sEEnergies

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

D2.3 Report on energy efficiency potentials in the transport sector and conclusions from the developed scenarios

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List of Abbreviations

AD	Alternative Drivmidler
BEV	Battery Electric Vehicles
CNG	Compressed Natural Gas
DME	Di-Methyl Ether
EE	Energy Efficiency
EFTA	European Free Trade Association
ERS	Electric Road Systems
EU	European Union
FCEV	Fuell Cell Electric Vehicle
GHG	Green House Gas
HFO	Heavy Fuel Oil
ICE	Internal Combustion Engine
PHEV	Plugin Hybrid Electric Vehicle
PRIMES	Price Induced Market Equilibrium System

1 Introduction

The sEEnergies project is based on the concept of Energy Efficiency First Principle and is aimed at the identification of energy efficiency potentials on which the future European energy system should be designed. The transport sector is among one of the three major sectors of energy consumption, the other ones being industry and buildings, and is responsible for around 30 % of Europe's energy consumption [1].

Within the scope of the sEEnergies project, WP2 deals with the assessment of energy efficiency potential by analyzing three main strategies:

1. Making each separate mode of transport more energy efficient
2. Reducing the movement of goods and persons
3. Modal shifts from more energy-intensive to more energy-efficient modes of transport

In light of these measures, WP2 also deals with the development of different transport scenarios with a detailed breakdown of efficiency measures such as technological advancements, modal shifts, and demand reduction. All of these scenarios encompass the goal of energy-related GHG emissions reduction of the European mobility sector.

The title of this deliverable D2.3 is "Report on energy efficiency potentials in the transport sector and conclusions from the developed scenarios" which is a continuation of the work that has been described in D 2.1 [2]. The insights from these two deliverables provide key insights about the EU-28 transport sector and in parallel with the insights from similar results from other work packages about different sectors will form the basis of the quantification of synergies among all sectors in WP6. This report is mainly focused on the quantified assessment of different energy efficiency scenarios for the EU-28 transport sector in 2050.[1]

Aalborg University (AAU) is the lead beneficiary of the deliverable and has carried out this work in cooperation with the Norwegian University of Life Sciences (NMBU), which is the work package leader of Work Package 2.

This report is structured as follows: Chapter 2 provides an overview of the methodology followed for the analysis, this is followed by a detailed explanation of the methodology behind creating an EU 28 transport baseline and energy efficiency transport scenarios. This chapter also details the workings of the AAU's scenario modeling tool TransportPLAN used for the analysis. In addition, it also describes the work done for creating different future energy efficiency scenarios including the calculations performed for alternative growth rates and modal shift rates. Finally, the results are presented in Chapter 3 and a short note on discussions and recommendations is provided in Chapter 4.

[1] *In this report, the effects of Covid-19 on the EU-28 transport sector in 2020 are not included mainly owing to a large uncertarinity surrounding the magnitude of demand reductions and the continuation of such decreased demand in the future. More research needs to be done on the long term effects of Covid-19 on European transport sector*

2 Methodology

This section describes the methodology of the analysis carried out in this deliverable. The extensive process of generating a transport model of the EU-28, analyzing the overall transport energy demand, and identifying energy efficiency scenarios can be split into two major parts:

1) Developing a reference model and baseline scenario, and
2) identifying alternative future scenarios

The development of a reference model and the baseline scenario is based on the accumulation of transport data from a variety of different sources and combining it with the growth and technology development rates from the Baseline 2050 scenario from PRIMES [3]. After establishing a reference model and a baseline scenario for the EU28, alternate growth rates and modal shift rates are calculated based on the outputs of Deliverable 2.1. These are the result of having an energy-efficient urban spatial and infrastructure development following the rule of best practices in Europe. These alternate growth rates are then combined with different energy efficiency technology implementation rates and several future transport scenarios are analyzed.

The processes of developing a reference model and a baseline scenario for the EU-28 transport system and energy efficiency scenarios are described in detail in the following sections.

The alternate growth rates and different scenarios are compared to the baseline scenario based on final energy demand and transport system cost. The upstream energy demand related to fuel production will not be considered in the comparison. The transport system cost relates to the annual investment and O&M cost of road vehicles, the annual fuel cost for all types of vehicles, annualized investment and maintenance cost related to road and rail infrastructure, as well as the annual cost of expanding the electric vehicle charging infrastructure.

2.1 Reference Model and Baseline Scenario

To create a reference model for the EU-28, a bottom-up approach is used where different transport data is gathered from a variety of different sources and analyzed accordingly. For the accumulation of transport demand, different sources have been used to make reasonable estimates. These sources include national travel surveys from individual countries, “EU transport in Figures” (Eurostat statistical pocketbook) [4], and Eurostat database [5].

This data is key to the AAU’s transport modeling tool “TransportPLAN”. TransportPLAN is a scenario modeling tool which is further explained in subsection 2.2.3. During the extensive task of data collection for the EU-28, care has been taken to ensure that the transport demand data matches the resolution of the TransportPLAN tool used for the analysis. The different modes of transport considered for the analysis are shown in Figure 1.

The transport sector is split into two parts; passenger and freight, each of which has different modes of transport. The transport demand of passenger cars, trucks, buses, and bicycle/walking are analyzed based on different distance bands whereas a split between international and national transport is applied for air, rail, and sea transport. Determination of transport energy demand and transport activity demand is key in estimating the energy efficiency potentials for the EU-28 transport sector. 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 [5].

As detailed in Appendix A of the report on sEEnergies Deliverable 2.1 [2], 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 for retrieving the tonnage (or number of passengers) traveling between the different ports (or 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 traveled 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 the ICAO's guidelines [6]. 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 Distance Between Ports [7] 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 [8] to increment the number of port pairs for which information was available. On the other hand, the Eurogeographic Dataset EuroGlobal Map [9] was utilized for retrieving the most transited ferry routes in Europe, which were further processed for calculating the distances between the connected ports.

The energy efficiency of all vehicles used in the analysis follows the methodology introduced in the Danish transport system model "Alternative Drivmidler" (AD) [10]. 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 tank to wheel efficiencies for different modes of transport are presented in Appendix 6.1.

The energy efficiency here 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 forwarding 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 ICE vehicles, due to the added weight of the battery pack.

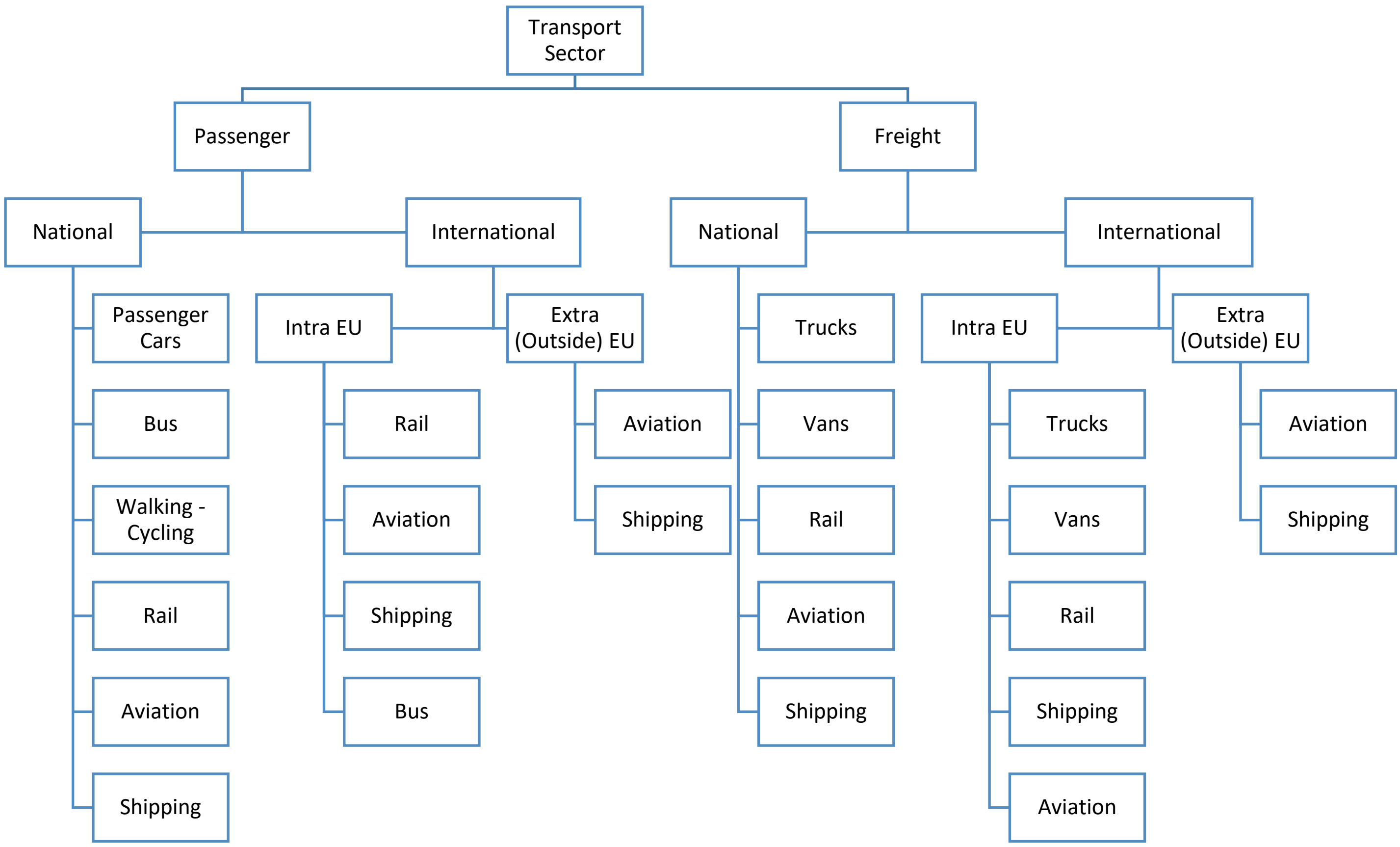


Figure 1: Modes of transport analyzed in TransportPLAN

Figure 2 describes the methodology followed for creating a reference model and baseline scenario in TransportPLAN. The data inputs include different transport demand data, transport system cost data, future annual growth rates, and transport technology efficiencies.

The future annual growth rates and transport technology shares in the reference model and the baseline scenario are obtained from the Clean Planet for All report [3]. The transport technology efficiencies and the cost of road vehicles and charging stations are found in the Danish Energy Agency's transport model [10]. The transport system infrastructure cost for road and rail infrastructure is calculated for each country based on historic infrastructure investment and maintenance cost. [11]

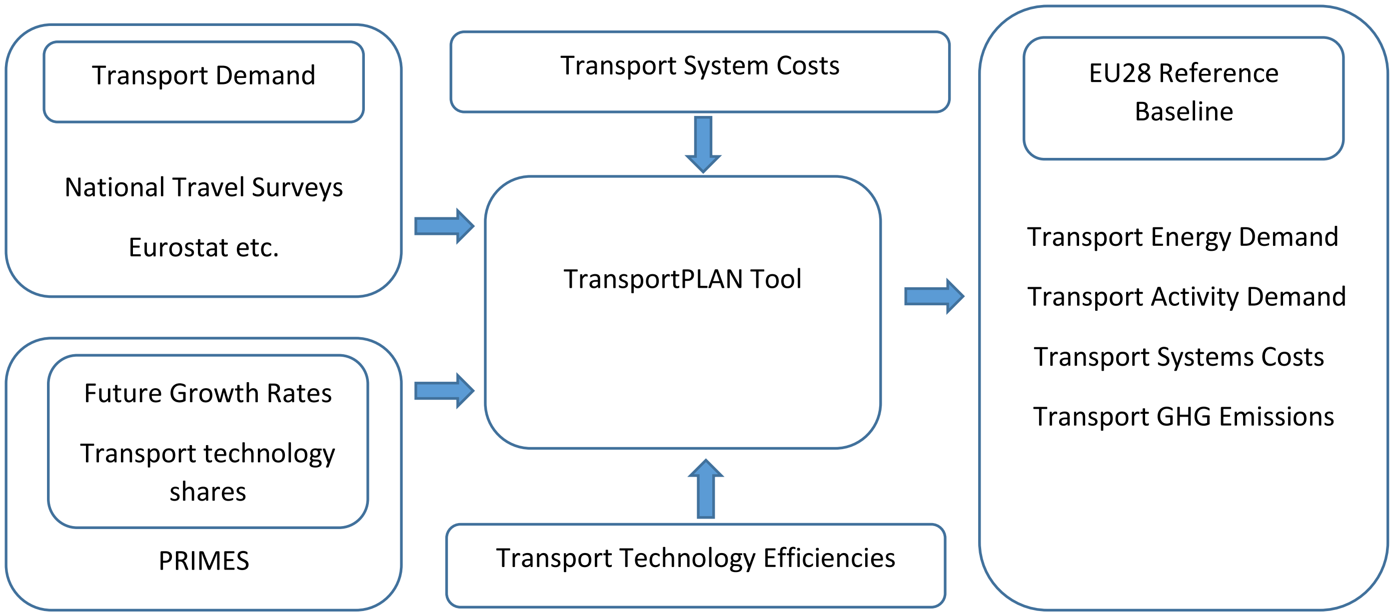


Figure 2 Methodology followed for creating a EU 28 transport baseline

2.2 Scenarios

In this report, different 100% renewable energy scenarios were developed to give an overview of how a sustainable European transport sector could look like. This section describes the methodology followed in the sEEnergies project for creating smart transport energy scenarios. The methodology used to make these smart scenarios follows a two-pronged approach.

The first step builds upon the previous work performed in the Deliverable 2.1 report [2] which identifies different energy efficiency potentials in the four regions of Europe by taking into account societal development factors such as urban spatial development, infrastructure development, and road pricing initiatives. These factors help us make careful estimates on alternate growth rates and modal shift rates based on best practices that would lead to a more energy-efficient development of the transport sector.

Once these alternate growth rates and modal shift rates are calculated, we can combine them with different sustainable transport technology developments, transport systems costs, and transport systems efficiency improvement potentials which give us our desired 100 % renewable smart transport energy scenarios. This methodology is illustrated in Figure 3.

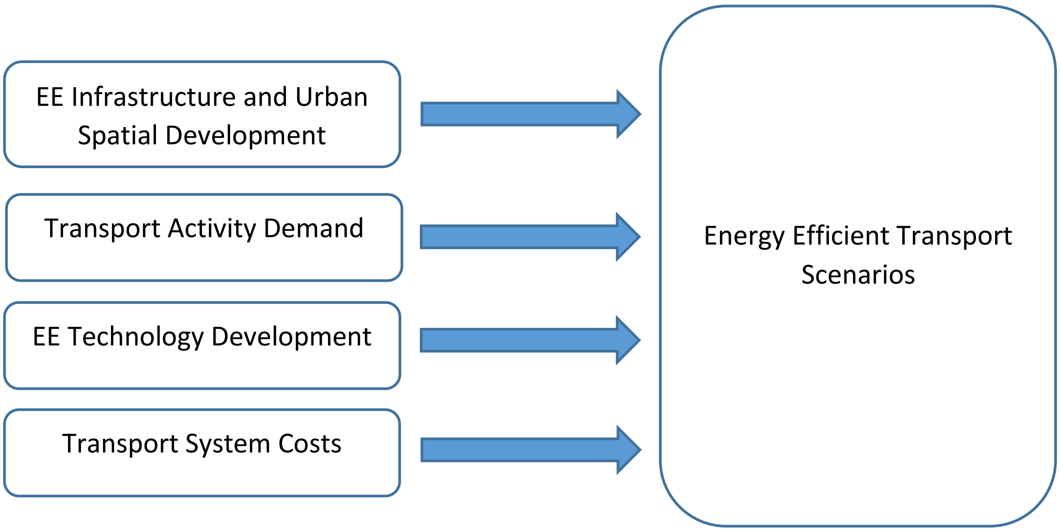


Figure 3: Methodology followed for creating energy efficiency transport scenarios

2.2.1 Energy-Efficient Infrastructure and Urban Spatial Development

The following sub-section describes the calculations performed on the results of the sEEnergies Deliverable 2.1 [2] for determining alternate growth and modal shift rates.

Based on data from various sources (see Deliverable D2.1 for relevant references) combined with the calculations for the D2.1 deliverable, reductions in annual intra-metropolitan travel distances in total and by car, respectively, due to the urban spatial development presupposed in the energy efficiency scenario have been calculated. The percentages of reduction in total intra-metropolitan travel distances and modal shares of car attributable to the urban spatial development have also been calculated. The main issues dealt with are the urban spatial development and the transport infrastructure development, supplemented with the instruments of road pricing, parking fees, and flight taxes.

The quest has been to find relations between measures and effects that are well documented in the scientific literature. A very thorough literature review has revealed that very few relations have been quantified in the literature in a way satisfactory for the sEEnergies project. Concerning urban spatial development the relationship between this development and energy use for transport have been described convincingly with two parameters concerning intra-urban travel purposes and at the same time compatible with the available data sets of the sEEnergies project:

- The effect on average distance driven in automobiles in relation to the distance from the residence to the city center of the main city of the metropolitan area.
- The effect on energy use for transport per capita of the density of the urban area.

The distance to center and density are not independent parameters. It is also quite evident that they both affect the reduction of transport demand (fewer kilometers are driven) and in a modal split: with a shorter distance to the city center of the main city of the metropolitan area the transport demand is reduced and the modal split changes to the favor of public transport and soft mobility. The density makes public transport more efficient, and the shorter distances favor soft mobility. Intra-urban transport is decisive for the everyday life of people.

In the D2.1 report [2], it was assumed, based on energy data from Nordic studies in the 1990s, that 71% of the energy used in 2020 for intra-metropolitan transportation was gasoline, which we assumed was all used for car travel, whereas about 5% was electricity and the remaining 24% auto diesel. It is assumed that the two latter energy carriers, amounting to 29% together, were used for travel by transit and freight. There is not enough information on how large a percentage freight makes up of the intra-metropolitan transportation energy use. On an OECD Europe scale, freight makes up about one fourth and travel about three-fourths of the energy used for surface transportation [12], but it is reasonable to assume that the share of freight is considerably lower for intra-metropolitan transportation than at a national or European scale. It is therefore assumed that freight accounts for 10% of the energy used for intra-metropolitan transportation and that the remaining 90% is used for passenger transport (including travel by car, transit as well as other modes).

In the studies of three Nordic cities where data allowing decomposition of effects of the built environment (in this case residential location) on energy use (in this case represented by car-driving distance) were available, 62 – 70 percent of the energy-saving from the favorable residential location was due to shorter weekly traveling distances and 30-38 percent due to a lower proportion of travel distance carried out by car [2].

However, for other aspects of urban spatial development, the part of the energy-saving effect via a changed modal split may be higher. This is particularly the case for workplace location, where the energy-saving effect of a central workplace location stems mostly from a lower share of car commuting and only to a moderate degree from shorter commuting distances. Because of this, and because of the generally high uncertainty and lack of empirical data on the matter, it has been cautiously chosen to estimate that shorter traveling distances and reduced share of car travel account for one half each of the energy saved from energy-efficient urban spatial development.

Based on these considerations, our calculations concerning the effects of urban spatial development show the following results, relating to the four corners of Europe Table *1*.

Table 1: Decomposition of energy saving from energy-efficient urban spatial development into reduced travel distances and reduced shares of travel by car

	Northern Europe	Western & Central Europe	Southern Europe	Eastern Europe	Whole EU/EFTA area[2]
Annual transportation energy saving (PJ) from urban densification and concentrated residential location	27	150	84	48	308
Annual energy savings from lower car share (PJ)	13	75	42	24	154
Annual energy savings from reduced travel distances (PJ)	13	75	42	24	154
Million pkm of car travel annually replaced by other modes	7200	40800	22900	13000	83800
Million pkm annually reduced (regardless of mode)	7500	42500	23800	13500	87300
Percentage points reduced modal share of cars	1.77 %	1.09 %	1.39 %	1.39 %	1.25 %
Percent reduction in overall intra-metropolitan travel distance	1.84 %	1.14 %	1.45 %	1.45 %	1.30 %
Reduced modal share[3] of cars, percent of present share	2.33 %	1.44 %	1.84 %	1.84 %	1.65 %

Another key important difference between energy efficiency and business as usual scenario is transport infrastructure development. In the business as usual scenario, highway capacity increases according to the TEN-T + other motorway construction. There is scientific evidence showing that this will increase road transport by induced traffic. In the energy efficiency scenario, no such infrastructure development is envisaged. This will not only alter the modal split but also reduce the transport demand. Similar assumptions have been made regarding abstinence from motorway construction and economic instruments targeting surface transportation as for urban spatial development, i.e. that half of the energy savings occurs via reduced travel distances and the other half via a reduced modal share of car travel. The results of these calculations are shown in Table 2 and Table 3.

[2] *The results from Deliverable 2.1 are calculated for EFTA area and are approximated to be equal to EU 28 in Deliverable 2.3, this does not imply a signifacnt change in the results in Section 3*

[3] *Measured as proportion of travel distance, not as proportion of the number of trips*

Table 2: Decomposition of energy saving due to abstaining from motorway construction into reduced travel distances and reduced shares of travel by car

	Whole EU/EFTA area
Annual transportation energy saving (PJ) from abstaining from motorway construction	1057
Annual energy savings from lower car share (PJ)	528
Annual energy savings from reduced travel distances (PJ)	528
Million pkm of car travel annually replaced by other modes	287100
Million pkm annually reduced (regardless of mode)	299100
Percentage points reduced modal share of cars	4.37 %
Percent reduction in overall travel distance of road traffic	4.55 %
The reduced modal share of cars, percent of present share	5.27 %

Table 3: Decomposition of energy saving due to economic instruments targeting surface transport into reduced travel distances and reduced shares of travel by car

	Whole EU/EFTA area
Annual transportation energy saving (PJ) due to economic instruments targeting surface transport	537
Annual energy savings from lower car share (PJ)	268
Annual energy savings from reduced travel distances (PJ)	268
Million pkm of car travel annually replaced by other modes	145800
Million pkm annually reduced (regardless of mode)	151900
Percentage points reduced modal share of cars	2.27 %
Percent reduction in overall travel distance of road traffic	2.36 %
The reduced modal share of cars, percent of present share	2.73 %

It is important to note that several economic instruments, targeting surface transport, like parking fees and several types of road pricing are closely related to dense cities.

For air travel, it is assumed that half of the reduction in travel distance by airplane is replaced by national and international train travel and that the other half of the reduced air travel results in trips not being made or distances closer to the origin being chosen. This means that the overall reduction in travel distance due to economic instruments targeting air transport and abstaining from airport expansions will be half of the reduction in air travel distance.

Table 4: Decomposition of energy saving due to economic instruments targeting air transport and abstaining from airport expansions into reduced travel distances by plane and reduced overall travel distances

	Whole EU/EFTA area
Annual transportation energy saving (PJ) due to economic instruments targeting surface transport	1333
Million pkm of reduced air travel (intra-EU/EFTA)	789700
Million pkm of increased train travel (intra-EU/EFTA)	394900
Million pkm of reduced overall travel distance (for airplane and train combined, intra-EU/EFTA)	394900

Peak Car Phenomenon

Based on the calculations performed in the previous sections, reduced annual growth rates and modal shift rates were calculated to be implemented in TransportPLAN to make future scenarios. In the process of implementation of these growth rates for road transport, the phenomenon of peak cars was taken into consideration. Peak car is a phrase linked to the observation of slower rates of growth, leveling off, or reduction in various measures of car use. This observation has been done in many, but not all, developed countries. The peak car discussion is contrasting the former idea that car use would grow with the growth of GDP – with the assumption that people would replace slower forms of transport with transport by car when they could afford it. According to some studies such as [13] we have reached the fourth era of travel in which the average per-capita growth of 'daily travel' has ceased. As shown in Figure 4, the per capita vehicle travel grew rapidly between 1970 and 1990, but has since leveled off in most OECD countries, and is much lower in European countries than in the US [14].

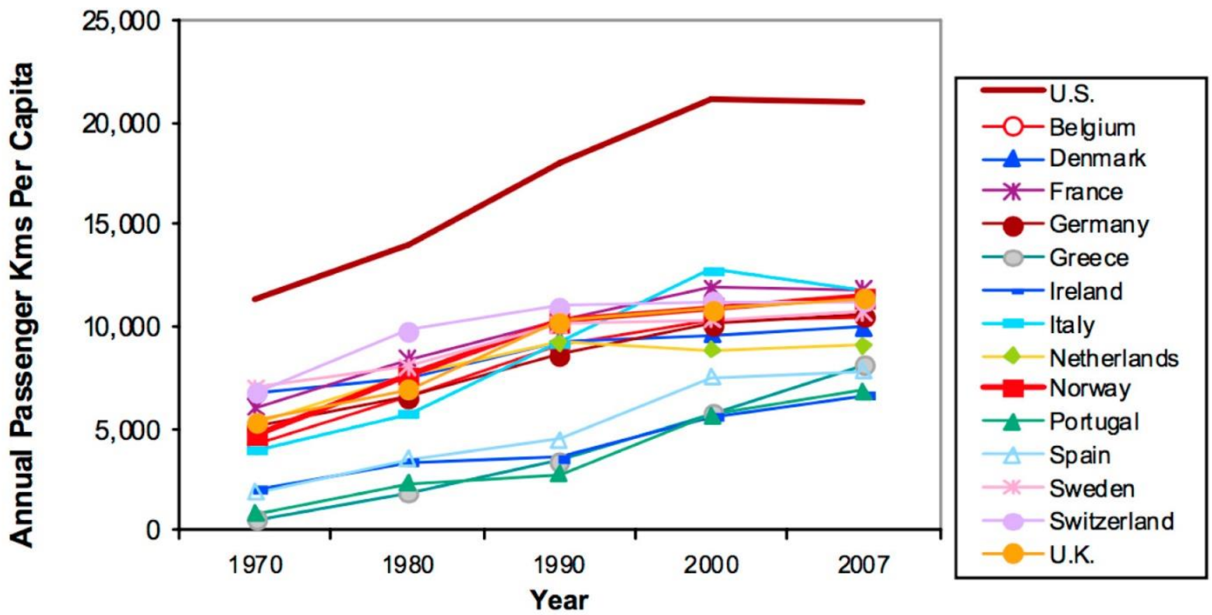


Figure 4 Evolution of car travel per capita in OECD countries [14]

One of the driving forces in the decrease of the share of car-based transport is the fact that young people are less likely to have a driver's license and to travel exclusively by car than the previous generation. The decline in the number of young people with a driver's license can be used as an indicator of a coming peak car situation [15]. This is partly due to the increasing cosmopolitan globetrotting culture popular among young adults that are increasing replacing holiday car travel with flights to exotic international destinations. This is not taking into account the effects of Covid-19 on reduction in air travel and transport demand in 2020.

There is not much data aviable on part of Eastern Europe. Private cars have become more common after the fall of The Wall in 1989. It can be assumed that the private car still is a symbol of freedom in Eastern Europe and the peak car situation will occur later here than in the rest of Europe. This will mirror the situation in the global South where car peak will be expected to occur later [16].

This has been implemented in "TransportPLAN" by assuming different peak car periods for the four regions of Europe. As shown in Figure 5, it is assumed that cars will peak later in Eastern Europe than in Northern, Southern, West, and Central Europe.

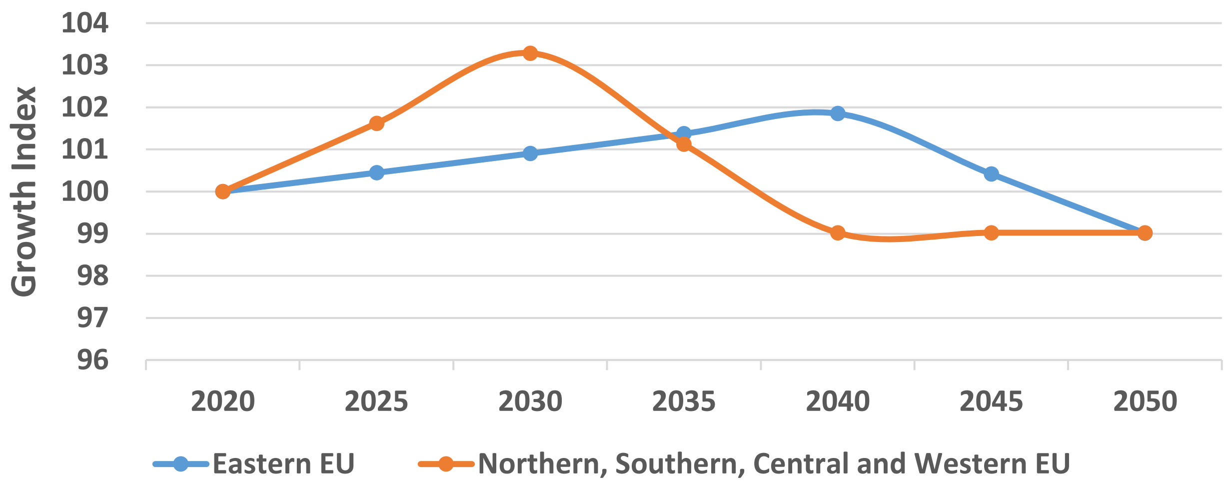


Figure 5: Passenger car evolution for four regions of Europe

As shown in Figure 5 it is estimated that car travel would peak by 2040 in Eastern Europe whereas the same would happen much earlier in 2030 in the other three regions.

Figure 6 shows the aggregated EU level traditional (reference baseline) passenger car travel demand development compared with the development when the energy-efficient practices of urban spatial development, infrastructure development, etc. as mentioned in section 2.2.2 are implemented.

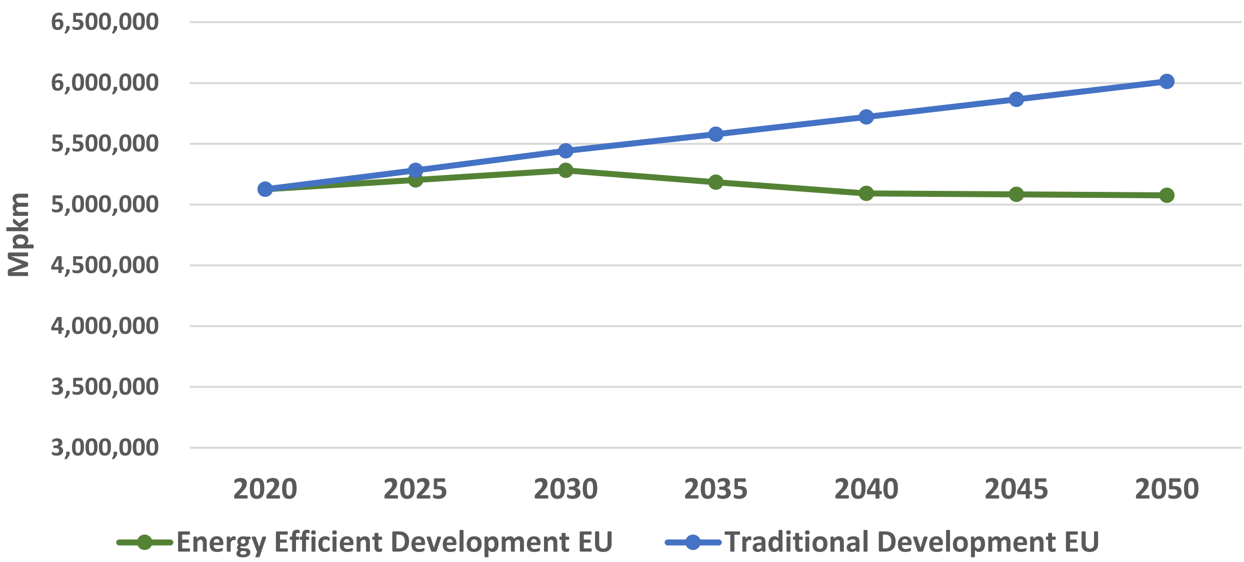


Figure 6: EU passenger car evolution with and without energy-efficient development

2.2.2 Energy-Efficient Technology Development

To quantify the effects that propagation of different technology initiatives might have in the transport sector, mainly in terms of final energy demand and total transport systems costs, many different energy efficient technology transport scenarios were analyzed. These different transport technology scenarios are dominated by one technology and coupled with the lower growth rates and modal shifts as compared to the baseline, based on the analysis performed in section 2.2.1. The scenarios are designed to reach zero emissions at tailpipe in 2050, hence no fossil fuels are consumed. All the scenarios are built on top of the Baseline scenario, so all zero-emissions transport technologies already implemented in the Baseline scenario will not be replaced.

Table 5 gives an overview of the final transport technology share in 2050 for different energy efficient technology scenarios and the baseline scenario. The 1.5 TECH scenario as stated in the Clean Planet for All report [3] has also been replicated for comparison.

Table 5: The share of different transport technologies in 2050 in the analyzed scenarios

	Baseline	Biofuels	Hydrogen (H2)	Electrification and e-fuels	Electrification +	1.5 TECH
Passenger Transport						
Passenger Cars	35% BEV 19% PHEV 4% FCEV 4% Gaseous 18% Gasoline 20% Diesel	35% BEV 40% Biodiesel 25% Bioethanol	35% BEV 65% FCEV	95 % BEV 5% Electrofuels	95 % BEV 5% Electrofuels	80% BEV 15 % FCEV 2% PHEV 1% Diesel 1% Gasoline 1% Gaseous
Buses	5% BEV 36% Hybrid 21% Gaseous 38% Diesel	5% BEV 95% Biodiesel	5% BEV 95% FCEV	100% BEV	100 % BEV	5% BEV 25% Hybrid 5% FCEV 65% Biodiesel
Rail	87 % Electric, 13 % Diesel	87% Electric 13% Biofuels	87% Electric 13% Hydrogen	100% Electric	100% Electric	95% Electric 5% Diesel
Aviation	3% bio-jetfuel 97% kerosene jetfuel	100% Bio-jetfuels	50% Bio-jetfuels 50% Hydrogen	19% Electric 81% Electrofuels	22% Electric 78% Electrofuels	2% Electric 57% Electrofuels 41% Kerosene jetfuel
Shipping	13% Gaseous 87% Diesel and HFO	100% Biofuels	100% Ammonia	50% Electric 35% Electrofuels 15% Ammonia	50% Electric 35% Electrofuels 15% Ammonia	37% Biofuels 13% Ammonia 50% Diesel and HFO
Freight Transport						
Trucks	1% BEV 29% Hybrid 18% Gaseous 51% Diesel	1% BEV 49,5% Biogas 49,5% Biodiesel	1% BEV 99% FCEV	27% BEV 73% Electrofuels	27% BEV 73% ERS-BEV	8% BEV 6& FCEV 20% Hybrid 34% Gaseous 32% Diesel
Vans	26% BEV 1% FCEV 19% PHEV 54% Diesel	26% BEV 38% Biodiesel 36% Biogas	26% BEV 74% FCEV	95% BEV 5% Electrofuels	100% BEV	79% BEV 13% FCEV 3% PHEV 5% Diesel
Rail	87 % Electric, 13 % Diesel	87% Electric 13% Biofuels	87% Electric 13% Hydrogen	100% Electric	100% Electric	90% Electric 10% Diesel
Aviation	100 % Kerosene jetfuel	100% Bio-jetfuels	50% Bio-jetfuels 50% Hydrogen	100% Electrofuels	100% Electrofuels	2% Electric 57% Electrofuels 41% Kerosene jetfuel
Shipping	100 % Diesel and HFO	100% Biofuels	100% Ammonia	100% Electrofuels	100% Electrofuels	37% Biofuels 13% Ammonia 50% Diesel and HFO

The energy efficient technology scenarios presented in Table 5 are analyzed in the context of both traditional urban development and energy efficient urban development. The main synthesis behind the energy efficient urban development is already described in Section 2.2.1 and is illustrated in the following Figure.

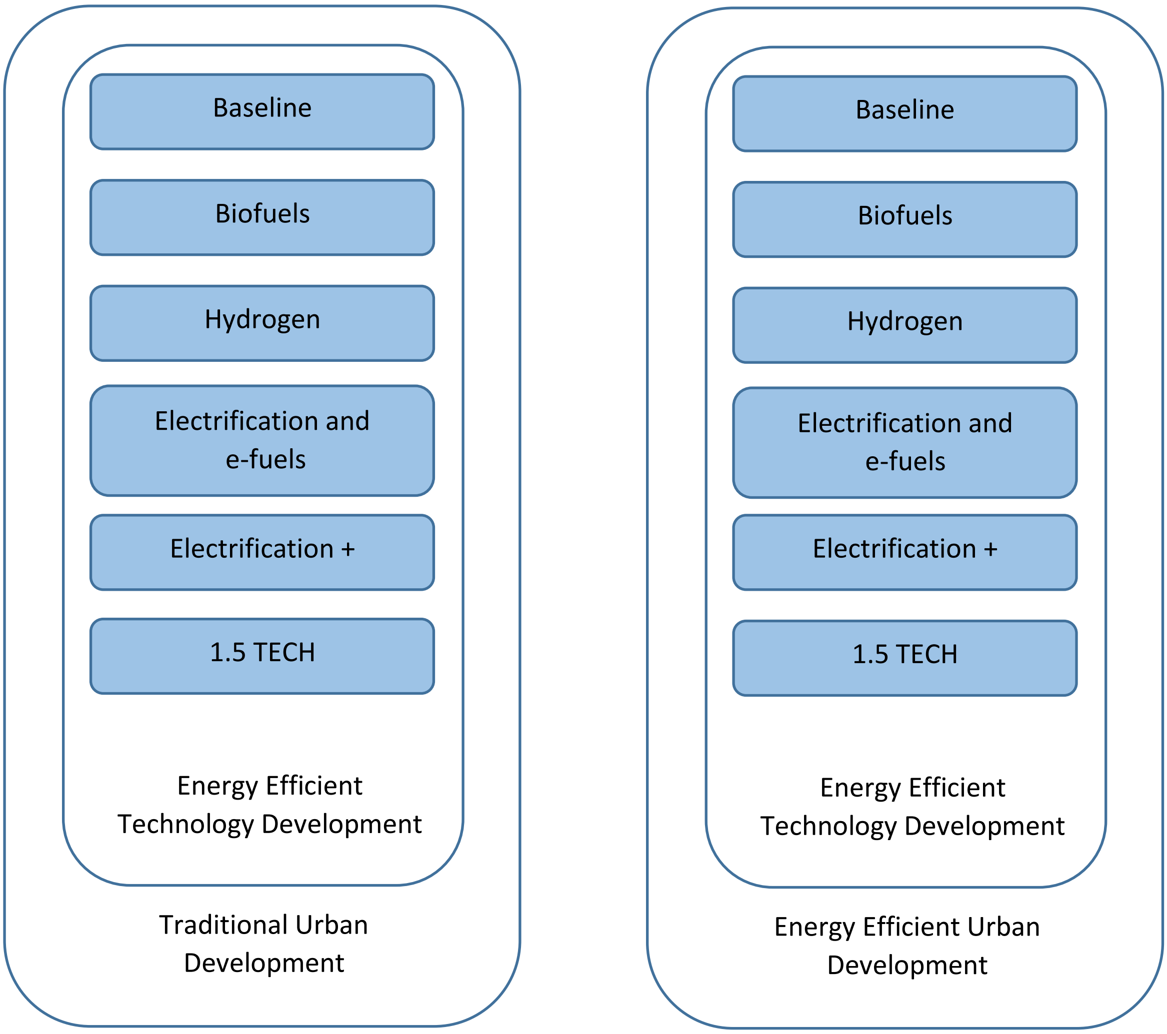


Figure 7: Transport Scenario Outline for 2050

In the Biofuels scenario, all remaining petrol and diesel for road transport and rail are assumed to be replaced by biodiesel and bioethanol. For aviation and shipping, fossil fuels are replaced by bio-based electrofuels. The biofuel production pathways and the bioenergy resource needed to produce the biofuels will not be investigated further in this deliverable.

In the Hydrogen scenario, all fossil fuels left in the road transport sector from the Baseline scenario are replaced with hydrogen in fuel cell electric vehicles (FCEV). It is assumed that FCEVs are a reliable option to replace all long-haul trucking transport. For aviation, all national transport is converted to hydrogen along with 45% of the intra-EU air transport. All shipping, both for passenger and freight transport is converted to ammonia.

In the Electrification and e-fuels scenario, the electrification of road transport is intensified. 95% of all passenger cars, buses, and vans in the EU-28 are converted to BEVs. For the remaining road transport, primarily freight, it is estimated that it is possible to convert all transport demand of trips under 150 km to electricity. That corresponds to 41% of all national road freight transport and 27% of the total transport demand for trucks. The remaining transport demand is covered with electrofuels in internal combustion engines. It is assumed that it is possible to electrify all national air transport by 2050. The average flying distance for national air transport in the EU28 is 450 km. The average flying distance between countries within the EU28 is 1350 km. In the Electrification and e-fuels scenario, it is assumed that 25% of the intra-EU air transport is electrified.

In the Electrification + scenario, the electrification of road transport is intensified even further than in the Electrification and e-fuels scenario. Like the Electrification and e-fuels scenario, 95% of all passenger cars, buses, and vans in the EU28 are converted to BEVs. The largest difference is seen in road freight transport, where 27% is converted to BEV, while the remaining 73% are converted to BEVs with smaller onboard batteries with on-road charging support from Electric Road Systems (ERS).

ERS is becoming increasingly interesting for road freight transport. As the current energy density and lifetime of batteries remain relatively unsuited for freight transport because of long-distance travel and heavy goods that need to be transported, different innovative solutions with mature technical developments are taking the lead for electrification of heavy-duty freight transport.

Extensive implementation of a trans-European network of ERS is assumed to take place from 2025 and onwards, to support the transition of heavy-duty road transport towards electricitication. Sweden has already announced its ambious targets of implementing 3000 km of ERS infrastructure by 2035 and many others are expected to follow suit.

Further, it is assumed that it is possible to electrify all national air transport, while 35% of intra-EU aviation is estimated to be electrified by 2050. 50% of national passenger transport by sea is electrified in 2050, while the remaining transport demand for passenger and freight transport are converted to electrofuels and ammonia.

In following paragraphs, the methodology behind the implementation of ERS is elaborated in further detail.

Implementation of ERS

One important element taken into consideration in this report is the implementation of ERS for the Heavy electrification scenario listed in Table 5.

The following text describes the data and methods followed in this deliverable for calculating the length of ERS for different parts of Europe.

Data and Methods

This description aims to assess the potential for ERS, as a solution to electrify trucks used for freight. The concept of ERS is well-described in [17], where the purpose is to use electricity directly from the electricity grid in the trucks rather than relying on batteries for the full journey. The trucks are EVs and include batteries, but can only drive around 100 km on battery. By establishing ERS between the main cities, where the trucks can use electricity directly and charge the batteries, the trucks only need a battery large enough to reach the roads with ERS, instead of the full distance, significantly reducing battery sizes and enables larger electrification of trucks, than what would otherwise be possible. In this description, the main purpose is to identify different potentials for establishing ERS on an EU-28 scale, by identifying the length of routes (km) and coverage potential (percentage of urban population). This coverage potential refers to the percentage of urban population that lie within a specified buffer distance i.e (25 km, 50 km, 75 km etc.). For this analysis, a buffer distance of 50 km was assumed as done by a previous study for Denmark [17].

Due to the large geographic coverage of the analysis, the methodology applied, is rather basic, as going into a detailed analysis of transport work on an EU scale, would be rather time-consuming. The basic analysis could be seen as a first attempt to estimate ERS routes on an EU-28 scale, which in the future should be supported by more in-depth local analyses, e.g. on the country level. That being said, in the analysis five different scenarios are analyzed:

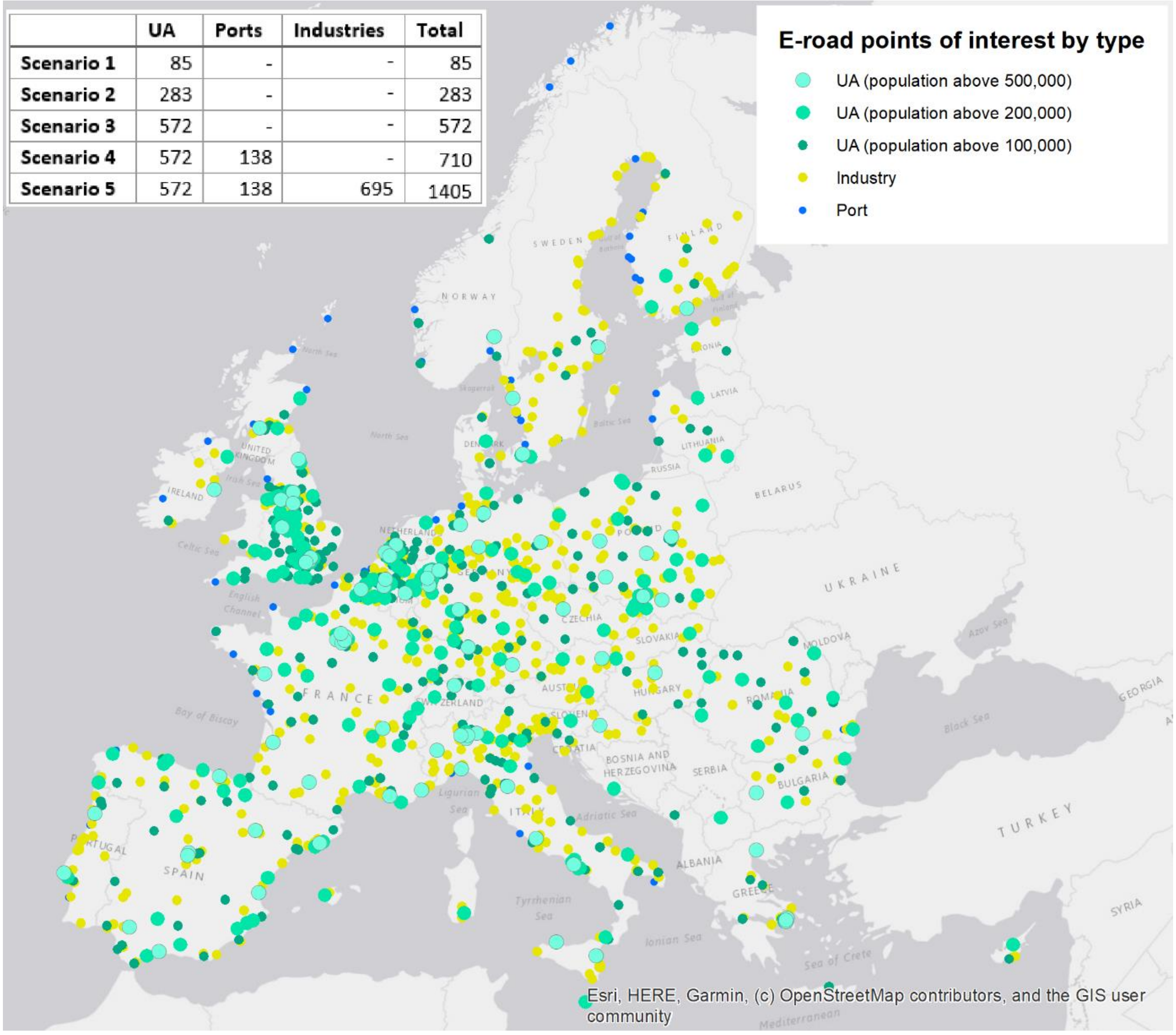
Scenario 1 (s1): Connecting cities above 500,000 inhabitants
Scenario 2 (s2): Connecting cities above 200,000 inhabitants
Scenario 3 (s3): Connecting cities above 100,000 inhabitants
Scenario 4 (s4): Connecting cities above 100,000 inhabitants and large ports
Scenario 5 (s5): Connecting cities above 100,000 inhabitants, large ports, and large industries

The first scenario is expected to have the smallest network of ERS, but also the lowest coverage of the population. By increasing the points of interest (number of cities, ports, and industries), the length of ERS and coverage potential is expected to increase as well. Finally, by having the length of the network, the investment costs in ERS infrastructure can be estimated, which can help to determine the economic feasibility of implementing the different scenarios.

As a point of departure, five datasets have been used in the analysis:

1. Road network from OpenStreetMap (OSM) [18]
2. Urban areas from D5.2 [19]
3. Industrial sites from D5.1 [20]
4. Ports from [21]
5. Country maps [22]

Figure 8 shows a map of the points of interest for each of the five scenarios by type. Furthermore, it includes the total number of points that are included in each scenario.



	UA	Ports	Industries	Total
Scenario 1	85	-	-	85
Scenario 2	283	-	-	283
Scenario 3	572	-	-	572
Scenario 4	572	138	-	710
Scenario 5	572	138	695	1405

Figure 8: Points of interest divided by type for the five scenarios. The map includes a table showing the total number of points used in each scenario [4]

The analysis was performed in ESRI's ArcMap 10.7.1 software, using various functions and creating a tailored model to assess the ERS potential.

The method developed uses the following steps:

1. A network dataset from the road network from OSM was created. In this report, the classes motorway, primary, secondary and tertiary roads were used. When making a network dataset, it is important to include enough roads to ensure connectivity in the network. Furthermore, an impedance was added to each type to make sure that motorways were always the highest priority. The following impedances were used: 1 for motorways, 10 for primary roads, and 20 for all other roads.

[4] *Even though the map shows point of interests for countries outside EU 28, only EU 28 countries have been considered in the analysis and for the final energy and transport demands in Section 3*

2. The network analyst function “Make Closest Facility Layer” was used to find the routes between the points of interest in each scenario. The function finds the route with the least impedance from each incident to the three nearest facilities.
3. All the points from a scenario were loaded as incidents.
4. The points for the 85 largest UA was loaded as facilities.
5. Each route was saved into a combined layer of routes for each scenario.
6. To find the routes without the roads that are within close distance to the points of interest the first and last 5 km of each route was erased in an alternative version of each scenario named s1e, s2e, s3e, s4e, and s5e.
7. The routes for the scenarios were dissolved so that overlapping road segments only were counted once.
8. A straight-line buffer analysis for four different buffer distances (25, 50, 75, and 100 km) was applied to the routes.
9. For each buffer area, the population of the intersecting urban areas was summarised on a national level.

The output datasets for the points, routes, and buffers, resulting from this methodology, can be downloaded in the sEEnergies Open Data Hub [23].

Results

This section presents the results of the ERS analysis. First, the general result for all the scenarios, followed by an illustration for Scenario 2e, which is the main scenario used in TransportPLAN.

Figure 9 shows the total ERS length in km for each alternative (erased) scenario and country. There is a significant increase in ERS length from Scenario 1e-5e, as well as longer ERS length for the large countries, where Germany, France, Spain, United Kingdom, Poland, and Italy are the countries with most km of ERS.

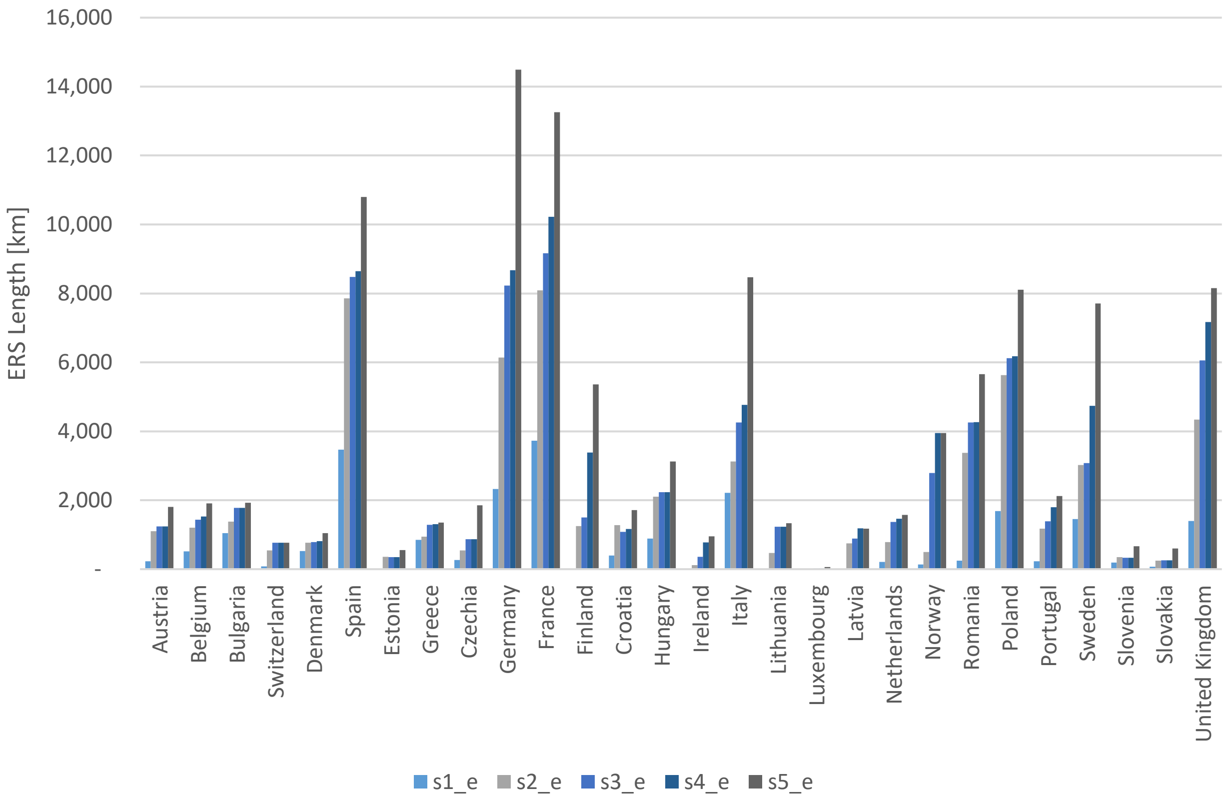


Figure 9: ERS length in each alternative (erased) scenario

Detailed results from the analysis are presented in Appendix B. The results indicate that the coverage potential varies significantly between countries, due to differences in the number of urban areas, ports, and industries the spatial distribution of these, and the layout of the road network in each country. From the main results, it was chosen to use Scenario 2e in TransportPLAN as a compromise between the increased length of e-roods (which obviously incurs increased implementation costs) and coverage potential (percentage of urban area population within a 50 km buffer to ERS). Thus, Figure 10 shows an illustration of the suggested ERS length for Scenario 2e.

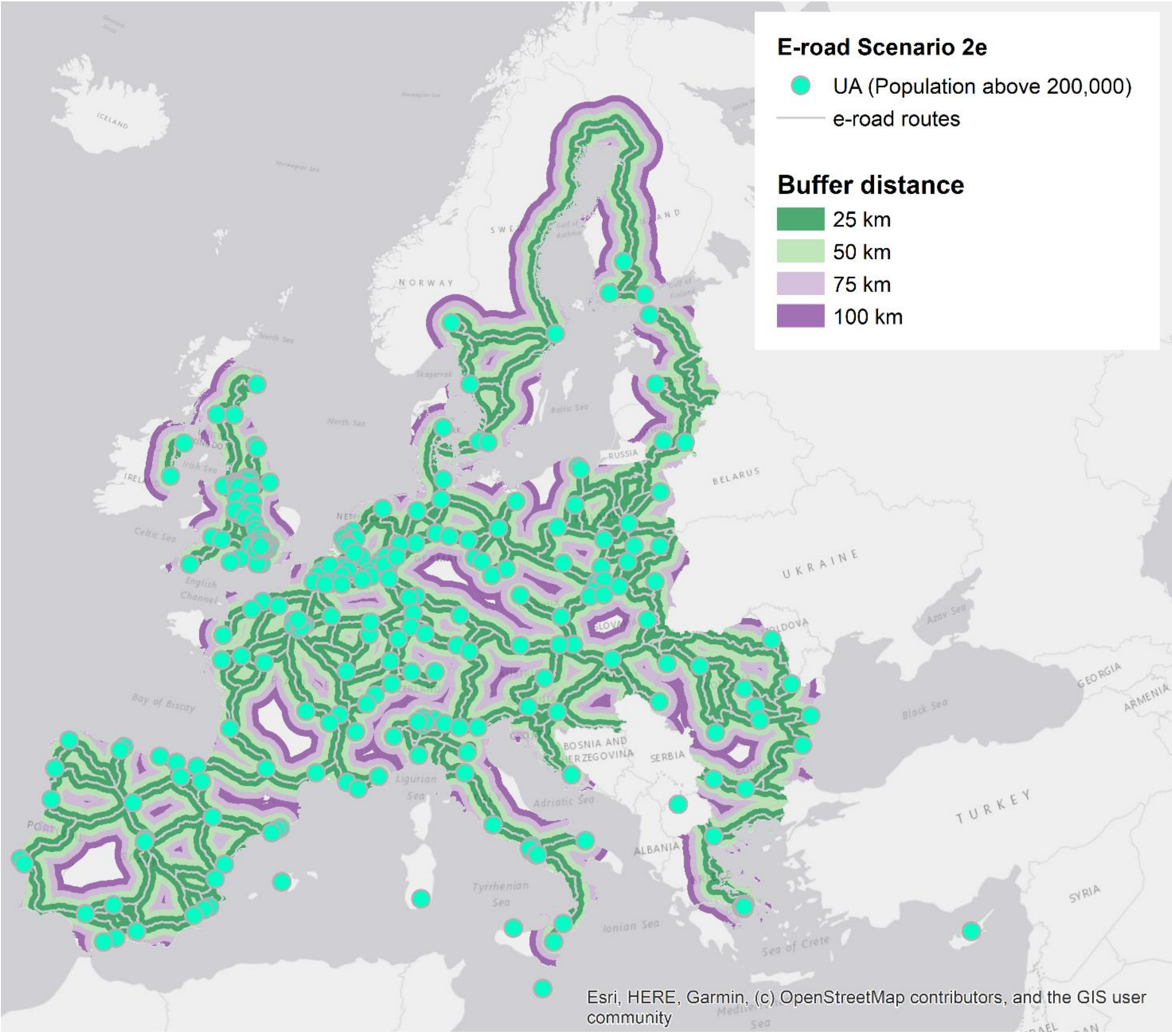


Figure 10: Suggested ERS routes for Scenario 2e (including buffer distances of 25, 50, 75 and 100 km)

2.2.3 TransportPLAN Tool

The scenarios for the transition to a energy-efficient and renewable energy based EU-28 transport system are analyzed in detail in the modeling tool TransportPLAN. TransportPLAN tool is a transport scenario modeling tool, originally developed as a part of the CEESA project [24]. The tool has been further developed during the work on this deliverable. TransportPLAN allows for the user to create detailed transport scenarios with five-year intervals from 2020 to 2050.

For all modes of transport the transport demand, energy demand, share of fuels and technologies, and vehicle and infrastructure costs are found through statistics, models, and publications and make up the foundation of the scenario development.

To develop renewable scenarios towards 2030 and 2050, TransportPLAN allows for adjustment of five parameters:

- Annual growth of transport demand
- Market share of renewable technologies
- Modal shifts
- Annual energy efficiency improvements
- Annual capacity utilization improvement

The parameters enable the user to create alternative scenarios with different forecasts of transport demand, variable rates of implementation of renewable transport technologies, move transport demand between modes of transport, improve the energy efficiency of conventional vehicles and improve the capacity utilization for both passenger and freight transport.

The results from the TransportPLAN scenario tool are the annual transport demand in all modeled years, the energy consumption by mode of transport and type of fuel and the costs associated with vehicles, fuel, and infrastructure.

The transport energy consumption by fuel type allows for a detailed analysis of the fuel consumption and end-use. These outputs are compatible with a range of energy system analysis tools, for further analysis of the results and the impact of the scenarios on the entire energy system.

The analysis performed in this study is constrained by several system boundaries that when considered might affect the results albeit not to a great extent. The transport activity demand set up in the TransportPLAN tool is based on survey data from EU-28 countries and not the EFTA countries. The model is set up on a bottom-up approach where different modes of transport have different categorizations in distance bands. This categorization is not uniformly available in the national travel surveys of the different countries up to such a fine resolution and the available data was approximated to fit the resolution needed for the TransportPLAN tool. The results could be enhanced with the availability of better data in the future.

Regarding system costs, the transport systems costs related to the annual investment and operation and maintenance costs of road vehicles were only considered, because of large deviations and unavailability of reliable references, the vehicle costs data for other modes such as rail, shipping, and aviation is not included in the analysis.

However, the annual fuel cost for all types of vehicles, annualized investment, and maintenance cost related to road and rail infrastructure, as well as the annual cost of expanding the electric vehicle charging infrastructure was included. The distribution network costs for establishing a hydrogen fueling network were not included in the transport systems costs for the hydrogen-based scenarios. As described in Section 2.2.1, a detailed analysis was performed to have an idea of possible modal shifts in the future for passenger transport originating mainly from energy-efficient transport urban spatial and infrastructure development. However, no parallel could be drawn from the analysis to the modal shifts for road freight transport and is not included in the results as part of this deliverable.

3 Results

In this section, the results of the Baseline and energy efficient technology scenarios are presented. The results are presented for both the traditional urban growth scheme and the energy-efficient urban growth scheme presented in section 2. All the scenarios are built on top of the same reference model of the current transport system in the EU28. The reference model is developed to represent the transport demand for the passenger (mpkm) and freight (mtkm) transport in 2017. The 2017 reference model is presented along with the Baseline scenario.

The scenarios are compared by final energy demand, i.e. the energy consumption of the end-user, hence without the consideration of fuel production energy losses. Furthermore, the scenarios will be compared based on the total transport system cost, including cost and maintenance of vehicles, fuel production cost, and cost associated with renewal and development of transport infrastructure.

3.1 Baseline Scenario

The composition of the current state of the transport system in the EU28 in this study is based on travel data from national travel surveys along with transnational European transport statistics. The transport activity is analyzed for passenger and freight transport separately. In the following, the current transport system is presented along with the forecasted development in the Baseline scenario under the two different transport demand development schemes. The development of the Baseline scenario, in terms of implementation of new transport technologies and fuels, in this work is based on the Baseline 2050 scenario from the European Commission. [3]

3.1.1 Passenger Transport

The passenger transport demand in the 2017 reference model is split between transport in personal vehicles, public transport (buses, coaches, and railways), bikes and walking and aviation. The majority of the passenger-kilometers are traveled in personal vehicles, which constitute 72% of the total transport demand. Public transport comprises 14%, while bikes and walking and aviation make up the remaining 4% and 10% respectively. The share of transport demand differs from country to country and a clear pattern emerges, that in Central, West and Northern Europe the vast majority of passenger kilometers are traveled in personal vehicles and a small share in public transport, by walking or cycling or by aviation. In the Southern and Eastern regions, a much larger share of the transport demand is covered by public transport or by walking or cycling. The composition of passenger transport demand split by mode of transport is presented for Poland, Spain, Germany, and Sweden in Figure 11.

The development of passenger transport demand towards 2050 in the traditional urban development scheme sees an overall increase of 28% in total passenger-kilometers for all modes of transport combined. This transport demand in passenger vehicles grows by 20% in the period, public transport grows 34% and transport activity by air grows 84%. No increase is considered for bicycling and walking under the traditional urban growth scheme. The split between modes of transport in terms of transport demand in 2050 is: passenger vehicles 67%, public transport 15%, while bicycle and walking and aviation comprise 3% and 15% respectively.

Under the Energy-efficient urban growth scheme, the development of the passenger transport demand towards 2050 follows a different trajectory. The energy-efficient urban spatial development along with abstaining from motorway construction and economic instruments to reduce shares of travel by car leads to an overall reduction in the transport demand by passenger car towards 2050 of 1%. Meanwhile, the energy-efficient urban spatial development incentives form the basis of significant modal shifts towards public transport and bicycling and walking. The transport activity for bicycle and walking grows by 116% towards 2050, while the passenger-kilometers traveled by public transport increase 108% in the period.

The economic instruments targeting air transport and abstaining from expanding airports amounts to a reduction of 53% in the transport demand for aviation in the period from 2017 to 2050.

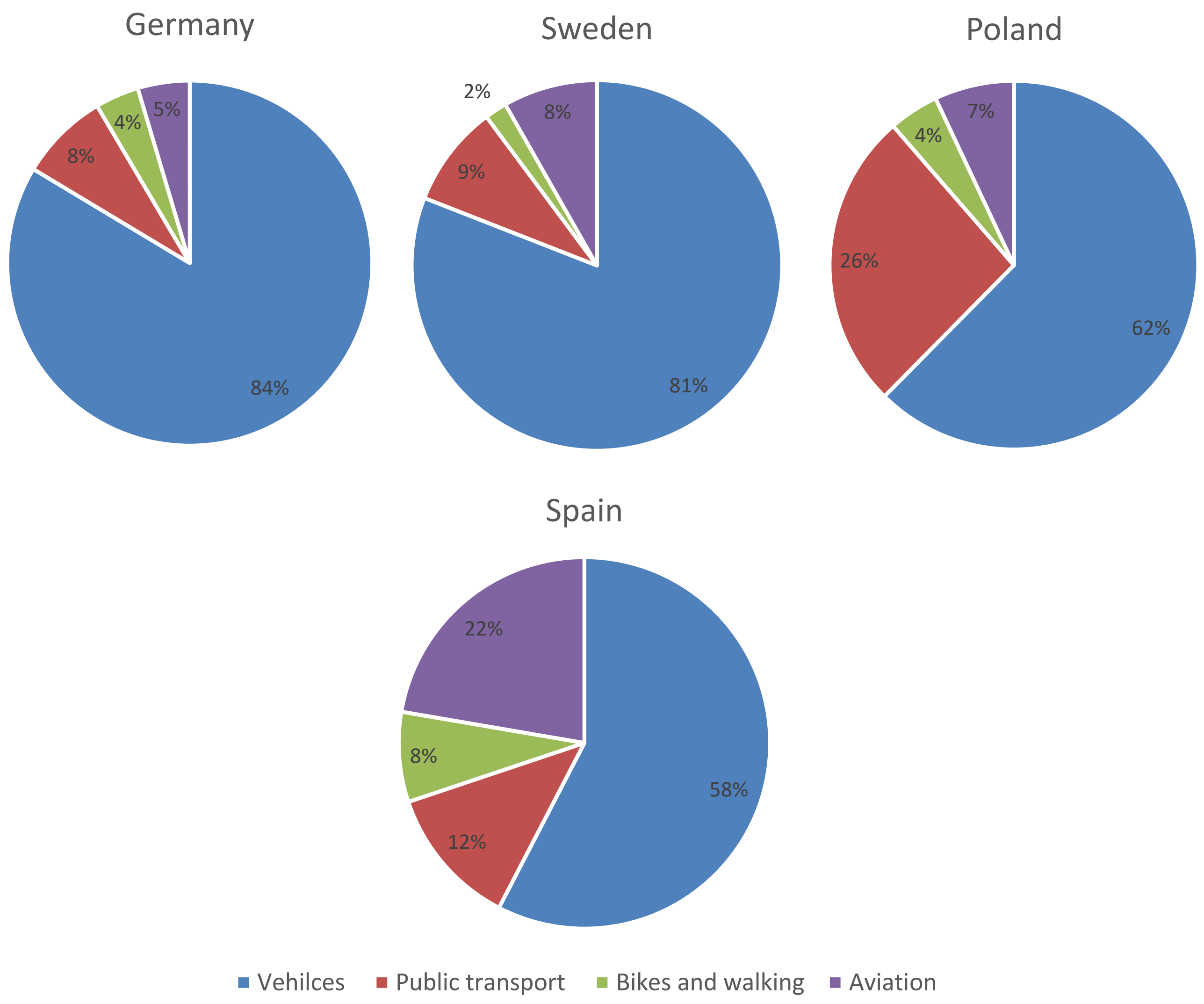


Figure 11: Passenger transport demand (pkm) split by mode of transport in Poland, Spain, Germany and Sweden

In Figure 12, the development of the passenger transport demand under the traditional urban growth scheme and the energy-efficient growth scheme are compared.

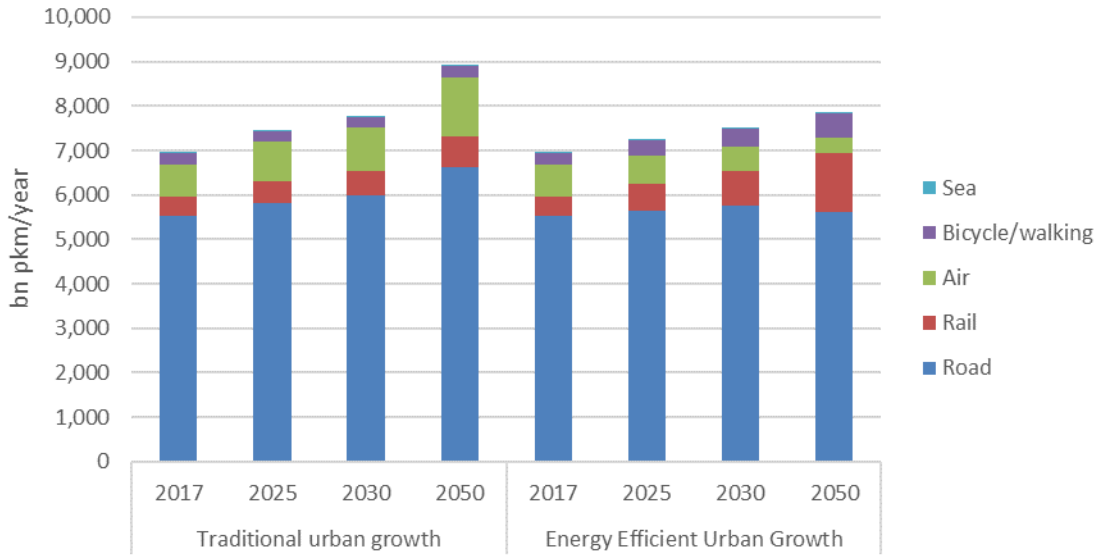


Figure 12: Development of the passenger transport demand (bn pkm) divided by mode of transport in the EU28 from 2017 to 2050 under the traditional urban growth scheme and the energy-efficient urban growth scheme

3.1.2 Freight Transport

The freight transport demand in the 2017 reference model is covered by trucks, vans, railways, aviation, and by sea. The majority of goods are transported by sea-going vessels, hence sea transport is responsible for the majority of the transport demand. Trucks and vans cover 24% of the total ton-kilometers in the EU28. 6% of the freight transport demand are covered by rail, while aviation and sea transport cover the remaining 0,5% and 69,5% respectively.

The modal split differs slightly between different countries in the EU28, depending primarily on the access to freight transport by sea. In all countries, freight transport on road covers the majority of the transport demand.

The development of the freight transport demand in the EU28 is in this work only considered under the traditional urban growth scheme. The incentives briefly described above and outlined in detail in deliverable D2.1 target passenger transport and the reduction of transport in cars and by aviation mainly. The implementations will most likely have an effect on freight transport, but the effects have not been quantified in this work, hence only the development under the traditional urban growth scheme is considered. In Figure 13, the development of the transport demand by the mode of transport is presented. Road freight transport increases by 40% in the period from 2017 to 2050, while freight transport by rail grows by 59%. The transport demand for aviation and sea increases by 84% and 31% respectively.

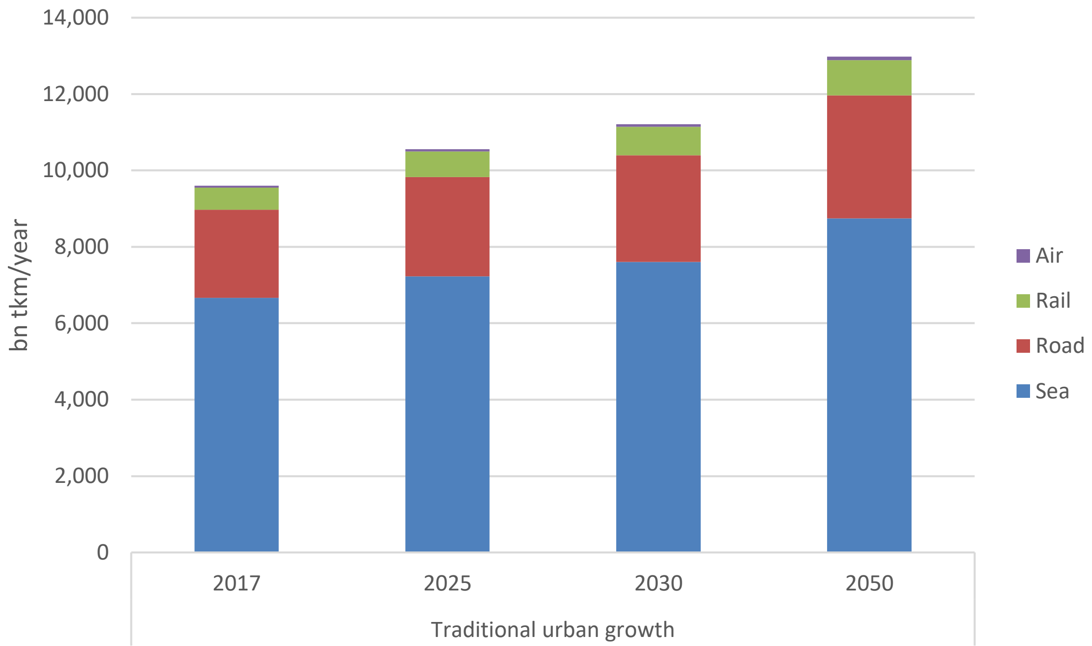


Figure 13: The development of the freight transport demand (bn tkm) in the EU28 under the traditional urban growth scheme

3.1.3 Final Energy Demand

The final energy demand for the transport sector in the EU28 in the 2017 reference model amounts to 17.656 PJ. Diesel-type fuels and petrol cover 75%, while 20% is met with jet fuel. The remaining energy demand is covered with biofuels and electricity. Electricity is primarily consumed by trains and the biofuels are blended with diesel and petrol for road vehicles.

In Figure 14, the development of the final energy demand in the Baseline scenario is presented under the traditional urban growth scheme and the energy-efficient urban growth scheme. The same growth of the transport demand observed in the EU28 under the traditional urban growth scheme is not visible in the final energy demand. Primarily due to the implementation of a large share of electric vehicles in the passenger vehicle fleet, hybrid vehicles in road freight transport, and significant electrification of the EU28 railway network, the final energy demand decreases 19% from 2017 to 2050 under the traditional urban growth scheme. If the energy-efficient urban growth scheme is achieved, the final energy demand decreases 37% in the same period. Under the energy-efficient urban growth scheme, the final energy demand for diesel and petrol for road vehicles decreases slightly, but more noticeable, the final energy demand for jet fuel decreases significantly when restraining from expanding airport infrastructure and implementing economic incentives to reduce air transport.

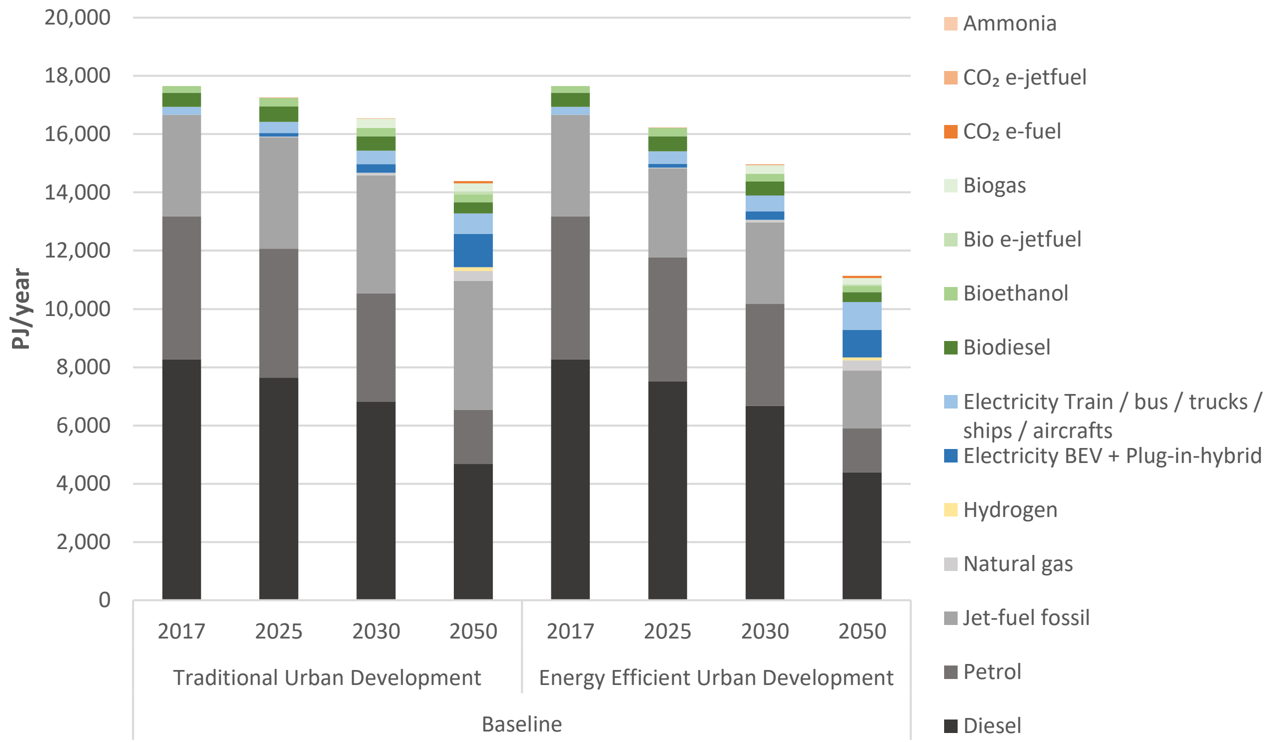


Figure 14: Development of the final energy demand in the Baseline scenario from 2017 to 2050

3.1.4 Transport System Cost

The annual transport system costs comprise the cost of new vehicles and maintenance of existing vehicles, the cost related to road and railway infrastructure, as well as charging infrastructure and fuel cost. The fuel cost and especially the production cost of renewable transport fuels are uncertain, hence three different fuel cost scenarios are investigated. In the following section, the fuel cost refers to the medium fuel cost scenario, and in section 3.3 the impact of the low and high fuel cost scenario is investigated.

The annual transport system cost in the EU28 in the 2017 reference model is 1.281 €bn/year. The cost related to vehicles comprise 68% of the total annual transport system cost, while fuel cost comprises 22%. In Figure 15 the development of the annual transport system cost is outlined for the traditional urban growth scheme and the energy-efficient urban growth scheme. Under the traditional urban growth scheme, the annual transport system cost increases by 19% from 2017 to 2050. Vehicle and fuel costs still comprise the majority of the annual cost in 2050.

If the transport demand growth follows the energy-efficient urban development schemes, the annual transport system cost will remain stable from 2017 to 2050 and an no increase is observed. Less transport in passenger vehicles and a modal shift towards public transport leads to a smaller increase in cost related to vehicles. The lower energy consumption per passenger-kilometer in public transport compared to passenger cars leads to a decreased annual cost of fuel. The increased cost of rail infrastructure is balanced by a decreased cost of new road infrastructure.

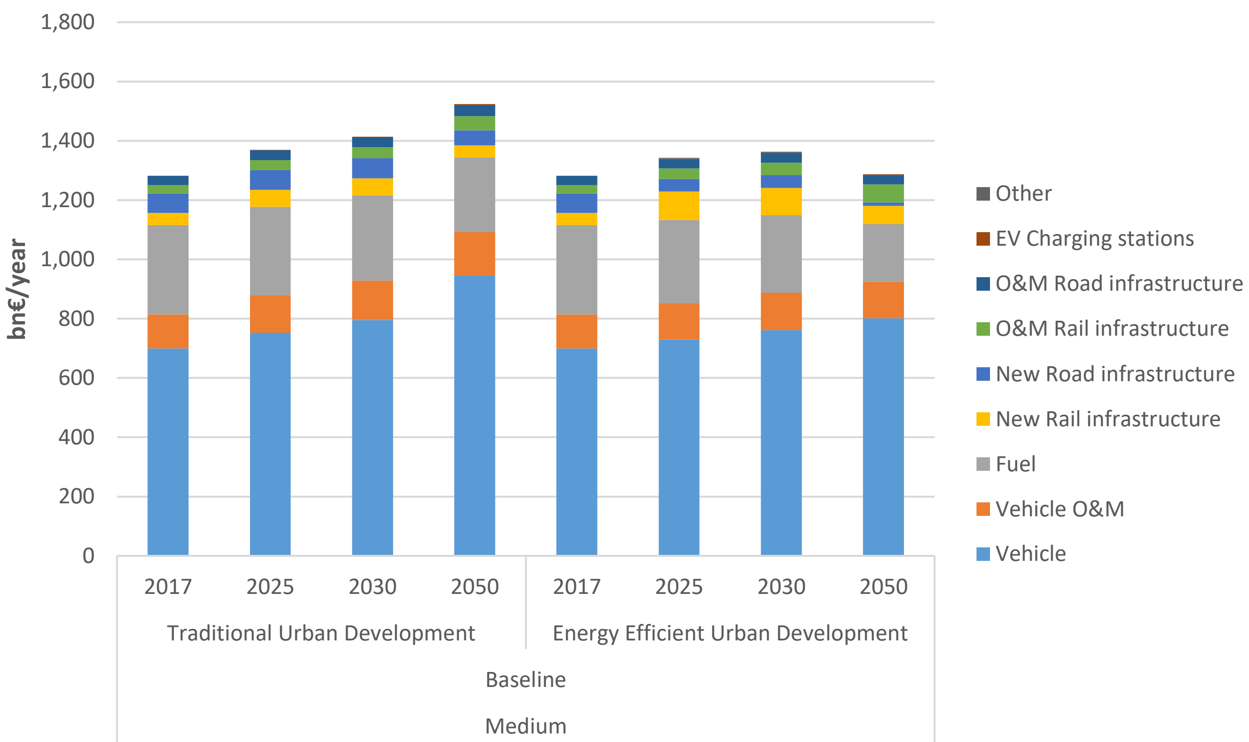


Figure 15: The development of the annual transport system cost in the Baseline scenario under the traditional urban growth scheme and the energy-efficient urban growth scheme from 2017 to 2050. The medium fuel cost scenario is chosen to present the fuel cost in this figure.

3.2 Energy Efficient Technology Scenarios

In the following, the results of the four different energy efficient transport technology scenarios, presented above, are examined, along with the 1.5 TECH scenario from PRIMES. The four transport technology scenarios, all accomplish net-zero emissions in 2050, whereas the 1.5 TECH scenario still contains some fossil fuels.

The scenarios are compared to the baseline in 2050 based on final energy demand and total transport system cost under both the traditional urban growth and the energy-efficient urban growth scheme.

3.2.1 Final Energy Demand

Following the development of the traditional urban growth scheme, all the proposed alternative transport technology scenarios apart from the biofuels scenario, present a significantly reduced annual final energy demand (Figure 16). It is important to note, that the energy consumption presented in the following only represents final energy, hence no upstream conversion losses are accounted for. The production process of renewable hydrogen or electrofuels requires additional energy and involves conversion losses, but in the following results, only the efficiencies and energy losses in the vehicle engine are considered.

In the Biofuels scenario, liquid fossil fuels are replaced by liquid biofuels in internal combustion engines with similar efficiencies, hence no noteworthy difference is observed in the final energy demand. In the Electrification and e-fuels scenario, H2 scenario, and the Electrification+ scenario, internal combustion engines in road transport are replaced by energy-efficient electrical engines and fuel cells. For aviation and sea transport, some of the fossil-fueled aircraft and vessels are replaced by electric or fuel cell options.

The Electrification and e-fuels scenario reduces final energy demand in 2050 by 26% compared to the 2050 Baseline. The H2 scenario reduces the final energy demand by 28% in 2050 compared to the 2050 Baseline and the Electrification+ scenario reduces the final energy demand by 33%. In the 1.5 TECH scenario, which still relies on fossil fuels for some of the heavy-duty road transport, aviation, and sea transport, the final energy demand is reduced 28% compared to the Baseline in 2050.

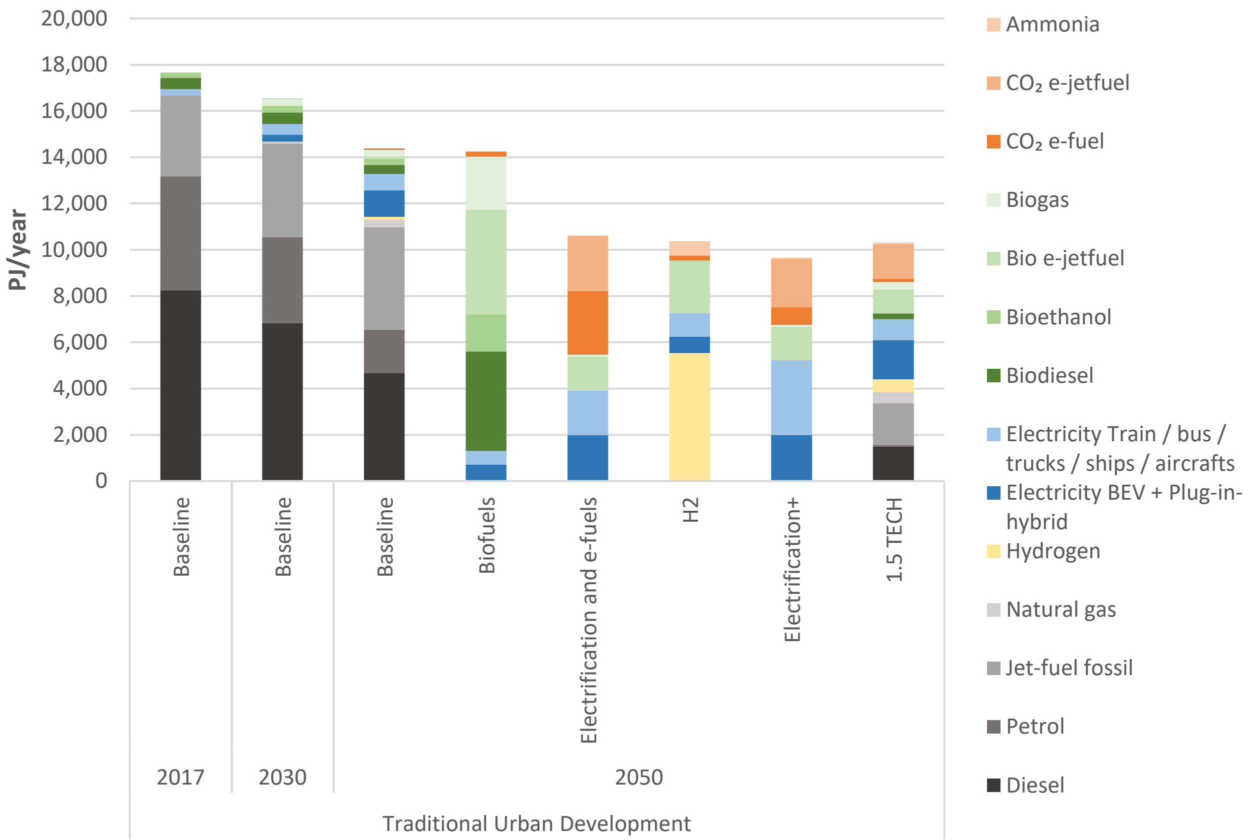


Figure 16: Annual final energy demand in the EU28 in the Baseline and alternative transport technology scenarios under the traditional urban growth scheme

Notable from Figure 16 is, that deep electrification of all sectors will have a significant impact on the final energy demand. Primarily the electrification of passenger vehicles, as it is in the Electrification and e-fuels, Electrification + and 1.5 TECH scenarios, drive the significant reduction in final energy demand. In the H2 scenario, internal combustion engines are replaced in passenger vehicles by fuel cells and electric engines, which in turn improves the vehicle energy efficiency significantly. The additional reductions in the final energy demand in the Electrification+ scenario compared to the Electrification and e fuels scenario come from the more extensive electrification of heavy-duty transport and aviation. In the Electrification+ scenario, large infrastructure investment leads to the development of an extensive ERS network across the EU28. This improves the energy efficiency of EU trucks remarkably and reduces the final energy demand further.

In the H2 scenario, all passenger vehicles and heavy-duty road freight transport are expected to be covered by fuel cell vehicles, as range limitations are not expected to play the same role as for battery electric vehicles in the Electrification and e-fuels, and Electrification plus scenarios.

Under the energy-efficient urban growth scheme, presented in Figure 17, the same pattern is observed. The largest reduction in the final energy demand is seen in the Electrification + scenario. The final energy demand in the Electrification+ scenario is reduced by 27% under the energy-efficient urban growth scheme compared to the traditional urban growth scheme.

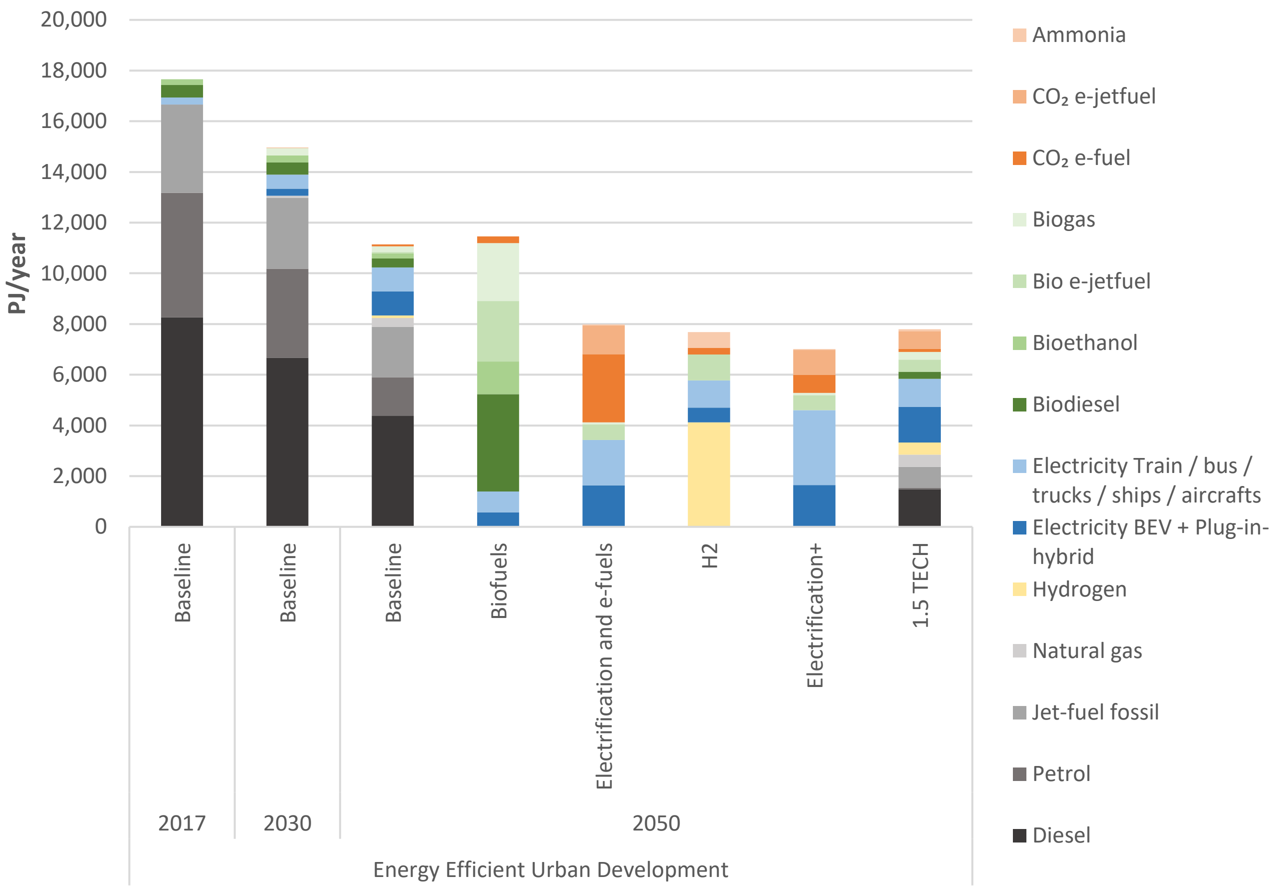


Figure 17: Annual final energy demand in the EU28 in the Baseline and alternative transport technology scenarios under the energy-efficient urban growth scheme

3.2.2 Transport System Cost

The annual transport system cost in the alternative technology scenarios increases compared to the Baseline in 2050, apart from the Electrification+ scenario and the 1.5 TECH under the traditional urban growth scheme. The cost related to vehicles increase slightly in the scenarios with large electrification compared to the Baseline, but the increased cost is balanced out by the reduced fuel cost.

In Figure 18, the annual transport system costs in 2050 are compared for all scenarios under the traditional urban growth scheme and the energy-efficient growth scheme. Under the traditional urban growth scheme, the annual transport system cost in 2050 of the Electrification+ scenario is comparable to the Baseline, while the annual cost is lower for the Electrification + scenario compared to the Baseline in 2050 under the energy-efficient urban growth scheme.

The majority of aviation transport is fueled by e-jet fuels in the Electrification + scenario, which is more expensive than conventional jet fuel. Under the energy-efficient urban growth scheme, the aviation transport demand is decreased significantly compared to the traditional urban growth scheme, hence significant fuel cost savings are achieved in the Electrification+ scenario.

The infrastructure costs comprise only a small share of the total annual transport system costs, hence the annual cost of implementing a comprehensive network of ERS across the EU28 does not increase the total cost significantly.

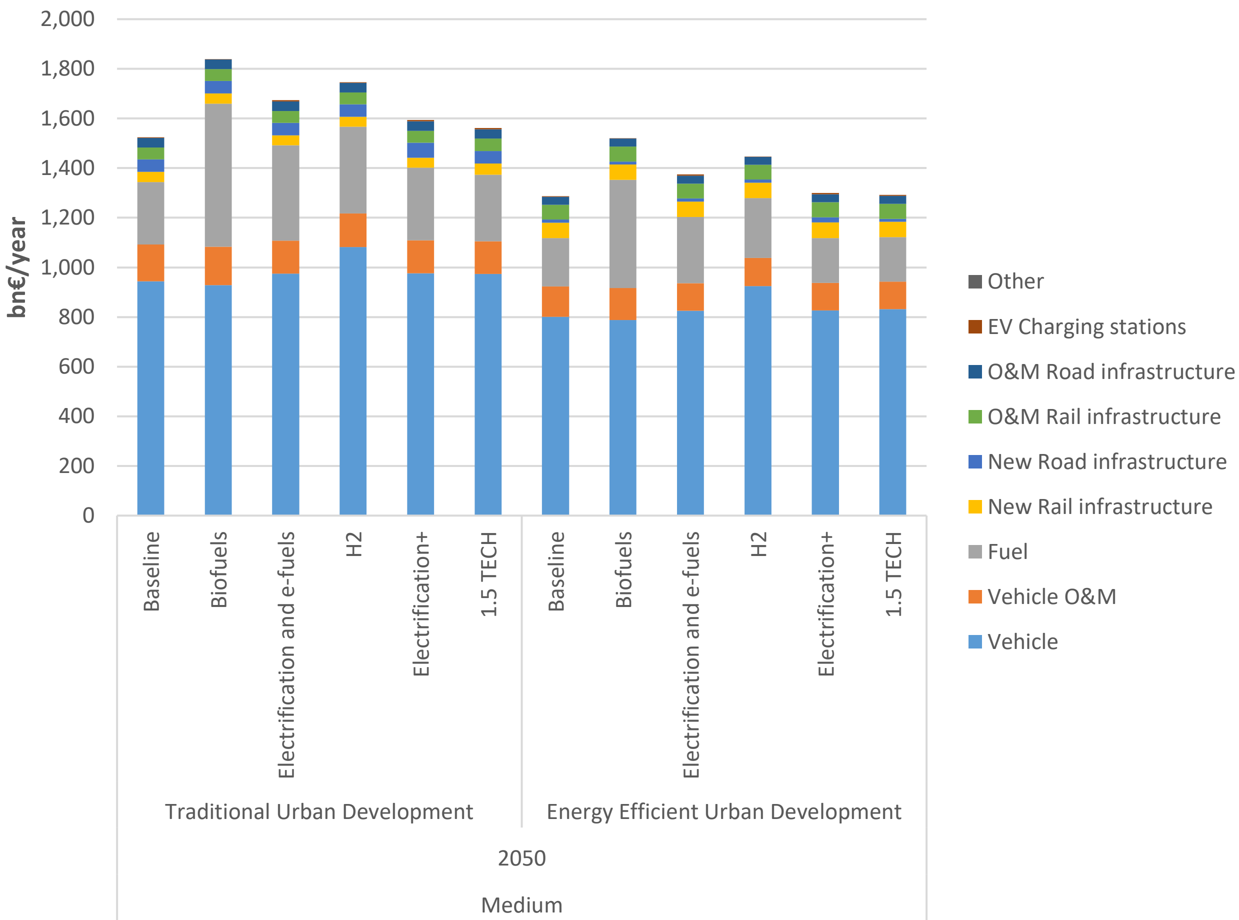


Figure 18: The annual transport system cost in the Baseline and the transport technology scenarios under the traditional urban growth scheme and the energy-efficient urban growth scheme in 2050.

3.3 Sensitivity Analysis

The costs associated with the investment and maintenance of vehicles represent, as highlighted above, the most significant annual cost of the EU28 transport system. Apart from vehicles, the cost of fuel has a noticeable impact on the total annual cost. The fuel cost presented above represents the author's best estimate of a 2050 scenario. In the following, different fuel price developments are considered and the impact on the total annual transport system cost is evaluated.

In the following, only the Baseline and the Electrification + scenarios are considered. The Electrification+ scenario showed the most promising results in terms of final energy demand and annual transport system cost. In these two scenarios, the cost of fossil fuels, petrol, diesel jet fuel-kerosene, etc., have a significant influence on the fuel cost in the Baseline scenario, while the cost of electricity and electrofuel production has an important role in the annual cost in the Electrification+ scenario.

In Table 6, the fuel costs applied in the sensitivity analysis are presented. Three different cost levels are considered, High, Medium, and Low. The medium cost level has been used to forecast fuel costs in the results presented above.

Table 6. Fuel costs in three different cost development scenarios

EUR/MWh	**Diesel**	**Petrol / JP**	**E-fuel**	**E-jet fuel**	**Ammonia**	**Hydrogen**	**Natural gas**	**Electricity**
High fuel costs	76	76	670	780	102	420	36	100
Medium fuel costs	58	58	210	220	93	170	29	50
Low fuel costs	43	43	120	140	83	110	22	35

Especially the costs of renewable fuels, which are still in a relatively early stage of development, have a broad range from the High to the Low fuel cost scenario. The costs of producing hydrogen from renewable sources in electrolysis depend on the achieved conversion efficiencies. The efficiency of the synthesis processes to convert the hydrogen further into various types of electrofuels, also have a significant impact on the product price. As can be seen from Table 6, the costs of synthetic fuels produced from electrolysis are not expected to reach price parity with the fossil alternatives, even in the Low fuel cost scenario. Hence, this follows the conclusion from section 3.2, that internal combustion engines should be replaced by electric engines wherever possible and abstaining from increasing the transport demand for air transport, will have a significant positive impact on final energy demand and fuel costs.

Presented in Figure 19 are the annual transport system costs in 2050 in the Baseline and the Electrification+ scenarios in the High, Medium, and Low fuel cost scenarios under the traditional urban growth scheme. The fuel cost development has an impact on the Baseline scenario: the total annual fuel costs are 9% lower in the low fuel cost scenario than in the the High fuel cost scenario. In the Electrification+ scenario, the total annual fuel costs in the Low fuel cost scenario are 21% lower than in theHigh fuel cost scenario.

If the costs of electrofuels follow the development in the High fuel cost scenario, the annual transport system costs in the Electrification+ scenario will be 8% higher than the Baseline scenario in 2050. However, if the product price of electrofuels follows the Low fuel cost scenario the total transport system cost of the Electrification+ scenario will be 1% lower than the Baseline scenario in 2050.

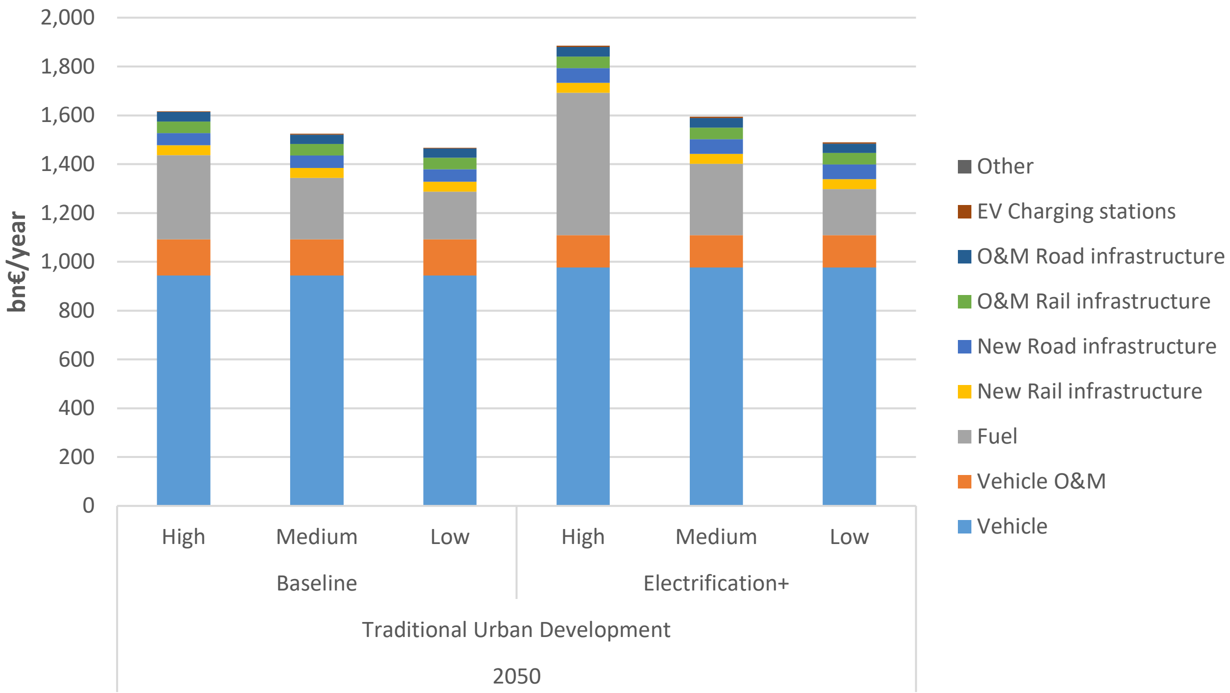


Figure 19: Annual transport system costs in 2050 in the Baseline and the Electrification+ scenario under the traditional urban growth scheme. The cost is shown for the High, Medium, and Low fuel cost scenarios

It is clear from Figure 19, that converting the aviation fuels to mainly electrofuels will present a challenge and possibly increase the annual transport system cost compared to the Baseline scenario under the traditional urban growth scheme. If it is possible to decrease the annual aviation transport activity as proposed under the energy-efficient urban growth scheme, the annual transport system cost will not surpass the annual cost of the Baseline scenario, even if the cost of electrofuel production follows the trajectory of the High fuel cost scenario. The annual transport system costs of the Baseline and the Electrification+ scenarios in 2050 under the energy-efficient urban growth scheme are presented in Figure 20.

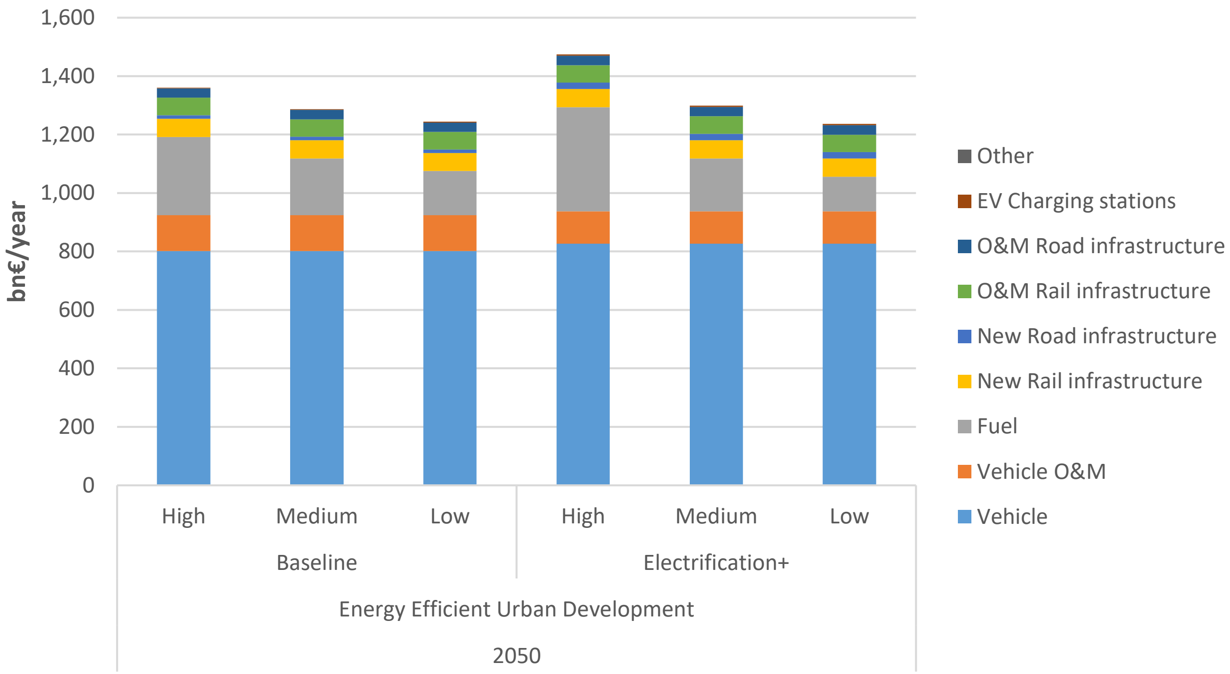


Figure 20: Annual transport system costs in 2050 in the Baseline and the Electrification+ scenario under the energy efficient urban growth scheme. The cost is shown for the High, Medium, and Low fuel cost scenarios.

4 Conclusion

In this work, the development of the transport system in the EU28 towards 2050 considering different urban developments and different implementation rates of renewable transport technologies has been explored. A reference model of the current state of the transport system for the EU28 was built in the TransportPLAN tool, developed at Aalborg University, to create alternative scenarios from a well-documented, comprehensive starting point.

The development of the transport demand was analyzed in a traditional urban growth scheme and an energy-efficient growth scheme. This strongly indicated that urban spatial planning focused on energy-efficient transport behavior along with economic incentives to discard travel in cars and by air and abstaining from large investments in road infrastructure and airports, will have a noticeable effect on the final energy demand for the transport system. If the trajectory of the energy-efficient urban growth scheme is followed, the annual final energy demand will decrease by 20% in 2050 compared to the final energy demand in the traditional urban growth scheme. Hence, an energy-efficient urban growth is recommended to pursue, as this will significantly reduce the need for implementation of renewable transport technologies and fuels and thus reduce the total cost of the transition.

To reach net-zero emissions from the EU28 transport sector in 2050 it is essential to replace fossil fuels with renewables. In this work, four different fuel pathways were analyzed and compared;

- Biofuels
- Hydrogen
- Electrification and electrofuels
- Electrification +

It was evident from the analysis that extensive electrification of all sectors benefits the transport system greatly in terms of improving the overall energy efficiency and limiting the total annual costs. All road transport should preferably be converted to electricity. Where battery electrification is limited, options like ERS provide an energy-efficient alternative to synthetically produced liquid fuels. As aviation and shipping prove more difficult to electrify, the expensive and inefficient electrofuels should be prioritized for these sectors.

In traditional urban development, the electrification + scenario reduces the final energy demand by 42%, while maintaining similar annual transport system costs compared to the Baseline scenario. Replacing fossil fuels with hydrogen, as in the H2 scenario, also significantly reduces final energy demand, but will entail substantial upstream energy demands for the production of hydrogen, which is not considered in this analysis. In conclusion, the electrification + scenario represents the most energy-efficient scenario and provides an alternative to the Baseline scenario that does not increase the annual transport system costs.

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6 Appendix

6.1 Appendix A

The tank to wheel efficiencies as extracted from the AD model [10] are represented graphically in this section. As shown in the following figures electrification, wherever feasible seems to provide the most energy-efficient pathway compared to the conventional internal combustion engine technologies. The hydrogen fuel cell also provides an energy-efficient alternative to the ICE vehicles. However, the development of fuel cell technology remains a potential barrier for 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.

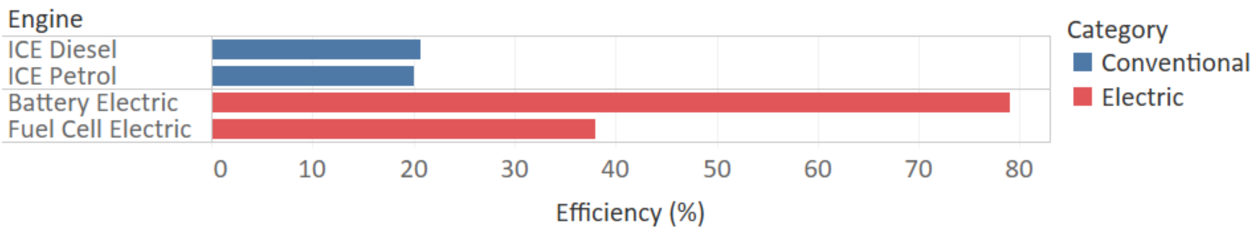

Figure 21: Efficiency of different engine technologies for passenger cars [10]

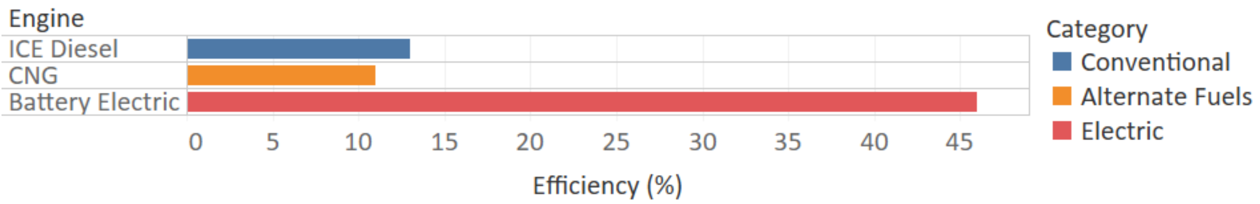

Figure 22: Efficiency of different engine technologies for buses [10]

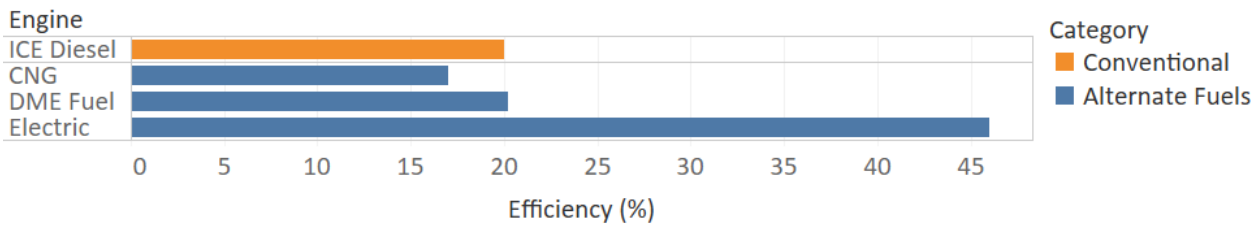

Figure 23: Efficiency of different engine technologies for trucks and coaches [10]

6.2 Appendix B

Table 7 shows the urban area population coverage by country for each scenario if a buffer distance of 50 km is applied to the e-roads in the main scenarios. Some countries do not have urban areas with a population above 500,000, so these do not have any potential in s1, but the potential increases significantly in s2. Most countries reach a quite significant coverage in s5 of 90-100%, however, this also comes with a high ERS implementation which increases costs signifacntly.

Table 7: E-road urban area population coverage by scenario for a 50 km buffer

	s1	s1_e	s2	s2_e	s3	s3_e	s4	s4_e	s5	s5_e
AT	45.6%	45.1%	90.2%	90.1%	97.9%	95.7%	97.9%	95.7%	98.3%	98.3%
BE	96.1%	95.9%	98.7%	98.7%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
BG	71.1%	71.1%	72.5%	72.5%	90.4%	89.7%	90.4%	89.7%	91.6%	91.5%
CH	56.6%	55.9%	95.4%	95.4%	96.1%	96.0%	96.1%	96.0%	96.1%	96.0%
CZ	50.2%	49.9%	69.8%	69.3%	92.5%	92.2%	92.5%	92.2%	99.5%	99.4%
DE	70.0%	69.8%	89.5%	89.3%	97.8%	97.5%	97.8%	97.6%	99.5%	99.5%
DK	65.8%	65.8%	79.9%	79.8%	90.0%	90.0%	90.0%	90.0%	90.1%	90.0%
EE	-	-	74.1%	74.1%	74.1%	74.1%	74.1%	74.1%	87.2%	87.2%
EL	74.1%	74.0%	74.4%	74.4%	82.5%	81.8%	82.6%	81.8%	82.6%	81.8%
ES	60.3%	60.1%	87.6%	87.6%	92.6%	92.1%	92.7%	92.2%	95.5%	95.5%
FI	-	-	65.4%	65.4%	70.1%	70.1%	82.0%	82.0%	97.1%	97.1%
FR	68.9%	68.8%	91.2%	91.0%	95.5%	95.0%	97.3%	97.1%	98.6%	98.5%
HR	68.6%	68.6%	89.1%	89.1%	94.3%	94.2%	94.3%	94.2%	99.1%	98.7%
HU	63.0%	63.0%	90.1%	90.1%	98.6%	96.8%	98.6%	96.8%	97.5%	97.5%
IE	-	-	57.2%	57.2%	79.4%	79.4%	85.9%	85.9%	87.4%	86.8%
IT	64.2%	64.1%	76.2%	76.0%	86.7%	84.5%	87.7%	85.8%	96.2%	96.1%
LT	-	-	62.7%	62.6%	96.6%	96.6%	98.9%	98.9%	99.0%	98.9%
LU	73.4%	73.4%	73.4%	73.4%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
LV	-	-	81.6%	81.4%	85.0%	85.0%	97.5%	97.5%	97.5%	97.5%
NL	75.2%	75.2%	96.1%	96.0%	100.0%	99.9%	100.0%	100.0%	100.0%	100.0%
NO	39.6%	38.3%	42.4%	41.1%	77.4%	77.4%	81.6%	81.4%	81.6%	81.4%
PL	55.2%	54.9%	91.6%	91.3%	97.5%	96.4%	97.5%	96.4%	98.9%	98.8%
PT	38.7%	38.7%	95.0%	95.0%	96.0%	96.0%	96.1%	96.1%	97.4%	97.4%
RO	20.2%	20.0%	88.3%	87.9%	93.7%	93.3%	93.7%	93.3%	96.2%	96.1%
SE	66.8%	66.8%	71.7%	71.7%	81.4%	79.0%	87.2%	87.2%	97.4%	97.4%
SI	83.7%	83.7%	96.6%	96.6%	96.6%	89.9%	96.6%	89.9%	100.0%	100.0%
SK	25.5%	25.5%	52.1%	51.5%	55.3%	54.7%	55.3%	54.7%	93.9%	93.6%
UK	72.1%	72.0%	93.1%	92.7%	97.7%	97.7%	99.0%	99.0%	99.1%	99.1%

Table 8 shows the ERS population covered per meter ERS for each scenario and country. The general trend is that the coverage per meter ERS is largest in the first scenarios, decreasing in the higher scenarios. However, when comparing countries there is a large variation, where some countries, like Switzerland and Netherlands, have an efficiency of 50 people per meter ERS in s1, while many countries are below 10 people per meter in s1.

Table 8: Population covered per meter e-road for all scenarios by member state

	s1	**s1_e**	**s2**	**s2_e**	**s3**	**s3_e**	**s4**	**s4_e**	**s5**	**s5_e**
AT	14.4	14.7	5.8	6.0	4.5	5.6	4.5	5.6	3.5	4.0
BE	18.9	19.5	8.1	8.7	6.5	7.4	6.2	6.9	4.8	5.5
BG	4.7	4.7	3.6	3.7	3.1	3.5	3.1	3.5	3.1	3.3
CH	50.5	53.4	12.1	12.9	8.1	9.2	8.1	9.2	8.1	9.2
CZ	17.4	17.6	11.5	11.9	9.1	10.0	9.1	10.0	4.6	5.1
DE	21.4	22.0	10.3	10.7	7.3	8.7	7.0	8.2	4.5	5.0
DK	5.9	5.9	4.7	4.9	4.5	5.4	4.3	5.2	3.7	4.1
EE	-	-	2.2	2.3	2.2	2.3	2.2	2.3	1.6	1.7
EL	7.4	7.6	6.6	6.9	5.3	5.5	5.2	5.5	4.7	5.3
ES	7.0	7.2	4.5	4.6	3.9	4.5	3.8	4.4	3.4	3.7
FI	-	-	2.2	2.2	1.9	2.0	1.0	1.0	0.7	0.8
FR	9.8	10.1	6.0	6.2	5.1	5.7	4.7	5.2	3.8	4.1
HR	5.8	5.9	2.4	2.4	2.3	3.0	2.1	2.8	1.9	2.0
HU	6.6	6.7	4.0	4.0	3.2	4.1	3.2	4.1	2.8	2.9
IE	-	-	14.2	14.8	6.4	6.6	3.1	3.2	2.6	2.7
IT	14.1	14.4	11.6	12.1	8.4	9.9	7.6	9.0	5.1	5.6
LT	-	-	3.3	3.4	1.9	2.0	1.9	2.1	1.8	1.9
LU	-	-	-	-	12.9	15.9	12.9	15.9	4.4	7.8
LV	-	-	1.9	1.9	1.6	1.6	1.4	1.4	1.4	1.4
NL	47.0	53.6	16.1	18.3	8.8	11.0	8.1	10.3	7.4	9.6
NO	10.3	10.3	3.1	3.0	1.0	1.0	0.7	0.8	0.7	0.8
PL	10.2	10.5	5.1	5.2	4.3	5.1	4.3	5.0	3.6	3.9
PT	12.3	12.9	6.0	6.1	5.1	5.2	3.9	4.0	3.2	3.5
RO	14.8	15.0	4.8	4.9	4.0	4.1	4.0	4.1	3.1	3.2
SE	3.7	3.8	1.9	1.9	1.9	2.1	1.4	1.5	1.0	1.0
SI	5.5	5.5	3.4	3.5	2.3	3.4	2.3	3.4	1.9	1.9
SK	17.7	17.7	10.2	10.4	10.4	10.9	10.4	10.9	7.0	8.0
UK	28.4	30.1	11.1	12.5	7.8	9.4	6.7	8.1	6.0	7.1