra-metropolitan energy use car driving accounts for.

The differentials between the energy efficiency and business as usual scenarios for urban spatial development thus calculated should also be adjusted for energy saving due to expected average reduction in energy use per km jointly for all modes of urban-regional transportation over the period 2020-2050 due to more energy-efficient vehicles. This will be done in a forthcoming sEEnergies report.

Since we do not have available data for the level of energy use for intra-metropolitan transportation in 2020 in European countries, we have to apply the old 1990 data, adjusted for the general growth in energy use for road and rail transport in Europe since then. According to the European Environment Agency (2019b), energy use for road transportation within the European Economic Agreement area (EEA-33) increased by 34.5% between 1990 and 2017, while there was a reduction in the energy use for rail transportation by 19.7%. Since rail transportation accounts for only 2% of the energy used for road transportation (European Commission, 2019a), there was a 32.7% growth in energy use for road and rail transport together. Extrapolating growth in energy use for road and rail transportation from 2017 to 2020 based on the development of such energy use in the EU over the three years prior to 2017 (European Commission, 2019a), we find a growth in energy use for road and rail transport together of 34.3% for the period 1990 – 2020 within the European Economic Agreement area. If we further assume, cautiously, that the share of road and rail transportation energy spent on intra-metropolitan travel has remained the same as in 1990, and that the differences between the four parts of Europe in per capita energy use for transportation are the same in 2020 as in 2015, the current and future energy use per capita and in total per Europe-region for intra-metropolitan transportation can be estimated as shown in Table 6.9, accounting for population forecasts:

Table 6.9: Estimated annual energy use for intra-metropolitan transportation (per capita and in total for each region) in four regions of Europe in the absence of changes in vehicle technology, and in total for each region over the 2020-2050 period.

| | Northern Europe | Western & Central Europe | Southern Europe | Eastern Europe | Whole EU/EFTA |
|---|---|---|---|---|---|
| Annual energy use per capita for intra-metropolitan transportation (GJ) | 30.3 | 27.9 | 24.4 | 17.7 | 25.7 |
| Annual total energy use for intra-metropolitan transportation (PJ) | 800 | 7300 | 3200 | 1800 | 13,500 |
| Total energy use for intra-metropolitan transportation over the period 2020-2050 in the absence of changes in vehicle technology (PJ) | 25,000 | 224,000 | 96,000 | 52,000 | 403,000 |

Like in the estimation of hypothetical energy savings if ‘best practice’ had been pursued in the 1990-2015 period(cf. Chapter 6), we need to take into regard how large share urban regions in each of our three population size classes makes up of the total population of urban regions with at least 10,000 inhabitants in the main city. For simplicity, we assume that these shares are the same as in 2015 and will remain constant over the period 2020-2050. For the different parts of Europe, these shares are shown in Table 6.10.

Table 6.10: Percentages of the total population of urban regions with at least 10,000 inhabitants in the main city living in urban regions with main city population above 1 million, 100,000-999,999 and 10,000-99,999 in different parts of Europe. Population sizes calculated for 2015, with shares between region sizes assumed to remain constant for the period until 2050.

| | Northern Europe | Western & Central Europe | Southern Europe | Eastern Europe | Whole EU/EFTA |
|---|---|---|---|---|---|
| Urban regions with at least 1 million inhabitants in the main city (%) | 37.3 | 32.9 | 43.2 | 22.3 | 33.7 |
| Urban regions with 100,000 – 999,999 inhabitants in the main city (%) | 29.0 | 50.1 | 33.4 | 39.4 | 43.0 |
| Urban regions with 10,000 – 99,999 inhabitants in the main city (%) | 33.7 | 17.1 | 23.4 | 38.3 | 23.3 |
| Total for urban regions with at least 10,000 inhabitants (%) | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |

Given the elasticities, data and assumptions presented in Chapters 4, 5, 6 and this chapter, we have calculated the estimated energy savings from pursuing the energy efficiency scenario over the years 2020-2050, compared to the business as usual scenario. It should be noted that any effects of vehicle technology changes over the period 2020-2050 have not been taken into consideration. First, shown in Table 6.11, we have calculated the saving in annual transportation energy use in 2050 resulting the spatial urban development energy efficiency scenario, compared to the estimated annual transportation energy use in 2050 in the business as usual scenario. Thereupon, we have calculated the difference between the Energy efficiency and Business as usual trajectories in accumulated energy use over the period 2020-2050. Like in Chapter 6, we have taken into consideration that the difference between the energy efficiency and the business as usual scenario builds up gradually from zero in 2020 to the whole differential in 2050. Assuming a linear increase in this differential, the average annual potential energy saving in the 'best practice' scenario will therefore be only a half of the difference between the scenarios in energy use in the year 2050.

The results of the calculations of the difference in accumulated energy use over the 25-year period are shown in Table 6.12.

Table 6.11: Annual energy saving in the year 2050 due to urban spatial development in the energy efficiency scenario, compared to the annual energy use for intra-metropolitan transportation in the business as usual scenario. Effects of future vehicle technology changes are not included.

| | Northern Europe | Western & Central Europe | Southern Europe | Eastern Europe | Whole EU/EFTA |
|---|---|---|---|---|---|
| Energy saving in 2050 in the energy efficiency scenario (PJ) | 46 | 262 | 146 | 91 | 544 |
| Energy saving in percent of estimated total energy use for intra-metropolitan transportation in 2050 | 5.7 | 3.6 | 4.5 | 5.0 | 4.1 |

Table 6.12: Estimated energy savings over the years 2020-2050 due to urban spatial development in the energy efficiency scenario, compared to the business as usual scenario. Effects of future vehicle technology changes are not included.

| | Northern Europe | Western & Central Europe | Southern Europe | Eastern Europe | Whole EU/EFTA |
|---|---|---|---|---|---|
| Estimated transportation energy saving 2020-2050 (PJ) | 730 | 4000 | 2200 | 1300 | 8000 |
| Energy saving in percent of total energy use for intra-metropolitan transportation | 2.9 | 1.8 | 2.3 | 2.5 | 2.0 |

Compared to the hypothetical energy savings if all urban regions had followed 'best practice' urban spatial development over the years 1990-2015, the energy savings of the energy efficiency scenario for urban spatial development 2020-2025 compared to business as usual are smaller, actually less than half as large. An important reason for this is the low population forecasts, where the population is expected to decline considerably in the urban regions of Eastern Europe, decrease slightly in Southern Europe, increase modestly in Western & Central Europe and increase considerably in Northern Europe, and with an average slight decrease for the European Economic Agreement area as a whole. Without population growth, the urban population density cannot be increased unless built-up areas in the outskirts of the urban area are demolished without being replaced with new buildings. Since this is something that we have only assumed to take place in shrinking cities, a large proportion of the urban areas area assumed to have no density increase, even in the energy efficiency scenario. And since the population growth in the non-shrinking cities is mostly forecasted to be low, the density increase in most of these cities will also be low. There might still be a need for more radical transformations, for example by replacing unfavorably located peripheral residential and employment areas and low-density buildings in central neighborhoods with dense apartment and office buildings in the latter areas.

Moreover, the 'business as usual' urban spatial development against which the energy efficiency scenario is to be compared is already fairly energy efficient, especially in the Nordic countries where there has been a strong density increase in the largest urban regions since the turn of the millennium and a fair density increase also in the urban regions with medium-sized main cities. In Western & Central Europe too, urban population densities have increased since the beginning of the present century.

Our calculations indicate that the largest energy-saving effect in the energy efficiency scenario stems from changes in the mean residential distance to the main city center of the urban region. New construction in this scenario takes place closer to the city center than the average for the existing housing stock. This applies to new development to accommodate for increased floor area per person and any population growth as well as for replacement of demolished buildings. The latter implies that buildings demolished in the outer suburbs will be replaced in the inner city rather than at their original location. All these features contribute to a steeper center-periphery density gradient for dwellings as well as for other buildings.

Regarding the latter, it should also be remembered that the effects of workplace location on commuting distances, travel modes and energy use for commuting have not been included in the present analysis due to lack of geospatial data on workplace location in European urban regions. As mentioned in Chapter 3.1, location of specialized, labor-intensive or visitor-intensive jobs close to the main center of the city/the metropolitan area is favorable in terms of reducing energy use for commuting. According to earlier analyses, the effect of energy-efficient intra-metropolitan workplace location on energy use for commuting is similar to the effect of energy-efficient intra-metropolitan residential location (Næss, 1995: 260-262), and these effects are at least to some extent cumulative. The omission of the effect of energy-favorable workplace location in the energy efficiency scenario thus contributes to some underestimation of the energy-saving potential.

Finally, it should be remembered that a restrictions on urban motoring such as road pricing, road tolls and high parking fees may be difficult to implement unless the urban structure is relatively compact and concentrated, as such a spatial structure facilitates non-motorized and public transportation modes as alternatives to the private car (cf. Chapter 1). Compact urban development also lays the ground for a higher-quality mass transit system and thus reduces the need for highway development. The traffic-inducing effects of road capacity expansion can thus be avoided.

### 6.3.2 Transport infrastructure development

#### Road infrastructure development – avoiding induced traffic from motorway construction in the energy efficiency scenario

The business as usual scenario involves a continuation of motorway development in line with the Comprehensive program for the Trans-European Transport Network (TEN-T). In addition, this scenario assumes continued construction of motorways in settings not included in the TEN-T program, notably in urban regions but also in non-urban areas, and capacity increase of already existing motorways. The energy efficiency scenario includes none of this motorway construction. Concerning road infrastructure development, the energy saving potential of the latter scenario is thus due to its absence of induced traffic resulting from the motorway construction presupposed in the business as usual scenario. The business as usual scenario includes the following kinds of motorway construction:

- Motorway upgrading of present non-motorway TEN-T roads
- Motorway upgrading of present non-TEN-T, non-motorway urban roads
- Motorway upgrading of present non-TEN-T, non-motorway non-urban roads
- Capacity increase of existing motorways

The TEN-T program includes a core part consisting of a number of core road links as well as a portfolio of non-core roads. The Comprehensive program has 2050 as its time horizon, which is identical to the scenario horizon of the present report. The road infrastructure part of the TEN-T program - The trans-European road network – comprises motorways and high-quality roads. The network aims to guarantee users a high, uniform and continuous level of service, comfort and safety. Projects look at adapting existing roads or building new ones to meet TEN-T objectives (INEA, 2020). According to the European Commission (2017), the TEN-T program aims to upgrade both the core network (by 2030) and the entire comprehensive network (by 2050) to motorway or expressway standard.

Unfortunately, the actual length, number of lanes and capacity increase compared to existing road networks are not specified in the documents available from the various TEN-T websites. This is especially the case for the non-core road links, but even the core links are specified only crudely, identified on maps but without specification of the number of new lane kilometers to be constructed. Moreover, the TEN-T program does not include all existing or planned major roads in European countries. Particularly in Eastern Europe, a large part of the main existing roads is not defined as TEN-T roads. There is generally great variation between European countries in the shares that TEN-T roads, and particularly those belonging to the core part of the program, account for of the countries' total road networks. In several countries, there are also many motorways not included in the TEN-T program, particularly in urban areas.

In the absence of more specific indications of the amount of road capacity increase presupposed in the TEN-T Comprehensive program, we instead have to rely on historical data on road construction and the proportions of traffic volumes accounted for by different road types in the EU/EFTA area and in individual countries. Regarding motorways, Eurostat (2018) shows how the total length of motorways in most of the EU/EFTA countries has evolved over the period 2007-2018. In addition, a recent

Wikipedia article offers data for the accumulated construction of motorways in European countries over the period from 1924 to 2018/2019 (Wikipedia, 2020a). This latter list also includes data for some countries that were missing in the Eurostat (2018) account. We will thus use the two above-mentioned lists as our sources on the historical development of motorways in Europe.

The proportion of the total TEN/T road network that is made up by motorways has been estimated by CEDR (2018). For the roads for which classifications are available[37], there were nearly 60,000 km of motorways, which makes up 60.5 % of the total TEN-T road length in these countries. CEDR (2018) also offers information about the length of the TEN-T roads network in different countries by number of lanes, as well as the proportions of total vehicle kilometers on motorways and other roads, respectively, as well as on core TEN-T roads and non-core roads. The CEDR (2018) report also informs about the proportions of motorways and other TEN-T roads located in urban and rural areas, respectively.

We will combine the above-mentioned three data sources to estimate the amount of motorway and expressway construction in different parts of Europe during recent decades, and use these data as a base for estimating the amount of construction of motorways and expressways in the business as usual scenario.

According to Eurostat (2018) and Wikipedia (2020a), the total length of motorways in the EU/EFTA area was around 80,000 km in 2017. According to CEDR (2018), the total length of TEN-T motorways in 2017 (core as well as non-core roads) was close to 50,000 km. This implies that a total of approximately 30,000 km of motorways in the EU/EFTA area were not parts of the TEN-T network. It is reasonable to assume that a large proportion of these latter motorways are within the urban areas of large and medium-sized cities and their immediate surroundings. Here, we will assume that two thirds of the non-TEN-T motorways are in urban areas of large and medium-sized cities or in the immediate surroundings of such areas. For the TEN-T network as a whole, the proportion situated in urban areas is 9%. While making up a minor part of the total road length, the TEN-T roads located in urban areas account for approximately twice as high traffic flow (measured in AADT) as the non-urban TEN-T roads.

Whereas the TEN-T network accounts for only 1.4% of the total length of the road network within the European Union (Wikipedia, 2020b), it carries a considerably higher proportion of the total traffic volume. Based on CEDR (2018) and OECD (2015), the traffic volume on the TEN-T road network makes up roughly 15% of the total traffic on the roads of the European OECD countries. Of the TEN-T network traffic, as much as 87.5% takes place on motorways and only 12.5% on other TEN-T roads. Assuming that the traffic density ratio between motorways and other roads is similar for TEN-T roads and roads outside the TEN-T network, the present traffic on the TEN-T road network plus traffic on non-TEN-T motorways can roughly be estimated to amount to around 20% of the present traffic on the entire European road network.

According to Eurostat (2018) and Wikipedia (2020a), the length of the network of motorways in the EU/EFTA area increased by 36% over the period 2001-2018. Given the aims of the TEN-T program to upgrade both the core network (by 2030) and the entire comprehensive network (by 2050) to

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[37] Roads not classified into either motorway or non-motorway accounted for only 3% of the TEN-T network in 2018.

motorway or expressway standard (European Commission, 2017), we assume that the future motorway[38] construction as part of the TEN-T program will be of a magnitude sufficient to reach this standard. This implies the conversion of approximately 32,500 km of non-motorway parts of the TEN-T network into motorways until 2050. Moreover, assuming that the length of the non-TEN-T motorways will grow linearly at the same pace as over the period 2001-2018, this implies the construction of another 62,500 km. Together, motorway construction on TEN-T and non-TEN-T parts of the European road network will then make up 95,000 km over the years 2020-2050.

If we assume that the above-mentioned upgrading implies on average a doubling of the road capacity (measured in number of lanes) on the road links in question (e.g. from two to four lanes, and from three to six lanes), and that there will also be some capacity increase on the motorways already existing in 2020 (here estimated to be on average 25%), we can calculate the resulting amount of induced traffic, applying the elasticities derived in Chapter 3. In order to carry out these calculations, we must also make an assumption about the present traffic densities (measured as annual vehicle kilometers traveled per kilometer of road length) on the existing non-TEN-T and non-motorway roads that will be upgraded to or replaced with motorways during the period 2020-2050. Since a large part of such motorway construction, estimated above as two thirds, is presupposed to take place in urban areas (cf. above), we accordingly assume that two thirds of the non-TEN-T motorway construction will take place in contexts where the existing traffic densities are similar to the present average for existing motorways. We think this is reasonable because traffic densities on the TEN-T network are on average about twice as high in urban as in non-urban areas, and because the parts of the non-TEN-T urban roads likely to be upgraded to motorways must be expected to be those roads that already carry a high traffic volume. For the remaining non-TEN-T motorway construction, we will assume traffic densities on the existing roads similar to the present average for non-motorway TEN-T roads. Traffic volumes and traffic densities in 2020 are here estimated based on an extrapolation from the 2014 data assuming a continuation of overall traffic growth trends in European OECD countries over the years 2000-2014 (OECD, 2015).

The OECD (2015) statistics includes traffic volume data for only 19 of the 33 EU/EFTA countries included in our analyses, with many missing countries particularly in South and Eastern Europe. Moreover, in the estimations of growth in the motorway construction over the period 2020-2050, we have assumed that the growth rates will differ between different parts of Europe in the same way as during the period 2001-2018. This would imply a continued, intensive motorway construction particularly in Southern Europe (reflecting the substantial motorway development especially in Spain during the period since 2001) but also in Eastern Europe. We have cautiously applied this differentiation between European regions in motorway growth rates when applying the differentiated elasticities for induced traffic presented in Chapter 3. However, due to the very high uncertainty about whether the differences in between different parts of Europe in 2001-2018 will also persist in the forthcoming 30-year period, we have chosen to present the estimations on induced traffic due to motorway construction only at an aggregate EU/EFTA scale.

Based on the numerous and, admittedly, highly uncertain and contestable assumptions presented above, we have estimated the amount of induced traffic that could be expected from anticipated

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[38] Since the available statistics on road types of the existing TEN-T network (CEDR, 2018) does not differentiate between motorways and expressways, we will in our calculations not make any such differentiation but treat both categories as motorways.

motorway construction in the EU/EFTA area over the period 2020-2050. The results of this calculations are shown in Table 6.13.

Table 6.13: Estimated induced annual traffic by 2050 due to motorway construction in the EU/EFTA area in the business as usual scenario.

| | Annual billion vehicle kilometers in 2050 | Percent increase from 2020 total traffic volume |
|---|---|---|
| Motorway upgrading of present non-motorway TEN-T roads | 52 | 1.3 % |
| Motorway upgrading of present non-TEN-T non-motorway urban roads | 428 | 10.6 % |
| Motorway upgrading of present non-TEN-T non-motorway non-urban roads) | 33 | 0.8 % |
| Capacity increase of existing motorways | 102 | 2.5 % |
| Sum | 615 | 15.2 % |

Based on assumptions about the proportion of heavy-goods vehicles using the road network (13.7% in 2017, according to CEDR, 2018) and energy use per km for light and heavy vehicles, respectively, we have also estimated the energy consumption associated with the estimated induced traffic. Again, effects of future vehicle technology changes are not included. According to Odyssee-Mure (2020), mean energy use per vehicle kilometer for car transport within the EU/EFTA area is around 2.2 MJ/km. Data on the energy use per vehicle kilometer for the fleet of heavy-goods vehicles are scarce. Based on Transport & Environment (n.d.), average fuel consumption per km in 2014 for ten truck models produced by five key truck manufacturers (DAF, MAN, Mercedes, Scania and Volvo) was 36.5 liters of diesel per 100 km, which translates into 13.5 MJ/km. We will use these values in our calculations of energy consumption differentials between the energy efficiency and business as usual scenarios.

Assuming an average construction time of three years, the new and expanded motorways built 2020-2050 will be open for traffic on average 13.5 years during this period. The total amount of energy saved in the energy efficiency scenario will therefore be 13.5 times higher than the energy saved in the last year of the period. Table 6.14 shows the annual estimated energy saving in 2050 from halt in motorway construction, and the total estimated saving 2020-2050.

Table 6.14: Estimated reduced transportation energy consumption in 2050 in the EU/EFTA area in the energy efficiency scenario due to halt in motorway construction since 2020, compared to the road construction assumed in the business as usual scenario. Effects of future vehicle technology changes are not included.

| | Annually in 2050 | Over the period 2020-2050 |
|---|---|---|
| Estimated transportation energy saving (PJ) | 2300 | 31,000 |
| Energy saving in percent of total estimated annual energy use for road transportation in 2020 in the EU/EFTA area | 15 % | --- |

### Road infrastructure development – avoiding energy use from the construction stage of motorway development in the energy efficiency scenario

As mentioned in Chapter 3, the energy consequences of road construction include not only the energy use of the additional traffic that the new or expanded roads might induce, but also the energy used during the construction phase. Since the road construction differentiating between the energy efficiency and the business as usual scenario includes motorways only, we only need to apply the energy use factors for roads with four or more lanes. As also mentioned in Chapter 3, energy use for road construction will be higher in mountainous areas than in a flat terrain. In line with the considerations in Chapter 3, we roughly assume one fourth of the motorway construction in the business as usual scenario to take place under topographic conditions similar to those for the Norwegian motorways on which the empirical data are based, with the remaining three fourths assumed to take place in relatively flat terrain with only half as much energy use per kilometer of road construction.

The estimation of energy use for construction also needs to take consideration the number of lanes of the new roads (and the number of additional lanes when expanding existing roads). We will, in line with our assumption in the previous sub-section, assume that the new motorways constructed construction in the business as usual scenario will have on average four lanes, and that the capacity of the existing, expanded motorways is increased by 25%. Since many of the latter motorways must be assumed to be urban motorways where the number of lanes is already higher than four, we will here assume that the 25% increase in capacity corresponds to 1.5 additional lanes on average. Since the occurrence of mountainous areas does not vary in a systematic way between North, West & Central, South and Eastern Europe, we will present estimates only for the whole EU/EFTA area.

Since the energy efficiency scenario includes no motorway construction, the entire energy use for motorway construction in the business as usual scenario will count as energy savings in the energy efficiency scenario.

In addition to the energy required for construction of the infrastructure, energy must also be used for maintenance (e.g. re-asphalting) and operation (e.g. snow-clearing, cleaning, lighting, signal systems, etc.). The energy required for these purposes is considerable, and over the lifetime of a road the greenhouse gas emissions resulting from this activity have been estimated to be around twice as high as the energy use for the construction of the road (Strand et al., 2009; Secretariat for the National Transport Plan, 2010). For simplicity, we will here assume that the greenhouse gas emissions for construction as well as maintenance and operation to be proportionate to the energy use for these purposes. Furthermore, assuming a stipulated lifetime of 40 years, the average annual energy use for maintenance and operation could roughly be estimated to be around 5% of the energy used for construction of the road itself. Given the 2050 horizon of the present analysis, the roads constructed in the beginning of the period will be in use for 30 years minus the construction period, whereas the roads constructed towards the end of the period will not involve any energy use for maintenance and operation. Assuming an average construction time of three years, the roads in the business as usual scenario will be subject to maintenance and operation on average for a period of 13.5 years within the 2050 horizon of our analysis. Based on the above assumptions, the energy use for maintenance and operation over the years 2020-2050 of the motorways constructed during that period will be approximately 65% of the energy used for the construction itself.

Based on the energy consumption factors for highway construction presented in Chapter 3 and the assumptions above about energy use for maintenance and operation, Table 6.15 shows the energy savings in the energy efficiency scenario due to abstaining from further motorway construction.

Table 6.15: Estimated reduced energy use for infrastructure construction in the period 2020-2050 in the EU/EFTA area in the energy efficiency scenario due to halt in motorway construction since 2020, compared to the motorway construction assumed in the business as usual scenario.

| | Annually | In total 2020-2050 |
|---|---|---|
| Estimated saving of construction energy use by abstaining from motorway construction over the period 2020-2050 (PJ) | 12.4 | 373 |
| Estimated saving of maintenance and operation energy use by abstaining from motorway construction over the period 2020-2050 (PJ) | 8.4 | 252 |
| Sum (PJ) | 20.8 | 625 |

### Rail infrastructure development

As argued in Chapter 3.2, we have therefore chosen to consider rail investments as ‘neutral’ in terms of its impacts on future energy demand for transportation. The reason for this is that such investments trigger a number of mechanisms that work in opposite directions in terms of energy consumption levels. Quantifying these effects, let alone their combined net effect, is very difficult both because of the high context-dependency of the effects and because of limited empirical evidence. On the one hand, construction of rail infrastructure can make trains, metros and streetcars more attractive, compared to other, more energy-demanding modes. On the other hand, improved rail transport is also likely to induce an increase in the overall mobility of the population, and the resulting higher volumes of person kilometers and ton kilometers imply a higher demand for energy. Moreover, the construction of new rail lines is energy-demanding, particularly if large parts of the lines are built in tunnels. Since the various effects work in opposite direction, we have for the purpose of the present study assumed their impacts on the amount of energy use to rail infrastructure construction to roughly balance each other, which means that the overall effect of rain construction is assumed to be ‘neutral’ in terms of energy use.

### Airport expansions and flight taxation

Energy use for air travel is steeply on the rise. According to Capros et al. (2016:58, Figure 27)), the number of passenger kilometers in aviation within the European Union is projected to increase by 73% over the period 2020 – 2050 from about 1.8 to 3.1 Giga-person-kilometer (Gpkm) annually. Such increase depends on, among other things, airport expansions to accommodate such growth and the absence of heavy flight taxation and other policy measures to curb the growth in air traffic. In the energy efficiency scenario, taxation and other relevant regulations will be applied to an extent sufficient to keep air travel volumes at the present level, and no airport expansion to facilitate increased air traffic will take place.

In the energy efficiency scenario, the increased energy use associated with growth in air traffic is thus avoided. Based on Aamaas & Peters (2017), fuel consumption for air trips up to 800 km is estimated to be 7.7 liter per 100 pkm, while the fuel consumption for air trips up to 2500 km have an estimated fuel consumption of 4.7 liter per 100 pkm. We will use the mean value of these two figures (6.2 liter) as an approximate average fuel consumption per 100 pkm for air trips within the EU/EFTA area. Here, any future energy savings due to improved aircraft technology is not taken into consideration.

Based on the above assumptions, the energy savings in the energy efficiency scenario in 2050 due to absence of airport expansions and the use of economic and other policy measures are estimated to be around 2700 PJ compared to the business as usual scenario. For the whole period 2020-2050, the corresponding energy savings estimate is around 40,000 PJ.

One might argue that such curbing of the growth in air traffic is a strategy involving a reduction of activities in society rather than being an energy efficiency strategy (cf. Chapter 1.2). However, as mentioned under the sub-section about rail infrastructure development, we assume that high-quality rail transportation will to a considerable extent replace air travel, at least for distances below some 600-800 km. Such a modal shift does not necessarily imply a waste of time, seen from a productivity point of view. On the contrary, for a large proportion of professionals, the option to work during a train journey implies that the travel time can largely be utilized as productive time. Distinct from this, restrictions on the use of electronic devices while on board severely limit the possibility of working during flights. In addition, you can often go directly from the center of one city to the center of another city by train, whereas flights involve trips to and from the airport and time-consuming check in and security procedures. For moderate-length trips, the difference between airplane and train in door-to-door travel time is therefore often not so large. Moreover, we assume that videoconferences etc. can in the future replace a large number of work-related flights with few, if any negative efficiency impacts. Instead, there may be efficiency gains due to less time spent on non-crucial travel. Several European universities had already before the Corona pandemic adopted or were in the process of adopting policies to halve their travel-related climate footprint by 2025 (Wisborg et al., 2019). Since then, many more universities as well as other public-sector and private-sector workplaces have, in response to the Corona pandemic, made a very rapid adaptations to work practices involving dramatically less air travel than earlier. The energy efficiency scenario implies that at least some of these new emerging practices will persist, also for leisure trips, and that societies will not return to the steep growth in air travel as the 'normal' when the pandemic situation is over. The business as usual scenario, on the other hand, assumes that the current reduction in air travel is only a temporary drop and that the growth trajectory will be re-established after a few years.

### 6.3.3 Economic instruments

#### Road pricing

As mentioned in Chapter 3.3.1, the energy efficiency scenario includes the use of road pricing in metropolitan areas, with taxes differentiated between the morphological city and the remaining parts of a metropolitan area, and between urban regions differing in the population size of their main morphological city. As shown in Table 3.6, the average road pricing tax per km for the whole metropolitan area is presupposed to be 1.5 Euro in urban regions with more than one million inhabitants in the main city, 0.8 Euro in urban regions whose main city has a population between

100,000 and one million, and 0.3 Euro in urban regions whose main city has a population between 10,000 and 100,000. The corresponding reductions in the share of car travel resulting from these levels of road pricing are 13%, 8% and 4%, respectively. For urban regions whose main city has a population of less than 10,000, no road pricing is presupposed.

Based on experience from Greater Oslo (Sletten &Gulbrandsen, 2012), we cautiously assume that about 60% of the car trips reduced through road pricing will be replaced by trips by public transport and about 40% by non-motorized trips. According to Kenworthy (2020), energy use per person kilometer for travel in European cities and, is 2.30 MJ by car and 0.76 MJ by transit. Given these figures, we estimate each person kilometer of urban car travel replaced by other modes to yield a reduction in energy use of 1.84 MJ per person kilometer, i.e. by 80%.

According to recent studies in two Norwegian metropolitan areas (the Oslo and the Stavanger metropolitan area, with main city populations of 1 million and 0.22 million, respectively), mean trip distances by car and transit are very similar both for commuting and for non-work trip purposes such as purchase of daily necessities (Næss et al., 2019). We have therefore in our analysis of road pricing impacts on transportation energy use disregarded any differences in mean trip length by car and by transit. The 80% reduction in energy use per person kilometer when shifting from car to other modes will then also imply an 80% reduction in energy use per trip, since the trip distances by car and transit are on average equal. A 10% reduction in the share of car travel will accordingly lead to an 8% reduction in the energy originally used for car travel in the urban region in question.

Given an estimated annual total energy use per capita for intra-metropolitan transportation within the EU/EFTA area of 25.7 GJ in 2020 and assuming that 71% of this is for car travel, as in 2015, average per capita energy use for intra-metropolitan car travel is estimated to be 18.2 GJ in 2020.

From the above, and with the number of inhabitants in urban regions of different main city population classes in 2020, this yields the following annual energy savings in the energy efficiency scenario due to road pricing (Table 6.16):

Table 6.16: Estimated energy savings in the energy efficiency scenario due to road pricing in metropolitan areas.

| Population of the main morphological city of the urban region | Annual energy saving due to road pricing (PJ) | Total energy saving 2020-2050 due to road pricing (PJ) |
|---|---|---|
| 1 million and above | 218 | 6500 |
| Between 100.000 and 1 million | 172 | 5100 |
| Between 10.000 and 100.000 | 46 | 1400 |
| Total | 436 | 13,000 |

As can be seen, the estimated energy savings from introducing large-scale metropolitan road pricing schemes are substantial. Since road pricing, unlike urban spatial development and transportation infrastructure construction, can be implemented very quickly, given that there is political will, the estimated total energy saving is based on the assumption that such schemes will be in force already from the first year of the period. In comparison, the effect of the urban spatial development presupposed in the energy efficiency scenario is supposed to grow gradually from zero in 2020 to full effect in 2050 after 30 years of transportation-wise energy-favorable urban spatial development.

On the other hand, as discussed earlier, it is difficult to introduce road pricing schemes in sprawled metropolitan areas where the provision of public transit is poor. In such urban regions, it may not be politically possible to adopt road pricing until after several years of urban densification and improvement of the public transport services. The estimation of the energy-saving potential of road pricing for the whole period 2020-2050 is therefore arguably not very realistic, since it will in practice hardly be possible to implement the assumed road pricing schemes overall from day one, even with strong political backing for such solutions.

One more concern should be added here. Given that many urban regions throughout Europe have been developed in ways where substantial parts of the population live in more or less car-dependent suburbs, and with the housing price increases and gentrification that have taken place in many city centers worldwide (Rice et al., 2020), there is a risk that low-income people living in suburban and peripheral parts of the urban regions will be in a vulnerable situation if schemes of high road pricing are introduced. Such schemes should therefore be designed with compensation mechanisms to prevent negative social equity effects of road pricing. A combination of a scheme similar to the Carbon fee and dividend scheme introduced in 2018 in Switzerland and Canada (Nuccitelli, 2018) and deduction possibilities for households with low income and/or special needs could be a possible solution.

### Parking fees

In Chapter 3.3.2, we discussed the effects of parking fees in downtown and inner-city areas. For the energy efficiency scenario, we assumed hourly parking fees of 8 Euro, 6 Euro and 3 Euro, respectively, for downtown areas of cities with population of 1million and above, between 100,000 and 1 million and between 10,000 and 100,000 inhabitants. For inner city districts outside the very downtown areas, hourly parking fees of 3 Euro were assumed for cities of more than one million inhabitants and 2.25 Euro for cities between 100,000 and one million inhabitants, with no fees outside the downtown area for smaller cities. In the EU/EFTA area except Eastern Europe, these parking fee schemes were estimated to result in reductions in the modal share of car travel of 1.5 percentage points urban regions with main city population above 1 million, 1.1 percentage points in urban regions with main city population between 100,000 and 1 million, and 0.3 percentage points in urban regions with main city population between 10,000 and 100,000. In Eastern Europe, the corresponding estimated reductions were 2.0 percentage points, 1.6 percentage points and 0.5 percentage points, respectively.

Based on the similar assumptions as for road pricing regarding the modal shares of transit and non-motorized trips replacing car trips and the mean length of such transit trips compared to car trips, and assuming present overall average modal shares of car traffic of 50%, 60% and 70% in urban regions with large, medium-sized and small main cities, respectively, Table 6.17 shows estimated energy savings in the energy efficiency scenario due to parking fees in cities.

Table 6.17: Estimated energy savings in the energy efficiency scenario due to parking fees in cities.

| Population of the main morphological city of the urban region | Annual energy saving due to parking fees (PJ) | | Energy saving for the whole EU/EFTA area (PJ) | |
|---|---|---|---|---|
| | N, W/C and S Europe | Eastern Europe | Annually | Total over 2020-2050 |
| 1 million and above | 44 | 8 | 52 | 1570 |
| Between 100.000 and 1 million | 33 | 11 | 43 | 1300 |
| Between 10.000 and 100.000 | 3 | 3 | 7 | 200 |
| Total | 80 | 22 | 102 | 3060 |

The energy savings due to parking fees are considerably smaller than those from the road pricing schemes of the energy efficiency scenario. On the other hand, parking fees in downtown and inner city areas depend less than road pricing on precedent urban densification and transit improvement processes. Upscaling the annual energy saving potential to the whole 2020-2050 period thus seems more realistic than for the road pricing schemes.

It should be noted that the levels of road pricing and parking fees in the energy efficiency scenario both apply to the 2020 situation. In order to keep their effects, the fees should be adjusted for income growth during the period up to the 2050 horizon.

### 6.3.4 Sum of the three groups of effects

Table 6.18 summarizes the estimated energy saving potentials in the energy efficiency scenario from each of the three main categories of energy efficiency measures discussed in the preceding sub-chapters: urban spatial development, transport infrastructure development and the use of economic instruments. As mentioned earlier, we have for this report not been able to estimate how large annual energy efficiency gains vehicle technology improvements amount to, nor the total energy efficiency gain from such improvements over the period 2020-2050.

Table 6.18: Estimated energy savings in the energy efficiency scenario due to each of three groups of energy efficiency measures.

| | Annual energy saving in 2050 (PJ) | Total energy saving 2020-2050 (PJ) |
|---|---|---|
| Urban spatial development | 544 | 8,200 |
| Development of surface transport infrastructure | 2,320 | 31,700 |
| Economic instruments targeting surface transport | 538 | 16,100 |

In addition to the three above-mentioned categories of measures, we have estimated non-growth in air travel within the EU/EFTA over the period 2020-2050 to save around 40,000 MJ. Such non-growth would be the combined result of a halt in airport expansions, heavy taxation on flight and improved national and international railroad connections.

The numbers shown in Table 6.18 are separate estimate for each group of measures. However, the combined effect of all these measures cannot be estimated simply by adding the energy saving estimate through each group of measures. The reason for this is partly that some of the measures may be synergetic, as mentioned above regarding the higher possibility of implementing economic instruments to curb car traffic if the spatial urban development reduces the need for car travel. On the other hand, the difference in energy use with and without the implementation of energy-efficient urban spatial development, transportation infrastructure development and economic instruments to reduce transportation energy use will be smaller if the specific energy requirement per km by each mode is reduced. The higher the improvement in terms of energy-efficient vehicles, the smaller will be the energy-saving potential of each of the three other groups of measures, measured in absolute units. (The relative differences between the energy efficiency and the business as usual scenario will still remain more or less the same.)

In Section 6.4 below, we will discuss how synergies and overlap effects as those mentioned above may affect the total energy efficiency potential within the transportation sector.

## 6.4 Energy savings 2020-2050 in the energy efficiency scenario, compared to the business as usual scenario

Based on the calculation presented in the preceding sub-chapters, we will now attempt to estimate total energy saving potentials in the energy efficiency scenario from urban spatial development, transport infrastructure development and the use of economic instruments. Since we have not been able to quantify the annual energy efficiency gains or total energy efficiency gain over the period 2020-2050 through vehicle technology improvements, these effects are not included in the estimates. Energy efficiency potentials thorough vehicle technology improvements are substantial, and they also affect the magnitude of energy savings through other approaches.

Vehicle technology improvements for navigation contributes directly to energy efficiency gains but do not have any indirect effects worth mentioning on the energy efficiency gains of through other pathways discussed in this report. Vehicle technology improvements for aviation affects the magnitude of the energy gains from halting the growth in aviation but does not affect the estimated energy gains from surface or sea transportation. Vehicle technology improvements for road and rail transportation influence, in addition to their direct effects, the estimated energy gains from energy-efficient urban spatial development, halt in motorway construction and economic instruments to reduce car traffic in metropolitan areas. All these separately estimated energy savings will be diminished as vehicle technology improvements reduces energy use per person kilometer or ton kilometer of goods. Finally, urban spatial development reducing the need for car travel can facilitate the implementation of economic instruments for reducing urban motoring and thus has positive indirect energy-saving gains in addition to its direct effects. The same applies to improvements in the public transit provision for intra-metropolitan travel. On the other hand, road pricing is likely to reduce the induced traffic in urban areas from motorway construction and will thus reduce the energy saving potential of abstaining from such road building.

Finally, the originally estimated energy saving due to improved energy efficiency of vehicles will be diminished when, as in the energy efficiency scenario, the transport volumes by some of the modes of transportation are reduced compared to the business as usual scenario. Since energy efficiency potentials through vehicle technology improvements are not estimated in the present report, this does not affect our adjusted estimates, but it should be taken into consideration in later sEEnergies reports where vehicle technology energy efficiency potentials are estimated.

How, then, can the above-mentioned direct, indirect and reduced effects be combined in an overall estimate of the energy efficiency potential within the transportation sector?

Regarding the diminishing of originally estimated energy savings when taking vehicle technology improvements into account, adjusted estimates can be made simply by multiplying the unadjusted estimates by the future energy use per km measured as a percentage of the present energy use per km. The positive indirect effect of energy-efficient urban spatial development and improved transit provision via higher likelihood of road pricing and parking fees is more difficult to assess, as is the negative effect of road pricing on the energy saving from halt in motorway construction.

Here, we can only speculate about the magnitude of the above-mentioned indirect effects, although they are theoretically very plausible and the dependency of road pricing on accessibility by other travel modes is often mentioned in public debates on road pricing and road tolls. Below, we will cautiously and very roughly assume that:

- The effects of road pricing and parking fees in terms of reduced car driving in metropolitan areas will be 50% higher with energy-efficient (i.e. dense and concentrated) urban spatial development than with urban spatial development as in the business as usual scenario
- The effects of road pricing and parking fees in terms of reduced car driving in metropolitan areas will also be 50% higher with the improved transit provision presupposed in the energy efficiency scenario. However, an estimated half of this increase is considered to be already accounted for in the indirect effect of energy-efficient spatial development, since such spatial development facilitates a higher standard on urban transit systems.
- The induced traffic on metropolitan motorways constructed in the business as usual scenario will be half as large with urban road pricing as it would have been in the absence of such pricing.

Based on the above assumptions we have derived the following adjusted estimates for total energy efficiency potential in the energy efficiency scenario, compared to the business as usual scenario (Table 6.19). The annual savings are calculated as the average over the whole 2020-2050 period and are, due to long-term implementation of several of the measures, lower than the annual estimated energy saving in the year 2050.

Table 6.19: Estimated energy savings in the energy efficiency scenario due to each of four groups of energy efficiency measures, adjusted for interdependencies between the various groups of measures.

| | Unadjusted energy saving in 2050 (PJ) | Unadjusted energy saving 2020-2050 (PJ) | Adjusted energy saving 2020-2050 (PJ) | Adjusted average annual energy saving (PJ) |
|---|---|---|---|---|
| Urban spatial development | 544 | 8,200 | 12,300 | 410 |
| Development of surface transport infrastructure | 2320 | 31,700 | 22,800 | 760 |
| Economic instruments targeting surface transport | 538 | 16,100 | 13,200 | 440 |
| Halt in the growth of aviation within the EU/EFTA area | 2700 | 40,000 | 40,000 | 1330 |
| Total | 6100 | 96,000 | 88,000 | 2940 |

Compared to the total annual energy use for transportation within the EU/EFTA area in 2020 of approximately 14,500 PJ (estimated based on European Commission, 2019), the estimated energy efficiency potential within the transportation sector is considerable. The high uncertainty and the many contestable assumptions on which our estimates are based must still be borne in mind.

One additional caveat should also be considered: when less energy is consumed for the same activities as before, rebound effects are likely to occur. Rebound effects can broadly be understood as reductions in expected resource-saving gains from new technologies that increase the efficiency of resource use. Historically, such effects were first theorized by the economist William Jevons (1866), who observed that technological improvements increasing the efficiency of coal use led to the increased consumption of coal in a wide range of industries. In addition to increasing the consumption of a particular resource such as coal, indirect rebound effects can shift impacts to other sectors or types of consumption due to the money saved when using less of the resource subject to efficiency increase in the first place. For example, within the transportation sector, researchers have identified rebound effects for road freight traffic (Walnum & Aall, 2016). Other researchers have pointed at an increase in energy-intensive international holiday flights as a rebound effect of living in dense inner-city areas where residents save money due to a low need for car ownership and car driving (Næss, 2016; Czepkiewicz et al., 2020).

It would of course be meaningless, for example, to develop cities in a more car-depended way in order to make people less able to afford leisure flights. Such rebound effects could be addressed much more effectively by measured targeting the rebound activity directly, such as increased taxes on flights. Nevertheless, indirect rebound effects due to money saved may be hard to avoid. As long as the purchasing power remains the same or increases, resource efficiency improvement resulting in money-saving is like squeezing the balloon. Avoiding such effects seems impossible unless the purchasing power decreases. In a situation with economic growth, the metaphoric balloon is on top of that pumped up with more and more gas.

The existence of rebound effects points at the wider issue of whether energy efficiency improvements are enough to curb the growth in energy to a degree sufficient to reach climate mitigation objectives. According to the 2016 EU PRIMES reference scenario (Capros et al., 2016), final energy demand in the European Union will be roughly the same in 2050 as in 2020 despite rather optimistic assumptions about the degree of decoupling between GDP growth and energy consumption. We will not elaborate on this question here but only point at the nexus between energy efficiency, economic growth and level of energy consumption as an important area of future research.

# 7 Examples from selected urban regions

The purpose of this chapter is to supplement the previous chapters with short tangible examples of how different cities in Europe are implementing different tools in order to reduce car-based transport – and thereby make the combination of urban structure and transport related infrastructure more energy efficient. The cities chosen to be examples in this chapter are all larger cities that have been working with a combination of different strategies in relation to urban development and changes in transport infrastructure. The choice is made based on a dialog with experts in the field combined with a literature review.

It is, however, a challenge that much of the case related literature relates to cities as administrative units and not urban regions or continuous urban areas (morphological cities). The administrative boundaries of cities are very different across Europe. Some cities – like Vienna and Hamburg – have a large part of the continuous urban area within the administrative borders of the core municipality, other cities – like Zürich and Copenhagen – only have the inner parts of the city within the administrative borders. Municipalities covering a large part of the continuous urban area will probably have lower urban population density and have longer average distances to the city center. According to our research, presented in the previous part of the report, this would imply an average larger share of kilometers traveled by car. Municipalities with only the inner part of the morphological city within the municipal borders tend, on the other hand, to have a higher population density and have a shorter average distance to the city center than for the whole morphological city. The registered kilometers per capita traveled by car and the modal share of car travel would therefore tend to be underestimated, compared to whole morphological cities.

### Vienna

Vienna, placed in the South-Eastern part of Western & Central Europe, has 1.9 million inhabitants within the borders of the core municipality: Stadt Wien, and 2.8 million inhabitants the continuous urbanized area. The city as an administrative unit covers a relatively large part of the continuous urbanized area. Vienna has succeeded in reducing the share of daily trips by car from 40 % in 1993 to 27 % in 2013 (Buehler et al., 2017). Throughout history, Vienna has remained a compact, monocentric city. The population in the city has been increasing from 1.5 million in 1990. Less than 50 % of the 415 km$^2$ land area of the municipality Stadt Wien is used for urban development and transport infrastructure. The preservation of the old town with its narrow streets has been a political priority since the late 1960ies. The suburbs surrounding Stadt Wien (the rest of the morphological city) are less dense and more car-oriented.

Some of the reasons for the major shift in modal split has been a strong political will to establish and expand the Viennese metro system (U-Bahn) combined with the implementation of parking management systems. These policies are part of making Vienna have a relatively large part of public transport, measured in trips: 44 % in the city center and 38 % outside the city center – but only 9 % in the surrounding suburbs (Buehler et al 2017b). The policies concerning improvement of public transport and restricting car transport have been supplemented with policies for improved walking and cycling conditions. The share of bicycle trips has increased from 3 % in 1993 to 6 % in 2020 (Buehler, 2017b).

Aspern Seestadt is an example of new urban development in Vienna, situated 7 kilometers from the center of the city. Transit oriented development can be seen as a tool for more energy efficient urban development in situations where the distance to the city center is considered too long for cycling and walking. The new district is 2.4 km$^2$ and is envisaged to have 20,000 future residents and 20,000 potential workplaces. It is a transit-oriented development with three rail stations, promoting walking and cycling, combined with restriction on car use (City of Vienna, 2015).

Vienna has not been a frontrunner in developing very innovative solutions to make its transport more energy efficient. But the administration of Vienna has been very sensitive towards learning from experiences in other European cities and implementing policies which reduce the dependency of cars. In our interpretation, the most essential policy has been to keep Vienna as a compact, monocentric city, allowing the city to have a focus on developing public transport infrastructure.

### Stockholm

Stockholm is placed in Northern Europe, having 975,000 inhabitants in the core municipality – Stockholm Stad, approximately 1.6 million in the continuous urban area and 2.4 million in the metropolitan area. Stockholm has implemented congestion charging in the inner parts of the city. The tax/fee paid depends on the hour of the day and the season. Stockholm's introduction of congestion charging began with a trial period in 2006. The trial period led to a decision of making the congestion charge permanent. The congestion charge has reduced car traffic crossing the border to the inner pars of the city by approximately 20 %, predominantly moving people to public transport, which is of high quality in the inner part of the city. It had been feared by some that congestion would increase in roads close to the congestion charged area, but this does not seem to be the case (Börjesson et al., 2012).

There was a strong opposition against the congestion charge prior to its implementation. This changed with the implementation, one of the probable reasons being that the congestion charge actually helped reducing congestion and emissions. The effect of the congestion charge has not been weakened during the first five years of implementation, and it is supported by the public and the politicians (Börjesson et al., 2012). However, as part of the political bargaining about the introduction of the congestion charge, it was decided that the revenues should be spent on highway development in the Stockholm area, including a new motorway tunnel in its western part (Eliasson, 2014). At metropolitan scale, this part of the package counteracted the traffic-reducing effects of the congestion charging.

The congestion charge is a way of reducing the cars' share of the modal split in central areas of larger cities. It requires the existence of attractive alternatives; in the case of Stockholm this is public transport of a relatively high quality.

### Barcelona

Barcelona is located in Southern Europe, having about 1.6 million inhabitants within the limits of the core municipality and 4.8 million inhabitants within the continuous urban area. The Municipality of Barcelona covers 102.2 km$^2$, thus having a population density of almost 16,000 inhabitants per square kilometer. Around the very dense city center from the middle age, Barcelona was developed according to the plan of Cerdá in the 19th century followed by Plan Marcia in 1932. This laid the foundation for the urban development in large 9 story blocks in a very regular grid pattern, making Barcelona an example of a very dense city. Today, most of the streets are equally challenged with car-based transport and the consequences of this: lack of space for pedestrians, lacking accessibility of sidewalks, bad air quality, low acoustic comfort and in general: low livability index in public space. The idea of the superblocks is to make one superblock out of nine of the original blocks, reducing car-based traffic dramatically in the interior of the superblock. The superblock will be approximately 400 x 400 meter and have 5000 – 6000 inhabitants. This will free space for pedestrians, increase accessibility, improve air quality, better the acoustic quality and improve livability – especially if you only consider the interior of the superblock. The superblocks will not only affect the individual block. It is estimated that the number of circulating cars is reduced by 13 %, reducing the space that the cars take up by 70%. This will have remarkable positive economic consequences. The new model enables a substitution of cars with public transport, increasing the number of bus lanes and bike paths among others (López et al., 2020).

It is possible to have 503 superblocks in Barcelona over time. Right now, 18 superblocks have been decided and 6 superblocks have been implemented. The first superblock was decided in 1993, the next in 2003. The following four in 2016 or later (Lopez et al., 2020).

Most European cities do not have the same type of regular grids and a density like Barcelona. But the idea of making traffic calmed zones in ‘superblocks’ in dense parts of the city, using this to promote public transport and reduce car dependence, can be copied to many European cities The main challenge is the democratic one: which roads are chosen for carrying the transport, and which roads are in the calm interior of the superblocks? This might be the reason for the very slow development of the superblocks in Barcelona.

It is, however, important to remark that the superblocks are not only making the city more energy efficient: they are freeing expensive urban space for other activities and making the city more livable. If the cars predominantly only are allowed to park along the major streets – and not in the interior of the superblock, it will make public transport and soft mobility more competitive.

It is also important to remark that superblocks relate to the dense city. In the dense city, it is possible to replace car-based transport with public transport (or soft mobility). A superblock with 5000 – 6000 inhabitants in a single-family house area would result in very long distances from the house to a public transport stop.

### Zürich

Zürich is the largest city in Switzerland, 1.9 million people live in the metropolitan area, 1,3 million in the continuous urban area – but only 434,000 in the municipality Stadt Zürich. Zürich is located in the Southern part of Western & Central Europe.

The Stadt Zürich has high quality densification as a central part of the urban development strategy (Stadt Zürich, 2016). Any additional mobility demand has to be satisfied by walking, bicycling and the use of public transport. The existing regulation requires one parking place for private cars per 120 m2 of floor space (sometimes per 40 m2, depending on the land use). The Stadt Zürich has, however, decided to establish a maximum of 10 % of the existing norm in the central areas of the city, corresponding to one parking place per 1200 m2 of floor space (Cao et al., 2019b). The very restrictive parking policy makes it unattractive to bring a car to the center of the city, as it is very hard to find an appropriate place to park the car between 11 and 16 (Cao et al., 2019b). Most likely, the very restrictive parking policy has been an essential part of bringing the car share of the modal split in Zürich down from 39 % in 1994 to 30 % in 2010 (Buehler et al., 2017b).

### Gothenburg

Gothenburg is a city in Northern Europe with approximately 580,000 inhabitants in the municipality 'Göteborg Stad', and approximately 1 million inhabitants in the metropolitan area. Gothenburg has experimented with parking restrictions. In the urban transformation area 'Porslinsfabriken' - the porcelain factory – the idea was to build the area with a limited number of parking spaces – 0.52 space per housing unit + 0.05 space added for guest parking. This parking policy is intended to encourage people to choose public transport or the bicycle instead of the car. The municipality of Gothenburg strives for improving public transport, making public transport attractive in the entire city.

Porslinsfabriken is located only 2.3 kilometers from the central train station – which is a part of the city center. Some of the families moving to the area have reduced their car ownership and discovered how easy and comfortable it is to use public transport or their bicycles. The parking requirement applied in Porslinfabriken is not particularily strict in practice, and the changes in residents' car use reflects that their new residences are closer to the city center than their prior ones (Antonson et al., 2017).

### Copenhagen

Copenhagen is a city in Northern Europe with 632,000 citizens in the administrative unit 'City of Copenhagen' (i.e. the core municipality) and approximately 1.3 million in the continuous urban area. Almost 1,9 million people are living in the area covered by the 'Finger Plan', and 4.3 million people live within what has been proposed as an extended urban region, including parts of Southern Sweden.

Copenhagen is known as the city of bicycles. The municipality of Copenhagen has been documenting it qualities of bicycling for many years. The municipality of Copenhagen had, however, at very low share of trips carried out by bicycles in the early 1970ies. Public pressure, with approximately 40,000 cyclists demonstrating in the late 1970ies, gradually made the city invest in bicycle infrastructure, improving the conditions for bicyclists. Gradually, bicyclists gained territory in the central parts of the city. On January 10th, 2017, almost 70% of people living and working in the Municipalities of Copenhagen and Frederiksberg, commuted by bicycle: dark and cold in the morning and dark and cold in the evening.

At one point in time, the municipality of Copenhagen realized that it wasn't possible to increase the number of cyclists in Copenhagen without involving the surrounding suburban municipalities. People from the suburbs needed better conditions for commuting by bicycle (and not by car). A network of superhighways for bicycles had to be established. The first cycle superhighway was established in 2012. By now, an entire network is incorporated in the Danish Finger Plan. A traditional consulting company has calculated that investments in new cycle superhighways has a good internal rate of return – up to 37% (Incentive, 2018). What makes the cycle superhighways attractive is not only the highway stretches themselves but also the favorable conditions for bicycles in the inner part of the city.

Establishing the cycle superhighways has led to a remarkable increase in the number of cyclists in the suburbs surrounding the municipality of Copenhagen. Most or the suburbs are, however, still dominated by cars. The bicycle superhighways are still dependent on a dense city. It is, however, remarkable that those who use the cycle superhighways are commuting for longer distances than people using public transport. The average trip length among the cycle superhighway users is 11 kilometers (supercykelstier.dk 2020; Københavns Kommune, 2019). Improving the infrastructure for cyclists is creating more trips carried out by bicycle; the number of bicyclists has increased by 23 %. However, only 14 % of the new bicyclists have replaced car trips by using a bicycle.

The case of Copenhagen shows that it is essential to consider the density and the distance to the city center when bicycling is described as an alternative to transport by car. Bicycles can easily compete with cars in the dense city center. The cycle superhighways demonstrate that bicycle trips are not necessarily short trips, and that investments in an improved bicycle infrastructure in the urban region will make more people choose the bicycle. Replacing car trips with bicycle trips will save energy. The most important effect – which make investments in bicycle infrastructure highly profitable – is, however, the effects on public health (incentive, 2018).

### Oslo

Oslo is a city in Northern Europe, with approximately 693,000 inhabitants in the core municipality – Oslo kommune. The morphological city has approximately 1 million inhabitants and the urban region approximately 1.5 million inhabitants (Tiitu et al., 2020). Oslo is an interesting example of multiple policies pointing towards a more sustainable mobility development, including the avoiding of urban sprawl.

The urban spatial expansion was higher than the population growth in the 1960s and 1970s in the Oslo Metropolitan Area. Oslo experienced urban sprawl. From the early 1980s, however, development turned from the previous outward expansion to densification and re-urbanization. Urban development started to take place considerably closer to the city center than earlier (Næss et al., 2011). Between 2000 and 2018, the population density of the morphological city increased by 18 %, and within the municipality of Oslo the population density increase was as high as 29 % (Tiitu et al., 2020). The municipality has invested considerably in technical and social infrastructure in the inner city. Large sums have been invested in improving public transport, for instance in a new metro ring and improved streetcar lines with high frequency of departure (Næss et al., 2011).

Oslo implemented a toll ring around the city center in February 1990. In the beginning – with Oslo Package 1 - the revenue was used to finance road infrastructure. Later – in packages 2 and 3 – the focus has been on financing improvements of public transport (Vold, 2006, Tiitu et al., 2020).

It is worth mentioning that continuation of the urban sprawl of the decades prior to the mid-1980s would have led to a very high demand for investments in transport infrastructure outside the city, especially considering that the city is naturally limited by hills. The global development led to industries leaving Oslo, making large areas closer to the city center available for new urban development. Strong economic growth has led to a fast urban development with investments in infrastructure. The inner parts of the city have become more attractive as a location for both jobs and living. The increasing population is facilitating further investments in infrastructure development. (Tiitu et al, 2020). Densification makes public transport and bicycling an attractive alternative to the car.

Oslo is clearly demonstrating how different planning tools in combination can enhance urban development relatively close to the city center and urban densification. Nearly all central actors support this deployment (Næss et al., 2011). An important take-away from the Oslo example is that the implemented policies does not only reduce the dependence on car-based transportation but also increases the urban quality, making the city able to attract new jobs and new citizens. On the other hand, increased land values and absence of policies to provide affordable housing have led to skyrocketing housing prices, currently pushing an increasing number of low- and middle-income households to move to outer parts of the metropolitan area.

# 8 Concluding remarks

The purpose of this report was to illuminate the energy efficiency potential in the EU/EFTA area within the transportation sector, with 2050 as the time horizon. More than for many other sectors, the energy use within the transportation sector and the potentials for improved energy efficiency depend crucially on human motivations, attitudes, social networks or other conditions enabling or constraining their actions. The actual energy use and the potential energy efficiency improvements also vary substantially with geographical contexts, and for many of the measures for increased energy efficiency, the magnitude of potential savings is difficult to measure accurately. Add to this that the effects of relevant measures are unlikely to remain constant over time. The baseline trajectory against which an energy efficiency scenario is compared is also encumbered with great uncertainties. The impacts of the Covid-19 pandemic, which are likely to affect the transportation sector more than many other sectors, adds to the already high uncertainty of how transportation will develop in the future.

To put it short: energy use within the transportation sector and the potential energy savings though energy efficiency measures are parts of open systems where a multitude of causal mechanisms operate at the same time[39]. Some of the causal mechanisms amplify their effects, some counteract each other, and some are only activated in combination with other causes. The influencing causal mechanisms belong to different domains of reality (the natural world, the social world, and the sphere of individual humans), and the knowledge about them is typically situated in different academic disciplines. The available knowledge about the *nature* of relevant mechanism is mostly theoretically well-founded and based on solid empirical research. However, the magnitude of effects is highly context-dependent and subject to change over time. Trying to quantify the energy efficiency potential thirty years ahead within the transportation sector might thus appear as an utterly hazardous endeavor.

Nevertheless, this is what the sEEnergies project aims to do for transportation and mobility, buildings, industry and regarding energy grids, and what we have tried to do in the present report for the transportation sector. As evident from the above, these estimates obviously can only be very rough. However, as a base for informed decision-making, a rough estimate is far more useful than no estimate at all. Knowing something about the order of magnitude of effects is important in order to judge, for example, whether sustainable mobility (Banister, 2008; Holden, 2016) can be achieved through energy efficiency measures or requires measures that go beyond an efficiency paradigm.

With these remarks about the limitations of our study, let us cautiously summarize its main conclusions. Keeping vehicle technology improvements aside, our estimations suggest an average annual energy-saving potential of nearly 3000 PJ from applying energy-efficiency measures within urban spatial planning, transport infrastructure planning and economic measures for transportation demand management. This suggested energy-saving potential corresponds to 22% of the total annual energy use for transportation in the EU/EFTA area in 2020. In addition, there is a considerable energy efficiency potential through vehicle technology improvement, but we have in this report not been able to quantify this potential.

Around 45% of the estimated energy efficiency potential (excluding vehicle technology improvements) is due to replacement of growth in air travel with growth in other public transport modes, particularly

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[39] For example, a Danish study identified 22 different driving forces behind traffic growth (Clausen et al., 2001).

rail transport, and replacement of corporeal business travel with virtual communication. The main policy instruments presupposed for this to take place are partly economic (flight taxation) and partly physical (abstaining from the construction of additional runways and other capacity-increasing airport infrastructures). About 25% of the energy efficiency potential is attributable to abstaining from construction of new and expanded motorways, which would otherwise induce a substantial amount of additional traffic resulting in increased energy consumption. Energy-efficient urban spatial development and economic transportation demand measures are estimated to contribute with around 15% each to the average annual energy efficiency potential.

As shown in Appendix A, a long array of vehicle technology measures can improve the energy efficiency of cars, buses, trucks, trains, vessels and airplanes. Combined, such technological improvements represent a substantial energy efficiency potential.  We have, however, not so far been able to estimate how large annual energy efficiency gains these efficiency improvements together would amount to, nor their total energy efficiency gain over the period 2020-2050. Such estimates will instead be offered in a later deliverable report from the sEEnergies project, based on Aalborg University's TransportPlan model.

Together, the estimated energy savings from energy efficiency measures within urban spatial development, transport infrastructure development and transportation demand management and the expected gains from energy-efficient vehicle technologies represent a substantially lower energy consumption than in a business as usual scenario. On the other hand, mobility has been steadily on the rise over more than a century, apart from small drops in periods of crisis or war. Time will show whether the present mobility decrease due to the Covid 19 pandemic will leave lasting impacts on the mobility trajectory or be, as assumed in this report, just another temporary drop of an otherwise steadily rising curve. According to a 2011 OECD report, passenger mobility (measured in person kilometers) was expected to increase by 22% – 30% between 2020 and 2050, whereas an increase of 16% - 36% was expected for freight mobility (International Transport forum, 2011). Although some of the energy efficiency measures envisaged in the present report aim at improving accessibility by facilitating proximity between trip origins and destinations instead of through increased mobility, general trends of overall increased mobility will counteract the energy efficiency measures and cause a lower degree of decoupling between GDP growth and transport energy consumption than what might be obtained in the absence of general mobility growth. Not the least, increases in tourism and leisure travel represent a challenge in this context.

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# Appendix A: Measures for making each mode of transport more energy-efficient

## A.1 Introduction

The European transport sector is the second largest energy consumer in the EU after households and services contributing to more than 30% of the overall EU energy demand (European Commission, 2019a). The main modes of transport discussed in this report are as follows:

- Roads: including Light Duty Vehicles (LDVs) and Heavy Duty Vehicles (HDVs)
- Railways
- Aviation
- Shipping

Amongst all modes of transport, road transport is the major consumer of energy in EU 28. Figure A.1 shows the share of different modes of transport and their energy consumption, both when taking into account aviation and shipping outside the EU (left) and without EU-external aviation and shipping (right).

Road transport represents around 82% of the final energy use for intra EU transport and still around 54% of the share when extra EU transport is accounted for. Followed by road is aviation (25%), shipping (18%), while rail at 2 % has the smallest share as shown.

It is interesting to note that when extra EU transport mainly coming from freight activity of shipping and passenger aviation is accounted for in the total energy demand, raises the transport energy demand by more than 30 % as shown in Figure A.1.

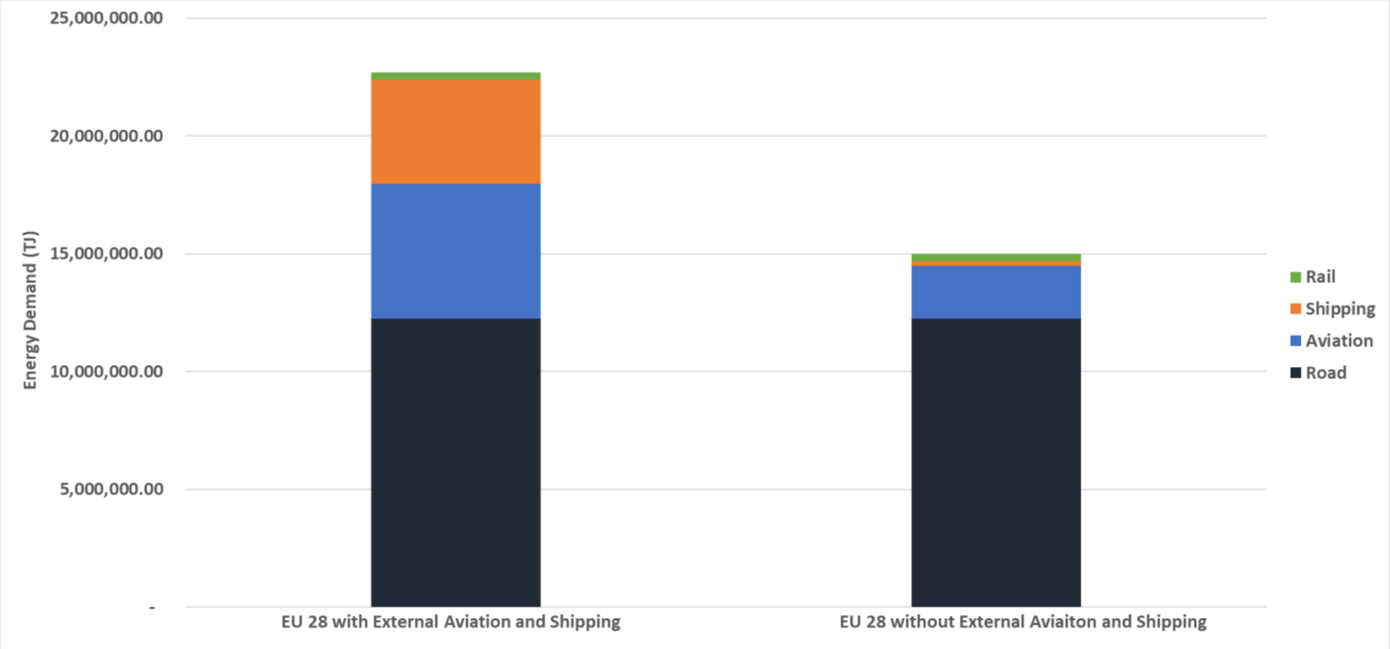

Figure A.1: EU 28 transport energy demand share (TJ) in 2015 (Capros et al., 2016)

Road transport is the backbone of passenger activity in EU 28 contributing about 5,500 Gpkm in 2015 which adds up to more than 75% of the total EU passenger activity demand as shown in Figure A.2.

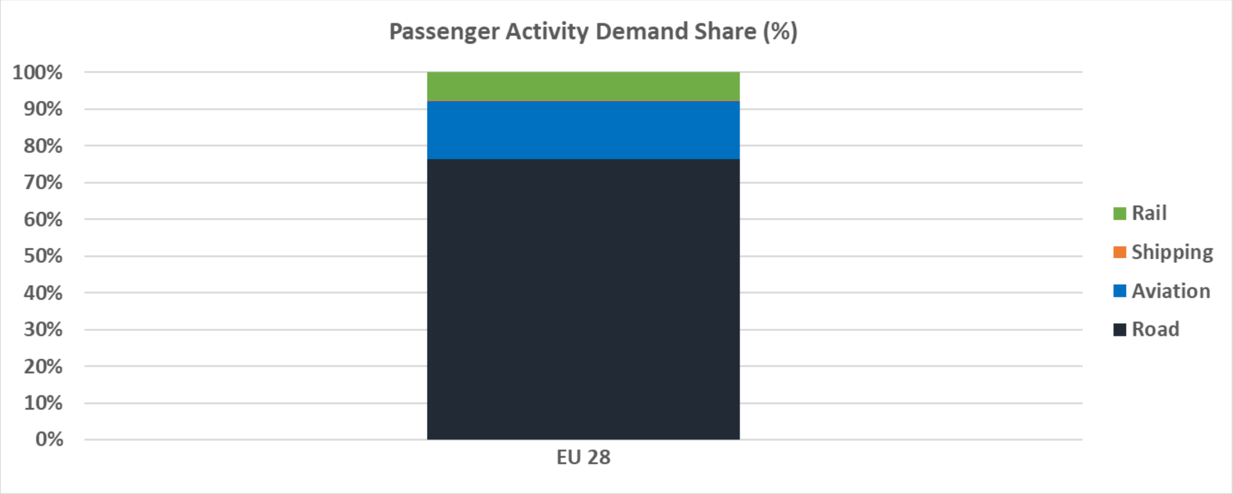

Figure A.2: EU 28 passenger activity demand share (%) in 2015 (Capros et al., 2016)

Figure A.3 shows the distribution for different modes of transport contributing to freight in the EU 28, including external EU freight transport demand for shipping and aviation. It can be seen that shipping takes a huge share in freight activity (76%) mainly coming from freight activity between EU and rest of the world almost 6000 Gtkm of freight transport.

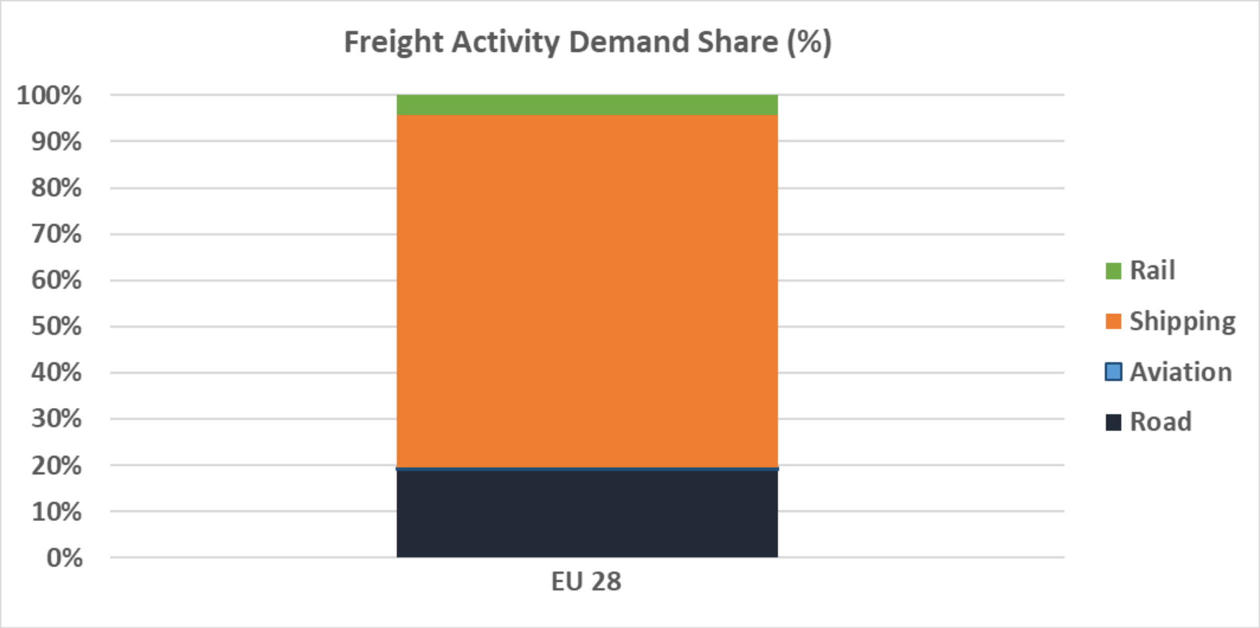

Figure A.3: EU 28 freight activity demand share (%) in 2015 (Capros et al., 2016)

In this report, the tank-to-wheel (TTW) efficiency will be the primary focus. There are several considerable conversion losses, for instance in the process of producing hydrogen from electrolysis or in synthesis processes for producing electrofuels but in this report the vehicle technologies will be compared on the efficiency of the drivetrain. The energy efficiency of all vehicles is calculated in this report following the methodology introduced in the Danish transport system model "Alternative drivmidler" (AD). The methodology is adapted to display the energy efficiencies in a Danish context, but it is estimated that the methodology is applicable in a European context. (Danish Energy Agency & Cowi, 2013)

The applicability of the highlighted vehicle technologies and propulsion systems in the following will depend on the type of vehicle. Battery electric drivetrains are more suitable for short-distance, light-duty vehicles, while energy-dense liquid fuels for internal combustion engines provides more resilience for long-distance heavy-duty vehicles. Fuel cell propulsion systems still represent a novel technology but could in the future play an important role both for long- and short-distance transport.

Adequate transport infrastructure to accommodate new transport demands and alternative transport technologies is essential to support a renewable transition of the transport sector. This relates to development of road and rail infrastructure, ports and airports, as well as a substantial fueling infrastructure. If an extensive electrification is desired, sufficient charging infrastructure must be in place. In this report the need for infrastructure is not analyzed, but it is recognized that an implementation of alternative transport technologies will require investment in new transport infrastructure.

### Methods for the work on this Appendix

Determination of transport energy demand and transport activity demand is key in estimating the energy efficiency potentials for the EU-28 transport sector. For data collection, the main sources used for different modes of transport were the Eurostat database on transport and energy (Eurostat, 2020a) and the EU reference scenario 2016 (Capros et al., 2016). The specific energy consumptions for both passengers and freight transport were estimated for each country and along with the transport activity, were used to calculate the overall energy demand of each mode. Finally, the fuel share distribution for each mode is obtained from the Eurostat database (Eurostat, 2020a).

The determination of the international (outside of the EU-28) transport demand in the maritime and air sectors shares some common features but also present discrepancies due to data availability or quality. The common denominator for both cases has been the employment of Eurostat's database (European Commission, 2019a) for retrieving the tonnage (number of passengers) traveling between the different ports (airports). In some cases, this information is provided on a port-to-port basis but in others, only information on a country-to-country basis is at hand. In general, the former type of information has been preferred given its higher accuracy, but the latter, less granular, was used too to achieve a comprehensive picture of the transport demands.

The differences between the four subsectors lie in the method to determine the distance travelled by passengers or cargo. In the case of air transport, the procedure has been rather straightforward as the distances along the geodesic between airports were almost directly used. Only some minor corrections were applied following ICAO's guidelines (ICAO, 2017). The distances followed by vessels were, on the contrary, rather more difficult to estimate and two different databases were consulted to assess the distances between the multiple port pairs.

On the one hand, the US Navy's PUB. 151 DISTANCES BETWEEN PORTS (National Geospatial Intelligence Agency, 2001), which contains distances between the World's main ports, was utilized for freight transport. This database had to be extended thanks to the A* Algorithm (Hart et al., 1968) to increment the number of port pairs for which information was available. On the other hand, the Eurogeographic's Dataset EuroGlobalMap (Eurographics, 2020) was utilized for retrieving the most transited ferry routes in Europe, which were further process for calculating the distances between the connected ports.

The energy efficiency of all vehicles calculated for this appendix follows the methodology introduced in the Danish transport system model "Alternative drivmidler" (AD) (Danish Energy Agency, 2015). The methodology is adapted to display the energy efficiencies in a Danish context, but it is estimated that the methodology is applicable in a European context.

The energy efficiency in this appendix is defined as the relationship between the mechanical energy needed at the wheel to prompt propulsion and the total energy consumption to move the vehicle. The mechanical energy consumption at the wheel needed for forward propulsion depends on the frictional resistance from the road, air, and/or water. The assumption is, that this is the absolute minimum of energy required to achieve forward propulsion. All additional energy consumption is considered as losses. The total energy consumption per kilometer includes thermal, idle, and mechanical losses and lost energy related to braking. The engine efficiency alone is therefore not representative of the vehicle efficiency as cabinet losses among others reduce the overall efficiency when driving. The vehicle weight is significant for road friction, hence the energy consumption is slightly higher for electric vehicles than conventional internal combustion engine (ICE) vehicles, due to the added weight of the battery pack.

## A.2 Light Duty vehicles

The European fleet of passenger vehicles has grown from 238 million in 2009 to 271 million in 2018. European cars represent 44% of EU's total transport related greenhouse gas emissions. (Transport & Environment, 2018a; European Automobile Manufacturers Association, 2020).

Car transport in the EU is fueled primarily by petrol and diesel, covering 96% of all cars (Figure A.4). Liquefied petroleum gas (LPG) is the most widely used alternative fuel, while electric vehicles, both hybrids, battery electric and plug-in hybrids, cover only approximately 1% of all cars in the EU. (European Automobile Manufacturers Association, 2019.)

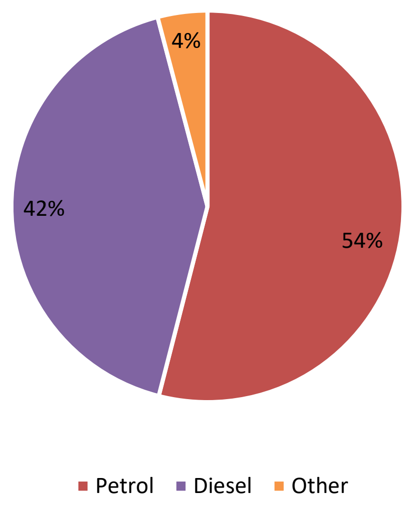

Figure A.4: Fuel distribution for cars and vans (European Automobile Manufacturers Association, 2019).

The internal combustion engine (ICE) is and has been for decades the dominant vehicle technology in Europe and globally. The low energy efficiency of the ICE is compensated by the high energy density of liquid fuels, such as petrol or diesel, which provides even vehicles with small fuel tanks sufficient range. The IEA and ICCT found that the energy efficiency of conventional ICE vehicles in Europe has improved since 2005. Several factors are responsible for this development, such as a market uptake of small city/urban cars in many dense European cities, a high share of diesel vehicles and technological development of vehicle drivetrain, such as turbocharging and a higher number of gears. (International Energy Agency (IEA), 2017).

In the following, three different drivetrains for passenger vehicles are investigated: battery electric, hydrogen fuel cells, internal combustion engines. Battery electric vehicles and fuel cell electric vehicles have different drivetrains than conventional internal combustion engine (ICE) vehicles. Biofuels and electrofuels are alternative fuels to replace fossil fuels in ICE vehicles, hence the existing fleet of vehicles can be decarbonized. Hybrid electric vehicles will not be described in any further detail.

### A.2.1 Electric Vehicles

Both battery electric vehicles (BEV) and fuel cell electric vehicles (FCEV) are considered in the following. BEVs use a battery pack to store electric energy on-board and an electric engine as the sole sources of propulsion. The electric drivetrain alone operates at high efficiencies in the region of 90%. Considering all energy losses, the overall efficiency of an average BEV is estimated to be 79%. Hence in an energy system powered by renewable sources of electricity, BEVs offers an energy efficient alternative to conventional ICE vehicles. (European Commission, 2020.)

The uptake of battery electric vehicles and plug-in hybrids in Europe are apparent in Figure A.5. While annual registrations have increased since the first introductions of BEVs in the beginning of the decade, electric vehicles still only constitute 1% of the European light-duty car stock. (European Automobile Manufacturers Association, 2019.)

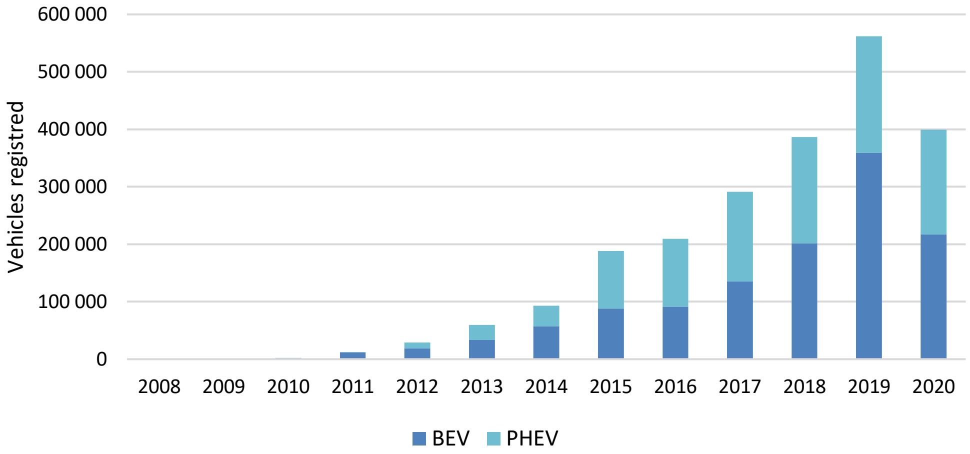

Figure A.5: New vehicle registrations in EU + UK + EFTA + Turkey. (Until June 2020) (European Alternative Fuels Observatory, 2020a).

The battery is the key component in electric vehicles. The range and electrical conversion efficiency in EVs are dependent on the battery and electrical engine. The development of the battery technology, in terms of specific power, energy density nominal voltage etc., is significant, as the battery determines the electric drive range of the electric vehicle. The current EV battery technology has relatively low energy densities, which limits the range of most electric vehicles, as the battery becomes too large and heavy. The most widespread EV battery technology today is lithium-ion. The lithium based batteries have during the recent decade improved the energy density of electric vehicle batteries considerably and hence increased the drive range.

Current high-density EV battery cells can have energy densities in the range of 240-300 Watt-hours per kilogram (Wh/kg), which equate to pack-level densities of 130-200 Wh/kg (International Energy Agency (IEA), 2020). The International Energy Agency (IEA) anticipates upper performance bounds of the Li-Ion technology to be about 325 Wh/kg at cell level and 275 Wh/kg at pack level. Further improvement would require a shift in technology. Bloomberg New Energy Finance (BNEF) estimates the practical limit for Li-Ion batteries to be in the range of 350-400 Wh/kg. (International Energy Agency (IEA), 2020; Bloomberg New Energy Finance, 2019.)

IEA anticipates Li-Ion batteries to dominate the market during at least the next decade. Beyond 2030, alternative battery technologies, like Lithium-metal solid state batteries (LMSS) may provide competition to Li-Ion batteries, as LMSS manufacturers have shown higher energy densities and longer deterioration times (International Energy Agency (IEA), 2020). The European Commission expects LMSS to play a role before 2030 as well and replace some Li-Ion capacity. In a long-term, Li-air have the highest theoretical energy density of known battery technologies. Li-air batteries are currently still a novel technology, hence the future of the technology is uncertain. (European Commission, 2019b).

The electric powertrains accounts for almost 50% of the EV cost. The battery pack accounts for 75% of the total EV powertrain costs, hence the battery pack accounts for approximately 35% of the overall vehicle cost according to Boston Consulting Group (2018). The average cost of batteries for electric vehicles has declined rapidly during the last decade, reaching an average price of $156/kWh, down from $1160/kWh in 2010. (International Energy Agency (IEA), 2020; Boston Consulting Group, 2018; Berckmans et al., 2017.)

Bloomberg New Energy Finance (BNEF) have observed a historic learning rate of around 18% for batteries. Using this learning rate and applying BNEF's battery demand forecast, BNEF estimate that European EVs reach price parity with combustion vehicles in mid-2020's. Different size segments will reach parity at different times, large vehicles will reach faster than small vehicles, but all vehicle classes will have reached parity before 2030 (Bloomberg New Energy Finance, 2019b, 2020a, 2020b). Blanco et al. (2019) and Transport & Environment (2018a) anticipate that if battery pack costs decrease to below $100/kWh the purchase price of an electric vehicle would be less than that of a similar ICE vehicle.

Hydrogen fuel cell vehicles provide, as BEVs, a zero tail-pipe emission alternative to conventional ICE vehicles. Hydrogen fuel cell vehicles use electricity to power an electrical engine. Differently from the BEV, the electricity is not stored in an on-board battery, but as hydrogen in a fuel tank. The hydrogen is converted to electricity in the fuel cell. The most common type of fuel cell for vehicles is the polymer electrolyte membrane (PEM). The hydrogen fuel cell vehicles offers longer range than battery electric vehicles due to better energy storage. (Transport & Environment, 2018a; European Commission, 2020; Hänggi et al., 2019.)

The TTW efficiency of hydrogen fuel cell vehicles is significantly higher than that of ICE vehicles, but lower than BEVs. The electric engine in FCEVs operates at the same efficiencies as for BEVs, but the conversion process of hydrogen to electricity reduces overall vehicle efficiencies. The efficiency of a fuel cell for passenger vehicles is approximately 55% under optimal conditions and approximately 45% under actual driving conditions. The overall vehicle efficiency is estimated to be approximately 38%. (Hänggi et al., 2019; Winther & Jeppesen, 2016.)

The production of hydrogen has significant influence on the well-to-wheel (WTW) efficiency of FCEVs. The efficiency relies primarily on the pathway chosen for hydrogen production. Hydrogen has historically been produced primarily from thermal processes, such as steam methane reforming (SMR), decomposition of natural gas etc. This technology relatively higher efficiencies of around 50 %. Hydrogen produced from electrolysis powered by renewables can further increase efficiency. (European Commission, 2020.)

Currently, approximately 1350 hydrogen passenger vehicles are registered in the European Union. Despite decades of investment, the fuel cell technology remains too expensive for vehicle manufacturers to pursue the technology. (Transport & Environment, 2018a; European Alternative Fuels Observatory, 2020b.)

### A.2.2 Internal combustion engine vehicles

As stated above, the internal combustion engine operates at relatively low efficiencies, but offers convenient driving capabilities and long range. ICE vehicles fueled by petrol or diesel, however, need to be replaced in the development towards a renewable transport system. The internal combustion engine reaches efficiencies of up to 35%-45% under optimal conditions. The diesel engine is generally more efficient than the gasoline engine due to a higher compression ratio within the cylinder. In practice, the overall vehicle efficiency is between 18%-21%. (Winther & Jeppesen, 2016.)

Alternative liquid fuels, such as biofuels and synthetic fuels (i.e. electrofuels) offer the same properties in terms of TTW efficiency as conventional fossil fuels. The introduction of both will have a positive impact in terms of transport sector GHG emissions, if produced with renewable energy sources and

2nd generation biomass feedstock. 1st generation biofuels, produced from starch or sugar crops for instance or based on vegetable oil, have significant indirect implication on land use-changes (ILUC) and are not considered a sustainable alternative to fossil fuels. In the EU, palm oil is the second largest feedstock for biodiesel. 2nd generation biofuels, on the other hand, produced from non-edible residues or grass and trees grown specifically for energy purposes, offers a sustainable alternative to conventional petrol and diesel. (Transport & Environment, 2016; Di Lucia et al., 2012; Nigam & Singh, 2011.)

Liquid biofuels have so far been a successful measure to integrate renewable energy in the transport sector. Biofuels can without any modifications to the vehicle fleet be blended with fossil gasoline or diesel in small shares. If high blends of biofuels are to be achieved, minor adaptions to the vehicle engine is necessary.

Several different synthetic fuels could be available for passenger vehicles in a future transport system. In this work, no distinction is made between methane, methanol, Dimethyl Ether (DME) or Fischer-Tropsch fuels as the overall efficiency is similar (slightly lower for FT fuels, as the production process requires an additional refining process).

The energy consumption of ICE vehicles is approximately 4 times higher than for battery electric vehicles. The numerous conversion and refining processes from electricity production to electrofuels to propulsion of the vehicle reduces WtW efficiency considerably. The low WtW efficiency of electrofuels means that very few stakeholders consider electrofuels as a viable option for the decarbonization of cars. Transport & Environment and Hänggi et al. conclude that electrofuels have little or no role to play in the light-duty transport sector in a future renewable transport system. (Transport & Environment, 2018a; Hänggi et al., 2019.)

It is evident from the assessment above that electrification of the light-duty vehicles via batteries proposes the most energy efficient pathway towards a renewable transition. Electric engines provide a much more efficient alternative to the conventional internal combustion engine, and battery technology development indicates that the price gap between BEVs and ICE vehicles is closing, and price parity is expected to be reached within the next decade.

Hydrogen fuel cell vehicles provide, as well, an energy efficient alternative to ICE vehicles. The development of fuel cell technology remains a prominent barrier for a significant market uptake. The development and penetration of efficient electrolysis processes are necessary to produce sufficient quantities of renewable hydrogen before it can be considered a 100% renewable alternative to fossil fuels.

It seems unlikely that the ICE vehicles will have a significant role to play in the renewable transition of passenger cars. Their low efficiency makes electric alternatives more attractive. The blend in of biofuels or electrofuels with conventional petrol or diesel could possible provide a short-term decarbonization strategy, but in a long-term, electric vehicles will provide a more energy efficient alternative. The efficiencies of ICE and electric vehicles are compared in Figure A.6.

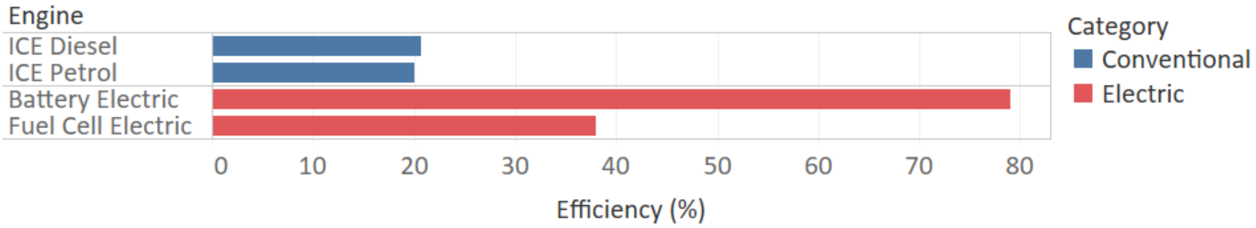

Figure A.6: Energy efficiency for passenger car drive train technologies (Danish Energy Agency, 2015).

## A.3 Heavy Duty Vehicles

Heavy-duty vehicles, which primarily include trucks, buses, and coaches, perform a wide variety of activities and come in many shapes and sizes. The European Commission defines heavy-duty vehicles as freight vehicles of more than 3.5 tons (trucks) or passenger transport vehicles of more than 8 seats (buses and coaches) (European Commission Press Corner, 2020).

These are also classified as medium and heavy commercial vehicles (over 3.5 tons) by the ACEA (European Automobile Manufacturers Association, 2019).

The best power train option for heavy-duty vehicles greatly depends on the intended purpose of the vehicle as a similar vehicle might be used to perform entirely separate functions. For example, the same model truck might be used for garbage collection intercity or could be customized to transport goods between two cities. This customization and varying needs make decarbonization of heavy-duty vehicles quite challenging.

In the following sections, HDVs are divided into two major categories, namely buses (intercity urban passenger transport), and coaches and trucks (long haul inter-region, high load capacity transport).

### A.3.1 Buses

Buses are the most widespread form of public transport in the EU due to the ease and flexibility of launching new routes. Based on the European classification system, buses are defined as vehicles having at least four wheels, designed and constructed for the carriage of passengers, comprising more than eight seats in addition to the driver seat.

After aviation and private cars, buses are the third-largest consumer of energy in passenger transportation, accounting for about 8 % of the passenger energy demand in 2016. (Capros et al., 2016.)

#### ICE Buses

Like passenger cars and vans, diesel is the preferred choice of use in buses as well, covering as much as 96 % of the EU energy demand (European Automobile Manufacturers Association, 2019). The high energy density and low fuel costs allow it to carry heavy loads of passengers from one point to another. However, along with being emissive, diesel has a high cost for externalities, especially for city buses like noise and air pollution (Smart choices for cities, n.d.).

Alternative Fuels as the name suggests are relatively greener alternatives to diesel, these include natural gas, LPG, biofuels, and a range of electro fuel options.

Figure A.7 shows the vehicle efficiencies for different types of buses. LPG and natural gas contribute a bit more than 2 % of the energy demand of the buses in the EU, however, almost 95 % of the alternately powered fleet is natural gas and LPG. Due to lower efficiencies than diesel, compressed natural gas (CNG) buses consume more energy but offer a less polluting alternative with the added adaptability to use bio-methane as a fuel to further reduce WTW emissions.

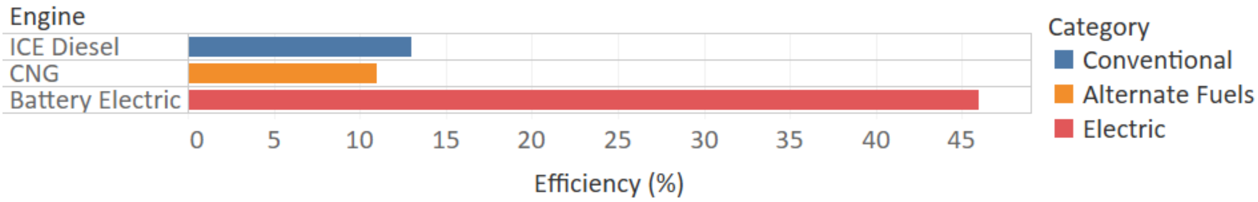

Figure A.7: Efficiency of different engine technologies for buses (Danish Energy Agency, 2015).

As shown in Figure A.8, the alternate fuels increased their sales by 67 % from 2018 to 2019, whereas the new diesel vehicle registrations decreased by 3 % from 35,221 units in 2018 to 34,123 units in 2019.

Biodiesel for buses also offers a good alternative for buses without compromising vehicle efficiencies. There exist successful pilot demos of biodiesel used for decarbonizing the public transport sector. Stockholm runs its entire fleet of buses on fossil-free fuels, with 85 % of the buses powered by biodiesel and ethanol (Biofuel Express, 2020).

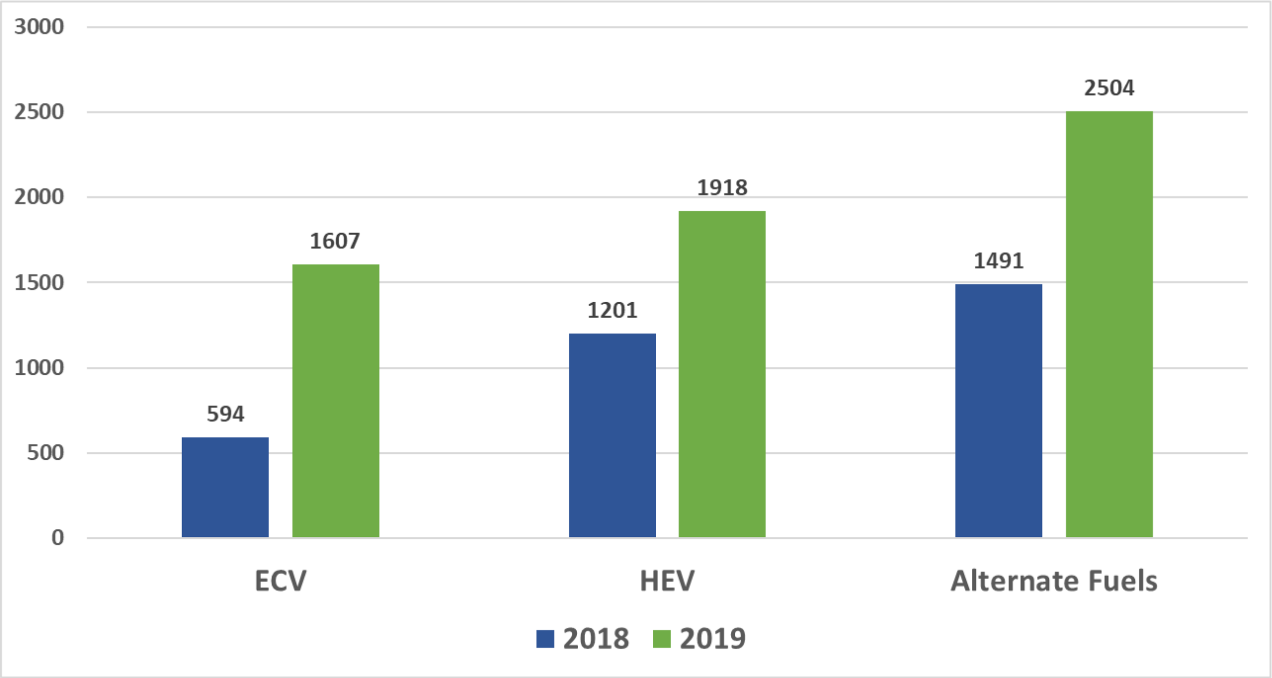

Figure A.8: New vehicle registrations of alternative fuels[40] for buses in 2018-2019 (European Automobile Manufacturers Association, 2019).

### Electric Buses

Electric buses are some of the cleanest form of technologies for buses with zero fuel emissions and lower noise than other drivetrain buses. Some of the drawbacks of battery electric buses like low energy density and the need for charging can be tackled by the use of trolley buses that use overhead lines for electricity supply rather than onboard batteries. Such 131 trolley buses are in fleet of Lyon in France as of 2012 (Trolleymotion, 2019) but require dedicated infrastructure for overhead lines.

Fuel cell electric buses have a similar drivetrain as of electric buses but unlike electric buses obtain their electricity from fuel cells onboard the vehicles that use compressed hydrogen and oxygen from the air to produce electricity. These buses rely on dedicated hydrogen filling stations and are still a nascent market that remains in pilot phases with demos being rolled across some cities in the EU. For example, the city of Aalborg in Northern Denmark has 3 fuel cell electric buses in operation since March 2020 (Fuel Cell Electric Buses, 2020).

Hybrid Electric buses have an electric battery-powered motor along with an internal combustion engine. The electricity generated from regenerative braking is used to charge the batteries. These vehicles do not require charging infrastructure. (ACEA, 2019.)

As shown in Figure A.8, the number of electrically charged buses (including full battery-electric, fuel-cell electric, and plug-in hybrid electric vehicles) increased from 594 to 1607 which is a 170 % increase in 2018-2019.

All these technologies have their advantages and challenges where some might prove viable in one setting, the other might not. Local characteristics for buses like frequency of stops, topography, and

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[40] ECV = electrically charged vehicles. HEV = hybrid electric vehicles

passenger density also play a key role in determining the optimal technology drivetrain and should be taken into account.

### A.3.2 Trucks and Coaches

The European classification system defines trucks as vehicles with at least four wheels with a mass of more than 3.5 tons used for the carriage of goods. Coaches are classified as buses exceeding 5 tons and used for the transport of passengers. (European Commission Press Corner, 2020.)

Buses and coaches are mostly bundled together. However, in terms of fuel demand, coaches and heavy trucks face similar challenges in terms of energy demand owing to long distances traveled and high load capacity. Road freight transport and trucks in particular is the backbone of the EU freight industry. Trucks cover 76 % of the overall EU land freight demand, and at present there are more than 6 million trucks in circulation. (European Automobile Manufacturers Association, 2019.)

#### ICE Trucks and Coaches

Long haul coaches and heavy duty trucks are more dependent on diesel than any other mode of transport. It covers more than 98% of the medium and heavy commercial vehicles' energy demand. Diesel seems well suited for trucks and coaches owing to low fuel costs, high mileage ensuring long ranges, high load-carrying capacity and widespread refueling infrastructure, all of which are crucial for both trucks and coaches. There is a strong need to explore different options for long haul transport. Figure A.9 compares the vehicle efficiency of different fuel options for heavy trucks and coaches. Biofuels like biodiesel and Dimethyl ether (DME) are seen as good alternate fuels to conventional diesel for long haul transport. Thee fuels have almost similar efficiencies as of a diesel vehicle, whereas natural gas, which is essentially a fossil-based methane gas, is less efficient than diesel but has the lowest carbon intensity of any hydrocarbon (Delgado & Muncrief, 2015).

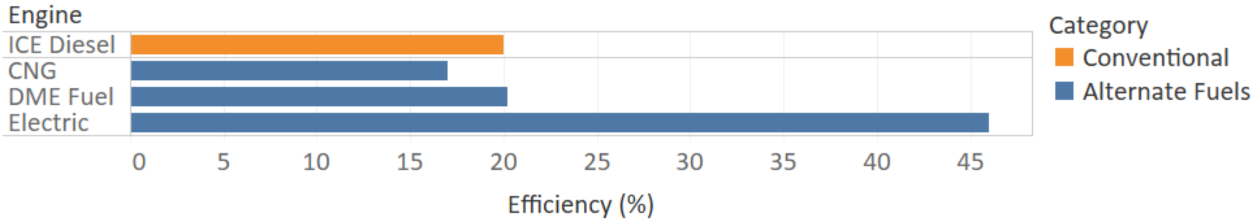

Figure A.9: Efficiency of different engine technologies[41] for trucks and coaches (Danish Energy Agency, 2015)

Alternate fuels are slowly starting to take a share in the heavy-duty market. As shown in A.10, registrations for new alternate fuel heavy duty vehicles increased by 71%, with the majority share coming from natural gas. (European Automobile Manufacturers Association, 2019.)

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[41] The energy efficiency of electric trucks are assumed identical to electric buses.

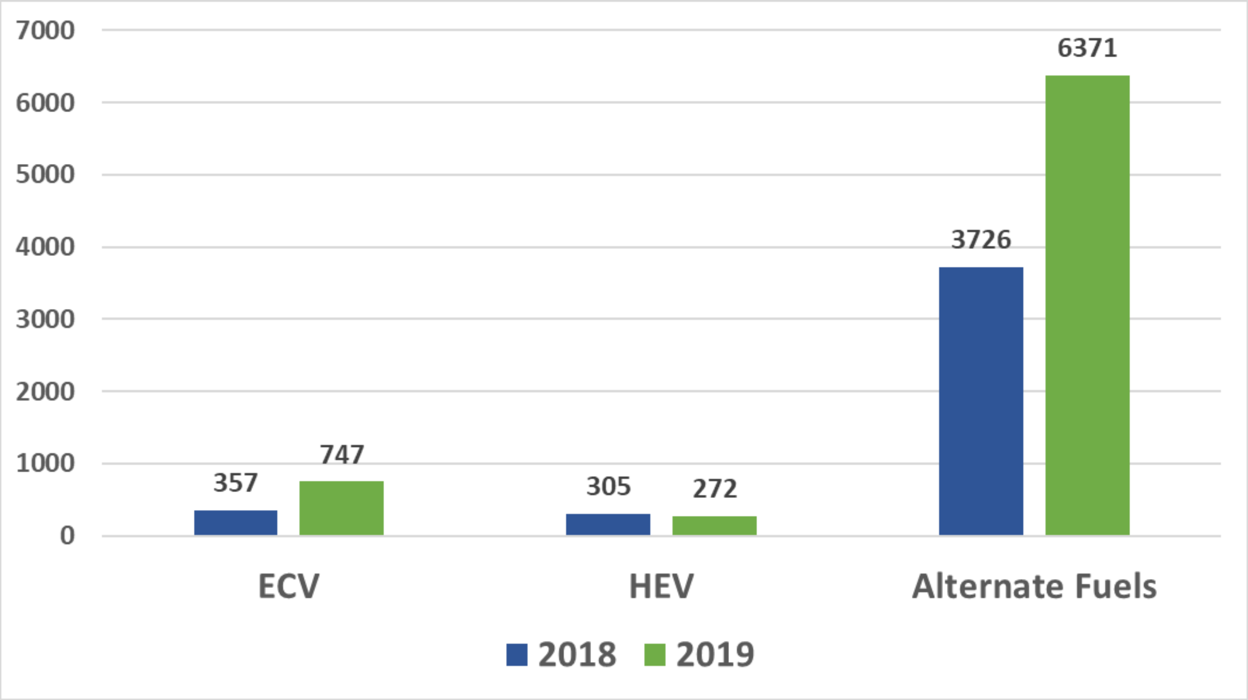

Figure A.10: New vehicle registrations of alternative fuels for heavy duty vehicles in 2018-2019 (European Automobile Manufacturers Association, 2019.)

### Electric Trucks and Coaches

The electrification of heavy-duty trucks is a relatively new development compared to passenger electric vehicles. In the EU, this is mainly driven by the adoption of new heavy-duty vehicle $CO_2$ emissions standards (30 % emissions reduction by 2030 compared to 2019 (Transport & Environment, 2020). Nearly all major European truck manufactures are starting to enter the market with their version of electric trucks, Mercedes became the first automobile manufacturer in the world to introduce a fully electric truck in 2016, with a range of 200 km and three lithium-ion battery packs, and has since then introduced a newer version in 2018 which is expected to be in series production in 2021. Renault in 2016 presented at COP21 a 16-tonne electric truck currently in customer testing phases.

The following table shows a summary of the current and planned zero-emissions trucks in Europe.

Table A.1: Planned electric truck portfolio in Europe (Rodríguez & Delgado, 2019).

| | Model | Stage | Production | GVW (tons) | Battery (kWh) | Range (km) |
|---|---|---|---|---|---|---|
| Daimler Trucks | eCanter | In Production | - | 7.5 | 83 | 120 |
| | eActors | Customer Tests | 2021 | 26 | 240 | 200 |
| MAN | eTGM 6x2 | Customer Tests | 2021 | 26 | 225 | 200 |
| | eTGM 4x2 | Customer Tests | 2021 | 32 | 149 | 130 |
| | CiTE | Prototype | 2021 | 15 | 110 | 100 |
| Volvo Trucks | FL Electric | Customer Tests | 2019 | 16 | 300 | 300 |
| | FE Electric | Customer Tests | 2019 | 27 | 300 | 200 |
| Renault Trucks | D.Z.E | Customer Tests | 2019 | 16 | 300 | 300 |
| | D Wide Z.E | Customer Tests | 2019 | 26 | 222 | 220 |
| DAF | LF Electric | Customer Tests | Not Announced | 37 | 170 | 100 |
| | CF Electric | Customer Tests | Not Announced | 19 | 222 | 220 |
| Scania | R 450 Hybrid | Customer Tests | Not Announced | 40 | Overhead (Does not Apply) | 10 (Battery) |
| E force | EF18/26 | Customer Tests | Not Announced | 18/26/40 | 105-630 | Up to 500 |
| BYD | T5 | Production (US, China) | | 7.5 | 155 | 250 |
| | T7 | | | 11 | 221 | 200 |
| | T9 | | | 36 | 435 | 270 |
| Tesla | Semi | Customer Tests (US) | 2019 (US) | 36 | Not Announced | 800 |
| Nikola | Tre (Battery) | Prototype | 2023 | 40 | 500- 1000 | Up to 650 |
| | Tre (Fuel Cell) | Prototype | 2023 | 40 | 320 | 1200 ($H_2$) |

For electric trucks and buses, batteries and charging points are a major concern. Because of their nature and need of carrying heavy goods, buses and trucks need a heavier battery pack compared to passenger vehicles. However, the ability to use a smaller engine and negating the need for a complex gearbox compensates this to some extent (Cedelft, 2013).

According to a report published by Transport and Environment (2020) charging needs of electric trucks can be classified into three major categories:

- Depot Charging, which is essentially overnight charging at the operator's depot
- Destination Charging with charging spots at pick up and drop off destinations
- Public Charging covers publicly accessible areas such as rest areas along the highway etc.

Some studies suggest that in the initial rollout of electric trucks, depot charging will cover 80 % of the charging needs while the other charging methods are being rolled out sequentially as the market grows in time. Electric road systems (ERS) are currently being tested in both Sweden and Germany. The development of this technology would allow for electrification of long-haul heavy duty vehicles, without the need for heavy on-board battery packs. (The Verge, 2019.)

## A.4 Aviation

The transport demand in aviation is increasing rapidly. The number of passengers traveling in aviation has increased thirteen-fold from 1970 to 2017 and the tendency is expected to continue in the decades to come. (IDA, 2019; International Civil Aviation Organization, 2016.)

As shown in Figure A.1, aviation is the second largest energy consuming mode of transport after roads, making up around 25 % of the European transport energy demand.

In the aviation sector fossil jet-fuel is used in jet engines for more than 99% of all kilometers travelled. Jet fuels must meet strict standards, hence only few alternatives exist to this date. Energy efficiency improvements in aviation has historically been driven primarily by development in motor/engine technology and improved aerodynamics. The development is not expected to be altered by an introduction of alternative fuels as the energy efficiency and weight of the fuel is expected to be identical to fossil jet-fuel. The expected development in fuel efficiency per seat-kilometers is estimated by NLR to follow a regression line, which indicates a reduced energy consumption per seat-kilometer compared to 2015 of 3.7% in 2020, 12.5% in 2035 and 19.1% in 2050. (Peeters et al., 2005; IRENA, 2017.)

Along with energy efficiency improvements, sustainable aviation fuels (SAFs), such as advanced biofuels, are necessary to decarbonize the aviation sector. There is no single agreed definition of SAFs, but in most studies they are defined as bio-based aviation fuels that reduce GHG emissions compared to conventional aviation fuels. Electrofuels offer an alternative to bio-based aviation fuels but are currently too expensive to be implemented. Currently, six aviation biofuel production pathways are approved to be blended with fossil jet-fuel. The most developed SAF is the hydroprocessed fatty acid esters and free fatty acid (HEFA). The production depends on conversion of lipid feedstocks, such as vegetable oils that are converted into diesel using hydrogen. The diesel can then be further separated to aviation fuel. The maximum allowed blend with fossil jet-fuel is 50%. (International Energy Agency (IEA), 2020.)

The development of production costs of SAFs will be difficult to determine as it depends on production capacity and future feedstock availability. It is commonly agreed, though, that the cost of SAFs will most likely remain a significant challenge. The feedstock price currently represents the biggest component of the bio-based aviation fuel price. Average price for fossil aviation fuel is estimated to be €600/ton (IRENA (2017) assumes $400/t), while the price of bio-based fuels is estimated to be in the range of €950-€1015/ton. IATA estimated in 2015 that the costs of SAFs on average were 2-7 times higher than for conventional fossil aviation fuel. (IATA, 2016; European Environment Agency, 2019a.)

The International Council on Clean Transportation estimates that a maximum of 20% of the aviation fuel demand can realistically be covered by biofuels in 2050. Electrofuel production with alternative $CO_2$ sources other than biomass is consequently necessary to investigate. (Pavlenko et al., 2017.)

Other potential technologies to improve the overall energy efficiency of aircrafts are hydrogen and electricity. Hydrogen as an alternative aviation fuel is a potential option, but the storage of hydrogen requires high pressure and low temperatures which makes the handling more difficult than conventional aviation fuels. (IDA, 2019.)

Battery electric aircrafts depend heavily on the development of efficient battery technology. The current energy density of state-of-the-art Li-Ion batteries entails that batteries are large and heavy and would typically weigh 100% more than liquid conventional fuels. Electrical propulsion of aircrafts will therefore most likely in the near future only be considered for small and short-distance aircrafts. (IDA, 2019.)

## A.5 Railways

Railways arguably provide the most value amongst all modes of transport in terms of transporting goods and passengers in huge masses over long distances. With a high capacity of transportation, rail is among the most efficient and least polluting ones with the ability to expand its reliance on diverse energy sources due to electrification. In Europe (2016), passenger rail covered 8 % of the passenger transport demand whereas the share of total energy demand for passenger rail was only around 1% as shown in Figure A.1.

Similarly for freight transport, freight rail takes up around 2% of the total freight energy demand for EU-28, whereas it covers more than 4 % of the total EU freight transport activity demand. Compare that to the heavy duty and light duty vehicles on road that cover 20 % of the total freight activity demand and took up around 66% of the freight energy demand share in 2016.

On a global scale, rail in 2017 covered 8% of the world's motorized passenger transport and around 7% of the freight transport demand but accounted for only 2 % of energy use in the transport sector. This is because rail in terms of energy consumption per traffic unit outperforms all other transport modes mainly due to low rolling friction losses of steel contacts, the ability to utilize economies of scale, right of way, and infrequent stops. (IEA & UIC, 2019.)

The following figure (A.11) shows the mechanical conversion energy efficiency (%) of the most common types of railway technologies currently used across the EU.

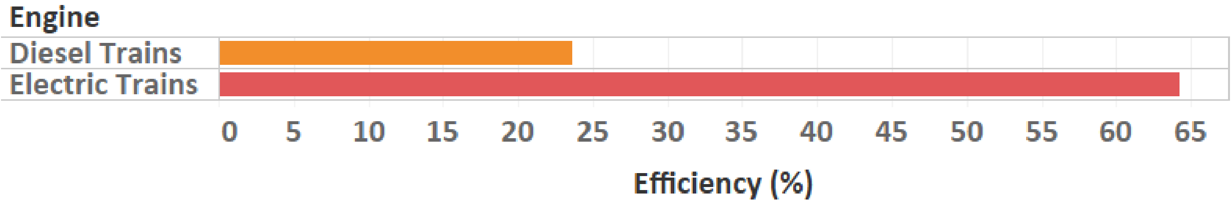

Figure A.11: Energy efficiency of different railway technologies (Danish Energy Agency, 2015.)

Diesel trains operates with average efficiencies of approximately 23%, whereas electric trains are the most efficient with 65% conversion efficiency. (Danish Energy Agency, 2015.)

In Europe, the railways have a strong reliance on electricity with almost 70 % of the tracks electrified in 2015 and the rest being powered by diesel as shown in Figure A12. Almost half (52 %) of the energy demand for railways in the EU-28 is from Germany, France, and the United Kingdom. (European Commission, 2019a.)

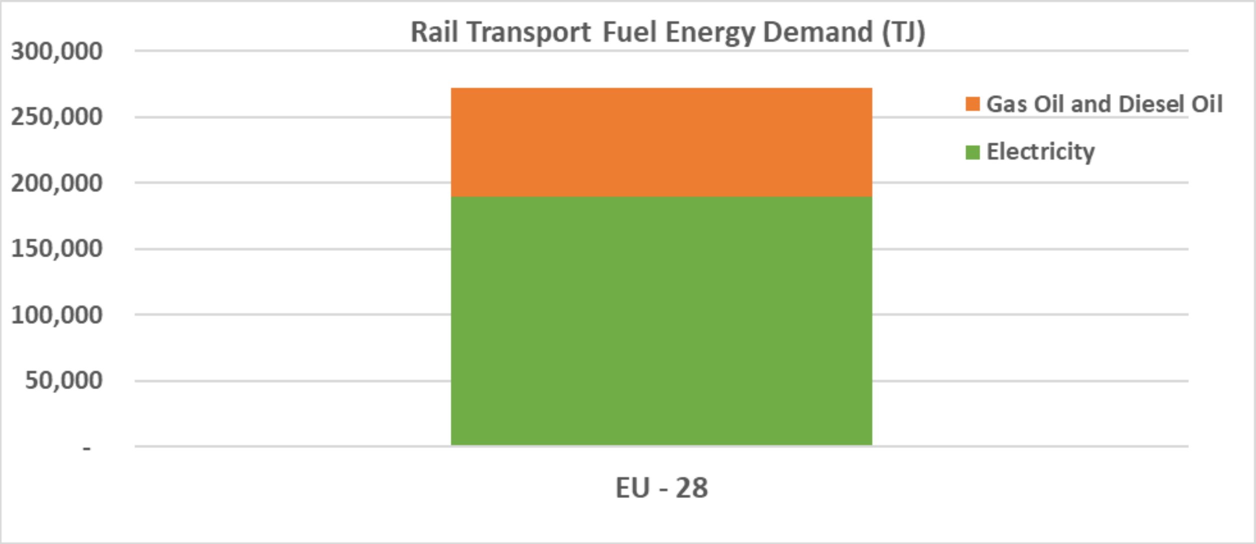

Figure A.12: EU-28 rail transport energy demand TJ (European Commission, 2019a).

Electric trains compared to diesel considering all else being equal, are significantly less energy-intensive because of higher thermodynamic efficiencies and include the possibility of regenerative braking that minimize inertial losses. This becomes quite relevant in the case of local or regional railway systems with frequent stops and provides more rapid acceleration than diesel trains. It is noted that electrified rail routes also have higher utilization rates than non-electrified ones and can carry five times more pkm (passenger-kilometers) per kilometer track than non- electrified lines and almost twice as many tkm (ton-kilometers) (IEA & UIC, 2019).

At present, the major source of electricity for railways in Europe is fossil (43 % in 2015), and the rest is split between nuclear and renewables as shown in Figure A.13 (IEA & UIC, 2017). This indicates a need for a shift in the primary energy supply of electricity production for transport. Along with the already mentioned advantages of much higher efficiency and higher utilization rates than their diesel counterpart, electrification of railways also provides the added advantage of diversifying the energy source vector, hence providing a huge opportunity to decarbonize the railway sector.

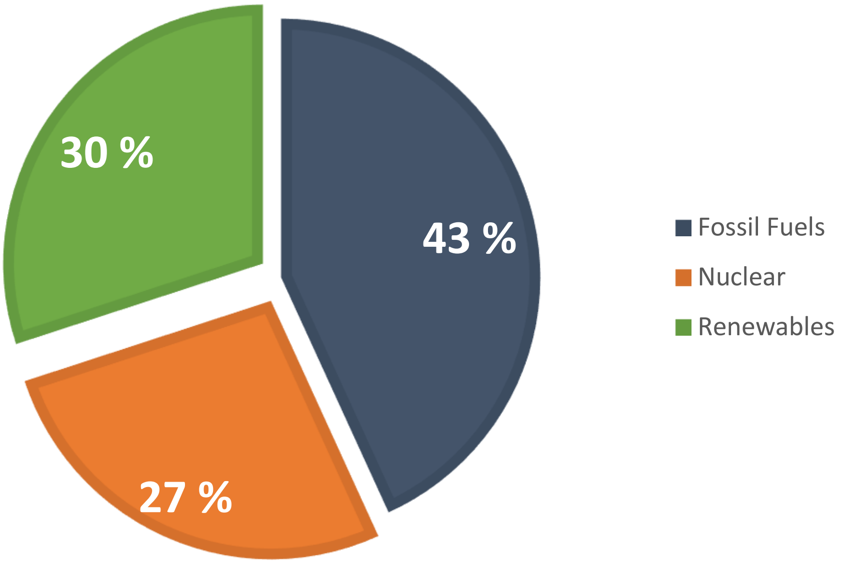

Figure A.13: Electricity generation share for railways EU 28 in 2015 (IEA & UIC, 2017).

This is also possible with the train companies acquiring Guarantees of Origin (GoO) certificates mechanism, which ensures that the electricity that they consume for their railway operations comes from renewable energy production rather than fossil fuels.

This is evident from the case of one of the largest train operators in Europe and the largest one in the Netherlands, Nederlandse Spoorwegen (NS), which runs entirely on wind power using GoOs for their electric trains (Quartz, 2017).

Since rail is already the most electrified form of transport and the share of electrified tracks is further expanding, further electrification of railways would lead to diminishing returns on investments (IEA & UIC, 2019). since the highly utilized lines are the ones to be electrified first. As an intermediate step for complete electrification, railway technology providers have also moved to provide bi-modal hybrid diesel-electric trains for increased coverage to areas without electrified tracks (Railway-technology, 2018).

Hybridization can be an enabler for electrification, it is estimated that the energy-saving potential of hybridization range from 17 % to 32 % (Evans, 2010). Since hybridization also enable the trains to deploy regenerative braking, relying more on stored regenerative energy could allow the train’s primary propulsion system to be reduced in size allowing to offset some of the higher costs of batteries on board (IEA & UIC, 2019)

Rail technology, despite its numerous advantages such as being less energy-intensive, comfort for passengers, and economies of scale, seems to be far off behind especially in freight where it covers only 8 % of the freight transport activity demand in the EU. One of the reasons is the need for increased cross-border capacity and standardization to ensure interoperability between multiple operators. Due to advances in data analytics and communication technologies, there is an opportunity in unlocking the full potential of railway networks.

The European Traffic Management System is an advanced traffic management and control system that uses control and command communication systems to ensure interoperability between different regions (IEA & UIC, 2019).

Advances in these technologies along with automation of trains can help maximize track utilization and can increase the energy efficiency of the railway systems by up to 15 % (Dunbar et al. 2017).

## A.6 Shipping

Shipping is an important mode of transport both for passenger and freight and contributes to around 16 % of the freight activity demand within the EU (European Commission, 2019a). Domestic shipping in EU-28, which includes inland waterways and small ferries, is predominately powered by marine diesel oil (70 %) and heavy fuel oil (25 %) as shown in Figure A.14. Ship engines burning HFO emit SOx, NOx, and other particulates like black carbon that are particularly harmful to human health. The Danish Center for Energy, Environment, and Health found that international shipping were responsible for around 50,000 premature deaths each year in Europe because of air pollution and shipping in the North Sea was estimated to cause about 14,000 annual premature deaths in Europe in 2011 with only a reduction of 6 % in 2020 due to reductions in fuel sulfur content (Eurostat, 2020f).

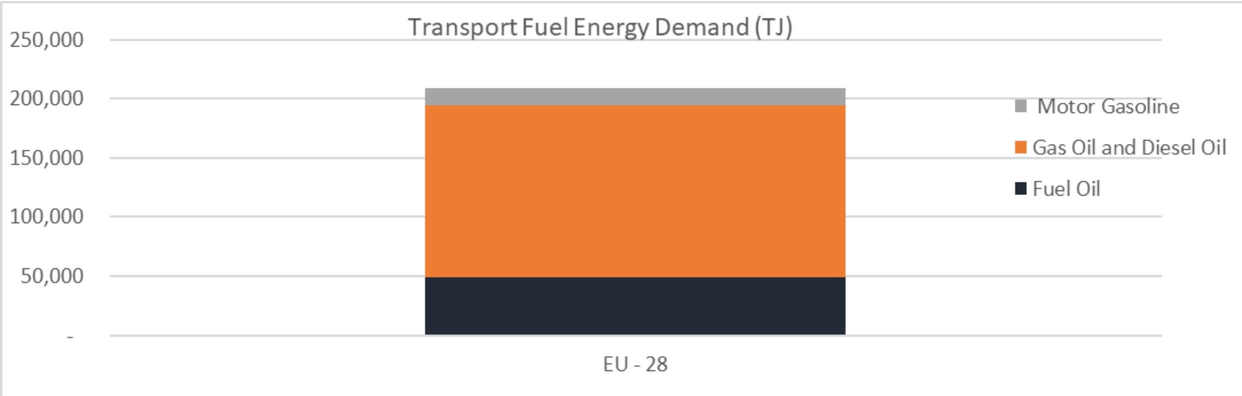

Figure A.14: EU 28 domestic shipping energy demand (2016) (Eurostat, 2020f.)

Decarbonization of the shipping sector can be achieved through multiple pathways using alternate fuels or electric batteries where each fuel comes with its benefits and challenges. It is important to note that while discussing the replacement of fossil fuels, along with simple fuel conversion engine efficiencies, other factors such as volumetric energy densities and gravimetric energy densities need to be taken into account. These factors become crucial as we increase the size of the shipping vessel. Figure A.15 shows the relative placement of different fossil alternatives with volumetric energy densities on the x-axis and gravimetric efficiencies on the y-axis. The following section discusses some of the pros and cons of each of these alternate choices:

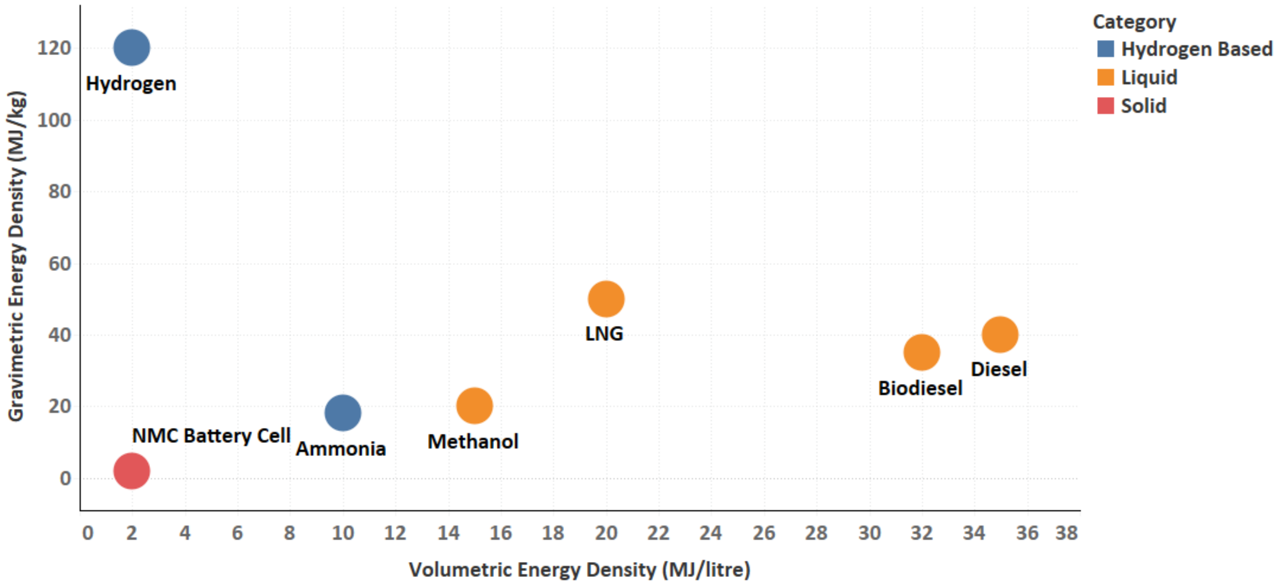

Figure A.15: Energy densities for different fuel types for shipping (Marigreen, 2018).

### Ammonia

In a decarbonized shipping sector, ammonia sourced from renewables has the potential to be a carbon-free energy carrier. There exist some differences in the use of ammonia onshore and on marine vessels. Ammonia fuel can be used using a steam turbine, gas turbine, ICE (compression-ignition or spark ignition), fuel cell (solid oxide fuel cell, proton exchange fuel cell), or alkaline fuel cell. Among these, gas turbine and the steam turbine are deemed not suitable for marine applications due to low power density and lower efficiencies as compared to ICE. A small amount of hydrogen also needs to be added to ammonia for ignition in ICE. Under atmospheric conditions, ammonia is a gas and is toxic to humans and contact needs to be limited as much as possible. Safety standards ensured raises the cost of the system, making it around 3 times more expensive the conventional options with the current technological development. (De Vries, 2019.)

### Methanol

Methanol is a liquid fuel that could either be 100 % renewable, be sourced from different feed-stocks, or be obtained from natural gas. Methanol has the advantage that it is much similar to the Heavy Fuel Oil (HFO) being used for marine transportation, and existing infrastructure could be adopted to 100 % renewably sourced methanol with slight modifications (Andersson & Salazar, 2015). It has a lower volumetric energy density like ammonia (almost 40 % less than that of LNG) as shown in Figure A.16. Being biodegradable, it poses much fewer risks in terms of environmental impact in case of large spillages. Methanol has low storage costs which translate to low capital costs, however still more expensive than conventional diesel fuels but less expensive than biodiesel (Andersson & Salazar, 2015). In 2015 Stena Line, one of the largest marine transport operators, retrofitted a 24 MW RoPax ferry to methanol with gas fuel as a backup. The ferry is now operational between Gothenburg (Sweden) and Kiel (Germany). Based on the successful attempt, the company plans to convert 25 more vessels in its fleet to run on methanol. (Ship-technology, 2020.)

### Diesel Fuels

Renewably sourced fuels such as DME (Di Methyl Ether) and Hydrogenated Vegetable Oils (HVO) or biodiesel can provide similar efficiencies as conventional diesel and have a major advantage of being a drop-in fuel that require almost no or slight modification to existing infrastructure. Being the only fuel close to diesel in terms of energy density ratios, as shown in Figure A.16, biodiesel could be adopted as a low carbon-intensive alternate to diesel. However, the level of GHG emission reductions possible depend on the feedstock processes, and there exists a debate about scalability issues and the level of emissions reductions possible. There is a wide range of life cycle emission reductions with the use of biodiesel (20 - 90 %) (Sea-ing, 2019.)

Hydrogenated Vegetable Oil (HVO), a high-quality biofuel, is being used in Norway onboard three ferries at present (TU.no, 2020).

### Hydrogen

Liquid hydrogen, having no carbon atoms when used in fuel cells, has only water as the by-product. Having zero tank to wake emissions, hydrogen fuel cells are a good climate-neutral option. In terms of energy densities, from Figure A.15 it seems that hydrogen has a very high gravimetric energy density of 110 MJ/kg. However, Figure A.15 only indicates the energy densities of the fuel without taking into account the storage tanks needed for the fuel. When storage is added for liquid hydrogen, the gravimetric energy density drops dramatically from 120 MJ/kg to 10 MJ/kg for liquid hydrogen (MariGreen, 2018) as shown in Figure A.16.

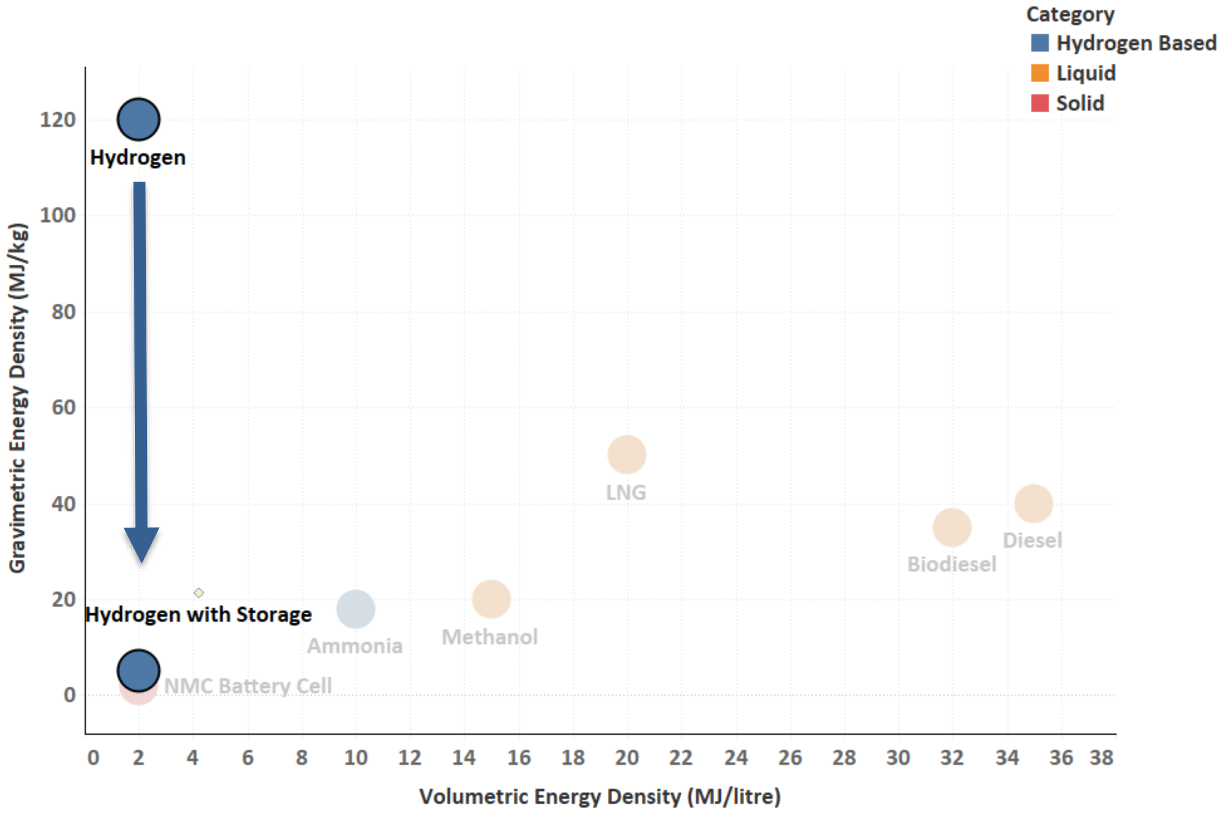

Figure A.16: Energy densities for different fuel types for shipping with hydrogen storage (MariGreen, 2018).

### Electricity

Driven by the sharp decrease in battery prices, electric batteries, like in other modes of transport, are becoming more and more important in the shipping sector as well. With the advantages of being zero emissions and relatively mature technology, batteries are being adopted in shipping on the level of car and passenger ferries with more than 400 vessels in operations or development globally. Batteries, though efficient in terms of technology, perform poorly in energy densities. This becomes important for large container and cargo ships making adoption of electric batteries challenging without further technological advancements. However, for small route ferries, owing to the high tank to wake efficiency of > 80 % and relatively lower levelized cost of fuel, battery journeys could become competitive with journeys made from conventionally powered ships (Transport & Environment, 2018b).

Some notable examples of electric ferries in operation in Northern Europe include ‘The Aurora’ and ‘M/F Tycho Brahe’ between Sweden and Denmark powered by ABB (ABB Marine & Ports, 2020), and ‘The Ampere’, the world’s first electric ferry from Norway, which can carry 120 vehicles and 360 passengers (Nordregio, 2020).

# Appendix B: Studies on urban built environment characteristics and transportation from which elasticities have been assessed

**Effects of residential distance to the main city center on car driving distance or distance traveled by car:**

| Geographical case | City size | Built environment variable | Travel behavior variable (intra-metropolitan travel unless otherwise indicated) | Elasticit | Reference |
|---|---|---|---|---|---|
| Athens morphological city | 3.8 mill. | Residential distance to the city center | Car driving distance | 0.21 | Milakis, Vlastos & Barbopoulos (2008) |
| Bergen morphological city | 0.25 mill. | Residential distance to the city center | Daily car driving distance | 0.390 | Engebretsen, Næss & Strand (2018) |
| Copenhagen metropolitan area | 1.8mill | Residential distance to the city center | Travel distance by car on weekdays, including intra-& outside-metropolitan travel | 0.27 | Næss (2005) |
| Copenhagen morphological city | 1.3 mill | Residential distance to the city center | Weekely traveling distance by car or motorbike | 0.37 | Næss (2015) |
| Fredrikshavn municipality | 0.035 mill | Residential distance to the city center | Weekly car driving distance including intra-& outside-municipality travel | 0.329 | Næss & Jensen (2000, 2004) |
| Greater Oporto morphological city | 1.1 mill. | Residential distance to closest main urban regional retail center | Weekely traveling distance by car or motorbike | 0.290 | Næss (2015) |
| Greater Oporto morphological city | 1.1 mill. | Residential distance to the city center | Weekely traveling distance by car or motorbike | 0.272 | Næss (2015) |
| Kongsvinger city | 0.12 | Residential distance to the city center | Car driving distance (km) | 0.265 | Wolday (2018) |
| Oslo metropolitan area | 1.2 mill. | Residential distance to the city center | Weekly car driving distance including intra-& outside-metropolitan travel | 0.287 | Næss, Cao & Strand (2017) |
| Oslo metropolitan area | 1.2 mill. | Residential distance to the city center | Weekly distance traveled by car | 0.823 | Næss, Strand, Wolday & Stefandottir (2019) |
| Oslo metropolitan area | 1.2 mill. | Residential distance to the city center | Weekday car driving distance including intra-& outside-metropolitan travel | 0.442 | Næss, Cao & Strand (2017) |
| Oslo metropolitan area | 1.2 mill. | Residential distance to the city center | Weekend car driving distance including intra-& outside-metropolitan travel | 0.130 | Næss, Cao & Strand (2017) |
| Oslo morphological city | 0.98 mill. | Residential distance to the city center | Daily car driving distance | 0.238 | Engebretsen, Næss & Strand (2018) |
| Reykjavik urban region | 0.23 mill | Distance from dwelling to the main city center | Weekly car driving distance including intra-& outside-metropolitan travel | 0.330 | Næss, Stefansdottir, Peters, Czepkiewicz & Heinonen (2020) |
| Stavanger metropolitan area | 0,22 mill. | Residential distance to the city center | Weekly distance traveled by car | 0.525 | Næss, Strand, Wolday & Stefandottir (2019) |
| Stavanger metropolitan area | 0,22 mill. | Residential distance to the city center | Weekly car driving distance including intra-& outside-metropolitan travel | 0.259 | Næss, Cao & Strand (2017) |
| Stavanger metropolitan area | 0,22 mill. | Residential distance to the city center | Weekday car driving distance including intra-& outside-metropolitan travel | 0.279 | Næss, Cao & Strand (2017) |
| Stavanger metropolitan area | 0,22 mill. | Residential distance to the city center | Weekend car driving distance including intra-& outside-metropolitan travel | 0.215 | Næss, Cao & Strand (2017) |
| Stavanger/Sandnes morphological city | 0.21 mill. | Residential distance to the city center | Daily car driving distance | 0.256 | Engebretsen, Næss & Strand (2018) |
| Trondheim morphological city | 0.18 mill | Residential distance to the city center | Daily car driving distance | 0.365 | Engebretsen, Næss & Strand (2018) |

**Effects of population density for the whole city (urban area per capita) on energy use for transportation:**

| Geographical case | City size | Built environment variable | Travel behavior variable | Elasticity | Reference |
|---|---|---|---|---|---|
| 22 Nordic cities/towns | | Urban area per capita | Annual energy use per capita for transport | 0.292 | Næss, Sandberg & Røe (1996) |
| 97 Swedish cities | | Urban area per capita | Annual energy use per capita for transport | 0,41 | Næss (1993) |

**Effect of the degree of residential concentration toward the center of the urban area on energy use for transportation:**

| Geographical case | City size | Built environment variable | Travel behavior variable | Elasticity | Reference |
|---|---|---|---|---|---|
| 22 Nordic cities/towns | | Consentration index | Annual energy use per capita for transport | 0.612 | Næss, Sandberg & Røe (1996) |

This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 846463.

# Appendix C: Gross sample of reviewed studies on urban built environment characteristics and transportation[42]

| Study area, its population and population of main city (at time of investigation) | Geographical scale covered (distances as the crow flies) | Predominant center structure | Publication reference | Main methodology | Urban form variable of interest (Partial effect of…) | Travel behavior variable | Linear or transformed variable measurement? | Built environment variable(s)controlled for | Control for residential self-selection? | Control for car ownership? | Elasticity | Regression estimates | Standar-dized estimates | P-value | Note |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 11 European cities: Amsterdam, Brussels, Copenhagen, Frankfurt, Hamburg, London, Munich, Paris, Stockholm, Vienna & Zurich | Agregate study of 11 european cities | | Schwanen (2002) | crossectional, OLS regression | Urban area population density | Commuting distance | Untransformed X & Y distances (KM) | Proportion of population, inner areas; Proportion of employment in CBD | No | Not relevant | | -0.805 | | 0.007 | Aggregate study (based on data from 1990) |
| 11 European metropolitan areas (Amsterdam, Brussels, Coppenhagen, Frankfurt, Hamburg, London, Munic, Paris, Stockholm, Viena & Zurich) | Metropolitan areas | | Covering and Schwanen (2006). | OLS regression | Population density metropolitan area (residents per hectar | Total distance travelled by private car | | Population density, population centrality, employment density and employment centrality at different regions (metropolitan level, inner area, and CBD) of the metropolitan area. | No | Yes | | -105.93 | | p<0.05 | Builds and extends on Newman and Kenworthy's 1999, 2000 approach |
| 22 Nordic cities | Continuous urban area in 22 Nordic cities | | Næss, Sandberg & Røe (1996) | OLS regression | Urban area per capita (m2) | Energy use per capita for transport (MG) | | Concentration index | | | 0.292 | 0.0143 | 0.37 | p<0.05 | |
| 22 Nordic cities/towns | Continuous urban area in 22 Nordic cities | | Næss, Sandberg & Røe (1996) | OLS regression | Consentration index | Energy use per capita for transport | | Urban area per capita | | | 0.612 | 15.85 | 0.363 | p<0.05 | Konsentrasjonsindeks: grad av sentralisert eller desentralisert bosetting innenfor tettstedsarealet, høy verdi = desentralisert bosetting. |
| 97 Swedish cities | All Swedish cities with more than 10,000 inhabitants in 1990 | | Næss (1993) | | Urban area per capita | Annual percapita energy use | | Percentage living in the central town of the municipality, percentage living in rural parts of the municipality | | | 0,41 | 0.0178 | 0.481 | p<0.0000 | |
| All Swedish urban settlements | Populated parts of Sweden | Polycentric | Elldér (2014) | Quantitative (multilevel analysis); crosssectional | Job-worker ratio in a 10K radius of residence | Commuting distance (Euclidian home–work distance) | X&Y natural log transformed | Local jobs to workers ratio, size category of urban area, regional location of settlement areas | No | Yes | 0.435 | 0.435 | | p < .005 | |
| All Swedish urban settlements | Populated parts of Sweden | Polycentric | Elldér (2014) | Quantitative (multilevel analysis); crosssectional | Regional location: distancebetween settlement area and largest city in the central municipality of the local labor market region the area falls within | Commuting distance (Euclidian home–work distance) | X&Y natural log transformed | Local jobs to workers ratio, size category of urban area, regional location of settlement areas | No | Yes | 0.181 | 0.181 | | p < .005 | |
| All Swedish urban settlements | Populated parts of Sweden | Polycentric | Elldér (2014) | Quantitative (multilevel analysis); crosssectional | Settlement size: urban area (ref = urban area population >10,000) | Commuting distance (Euclidian home–work distance) | X&Y natural log transformed | Local jobs to workers ratio, size category of urban area, regional location of settlement areas | No | Yes | 0.373 | 0.373 | | p < .005 | Dummy variable |
| Athens metropolitan area (3.83 mill.) | Metropolitan area (all municipalities in the | Monocetric | Milakis, Vlastos & Barbopoulos (2008) | quantitative cross-sectional. Multiple linear regression | Distance from city center (meters) | trips/person/day by public transport | Residential density (log-transform) | Residential density, jobs-employment balance, land use balance, road space per person, | Controlled only for socio-economic variables | | | -6.0E-06 | | 0.003 | |
| Athens metropolitan area (3.83 mill.) | Metropolitan area (all municipalities in the | Monocetric | Milakis, Vlastos & Barbopoulos (2008) | quantitative cross-sectional. Multiple linear regression | Distance from city center (meters) | Mean trip length by car | Residential density (log-transform) | Distance from city centre, residential density, jobs-employment balance, land use balance, road space per person, | Controlled only for socio-economic variables | | | 0.210 | | 0.000 | An increase in distance from CBD by 1000 meters increases trip length by 210 meters |
| Athens metropolitan area (3.83 mill.) | Metropolitan area (all municipalities in the | Monocetric | Milakis, Vlastos & Barbopoulos (2008) | quantitative cross-sectional. Multiple linear regression | Distance from city center (meters) | Energy consumption by car | Residential density (log-transform) | Distance from city centre, residential density, jobs-employment balance, land use balance, road space per person, | Controlled only for socio-economic variables | | | -0.0004 | | 0.103 | |

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[42] In addition to the publications shown in Appendix C, we reviewed four Eastern European studies (Tammaru, 2005; Niedzielski, 2006; Marcińczak & Bartosiewicz, 2018; and Radzimski & Gadziński, 2019). However, none of these studies included evidence about effects of urban built environment characteristics on travel relevant for the present project.

| Study area, its population and population of main city (at time of investigation) | Geographical scale covered (distances as the crow flies) | Predominant center structure | Publication reference | Main methodology | Urban form variable of interest (Partial effect of…) | Travel behavior variable | Linear or transformed variable measurement? | Built environment variable(s)controlled for | Control for residential self-selection? | Control for car ownership? | Elasticity | Regression estimates | Standar-dized estimates | P-value | Note |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Bergen (0.25 mill.) | Morphological city (up to max. 17 km from main city center). All trips≤50 km | Monocentric | Engebretsen, Næss & Strand (2018) | Quantitative, cross-sectional | Residential distance to city centre | Daily distance travelled as car driver. | Linear | Residential distance to closest second-order and local center, local area population density, local transit provision | None | No | 0.390 | 0.511 | 0.123 | p < .01 | Distance from city center in km; density in a 750 × 750 m grid |
| Bergen (0.25 mill.) | Morphological city (up to max. 17 km from main city center). All trips≤50 km | Monocentric | Engebretsen, Næss & Strand (2018) | Quantitative; crosssectional | Distance residence to city centre | Commuting distance | Linear | Residential distance to closest second-order and local center, local area population density, local transit provision | None | No | 0.449 | 0.455 | 0.315 | p < .01 | Distance from city center in km; density in a 750 × 750 m grid |
| Copenhagen metropolitan area (1.8mill./1.2mill) | Functional urban region (approx. up to 60 km from city center) | Monocentric | Næss (2005) | quantitative and qualitative; cross-sectional. | Location of the residence relative to down town Copenhagen | Travel distance by car on weekdays | | Residential distance to the closest second-order center, residential distance to the closest rail station, local residential area popl & workplace density | No | No | 0.27 | 0.114 | | p<0.0005 | Non-linear distance function, values ranging from 0.66 to 3.80 |
| Copenhagen metropolitan region | | | Nielsen (2019) | Quantitative | Distance to the regional centre | Nonwork daily travel distance | Y-log, X-untransformed and x-sqrd. | Distance to closest level 3 employment subcentre, distance to closest level 3 retail subcentre | No | No | | 0.221 | | P<0.01 | since X is in quadratic, the comulative effect for a 1 unit change from the mean would be: 0.221-0,139=0.08; a semi elasticity of 8% |
| Copenhagen metropolitan region | | | Nielsen (2019) | Quantitative | Distance to the regional centre | Daily travel distance to/from work | X &Y log | Distance to closest level 3 employment subcentre, distance to closest level 3 retail subcentre | | | | 0.682 | | P<0.01 | since X is in quadratic, the comulative effect for a 1 unit change from the mean would be: 0.682-0,543=0.139; a semi elasticity of 14% |
| Drøbak city (0.013 mill.) | Continuous built-up area in Drøbak | dual-centered | Wolday (2018) | Quantitative | Residential distance from the city centre | Car driving distance (km) | X&Y log transformed | Neighborhood job density; Neighborhood population density; Residential distance from the city center | Yes | No | - | | | | A small city withinn greater Oslo region (about 39km from Oslo). Regional influence is stronger than distance from local city center |
| East Jutland corridor (1.2 mill./0.26 mill.) | Large functional urban region (about 175 km from north to south) | Polycentric | Grunfelder & Nielsen (2012) | Quantitative; crosssectional and longitudinal | Distance from residence to the closest large urban center | Commuting distance | X logged, Y logged | Distance to closest second-order center, local area job density, distance to transit | None | No | 0.08 | 0.08 | 0.068 | p < .05 | |
| East Jutland corridor (1.2 mill./0.26 mill.) | Large functional urban region (about 175 km from north to south) | Polycentric | Grunfelder & Nielsen (2012) | Quantitative; crosssectional and longitudinal | Distance from residence to the closest urban center | Commuting distance | X logged, Y logged | Distance to closest second-order center, local area job density, distance to transit | None | No | 0.126 | 0.126 | 0.106 | p < .05 | |
| East Jutland corridor (1.2 mill./0.26 mill.) | Large functional urban region (about 175 km from north to south) | Polycentric | Grunfelder & Nielsen (2012) | Logistic regression | Distance from residence to the closest large urban center | Likelihood of commuting by car | X logged, Y logged | Distance to closest second-order center, local area job density, distance to transit | None | No | exp B=1.221 | 0.199 [exp B=1.221] | | p < .05 | Percentage change in odds of car commuting when the independent variable changes by 1 unit |
| East Jutland corridor (1.2 mill./0.26 mill.) | Large functional urban region (about 175 km from north to south) | Polycentric | Grunfelder & Nielsen (2012) | Logistic regression | Distance from residence to the closest urban center | Likelihood of commuting by car | X logged, Y logged | Distance to closest second-order center, local area job density, distance to transit | None | No | expB=1.268 | 0.238 [expB=1.268] | | p < .05 | Percentage change in odds of car commuting when the independent variable changes by 1 unit |
| Fredrikshavn (0.35 mill.) | Municipality | Monocentric | Næss & Jensen (2004) | quantitative and qualitative; cross-sectional. | Hyperbolic tangent to the distance (km) along the road network between residence and town centre (turning point at a distance from the centre of 3 km) | Logarithm of the total weekly travel distance (km) | Originally log Y and hyperbolic tangent X, new analysis with both X and Y logged | | Yes | yes | 0.329 | | 0,24 | p<0.0001 | |
| Greater Copenhagen (1.3 mill.) | Continuous urban area of Copenhagen (i.e. the morphological city) | Monocentric | Næss (2015) | quantitative and qualitative; cross-sectional. | Distance residence to main city centre (KM) | Weekely traveling distance by car or motorbike | Logged Y | Population adn job density, residential distance to second-order center, residential distance to closest urban retail center and residential distance to closest main urban retail center | Yes | No | 0.37 | 0.0378 | 0,11 | p<0.0001 | Chapter 8 in an edited book: Mobility patterns and urban structure |
| Greater Oporto (1.1 mill.) | Morphological city of greater Oporto | Polycentric | Næss (2015) | quantitative and qualitative; cross-sectional. | Residential distance to closest main urban regional retail center | Weekely traveling distance by car or motorbike | Logged X, logged Y | Residential distance to the main city center; opulation and job density; residential distance to second-order center; residential distance to closest urban retail center | Yes | No | 0.290 | 0.294 | 0-132 | p<0.0001 | |
| Greater Oporto (1.1 mill.) | Morphological city of greater Oporto | Polycentric | Næss (2015) | quantitative and qualitative; cross-sectional. | Distance residence to main city centre (KM) | Weekely traveling distance by car or motorbike | Logged X, logged Y | Residential distance to the main city center; population and job density; residential distance to second-order center; residential distance to closest urban retail center | Yes | No | 0.272 | 0.272 | 0.107 | p=0.006 | When 'residential distance to closest main urban regional retail center' is excluded from the model. |

| Study area, its population and population of main city (at time of investigation) | Geographical scale covered (distances as the crow flies) | Predominant center structure | Publication reference | Main methodology | Urban form variable of interest (Partial effect of…) | Travel behavior variable | Linear or transformed variable measurement? | Built environment variable(s)controlled for | Control for residential self-selection? | Control for car ownership? | Elasticity | Regression estimates | Standar-dized estimates | P-value | Note |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Jessheim city (0.017 mill.) | Continuous built-up area in Jessheim | Single-centered | Wolday (2018) | Quantitative | Residential distance from the city center | Car driving distance (km) | X&Y log transformed | Neighborhood job density; Neighborhood population density; Residential distance from the city center | Yes | No | - | | | | A small city withinn greater Oslo region (about 45km from Oslo). Regional influence is stronger than distance from local city center |
| Kongsvinger city (0.012 mill.) | Continuous built-up area in Kongsvinger | Single-centered | Wolday (2018) | Quantitative | Residential distance from the city center | Car driving distance (km) | X&Y log transformed | Neighborhood job density; Neighborhood population density; Residential distance from the city center | Yes | No | 0.2645 | | | p<0.001 | A regional center, with about 80km dist. from any higher order city |
| Lisbon metropolitan area (2.64 mill.) | | Pollycentric | de Abreu e Silva, Golob & Goulias (2006) | Structural equation modling | Effect of residence in traditional residential area on km traveled by car | Km traveled by car | Km traveled by car | Distance to CBD, neighborhood typologies at residence and workplace, density, etc. | yes | yes | | | −0.03 | (−3.33) t-statistik | Various built environment variables are computed together as factor loadings to determine land-use categories |
| | | | | | | | | | | | | | | | |
| Lisbon metropolitan area (2.64 mill.) | | Pollycentric | de Abreu e Silva, Golob & Goulias (2006) | Structural equation modling | Effect of residence in traditional residential area on km traveled by car | Km traveled by transit | Km traveled by transit | Distance to CBD, neighborhood typologies at residence and workplace, density, etc. | yes | yes | | | 0.02 | (1.07) t-statistik | Various built environment variables are computed together as factor loadings to determine land-use categories |
| Lisbon metropolitan area (2.64 mill.) | | Pollycentric | de Abreu e Silva, Golob & Goulias (2006) | Structural equation modling | Residnce in traditional residential area | Km traveled by car | Km traveled by car | Distance to CBD, neighborhood typologies at residence and workplace, density, etc. | yes | yes | | | −0.03 | (−3.33) t-statistic | Supporting literature |
| Lisbon metropolitan area (2.64 mill.) | | Pollycentric | de Abreu e Silva, Golob & Goulias (2006) | Structural equation modling | Residnce in traditional residential area on Km traveled by transit | Km traveled by transit | Km traveled by transit | Distance to CBD, neighborhood typologies at residence and workplace, density, etc. | yes | yes | | | 0.02 | (1.07) t-statistic | Supporting literature |
| Lisbon metropolitan area (2.64 mill.) | | Pollycentric | de Abreu e Silva, Golob & Goulias (2006) | Structural equation modling | Residnce in traditional residential area on Km traveled by nonmotorized | Km traveled by nonmotorized | Km traveled by nonmotorized | Distance to CBD, neighborhood typologies at residence and workplace, density, etc. | yes | yes | | | 0.11 | (8.15) t-statistic | Supporting literature |
| Lisbon metropolitan area (2.64 mill.) | | Pollycentric | de Abreu e Silva, Golob & Goulias (2006) | Structural equation modling | Residnce in traditional residential area on No. of trips by car | No. of trips by car | No. of trips by car | Distance to CBD, neighborhood typologies at residence and workplace, density, etc. | yes | yes | | | −0.04 | (−3.33) t-statistic | Supporting literature |
| Lisbon metropolitan area (2.64 mill.) | | Pollycentric | de Abreu e Silva, Golob & Goulias (2006) | Structural equation modling | Residnce in traditional residential area | No. of trips by transit | No. of trips by transit | Distance to CBD, neighborhood typologies at residence and workplace, density, etc. | yes | yes | | | 0.12 | (10.19) t-statistic | Supporting literature |
| Lisbon metropolitan area (2.64 mill.) | | Pollycentric | de Abreu e Silva, Golob & Goulias (2006) | Structural equation modling | Residnce in traditional residential area | No. of trips, nonmotorized | No. of trips, nonmotorized | Distance to CBD, neighborhood typologies at residence and workplace, density, etc. | yes | yes | | | 0.15 | (13.51) t-statistic | Supporting literature |
| Literature review (UK) | | | Banister (2011) | | Density people or jobs per unit of land area [Empirical research in developed cities has concluded that the key parameters of a sustainable city are that they should be over 50,000 population, with medium densities (over 40 persons per hectare), with mixed use developments, and preference given to developments in public transport accessible corridors and near to highly public transport accessible interchanges where densities would be substantially higher (over 80 persons phectare) (Banister, 2005).] | Vehicle miles traveled (VMT) | | | | | | Increased density tends to reduce per capita vehicle travel. Each 10% increase in urban densities typically reduces per capita VMT by 1–3% | | | Support dokkument |
| National travel survey of German urban settlements | Municipalities | Various settlement sizes | Holz-Rau, Scheiner & Sicks (2014) | Quantitative, cross-sectional | Effect of population density on daily travel distance (ref.: <250 pers/km2) | Total daily travel distance | Y natural logged | urba structure at place of residence: Land-use mix, population density per km2, municipal population size | No | No | | | 250-499 = --<br>500-999 = -0.122<br>1000-1999 =-0.158<br>2000-4999 = -0.249<br>>5000 = -0.426 | p<0.001 | |

| Study area, its population and population of main city (at time of investigation) | Geographical scale covered (distances as the crow flies) | Predominant center structure | Publication reference | Main methodology | Urban form variable of interest (Partial effect of…) | Travel behavior variable | Linear or transformed variable measurement? | Built environment variable(s)controlled for | Control for residential self-selection? | Control for car ownership? | Elasticity | Regression estimates | Standar-dized estimates | P-value | Note |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Neighbourhoods of **five** District administrative local government areas which make up the Tyne and Wear metropolitanarea, UK. (1.1 mill.) | Neighbourhoods of metropolitanarea | | Aditjandra, Mulley & Nelson (2013) | OLS (cross-sectional) | Comparison of neighborhood typologies with high/low insidence of sustainable commuting. Neighborhood dummy ( Traditional=1, Sub-urban=0) | log weekly VMD as the dependent variable | log transformed weekly total household VMD (log VMD) | Five traditional and five sub-urban neighborhoods are studied | Travel attitude and residential preferences | yes | | −.212 | −.053 | p .028 (t-stat: −2.201) | Somewhat tautological in its analysis |
| Oslo (0.98 mill.) | Morphological city (up to max. 22 km from city center). All trips≤50 km | Monocentric | Engebretsen, Næss & Strand (2018) | Quantitative, cross-sectional | Residential distance to city center | Daily distance traveled as car driver. | Linear | Residential distance to closest second-order and local center, local area jobs and population density, local transit provision | None | No | 0.238 | 0.208 | 0.082 | p < .01 | Distance from city center in km; density in a 750 × 750 m grid |
| Oslo (0.98 mill.) | Morphological city (up to max. 22 km from city center). All trips≤50 km | Monocentric | Engebretsen, Næss & Strand (2018) | Quantitative; crosssectional | Residential distance to city center | Commuting distance | Linear | Residential distance to closest second-order and local center, local area jobs and population density, local transit provision | None | No | 0.429 | 0.400 | 0.345 | p < .01 | Distance from city center in km; density in a 750 × 750 m grid |
| Oslo metropolitan area (1.2 mill.) | The Oslo region within 30 km (as the crow flies) from the city center of Oslo | Monocentric | Næss, Cao & Strand (2017) | qualitative, quantitative, Poisson regression | Residential distance to city center | Weekly driving distance | X-logged (poisson model) | Distance to second-order center, distance to local center, population density, job density, job-housing ratio, and distance to transit | Yes | No | 0.287 | | 0.020 | p<0.0001 | Average opulation density (Oslo=36.7 and Stavanger= 29.0 prs. per hectare respectively |
| Oslo metropolitan area (1.2 mill.) | Continuous built-up area in Oslo region | Monocentric | Næss, Strand, Wolday & Stefandottir (2019) | qualitative, quantitative, OLS regression | Residential distance to city center | Weekly distance traveled by car | Untransformed X & Y distances (KM) | Distance to second-order center, distance to local center, population density, job density, job-housing ratio, and distance to transit | Yes | No | 0.823 | 4.72 | 0.401 | p<0.0001 | Intra-metropolitan weekly distance traveled by car (both as driver and as passenger). |
| Oslo metropolitan area (1.2 mill.) | Continuous built-up area in Oslo region | Monocentric | Næss, Strand, Wolday & Stefandottir (2019) | qualitative, quantitative, OLS regression | Residential distance to city center | Oneway commuting distance | Untransformed X & Y distances (KM) | Distance to second-order center, distance to local center, population density, job density, job-housing ratio, and distance to transit | Yes | No | 0.588 | 0.510 | 0.461 | p<0.0001 | Commuting distance exceeding 100km have been excluded. |
| Oslo metropolitan area (1.2 mill.) | Continuous built-up area in Oslo region | Monocentric | Næss, Cao & Strand (2017) | qualitative, quantitative | Residential distance to city center | Weekly total car driving distance | X-logged (poisson model) | Distance to second-order center, distance to local center, population density, job density, job-housing ratio, and distance to transit | Yes | No | 0.287 | | | p<0.0001 | both Intra- & outside-metropolitan area driving distance |
| Oslo metropolitan area (1.2 mill.) | Continuous built-up area in Oslo region | Monocentric | Næss, Strand, Wolday & Stefandottir (2017) | qualitative, quantitative, OLS regression | Residential distance to city center | Car driving distance on weekdays | | Local area population density & job density | Yes | No | 0.442 | | | p<0.01 | both Intra- & outside-metropolitan area driving distance |
| Oslo metropolitan area (1.2 mill.) | Continuous built-up area in Oslo region | Monocentric | Næss, Strand, Wolday & Stefandottir (2017) | qualitative, quantitative, OLS regression | Residential distance to city center | Car driving distance on weekends | | Local area population density & job density | Yes | No | 0.130 | | | p<0.01 | both Intra- & outside-metropolitan area driving distance |
| Reykjavik urban region (0.228 mill) | Continuous urban area of Reykjavik | Weakly monocentric | Næss et al (2020) | qualitative, quantitative, regression | Residential distance to the main city center | Weekly car driving distanceincluding intra-& outside-metropolitan travel | X & Y untransformed | Distance from dwelling to the Smáralind second-order center , distance from dwelling to the closest local center, and local-area population density | Yes | No | 0.330 | 0.708 | 0.195 | p<0.0001 | |
| Reykjavik urban region (0.228 mill) | Continuous urban area of Reykjavik | Weakly monocentric | Næss et al (2020) | qualitative, quantitative, regression | Distance from dwelling | Likelihood of car commuting | X & Y untransformed (logistic regression) | Distance from dwelling to the Smáralind second-order center , distance from dwelling to the closest local center, and local-area population density | Yes | No | | 0.137 | | p<0.0001 | Average pop. density: 30.8 pers/hectare |
| Reykjavik urban region (0.228 mill) | Continuous urban area of Reykjavik | Weakly monocentric | Næss et al (2020) | qualitative, quantitative, regression | Distance from dwelling | One-way commutingn destance (km) | X & Y untransformed | Distance from dwelling to the Smáralind second-order center , distance from dwelling to the closest local center, and local-area population density | Yes | No | 0.611 | 0.496 | 0.513 | p<0.0001 | |
| Stavanger metropolitan area (0,22 mill.) | The Stavanger region within 12 km (as the crow flies) from one of the city centers of Stavanger and Sandnes | Polycentric | Næss, Cao & Strand (2017) | qualitative, quantitative, Poisson regression | Residential distance to the city center (KM) | Weekly driving distance | X-logged (poisson model) | Distance to second-order center, distance to local center, population density, job density, job-housing ratio, and distance to transit | Yes | No | 0.259 | | 0.025 | p<0.0001 | Average opulation density (Oslo=36.7 and Stavanger= 29.0 prs. per hectare respectively |
| Stavanger metropolitan area (0,22 mill.) | Continuous built-up area Stavanger region | Polycentric | Næss, Strand, Wolday & Stefandottir (2019) | qualitative, quantitative, OLS regression | Residential distance to the city center (KM) | Oneway commuting distance | Untransformed X & Y distances (KM) | Distance to second-order center, distance to local center, population density, job density, job-housing ratio, and distance to transit | Yes | No | 0.198 | 0.152 | 0.164 | p<0.0001 | Commuting distance exceeding 50km have been excluded. |
| Stavanger metropolitan area (0,22 mill.) | Continuous built-up area Stavanger region | Polycentric | Næss, Cao & Strand (2017) | qualitative, quantitative | Residential distance to the city center (KM) | Weekly total car driving distance | X-logged (poisson model) | Distance to second-order center, distance to local center, population density, job density, job-housing ratio, and distance to transit | Yes | No | 0.259 | | | p<0.0001 | both Intra- & outside-metropolitan area driving distance |
| Stavanger metropolitan area (0,22 mill.) | Continuous built-up area Stavanger region | Polycentric | Næss, Strand, Wolday & Stefandottir (2019) | qualitative, quantitative, OLS regression | Residential distance to the city center (KM) | Car driving distance on weekdays | | Local area population density & job density | Yes | No | 0.279 | | | p<0.01 | both Intra- & outside-metropolitan area driving distance |
| Stavanger metropolitan area (0,22 mill.) | Continuous built-up area Stavanger region | Polycentric | Næss, Strand, Wolday & Stefandottir (2019) | qualitative, quantitative, OLS regression | Residential distance to the city center (KM) | Car driving distance on weekends | | Local area population density & job density | Yes | No | 0.215 | | | p<0.01 | both Intra- & outside-metropolitan area driving distance |

| Study area, its population and population of main city (at time of investigation) | Geographical scale covered (distances as the crow flies) | Predominant center structure | Publication reference | Main methodology | Urban form variable of interest (Partial effect of…) | Travel behavior variable | Linear or transformed variable measurement? | Built environment variable(s)controlled for | Control for residential self-selection? | Control for car ownership? | Elasticity | Regression estimates | Standar-dized estimates | P-value | Note |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Stavanger metropolitan area (0,22 mill.) | Continuous built-up area Stavanger region | Polycentric | Næss, Strand, Wolday & Stefandottir (2019) | qualitative, quantitative, OLS regression | Residential distance to the city center (KM) | Weekly distance traveled by car | Untransformed X & Y distances (KM) | Distance to second-order center, distance to local center, population density, job density, job-housing ratio, and distance to transit | Yes | No | 0.525 | 4.39 | 0.0325 | p<0.0001 | Intra-metropolitan weekly distance traveled by car (both as driver and as passenger). |
| Stavanger/Sandnes (0.21 mill.) | Morphological city (up to max. 16 km from main city center). All trips≤50 km | Polycentric | Engebretsen, Næss & Strand (2018) | Quantitative, cross-sectional | Residential distance to city centre | Daily distance travelled as car driver. | Linear | Residential distance to closest second-order and local center, local area jobs and population density, local transit provision | None | No | 0.256 | 0.388 | 0.127 | p < .01 | Distance from city center in km; density in a 750 × 750 m grid |
| Stavanger/Sandnes (0.21 mill.) | Morphological city (up to max. 16 km from main city center). All trips≤50 km | Polycentric | Engebretsen, Næss & Strand (2018) | Quantitative; crosssectional | Distance residence to city centre | Commuting distance | Linear | Residential distance to closest second-order and local center, local area jobs and population density, local transit provision | None | No | 0.418 | 0.380 | 0.402 | p < .01 | |
| Suburban neighborhoods of Waloon region, Belgium. | Tintigny, Fontaine & Jambes (distance from CBD: 29km, 9km & 6km respectively). | | Marique & Reiter (2012) | sensitivity analysis, with Fontain neighborhood taken as reference | Tintigny, Fontaine & Jambes (bus service quality: very low, good & and low respectively). | Potential reduction in energy consumption in Tintigny as a result favorable location (bus service and distance from the city center) corresponding to Fontaine level | | Residential distance from the city center | | | | -18% | | | Does not directly fit into our model but can be used as support material |
| Suburban neighborhoods of Waloon region, Belgium. | Tintigny, Fontaine & Jambes (distance from CBD: 29km, 9km & 6km respectively). | | Marique & Reiter (2012) | sensitivity analysis, with Fontain neighborhood taken as reference | Tintigny, Fontaine & Jambes (bus service quality: vely low, good & and low respectively). | Potential reduction in energy in Jambes consumption as a result favorable location (bus service and distance from the city center) corresponding to Fontaine level | | Residential distance from the city center | | | | -6.1% | | | Does not directly fit into our model but can be used as support material |
| Surrey county, London (1 mill) | Surrey county (south-west of London) | | Hickman & Banister (2015) | Longitudinal analysis, descriptive statistics | energy consumption for Town Center residents with a given commute distance and car share | Job-commute related energy consumption (MJ) | | Not relevant | | | | Energy consumption; Journey distance; Car mode share = 41.4; 29,9; 50% | | | Supporting literature |
| Surrey county, London (1 mill) | Surrey county (south-west of London) | | Hickman & Banister (2015) | Longitudinal analysis, descriptive statistics | energy consumption for Rest of Urban Area residents with a given commute distance and car share | Job-commute related energy consumption (MJ) | | Not relevant | | | | Energy consumption; Journey distance; Car mode share = 52.3; 28.3; 70% | | | Supporting literature |
| Surrey county, London (1 mill) | Surrey county (south-west of London) | | Hickman & Banister (2015) | Longitudinal analysis, descriptive statistics | energy consumption for Rural residents with a given commute distance and car share | Job-commute related energy consumption (MJ) | | Not relevant | | | | Energy consumption; Journey distance; Car mode share = 68.9; 30.3; 80% | | | Supporting literature |
| The Lisbon metropolitan area (2.64 mill.) | | Pollycentric | de Abreu e Silva, Golob & Goulias (2006) | Structural equation modling | Residnce in traditional residential area | commuting distance | Log transformed commuting distance variable | Distance to CBD, neighborhood typologies at residence and workplace, density, etc. | yes | yes | | | −0.38 | (−39.74) t-statistik | Supporting literature |
| Trondheim (0.18 mill.) | Morphological city (up to max. 13 km from main city center). All trips≤50 km | Monocentric | Engebretsen, Næss & Strand (2018) | Quantitative, cross-sectional | Residential distance to city centre | Daily distance travelled as car driver. | Linear | Residential distance to closest second-order and local center, local area population density, local transit provision | None | No | 0.365 | 0.521 | 0.109 | p < .01 | Distance from city center in km; density in a 750 × 750 m grid |
| Trondheim (0.18 mill.) | Morphological city (up to max. 13 km from main city center). All trips≤50 km | Monocentric | Engebretsen, Næss & Strand (2018) | Quantitative; crosssectional | Distance residence to city centre | Commuting distance | Linear | Residential distance to closest second-order and local center, local area population density, local transit provision | None | No | 0.413 | 0.465 | 0.245 | p < .01 | Distance from city center in km; density in a 750 × 750 m grid |

## Workplace studies (not used in the present study due to lack of available statistics on job locations in European urban regions and their development over time)

| Study area, its population and population of main city (at time of investigation) | Geographical scale covered (distances as the crow flies) | Predominant center structure | Publication reference | Main methodology | Urban form variable of interest (Partial effect of…) | Travel behavior variable | Linear or transformed variable measurement? | Built environment variable(s) controlled for | Control for residential self-selection? | Control for car ownership? | Elasticity | Regression estimates | Standardized estimates | P-value |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| All Swedish urban settlements | Populated parts of Sweden | Polycentric | Elldér (2014) | Quantitative (multilevel analysis); crosssectional | the job-worker ratio in a 10 km radius of residence | Commuting distance (Euclidian home–work distance) | X logged | Local jobs to workers ratio, size category of urban area, regional location of settlement areas | No | Yes | 0,23 | | | p < .005 |
| Bergen (0.25 mill.) | Morpho-logical city (up to max. 17 km from main city center). All trips≤50 km | Monocentric | Engebretsen, Næss, and Strand (2018) | Quantitative; crosssectional | Distance from workplace to city centre | Commuting distance | Linear | Residential distance to closest 2nd-order and local center, local area population density, local transit provision | None | No | 0.425 | 0.549 | 0.520 | p < .01 |
| Bergen (0.25 mill.) | Morpho-logical city (up to max. 17 km from main city center). All trips≤50 km | Monocentric | Engebretsen, Næss, and Strand (2018) | Quantitative; crosssectional | Distance from workplace to city centre | Commuting likelihood as car driver | Logistic regression | Residential distance to closest 2nd-order and local center, local area population density, local transit provision | None | No | exp(b)=1.074 | 0.071; exp(b)=1,074 | | p < .01 |
| Bergen (0.25 mill.) | Morphological city (up to max. 17 km from main city center). All trips≤50 km | Monocentric | Engebretsen, Næss, and Strand (2018) | Quantitative; crosssectional | Density of population and jobs at workplace | Commuting likelihood as car driver | Logistic regression | Residential distance to closest second-order and local center, local area population density, local transit provision | None | No | exp(b)=0.967 | -0.033; exp(b)=0.967 | | p < .01 |
| Copenhagen metropolitan area (1.8mill./1.2mill) | Functional urban region (approx. up to 50 km from city center) | Monocentric | Næss (2007) | Mixed qualitative; cross-sectional and longitudinal | 0.34 | | X transformed by non-linear function | Residential distance to the closest second-order center, distance to rail, local job and population density | yes | yes | | | | p<0.0005 |
| Greater Oslo, Norway | Greater Oslo, Norway | Monocentric | Næss et al. (1996). | Multiple OLS regression | Floor area density in the local area of the workplace | Proportion of commuting distance travelled by car | | Distance from the workplace to downtown Oslo | No | yes | | | -0.282 | 0.0000 |
| Greater Oslo, Norway | Greater Oslo, Norway | Monocentric | Næss et al. (1996). | Multiple OLS regression | Distance from the workplace to downtown Oslo | Proportion of commuting distance travelled by car | | Density in the local area of the workplace, accessibility by train | No | yes | 0.504 | 1.106 | 0.354 | 0.0000 |
| Greater Oslo, Norway | Greater Oslo, Norway | Monocentric | Næss et al. (1996). | Multiple OLS regression | Distance from the workplace to downtown Oslo | Daily energy use for journeys to and from work | | | | yes | 0.324 | 0.712 | 0.276 | 0.0000 |
| Oslo (0.98 mill.) | Morphological city (up to max. 22 km from city center). All trips≤50 km | Monocentric | Engebretsen, Næss, and Strand (2018) | Quantitative; crosssectional | Distance from workplace to city centre | Commuting distance | Linear | Residential distance to closest 2nd-order and local center, local area jobs and population density, local transit provision | None | No | 0.406 | 0.453 | 0.495 | p < .01 |
| Oslo (0.98 mill.) | Morpho-logical city (up to max. 22 km from city center). All trips≤50 km | Monocentric | Engebretsen, Næss, and Strand (2018) | Quantitative; crosssectional | Distance from workplace to city centre | Commuting likelihood as car driver | Logistic regression | Residential distance to closest 2nd-order and local center, local area jobs and population density, local transit provision | None | No | exp(b)=1.065 | 0.063; exp(b)=1,065 | | p < .01 |
| Oslo (0.98 mill.) | Morphological city (up to max. 22 km from city center). All trips≤50 km | Monocentric | Engebretsen, Næss, and Strand (2018) | Quantitative; crosssectional | Density of population and jobs at workplace | Commuting likelihood as car driver | Logistic regression | Residential distance to closest second-order and local center, local area population density, local transit provision | None | No | exp(b)=0.952 | -0.049; exp(b)=0.952 | | p < .01 |
| Oslo metropolitanp area (1.2 mill.) | Areas within approx. 30 km from the city center of Oslo (as the crow flies) | Monocentric | Wolday, Næss & Tønnesen (2019) | Multiple OLS regression | Job distance from the city center | Commuting distance | Untransformed X & Y distances (KM) | Workplace distance to 2nd order center, jobs&popln density in workplace neighborhood (prs/hect) | No | No | 0.136 | 0.117 | 0.091 | 0.003 |
| Oslo metropolitanp area (1.2 mill.) | Areas within approx. 30 km from the city center of Oslo (as the crow flies) | Monocentric | Wolday, Næss & Tønnesen (2019) | crossectional logistic regression | Job distance from the city center | Likelihood of commuting by car | Untransformed X & Y distances (KM) | Workplace distance to 2nd order center, jobs&popln density in workplace neighborhood (prs/hect), transit accessibility | No | No | 0.519 | 0.0803 | 0.333 | 0.000 |
| Oslo metropolitanp area (1.2 mill.) | Areas within approx. 30 km from the city center of Oslo (as the crow flies) | Monocentric | Wolday, Næss & Tønnesen (2019) | crossectional logistic regression | Job distance from the city center | Likelihood of commuting by transit | Untransformed X & Y distances (KM) | Workplace distance to 2nd order center, jobs&popln density in workplace neighborhood (prs/hect), transit accessibility at workplace | No | No | -1.271 | -0.0934 | -0.441 | 0.000 |
| Oslo metropolitanp area (1.2 mill.) | Areas within approx. 30 km from the city center of Oslo (as the crow flies) | Monocentric | Wolday, Næss & Tønnesen (2019) | crossectional logistic regression | Combined jobs and population density in workplace | Likelihood of commuting by car | Untransformed X & Y distances (KM) | Job distance from the city center; workplace distance to 2nd order center; transit accessibility | No | No | -0.723 | -0.000 | -0.325 | 0.000 |
| Oslo metropolitanp area (1.2 mill.) | Areas within approx. 30 km from the city center of Oslo (as the crow flies) | Monocentric | Wolday, Næss & Tønnesen (2019) | crossectional logistic regression | Combined jobs and population density in workplace | Likelihood of commuting by transit | Untransformed X & Y distances (KM) | Job distance from the city center; Workplace distance to 2nd order center; transit accessibility at workplace | No | No | 0.172 | 0.0002 | 0.102 | 0.004 |

| Study area, its population and population of main city (at time of investigation) | Geographical scale covered (distances as the crow flies) | Predominant center structure | Publication reference | Main methodology | Urban form variable of interest (Partial effect of…) | Travel behavior variable | Linear or transformed variable measurement? | Built environment variable(s) controlled for | Control for residential self-selection? | Control for car ownership? | Elasticity | Regression estimates | Standardized estimates | P-value | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Eastern Paris region | 26 municipalities in the New Town of Marne-la-Vallée | | Aguiléra & Voisin (2014) | Quantitative based on census data aggregated to the municipal level | Jobs to housing ratio | Several: CO2 emissions, shares of different travel modes | | | | | | | | | No effect estimates, only a correlation table |
| Eastern Paris region | 26 municipalities in the New Town of Marne-la-Vallée | | Aguiléra & Voisin (2014) | Quantitative based on census data aggregated to the municipal level | Density/Compactness | | | | | | | | | | No effect estimates, only a correlation table |
| Stavanger (0.21 mill.) | Morphological city (up to max. 16 km from main city center). All trips≤50 km | Polycentric | Engebretsen, Næss, and Strand (2018) | Quantitative; crosssectional | Distance from workplace to city centre | Commuting distance | Linear | Residential distance to closest 2nd-order and local center, local area jobs and population density, local transit provision | None | No | 0.500 | 0.345 | 0.429 | p < .01 | |
| Stavanger (0.21 mill.) | Morphological city (up to max. 16 km from main city center). All trips≤50 km | Polycentric | Engebretsen, Næss, and Strand (2018) | Quantitative; crosssectional | Distance from workplace to city centre | Commuting likelihood as car driver | Logistic regression | Residential distance to closest 2nd-order and local center, local area jobs and population density, local transit provision | None | No | exp(b)=1.035 | 0.034; exp(b)=1,035 | | p < .05 | |
| Stavanger (0.21 mill.) | Morphological city (up to max. 16 km from main city center). All trips≤50 km | Monocentric | Engebretsen, Næss, and Strand (2018) | Quantitative; crosssectional | Density of population and jobs at workplace | Commuting likelihood as car driver | Logistic regression | Residential distance to closest second-order and local center, local area population density, local transit provision | None | No | exp(b)=0.907 | -0.097; exp(b)=0.907 | | p < .01 | |
| Trondheim (0.18 mill.) | Morphological city (up to max. 13 km from main city center). All trips≤50 km | Monocentric | Engebretsen, Næss, and Strand (2018) | Quantitative; crosssectional | Distance from workplace to city centre | Commuting distance | Linear | Residential distance to closest 2nd-order and local center, local area population density, local transit provision | None | No | 0.582 | 0.782 | 0.780 | p < .01 | |
| Trondheim (0.18 mill.) | Morphological city (up to max. 13 km from main city center). All trips≤50 km | Monocentric | Engebretsen, Næss, and Strand (2018) | Quantitative; crosssectional | Distance from workplace to city centre | Commuting likelihood as car driver | Logistic regression | Residential distance to closest 2nd-order and local center, local area population density, local transit provision | None | No | - | - | | p < .01 | |
| Trondheim (0.18 mill.) | Morphological city (up to max. 13 km from main city center). All trips≤50 km | Monocentric | Engebretsen, Næss, and Strand (2018) | Quantitative; crosssectional | Density of population and jobs at workplace | Commuting likelihood as car driver | Logistic regression | Residential distance to closest second-order and local center, local area population density, local transit provision | None | No | exp(b)=0.892 | -0.114; exp(b)=0.892 | | p < .01 | |

# Appendix D: Country-level aggregation of spatial development in urban regions with core urban areas in different population size classes

Table D.1: Percentage change in in urban population density and mean residential distance to the center of the urban region between 1990 and 2015 for urban regions with core urban area population of >=1mill.

| Country | Urban population density, %Δ 1990-2015 | Mean residential distance to the center of the urban region, %Δ 1990-2015 |
|---|---:|---:|
| Norway | 33.16 | -4.55 |
| Sweden | 27.40 | -5.30 |
| Denmark | 20.69 | -10.47 |
| Austria | 17.55 | -3.73 |
| United Kingdom | 16.44 | -2.27 |
| Czechia | 15.46 | -0.05 |
| Ireland | 15.18 | 14.36 |
| Finland | 12.76 | -5.74 |
| Spain | 12.07 | 0.64 |
| Belgium | 8.21 | -5.37 |
| Netherlands | 7.84 | 1.87 |
| France | 7.58 | -0.93 |
| Portugal | 4.28 | 3.02 |
| Italy | 4.13 | 5.98 |
| Germany | 2.28 | -2.77 |
| Bulgaria | 1.39 | -18.28 |
| Hungary | 1.18 | -17.49 |
| Greece | 0.58 | -0.78 |
| Poland | -11.01 | 3.42 |
| Romania | -12.21 | 30.54 |
| Latvia | -31.84 | 7.78 |

Table D.2: Percentage change in in urban population density and mean residential distance to the center of the urban region between 1990 and 2015 for urban regions with core urban area population of 100,000 – 999,999.

| Country | Urban population density, %Δ 1990-2015 | Mean residential distance to the center of the urban region, %Δ 1990-2015 |
|---|---:|---:|
| Estonia | 59.68 | 20.87 |
| Luxembourg | 37.65 | -4.51 |
| Cyprus | 27.11 | 6.17 |
| Norway | 24.02 | 0.35 |
| Iceland | 19.80 | 12.58 |
| Portugal | 19.16 | -11.57 |
| Switzerland | 18.41 | 0.88 |
| Slovenia | 17.32 | -2.16 |
| Sweden | 17.15 | -3.50 |

| | | |
|---|---|---|
| Malta | 15.45 | 7.71 |
| Montenegro | 12.35 | 5.75 |
| United Kingdom | 8.13 | -1.44 |
| Austria | 7.08 | -3.77 |
| Ireland | 6.72 | 23.97 |
| Finland | 5.07 | -0.51 |
| Denmark | 4.27 | -0.45 |
| Greece | 1.84 | -3.13 |
| Italy | 1.82 | 6.05 |
| North Macedonia | 1.48 | 2.71 |
| Netherlands | 1.13 | -2.56 |
| Belgium | -0.25 | -0.34 |
| France | -0.47 | 6.43 |
| Spain | -0.54 | 2.39 |
| Germany | -2.69 | -3.25 |
| Slovakia | -3.28 | 15.36 |
| Croatia | -6.94 | 4.31 |
| Czechia | -8.86 | -1.55 |
| Hungary | -9.07 | -9.61 |
| Poland | -12.49 | 2.06 |
| Bulgaria | -21.92 | -0.50 |
| Lithuania | -28.21 | 6.81 |
| Romania | -31.11 | -2.29 |

Table D.3: Percentage change in urban population density and mean residential distance to the center of the urban region between 1990 and 2015 for urban regions with core urban area population of 10,000-99,999.

| Country | Urban population density, %Δ 1990-2015 | Mean residential distance to the center of the urban region, %Δ 1990-2015 |
|---|---:|---:|
| Cyprus | 42.28 | 6.62 |
| Iceland | 32.60 | -0.18 |
| Liechtenstein | 19.68 | 3.04 |
| Switzerland | 13.35 | -1.59 |
| Malta | 9.32 | 1.07 |
| Portugal | 9.14 | 4.58 |
| United Kingdom | 5.34 | 1.64 |
| Norway | 1.79 | 6.77 |
| Italy | 0.66 | -0.78 |
| Ireland | 0.25 | 1.79 |
| Belgium | -3.02 | 12.40 |
| Spain | -3.40 | 3.02 |
| Sweden | -3.80 | 3.63 |
| Denmark | -6.38 | 0.20 |
| Austria | -6.50 | 0.62 |
| Greece | -6.73 | 1.99 |
| Slovakia | -7.02 | -0.34 |
| France | -7.35 | 4.76 |
| Netherlands | -11.45 | 2.12 |
| Slovenia | -11.56 | 0.41 |
| North Macedonia | -12.43 | -0.01 |
| Germany | -12.53 | 1.63 |
| Poland | -13.53 | 4.66 |
| Czechia | -14.39 | 1.53 |
| Finland | -16.59 | -6.17 |
| Croatia | -20.84 | 0.14 |
| Montenegro | -21.30 | 0.05 |
| Hungary | -26.73 | 2.40 |
| Latvia | -33.89 | 1.31 |
| Romania | -35.26 | 5.39 |
| Bulgaria | -37.16 | 4.25 |
| Lithuania | -37.64 | 3.14 |
| Estonia | -45.74 | 0.85 |

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