École polytechnique de Louvain

What are the energy, fleet, and economic impacts of different passenger landbased mobility scenarios in 2050 on Belgium's energy system?

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Abstract

This thesis explores how different land-based passenger mobility scenarios in Belgium could impact the country's energy system in 2050. An improved version of the EnergyScope TD model is used to better represent the passenger transport sector.

Three scenarios are investigated, each reflecting the three most common pathways considered for addressing climate change: no major changes, sufficiency and technological improvements. The Trends scenario continues current travel habits and policies. The Sufficiency scenario focuses on reducing travel demand while promoting active and public transport. Finally, the Technological Growth scenario maintains high travel demand but relies on improved vehicle efficiency.

The results show that all three scenarios can reduce operational GWP emissions enough to meet CORE95 climate targets, but through different approaches and costs. The Sufficiency scenario is the cheapest, consumes the least energy, and produces the lowest Scope 2 greenhouse gas emissions. In contrast, the Trends scenario has the highest cost, energy use and scope 2 GWP emissions, while the Technological Growth scenario falls between the two.

Some limitations must be highlighted. The model simulate only a single year and does not take into account the actual state of technological infrastructure. Additionally, it does not consider how changes in passenger mobility sector might impact demand in other sectors.

The findings shows that reducing emissions from the transport sector in Belgium is feasible but requires strong political commitment, significant investment, and broad public support. As highlighted in this study, the most effective way to reduce greenhouse gas emissions and associated costs from mobility is to follow the principle: "The cleanest and cheapest kilometer is the one not traveled."

Contents

1 Introduction

Passenger transport has always played a key role in human life. It allows people to reach resources, meet others, and take part in social and economic activities. From early forms of travel like walking, riding animals, and using basic boats, the need to move has steadily grown. However, it is primarily technological advancements such as the invention of the wheel, and the development of trains, cars, and airplanes that have driven this growth in demand. These innovations have not only made travel easier and faster but also triggered a rebound effect, where improved efficiency leads to even greater overall travel.

In Belgium today, people spend an average of 1 hour and 13 minutes per day traveling. This shows how central mobility is in everyday life. But the current transport system also causes serious environmental and energy challenges. In Belgium, passenger transport account to 20% of primary energy use [1] and 21% of total scope 1 GWP emissions [1]. These numbers show the importance of rethinking how we organize mobility.

This thesis explores three possible passenger mobility pathways to reduce scope 1 GWP emissions in Belgium using EnergyScope TD, a model for national energy systems. Each scenario adopts a different strategy to transform the passenger transport sector, focusing on changes in technology and travel behavior. The study examines how these changes impact the overall energy system, particularly in terms of energy use, fleet size, and system costs.

To allow for realistic modeling of mobility scenarios, the EnergyScope model was first adapted and improved. Then, mobility input data for the reference year 2019 were developed as a baseline. Based on this, three contrasting scenarios for 2050 were constructed, each reflecting a different strategic approach. Finally, these scenarios were analyzed using the model to evaluate their implications for Belgium's future energy system.

2 Energy System model

The model used in the study is the EnergyScope Typical Day (ESTD) model, developed by EPFL and UCLouvain, and described by Gautier Limpens et al. [2][3]. ESTD is a snapshot optimization model designed for regional energy systems, minimizing total annual cost under a CO2 emissions limitation, while meeting energy demand. It simulates a target future year without considering existing infrastructure but with resource limitation. The model is open-source, available on Github. Its results have been validated for Belgium in Gautier Limpens work [3].

2.1 Input

The energy model incorporates several types of inputs: resources, technologies, and demand.

Resources

Resources are classified as either endogenous (produced within Belgium) or exogenous (imported). Endogenous resources include solar, wind, hydro, biomass and waste, all of which are renewable beside waste. Their use is limited by technical and geographical potentials. For example, solar PV installed power is capped at 59.2 GW due to land constraints, while wind and hydro potentials are set at 15 GW and 0.115 GW, respectively. Exogenous resources such as imported electricity, bio-fuels, e-fuels, and hydrocarbons are characterized by import limits . No changes from the actual ESTD have been made for the resource in this study.

Technologies

Technologies are characterized by their investment and operational costs, efficiency, lifetime, and GWP emissions. These include all energy conversion and storage technologies. Only mobility related technologies and grid infrastructure has been changed or added.

Demand

In this model, End-Use Demand (EUD) is used instead of Final Energy Consumption (FEC) to focus on the actual demand for energy services at the point of use, such as heating in TWh.
The EUD is divided into several categories to reflect the specific energy services demanded in different sectors. These sectors are: electricity, heat, mobility, and non-energy demand. Within these main sectors, further subdivisions are made called End-Use Types (EUTs) to represent more specific applications. For example, mobility is divided into passenger transport and freight transport, while the heat sector is segmented into high-temperature heat for industry and low-temperature heat.

2.2 Model

In the preoptimization process, EnergyScope TD selects 12 typical days to simplify the model's representation of hourly demand. Five time series are used to define the typical days: two of these time series are related to end-use demand (electricity and space heating) and the other are based on the weather. The typical days chosen are then applied to all days that share similar characteristics. This approach reduces computational complexity while still capturing the variation in demand and enabling efficient optimization of both system design and operation.

The optimization process aimed at minimizing the overall system cost by adjusting two key variables: technology capacities and resource usage. The total system cost (C_{tot}) includes the annual investment cost (τC_{inv}), where τ is the annualization factor, annual maintenance costs (C_{maint}), and resource costs (C_{res}):

$$C_{\text{tot}} = \sum_{i \in \text{technologies}} (\tau C_{\text{inv},i} + C_{\text{maint},i}) + \sum_{j \in \text{resources}} C_{\text{res},j} \tag{2.1}$$

In addition to minimizing costs, the model incorporates constraints to ensure that specific GWP emissions limits are respected, hourly EUT are met and the energy balance of each technology is correct. As a snapshot model, EnergyScope TD projects the energy system for a specific future target year.

To ensure the scenarios reflect real-world conditions, several constraints are introduced. These constraints enhance consistency in the output and increase the model's reliability. For mobility, for instance, the percentage of Energy Use Technologies (EUT) for different vehicle types is predefined, allowing flexibility in adjusting the distribution across the sector. The share of each technology remains constant throughout the year. This means, for example, that if diesel cars account for 10% of the kilometers traveled during one hour in the morning, this proportion is maintained consistently throughout all hours of the year. Additionally, Vehicle-to-Grid (V2G) technology is incorporated, with a constraint limiting its use: only a maximum of 20% of V2G-enabled vehicles can be used for grid services at any given time.

2.3 Output

The model's output consists of the results from the optimization process, which include the installed capacities of the selected technologies and their corresponding hourly production profiles. The model also provides detailed information on the costs and the GWP emissions linked to the selected system configuration.

2.4 Limitations of EnergyScope TD

While EnergyScope TD is a valuable tool for strategic energy planning, it has several limitations that should be considered when interpreting its results. Those limitations are describe bellow.

The model is highly sensitive to input prices, such as fuel costs, technology investments, and operational expenditures. These values are inherently uncertain, particularly when projecting toward long-term horizons like 2050. This sensitivity can significantly influence the model's outcomes and reduce the robustness of the resulting scenarios.

The agriculture sector is not represented in the model. This omission limits the scope of the analysis and may lead to an underestimation of total energy needs and GWP emissions, particularly in countries where agriculture plays a significant role.

Active mobility modes such as walking and cycling are not explicitly represented. Instead, the model assumes that mobility the active mobility has no cost and consume no energy. As a result, the potential contribution of active mobility to reducing energy demand and emissions in the transport sector is neglected, potentially biasing the model toward more sufficiency and low tech mobility solutions. Additionally, the model does not differentiate between rural and urban land-based mobility, despite differences in travel demand and usage patterns. The limitations discussed in this paragraph will be addressed and further explained in the next section 2.5.

2.5 Improvement of Energyscope TD

2.5.1 Structure

The improvement of the model focuses on implementing more realistic mobility scenarios. To achieve this, the structure of the mobility model will be changed and refined. The EUD for mobility will be divided into different EUT, similar to the previous model, separating freight and passenger mobility. However, the passenger mobility will undergo an internal split, which will add more complexity. Specifically, passenger mobility will be categorized into an urban and rural part. These urban and rural categories will then be further split into private active and non-active mobility and public mobility segments. These changes are shown in Figure 2.1.

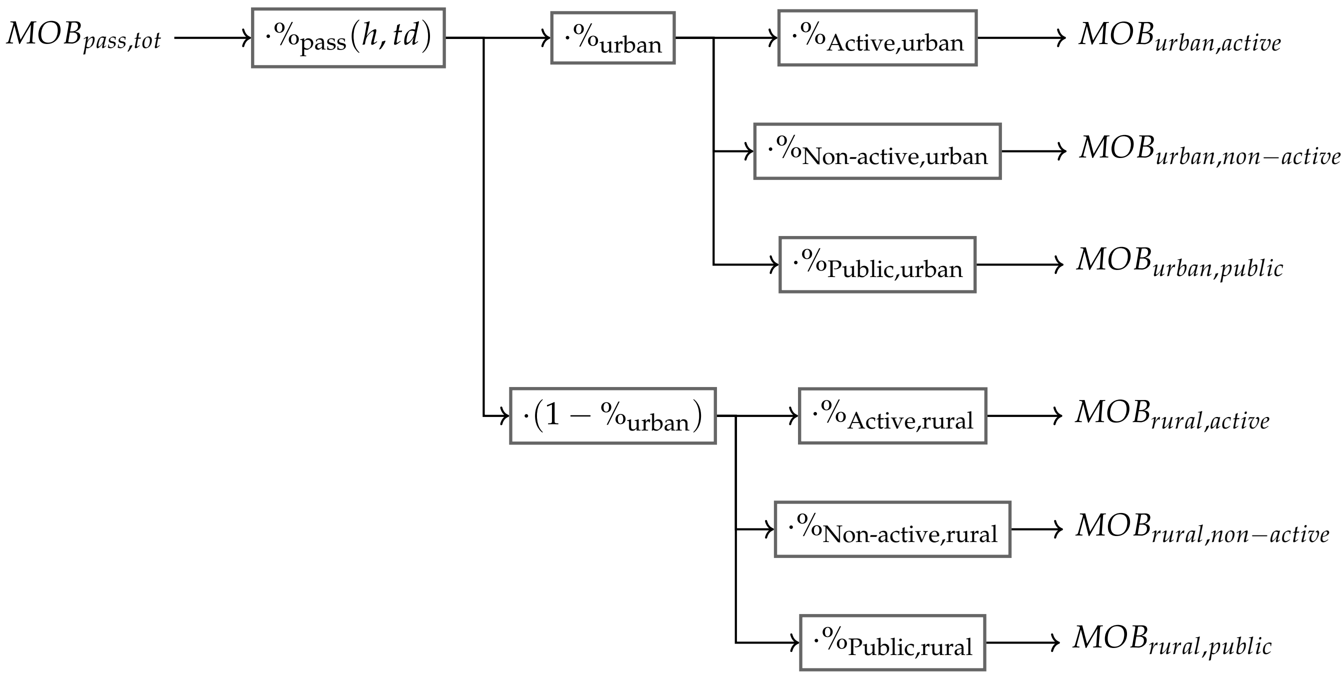

Figure 2.1 Hourly demands calculation for mobility starting from yearly passenger mobility demand input

2.5.2 Technologies

Some technologies are already implemented in EnergyScope, but active mobility technologies, such as bicycles and walking, as well as motorcycles, are not included. Moreover, some technologies are treated as equivalent in the model, when in fact, they are quite different. For instance, the tram and metro are considered similar in EnergyScope but they differ significantly in terms of infrastructure, operation,etc.

The availability and parameters of these technologies varies by area. Trams and metros are not available in rural areas due to the high cost of infrastructure and a low concentration passenger mobility demand. Additionally, with the definition[1] of the distinction between urban and rural areas, urban displacement is limited to travel within the city. Trains in city are used to reach this city or to go through, not for internal city travel. For this reason, the train technology will not be available for urban displacement. Since a passenger land-base mobility perspective is taken, the plane is not taken into account due to the small size of Belgium. The availability of all the private and public technologies by type of vehicle is visible on Table 2.1 and Table 2.1.

Table 2.1 Private technology availability by area

Private vehicle type	Urban	Rural
Bike		
Non-electric	✓	✓
BEV	✓	✓
Motorcycle		
Petrol	✓	✓
BEV	✓	✓
Car		
Diesel	✓	✓
Petrol	✓	✓
HEV - Gasoline	✓	✓
PHEV - Gasoline	✓	✓
BEV	✓	✓
Fuel cell	✓	✓
Natural gas	✓	✓

Table 2.2 Public technology availability by area

Public vehicle type	Urban	Rural
Bus		
Diesel	✓	✓
HEV - Diesel	✓	✓
BEV	✓	✓
Fuel cell	✓	✓
Natural gas	✓	✓
Tram		
Electric	✓	×
Metro		
Electric	✓	×
Train		
Electric	×	✓
Plane		
Kerosene	×	×

2.5.3 Infrastructure

In EnergyScope, the model is structured around primary energy resources, conversion technologies, and the fulfillment of end-use demands. However, an inconsistency arises: some energy vectors incorporate grid infrastructure between the primary energy source or end-use demand and the conversion technology, while others do not. Specifically, electricity and district heating already include grid infrastructure within the model. To ensure consistency and fairness across all energy carriers, grid infrastructure components will also be implemented for gas, hydrogen, and ammonia. Since the study focuses on transport scenarios, charging and fueling for passenger mobility have been explicitly integrated. Additionally, transport network infrastructure costs are independent of the optimization process. Those are then calculated in a post optimization step.

[1] The definition is explained in chapter 3

3 Passenger Mobility

After gaining a comprehensive understanding of how the model operates, this chapter presents the adjustments made to its input parameters. These modifications were motivated by significant discrepancies between the input values used in EnergyScope and those employed in other energy system models, such as the Climact Pathways and ADEME scenarios. In addition to adjustments to existing parameters, new inputs have been introduced.

All these changes follow the methodology proposed by Jonas Schnidrig [4], who improved the EnergyScope model from a mobility perspective in the context of Switzerland. His approach has been adapted to the Belgian context for this study.

3.1 Passenger demand

Passenger demand is expressed in passenger-kilometers (pkm) per hour, representing the kilometers traveled by a single person during one hour. Since this input is not directly available, the annual land-based pkm is estimated and then distributed hourly using a representative curve.

3.1.1 Total Passenger demand

This study focuses only on land-based transport within Belgium, excluding air and maritime modes. Data for non-active transport (road and rail until 2022) are available from the EU Statistical Pocketbook [5], as member states are required to report such data. However, active modes like walking and cycling growing steadily in recent years are excluded from this source. Instead, estimates for active mobility are drawn from national studies such as BELDAM [6], Monitor [7], and VIAS [8], which report the share of kilometers traveled by these modes. These estimates are combined with non-active mobility data to obtain total demand. For 2022, total passenger demand is estimated at 132,928 Mpkm.

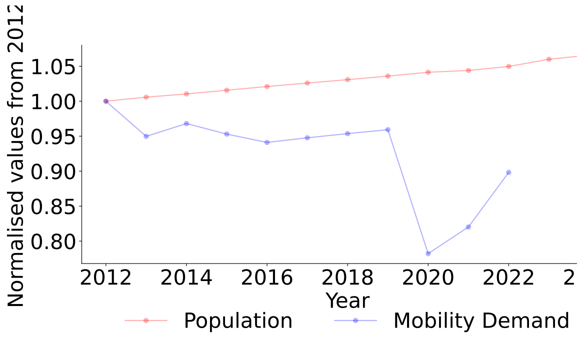

Figure 3.1 Population vs. passenger land-based mobility demand in Belgium. Both metrics are normalized to 2012 levels. Population data are from Statbel[1] [9].

As shown in Figure 3.1, land-based mobility declined until 2016, then grew steadily until the COVID-19 period, during which it dropped before attempting to return to previous levels. This indicates that demand is highly sensitive to the uncertainties of life. The year 2019 is taken as the last stable reference point, as mobility data typically takes two years to be published, and the COVID period does not represent a normal year.

The type of displacement can be categorized into different groups to allow better precision in defining transport types and flexibility in scenario modeling. Typically, mobility studies classify trips based on a threshold distance, with the European standard being around 100 km. However, this approach is not suitable in Belgium for two reasons. First, the only national study using such a classification applies a 300 km threshold [7], which mostly captures international travel, as the maximum internal distance in Belgium is 318 km. Second, the European standard of 100 km does not reflect Belgian travel patterns, where such long trips are uncommon especially for residents in areas like Brussels.

An alternative classification, already used in scenario modeling such as Clever [10], is to distinguish between "urban" and "rural" trips. Urban trips are defined as trips that both start and end within the same city. All other land-based mobility such as trips entering or leaving a city, traveling between cities, or occurring outside of urban areas are classified as "rural" displacement. The dispatch between those displacement classification can be seen in Table 3.1. This method is more relevant, as urban transport differs significantly from transport outside cities, both under current conditions and in future projections. For instance, public transport is far more developed within cities than in rural areas. Therefore, the "urban" and "rural" classification will be adopted to better reflect actual mobility patterns. A place is considered as a city when the population is over 100,000[2]

[1]The data used come from the National Register. The official population data do not include the waiting list of asylum claimants, i.e., individuals whose asylum applications are still being processed.

[2]Belgium count 7 cities that are above this threshold :Brussels, Antwerp, Ghent, Charleroi, Liège, Bruges, Namur, Leuven

Table 3.1 Area based Passenger Mobility distribution

	Urban	Rural	Sources
% of total km	23	77	[7]

3.1.2 Hourly curve

The hourly distribution curve is obtained by analyzing vehicle counters (bike, public transport, car) at traffic metering stations. By normalizing the hourly values, it is possible to determine the hourly passenger mobility for each transport mode throughout the year. Weighting and averaging the different time series from different type of mobility gives a good representative hourly mobility profile.

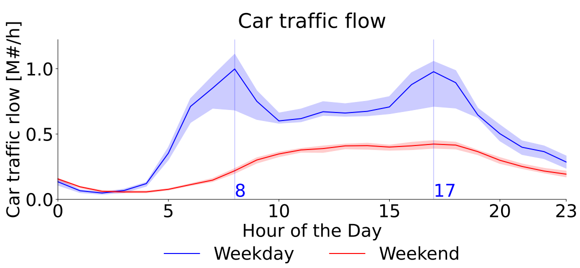

Figure 3.2 Typical hourly evolution of car flows based on a representative weekday and weekend for each month on Flanders highways [11].

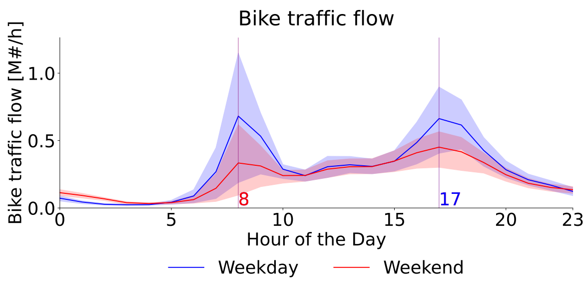

Figure 3.3 Typical hourly evolution of bike flows throughout the year in Brussel, based on GoodMove data [12], with hourly resolution over one year.

The shaded areas in Figure 3.2 and Figure 3.3 represent the 25th and 75th percentiles, reflecting the variability in traffic flows. Car traffic exhibits lower variability due to the use of hourly typical weekdays for each month, while bike data is based on 15-min observations. Both modes show pronounced peaks around 8 a.m. and 5 p.m. on weekdays, corresponding to commuting hours. On weekends, these peaks disappear, and the overall volume is lower throughout the day for both transport modes.

Due to the lack of publicly available data for public transport, the final time series is constructed using only car and bicycle data. Specifically, 94.1% of the time series is derived from car data and 5.9% from bicycle data, in line with the modal shares observed in 2019. The representative weekday and weekend day are applied to their respective days across the year to generate the final hourly distribution.

3.2 Fleet

The mobility fleet considered in this study includes a wide range of technologies, encompassing both individual and collective transport modes as seen in Table 2.1 and Table 2.2. Walking is excluded, as it does not involve investment, efficiency, or infrastructure constraints. For private vehicles, small cars are assumed, reflecting a conservative approach aligned with the new vehicle registration tax[3] in Wallonia. Actually, this tax is based on engine power, CO2 emissions, and fuel type. In July 1, 2025, vehicle weight will also be included[13]. This adjustment aims to encourage the adoption of a lighter vehicle fleet. The specific parameters of this fleet are shown in Table A.6 in Appendix 1.5.1.

3.2.1 Total Cost of Ownership

To compare the cost of different transport technologies, the Total Cost of Ownership (TCO) is used. TCO represents the overall cost of a vehicle over its entire lifespan, including investment, maintenance, operation, taxes, and other related expenses. However, in this model, fuel prices are determined during the optimization process, and taxes depend on detailed, vehicle-specific information. Since the model aggregates vehicles by fuel type, only investment and maintenance costs are considered in the TCO calculation.

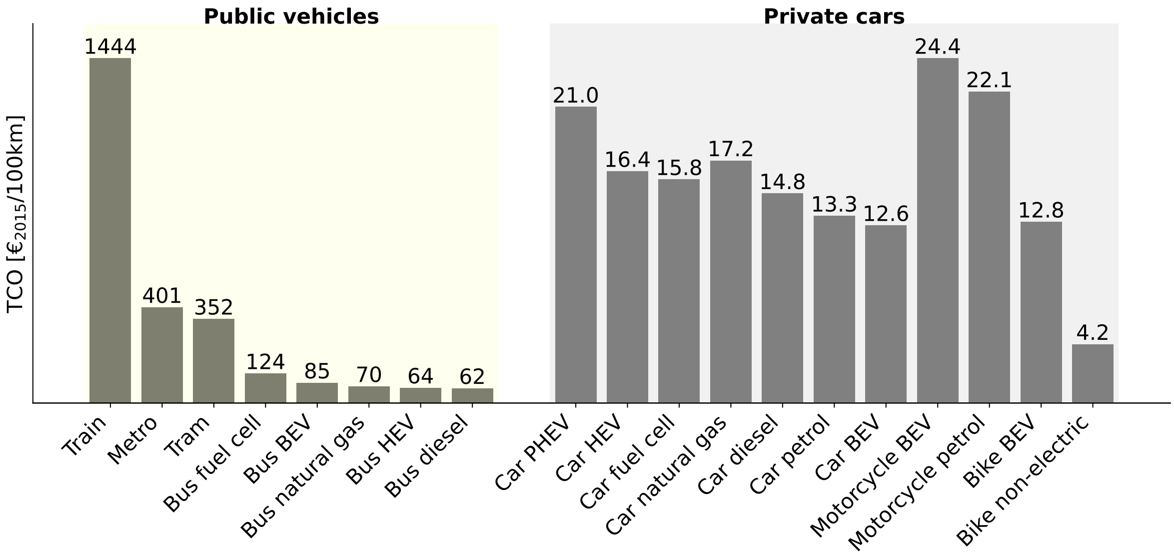

Figure 3.4 TCO per 100 km of public and private vehicles

[3] The registration tax or TMC (Taxe de Mise en Circulation) in french is a one-time tax that must be paid when a vehicle is registered for the first time in Belgium. The purpose of this tax is to contribute to the funding of road infrastructure and to encourage the use of cleaner and more efficient vehicles.

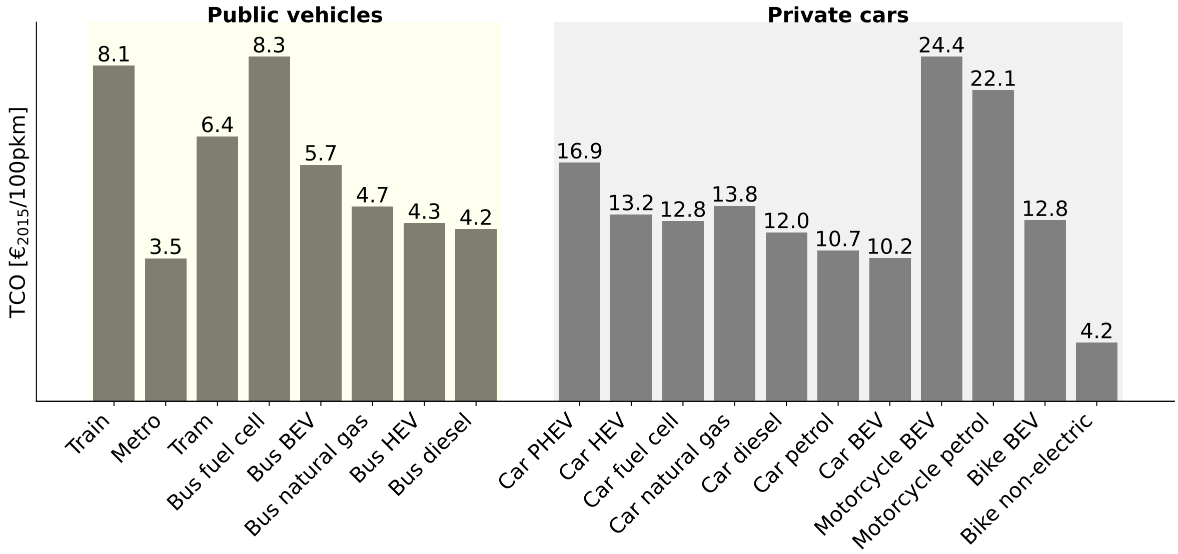

Figure 3.5 TCO per 100 pkm of public and private vehicles with the 2019 occupancy in Table A.6

As shown in Figure 3.4, the TCO per kilometer for public transport vehicles is significantly higher than for private cars. In particular, rail based technologies within public transport are much more expensive than other transport modes. For private vehicles, as expected, the TCO per kilometer for cars is higher than that for motorcycles and bikes.

In contrast, based on the TCO per passenger-kilometer (pkm) presented in Figure 3.5, public transport appears much cheaper. Among public modes, busses are generally cheaper than rail technologies, with the exception of the metro due to digging. In private transport, the TCO per pkm of motorcycles increases significantly, while cars and electric bikes show similar values. The non-electric bicycle remains the cheapest option.

3.2.2 Consumption

The energy consumption of a vehicle primarily depends on two factors: average speed and speed variation (i.e., braking and acceleration). Consumption increases with the square of the speed due to air resistance, while speed fluctuations cause inertia losses that lead to additional energy use. In urban areas, average speeds are lower but speed variations are more frequent. Conversely, rural areas typically feature higher average speeds and fewer fluctuations.

As a result, internal combustion engine (ICE) vehicles consume more fuel in cities, where frequent speed changes have a greater impact than the lower average speed. In contrast, vehicles equipped with regenerative braking such as BEV can recover energy during deceleration, partially compensating for these losses. In urban environments, the lower average speed becomes the dominant factor, leading to reduced energy consumption for EVs and fuel cell vehicles compared to rural driving conditions. On average, ICE vehicles consume about 30% more fuel in urban areas than in rural settings, whereas regenerative braking vehicles use roughly 10% less energy in cities than during rural trips.

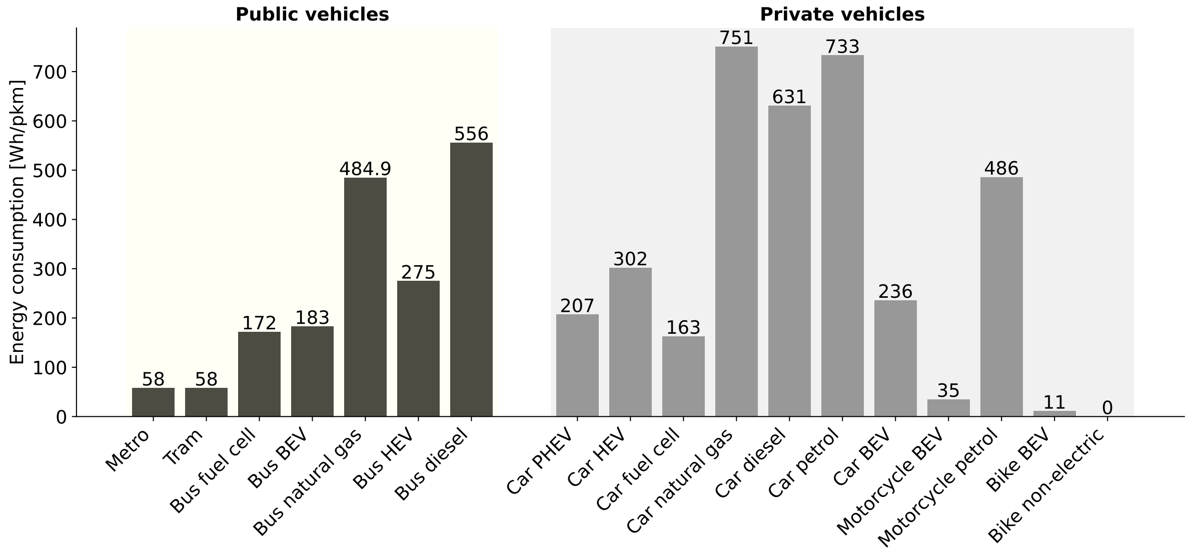

Figure 3.6 Energy consumption of various vehicle types in urban environments

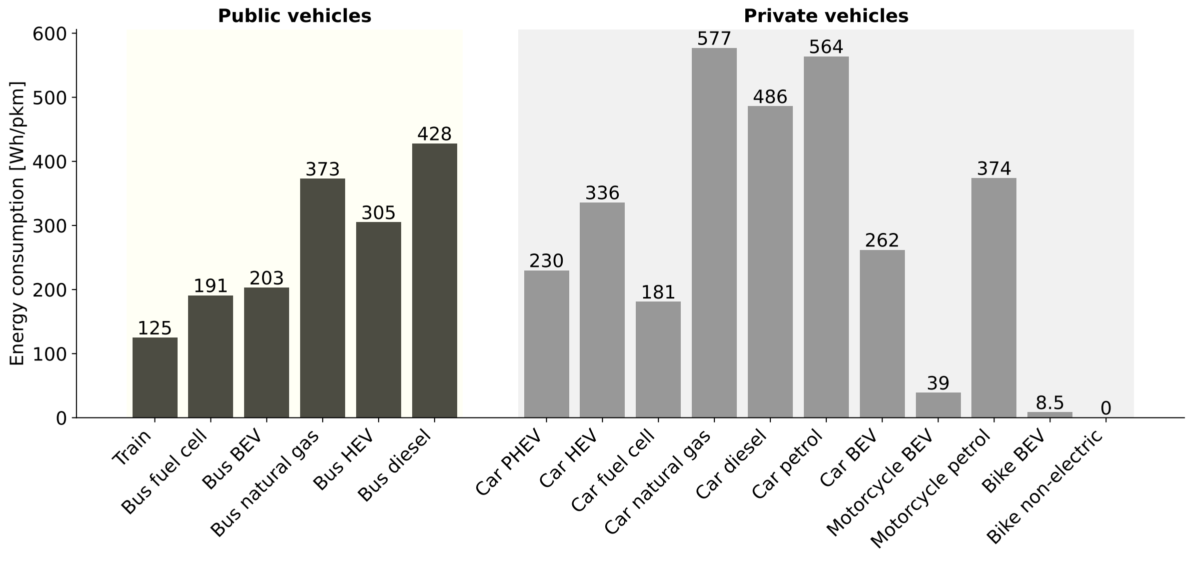

Figure 3.7 Energy consumption of various vehicle types in rural environments

The two graphs, Figure 3.6 and Figure 3.7, illustrate the energy consumption of various vehicle types in urban and rural settings, distinguishing between public and private transport. Overall, combustion engine technologies consume significantly more energy than other power trains. In general, public transport vehicles tend to use less energy per passenger than private ones. However, these results can vary significantly depending on occupancy in these graphs, 2019 occupancy rates have been used (see Table A.6).

As expected, active mobility modes exhibit very low energy consumption. The same technology, when used in the public sector, generally consumes less energy than in the private sector, due to higher occupancy rates. Within public transport, rail technologies consume significantly less energy than buses. This difference is less pronounced in rural areas, where trains and fuel cell (FC) buses show energy consumption levels closer to that of cars. However, for all internal combustion engine (ICE) public buses, energy consumption remains notably high.

Among private vehicles, 100% ICE cars consume substantially more energy than other technologies. Aside from that, the energy consumption of the remaining technologies is relatively close. Petrol motorcycles consume energy amounts comparable to other combustion vehicles. Despite their smaller size, motorcycles do not benefit from proportional consumptions gains, and their low average occupancy further reduces their efficiency compared to other modes where occupancy can be increased.

3.2.3 Size

The fleet size for each technology is determined by the maximum between the number of vehicles required during the peak hour based on vehicle capacity, which defines the number of pkm per hour per vehicle Equation A.6 and the number of vehicles needed over the course of a year defined in Equation A.7.

$$veh_{cap}(i) = occupancy_i * Av.Speed_i \qquad \forall i \in mobilitytechnology \qquad (3.1)$$

$$veh_{cap}(i) = occupancy_i * Av.distance_i \qquad \forall i \in mobilitytechnology \qquad (3.2)$$

3.3 Transport infrastructure

In the previous chapter, the various infrastructures required to support the energy and mobility systems were introduced. These include both energy grid infrastructures and transport-related infrastructures such as charging stations, road networks, and railways.

Among these, grid infrastructure and fuel/charging systems are directly integrated into the EnergyScope optimization model, as their costs are linked to the selected technologies. This integration ensures consistency when accounting for these costs. In contrast, network infrastructures that are not technology-specific such as road and rail networks are assessed in a post-optimization step, since they depend solely on the fleet composition, which is provided as an input to EnergyScope.

This section presents the data required to characterize each of the infrastructures are shown on Table 3.2 and Table 3.3 . The sources and assumptions underlying these data are explained in the different subsections.

Table 3.2 Transport infrastructure parameters for the optimization

	c_{inv}	c_{maint}	Lifetime	Number	Sources
Fuel & Charging	[M€$_{2015}$/#]	[k€$_{2015}$/#]	[years]	[veh/#][b]	
Private ICE station	1.5	150	20	1900	[14]
Public ICE station	1.5	150	20	100	[14]
Private CNG station	0.4	40	20	400	[15]
Public CNG station	0.6	60	20	40	[15]
Private H2 station	2	200	20	300	[16]
Public H2 station	3	300	20	30	[16]
Private EV charger[a]	0.006	0.3	10	15	[17][18] [19]
Public EV charger	0.05	0.5	10	1	[17][18] [19]
Train	7.5	330	100	555	[20] [21]
Grid	[M€$_{2015}$/GW]	[k€$_{2015}$/GW]	[years]		
Electricity[c]	74,919	0	80		[3]
Electricity-extra[d]	368	0	80		[3]
Hydrogen	600	30	20		[22]
Gas	840	25.2	20		[23]
Ammonia	800	28	20		[24]

[a] One charging station is consider to be 19.1 kW as it is the average power of one charging station in France. And 20% of the cost is dedicated to public cost [25].

[b] In energyscope, the number of of charger is determined by pkm/# which is different for each scenario.

[c] It is the total installation cost of the network and doesn't depend on the capacity of the lines

[d] It is based on the installed capacity of intermittent power sources, not on the maximum power capacity of the lines.

Table 3.3 Transport infrastructure parameters for the post optimization

	c_{inv}	c_{maint}	**Lifetime**	**Sources**
Transport network	[€$_{2015}$/vkm]	[€$_{2015}$/vkm]	[years]	
Active road[a]	0.2	600	20	[26]
Motorcycle	0.011	0.003	1	[27]
Car	0.018	0.0046	1	[27]
Bus	0.401	0.104	1	[27]
Tram	5.778	1.235	1	[27]
Metro	11.871	2.539	1	[27]
Train	18.700	4.000	1	[27]

[a] No data is available for cycling infrastructure per vkm, investment and maintenance costs are estimated based on the total length of the network. Investment costs are expressed in M€/km then annualized, while maintenance costs are in €/km considered as yearly.

3.3.1 Transport network infrastructure

Transport network infrastructure refers to the combination of physical assets and organizational systems that enable movement between locations. It includes tangible components such as roads, bridges, and railways, as well as intangible elements like traffic control systems, signage, and lighting.

The information in this subsection, excluding active mobility, is based on the European Commission's report on transport infrastructure expenditures and costs [27]. The overall cost is assessed using both investment costs and operation and maintenance (O&M) costs per vehicle-kilometre.

- Investment expenditures include spending related to the development and renewal of infrastructure:
  - Enhancement expenditures: investments in new infrastructure or extensions of existing infrastructure that improve capacity or extend its service life.
  - Renewal expenditures: replacement or refurbishment of infrastructure components with an expected lifetime of more than 1 to 2 years.
- Operation and Maintenance (O&M) expenditures refer to the ongoing costs of keeping infrastructure functional:
  - Maintenance expenditures: regular maintenance work that restores or preserves infrastructure without improving its original function. These activities typically have a short lifespan.
  - Operational expenditures: costs required for infrastructure operation, such as energy use, traffic management, and signage.

Transport network costs are estimated using historical data on enhancement, renewal, and O&M expenditures, applying the Perpetual Inventory Method. This method accounts for depreciation and includes a discount rate to reflect long-term capital use. These costs are then divided into fixed and variable components and allocated across transport modes using equivalency factors.This factor distributes infrastructure costs by calculating a cost per vehicle-kilometre for each vehicle type using an equivalency factor that reflects its impact on the transport network.

Road - non active mobility

Road infrastructure comprises various components such as roadways, bridges, tunnels, signage, and traffic management systems, all of which require substantial investment, renewal, maintenance, and operational efforts throughout their lifecycle. The associated costs are allocated to vehicle categories using the equivalency factor method.This method considers both capacity-related and weight-related components, with the weight-related part allocated according to the 4th power axle factor (see Appendix 1.1). More detailed information is available in the referenced study [27].

Road - Active mobility

Various types of cycling infrastructure are designed to ensure the safety and comfort of cyclists, primarily cycle lanes and cycle paths.

Cycle lanes are designated lanes for cyclists located on the roadway, marked by road signs or painted lines. They are typically indicated by a continuous or broken line and a bicycle pictogram. While they provide a dedicated space for cyclists, their close proximity to motorized traffic can create safety risks, particularly when vehicles overtake or when doors of parked cars are opened unexpectedly.

In contrast, cycle paths are physically separated from vehicular traffic, offering cyclists greater protection. These paths can be either unidirectional or bidirectional and are generally implemented on dedicated corridors or within the road infrastructure but always remain physically segregated from motorized vehicles.

Considering bicycles as a legitimate mode of transportation requires the establishment of dedicated infrastructure, specifically cycle paths. On average, the construction cost for such infrastructure is approximately 200,000 € per km, with annual maintenance expenses amounting to less than 1% of the initial investment [26]. Due to the light weight of bicycles, the wear on these paths remains relatively constant each year, regardless of usage intensity or type of bike. As there is no available information regarding the renewal costs, only the initial investment is considered, with operation and maintenance costs being treated as dependent on the kilometers of road. The investment is annualized over time

Rail - Train

Rail infrastructure costs are allocated across different train categories, including high-speed trains, conventional passenger trains (electric and diesel), and freight trains (electric and diesel), using an equivalency factor. This method accounts for both capacity-dependent and weight-dependent components, with weight-related aspects based on tonne-kilometre usage. More detailed information is available in the referenced study [27].

Currently, passenger rail transport in Belgium is operated by SNCB, which exclusively uses the rail network managed by Infrabel.[4] SNCB pays Infrabel fees of around 2€ per train-kilometre for infrastructure use covering the operation and maintenance (O&M) of the network and 17€/MWh for electricity consumption [29]. These fees are significantly lower than the 4€/km estimated by the European Commission for O&M costs. However, this gap is partially explained by public subsidies, as approximately 48% of Infrabel's total costs are covered by government funding [30].

Rail - Tram & Metro

Trams and metro systems are essential components of urban public transport, each with distinct infrastructure and operational costs [5]. Although detailed cost data for tram and metro networks were not available in the report, infrastructure investments are known to vary significantly between the two. In the absence of precise data, investment, operation, and maintenance costs are assumed to follow the same €/pkm values as the train system.

3.3.2 Fueling and Charging

Charging station

The deployment of electric vehicle charging infrastructure is based on the assumption that 1.3 kW of public charging capacity must be installed per electric car, in line with EU regulations. Charging stations are distributed across slow, fast, and rapid chargers according to the national shares observed in France, with one public station serving approximately 15 vehicles. It is assumed that 80% of chargers are privately installed. For electric buses, a single 50kW rapid charger is considered sufficient, with one overnight charge assumed to cover daily operations. The detailed information behind these assumptions is provided in the Appendix 1.3.

[4] Infrabel manages 2,934 km of track, with average infrastructure costs estimated at 6 million € per km [28].

[5] Tram infrastructure typically requires an investment of approximately 22 million € per kilometer, while metro infrastructure can reach around 90 € million per kilometer due to the complexity of construction, including tunneling and underground stations [31]

Fueling station

The number of vehicles served per station varies significantly depending on the fuel type and station usage. Conventional fuels like gasoline and diesel allow stations to handle large volumes typically 1,500 to 2,500 private vehicles per station due to fast refueling times and high fuel flow rates. This corresponds to the actual infrastructure setup in Belgium, where on average each station serves approximately 1,900 cars[6]. In contrast, public diesel stations designed for bus fleets are dimensioned for smaller, fixed groups, typically between 30 and 100 vehicles, as they are usually integrated into depot facilities rather than serving random traffic.

For compressed natural gas (CNG), the vehicle-to-station ratio is generally lower compared to conventional fuels due to longer refueling times caused by compression limitations. Private CNG stations typically serve between 400 and 800 cars, while public depot stations dedicated to bus fleets can handle approximately 30 to 50 buses, assuming a night-time refueling strategy similar to that used for electric bus fleets [15].

Hydrogen stations accommodate even fewer vehicles, as hydrogen refueling involves longer filling durations, high-pressure storage, and cooling systems. Consequently, a typical hydrogen station can serve around 100 to 300 private vehicles or 25 to 35 buses, depending on the configuration and operating conditions, and assuming the same night-time refueling approach used for electric buses [16].

These differences in capacity not only reflect the physical and technical characteristics of the fuels but also have a direct impact on the investment cost of the station. Regardless of the fuel type, the maintenance cost is equivalent to approximately 10% of the investment cost is typically assumed[15, 17] and the lifetime of a station is around 20 years.

3.3.3 Grid

Currently, only the electricity grid and the district heating network (DHN) are represented in EnergyScope. Both are sized based on peak power demand. The electricity grid includes an initial capital cost and accounts for additional costs related to the intermittency of renewable energy sources, proportional to the renewable energy source installed capacity in GW. The DHN is sized based on its maximum transfer capacity in GW.

[6] This ratio reflects the existing infrastructure designed to meet refueling demand efficiently across the country, with a total of 3,091 stations [32] serving 5.8 million fuel-dependent vehicles [33].

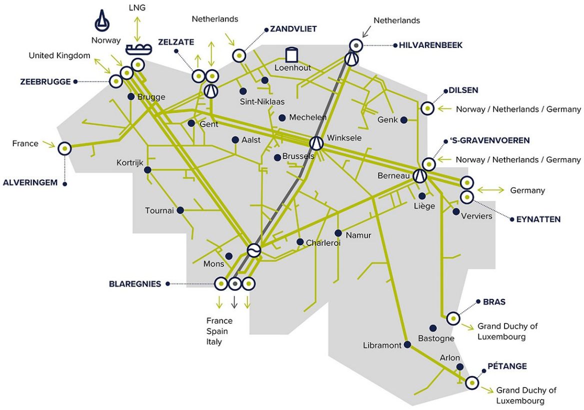

Figure 3.8 The Fluxys Belgium's pipeline network of natural gas from [34]

The electricity grid is designed to deliver power down to nearly every building, and is therefore composed of both transmission system and distribution system. In contrast, the natural gas, hydrogen, and ammonia networks serve a different purpose. These networks aim to interconnect various regions of the country, international borders, ports, industrial sites, and Combined Cycle Gas Turbines (CCGTs). Their structure is more comparable to the current natural gas infrastructure managed by Fluxys, which spans approximately 4,000 km as shown on Figure 3.8.

The associated costs of these grids are calculated in M€/GW-km. However, since the length of the required pipelines is fixed or known, the costs can be found with M€/GW. For hydrogen, the CAPEX is estimated at 0.15 M€/GW-km, with an OPEX of 5% [22]. Ammonia transport is slightly more expensive due to stricter safety requirements, with a CAPEX of 0.2 M€/GW-km and an OPEX of 3.5% [24]. For natural gas, the CAPEX is 0.21 M€/GW-km and the OPEX is 3% [23].

4 Scenarios

This chapter develops mobility scenarios for the year 2050, using 2019 as the reference year. These scenarios will be used to assess their impact on the energy system, fleet size, and overall cost. For each scenario, the following input data will be adjusted:

- The total land base passenger mobility demand of 2050 (see Table A.4)
- The distribution of the demand among all types of mobility (see Table A.4)
- The non fleet-dependent infrastructure (see Table 4.1)
- The fleet consumption (see Table A.5)

The three scenarios represent the most widely discussed pathways considered by policymakers and the public for decarbonizing society. The first reflects a continuation of current behaviors and policies, assuming no significant changes in lifestyle or travel patterns. The second adopts a sufficiency approach, based on the belief that reaching near carbon neutrality is only possible through behavioral change. The last scenario relies on technological optimism, assuming that advances in vehicle efficiency and clean technologies will be sufficient to address the climate challenge without requiring major changes in consumption patterns or mobility habits.

In alignment with the objective of this study, which is to analyze mobility alternatives for achieving carbon neutrality by 2050, all scenarios will be assessed using a CORE-95 perspective. This implies a 95% reduction in the operational CO2 emissions from the energy system compared to 1990 levels, corresponding to a target of 5.25 Mt CO2 [35].

4.1 Scenario 1 : Trends

This scenario is based on the most recent mobility projections for Belgium, published in 2022 by SPF Mobilité et Transports [36]. These projections extend the modal share to 2040, assuming no major policy changes, and are based on the latest reliable data (2019)[1]. These forecasts take into account transport costs, the perceived "time cost" of each mode, and population changes. The assumption of no major policy changes means that the evolution of transport demand is projected based on the continuation of current fiscal and tariff policies, the implementation of existing European directives (including new Euro standards and improvements in vehicle energy efficiency), and macroeconomic and sociodemographic perspectives from the Bureau fédéral du Plan. It also takes into account the most recent energy price projections and considers a structural increase in teleworking, accelerated by the COVID-19 pandemic. Since the change in mobility is relatively slow without significant political or societal changes, the results for 2040 will be extrapolated to 2050.
The evolution of transport demand is driven by two key factors: volume and behavior.

- Volume : The average number of kilometers traveled per person in Belgium increases slightly until 2030, before gradually declining, reaching a 1% reduction by 2050 compared to 2019. With an annual population growth of (+0.3%/year), it contributes to an increase of approximately 8.6% of the total passenger mobility demand from 2019.
- Behavior : The changes, particularly the rise of telecommuting, play a role. The study assumes that by 2040, 40% of employees will work remotely an average of two days per week. While this may seem like a significant shift, it is important to note that work-home commutes represent only 20% of the travel reasons. Moreover, trips not taken for commuting to work will often be replaced by other travel during remote workdays, such as supporting others in their transport needs or engaging in additional leisure activities. The changes in behavior lead to a slight shift in modal share, though cars remain dominant with only a 0.5% decrease. Active mobility has seen a growth of +35.2%, mainly driven by increased cycling in cities, while other forms of active mobility grow only proportionally to the population increase. In contrast, rail transport declines by 10%, especially due to teleworking. Bus usage shows a global increase of +8.8% in total pkm traveled, consistent in both urban and rural areas. The number of two-wheelers remains stable per person. All other pkm are traveled by car.

[1] The COVID years are not considered, and mobility data typically takes two years to be published

In a scenario where no major policy changes are implemented, public infrastructure and transportation offerings would largely remain unchanged, as significant investments are required to alter existing systems. Currently, these infrastructures are financed by the state through various subsidies and investments. Without political commitment and investment, the development of new infrastructure will be unlikely.

In the absence of state intervention, consumption improvements have been made, but they remain limited and insufficient to trigger a significant shift in vehicle consumption. This aligns with the vehicle consumption changes observed in lever 1 in the Pathway Explorer model [35], where only marginal improvements are achieved.

4.2 Scenario 2 : Sufficiency

This scenario assumes a significant behavioral shift in the population and is based on the CLEVER scenario [37], with some adjustments. The CLEVER scenario explores a carbon-neutral energy system for Belgium by 2050, emphasizing energy demand reduction, behavioral changes, and consumption improvements as key pillars for the mobility transition.

As in the previous scenario, changes in land-based mobility demand are primarily influenced by two factors:

- Volume: The CLEVER scenario assumes a per capita travel range between 11,000 and 15,000 pkm per year. In 2019, the average annual travel distance per capita in Belgium was approximately 12,500 km. This indicates that efforts should focus on reaching the lower limit of 11,000 pkm/cap/year. Assuming the same population growth rate as in the first scenario (+0.3% per year), the total passenger-kilometers is calculated accordingly.
- Behavior: Behavioral changes occur on two levels: a societal shift and localized adaptations in urban and rural areas.

  Across all the country, most car transport is currently individual, resulting in a low average car occupancy of 1.24 people per vehicle. This scenario aims to increase car occupancy to 2.0 by 2050, as suggested by the CLEVER scenario [37]. Public transport occupancy is also expected to rise by 20%, although this increase is limited to maintain acceptable comfort levels. The minimum national modal share targets set by the CLEVER scenario are 35% for public transport and 10% for active mobility. With the local measures proposed, these targets are expected to be achieved, with active mobility even surpassing the goal. In addition, car sharing is expected to grow, leading to fewer cars on the road due to a 20% increase in the average annual distance traveled per vehicle.

  At the local level, behavioral changes will vary between urban and rural areas.

  In urban areas, residents will increasingly opt for cycling and public transport, supported by improved infrastructure. Cities represent 29% of the total population, and people in these areas are expected to cycle as frequently as the Dutch, who average 3 km per person per day by bike [38]. To facilitate this change in behavior, all additional cycling distance will be covered by e-bikes, as encouraging the use of non-electric bicycles may be challenging. Public transport usage is projected to increase in cities. To reach the CLEVER scenario's 20% public transport share in total (excluding trains), urban public transport use must rise by 220%. The use of walking and manual bicycles will remain constant per capita, as these modes either require significant physical effort or are time-consuming. Motorized two-wheel vehicle usage per capita will also stay constant. Any remaining mobility demand will be met by cars.

In rural areas, residents will more adopt multi-modal transport strategies, combining modes like bike + train or bus + train. Trains will be preferred for long-distance travel, with SNCB targeting a 15% rail modal share by 2040 [39]. The increase of multi-modal will boost the increase of e-bike up to 5% [40]. The other changes will align with those in urban areas: public transport (excluding trains) will increase by 268%, manual bikes, motorized two-wheel vehicle and walking will remain constant per capita. Cars will cover the remaining modal share. These rural modal shares are consistent with the Wallonia scenario [40], validating the assumptions made.

To support these modal share shifts, significant infrastructure development is necessary. The cycling network will be expanded to match the Dutch cycling network, where dedicated cycle paths constitute a quarter of the national road network [41]. Applying this ratio to Belgium requires a 39,000 km cycling network, supplemented by cycle lanes integrated into existing roads where full separation is not feasible. The tram, metro, and train networks will be expanded and made more efficient to accommodate growing demand and ensure sufficient capacity for all passengers.

The energy consumption of the vehicle fleet will be enhanced by implementing new speed limits, as fuel consumption is directly related to speed. Reducing speeds from 90 km/h to 70 km/h can decrease fuel consumption by 15.4%, while lowering speeds from 120 km/h to 110 km/h results in a 16.4% reduction [42]. Since these measures impact only rural areas, rural vehicles are expected to experience an average 5% reduction in fuel consumption. Additionally, vehicle consumption will also be affected by following Level 2 of the Climact pathway [35].

4.3 Scenario 3 : Technological Growth

This scenario, derived from l'ADEME [43], envisions a pathway propelled by technological advancements. In this vision, the state plays a pivotal role in shaping energy policies and directing investments toward companies pioneering innovative green technologies. More specifically, within the transportation sector, the focus shifts toward improving vehicle energy efficiency, while the demand for transport remains relatively unrestrained.

- Volume: Passenger demand is expected to increase due to several important factors. The state focuses on supporting mobility needs instead of limiting them, which leads to a continuous, if not growing, transport demand. Additionally, remote work has changed mobility patterns. While remote work may reduce the number of home to work trips, new types of trips, like extended stays away from home or trips related to children, have emerged, affecting overall demand. The rebound effect, where improvements in transport efficiency lead to higher demand, also contributes to growth. Together, these factors are expected to result in a 13% increase in transport demand per capita.

- Behavior: Across all the country, public transport occupancy rates are expected to rise by 15% due to targeted policies and significant infrastructure investments. Additionally, shared mobility options, like car-sharing services, will be promoted as part of a broader strategy to improve vehicle occupancy and reduce the number of individual car trips. These changes are expected to increase car occupancy from 1.24 to 1.8.

  Locally, cities are undergoing a shift toward more sustainable modes of transport, such as cycling and public transport. Local government projects focused on improving cycling infrastructure and encouraging electric bikes are driving this change. Cycling is becoming more popular in city centers, and even suburban areas are seeing an increase in use, thanks to the convenience of electric bicycles. As a result, the number of cycling kilometers per person is expected to reach 3 km per day in cities. Public transport use is projected to grow by 20% in urban areas, due to large investments in express services, metro lines, trams, and high-service buses, improving connections and accessibility.

  In rural areas, the shift toward more sustainable transport options is slower. Although cycling is still used, it is mostly for short trips. Therefore, the effect of improving cycling infrastructure is expected to be limited in rural areas. Public transport use is expected to grow by only 3%, due to lower investments and longer travel times between destinations. Car use is still expected to be the main mode of transport in these areas, with only a small decrease projected. Additionally, train traffic between major cities is expected to rise by 37%, with new lines and better traffic control. As a result of these changes, car use is expected to decrease by 3%.

To achieve this modal shift, significant infrastructure changes will be required, with a primary focus on expanding the cycling network. Similar to scenario 2, the cycling infrastructure will be developed to match the level seen in the Netherlands, where a quarter of the national road network consists of dedicated cycle paths (excluding roads with cycle lanes).

The energy consumption of the vehicle fleet is expected to decrease significantly due to the transition to more energy-efficient fuels and improved vehicle performance. With the state fully committed to advancing internal efficiency, the expected improvements align with Level 4 of the Climact Pathway Explorer [35].

4.4 Summary

This section presents the outcomes of the scenarios based on the assumptions described earlier. The values used for the graphs are provided in Appendix 1.4.

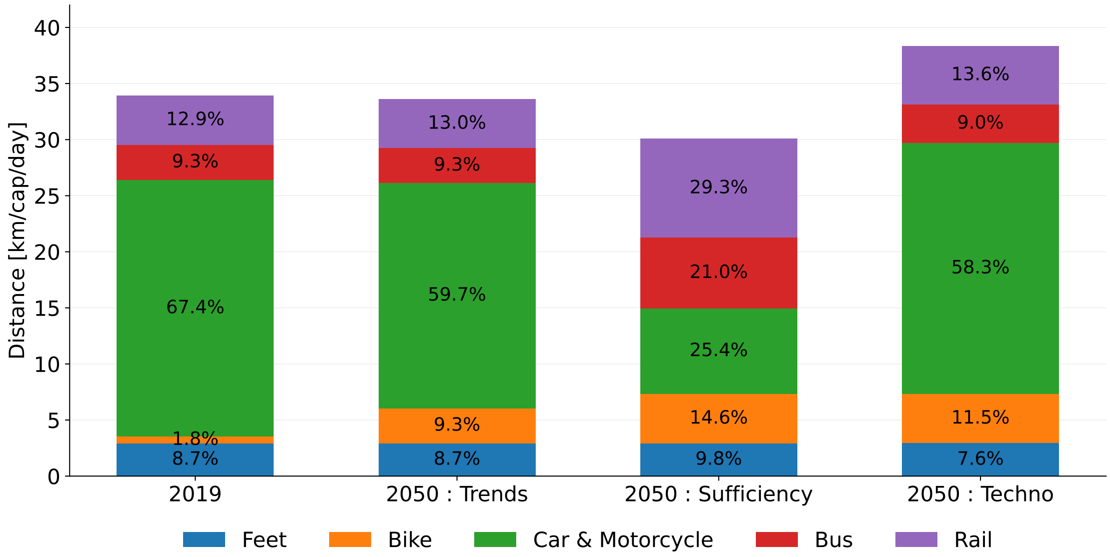

Figure 4.1 Daily travel distances by mode per capita in urban areas

In urban areas, the most notable change from 2019 appears in Scenario 2, where car and motorcycle usage declines significantly. This reduction is partially offset by an increase in travel by bicycle and public transport. In contrast, Scenarios 1 and 3 exhibit more moderate shifts, with cars and motorcycle remaining the dominant modes of transport, while bikes and public transport experience only modest growth.

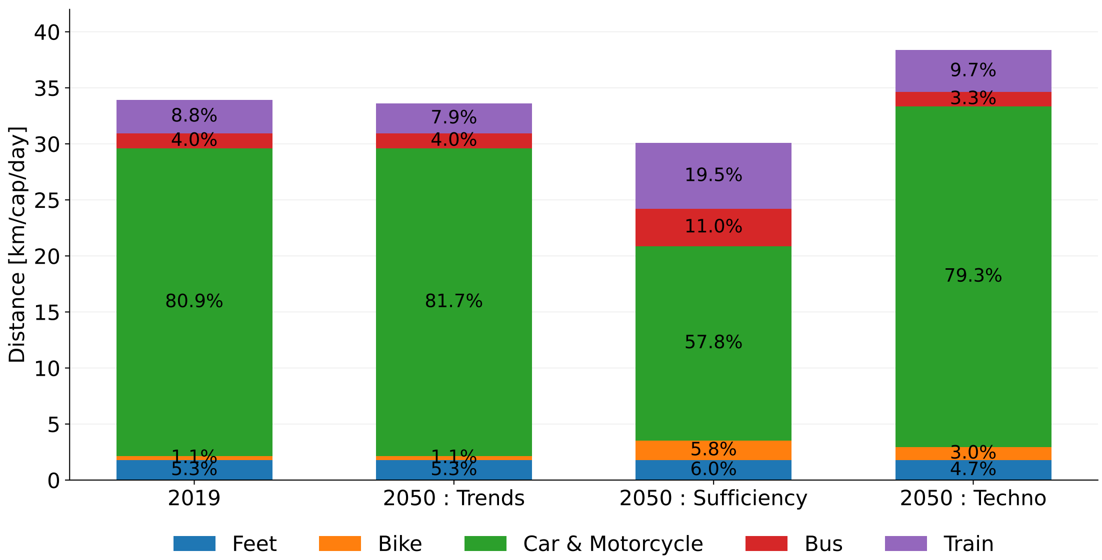

Figure 4.2 Daily travel distances by mode per capita in rural areas

In rural areas, cars and motorcycle remain the dominant transport modes across all scenarios. However, Scenario 2 shows a noticeable shift, with a reduction in car usage and a corresponding increase in train and bus travel. Scenarios 1 and 3 exhibit minimal changes compared to the base year, suggesting that rural mobility patterns are less sensitive to scenario driven transformations.

The corresponding cycling infrastructure developments for each scenario are shown in Table 4.1. As expected, both the Sufficiency and Techno scenarios exhibit a substantial increase, with cycling infrastructure expanding by 975%.

Table 4.1 Non-fleet dependent characteristics per scenario

Year/Scenario	2019	Trends	Sufficiency	Techno
Active road network	4000[a]	4000	39,000	39,000

[a] The considered non-active road network includes only those with a separated path as defined previously in subsubsection 3.3.1.

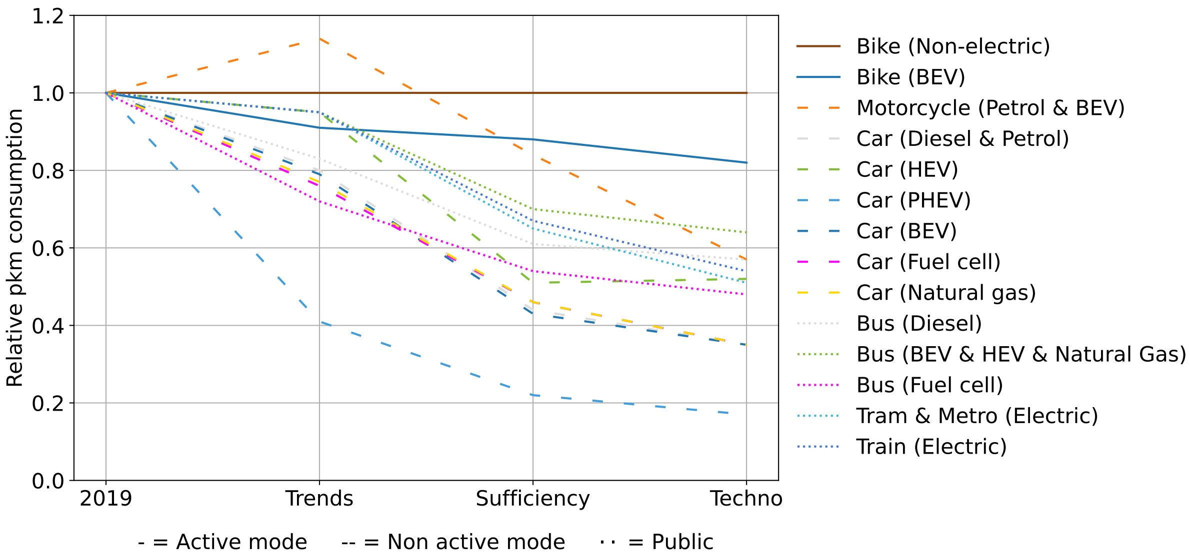

Figure 4.3 Relative passenger-kilometre consumption of different technologies across the scenarios, using 2019 as the reference year.

Fleet consumption per pkm varies across scenarios in the model, as it depends on both occupancy rates and the specific energy consumption of each vehicle type. Two factors that evolve differently depending on the scenario. The results, shown in Figure 4.3, highlight these differences.

Overall, the most significant decrease in consumption is observed for cars among non-active modes, primarily due to substantial increases in occupancy rates. Public transport modes also show moderate reductions, while motorcycles only experience a notable decrease in the Sufficiency and Techno scenarios, where bigger improvements in vehicle efficiency are assumed. Bicycles show minimal variation across scenarios, as their occupancy remains constant and they already have low energy consumption.

Among the scenarios, the Techno scenario achieves the greatest overall reduction, driven by both increased car occupancy and significant improvements in vehicle efficiency. The Sufficiency scenario also shows a substantial decrease, primarily due to higher occupancy rates. Its consumption levels remain slightly above those in the Techno scenario, but the two are close. The Trends scenario shows only minor reductions in most modes. Notably, motorcycle consumption increases in this scenario, reflecting the assumption that larger and more powerful models will be introduced in the future.

5 Results

This chapter presents the main results derived from the modeling performed across the different scenarios. It highlights key findings related to energy consumption, greenhouse gas emissions, and associated costs within each scenario.

5.1 Energy system - PEC & Conversion technologies

5.1.1 Primary Energy Consumption

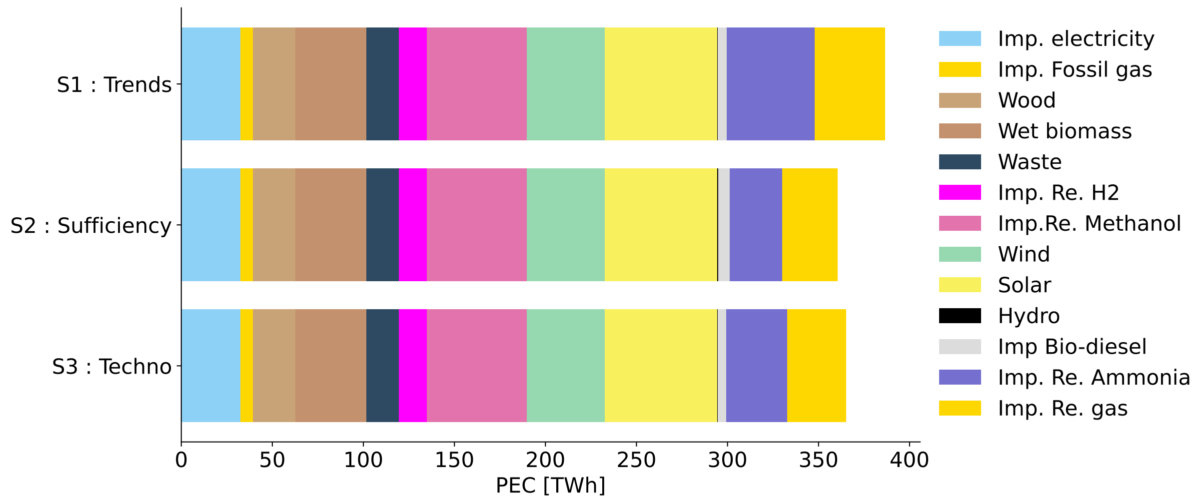

Figure 5.1 Primary energy consumption

The total primary energy consumption remains relatively similar across the three scenarios. The only noticeable differences come from variations in mobility demand, which in turn influence the quantities of imported bio-diesel or electricity produce by imported renewable gas ammonia.

The endogenous primary energy potential is fully utilized in all scenarios:

- 10 GW of onshore wind and 6 GW of offshore wind, together generating 43 TWh/year
- 59.3 GW of photovoltaic panels, generating 61.5 TWh/year
- 0.115 GW of hydropower, generating 0.5 TWh/year
- 23.4 TWh/year from wood
- 38.9 TWh/year from wet biomass[1]
- 17.8 TWh/year from waste[2]

Consequently, endogenous primary energy consumption reaches its maximum availability with 185 TWh and remains constant across scenarios. The remaining primary energy required to satisfy total demand must therefore be met through imports. As a result, the share of imported resources amounts to 50.8% in the Trends scenario, 46.9% in the Sufficiency scenario, and 48.1% in the Techno scenario.
Regarding imported resources, the only explicit constraint considered is on electricity imports, which reach the maximum allowed value of 32.4 TWh/year in all three scenarios.

5.1.2 Electricity Production

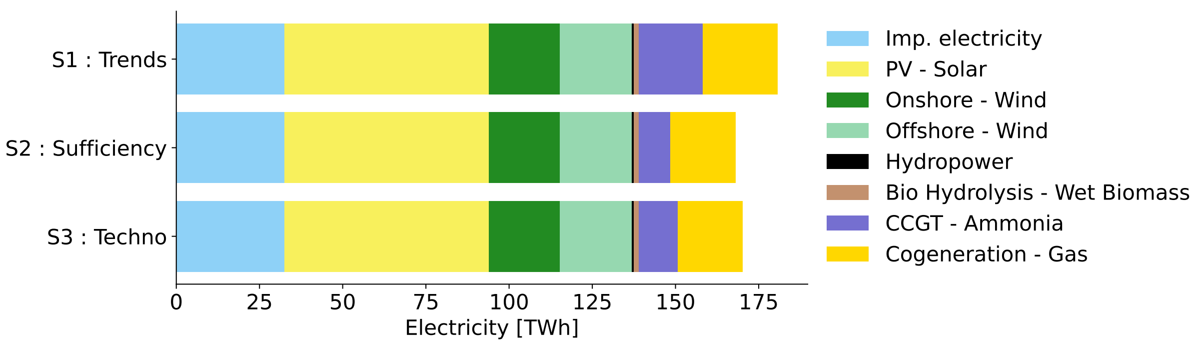

Figure 5.2 Electricity production

Electricity production is predominantly covered by domestic resources, accounting for more than 59% in all scenarios. The remaining share is supplied by electricity imports, which reach their maximum limit of 32.4 TWh in each case. Once this import capacity is fully used, the remaining electricity demand is met by gas-fueled CHP plants and by combined cycle gas turbines (CCGT) operating with imported renewable ammonia.
The average electricity price is highest in the scenario with the largest electricity demand since the additional electricity produced by CCGT and cogeneration is more

[1] Wet biomass includes the production of bioethanol, biomethanol, biogas, and biodiesel, as defined in EnergyScope TD.

[2] Waste includes common sludges, municipal solid waste (MSW) from landfills and non-landfill processes (e.g., composting, recycling), and paper/cardboard.

expensive. The resulting prices are 91.0€/MWh in the Trends scenario, 89.2€/MWh in the Sufficiency scenario, and 89.7€/MWh in the Techno scenario.

5.1.3 Heat production

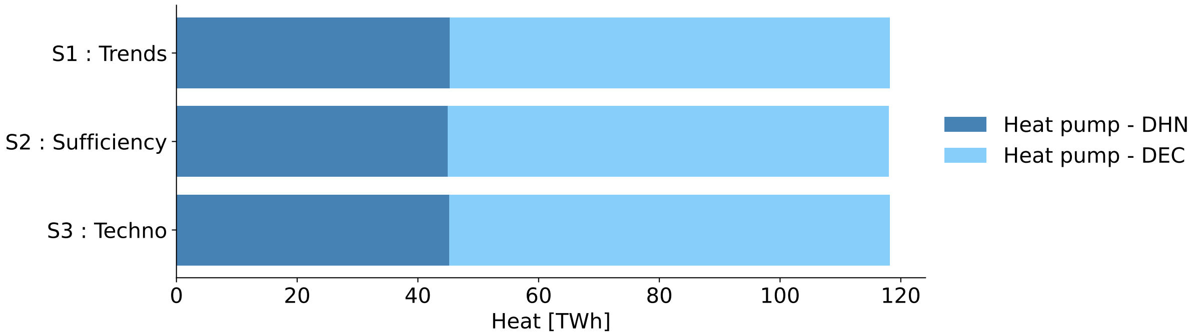

Figure 5.3 Low temperature heat production

The production of low-temperature heat is identical across the three scenarios and is entirely supplied by heat pumps. Decentralized heat pumps, which are generally smaller, are used to meet decentralized heating needs, while larger centralized heat pumps supply the District Heating Network (DHN).

A portion of the heat produced by decentralized heat pumps is stored directly within the units and used later when needed. This storage accounts for 14.2 percent of decentralized heat demand. During the storage process, 5.5 percent of the transferred heat is lost.

Similarly, in the DHN, part of the produced heat is also stored for later distribution. In this case, the amount of stored heat is higher, reaching 22.6 percent of the end-use demand. Losses during heat distribution in the network amount to 2.3 TWh, representing 5.1 percent of the DHN demand.

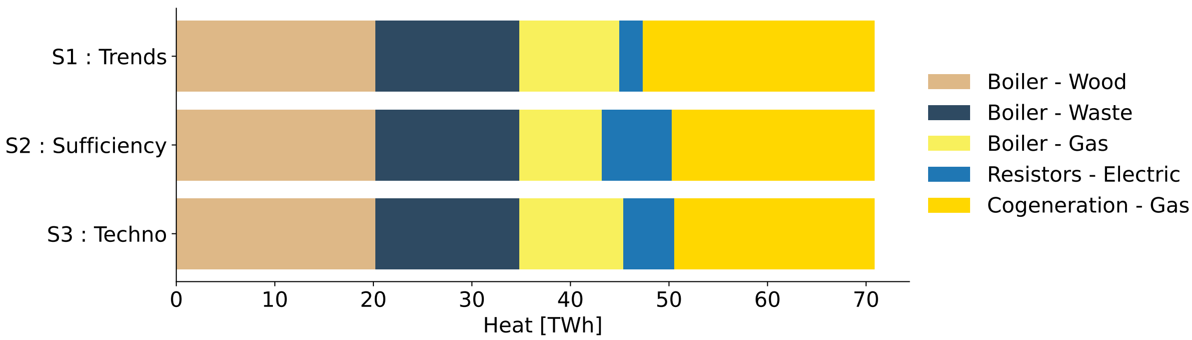

Figure 5.4 High temperature heat production

High-temperature heat production is identical across all scenarios. It is initially supplied by endogenous resources, namely wood and waste, with similar quantities in each case. The remaining heat demand is met by gas and electricity.

The main difference between scenarios lies in the dimensioning of the gas network, which is determined by the hourly peak gas demand. Gas is primarily used to produce electricity and high-temperature heat through CHP units, as well as to supply high-temperature boilers. When peak electricity demand increases largely due to higher electricity consumption related to mobility, the gas network must be sized accordingly to compensate. This larger gas infrastructure not only supports electricity production during peak periods but also enables greater use of gas for high-temperature industrial heat production during off-peak hours.

Higher electricity peaks result in increased electricity costs, which limits the use of electric resistors for high-temperature heat production in scenarios with greater electricity consumption.

5.2 Freight Mobility

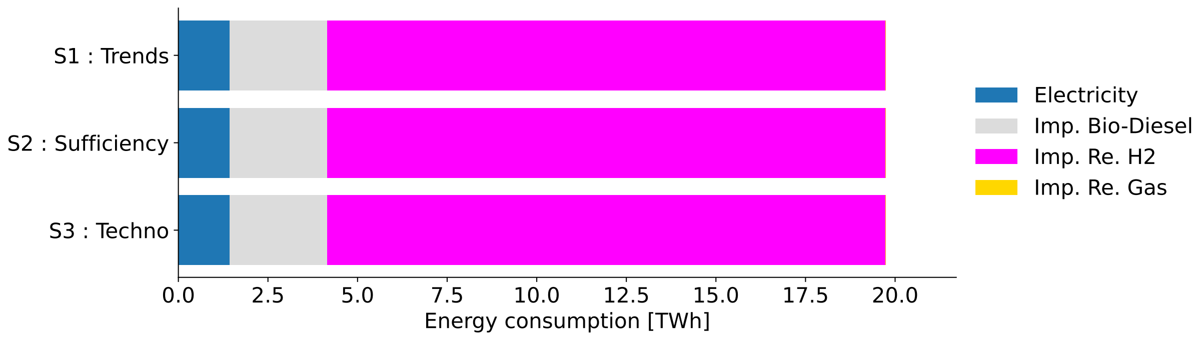

Figure 5.5 Energy consumption of the freight fleet

Freight transport demand is identical across all scenarios, comprising 45% road, 30% inland waterway, and 25% rail in terms of tonne-kilometres (tkm). Only one technology is available for rail transport, namely electric trains, which are therefore selected. Boat transport is powered by bio-diesel, while road freight is entirely handled by fuel cell trucks. However, the share of energy consumed by each mode differs from their respective shares in tkm due to the varying energy efficiencies of the technologies used.

5.3 Passenger Mobility

5.3.1 Fleet size

The real passenger fleet is calculated as the maximum between the hourly peak demand per technology divided by the hourly vehicle capacity of that technology, and the total passenger-kilometres per technology divided by the yearly distance traveled by a single vehicle of that technology (see subsection 3.2.3)

It is important to distinguish between the operational fleet and the real fleet size. The operational fleet refers to the number of vehicles in use on the road, while the real fleet includes both the operational vehicles and additional reserve vehicles used to cover periods of maintenance, repair, or unexpected breakdowns.

For private vehicles, the operational and real fleet sizes are nearly identical, as users can tolerate occasional downtime by using alternative transport options. In contrast, public transport systems require higher reliability and undergo more frequent maintenance. As a result, the real fleet size for public transport is significantly larger than the operational fleet, in order to maintain consistent service levels. This difference is not negligible. Therefore, the fleet size considered is the real fleet size.

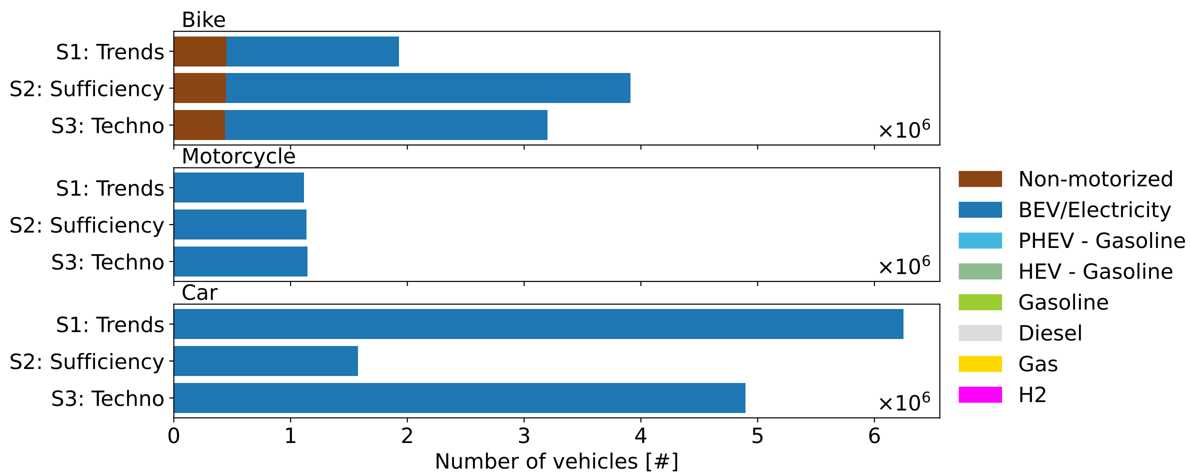

Figure 5.6 Number of real private vehicles

For private vehicles, bicycles represent a moderate share of the real fleet, showing a notable increase in the Sufficiency scenario, reaching nearly 4 million bikes compared to about 1.9 million in the Trends scenario and 3.1 million in the Techno scenario. Motorcycles account for a limited share, around 1.1 million vehicles across all scenarios, with little variation. Cars dominate the real private fleet in both the Trends and Techno scenarios, with more than 6 million and 4.9 million vehicles respectively. In the Sufficiency scenario, however, the number of cars drops significantly to around 1.6 million, making bicycles the most common vehicle type within the private fleet.

Electrification is visible across all private vehicle types. For bicycles, a small proportion remains non-motorized.

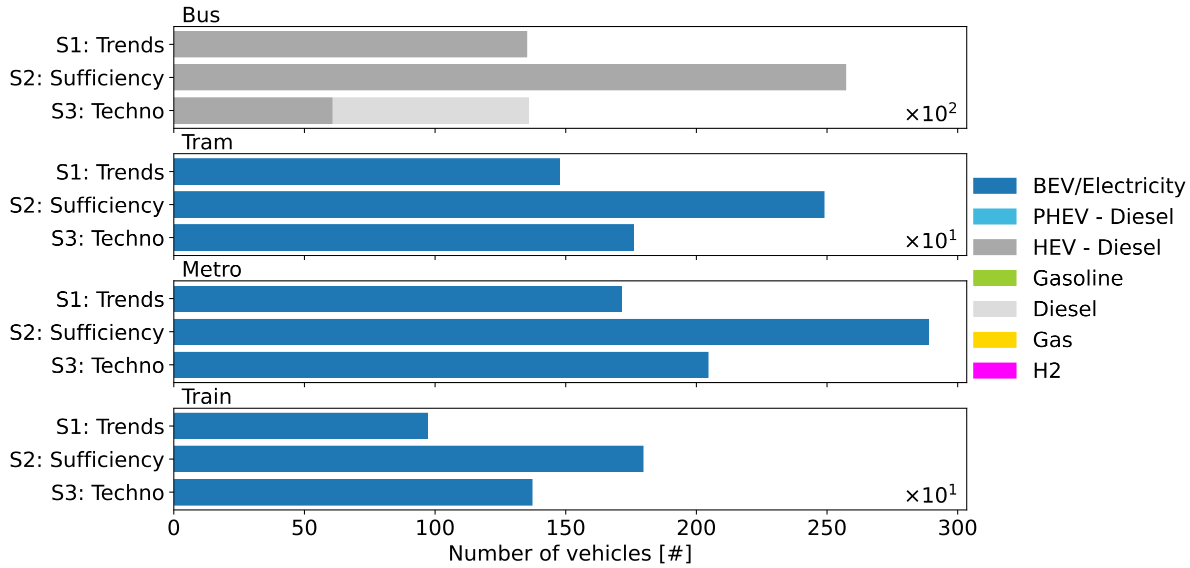

Figure 5.7 Number of real public vehicles

For public vehicles, the total number of real vehicles is much smaller in absolute terms compared to private vehicles and shows different dynamics. The real fleet includes buses, trams, metros, and trains. Buses represent the largest share, with around 13.5 thousand real vehicles in the Trends scenario and a substantial increase to 25.7 thousand in the Sufficiency scenario. Rail vehicles follow a similar trend, with a 20% increase in the Techno scenario and a much larger growth in the Sufficiency scenario. Trams and metros are approximately 1,500 and 171 vehicles respectively in the Trends scenario, both experiencing a 20% increase in the Techno scenario to about 1,800 and 205 vehicles. The Sufficiency scenario shows the most significant growth, with 2,500 trams and 289 metros. Trains follow the same pattern, growing from around 973 in the Trends scenario to 1,372 and 1,797 trains in the Techno and Sufficiency scenarios, respectively. Electrification becomes dominant across all rail public transport modes but buses remains ICE vehicles.

5.3.2 Energy consumption

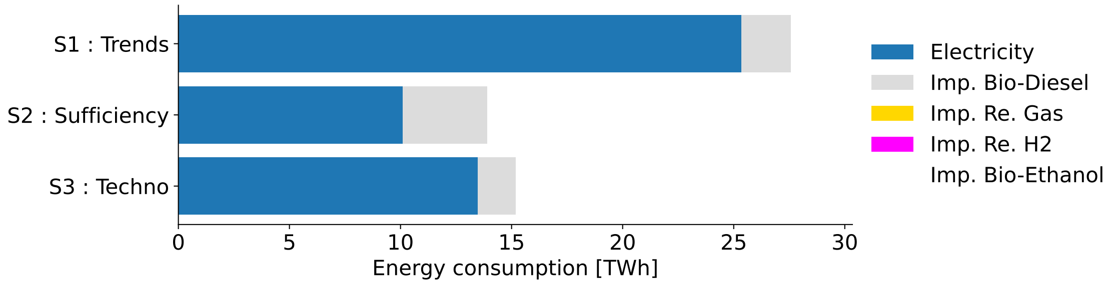

Figure 5.8 Energy consumption of the passenger fleet

The three scenarios show big differences in energy consumption levels, though the types of energy used remain consistent.. The Trends scenario records the highest overall consumption, reaching around 27.6 TWh per year, while the Techno and Sufficiency scenarios show significant reductions to approximately 15.2 TWh and 13.9 TWh, respectively. This corresponds to nearly or more than a 50% decrease compared to the Trends scenario for both alternative scenarios. In terms of the share of total final energy demand, the mobility sector represents 7.3% in the Trends scenario, 4.5% in the Techno scenario, and 3.8% in the Sufficiency scenario.

Electricity becomes the dominant energy carrier across all scenarios, illustrating the shift towards fleet electrification. The only part of the fleet that does not rely on electricity but instead uses alternative fuels is the bus fleet, which operates on imported bio-diesel. Bio-diesel accounts for 8.1%, 27.3%, and 11.3% of total energy consumption in the Trends, Techno, and Sufficiency scenarios, respectively.

The Sufficiency scenario, featuring the lowest overall energy consumption, reflects both a reduced fleet size and a modal shift towards more energy-efficient forms of transport, such as bicycles and public transportation. The Techno scenario, despite achieving a significant level of electrification and technological improvements, maintains a higher energy demand than the Sufficiency scenario due to a larger operational fleet. Renewable gases, renewable hydrogen, and bio-ethanol are not used by the passenger fleet in any of the scenarios.

5.3.3 Mobility Cost

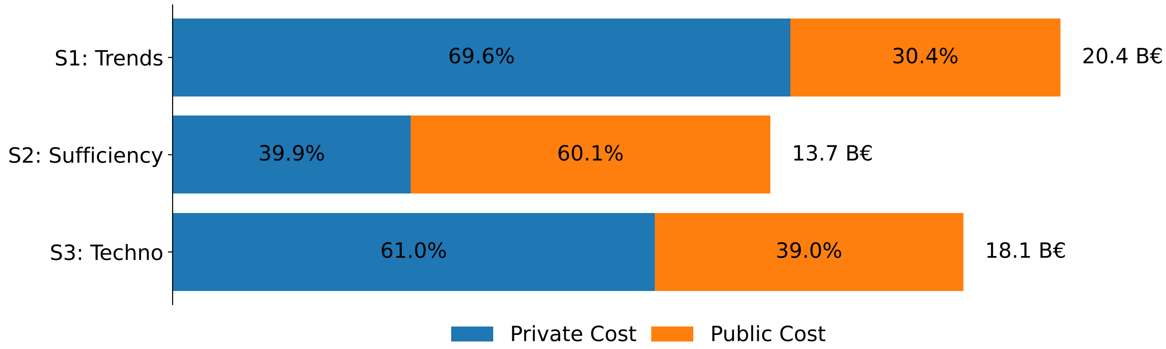

Figure 5.9 Distribution of the total mobility cost

The Trends scenario is the most expensive in terms of total system cost (€20.4 billion), followed by the Techno scenario (€18.1 billion), with the Sufficiency scenario being the least costly (€13.7 billion).

These costs will not be paid entirely and immediately by the population. A part will be paid directly by individuals, referred to as private costs, while the remaining portion will be covered by the state or private company[3], referred to as public costs. For example, in the case of a car, the owner is responsible for the purchase, maintenance, and operation, but the road infrastructure is financed by the state. With this distinction in mind, the Trends scenario results in the highest share of private expenditure, accounting for 69.6 % of the total cost, followed by the Techno scenario with 61.0 %. In contrast, the Sufficiency scenario reverses this pattern, with public costs exceeding private ones. In this case, private costs represent only 39.9% of the total.

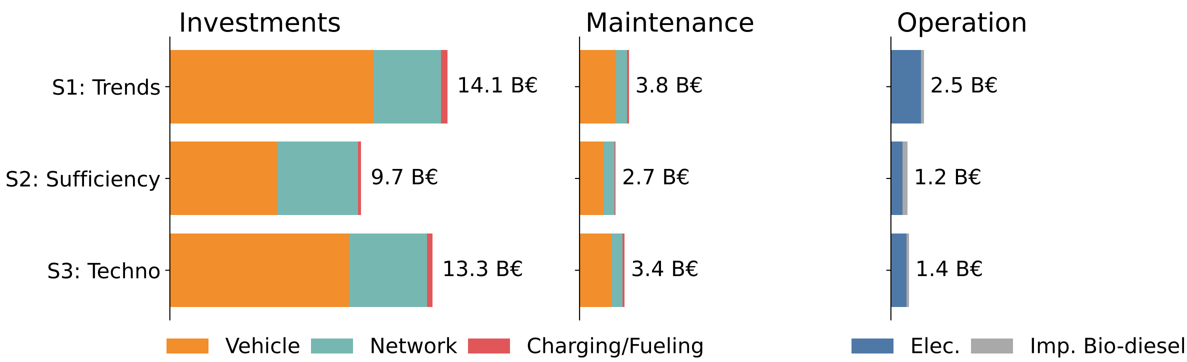

Figure 5.10 Total Mobility Cost Allocation

Most of the mobility cost comes from investments, followed by maintenance, and then operation. This is clearly seen in all three scenarios, where investments represent the

[3] It is assumed that the concept of company cars no longer exists

largest share of the total system cost: 69.1 % in the Trends scenario, 70.8 % in Sufficiency, and 71.7 % in Techno. Within these investments, the largest share is attributed to cars and the transport infrastructure network. These components will therefore be examined in more detail below.

Vehicles account for the majority of these investment costs, with 73.4 % of investment allocated to vehicles in the Trends scenario, 68.3 % in Techno, and 56.7 % in Sufficiency. Charging and fueling infrastructure remains marginal in all cases by never exceeding 2.3 % of total investment. Network costs, which correspond to passenger mobility transport infrastructure, also play a significant role, especially in the Sufficiency scenario where they make up 42.3 % of investment, compared to 24.3 % in Trends and 29.7 % in Techno.

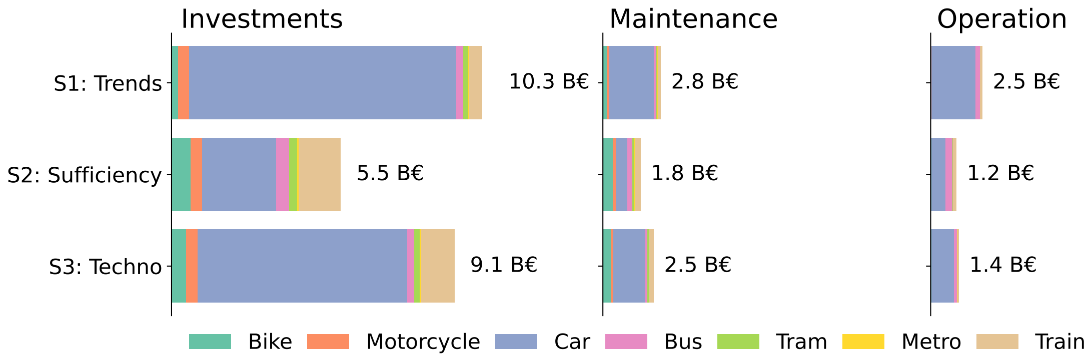

Figure 5.11 Distribution of the vehicle mobility cost across different type of mobility

Vehicle related costs are divided into three categories: investment, maintenance, and operation. The percentage distribution of vehicle types for investment varies across scenarios, but cars consistently dominate. In the Trends scenario, cars dominate with 83.1%, while trains and motorcycles represent only 7.4% and 3.4%, respectively. In the Sufficiency scenario, cars still make up the majority at 50.2%, but the share of trains increases to 13%, and bikes are introduced at 6.0%. The Techno scenario shows a shift, with cars at 74.0%, trains at 11.8%, and bikes at 5.3%.

The maintenance costs follow a similar distribution as the investment costs. In all scenarios, car-related maintenance costs are the highest, with a huge increase in the share of maintenance costs in the Sufficiency and Techno scenarios due to the increased use of bikes.

The operational costs, follow a similar trend. In the Trends scenario, car related costs account for 85.3%, with buses and motorcycles making up smaller portions at 8.1% and 4.0%, respectively. In the Sufficiency scenario, car-related costs drop to 53.9%, while bus costs increase to 25.3%, and train costs rise to 12.4%. In the Techno scenario, car-related operational costs remain high at 78.5%, but bus costs are more significant at 11.4%, and train costs are slightly lower at 5.2%.

The breakdown of vehicle related costs clearly shows the dominance of cars across all categories. Investment costs are the largest, followed by maintenance, with operational costs being the smallest part of the total vehicle cost. Maintenance, investment, and operational costs all follow similar patterns, with car-related costs decreasing significantly in the Sufficiency and Techno scenarios due to a higher reliance on public transport and bikes, and fewer cars on the road.

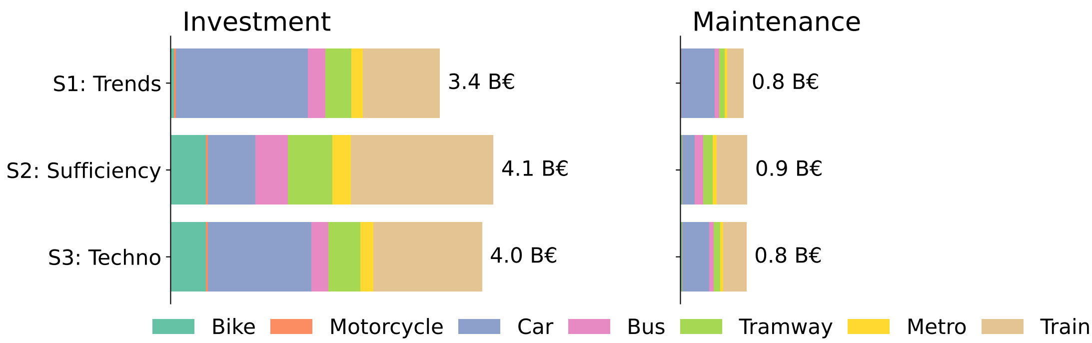

Figure 5.12 Distribution of the mobility transport network cost across different type of mobility

The investment pattern for the passenger transport network follows the opposite order of vehicle investment costs, with the Sufficiency scenario having the highest infrastructure investment, followed by the Techno and then the Trends scenario. The high cost in the Sufficiency scenario is mainly due to the development of rail infrastructure, which is expensive and outweighs the savings from reduced car infrastructure and the relatively low cost of bike infrastructure. The Techno scenario also requires a significant investment, nearly equal to the Sufficiency scenario. This is largely due to both the expansion of rail infrastructure and an increase in overall mobility demand, which raises the total infrastructure needs compared to the other scenarios. In contrast, in the Trends scenario, infrastructure investment is primarily driven by car-related infrastructure.

Maintenance costs show only minor differences across the three scenarios, and can therefore be considered approximately equal.

5.4 GWP emissions

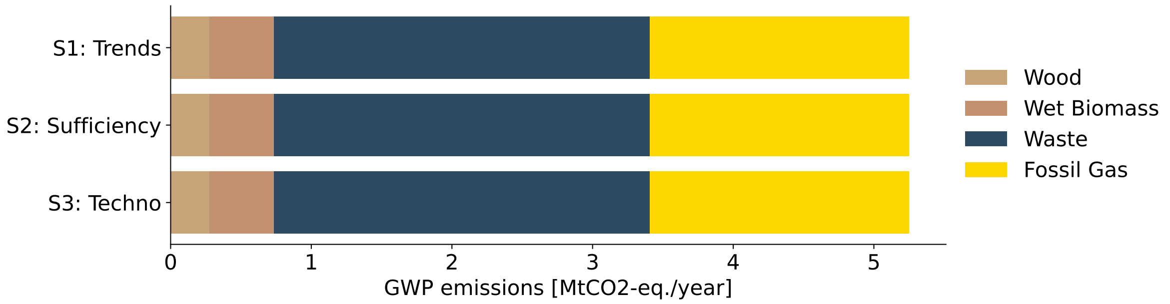

Figure 5.13 Operational GWP emissions

Operational GWP emissions are identical across all three scenarios, reaching 5.25 million tonnes per year. This is because the chosen technologies prioritize lower costs over the lowest possible operational CO2 emissions. Although technologies using wood, wet biomass, and waste are cheaper, their use is limited due to the endogenous nature of these resources. As a result, they represent the maximum available capacity which is similar across all scenarios. The remaining operational CO2 until reaching the CORE95 is covered by fossil gas.

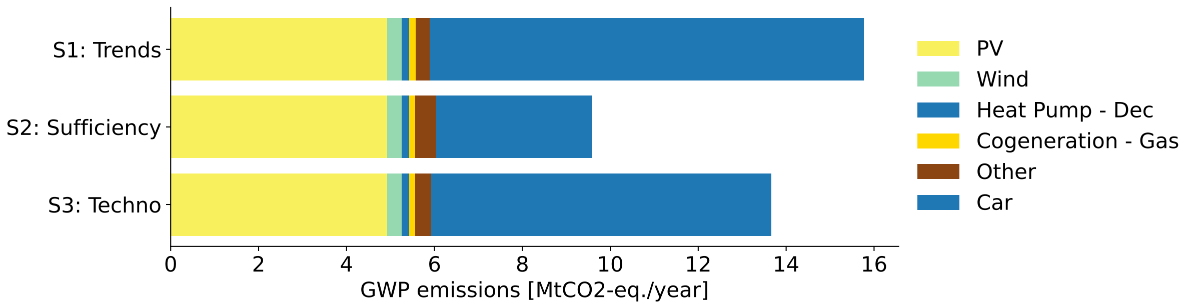

Figure 5.14 Construction GWP emissions

The GWP emissions associated with construction differ across the three scenarios: the Trends scenario results in 15.7 Gt CO2-eq, the Sufficiency scenario in 9.5 Gt CO2-eq, and the Techno scenario in 13.6 Gt CO2-eq. These differences are primarily driven by the construction of battery electric vehicles (BEVs), while the impact of other technologies changes only slightly.

The high emissions from car construction are mainly due to the large number of vehicles that need to be produced. As shown in Figure 5.14, GWP emissions from car construction are more than three times lower in the Sufficiency scenario compared to the Trends scenario as the size of the car fleet follows the same path.

The "other" category, which includes emissions from all other technologies and Gas CHP plants, varies only slightly and remains negligible compared to emissions from car construction. Another significant contributor to construction-related CO2-eq emissions is the installation of photovoltaic (PV) panels which is constant across the scenarios.

6 Discussion

6.1 Results

The Trends scenario represents a continuation of current mobility habits, with limited changes in behavior and only small improvements in vehicle efficiency. In this scenario, private cars remain the main mode of transport and are mostly used with low occupancy, which results in a large vehicle fleet. This leads to the highest energy demand, overall cost and greenhouse gas emissions among the scenarios. However, because there is no major shift toward rail-based transport, transport network infrastructure costs remain relatively low. Most of the cost in this scenario is private, coming from the purchase, use, and maintenance of personal vehicles. The continued reliance on individual transport places significant pressure on the energy system, especially in terms of electricity and fuel needs. While vehicle technologies are slightly more efficient, the absence of structural change means the transport sector remains a major contributor to emissions and overall system costs.

The Sufficiency scenario takes a very different direction. It focuses on reducing car use, promoting public and active transport, and encouraging shared mobility. This results in a much smaller vehicle fleet. Although this scenario has the lowest total cost overall, it comes with the highest transport network infrastructure cost due to the increased demand for rail transport. However, private costs are much lower, as fewer personal vehicles are needed. This scenario also achieves the lowest scope 2 greenhouse gas emissions, mainly due to the reduced number of car and lower energy demand. The limited reliance on energy-intensive vehicle production and the efficient use of energy make this the most sustainable option for both the energy system and the environment. It highlights how behavioral change and smarter mobility choices can reduce emissions effectively and affordably.

The Technological Growth scenario follows a middle path. Transport demand is the highest, but emissions and energy use are reduced through technological improvements such as electric vehicles, cleaner fuels, and more efficient engines. The vehicle fleet is smaller than in the Trends scenario but still remains large, requiring substantial investment. In this case, both private and public costs are quite similar: individuals continue to rely heavily on private cars, while the government must make significant investments in rail infrastructure. Moreover, the costs associated with improving vehicle consumption such as developing and deploying advanced technologies are not included in the model but would likely be considerable. When accounting for these, this scenario may in fact turn out to be the most expensive overall. Although energy demand is reduced, the impact on scope 2 emissions remains limited. Compared to the Sufficiency scenario, it is more costly, more resource-intensive, and results in higher emissions, but may be easier to implement since it allows people to maintain their current mobility habits.

6.2 Plausibility of results

The modeled energy system aligns well with the current decarbonization trajectory, particularly with a significant share of electricity production coming from renewable energy sources. Low-temperature heat demand is primarily covered by heat pumps, reflecting ongoing trends in the residential and service sectors. The most difficult decarbonization sector in the actual system beside aviation and agriculture is the high-temperature industrial processes which remains the case in our results since they emits the biggest part of the scope 1 GWP emissions.

The future direction of freight transport is still uncertain. While rail electrification is widely accepted and already underway, the outlook for inland waterway transport and truck freight remains less clear. A complete transition to hydrogen-powered vehicles appears improbable. A more realistic pathway may involve a partial electrification of the freight fleet, with hydrogen serving as a complementary solution where direct electrification is technically or economically unfeasible. This is different with our study where the trucks rely entirely on hydrogen

The results for the overall passenger vehicle fleet seem consistent with future predictions from other models, especially with a strong shift toward electrification. One result that may seem surprising at first is the presence of diesel and hybrid diesel buses, which is the opposite of what public operators are currently doing by electrifying their fleet. However, this can be explained by understanding the past decisions of public transport operators like STIB, TEC, and De Lijn. A few years ago, they could still choose between several fuel types, including hydrogen and natural gas, but those were eventually rejected due to technical problems, high costs, and concerns about fuel supply and price instability. This left diesel, hybrid diesel, and BEVs as the main options. While these had similar TCO (including infrastructure), BEVs were preferred because of their much lower GWP emissions, especially since the diesel used today is not bio-diesel. The impact of GWP emissions on the long-term costs of climate change is expected to be high, so in the end, BEVs will likely be the cheaper option [31]. Our model still selected diesel and hybrid diesel buses because it does not take into account bio-diesel supply limits or the future costs linked to climate change.

6.3 Comparison with existing literature

The comparison is based on results from Climact, which developed a CORE95 scenario along with two variants focusing on behavioral change and technological improvement. These correspond respectively to the Trends, Sufficiency, and Techno scenarios developed in this study. While Climact's results have been published in multiple reports, this analysis draws primarily on two references: one focusing on the energy systems perspective[44], and another addressing investment and cost considerations[45].

Table 6.1 Comparison of passenger demand with Climact CORE95 literature

	Scenario 1		Scenario 2		Scenario 3	
	Trends	**2050 REF**	**Sufficiency**	**Behavior**	**Techno**	**Tech**
Total Bpkm	154	12%	138	0%	176	2%
Active mobility [Bpkm]	14	76%	19	50%	18	38%
Car + Motorcycle [Bpkm]	118	−28%	69	−22%	132	−19%
Bus [Bpkm]	8	150%	18	43%	7	165%
Rail [Bpkm]	14	77%	29	−8%	18	25%

The total passenger demand are aligned across the three scenarios, though Climact adopts more ambitious targets regarding modal shift. This is particularly evident in the higher shares of active mobility and public transport. As a result, the scenarios developed in this study retain a greater reliance on private motorised transport, leading to higher values of car and motorcycle related pkm.

In terms of passenger vehicle fleet, both approaches assume widespread electrification, although the results in this study contrast by still including ICE buses. A key point of divergence lies in car ownership. Climact's CORE95 classic scenario estimates 0.5 cars per household, while the behavioral scenario targets one car for every three households. The most ambitious case in this study, the Sufficiency scenario, achieves 0.44 cars per household, compared to 0.94 in Techno and 1.2 in Trends. Therefore, Climact's scenarios result in a smaller overall fleet, driven by higher occupancy rates and more extensive use of car-sharing, which increase vehicle utilization. Fleet composition also reveals differences. When compared to the CORE95 classic scenario, the Trends scenario in this study includes 2.3% more trains and 26% fewer buses. This discrepancy in busses is primarily explained by differences in modal demand assumptions.

Climact identifies the TECH scenario as the most expensive, primarily due to a higher number of cars. This contrasts with the findings of this study, where the Trends scenario results in the highest total investment cost. Despite this discrepancy, both analyses agree that the Sufficiency scenario is the most cost-efficient, largely due to reduced vehicle investment.

Across all studies, vehicle investments constitute the largest share of mobility-related expenditures, followed by transport network infrastructure, while charging infrastructure consistently represents only a minor portion of the total.

Infrastructure costs follow a similar pattern in both studies. The Sufficiency scenario requires the greatest infrastructure investment, mainly driven by rail network expansion and the development of active mobility infrastructure. A notable difference, lies in the treatment of cycling infrastructure: in this study, the total length of cycling paths is 32% higher compared to those in Climact's analysis.

The operational GWP emissions are similarly dominated by industrial activities in both this study and the Climact results(excluding the agriculture sector). This underscores the critical role of industrial emissions in achieving climate neutrality.

6.4 Limitations of this work and further studies

This study focuses on projections for 2050, which involves making several assumptions about future societal and behavioral changes. In practice, implementing these changes could encounter various social, political, and practical challenges. For instance a significant decrease in car ownership and a major shift toward cycling and public transport, which can be difficult to predict and may face resistance from the population. The study also estimates transport network infrastructure costs based on the vehicle kilometers for each transport type, which is not entirely accurate. A more precise approach would involve detailing the needed road and rail length of each type of transport. Additionally, the EnergyScope model used to simulate the national energy system is based on a snapshot of current conditions and does not account for all existing technologies and infrastructure.

Future research could explore how the proposed scenarios might be supported through specific policies, such as pricing strategies, investment programs, or incentives to encourage behavior change. It would also be beneficial to include freight transport in the analysis, as it shares much of the same transport infrastructure as passenger mobility. Furthermore, although this study focuses on transport, these changes could also impact other sectors, such as housing, industry, and agriculture. For instance, increased use of public and active transport might lead to more compact urban areas, which could reduce heating demands. Future research could investigate how these changes in mobility might interact with other sectors, providing a more comprehensive understanding of their overall effect on Belgium's energy transition.

7 Conclusion

The transition to sustainable mobility represents a complex challenge in achieving Belgium's climate neutrality objectives by 2050. This study has assessed three distinct pathways: Trends, Sufficiency, and Technological Growth, using the improved EnergyScope TD model. It offers critical insights into their respective energy, economic, and environmental implications.

The analysis reveals that although all three scenarios can technically meet the CORE-95 emissions reduction target, they rely on fundamentally different approaches, each involving significant trade-offs. The Trends scenario, which includes small vehicle consumption improvements, emerges as the most resource-intensive option, with annual passenger mobility energy demand reaching 27.6 TWh and total mobility costs amounting to €20.4 billion. It also results in the highest Scope 2 GWP emissions, underscoring the environmental limitations of a pathway based on the actual trend. In contrast, the Sufficiency scenario proves the most economical, reducing energy demand to 13.9 TWh and costs to €13.7 billion, while also achieving the lowest Scope 2 GWP emissions. However, it requires high investments in transport network infrastructure and widespread behavioral change. The Technological Growth pathway falls between the two, with total costs of €18.1 billion and Scope 2 GWP emissions values between the two previous scenarios. This outcome highlights the limitations of relying solely on technological solutions without accompanying reductions in demand.

These findings carry significant implications for Belgium's future mobility strategy. The strong performance of the Sufficiency scenario, particularly at the lowest cost, underscores the importance of prioritizing demand-side measures such as modal shift, reduced travel demand, and adapted transport network infrastructure. Nevertheless, the analysis confirms that even with strong technological innovation, the Sufficiency scenario remains the most effective. While technological improvements can reduce energy consumption, they have a limited impact on Scope 2 GHG emissions and overall system costs. Therefore, a successful transition will require a combined approach that integrates behavioral changes with technological advancements to maximize impact.

Further research is needed to answer important questions raised by this study. One key area is how to design behavioral change strategies that people will accept and that are realistic for policymakers to support. Another is how to create funding solutions that ensure everyone has fair and equal access to sustainable mobility options.

As Belgium moves forward with its mobility transition, the key question is not if the change can happen, but if the right decisions will be made. The tools are available, and the path is clear. Now, it's up to everyone to work together and create a truly sustainable mobility future.

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A
Appendix

1.1 4th power axle factor

Several decades ago, the American Association of State Highway and Transportation Officials (AASHTO) conducted comparative wear tests between light and heavy trucks during the AASHO Road Test [46], concluding that road deterioration follows a fourth-power law, meaning that wear increases exponentially with vehicle weight. To quantify this effect, the Aggressivity Coefficient (AC), also referred to as the 4th power axle factor, is used to measure the relative damage caused by a vehicle compared to a reference vehicle. The coefficient, defined in Equation A.1, expresses the vehicle's impact on road wear based on its and the reference weight, following the fourth-power relationship between weight and road damage. The impact of various vehicles, using a motorcycle as the reference, is shown in Table A.1.

$$AC = \left(\frac{W}{W_r}\right)^4 \tag{A.1}$$

Where:

- W = weight of the vehicle whose impact is being measured
- W_r = weight of the reference vehicle

Table A.1 Impact of the flow of one vehicle on the road compare to a motorcycle

Vehicle type	**Motorcycle**[a]	**Car**[a]	**Bus**[a]	**Truck**[b]
Weight [T]	0.28	1.35	12	15.6
Impact with AC [-]	1	540	3,373,594	9,545,818

[a] The weight of the passenger is not negligible.
[b] The average weight of a loaded truck is 15.6 tons[47], but in reality, it heavily depends on the type of truck.

This table highlights the exponential increase of the AC coefficient as a vehicle's weight increases, forming the basis for the fourth-power axle load factor used in some transport network cost allocation.

Building on the AC formula, an example of road renewal expenditures and maintenance cost allocation, using only the 4th power axle factor, is now presented for Belgium. The renewal expenditures and maintenance costs for Belgium's roads are linearly extrapolated from the regional roads of Wallonia [48], as it is the only publicly available document. These roads cover 8,360 km, representing 10.3% of Wallonia's total road network and 5.4% of Belgium's total road length (see Appendix 1.2). Based on this data, the renewal and operation and maintenance (O&M) cost is estimated at 20.36 k€/km. The cost of new road is estimated at 1.26 M€/km.

To assess the impact of current road mobility, the Aggressivity Coefficient (AC) is multiplied by the kilometers traveled by each vehicle category (see the 2019 passenger distribution in Appendix 1.5). For passenger transport, the total impact is estimated at $2.69 \cdot 10^{15}$, with buses representing the majority of the total impact. The contributions from motorcycles and cars are negligible, as their impacts are millions and hundreds of times lower than that of buses.

For freight transport, the impact is calculated by multiplying the AC of each truck category by the corresponding vehicle-kilometres (vkm). Data on transported weight in tonne-kilometres (tkm) and vkm per weight category (less than 10T, 10–20T, 20–30T, 30–40T, and more than 40T) are available from Eurostat [47]. Taking into account that 11.2% of trips are made without load [49], the total AC impact for freight transport is calculated at $2.23 \cdot 10^{16}$, approximately ten times higher than that of passenger transport.

Consequently, only 10.7% of the total road maintenance cost, estimated at 2.18 k€/km/year or 339.85 M€/year, is allocated to passenger transport under this allocation rule. Since buses are the only passenger vehicles with a significant impact on road wear, they are assumed to be fully responsible for the maintenance cost attributed to passenger transport. The maintenance cost per kilometer per bus per year is then calculated by dividing the allocated maintenance cost by the total bus-kilometres traveled in 2023, which corresponds to 0.42 €/km-bus.

Actually, trucks in Wallonia are required to pay a kilometric tax ranging from 0.04 to 0.23 €/km-truck, depending on their weight and pollution class. However, based on our calculation, an average truck weighing 15.6T would need to pay 1.16 €/km. This shows that they currently pay much less compared to the road damage they cause, if only the fourth power axle load rule is considered.

1.2 Non active road size

The management of Belgium's roads is complex and divided between regional and communal networks, with each region or municipality responsible for investment and maintenance on his roads. The total road length is approximately 156,000 km, as detailed in Table A.2. This table also highlights that Brussels has the highest road density in Belgium. The country's road density is five times higher than the European average, confirming the extensive road penetration.

Table A.2 Length of the Belgium non active road network

	Wallonia	Flanders	Brussel[a]	Belgium	Europe	Sources
road [km]	81,300	65,400	9,300	156,000	4,932,284,214	[50, 51, 48]
road [km/km^2]	4.81	4.80	57.62	5.08	1.102	

[a] The data from brussel is deduce from the data of Wallonia,Flanders and Belgium to obtain the correct road density known.

1.3 Charging stations

Since some time, Europe has prioritized vehicle electrification. The first major recommendation on charging infrastructure came from Directive 2014/94/EU, which set an indicative target of one charging station per 10 electric vehicles (EVs). However, this guideline has since evolved. In July 2023, the EU adopted the Alternative Fuels Infrastructure Regulation (AFIR), introducing updated requirements for EV charging infrastructure. Under AFIR, EU member states are now required to provide an additional public charging capacity of 1.3 kilowatts (kW) per new solded electric car [52].

The number of charging stations required is a politically sensitive issue, as miscalculations could lead to economic inefficiencies and impact public perception. For instance, Transport & Environment (T&E), a non-governmental organization specializing in sustainable transport, analyzed the European car industry lobby (ACEA) proposal [53], which suggested 3 kW per battery electric vehicle (BEV) and 2 kW per plug-in hybrid electric vehicle (PHEV). While a higher number of public chargers may seem beneficial, such ambitious targets would result in low utilization rates. When it is below 5%, it will require continuous subsidies. In contrast, a sustainable charging network requires a minimum utilization rate of 15% to remain economically viable.

To address this challenge, T&E recommends an adaptive approach that aligns closely with EU regulations. Their proposal maintains the European Commission's fleet-based target in the long term but adjusts public charging power per BEV based on market share [53]. Specifically, they suggest starting with a higher requirement (3 kW per BEV) when BEV market share is below 1% and gradually reducing it to 1 kW as BEV penetration reaches 7.5%. This strategy accelerates infrastructure development in the early stages, supports EV adoption in slower-growing markets, and prevents overbuilding while ensuring efficient utilization rates as the market matures.

This recommendation is broadly aligned with EU policy, which has now reached a more stable phase. It also ensures compliance with EU regulations, which mandate that member states provide sufficient charging infrastructure for their EV fleets. For this study, it is assumed that 1.3 kW of charging capacity must be installed per electric car. The share between the type of charging will be as in France[4] and shown on Table A.3. Given that the average power per charging station is 19.1 kW based on the previous table, an average station can handle 15 cars.

To reflect real-world conditions, it is important to consider the public availability of charging infrastructure. In Belgium, only 20% of charging stations are public or semi-public, meaning that the remaining 80% are installed in private settings, and their costs are typically borne by individuals or private companies rather than public authorities [25]. As a result, when estimating the cost of deploying EV charging infrastructure, only 20% of car and motorcycle chargers will be considered as public investment.

Table A.3 Cost and power of charging station

	Slow	**Fast**	**Rapid**	**Source**
Power [kW]	3	22	50	[4]
Cost [€/#]	600	2500	50 000	[54]
Share [%]	27	65	8	[4]

1.4 Summary scenario

Table A.4 Total traveled pkm and modal share per scenario

Year/Scenario	**2019**[a]	**Trends** [%][b]	**Sufficiency** [%][b]	**Techno** [%][b]
Total pkm traveled [Mpkm]	141, 958	154,214	137,981	176,022
City				
Feet	8.65	8.73	9.76	7.65
Non-electric bike	1.57	1.58	1.77	1.39
BEV bike	0.20	7.75	12.87	10.10
2 Wheels	2.60	2.63	2.93	2.30
Car	64.79	57.08	22.45	56.04
Bus	9.26	9.28	20.96	8.96
Tram	9.04	9.05	20.46	9.48
Metro	3.89	3.90	8.80	4.08
Regional				
Feet	5.29	5.34	5.97	4.68
Non-electric bike	0.70	0.71	0.79	0.62
BEV bike	0.37	0.37	5.00	2.40
2 Wheels	0.94	0.95	1.06	0.94
Car	79.92	80.77	56.70	78.36
Bus	3.99	4.00	11.00	3.29
Train	8.79	7.86	19.48	9.71

[a] The share are taken from the mobility barometer of VIAS [8]. In those data, Brussel is taken as city reference with the yearly statistics of STIB [55] to distribute the common transport. Wallonia is taken as regional reference.

[b] The change explain in the scenarios are made from the number in the column 2019 from Table A.7 and not from the specific studies of each scenario

Table A.5 Consumption ratios of the fleet of each scenario compared to the reference year 2019

Year/Scenario	2019	Trends	Sufficiency	Techno
Bike				
Non-electric	1.00	1.00	1.00	1.00
BEV	1.00	0.91	0.88	0.82
Motorcycle				
Petrol	1.00	1.15	0.84	0.57
BEV	1.00	1.14	0.84	0.57
Car				
Diesel	1.00	0.80	0.44	0.35
Petrol	1.00	0.80	0.44	0.35
HEV	1.00	0.95	0.51	0.52
PHEV	1.00	0.41	0.22	0.17
BEV	1.00	0.79	0.43	0.35
Fuel cell	1.00	0.76	0.46	0.35
Natural gas	1.00	0.77	0.46	0.35
Bus				
Diesel	1.00	0.83	0.61	0.57
HEV	1.00	0.95	0.70	0.64
BEV	1.00	0.95	0.70	0.64
Fuel cell	1.00	0.72	0.54	0.48
Natural gas	1.00	0.95	0.70	0.64
Tram				
Electric	1.00	0.95	0.65	0.51
Metro				
Electric	1.00	0.95	0.65	0.51
Train				
Electric	1.00	0.95	0.67	0.54

1.5 Belgian passenger mobility data per scenario

The input data for EnergyScope is not based on kilometers or passenger-kilometers, but rather on passenger-kilometers per hour. Consequently, the data from the raw Table A.6 will undergo some modifications. The method of transformation from the raw to the input parameters for EnergyScope is illustrated in Equation A.3, Equation A.4, and Equation A.5. Therefore the parameters of each technology will vary on whether the mobility technology is applied in urban or rural area due to variations in the average speed. These changes are applied to the reference year and the different scenarios.

$$c_p(i) = \frac{Av.distance_i}{Av.speed_i \cdot 8760} \qquad \forall i \in mobilitytechnology \tag{A.2}$$

$$c_{inv}(i) = \frac{Veh.Cost_i}{Occupancy_i \cdot Av.Speed_i} \qquad \forall i \in mobilitytechnology \tag{A.3}$$

$$c_{maint}(i) = \frac{Maint_i}{Occupancy_i \cdot Av.Speed_i} \qquad \forall i \in mobilitytechnology \tag{A.4}$$

$$gwp_{constr}(i) = \frac{GWP_{constr,i}}{Occupancy_i \cdot Av.Speed_i} \qquad \forall i \in mobilitytechnology \tag{A.5}$$

The fleet size for each technology is determined by the maximum between the number of vehicles required during the peak hour based on vehicle capacity, which defines the number of pkm per hour per vehicle Equation A.6 and the number of vehicles needed over the course of a year defined in Equation A.7.

$$veh_{cap}(i) = occupancy_i * Av.Speed_i \qquad \forall i \in mobilitytechnology \tag{A.6}$$

$$veh_{cap}(i) = occupancy_i * Av.distance_i \qquad \forall i \in mobilitytechnology \tag{A.7}$$

1.5.1 Fleet characteristic of reference year 2019

Table A.6 Fleet technology information of 2019

Vehicle type	Veh.Cost [k€$_{2015}$/veh]	Maint.[a] [k€$_{2015}$/veh/y]	Occupancy [pass/veh]	Av. distance [km/y]	Av.Speed urban [km/h]	Av.Speed rural [km/h]	Lifetime [years]	GWP^{d}_{constr} [tCO_2]	Sources
Bike									
Non-electric	0.4	0.1	1	3,120[b]	17	17	15	0.005	[7, 56]
BEV	1.5	0.2	1	3,120[b]	17	17	8	0.218	[7, 56]
Motorcycle									
Petrol	2.6	0.2	1	1,790	42.2	57.1	15	0.711	[1, 57]
BEV	4.5	0.1	1	1,790	42.2	57.1	15	0.923	[1, 57]
Car[e]									
Diesel	15.0	0.6	1.24	15,000	39	54	10	10.343	[7, 1, 57, 58]
Petrol	12.8	0.6	1.24	15,000	39	54	10	9.720	[7, 1, 57, 58]
HEV	18.1	0.5	1.24	15,000	39	54	10	10.985	[7, 1, 57, 58]
PHEV[f]	24.4	0.5	1.24	15,000	39	54	10	12.711	[7, 1, 57, 58]
BEV[g]	12.8	0.4	1.24	15,000	39	54	10	15.923	[7, 1, 57, 58]
Fuel cell	17.3	0.5	1.24	15,000	39	54	10	27.12	[7, 1, 57, 58]
Natural gas	17.3	0.7	1.24	15,000	39	54	10	9.96	[7, 1, 57, 58]
Bus									
Diesel	218.1	8.4	14.86	40,000	15.7	30.1	15	82.65	[1, 55, 59, 60]
HEV	225.6	8.7	14.86	40,000	15.7	30.1	15	83.36	[1, 55, 59, 60]
BEV	353.4	7.5	14.86	40,000	15.7	30.1	15	108.78	[1, 55, 59, 60]
Fuel cell	488.7	12.86	14.86	40,000	15.7	30.1	15	116.15	[1, 55, 59, 60]
Natural gas	233.1	10.5	14.86	40,000	15.7	30.1	15	84.82	[1, 55, 59, 60]
Tram									
Electric	2,255.6	45.1	55	39,463	16.2	-	30	180.052	[55, 59]
Metro									
Electric	4,511.3	90.2	116	69,328	27.9	-	30	560.080	[55, 59]
Train									
Electric	18,797.0	150.4	178	53,922[c]	-	63.4	40	1,599.079	[61, 62]

a own calculation. The maintenance cost was assumed proportional to the investment cost and depending the type of powertrain

b The average trip distance is 6 km [7]. Assuming a person using a bicycle commutes to work twice a day, their annual travel distance amounts to 3,120 km.

c There are 236 electric locomotives, each pulling an average of 6 cars, and 737 electric multiple units composed of 2, 3, or 4 bodies (one body is equivalent to 3 cars)[63]. This brings the total to 973 trainsets. This number is then divided by the total number of train-kilometres travelled in 2021. It is assumed that the number of trains in 2019 was equal to that in 2021.

d The data are sourced from the thesis of Paulin Laurent [64], with missing values supplemented by ADEME [65].

e Entry-level models from DACIA were used as references for car specifications.

f The battery capacity of plug-in hybrid car is assumed to be 9.6 kWh.

g The battery capacity of electric car is assumed to be 48 kWh.

Table A.7 Fleet consumption in 2019

Vehicle type	**Fuel** [Wh/pkm] City	**Fuel** [Wh/pkm] Regional	**Electricity** [Wh/pkm] City	**Electricity** [Wh/pkm] Regional	**Sources**
Bike					
Non-electric	0	0	0	0	-
BEV	0	0	11[b]	8.5	Own experience
Motorcycle					
Petrol	486	374	0	0	[35]
BEV	0	0	35	39	[35]
Car					
Diesel	631	486	0	0	[35]
Petrol	733	564	0	0	[35]
HEV[c]	302	336	0	0	[35]
PHEV[a,c]	124	138	83	92	[35]
BEV	0	0	236	262	[35]
Fuel cell	163	181	0	0	[35]
Natural gas	751	577	0	0	[35]
Bus					
Diesel	556	428	0	0	[35]
HEV	275	305	0	0	[35]
BEV	0	0	183	203	[35]
Fuel cell	172	191	0	0	[35]
Natural gas	485	373	0	0	[35]
Tram					
Electric[d]	0	0	58	-	[35]
Metro					
Electric[d]	0	0	58	-	[35]
Train					
Electric[e]	-	0	-	125	[35]

[a] It is assumed that electricity covers 40% of the energy and diesel the remaining 60%[66]
[b] An electrical bike doesn't have energy regeneration
[c] Since HEV and PHEV have electric batteries, they can store energy from the braking
[d] This technology is assumed to exist only in cities
[e] This technology is assumed to exist only in rural areas

Table A.8 Fleet parameter in 2019

Vehicle type	$\mathbf{c_{inv}}$ [€$_{2015}$/pkm/h]		$\mathbf{c_{maint}}$ [€$_{2015}$/pkm/h/y]		$\mathbf{gwp_{constr}}$ [kgCO2/pkm/h]		$\mathbf{c_p}$ [%]		$\mathbf{veh_{cap}}$ [(pkm/h)/veh]	
	City	Regional	City	Regional	City	Regional	City	Regional	City	Regional
Bike										
Non-electric	22	22	5	5	0.29	0.29	2.1	2.1	17	17
BEV	89	89	9	9	13	13	2.1	2.1	17	17
Motorcycle										
Petrol	62	46	5	3	17	12	0.5	0.4	42	57
BEV	107	79	3	2	21	16	0.5	0.4	42	57
Car										
Diesel	311	225	13	9	214	155	4.4	3.2	48	67
Petrol	265	191	13	9	201	145	4.4	3.2	48	67
HEV	373	269	11	8	227	164	4.4	3.2	48	67
PHEV	504	364	11	8	263	190	4.4	3.2	48	67
BEV	265	191	8	5	329	238	4.4	3.2	48	67
Fuel cell	357	258	9	7	561	405	4.4	3.2	48	67
Natural gas	357	258	14	11	205	149	4.4	3.2	48	67
Bus										
Diesel	935	487	36	19	354	184	29.1	15.2	233	447
HEV	966	504	38	20	357	186	29.1	15.2	233	447
BEV	1788	932	32	17	466	243	29.1	15.2	233	447
Fuel cell	2096	1092	56	29	498	260	29.1	15.2	233	447
Natural gas	998	521	45	23	363	189	29.1	15.2	233	447
Tram										
Electric	2868	-	51	-	202	-	27.8	-	891	-
Metro										
Electric	1394	-	28	-	173	-	28.3	-	3236	-
Train										
Electric	-	1666	-	13	-	142	-	9.7	-	11,285

1.5.2 Fleet characteristic of scenario 1 : Trends

Table A.9 Fleet consumption for trend scenario

Vehicle type	Fuel [Wh/pkm]		Electricity [Wh/pkm]		Sources
	City	Regional	City	Regional	
Bike					
Non-electric	0	0	0	0	-
BEV	0	0	10[b]	8	Own experience
Motorcycle					
Petrol	559	429	0	0	[35]
BEV	0	0	40	44	[35]
Car					
Diesel	505	389	0	0	[35]
Petrol	586	451	0	0	[35]
HEV[c]	287	319	0	0	[35]
PHEV[a,c]	51	57	73	78	[35]
BEV	0	0	186	206	[35]
Fuel cell	130	145	0	0	[35]
Natural gas	607	468	0	0	[35]
Bus					
Diesel	462	355	0	0	[35]
HEV	261	290	0	0	[35]
BEV	0	0	174	194	[35]
Fuel cell	123	137	0	0	[35]
Natural gas	460	354	0	0	[35]
Tram					
Electric[d]	0	0	55	-	[35]
Metro					
Electric[d]	0	0	55	-	[35]
Train					
Electric[e]	-	0	-	119	[35]

[a] It is assumed that electricity covers 40% of the energy and diesel the remaining 60%[66]
[b] An electrical bike doesn't have energy regeneration
[c] Since HEV and PHEV have electric batteries, they can store energy from the braking
[d] This technology is assumed to exist only in cities
[e] This technology is assumed to exist only in rural areas

Table A.10 Fleet parameter for trend scenario

Vehicle type	$\mathbf{c_{inv}}$ [€$_{2015}$/pkm/h]		$\mathbf{c_{maint}}$ [€$_{2015}$/pkm/h/y]		$\mathbf{gwp_{constr}}$ [kgCO2/pkm/h]		$\mathbf{c_p}$ [%]		$\mathbf{veh_{cap}}$ [(pkm/h)/veh]	
	City	Regional	City	Regional	City	Regional	City	Regional	City	Regional
Bike										
Non-electric	22	22	5	5	0.29	0.29	2.1	2.1	17	17
BEV	89	89	9	9	13	13	2.1	2.1	17	17
Motorcycle										
Petrol	62	46	5	3	17	12	0.5	0.4	42	57
BEV	107	79	3	2	21	16	0.5	0.4	42	57
Car										
Diesel	311	225	13	9	214	155	4.4	3.2	48	67
Petrol	265	191	13	9	201	145	4.4	3.2	48	67
HEV	373	269	11	8	227	164	4.4	3.2	48	67
PHEV	504	364	11	8	263	190	4.4	3.2	48	67
BEV	265	191	8	5	329	238	4.4	3.2	48	67
Fuel cell	357	258	9	7	561	405	4.4	3.2	48	67
Natural gas	357	258	14	11	205	149	4.4	3.2	48	67
Bus										
Diesel	935	487	36	19	354	184	29.1	15.2	233	447
HEV	966	504	38	20	357	186	29.1	15.2	233	447
BEV	1788	932	32	17	466	243	29.1	15.2	233	447
Fuel cell	2096	1092	56	29	498	260	29.1	15.2	233	447
Natural gas	998	521	45	23	363	189	29.1	15.2	233	447
Tram										
Electric	2868	-	51	-	202	-	27.8	-	891	-
Metro										
Electric	1394	-	28	-	173	-	28.3	-	3236	-
Train										
Electric	-	1666	-	13	-	142	-	9.7	-	11,285

1.5.3 Fleet characteristic of scenario 2 : sufficiency

Table A.11 Fleet consumption for sufficiency scenario

Vehicle type	**Fuel** [Wh/pkm] City	**Fuel** [Wh/pkm] Regional	**Electricity** [Wh/pkm] City	**Electricity** [Wh/pkm] Regional	**Sources**
Bike					
Non-electric	0	0	0	0	-
BEV	0	0	9.5[b]	7.5	Own experience
Motorcycle					
Petrol	408	313	0	0	[35]
BEV	0	0	30	33	[35]
Car					
Diesel	274	211	0	0	[35]
Petrol	315	242	0	0	[35]
HEV[a]	155	172	0	0	[35]
PHEV[a,c]	27	30	18	21	[35]
BEV	0	0	102	113	[35]
Fuel cell	71	78	0	0	[35]
Natural gas	330	255	0	0	[35]
Bus					
Diesel	330	255	0	0	[35]
HEV	193	215	0	0	[35]
BEV	0	0	128	143	[35]
Fuel cell	93	102	0	0	[35]
Natural gas	305	235	0	0	[35]
Tram					
Electric[d]	0	0	37	-	[35]
Metro					
Electric[d]	0	0	37	-	[35]
Train					
Electric[e]	-	0	-	84	[35]

[a] It is assumed that electricity covers 40% of the energy and diesel the remaining 60%[66]

[b] An electrical bike doesn't have energy regeneration

[c] Since HEV and PHEV have electric batteries, they can store energy from the braking

[d] This technology is assumed to exist only in cities

[e] This technology is assumed to exist only in rural areas

Table A.12 Fleet parameters for sufficiency scenario

Vehicle type	$\mathbf{c_{inv}}$ [€$_{2015}$/pkm/h]		$\mathbf{c_{maint}}$ [€$_{2015}$/pkm/h/y]		$\mathbf{gwp_{constr}}$ [kgCO2/pkm/h]		$\mathbf{c_p}$ [%]		$\mathbf{veh_{cap}}$ [(pkm/h)/veh]	
	City	Regional	City	Regional	City	Regional	City	Regional	City	Regional
Bike										
Non-electric	22	22	5	5	0.29	0.29	2.1	2.1	17	17
BEV	89	89	9	9	13	13	2.1	2.1	17	17
Motorcycle										
Petrol	62	46	5	3	17	12	0.5	0.4	42	57
BEV	107	79	3	2	21	16	0.5	0.4	42	57
Car										
Diesel	192	139	8	6	132	96	5.7	4.1	78	108
Petrol	163	118	8	6	124	89	5.7	4.1	78	108
HEV	230	166	7	5	140	102	5.7	4.1	78	108
PHEV	313	226	7	5	162	118	5.7	4.1	78	108
BEV	163	118	5	3	203	147	5.7	4.1	78	108
Fuel cell	220	160	6	5	347	250	5.7	4.1	78	108
Natural gas	220	160	9	7	126	92	5.7	4.1	78	108
Bus										
Diesel	748	390	29	15	283	147	29.1	15.17	280	537
HEV	773	403	30	16	286	149	29.1	15.17	280	537
BEV	1430	746	26	14	373	194	29.1	15.17	280	537
Fuel cell	1677	874	45	23	398	208	29.1	15.17	280	537
Natural gas	798	417	36	18	290	151	29.1	15.17	280	537
Tram										
Electric	2294	-	41	-	162	-	27.8	-	1069	-
Metro										
Electric	1115	-	22	-	138	-	28.3	-	2589	-
Train										
Electric	-	1333	-	11	-	114	-	9.7	-	9028

1.5.4 Fleet characteristic of scenario 3 : Techno

Table A.13 Fleet consumption for Techno scenario

Vehicle type	Fuel [Wh/pkm] City	Fuel [Wh/pkm] Regional	Electricity [Wh/pkm] City	Electricity [Wh/pkm] Regional	Sources
Bike					
Non-electric	0	0	0	0	-
BEV	0	0	9[b]	7	Own experience
Motorcycle					
Petrol	277	213	0	0	[35]
BEV	0	0	20	22	[35]
Car					
Diesel	221	170	0	0	[35]
Petrol	257	197	0	0	[35]
HEV[c]	157	175	0	0	[35]
PHEV[a,c]	21	23	14	16	[35]
BEV	0	0	83	92	[35]
Fuel cell	57	63	0	0	[35]
Natural gas	263	202	0	0	[35]
Bus					
Diesel	314	241	0	0	[35]
HEV	176	195	0	0	[35]
BEV	0	0	117	130	[35]
Fuel cell	83	91	0	0	[35]
Natural gas	272	209	0	0	[35]
Tram					
Electric[d]	0	0	28	-	[35]
Metro					
Electric[d]	0	0	28	-	[35]
Train					
Electric[e]	0	0	-	60	[35]

[a] It is assumed that electricity covers 40% of the energy and diesel the remaining 60%[66]

[b] An electrical bike doesn't have energy regeneration

[c] Since HEV and PHEV have electric batteries, they can store energy from the braking

[d] This technology is assumed to exist only in cities

[e] This technology is assumed to exist only in rural areas

Table A.14 Fleet parameters for Techno scenario

Vehicle type	c_{inv} [€$_{2015}$/pkm/h]		c_{maint} [€$_{2015}$/pkm/h/y]		gwp_{constr} [kgCO2/pkm/h]		c_p [%]		veh_{cap} [(pkm/h)/veh]	
	City	Regional	City	Regional	City	Regional	City	Regional	City	Regional
Bike										
Non-electric	22	22	5	5	0.29	0.29	2.1	2.1	17	17
BEV	89	89	9	9	13	13	2.1	2.1	17	17
Motorcycle										
Petrol	62	46	5	3	17	12	0.5	0.4	42	57
BEV	107	79	3	2	21	16	0.5	0.4	42	57
Car										
Diesel	215	155	9	6	148	107	4.4	3.2	70	97
Petrol	183	132	9	6	139	100	4.4	3.2	70	97
HEV	257	186	8	6	157	113	4.4	3.2	70	97
PHEV	347	251	8	6	181	131	4.4	3.2	70	97
BEV	183	132	6	3	227	164	4.4	3.2	70	97
Fuel cell	246	178	6	5	386	279	4.4	3.2	70	97
Natural gas	246	178	10	8	141	103	4.4	3.2	70	97
Bus										
Diesel	935	487	36	19	354	184	29.1	15.2	233	447
HEV	966	504	38	20	357	186	29.1	15.2	233	447
BEV	1788	932	32	17	466	243	29.1	15.2	233	447
Fuel cell	2096	1092	56	29	498	260	29.1	15.2	233	447
Natural gas	998	521	45	23	363	189	29.1	15.2	233	447
Tram										
Electric	2868	-	51	-	202	-	27.8	-	891	-
Metro										
Electric	1394	-	28	-	173	-	28.3	-	3236	-
Train										
Electric	-	1666	-	13	-	142	-	9.7	-	11,285

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