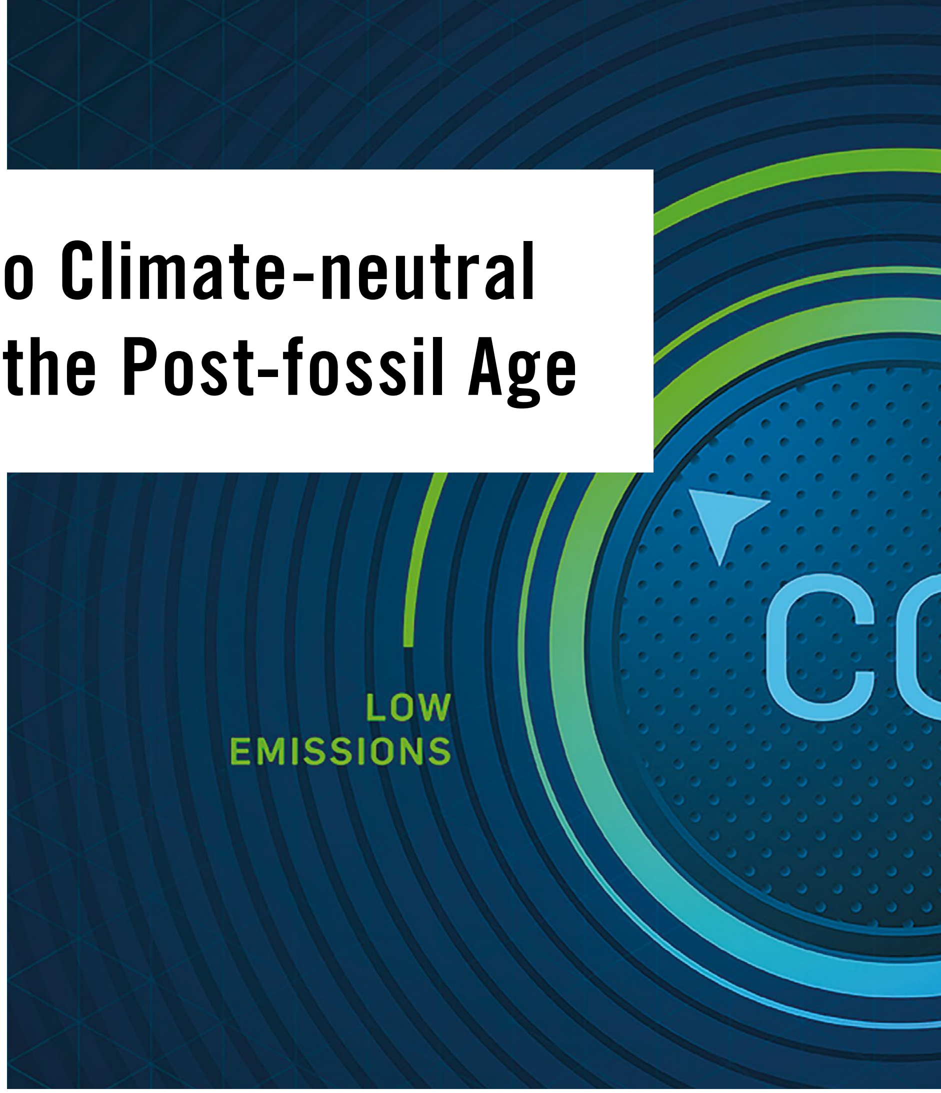
Pathways to Climate-neutral Mobility in the Post-fossil Age



In a new orientation study, the industrial research association FVV not only takes into account all climate-relevant emissions generated during the construction and operation of vehicles – for the first time, it also considers the provision of energy carriers across sectors, including the establishment of the infrastructure required for this. As such, it calculates both cumulative greenhouse gas emissions from mobility and the cumulative additional costs to the economy and analyses further dependencies.

1 STUDY DESIGN

In an orientation study by FVV [1] published in 2018, significant differences were revealed between the assumed 100 % carbon-neutral scenarios (direct use of electricity in electric vehicles, use of hydrogen in fuel cells or switching to synthetic fuels) in terms of the distribution of the required investments in infrastructure and the cumulative additional costs for vehicles. The urgent need to develop these technologies further was realised and pursued in the form of a life-cycle analysis [2] and this follow-up study completed by Frontier Economics and the Institute for Energy and Environmental Research Heidelberg (ifeu) on behalf of FVV [3]. The method used to determine the Greenhouse Gas (GHG) emissions in the CO_2 budget resulting from the construction of infrastructure must be highlighted as, unlike in many other studies, it is included in the remaining GHG budget immediately. The scenarios from 100 % fleet penetration using carbon-neutral energy carri-

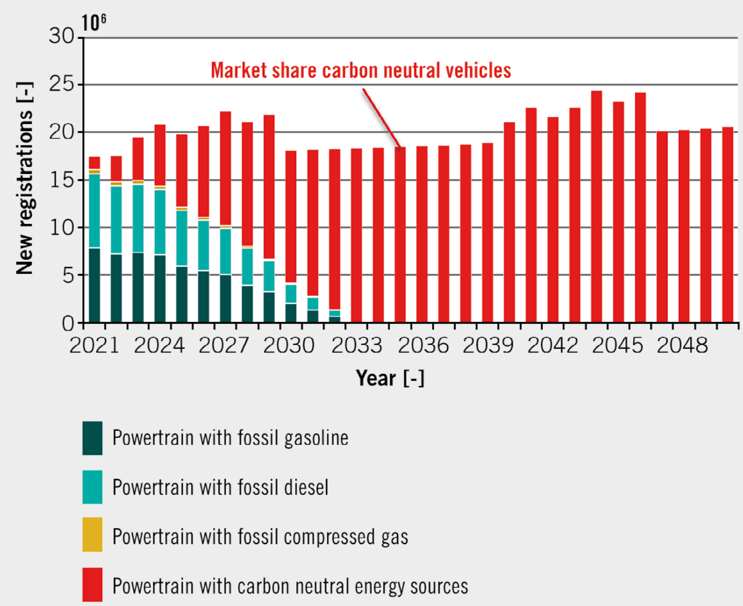
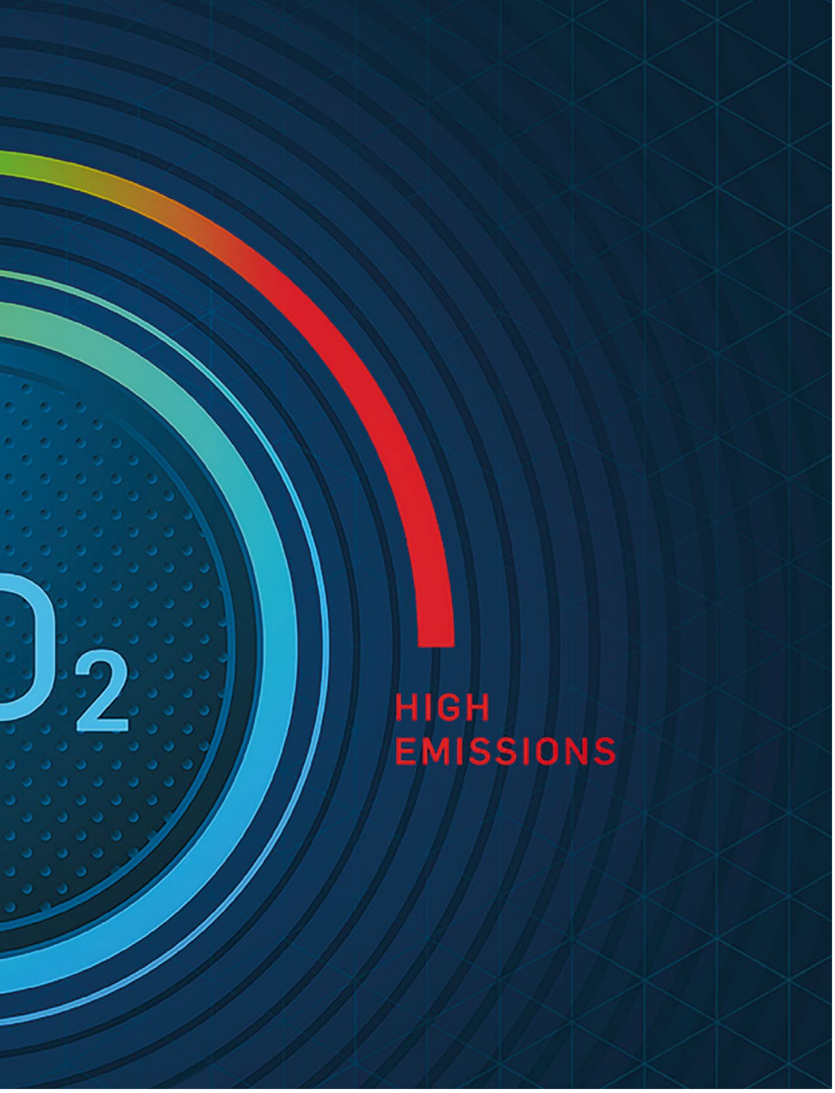


FIGURE 1 Market share of newly registered cars/commercial vehicles in the EU assuming that only climate-neutral vehicles are on the road in 2050 (© Frontier Economics)



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ers were retained, as they enable a comprehensive view of both the potential scalability and possible resource bottlenecks. A total of 42 possible transformation pathways were examined [4]. The effects of domestic generation in Europe and the United Kingdom (EU27 plus UK) or internationally in sunny or windy regions were also investigated for all energy carriers. Progress in the efficiency of the vehicles was taken into account by including three sub-scenarios:

- the "status quo" scenario which scales current series technologies and implements measures for meeting future limit values for emissions of pollutants
- the "balanced" scenario with additional efficiency technologies (for example, complete hybridisation of combustion engines)
- the "all-in" scenario, with all known technologies that enhance efficiency, (for example, also lightweight construction).

FIGURE 1 uses the average duration for which vehicles are kept to derive a year from which no more vehicles powered with fossil fuels will enter the market. This logic was also assumed for the internal combustion engine/Fischer Tropsch (FT) fuel combination. The mobility demands taken as the basis for all scenarios correspond to the reference scenario of the EU, which forecasts increasing total mileages for virtually all vehicle categories and does not assume restrictions on individual mobility.

VOICES OF THE FVV

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Dr.-Ing. Ulrich Kramer is Head of FVV's Future Fuels Working Group and is responsible for Fuel Research in Europe at Ford-Werke GmbH as an Expert in Research and Advanced Powertrain Engineering in Cologne (Germany).
"The study's comprehensive carbon balance approach gives us a complete picture of how different technological options will eat into our remaining CO_2 budget and what the work involved will cost in each case. Since the ramp-up rate of new technologies, together with the availability of critical raw materials, has a decisive influence on the climate balance of the European transport sector, we are currently looking at possible mix scenarios in a follow-up study."

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Dipl.-Ing. Dietmar Goericke is Managing Director of the Industrial Research Association FVV eV in Frankfurt am Main (Germany).
"Germany will only achieve its climate goals as part of Europe. Since it is not the powertrain technology but the availability of climate-neutral energy sources that determines how much GHG emissions in the European transport sector will fall, we need to phase out fossil energy carriers as fast as possible."

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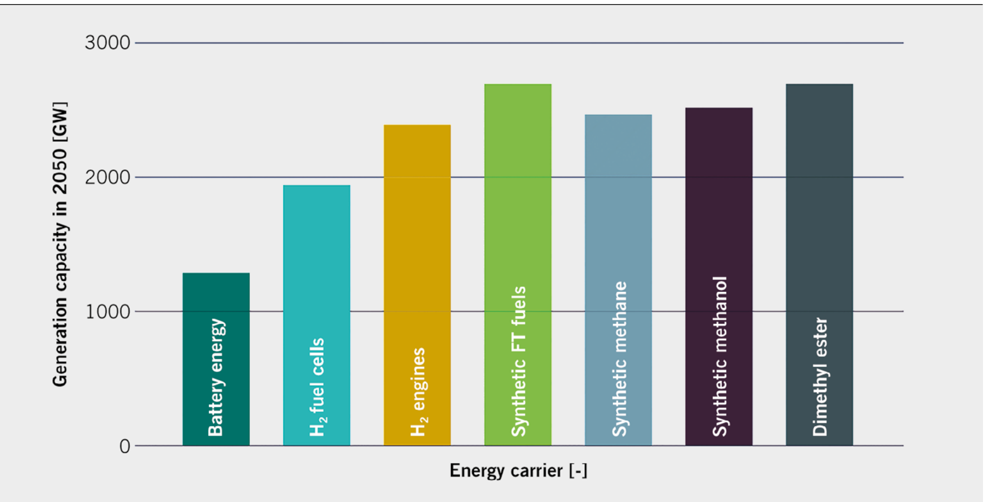

FIGURE 2 Generation capacity required to defossilize the entire European road transport sector; direct use of electricity generated within Europe, hydrogen and synthetic fuels from sunny and windy regions (© FVV)

The most important objective was to create a technical basis for a discussion about strategies for climate-neutral mobility. Therefore, the availability of raw materials and the type of energy generation promoted by the location were also included in the investigation. Overall, the FVV succeeded in achieving this neutral data foundation – at least for the 100 % scenarios and the European transport sector. Rounded figures are used in the following summary of results; the exact values can be found in [3].

2 CUMULATIVE GHG EMISSIONS

The total energy demand for each of the various powertrain and vehicle technologies for the year 2050 for Europe is approximately 2000 to 10,000 TWh/a for status quo technology, depending on the scenario. As expected, the direct use of electricity has the lowest final energy requirement and synthetic fuels have the highest. For battery electric scenarios, this already includes the required reconversion of the previously generated hydrogen to cover seasonal fluctuations. The primary energy demand for Battery Electric Vehicles (BEVs) undercuts that for Fuel Cell Electric Vehicles (FCEVs) by approximately a factor of two, and is a factor of around three to four lower than that for vehicles powered using synthetic fuels.

The costs and GHG emissions for building up a sustainable energy infrastructure are solely determined by the necessary capacities of the energy system. In turn, these capacities are decisively influenced by the energy return on investment of solar and wind power plants, as the achievable number of full load hours is heavily dependent on the location. These capacities were calculated for all 42 scenarios, even for extremely improbable cases such as the direct use of electricity generated close to the equator. There is therefore a spread between around 750 and 4800 GW in the plant capacity needed to supply the European road transport sector with energy. If only the scenarios are considered that are economically realistic and technically feasible and assumed that technical improve-

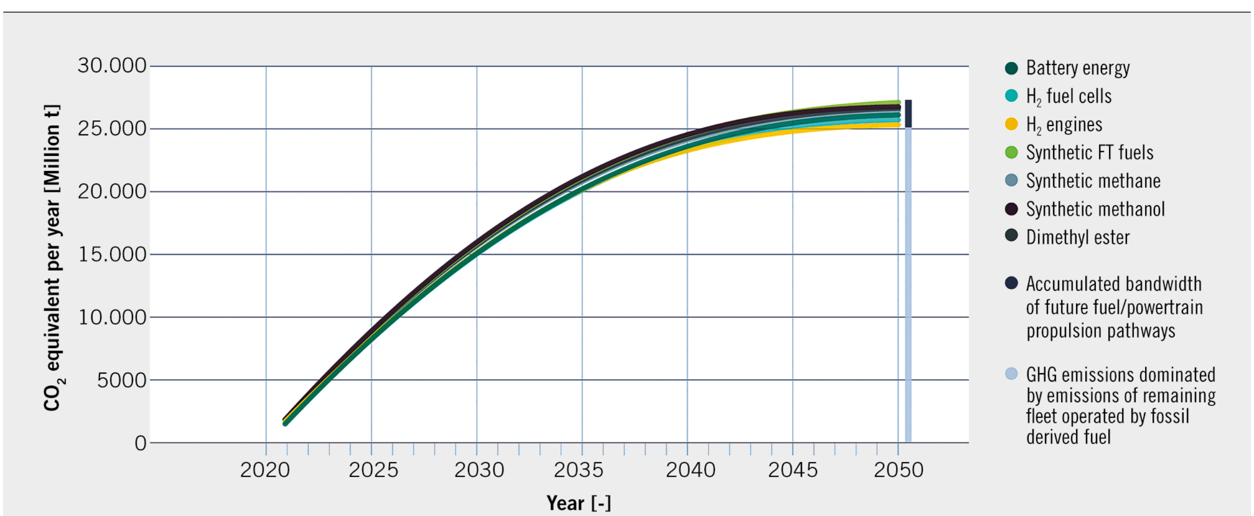

FIGURE 3 Cumulative CO_2 emissions of the car fleet in Europe (EU27 plus UK) for different combinations of powertrains and energy carriers with identical ramp-up speeds (© FVV)

ments that reduce overall vehicle emissions also become established, the spread is only half as great (1000 to 3000 GW), as shown in **FIGURE 2**. When modelling the capacities of all other plants, it became apparent that the electrolysis capacities needed for generating hydrogen for the necessary reconversion are also considerable for purely battery electric scenarios. Accordingly, an electrolysis capacity of slightly more than 1000 GW is required by 2050 for a "balanced" battery electric scenario with domestic power generation, with 8.9 % of the required electricity being assigned to seasonal buffer storage through this method. The subsequent analysis focuses on European road transport.

All GHG emissions relating to mobility were calculated for each year and then accumulated for the period from 2021 to 2050. The total value of all GHG emissions resulting from the use of fossil energy carriers in the part of the vehicle fleet that is not yet converted was determined for all scenarios. Depending on the scenario, these make up 66 to 74 % of total emissions. Considering only the car sector, the cumulative CO_2 emissions of different powertrain–energy carrier combinations only differ by a maximum of 14 % when the speed of conversion is identical, **FIGURE 3**.

The cumulative share of GHG emissions for building up the energy supply infrastructure is between 5 and 20 % of total emissions, with this share falling if electricity generation is shifted to sunny and windy regions. Vehicle production is responsible for around 11 to 24 % of emissions, with the highest shares attributable to battery electric vehicles as expected. Regardless of the technology path, the cumulative GHG emissions for vehicle production and scrappage, together with the construction of the entire energy supply system, total around 30 % of overall emissions, while around 70 % stem from running the remaining fleet with fossil fuels. For vehicles with combustion engines, both hybridisation and lightweight construction result in higher production-related GHG emissions. However, these are only overcompensated with saved emissions during the vehicle operation phase in the case of hybridisation. While hybridisation lowers total cumulative GHG emissions, aluminum lightweight construction raises them.

Comparing the cumulative emissions with the remaining CO_2 budget during the balance sheet period – a hypothetical value corresponding to Europe's share of the global population which is not politically defined – the following becomes clear: in all scenarios the cumulative emissions caused by road transport alone exceed the total budget for GHG that would be available to Europe for all sectors in order to stay within the target increase in mean global temperatures of 1.5 °C with a probability of 67 %, **FIGURE 4**. Two thirds of the emissions budget for an increase of 1.75 °C would be exhausted solely in order to cover mobility demands.

3 RAW MATERIALS

The availability of raw materials is a key prerequisite when introducing new technologies. Alongside cobalt and lithium, which are both key materials for modern batteries, and platinum, which is currently indispensable as a catalyst in fuel cells, further materials such as copper were investigated. An increasing recycling ratio was assumed among a growing vehicle population. In the case of lithium, existing reserves can cover European demand even in an unrealistic scenario assuming 100 % use of battery electric powertrains, while a complete switch to solid-state batteries with a pure lithium anode can lead to bottlenecks; **FIGURE 5**. This problem is exacerbated if the entire world follows the European example in its selection of carbon-neutral powertrains and energy carriers. The cumulative demand for cobalt for current battery technology would significantly exceed worldwide resources in a 100 % scenario, with the same also applying for platinum demand in a 100 % fuel cell scenario with today's technology. Copper would become far scarcer in all scenarios; however, it could be replaced with other conductive materials.

4 ECONOMIC COSTS

The economic costs of energy supply based on renewable resources are predominantly due to investments in infrastructure. A sound estimate of these

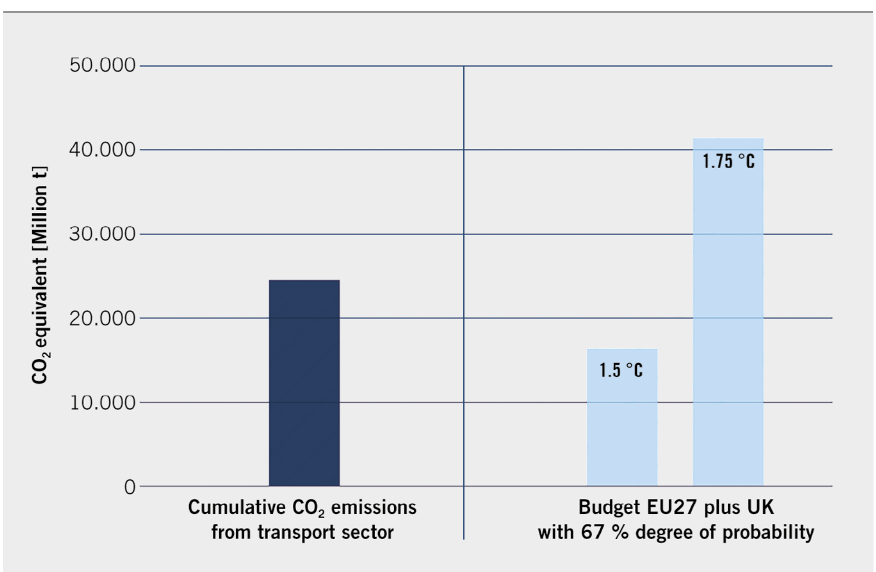

FIGURE 4 Comparison of cumulative CO_2 emissions from mobility compared to the European CO_2 budget upon achieving the goal of 1.5 °C and 1.75 °C respectively (© FVV)

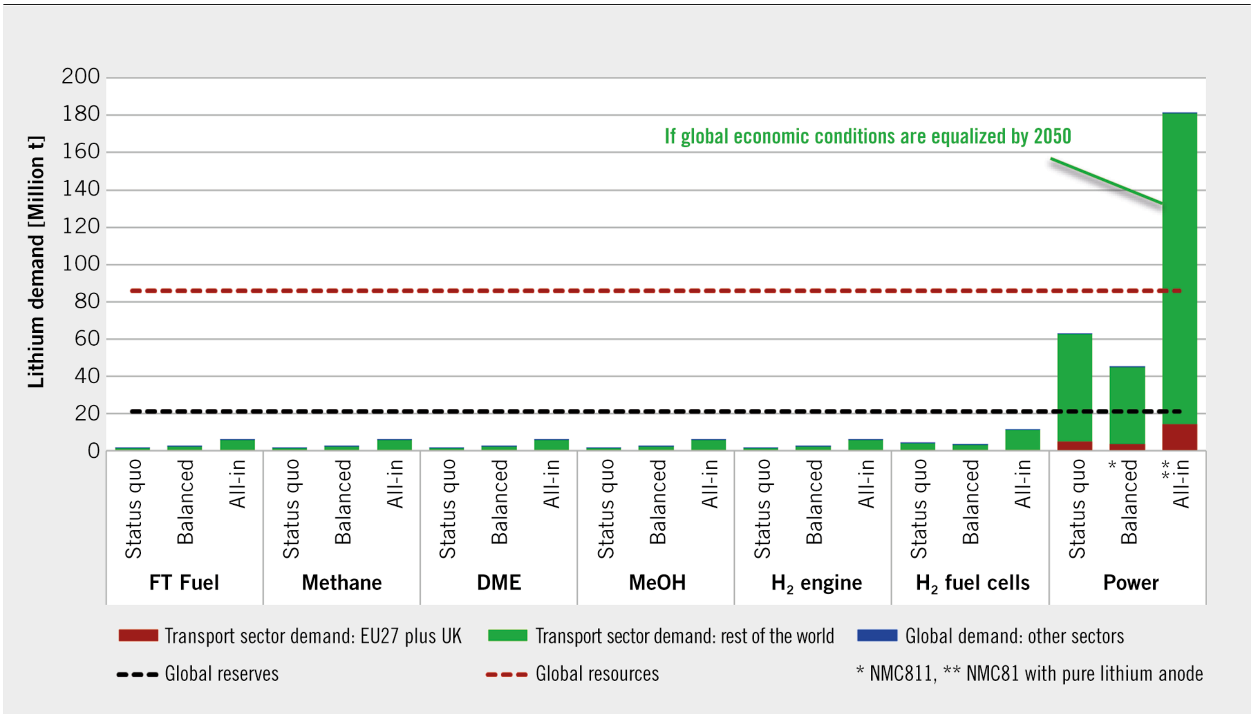

FIGURE 5 Cumulative lithium demand (100 % scenario) from 2021 to 2050 compared to worldwide reserves and resources (© ifeu)

costs can be made based on the capacities shown, whereby a significant reduction in costs is assumed for mature technologies such as solar or onshore wind power plants on the basis of substantial data and expert assessments. For the synthesis paths used to generate carbon-neutral fuels, the scaling of plant sizes in particular brings down costs. When calculated, thus, investment costs between 1500 and 3500 billion Euro are required solely for generating and distributing the required energy carriers. In general, the costs increase along with the number of conversion steps in the energy chain, with internationally produced methanol only slightly more expensive than the status-quo electric car supplied with domestic electricity at a little above 2000 billion Euro. The spread for investments is smaller than

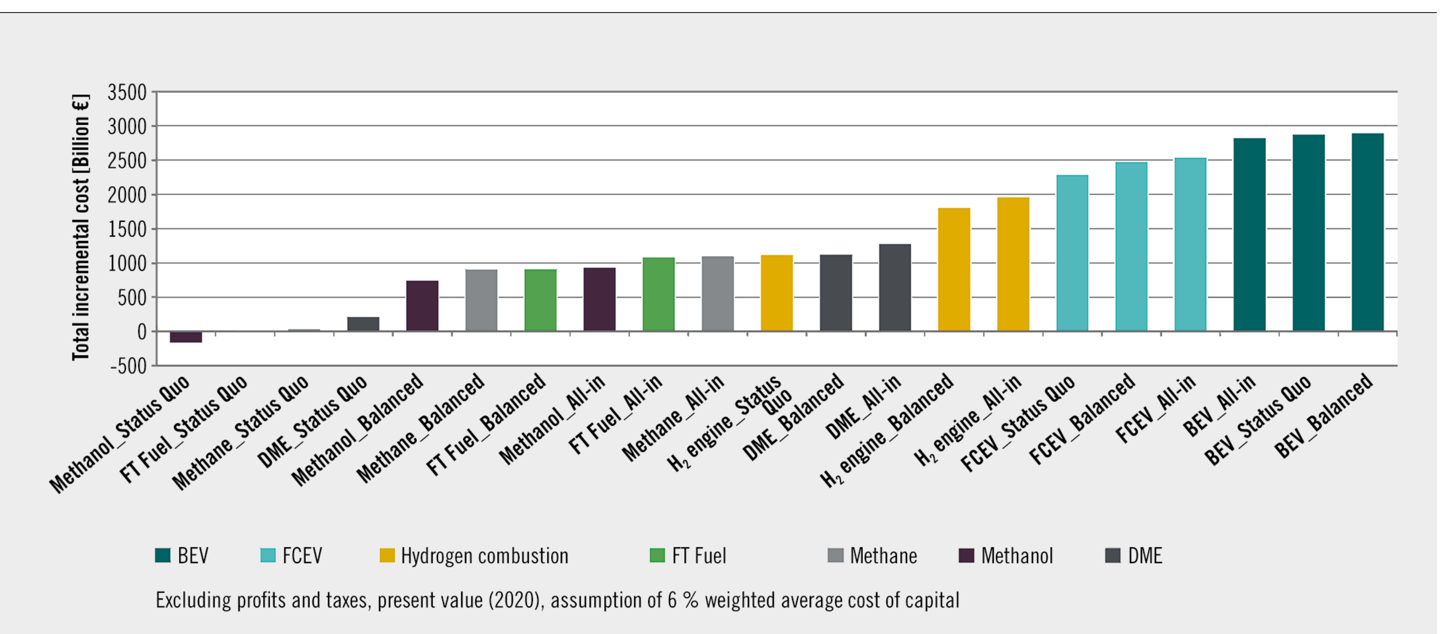

FIGURE 6 Cumulative additional costs for emission-free vehicles in Europe up to 2050 (© Frontier Economics)

that for the required power generation capacities primarily because carbon-neutral liquid fuels largely reach vehicles via the existing fuel infrastructure.

Calculating future net costs for vehicles is a special challenge as there is not yet experience of serial production in all the technologies. However, Frontier Economics has created a set of parameters that enables an approximate determination of the costs for certain vehicle categories by pricing individual subsystems and estimating possible cost degressions or increases, for example due to stricter emissions limit values for combustion engines. If the total costs for all climate-neutral vehicles registered in Europe by 2050 are accumulated, renewing the vehicle fleet would result in costs of around 6000 to 9000 billion Euro. Only the additional costs for future vehicles with gasoline and diesel engines (emissions standards EU7+) are relevant; **FIGURE 6**. When viewed this way, vehicles running on FT fuels do not create any additional costs. Because only combustion processes in spark-ignition engines were taken as the basis for methanol vehicles, this path results in lower vehicle costs than even the Fischer-Tropsch path. Significant cumulative additional vehicle costs are expected for FCEVs or battery electric powertrains.

If the extra costs for a climate-neutral vehicle fleet and the investment costs for providing the required energy are added together, this produces a similar picture to the additional vehicle costs due to the dominance of vehicle costs. With total costs of 2600 billion Euro, the use of internationally generated methanol in vehicles without any other expensive efficiency measures is the cheapest way to defossilize the entire road transport sector. Other concepts with relatively low total costs are the use of methane, dimethyl ether and some FT variants. At around 5000 billion Euro, 100 % battery electric mobility causes double the costs in order to achieve the same climate impact.

5 CONCLUSION

Every climate strategy exclusively aimed at the GHG neutrality of the new car fleet will fail to meet the goals of the Paris Agreement. If the assumed ramp-up speed of climate-neutral technologies is the same, the differences in cumulative emissions between the investigated combinations of powertrains and energy carriers are comparatively small. Effective climate protection in the transport sector is primarily related to the fast availability of renewable energy carriers that also have an impact in the existing vehicle fleet.

In reality, a linear and globally scalable ramp-up is faced with obstacles in every scenario, from a temporary lack of availability of critical raw materials to the lacking acceptance of the expansion of renewable power generation facilities among the general population. An intelligent mix of powertrains and energy carriers can at least help overcome these obstacles and thus play a role in reconciling individual mobility and climate protection, while also helping the vitally important expansion of renewable energy provision progress as quickly as possible. In a follow-up project, FVV is therefore examining what such a mix – which would enable fossil fuels to be replaced as a means for supplying energy to the transport sector as quickly as possible – could look like in the future, in a number of realistic scenarios.

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