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Transport electrification scenarios for decarbonization of the European transport sector by 2050

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Abstract

In response to the present climate crisis, increased penetration of energy-efficient technologies in the transport sector is of paramount importance if Europe is to achieve its goal of carbon neutrality by 2050. Electrification thus offers great opportunities for increasing the overall energy efficiency of the transport sector. This study analyzes two different electrification scenarios for a 100 % renewable energy-based transport sector in the EU. The first scenario – 'electrification and e-fuels' makes use of electro fuels and battery electric vehicles for electrification, whereas in the second – 'electrification +' scenario, a deeper level of electrification is envisioned with the use of electric roads for heavy-duty transport. The results from these scenarios are compared with a traditional baseline development for 2050 in terms of final energy demand and transport systems costs. The results indicate that it is entirely possible to achieve carbon neutrality in the transport sector without incurring huge additional costs by going forward with a deep level of electrification. The annual transport system costs for the 'electrification +' scenario are comparable to the baseline scenario in 2050. This is possible due to a reduction in the overall energy demand by 26 % in the 'electrification and e-fuels' scenario and by 33 % in the 'electrification +' scenario as compared to the baseline. The costs related to vehicles increase slightly in the electrification scenarios, but the increased costs are balanced out by the reduction in fuel costs. The results also highlight that options like electric road systems provide an energy-efficient alternative to synthetic electro-fuels for heavy-duty trucks where battery electrification is limited and that these fuels should be reserved for hard to electrify sectors like aviation and shipping.

Introduction

The transport sector plays a crucial role in economic prosperity and overall societal wellbeing. This is more so in a well-connected geographical region like the EU-28. In many developed countries, the transport sector can account for between 6 % to 12 % of the GDP, with logistics costs accounting for up to 25 % of the GDP (Rodrigue and Notteboom 2017). While a well-functioning transport sector is key for economic welfare, it is of paramount importance to tackle some of the challenges that are derivatives of a fossil-based transport sector, mainly air pollution-related health concerns, climate effects, and energy inefficiencies. The European transport sector is responsible for around 30 % of EU-28's final energy consumption and its share in the EU-28 GHG emissions have risen from 15 % in 1990 to 25 % in 2018 (European Commission 2017). This is because the transport sector is heavily dependent on combustion technologies based on fossil fuels. These combustion technologies such as the internal combustion engine though have spearheaded the transport revolution in Europe and the United States in the 19th Century (Muscato 2020), albeit being highly polluting and inefficient. According to an estimate of health cost externalities, the number of premature deaths in Europe for international shipping traffic is around 50,000 with an external cost of whopping 50–60 billion euros. In addition, the EU spends around 200 billion euros a year importing oil to power its transport fleet (Transport & Environment 2018). Considering these factors, it is important to transition from a fossil-based transport system to other more efficient and cleaner alternatives. Electrification offers multiple benefits for the transport sector, along with much higher efficiencies provided for example by electric motors as compared to combustion technologies, electrification also makes it possible to rid the transport sector of fossil fuels by shifting to utilizing renewably sourced electricity. This study analyzes two different electrification scenarios for a 100 % renewable energy-based EU-28 transport sector and compares it with a traditional baseline scenario for 2050 based on the European Commission's 'A Clean Planet for All' report (European Commission 2018). The study aims to understand and compare the differences from the baseline to the electrification scenarios in terms of final energy demand, transport systems costs. Hence, providing a deeper insight on the effects of different levels of electrification for the European transport sector.

Literature Review

Major transport electrification strategies involve either direct electrification or indirect electrification. Direct electrification in transport involves the use of battery electric vehicles mostly for use in road transport. This also includes the use of contact technologies like pantographs for trains and Electric Road Systems (ERS) for heavy-duty vehicles. There has been a strong interest in direct transport electrification in recent years owing to the increased energy density of electric batteries and a corresponding decrease in costs. The energy density of lithium-ion battery packs is reaching levels of around 200 Wh/kg in 2020, translating to a tripling of energy densities from 2010 levels (Bloomberg 2020). These improvements have been especially beneficial to the passenger car industry, providing passenger car manufacturers the opportunity to take advantage and introduce battery electric vehicles with longer ranges.

The increase in energy density in battery technology has also caused a corresponding decrease in battery costs. It has been observed that lithium-ion battery pack prices have decreased around 89 % from 2010–2020, with present prices at around USD 140/kWh, and future forecasts on battery pack prices reaching below USD 100/kWh in 2023. According to one analysis, at this price, it would be a breakthrough for most Battery Electric Vehicles (BEVs) manufacturers, as it would allow them to produce and sell BEVs at the same margins as for their internal combustion engine counterparts (Bullard 2017)

While the share of BEVs in passenger cars has been steadily on the rise, practical concerns like Dead Weight Tonnage (DWT) for ships and Maximum Take-off Weight (MTW) for airplanes, limit the amount of direct electrification for shipping and aviation. This is due to the low energy density of batteries as compared to conventional fuels like Heavy Fuel Oil (HFO) and Jet Fuel for shipping and aviation respectively. This is where indirect electrification techniques like the use of drop-in electro fuels can be a major contributing factor. Indirect electrification is mainly concerned with making use of Power to X technologies to generate electro-fuels like hydrogen, e-methanol, and ammonia. These fuels could be used directly as a drop-in fuel for example via e-methanol to gasoline conversion processes ("Synthetic Fuel Process | ExxonMobil Chemical" 2020) or as Hydrogen Fuel Cells (HFCs) or Direct Methanol Fuel Cells (DMFCs) (Zhao et al. 2009). If sourced from renewable electricity these fuels can dramatically reduce the GHG emissions from the aviation and shipping sectors. However, as is the case with direct electrification, some concerns limit the use of electro-fuels in their practicality at a massive scale. Particularly, the need for huge amounts of renewable electricity for electrolysis and poor well-to-wheel efficiency of around 13 % as compared to those achieved by direct electrification of around 73 % (Transport and Environment 2017).

Considering the present state of available technologies, some recent studies have called for indirect electrification to be limited to the modes of transport where direct electrification is not feasible i.e. aviation and shipping. However, for heavy-duty trucks, it remains to be seen whether direct electrification is more feasible economically, commercially and environmentally than the use of drop in electro fuels.

The high energy density needed for trucks translates to huge battery packs which ultimately leads to a decrease in payload capacity, making it harder for large battery-powered heavy-duty trucks to be competitive with their diesel counterparts at present battery energy densities. Hence, there is a strong need to reduce the on-board battery capacity for heavy-duty trucks. While major manufacturers across the EU have introduced their plans for bringing more and more battery-powered trucks to market, a rather well-known old technology of using sliding contacts for electric roads has been gaining traction recently. Some pilot projects are already underway in Sweden and Germany, initiated by some major players in the industry. The use of electric road systems provides the opportunity to charge these heavy-duty trucks whilst driving, hence reducing the need for huge batteries on-board. Keeping in view the relevant literature, this study presents a 2050 EU-28 renewable transport scenario with two different levels of electrification and compares them with a reference baseline scenario from the 'Clean Planet for All Report' by the European Commission based on the PRIMES model (European Commission 2018).

TRANSPORT PLAN TOOL

The transport scenarios for an energy-efficient and renewable energy-based EU-28 transport system are analyzed in detail using the modeling tool TransportPLAN in this study. TransportPLAN is a transport scenario modeling tool, originally developed as a part of the CEESA project (Mathiesen et al. 2014). TransportPLAN allows the user to create detailed transport scenarios with five-year intervals from 2020 to 2050. For all modes of transport the transport 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. 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 potential of the transport sector

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.

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

- Annual development of transport demand
- Market share of transport 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 of both passenger and freight transport. For the scenarios analyzed in this study, the only parameters that varied were the market share of transport technologies for different levels of electrification for the two scenarios. 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 model takes 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.

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. Figure 1 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. For the accumulation of transport demand, different sources have been used to make reasonable estimates. These sources include national travel surveys from individual countries, (Eurostat statistical pocketbook) ("EU Transport in Figures – Publications Office of the EU" 2020), and Eurostat database ("Database – Eurostat" 2020). The specific energy consumptions for both passenger 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 ("Database – Eurostat" 2020). The energy efficiency of all vehicles used in the analysis follows the methodology introduced in the Danish transport system model "Alternative Drivmidler" (AD) (Danish Energy Agency and Cowi 2013). The methodology is adapted to display the energy efficiencies in a Danish context, but it is considered that the methodology is applicable in the wider European context.

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 (European Commission 2018). The transport technology efficiencies and the cost of road vehicles and charging stations are found in the Danish Energy Agency's transport model (Danish Energy Agency and Cowi 2013). The transport system infrastructure cost for road and rail infrastructure is calculated for each country based on historic infrastructure investment and mainte-

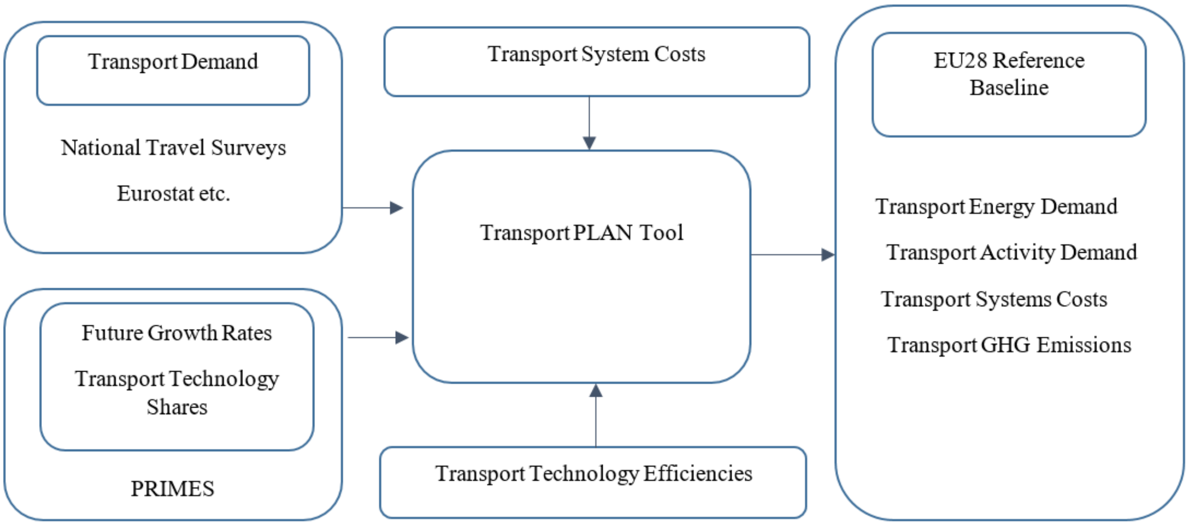

Figure 1. The methodology followed for creating an EU 28 transport baseline.

Table 1. Share of different transport technologies for the analyzed scenarios in 2050.

	Baseline	Electrification and e-fuels	Electrification +
Passenger Transport			
Passenger Cars	35 % BEV 19 % PHEV 4 % FCEV 4 % Gaseous 18 % Gasoline 20 % Diesel	95 % BEV 5 % Electrofuels	100 % BEV
Buses	5 % BEV 36 % Hybrid 21 % Gaseous 38 % Diesel	100 % BEV	100 % BEV
Rail	87 % Electric, 13 % Diesel	100 % Electric	100 % Electric
Aviation	3 % bio-jetfuel 97 % kerosene jetfuel	19 % Electric 81 % Electrofuels	22 % Electric 78 % Electrofuels
Shipping	13 % Gaseous 87 % Diesel and HFO	50 % Electric 35 % Electrofuels 15 % Ammonia	50 % Electric 35 % Electrofuels 15 % Ammonia
Freight Transport			
Trucks	1 % BEV 29 % Hybrid 18 % Gaseous 51 % Diesel	27 % BEV 73 % Electrofuels	27 % BEV 73 % ERS-BEV
Vans	26 % BEV 1 % FCEV 19 % PHEV 54 % Diesel	95 % BEV 5 % Electrofuels	100 % BEV
Rail	87 % Electric, 13 % Diesel	100 % Electric	100 % Electric
Aviation	100 % Kerosene jetfuel	100 % Electrofuels	100 % Electrofuels
Shipping	100 % Diesel and HFO	100 % Electrofuels	100 % Electrofuels

nance cost. (International Transport Forum 2020) 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 costs related to road and rail infrastructure, as well as the annual cost of expanding the electric vehicle charging infrastructure was included.

ELECTRIFICATION SCENARIOS

To quantify the effects that the propagation of different electrification technologies might have in the transport sector, mainly in terms of final energy demand and total transport system costs, two electrification scenarios differing mainly in terms of share of transport technologies are analyzed. The scenarios are designed to reach zero emissions at tailpipe in 2050; hence, no fossil fuels are consumed. However, the upstream emissions and energy losses are not considered in this study. Table 1 gives an overview of the final transport technology share in 2050 for different energy-efficient technology scenarios and the baseline scenario.

In the 'Electrification and e-fuels' scenario, the electrification of road transport is rather intensified than the baseline scenario. 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 EU-28 is 450 km. The average flying distance between countries within the EU28 is 1,350 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 EU-28 are converted to BEVs. The largest difference is seen in road freight transport, where 27 % is converted to BEV, while the remaining 73 % is converted to BEVs with smaller onboard batteries with on-road charging support from Electric Road Systems (ERS).

ERS is becoming an increasingly interesting concept 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 are taking the lead in terms of the 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 electrification. Sweden has already announced its ambitious target of implementing 3,000 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.

Implementation of ERS

The following text describes the data and methods used to calculate the length of ERS for different parts of Europe. The concept of ERS is well-described in (Connolly 2017), where the purpose is to use electricity directly from the electricity grid in 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 power alone. 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. This significantly reduces 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 used in a previous study for Denmark (Connolly 2017). 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. at 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:

- Road network from OpenStreetMap (OSM) (OpenStreetMap 2020)
- Urban areas from D5.2 (Wiechers, Möller, and Persson 2020)
- Industrial sites from D5.1 (Fleiter et al. 2020)
- Ports from (Maritime Safety Office 2016)
- Country maps (Eurostat 2020)

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.
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 were 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 summarized 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 (Nielsen and Moreno 2020). Figure 2 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, Poland, and Italy are the countries with the most km of ERS.

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-roads (which incurs increased implementation costs) and coverage potential (percentage of urban area population within a 50 km buffer to ERS).

Results and Discussion

In this section, the results of the baseline and electrification technology scenarios are presented. 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 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 investment cost and maintenance of vehicles, fuel production cost, and cost associated with the renewal and development of transport infrastructure. Both of the electrification technology scenarios represent zero-emissions scenarios in 2050. 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. The development of the baseline scenario in terms of annual growth in transport activity, the implementation of new transport technologies, and fuels and energy efficiency improvements, in this work is based on the baseline 2050 scenario from the European Commission (European Commission 2018).

TRANSPORT ENERGY DEMAND

The final energy demand for the transport sector in the EU28 in the 2017 reference model amounts to 18 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 3, the development of the final energy demand in the Baseline scenario is presented. The same growth of transport demand observed in the EU28 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.

In the ‘Electrification and e-fuels’ scenario and the ‘Electrification +’ scenario, energy-efficient electrical engines and fuel cells replace most internal combustion engines in road transport. 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 ‘Electrification +’ scenario reduces the final energy demand in 2050 by 33 % compared to the 2050 baseline and 45 % compared to 2017. Notable from Figure 3 is that deep electrification of all sectors will have a significant impact on final energy demand. The electrification of passenger vehicles, as it is in the ‘Electrification and e-fuels’ and the ‘Electrification +’ scenarios, is the primary driver of the significant reduction in final energy demand.

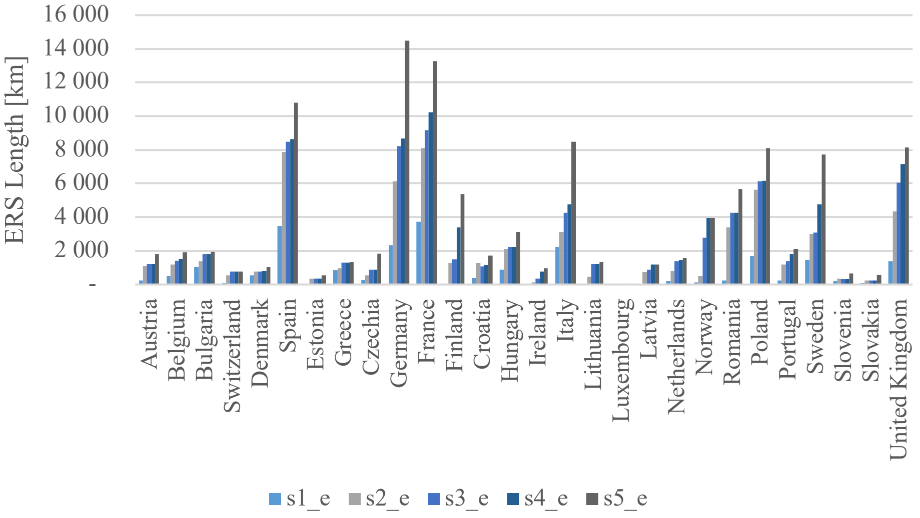

Figure 2. ERS length in each alternative (erased) scenario.

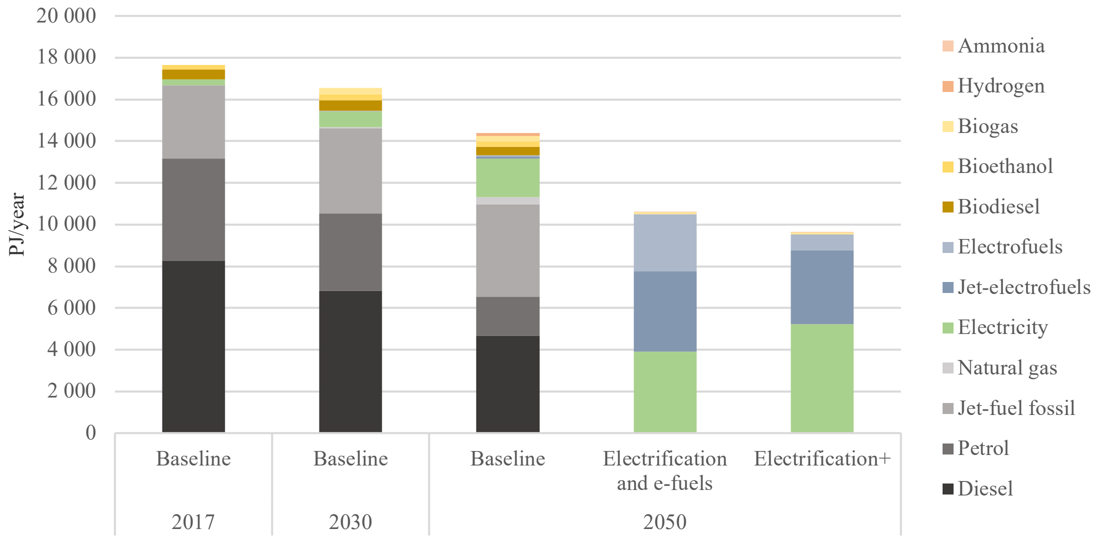

Figure 3. Annual transport energy consumption divided by fuel type in the Baseline scenario compared to the Electrification and e-fuels scenario and Electrification+ scenario in 2050.

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 investments lead to the development of an extensive ERS network across the EU28. This improves the energy efficiency of EU trucks remarkably and reduces final energy demand further.

TRANSPORT SYSTEMS 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 the fuel cost sensitivity analysis, the impact of a low and high fuel cost scenario is investigated. The costs related to transport system infrastructure are based on historic investments and maintenance costs, hence these are considered less uncertain. The additional cost of ERS infrastructure is subject to significant uncertainties and will depend heavily on the development and implementation of the technology. But as the cost related to ERS only comprise a small share of total annual costs, a sensitivity analysis will not be conducted.

The annual transport system cost in the EU28 in the 2017 reference model is €1.281 bn/year. The costs related to vehicles comprise 68 % of the total annual transport system cost, while fuel costs comprise 22 %.

In Figure 4, the development of the annual transport system cost is outlined for the baseline scenario compared to the 'Electrification and e-fuels' and 'Electrification +' scenarios. The annual transport system cost in the baseline scenario increases by 19 % from 2017 to 2050. Vehicle and fuel costs still comprise the majority of the annual cost in 2050. Both the 'Electrification and e-fuels' and the 'Electrification +' scenarios present an increase in the annual transport system cost. The cost of vehicles grows in the two scenarios, while especially the cost of replacing fossil liquid fuels with e-fuels increases the annual fuel cost significantly. In the 'Electrification +' scenario, the deep electrification of all sectors ensures low consumption of e-fuels, hence the fuel production cost is comparable to the baseline scenario.

Fuel Cost 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 Figure 5, different fuel price developments are considered and the impact on the total annual transport system cost is shown. 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 and e-fuels' and the 'Electrification +' scenario. The costs of renewable liquid or gaseous fuels, which are still in a relatively early stage of development, have significant uncertainties related to future production costs.

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. The costs of synthetic fuels produced from electrolysis are not expected to reach price parity with the fossil alternatives in the scenario period from 2017–2050.

Hence, the conclusion from above, that if electric engines replace internal combustion engines wherever possible, this will have a significant positive impact on final energy demand and fuel costs. If the costs of electrofuels follow the development of high production costs, because of high electricity prices, low conversion rates or high investment costs, etc., the annual transport system costs in the 'Electrification +' scenario will be 8 % higher than the baseline scenario in 2050. However, if the

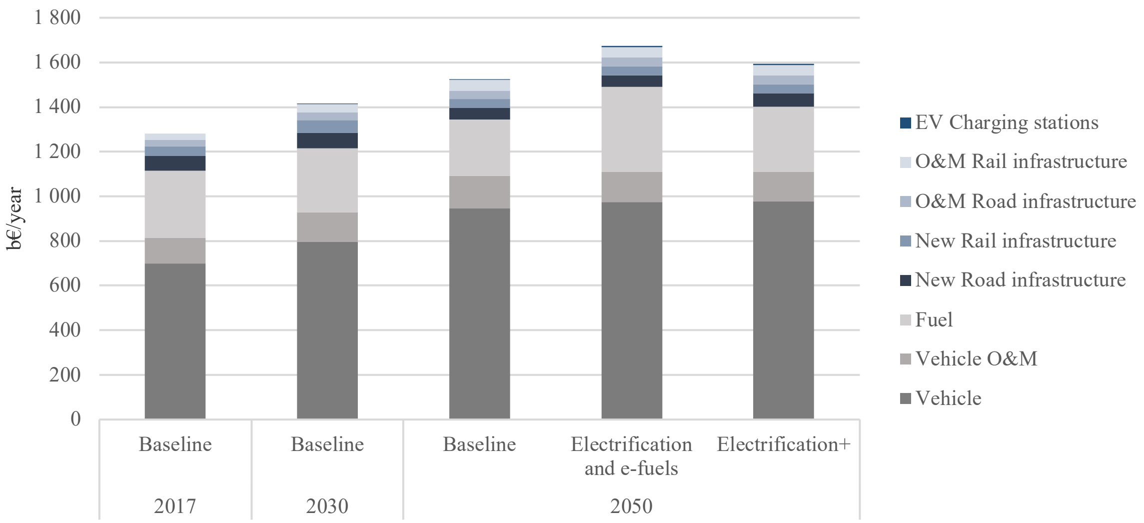

Figure 4. Annual transport energy system costs divided by cost in the Baseline scenario compared to the Electrification and e-fuels scenario and Electrification+ scenario in 2050.

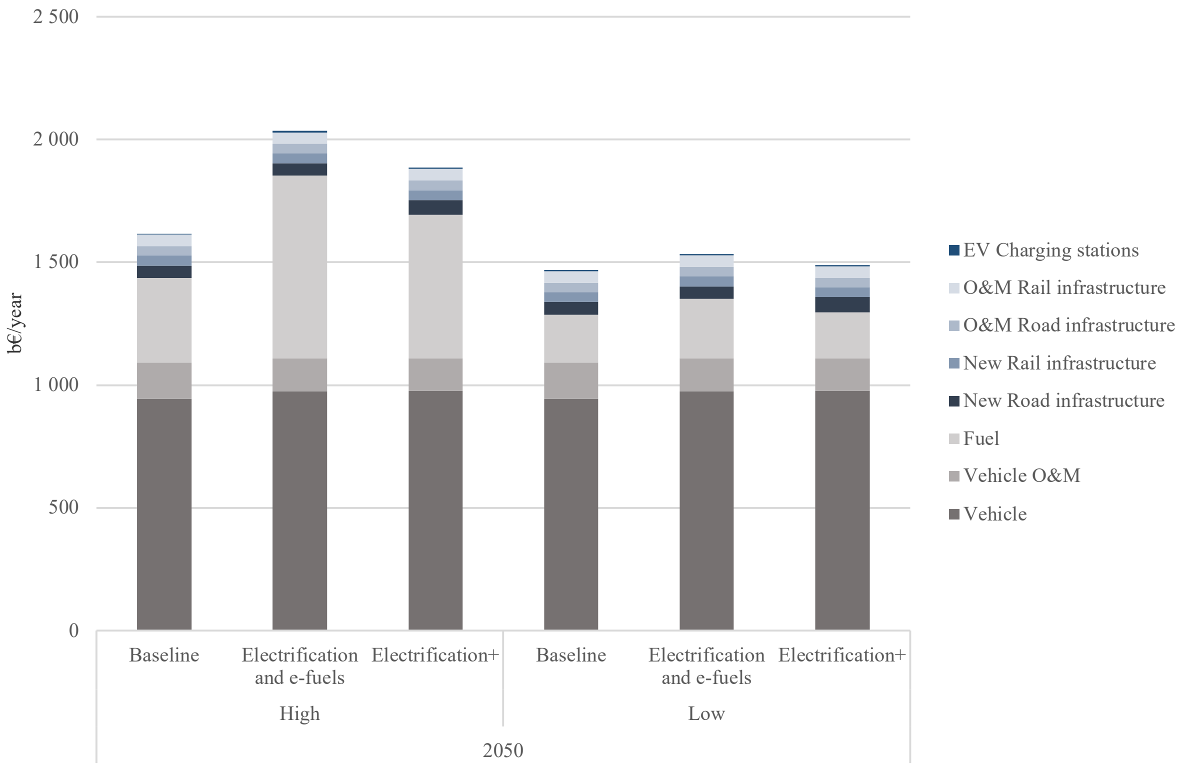

Figure 5. Fuel cost sensitivity impact on total annual transport system cost.

production cost follows a low-cost trajectory, the total transport system cost of the 'Electrification +' scenario will be 1 % lower than the baseline scenario in 2050.

Conclusion

It is 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 this analysis, only the final energy demand was considered, hence it is not possible to draw any comprehensive conclusions on the specific impacts, the scenarios would have on the European energy system as a whole.

The approach taken in this work, displayed the effects on the transport system in the EU28, in extreme scenarios where a single fuel path was chosen for the majority of the transport system. Scenarios like these are unlikely to occur, but help to highlight the importance of including the perspective of energy efficiency early, to avoid expensive and inefficient lock-in situations. A broad political focus from the EU, regarding energy efficient transport and implementation of electric propulsion in all areas possible, will be key factors in achieving a zero-emissions transport sector in the EU28 in 2050.

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