Net Zero 2050: Energy Demand Dynamics across the Transportation Sector

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01 Introduction

The global transport sector contributes almost one quarter of the energy-related carbon dioxide emissions to the annual emissions inventory [1]. Passenger cars and commercial on-road vehicles combined account for almost three-quarters of this total with the aviation and maritime industries each contributing around 10%.

To address these emissions, long-term decarbonization ambitions have been declared for these sectors at the local, regional, and global levels. Although leading technologies to achieve these targets have been defined by each sector, the ultimate path to be taken is yet to be fully defined. Because some technologies and preferred pathways are shared across several sectors, the potential for cross-sectoral competitive dynamics is high.

The aim of this study is to explore these dynamics and assess how the combination of energy vectors and feedstocks used by the respective regional transport fleets develop as a result of policies in a net-zero constrained environment. 40 different energy vectors produced from either fossil, fossil+CCUS, biomass or renewable electricity feedstocks were included in the analysis. The regions of interest are the EU and the US due to the maturity of their greenhouse gas-focused regulatory frameworks. China is chosen, because it has similar ambitions, but shifted by 10 years compared to EU and US [2]. The study is supplemented by the analysis of the Brazilian transport sector due to the distinctive characteristics of its vehicle fleet, its outstanding biomass feedstock capacity, and its affinity to use it to supply the transport sector with biofuels in the future. With this selection, the study covers regions that represent approx. 60% of the current global final energy demand of the transport sector [3].

To accomplish these objectives, the study´s authors pursued a multi-step process to analyze each of the regions individually. First, the relative attractiveness of powertrain options and energy carriers for each of the transportation sectors was evaluated. Second, a model of each sector's vehicle fleet evolution and the associated energy demand through 2050 was generated. With the base data in place and using the region's greenhouse gases (GHG) reduction targets as constraints, a Monte-Carlo simulation of energy vector costs was conducted to provide a statistical basis for the final transportation sector energy demand estimate for each vector. As a result, the study results present energy demand scenarios for the different regions.

In the following, the general methodology and detailed results are explained using the EU as an example.
At the end of the publication, the key results for all of the considered regions are compared with each other.

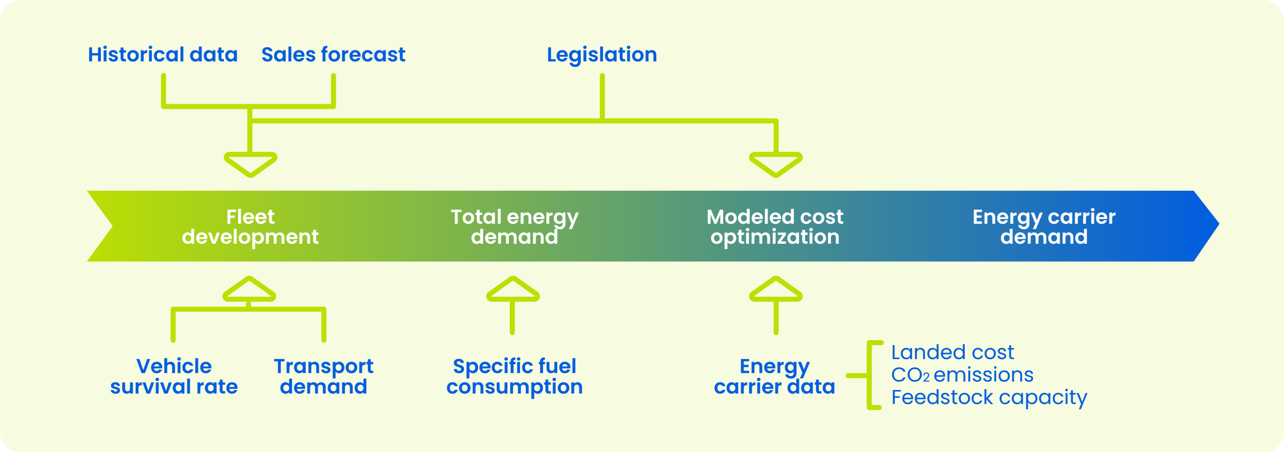
02

Methodology and input data

02 Methodology and input data

The motivation behind this work was to gain insight into the demand volumes of various energy vectors necessary to meet a net-zero GHG ambition within the transportation sector. To gauge these demand volumes, a model of the sector and its available energy pathways needed to be constructed. The main assumption behind the model was compliance with existing and announced global or regional climate protection targets and legislation. The model consisted of two main parts.

Figure 1: Overall methodology sketch.



The first part determined the expected demand for certain energy types (e.g. diesel-type fuels, jet fuel, hydrogen, etc.) based on a modeled fleet evolution and energy efficiency for all of the transport sub-sectors covered.

The second part divided the previously calculated energy type demands into individual demands for the underlying combinations of energy types and feedstocks, which is defined as “energy carrier demand.” An overview of the considered energy carriers can be seen in Table 1.

Table 1: Overview of the energy carriers considered within this study.

Energy type	Energy carrier	Feedstocks considered		
Electricity	Electricity	Renewable electricity		
Low carbon drop-in fuels	Power-to-Liquid fuels (Diesel/jet fuel/gasoline)	Renewable electricity		
	Biomass-to-Liquid fuels (Diesel/jet fuel/gasoline)	Advanced biomass		
	HVO/HEFA	Waste fats/oils	Vegetable oils	
Non-drop-in low carbon fuels	Ammonia	Renewable electricity	Advanced biomass	Petroleum & natural gas
	Methane	Renewable electricity	Advanced biomass	Petroleum & natural gas
	LPG	Renewable electricity	Advanced biomass	Petroleum & natural gas
	FAME	Waste fats/oils	Vegetable oils	
	Ethanol	Food & feed crops	Advanced biomass	
	Methanol	Renewable electricity	Advanced biomass	Petroleum & natural gas
Hydrogen	Hydrogen	Renewable electricity	Advanced biomass	Petroleum & natural gas

This was done by minimizing the total landed cost (i.e., production & transportation costs) across all transport sectors while being consistent with legislative, physical, and continuity boundary conditions. The total landed cost was selected as the primary optimization parameter, since it depends on existing and expected technology rather than global supply and demand. The decision to select landed costs over other, non-economic parameters (e.g., GHG emissions) reflects the underlying assumption that the future energy carrier mix will most likely be determined by the economic attractivity of the different options to meet the energy demand.

2.1 Fleet and energy type demand modeling

The modeling of the fleet development began with historical sales data and the current composition of the fleet. This work relied on official data from the European Commission, the International Maritime Organization (IMO) and the International Air Transport Association (IATA) [4, 5, 6]. The future fleet development was derived by subtracting old vehicles, vessels, and aircraft from the fleet in accordance with transport sector-specific scrapping patterns, and by adding new sales to it while accounting for the specific powertrain used.

For the on-road segment, the scrapping rate was determined via a distribution function to take different effects on the vehicle lifetime into account (accidents, individual car handling, driving pattern, etc.). The scrapping rate was taken as a constant over time since future vehicles and their powertrains are expected to have the same useful lives as today's vehicles. The distribution function was derived from Heywood/Bandivadekar [7]. For the maritime and aviation segment, the average lifetimes of vessels and aircraft were considered [4, 6].

The new sales forecasts for the different sectors were derived from proprietary intelligence from FEV. They combined FEV's industry insights into OEM strategy and worldwide R&D projects with continuous, structured gathering of further market intelligence. Regular market, customer and economic studies are performed by FEV's experts to understand the viability and probability of technologies from the customer's perspective. FEV's insights are further enriched with third-party databases and studies. The resulting sales forecasts were in line with national as well as international legislation and ambitions.

Energy efficiency, measured as energy consumption per unit of transport work, was modeled as the average energy efficiency at the fleet level. The modeling process followed the same approach as the modeling of the fleet development. Old vehicles, vessels, and aircraft with their specific energy efficiency were subtracted from the fleet average, and new ones were added. Historical energy efficiency data was derived from similar sources as for the historical sales data. Future predictions of energy efficiency improvements were made by FEV and were in line with legislative targets (e.g. energy efficiency reduction target of the IMO) [4, 5, 6, 8]. Projections of the specific energy demand considered industry outlooks on both new technologies and operational improvements. They combined meta-studies with FEV internal expert workshops and global insights into the latest powertrain and vehicle developments.

To derive the energy demand in the last step, the fleet evolution, average specific energy demand and future transport demand were combined. Different powertrain types and their associated energy carrier types were considered. For on-road transport, projections of future transport demand were derived from the "EU reference scenario 2020" (European Commission) [9]. A similar approach was taken for aviation and the IATA. For the marine industry, predictions from the IMO, DNV and United Nations (United Nations Conference on Trade and Development) were evaluated and incorporated [6, 10, 11]. The upper and lower limits of the Monte Carlo simulation were generated by varying the annual growth rate symmetrically by 25%.

2.2 Energy carrier demand modeling by minimizing landed cost

The second part of the model, the cost optimization determining the final energy carrier demand, is a linear optimization and is therefore defined by a target function with several constraints. In the following section, the target function is described and then the constraints are discussed.

Since the model used in this work targeted the cost-optimal energy carrier composition, the target function needed to be a cost function covering all energy types and transport sectors included in this work. In the most basic form, the target function needed to be the sum of all energy carrier demands (as decision variable) multiplied by their individual specific landed costs. These costs were derived from a broad literature review and then adjusted with more representative transport costs from the region of production to Europe. The target function used in this model, however, slightly differed from this basic version to allow for the introduction of CO_2 pricing mechanisms, which was why a specific CO_2 price and the energy carrier specific well-to-wheel GHG emissions were also included in the target function. In the example for the EU, the CO_2 prices were chosen to align with the expected price development of the European Emission Trading System, while the specific well-to-wheel GHG emissions were modeled by FEV and include emissions originating along the value chain from feedstock cultivation to fuel combustion. With the set of all energy carriers N, the set of transport sectors S, a CO_2 price p_{CO_2}, the specific GHG emissions of the energy carrier i e_i, the specific landed costs of the energy carrier i c_i and the demand of the energy carrier i in transport sector k x_{ik}, the target function can be written as:

$$\min \sum_{i \in N} \sum_{k \in S} [\,(p_{CO_2} * e_i + c_i) * x_{i,k}\,]$$

This target function was used with year-specific values for the CO_2 price, specific GHG emissions and specific landed costs for all 3 discrete points in time (2030, 2040 and 2050).

The numerous constraints used in this optimization model can be clustered into 4 groups: physical constraints, policy constraints, continuity constraints, and plausibility constraints.

Physical constraints

The physical constraints ensured the physical viability and technical feasibility of the results. Examples of these constraints include 1) those mandating the given energy type demands to be matched exactly by the sum of the associated final energy carrier demands and 2) those that ensured adherence to assumed biomass feedstock capacity limits. A list of physical constraints used in the model can be found in the appendix in Table 4.

Policy constraints

The policy constraints ensured the results' compliance with all relevant globally and regionally announced and existing legislation, including strategic climate ambitions. For the EU, these were, for example, the overall target of a 90% reduction by 2050 in greenhouse gas emissions from the transportation sector compared with 1990 and the mandated blending shares of sustainable aviation fuel under the proposed "ReFuelEU Aviation" policy. A list of policy constraints used in the model can be found in the appendix in Table 5.

Continuity constraints

The continuity constraints ensured a realistic course of development of energy carrier demands by linking adjacent points in time with each other. The underlying assumption was that production capacities for advanced biofuels and renewable fuels of non-biological origin (RFNBO) would, once built, still be used at least through 2050. To achieve this, the continuity constraints were implemented such that for each advanced biofuel and RFNBO the total demand across all transport sectors could not decrease from one point in time to the next. If this constraint led to a non-solvable optimization problem due to some energy carrier type demand decreasing over time, the continuity constraint was reduced in an iterative, stepwise approach to deliver a higher level of continuity in the results.

$$\sum_{k \in S} x_{i,k,t} \geq \sum_{k \in S} x_{i,k,t-1} \quad \forall\ i \in N_{cont,}\ t \in T$$

Plausibility constraints

In addition to the physical, regulatory, and continuity boundary conditions, other mechanisms and developments could have an impact on the future energy carrier demand of the transport sector. To anticipate these and further enhance the plausibility of the results, additional assumptions regarding the development of energy carrier demands were implemented in the model. A list of these plausibility constraints can be found in the appendix in Table 6.

Running the model in a Monte Carlo simulation

The target function of the previously described optimization model used the cost vector c. This cost vector contained a single value for the landed cost of each energy carrier for each of the points in time. The association of a single cost value for each energy carrier was problematic for at least three reasons:

1. **Real cost ranges: Differences in the technical implementation of production or regional boundary conditions (energy cost, salaries, etc.) could cause differences in landed costs that were not reflected when using a singular cost value.**
2. **Uncertainty of the forecast: Forecasting the future always comes with uncertainties. Unforeseen developments in raw material or energy prices and the occurrence or non-occurrence of technical innovations could have unexpected consequences for landed costs of energy carriers.**
3. **Optimization logic: A cost optimization model will always pick the least expensive solution, even if the cost advantage is minimal. Very small differences in landed costs could have significant consequences on the result, even if they would not be expected to do so.**

To mitigate the impact of these challenges, the model did not use singular cost values, but cost ranges instead. To allow the cost optimization itself to run using a single cost value, the optimization model was run 50,000 times in a Monte Carlo simulation, each time picking a single cost value at random from a predefined cost range (trials with different run counts showed no significant disparity in the results when exceeding 50,000 runs). To randomly assign a single cost value for each energy carrier, the cost range was interpreted as a triangular probability distribution and defined by a minimum cost value, a most likely cost value (base cost) and a maximum cost value. The results of all individual runs of the optimization model were then averaged to calculate the final result of the energy carrier demand model.

Since this approach of picking one random cost value for each individual energy carrier could lead to implausible scenarios, in which very closely related energy carriers (e.g. HVO & HEFA) were assigned very different cost values, the energy carriers were clustered into groups. For each group, only one energy carrier cost value was randomly assigned, while for the other energy carriers the same relative difference between the assigned and the base cost value was utilized. The six energy carrier groups were: petroleum-based energy carriers, grid electricity, electricity-based energy carriers, advanced biofuels, conventional biofuels, and waste oil-based biofuels.

2.3 Input data generation

As in the previous chapters, the EU serves as an example in this chapter to describe the type of input data that was used within the model.

Legislation

The future energy system is expected to be subject to both industry-wide and sector-specific regulations. For the purpose of this study, non-binding commitments to carbon reduction or energy transition from the private sector and industry trade associations were not considered.

With the ambition towards a carbon-neutral EU with a 90% reduction in GHG emissions from the transport sector by 2050 (compared to the 1990 levels), the European Green Deal (EGD) set out the legal foundation of the study for the EU region [12]. For 2030, the revision of the Renewable Energy Directive pledging a 14.5% GHG reduction by 2030 compared to a petroleum-based fuel baseline (or renewables taking up 29%) within the transport sector set a transportation-wide target for this timeline [13].

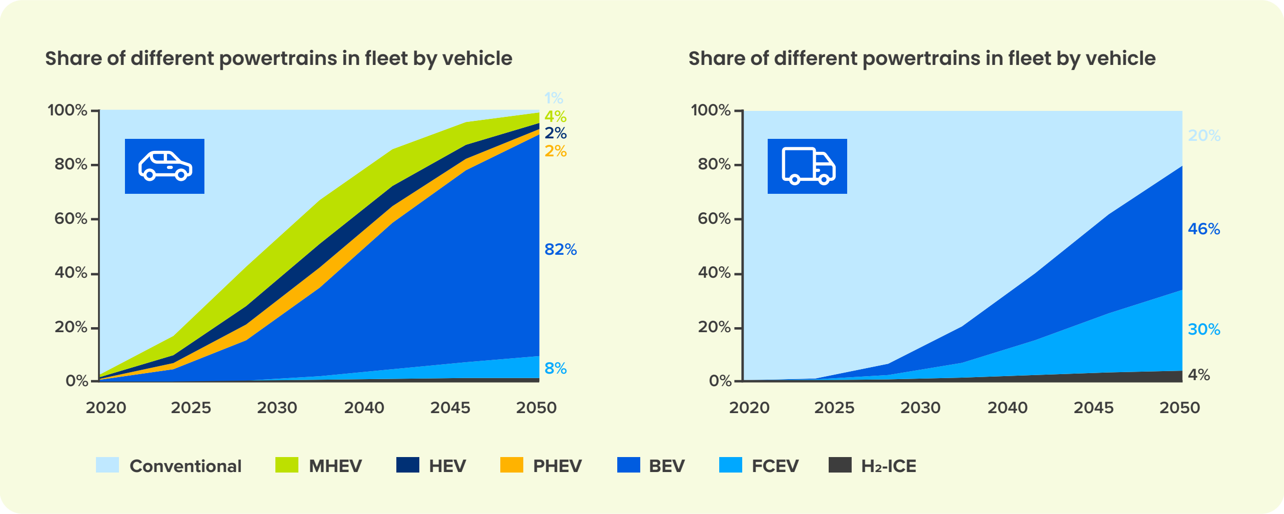
Considering that no GHG reduction for 2040 for the transport sector has been specified, we assumed a linear reduction between 2030 and 2050 to ensure sufficient constraints to support the optimization model. Further considerations included the Energy Taxation Directive, the EU ETS I, and EU ETS2, a new and separate emissions trading system adopted in 2023 covering fuel combustion in buildings, road transport and additional sectors [14].

Besides cross-sectoral targets, sector-specific requirements applying to the selected modes of transportation were also considered. For instance, a significant impact could be seen in the aviation sector due to the ambitious targets of SAF blending quotas and subsequent RFNBO targets defined by the ReFuelEU aviation as well as FuelEU Maritime for the maritime transport [15]. In addition, the market-based measures for offsetting GHG emissions of international flights via low-carbon fuels or emission allowances by the Carbon Offsetting and Reduction Scheme for International Aviation were considered.

Vehicle fleet development for EU

The development of the fleet relied on the input parameters defined in the previous chapter. Figures 2 and 3 illustrate the derived scenarios of vehicle fleet evolution and powertrain technology for each of the transportation sub-sectors in the EU through 2050.

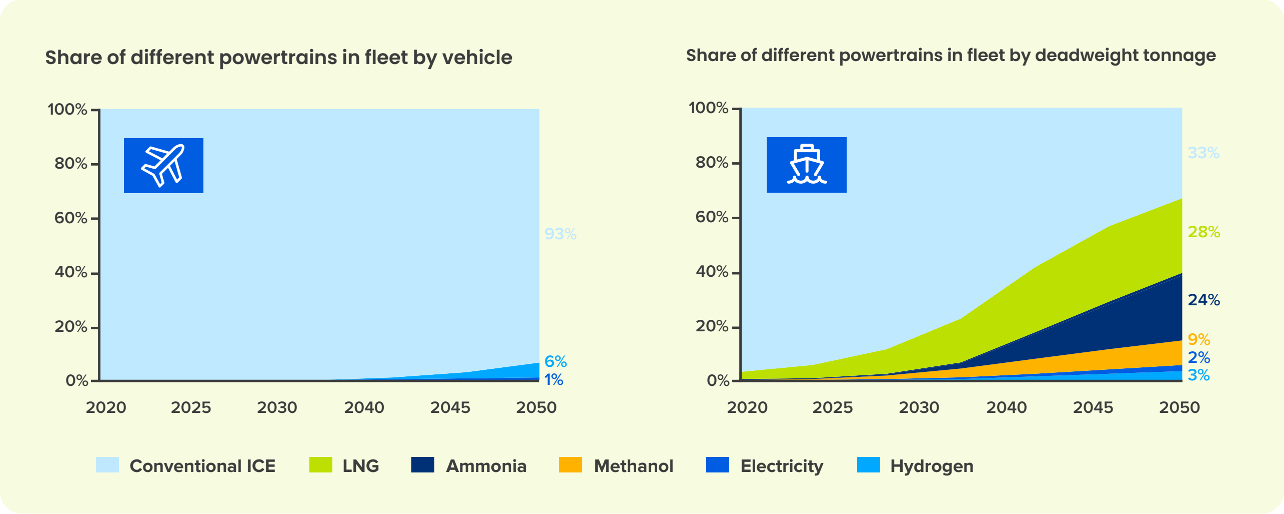
Figure 2: Vehicle fleet evolution for passenger cars and light commercial vehicles (left) and medium- and heavy commercial vehicles (right) in EU 27 through 2050.



The European passenger car and light commercial vehicle fleet model projected growth from ~275 million vehicles in 2020 to ~300 million vehicles in 2050. A fast-growing number of battery electric vehicles (BEV) were expected, with total numbers reaching over 100 million vehicles around 2035. In 2050 over 90% of the fleet was projected to be zero emission vehicles with a minor share of 9% hydrogen driven vehicles. There was still a significant share of conventional internal combustion engine (ICE) and hybrid vehicles anticipated in the legacy fleet in 2050 as no exceptional scrappage incentive for ICE vehicles after 2030 was considered in this study.

In the medium- and commercial vehicle segment, the vehicle fleet was projected to grow from ~4.9 million vehicles in 2020 to ~6 million vehicles in 2050. A focus on zero-emission vehicles was expected so that by 2050 around 80% of the fleet meets this limit. For this sector, the fuel cell electric vehicle (FCEV) was expected to be the most important powertrain (46%), mainly for the long-haul segment. At the same time BEVs were expected to dominate in urban and regional delivery applications. The remaining ICE & hybrid vehicle shares were nearly equally distributed between long-haul, regional, and urban delivery.

Figure 3: Vehicle fleet evolution for aviation (left) and marine (right) in EU 27 through 2050.



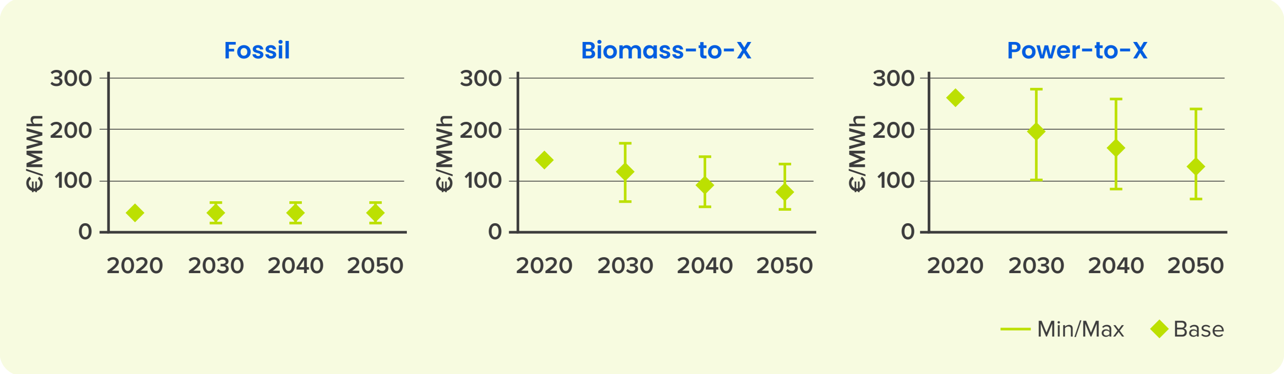
For the marine sector, this study focused on the activities and transport demands both within and external to the member states of the EU but considered only half of the energy demand from international voyages to reflect bunkering outside of the EU. A growing fleet of ships was expected with a capacity increase of ~50% by 2050 which raised deadweight tonnage from 340 million to 510 million. Several alternative powertrain options were considered for ocean going and inland/short sea shipping. Liquified natural gas (LNG) powered vessels were expected in the short-term, as the technology has been proven, and the direct CO_2 benefit compared to conventionally fueled ones was well understood. This ensured that regulatory compliance was achieved in the early years. Methanol powertrains have matured but have mostly been used in a niche of chemical tankers carrying large volumes of methanol as a cargo. Increasing market share was expected by 2025, with first movers in the container shipping industry. Ammonia powertrains are not yet mature, but first prototypes were expected within the next few years with a market introduction by 2030 at the latest. These resulted in a diverse powertrain distribution in the marine sector by 2050.

In aviation, the relevant fleet forecast needed to determine the associated regional energy carrier demand was not the combined active service fleet of all regional airlines, but a so called “virtual fleet” that also included the partial shares of aircraft that fly between regions. This means however, that the virtual fleet size cannot be directly compared with any physical fleet size observed today. Still, the increase of the virtual fleet size from approx. 6,500 aircraft in 2022 to approx. 13,100 aircraft in 2050 shows the significant rise of aviation transport demand assumed in this study in accordance with the ICAO post-COVID19 forecasts [16]. and previous work done by FEV Consulting. The market introduction of battery electric powertrains in regional jets on dedicated short trips (<500 km) is expected by 2035, but market penetration was expected to be low. Further improvements in energy density were expected to increase the usability of battery electric aircraft to up to 800 km of range, leading to further market penetration. Hydrogen technology for commercial aviation is currently immature, but market introduction was expected by 2035 for small narrow body aircraft on routes of up to 2,000 km. Nevertheless, most aircraft will continue to use conventional propulsion and liquid energy carriers, which will drive the need for sustainable aviation fuel in the coming decades.

Energy vector costs

The Optimization Model adopted the landed costs of energy carriers as a key input, which covered costs incurred in both the production process and transportation to a generic refueling location in Europe. Such an approach enabled better comparison between imported and domestically produced energy carriers. The cost ranges per point in time of all energy carriers were defined on the basis of a meticulous literature review and can be found in the appendix in Table 7. As an example Figure 4 displays the landed cost ranges of electricity-based and bio-based SAF in comparison to petroleum-based jet fuel. Despite the visible cost regression of bio-based and electricity-based SAF, their baseline costs were projected to exceed those of petroleum-based fuel in 2050. This was mainly caused by the costly provision of biomass, green hydrogen, and carbon dioxide, which can amount to over 50% of the production costs.

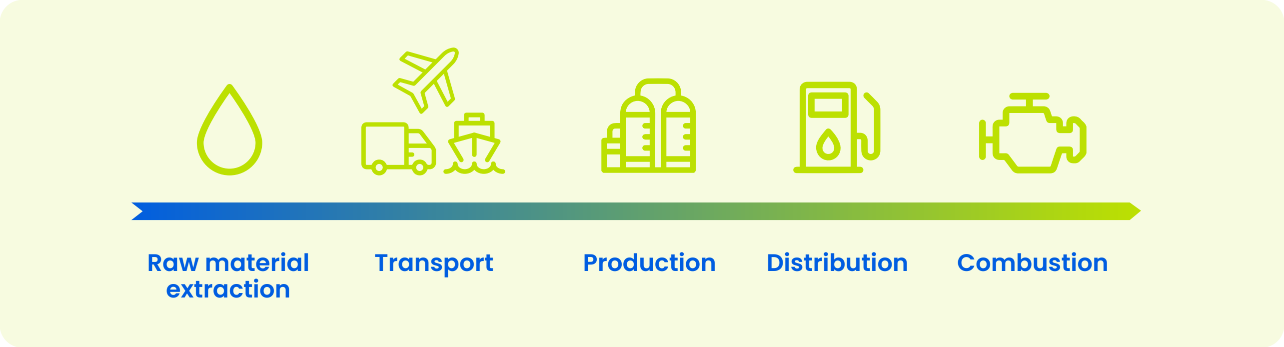
Figure 4: Energy carrier landed cost forecast for the example of liquid hydrocarbon fuels in €/MWh.



Carbon intensity of the energy carriers

In addition to the landed costs, the carbon intensity of the energy carriers was also essential for defining the future energy mix within the regulatory framework. The intensity values considered in this study encompassed the entire value chain of all energy carriers ranging from raw material extraction to combustion (illustrated in Figure 5), as well as relevant changes over time.

Figure 5: Schematic representation of the value chain used for determining GHG intensities.



The carbon intensity of the energy carriers was based on the study from the Joint Research Center (JRC) of the European Commission in their “Well-to-Wheels report” for the year 2025 [17]. The JRC provided likely carbon intensity values by modeling the “most probable production paths” of energy carriers. From the JRC values, GHG intensities in 2030, 2040, and 2050 were modeled and subsequently validated with expert interviews. Table 2 shows representative results for electricity-based and bio-based SAF in comparison to petroleum-based jet fuel.

Table 2: Carbon intensity for electricity-based and bio-based SAF in comparison to petroleum-based jet fuel in kg/MWh.

	2020	2030	2040	2050
Fossil Jet Fuel	320kg/MWh	320kg/MWh	302.4kg/MWh	284.4kg/MWh
PtX-Jet Fuel	6.0kg/MWh	5.0kg/MWh	2.9kg/MWh	0.8kg/MWh
BtX-Jet Fuel	34.6kg/MWh	30.7kg/MWh	17.1kg/MWh	3.6kg/MWh

Biomass feedstock limitations

While advanced biofuels can achieve lower production costs compared to e-fuels, especially in the short term, the supply of biomass for the transport sector may be limited. To forecast the future energy mix, it was important to consider the potential scarcity of advanced biofuels. Sustainable biomass was subdivided into two types, oil- or fat-containing wastes and other general sustainable biomass, and their availability estimated.

The EU set a limit of 1.7% of the total energy demand by 2030 for using oil- or fat-containing wastes in biofuel production. This limit was adopted for the study as the maximum available quantity of the feedstock, disregarding a more optimistic estimation of its actual availability [13].

A literature review and expert interviews were conducted to assess the availability of sustainable biomass (excluding oil- or fat-containing wastes) for transport. According to the general literature, there was a large disparity in the forecasted availability of sustainable biomass for EU, with estimates ranging from 50 Mtoe to 252 Mtoe [18].To accommodate the substantial uncertainties concerning the availability of other sustainable types of biomass, a moderately cautious estimate of around 90 Mtoe was adopted, which is consistent with the findings of a study conducted by Concawe in 2019 [19].

03

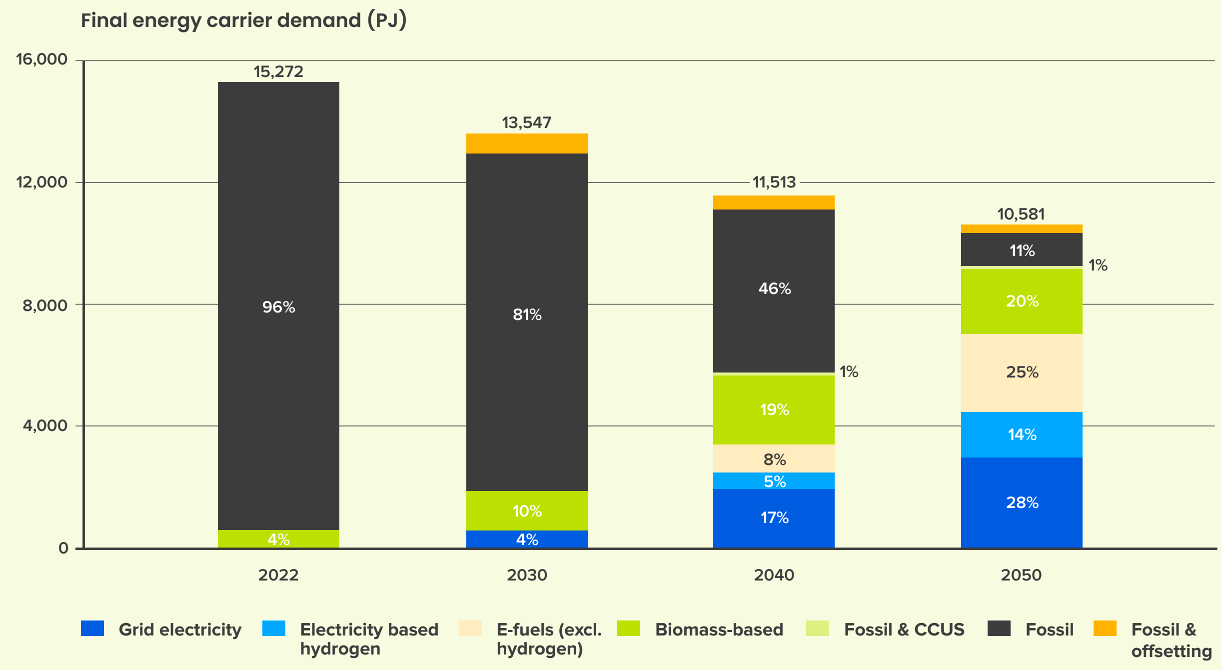
Results and discussion

03 Results and discussion

3.1 Energy carrier demand development for EU

The most likely outcome of the future final energy carrier demand from the European transportation sector, based on the Monte Carlo principle applied, is presented in Figure 6 and Figure 7. The first striking fact in the aggregated result is that the projection for total energy demand decreases over time, despite the fact that total transport demand is expected to increase in all sectors. There are several reasons behind this. The biggest impact is given by the improvements in powertrain and vehicle efficiency and the direct use of electricity in some of the applications. The strongest contribution to this comes from the high share of battery electric vehicles in the on-road sector.

Figure 6: Energy demand evolution in EU 27 through 2050.

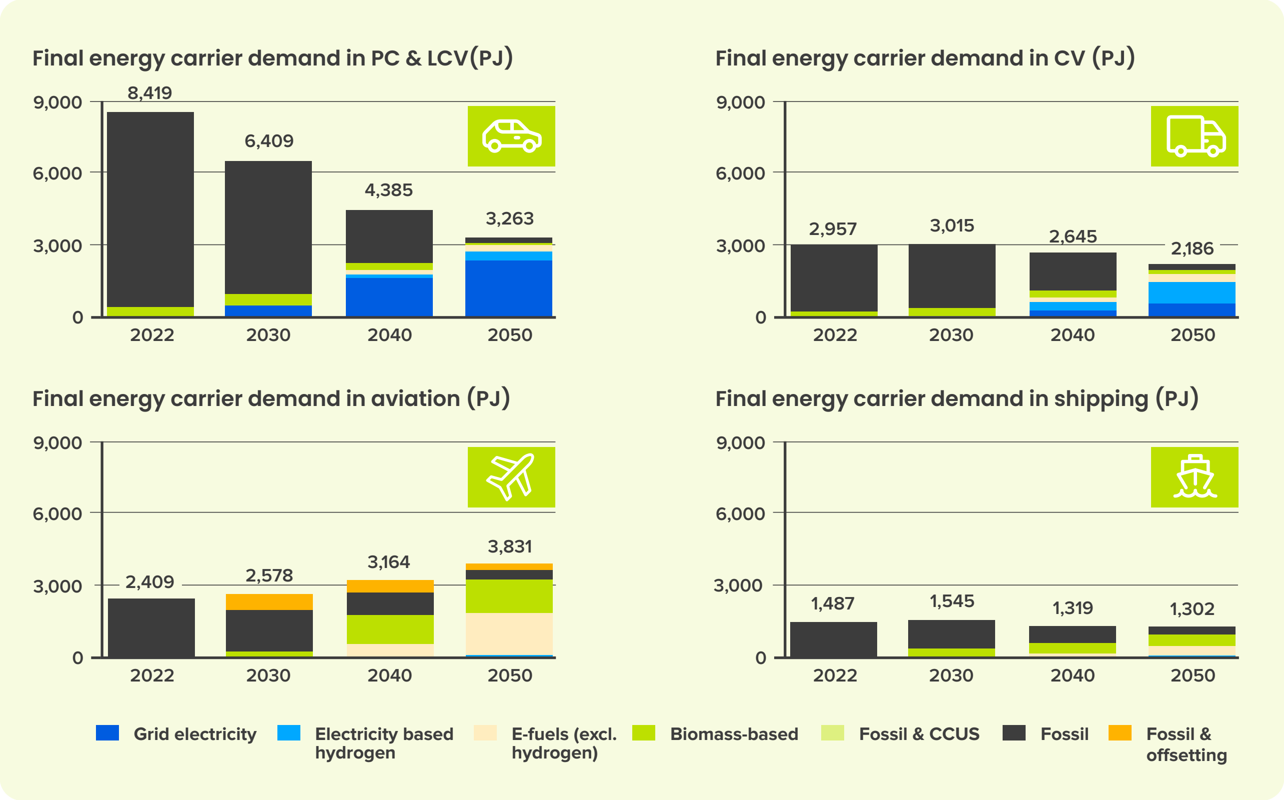


When it comes to the projected evolution of the energy vector mix, a significant diversification is expected through 2050 and beyond. Although petroleum-based fuels see a dramatic decline, the overall fuel market remains robust with direct use of electricity expected to account for only 28% and the remainder supplied by liquid and gaseous fuels with low carbon intensity. After 2030, hydrogen and electricity quickly gain market share, mostly driven by on-road transport, but more than 50% of the total transportation energy demand in 2050 is delivered through liquid fuels. Established first generation biofuels gradually disappear after 2030 due to enforced limits stemming from competition with the food industry. Next generation advanced biofuels play a critical role in meeting the EU's GHG reduction targets, driven at first by the Renewable Energy Directive (RED) sub-targets for advanced biofuels. After 2030, these fuels see a significant ramp up as an economically favorable option to reduce emissions. The aviation sector, especially, demands a large volume of biofuels to meet its targets. However, biomass feedstock capacity is limited, and a saturation point may be reached in the EU by 2040. Further demand for liquid fuels must then be met by increasing volumes of e-fuels.

E-fuels see a significant uptake after 2040 to ensure compliance with the 90% GHG reduction target of the EU [12]. Long-term demand primarily comes from aviation, where conventional powertrains and liquid fuels continue to dominate. The ReFuelEU aviation targets primarily push the e-fuel share in 2030 and 2040 for aviation [20]. To meet demand in other sectors, most of the hydrogen and ammonia is produced from electricity. This is driven primarily by sub-targets for renewable fuels with non-biological origin in the RED regulation [13]. However, by 2040 substantial amounts of blue hydrogen are required to meet demand even though the EU will likely target the use of green hydrogen & ammonia in the long-term.

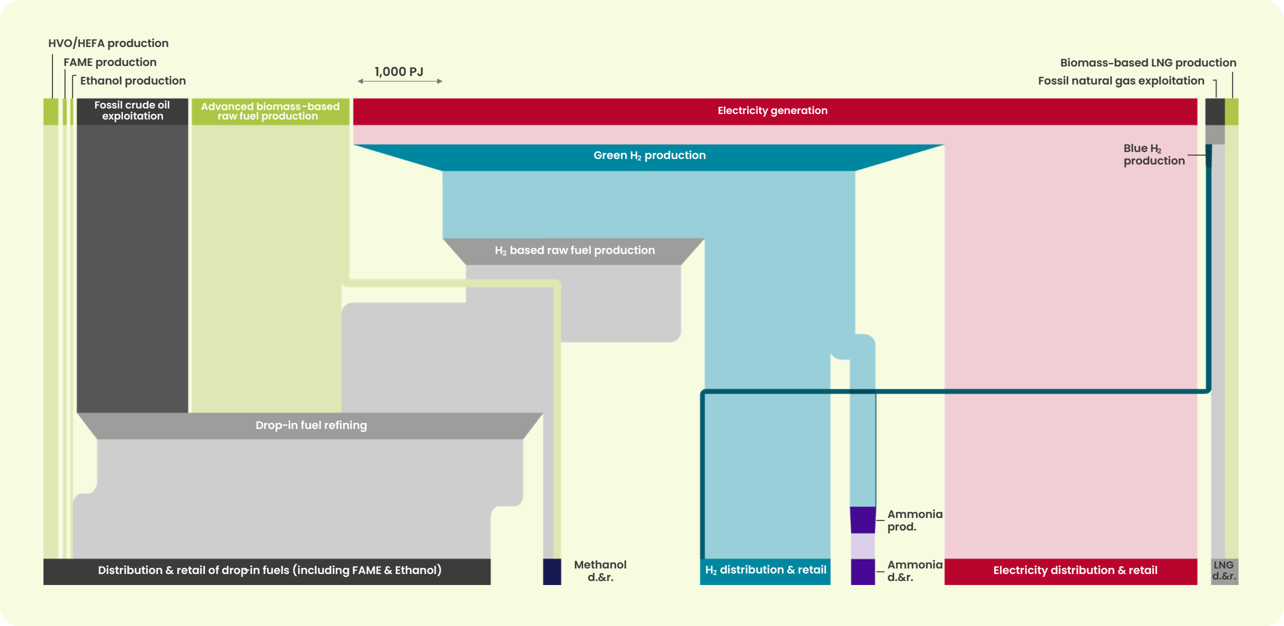
The Figure below shows the distribution of energy carriers across each of the transportation sectors through 2050 where significant differences between the sectors are visible.

Figure 7: Energy demand evolution for passenger cars / light commercial vehicles (top left), medium- / heavy commercial vehicles (top right), aviation (bottom left) and marine (bottom right) in EU 27 through 2050.



In figure 8 the study results are visualized as a Sankey diagram with the required primary energy demand at the top representing the upstream market potential and the downstream market potential at the bottom. Electricity generation becomes the largest upstream market in 2050 when counting by energy units. However, on the downstream side, the distribution and retail of liquid fuels remains the most important market.

Figure 8: Visualization of the upstream and downstream market potential in PJ based on the energy demand results for the transportation sector in EU in 2050. (d.&r. = distribution and retail).

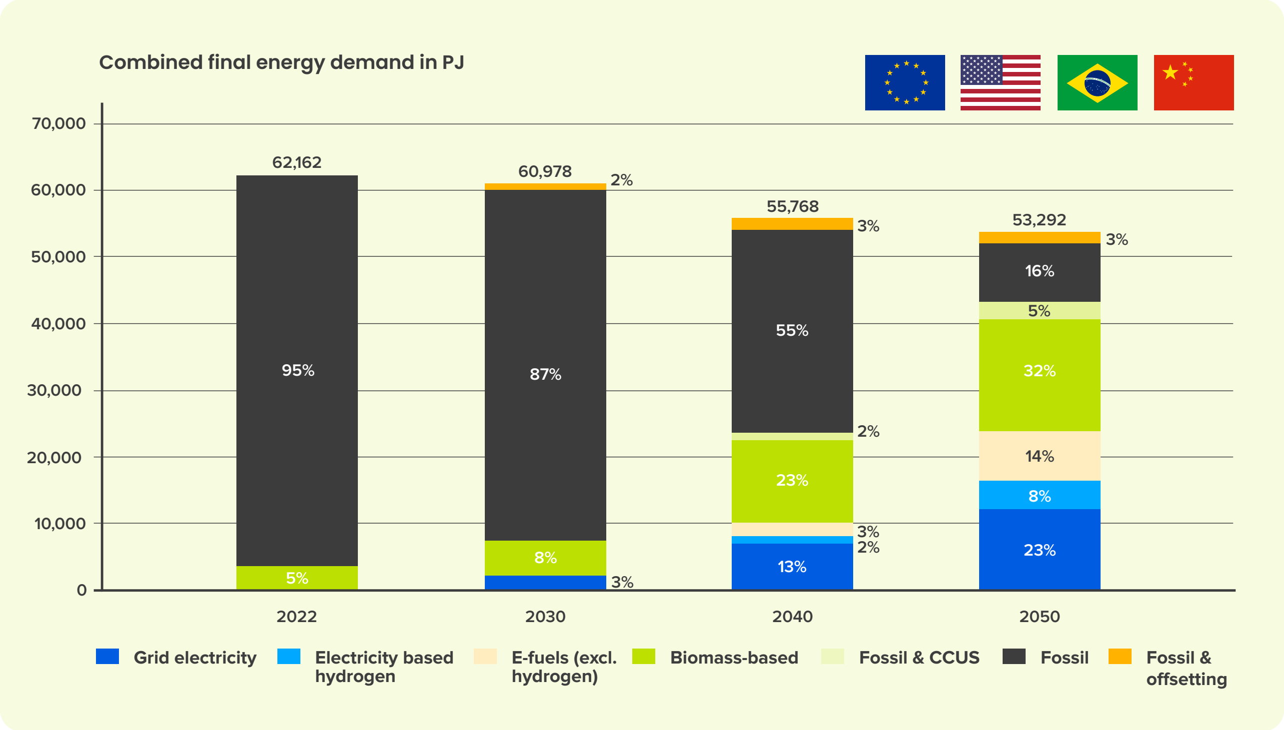


3.2 Regional comparison

When comparing the four regions, the overall ambitions and measures are similar, but the different CO_2 trajectories and sector specific regulations differ. When considering the targets defined in the US National Blueprint for Transportation Decarbonization, the US shows the most ambitious reduction of transport-related CO_2 emissions, closely followed by the EU and Brazil. China follows with a 10-year delay in striving for carbon neutrality [21].

Comparing the aggregated results of all regions, Figures 9 and 10, with the results for the EU, the evolution of the energy mix looks similar at first sight. In general, liquid hydrocarbons remain important in all regions and renewable liquid hydrocarbons increase in importance. However, the total amounts differ among the regions and are subject to regional characteristics.

Figure 9: Energy demand evolution in all four analyzed regions through 2050.



When comparing the individual energy vectors with the EU results, a significantly higher biofuel share is expected from 2040 onwards. This high share is mainly driven by the US and Brazil regions due to the high availability of biomass feedstock and the affinity to adopt it today and in the future. The absolute biofuel demand in the US by 2050 is equivalent to the combined biofuel demand of Brazil, China and EU.

This high share of biofuels is also the reason why the overall share of e-fuels is much lower compared to the EU results. A large volume of e-fuels will be needed in the US and EU by 2050, but their use will be delayed in China. In Brazil, e-fuels only represent a niche market as they are not the most cost-effective choice and are not needed to meet the overall CO_2 targets in that region.

Another difference emerges when comparing the hydrogen demand from the US and EU. While the US strongly pushes for blue hydrogen as a transition energy vector before focusing on green hydrogen, only a niche market is expected in the EU. It is assumed that the EU continues to push for green hydrogen, even though there is an increasing willingness to accept blue hydrogen on a temporary basis due to the energy crisis in 2022. However, the expected cost parity for blue and green hydrogen in 2040 supports a long-term push into green hydrogen.

When looking at the petroleum-based fuel share, 80% of that demand comes from China in 2050, due to the 10-year delay in the declared net-zero ambition. The US region emerges as the only region without petroleum-based fuels in 2050, due to the incorporation of the goals from the US National Blueprint for Transportation Decarbonization within this study.

Figure 10: Individual energy demand evolution for all four regions analyzed through 2050.

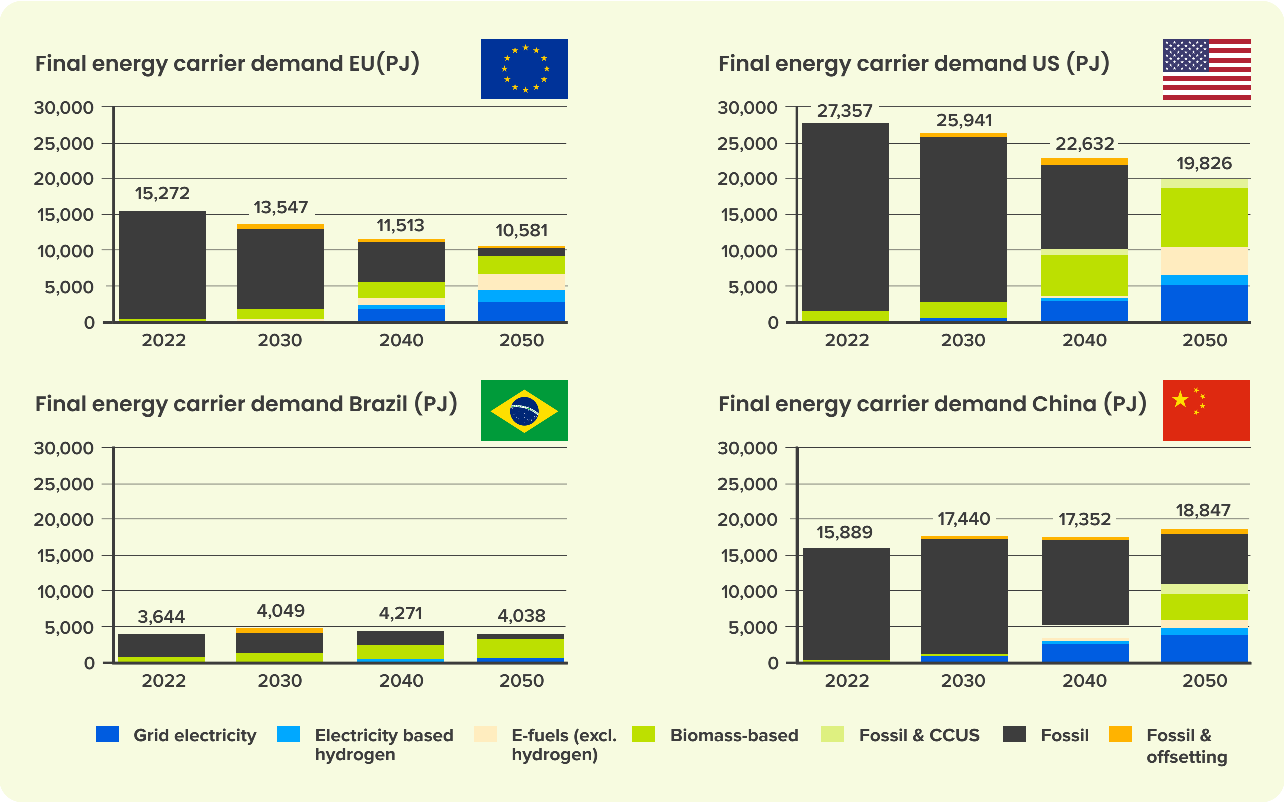
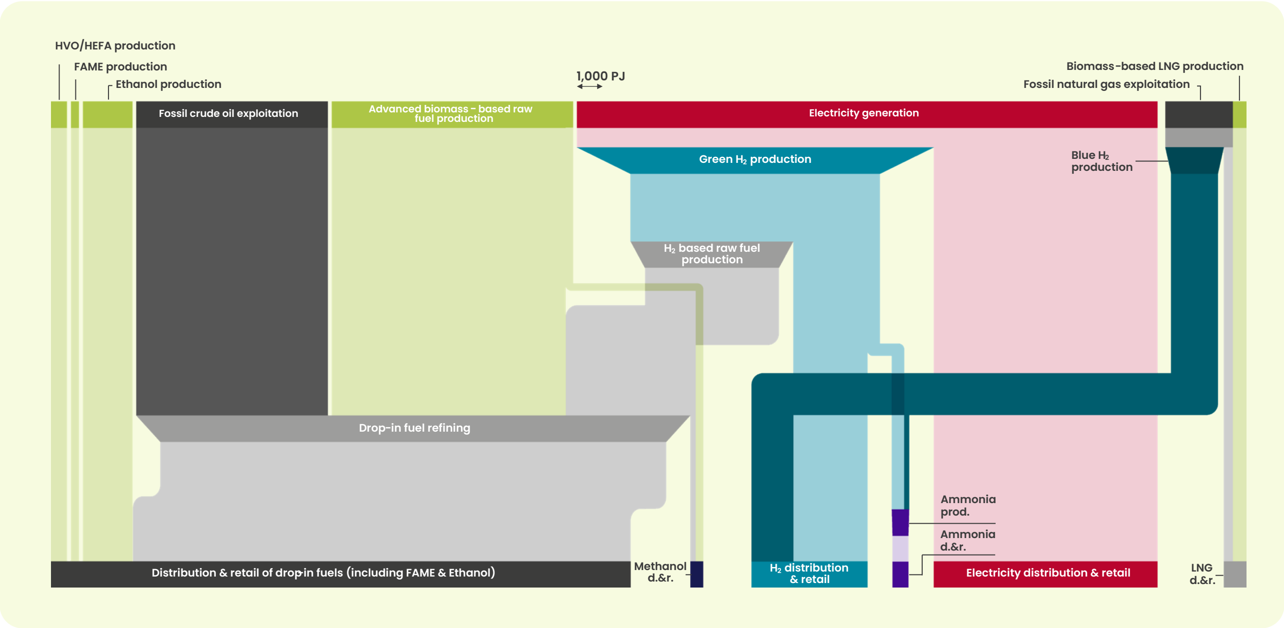


Figure 11 visualizes the upstream and downstream market potential in petajoules for all the analyzed regions. Similar to the EU, electricity generation represents the largest upstream market potential in 2050 when assessed in energy units. However, this is closely followed by biomass-based fuel production. On the downstream side, the distribution and retail of liquid fuels remains the most important market, even more-so than in the EU.

Figure 11: Visualization of the upstream and downstream market potential in PJ based on the energy demand results for the transportation sector in EU, US, Brazil, and China in 2050.



04

Conclusion

04 Conclusion

To meet the declared net-zero ambitions in the transportation sector of the four analyzed regions, a dramatic shift in energy delivery and consumption will be needed. Although changes are modest through 2030, the most severe changes emerge in the approach to 2040 and even more to 2050, driven by stringent regulations demanding electrified powertrains and alternative energy carriers.

The demand for conventional petroleum refining and the distribution of current liquid fuels will likely decline, but renewable drop-in fuels, driven heavily by the aviation and maritime sectors, will arrest this decline and take advantage of existing and established distribution infrastructure. After 2030 hydrogen and electricity quickly gain market share, mostly driven by on-road transport, but more than 50% of the total transportation energy demand in 2050 is still delivered through liquid fuels. Ensuring an adequate supply of these energy sources becomes the primary challenge and becomes even more critical when considering the demands emerging from other industries.

Key findings

- **Reaching Net Zero will require a shift in energy delivery and consumption**
- **Overall energy will drop due to efficiencies inherent to electrification**
- **Over half the energy for transportation is likely to be delivered as liquid hydrocarbons, utilizing existing infrastructure**
- **Biomass will play a strong role, but exact volumes rest on multiple assumptions surrounding supply and scalability**
- **E-fuels must fill the gap left by any biomass supply constraint**

Appendix

Table 3: Symbol overview.

Symbol	Description
blend	Maximum blend share (by energy content)
Cap	Feedstock availability / MWh
c	Specific landed cost / (€/MWh)
e	Specific GHG emissions / (kgCO_2-eq./MWh)
N	Set of energy carriers
P	Set of energy types
pCO_2	CO_2 price / (€/kgCO_2-eq.)
Q	Minimum blend share (by energy content)
R	Set of feedstocks
S	Set of transport modes
T	Set of points in time
GHG	Annual greenhouse gas emissions / kgCO_2-eq.
X	Energy type demand / MWh
x	Energy carrier demand / MWh
η_{prod}	Production efficiency (by energy content)

Table 4: Physical constraints used in the cost optimization model.

Physical constraints	Description
$\sum i \in N_p \, x_{i,k} = x_{p,k} \quad \forall p \in P, \, k \in S$	Meeting the energy carrier type demands
$\sum i \in N_r \sum k \in S \, \frac{x_{i,k}}{\eta \text{ prod}} \leq Cap_r \quad \forall r \in R$	Feedstock capacity limits
$\sum i \in N_{Ethanol} \, x_{i,k} \leq blend_{Ethanol} * X_{Otto,k} \quad \forall k \in S$	Maximum ethanol blend share
$\sum i \in N_{FAME} \, x_{i,k} \leq blend_{FAME} * X_{Diesel,k} \quad \forall k \in S$	Maximum FAME blend share
$x_{i,k} \geq 0 \; \forall i \in N, k \in S$	Non-negativity of demand

Appendix

Table 5: Policy constraints used in the cost optimization model.

Policy constraints	Description
$\sum i \in N \sum k \in S \; x_{i,k} * e_i \leq 0.1 * 1.25 * GHG_{TtW,1990}$	90% GHG reduction from transport by 2050 (Green Deal)
$\sum i \in N \sum k \in S \; x_{i,k} * e_i \leq 0.575 * 1.25 * GHG_{TtW,1990}$	Linear interpolation of 2050 Green Deal GHG reduction target and 2030 RED GHG reduction (2040)
$\sum k \in S \; \frac{e_{ref,el} - e_{el}}{X_{ges}} * x_{el,k} + \sum i \in N \sum k \in S \; \frac{e_{ref} - e_i}{X_{ges}} * x_{i,k} \geq 0.145 * e_{ref}$	RED: carbon intensity reduction target (-14.5%) (2030 only)
$\sum i \in N_{\text{adv bio \& RFNBO}} \sum k \in S \; x_{i,k} * f_{RED,i,k} \geq 0.055 * X_{ges}$	RED: 5.5% target share for advanced biofuels and RFNBO, including an energy carrier and transport mode-specific multiplier (2030 only)
$\sum i \in N_{RFNBO} \sum k \in S \; x_{i,k} * f_{RED,k} \geq 0.01 * X_{ges}$	RED: 1% sub-target share for RFNBO including a transport mode-specific multiplier (2030 only)
$\sum i \in N_{\text{1st bio}} \sum k \in S \; x_{i,k} \leq 0.07 * X_{ges}$	RED: maximum share for feed & food crop-based biofuels of 7%
$\sum i \in N_{\text{waste oil}} \sum k \in S \; x_{i,k} \leq 0.017 * X_{ges}$	RED: maximum share for waste oil-based biofuels of 1.7%
$\sum i \in N_{SAF} \; x_{i,aviation} \geq Q_{SAF,t} * X_{\text{jet fuel}}, \; t \in T$	ReFuelEU Aviation: minimum share of SAF
$\sum i \in N_{SAF} \; x_{i,aviation} \geq Q_{RFNBO,t} * X_{\text{jet fuel}}, \; t \in T$	ReFuelEU Aviation: minimum share of RFNBO in aviation
$\sum i \in N \; \frac{e_i}{X_{Mar}} * x_{i,\,Mar} \leq (1-Q_{red,t}) * e_{ref,\,Mar}, \; t \in T$	FuelEU Maritime: mandated GHG intensity reduction

Table 6: Plausibility constraints used in the cost optimization model.

Plausibility constraints	Description
$\sum k \in S \; x_{H_2\,grey,k} = 0$	No grey hydrogen in transportation
$\sum k \in S \; x_{MeOH\,grey,k} = 0$	No grey methanol in transportation
$\sum k \in S \; x_{NH_3\,grey,k} = 0$	No grey ammonia in transportation
$\sum i \in N_{\text{1st gen}} \sum k \in S \; x_{i,k,t} \leq \sum i \in N_{\text{1st gen}} \sum k \in S \; x_{i,k,t-1}, \; t \in T$	No growth in demand for feed and food crop-based biofuels

Appendix

Table 7: Landed cost forecasts for all energy carriers in €/MWh.

Cluster	Energy carrier	Scenario	2020	2030	2040	2050
Electricity-based Hydrogen & Ammonia	**Gaseous Hydrogen**	min		60	50	40
		base	130	95	80	70
		max		150	120	115
	Liquid Hydrogen	min		90	70	65
		base	170	120	105	95
		max		170	145	130
	Ammonia	min		65	55	45
		base	150	105	90	80
		max		200	165	160
Blue Hydrogen & Ammonia	**Gaseous Hydrogen**	min		45	40	40
		base	80	75	70	70
		max		95	90	90
	Liquid Hydrogen	min		66	59	59
		base	118	111	103	103
		max		140	133	133
	Ammonia	min		68	63	63
		base	95	90	85	85
		max		118	113	113
Electricity	**Electricity sourced via grid**	min		80	80	80
		base	90	90	90	90
		max		100	100	100
Power-to-Liquid	**e-Hydrocarbons (Diesel, Gasoline, Jet fuel & marine fuel oil)**	min		100	80	65
		base	260	200	150	130
		max		280	260	250
	e-Methanol	min		80	64	52
		base	208	160	120	104
		max		224	208	200
	e-LNG	min		93	77	65
		base	221	173	133	117
		max		237	221	213
Advanced Biofuels	**Bio-Hydrocarbons (Diesel, Gasoline & Jet fuel)**	min		55	50	50
		base	140	110	90	80
		max		165	145	135
	Bio-Marine Fuel Oil	min		50	50	50
		base	125	88	78	75
		max		165	145	135
	Bio-Methanol	min		50	50	50
		base	105	85	75	65
		max		135	130	125
	Bio-LNG	min		30	30	30
		base	100	80	70	65
		max		160	140	100

Appendix

Table 7 continued: Landed cost forecasts for all energy carriers in €/MWh.

Cluster	Energy carrier	Scenario	2020	2030	2040	2050
Established Biofuels	**HVO/HEFA (1st gen)**	min		55	50	50
		base	90	90	90	90
		max		110	105	105
	HVO/HEFA (2nd gen)	min		55	50	50
		base	90	90	90	90
		max		110	105	105
	FAME (1st gen)	min		60	60	60
		base	85	85	85	85
		max		90	90	90
	FAME (2nd gen)	min		60	60	60
		base	85	85	85	85
		max		90	90	90
	Ethanol (2nd gen)	min		65	60	60
		base	100	90	85	85
		max		125	95	90
	Ethanol (1st gen)	min		65	65	65
		base	85	85	85	85
		max		90	90	90
Fossil	**Gasoline**	min		30	30	30
		base	40	40	40	40
		max		50	50	50
	Diesel	min		30	30	30
		base	40	40	40	40
		max		50	50	50
	Jet fuel	min		30	30	30
		base	40	40	40	40
		max		50	50	50
	Marine Fuel Oil	min		13	13	13
		base	23	23	23	23
		max		33	33	33
	LNG	min		20	20	20
		base	30	30	30	30
		max		40	40	40
	Methanol	min		20	20	20
		base	35	35	35	35
		max		50	50	50
	Gaseous Hydrogen	min		35	35	35
		base	55	55	55	55
		max		70	70	70
	Liquid Hydrogen	min		52	52	52
		base	81	81	81	81
		max		103	103	103
	Ammonia	min		58	58	58
		base	70	70	70	70
		max		93	93	93

05

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05 References

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