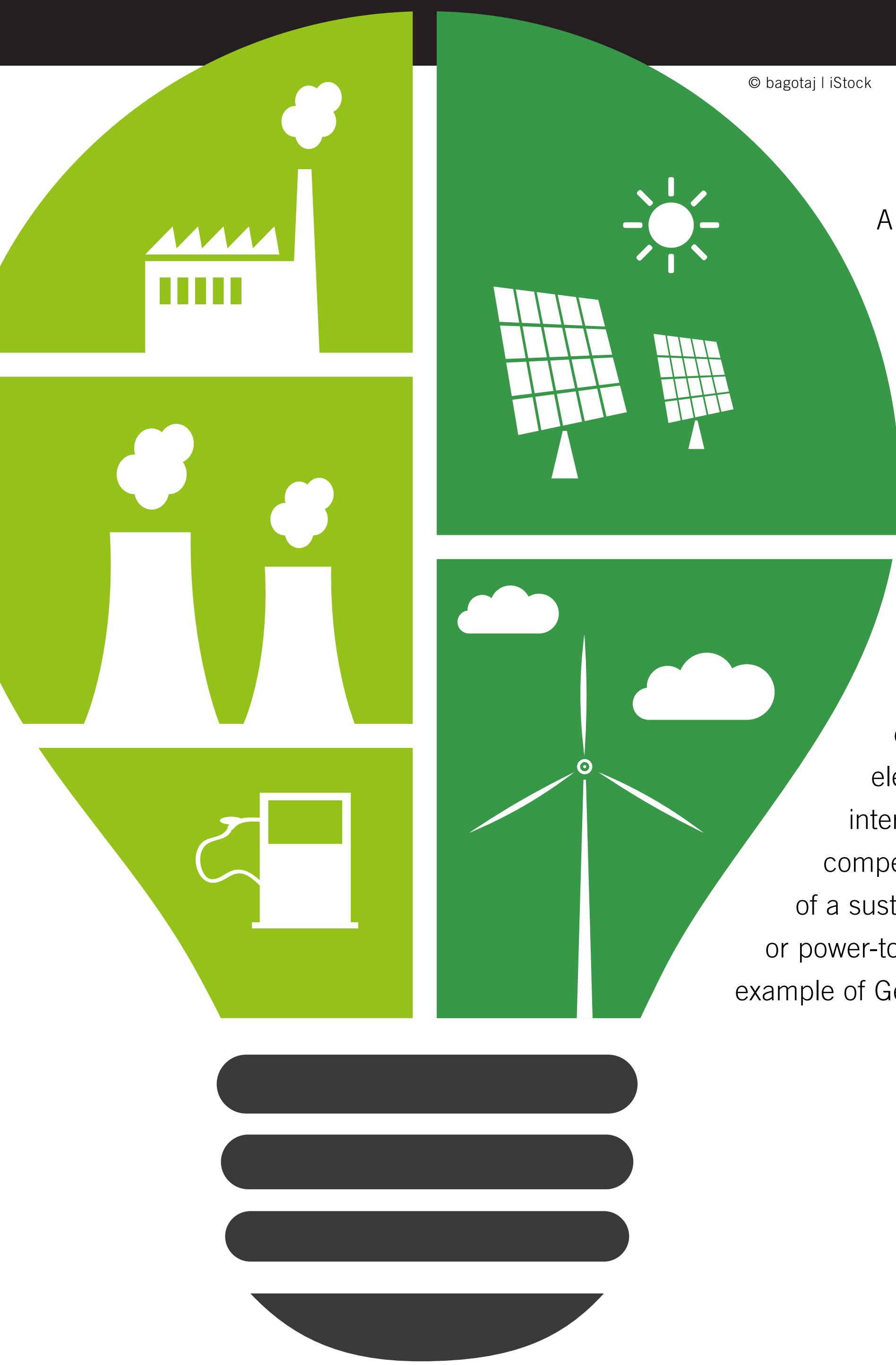
Alternative Fuels in the Well-to-Wheel Debate



A rearrangement of the fuel care in the mobility from conventional to regenerative energy sources as the basis for fuel in transportation can be guaranteed. This show studies from APL, LBST and FVV. It points towards the contradicting optimization of efficiency and system usefulness. Optimization of different fuel options is directly linked to the energy converter used in the vehicle. Today pure battery electric vehicles (BEV), fuel cell electric vehicles (FCEV) or vehicles with internal combustion engines (ICE) compete. The principal economic feasibility of a sustain-able fuel supply of power-to-gas or power-to-liquid is demonstrated using the example of Germany.

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WHAT IS FUEL?

The wish for mobility of persons and transport of goods is best answered on the level of services, since it cannot be assigned to a classical product category. Fuel, however, is a means to an end; that is in order to judge its importance for mobility one has to take the system environment into account. In the sense of a system boundary one could see the fuel as energy carrier to be stored on board of the vehicle and to be transformed with the help of an energy converter (or a system of energy converters) in the vehicle propulsion according to actual requirements.

The evaluation of a fuel or energy carrier in terms of its sustainability, efficiency, emissions and costs needs to be debated and assessed along the complete chain of supply and use, that means from the primary energy base to the point where wheels are turning (hence "well-to-wheel"). Therefore, upstream energy efforts for fuel production and supply have to be assessed on par with energy demands in the vehicle.

FUELS FROM CONVENTIONAL PRIMARY ENERGY BASE

Fossil-based fuels are mixtures of many different hydrocarbons, which are now mainly produced by refining crude oil. In addition to diesel, kerosene and gasoline more energy carriers have been established, such as methane, liquefied petroleum gas (LPG) and others shown in the left part of **FIGURE 1**. Through dedicated conversion processes liquid and gaseous fuels can also be generated from natural gas and coal.

Through downstream conversion of energy carriers of aconventional primary energy base in the vehicle and by using an internal combustion engine the desired propulsion of the vehicles can be generated. The high storage density of liquid hydrocarbons in particular is reflected in the small tank volumes of vehicle tanks or large range of vehicles with a given tank volume. With battery and fuel cell electric vehicles, the electricity is either temporarily stored in a battery or generated by a fuel cell on board from hydrogen. Today the hydrogen for fuel cell vehicles is either reformed from natural gas or stems from water electrolysis using renewable electricity.

The disadvantage of using fossil primary energy sources is that biogeochemical cycles, notably the carbon cycle, are not closed in reasonable time-scales after the fossil carbon emission occurred. Thus, hydrocarbons from biomass stored over millions of years in the form of fossil reservoirs are now used in a relatively short geological time scale and carbon dioxide is emitted into the atmosphere. The discussions about the climate impact of carbon dioxide are well known.

FUELS FROM REGENERATIVE PRIMARY ENERGY BASE

Regenerative primary energy base either generates hydrocarbons like those from

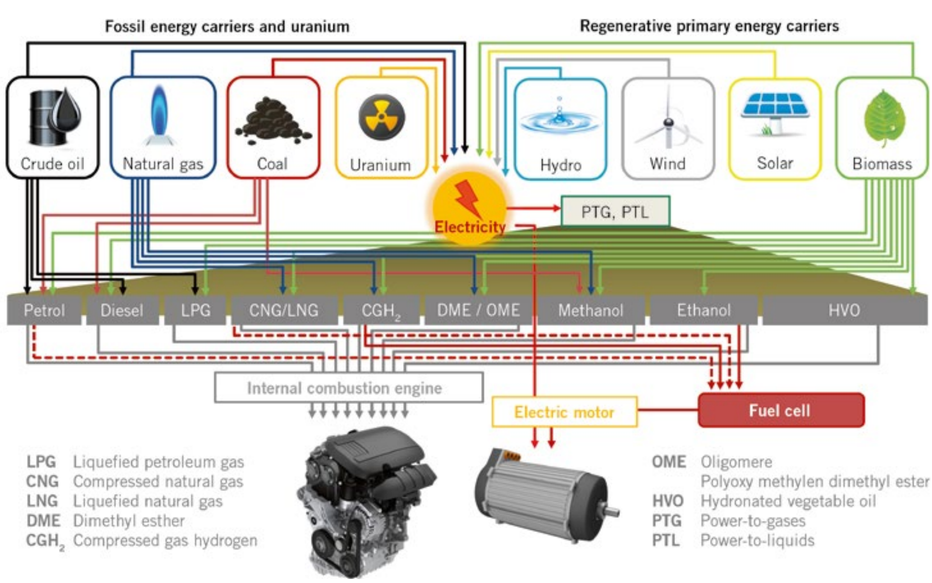


FIGURE 1 Energy carriers derived from fossil and renewable primary energy bases (© APL)

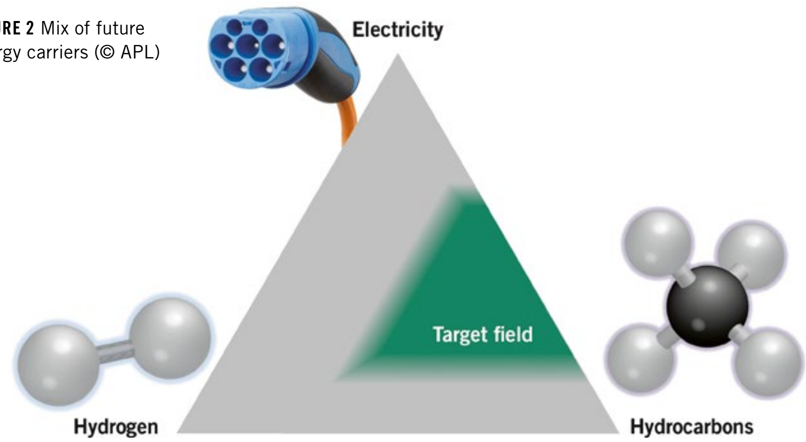


FIGURE 2 Mix of future energy carriers (© APL)

fossil origin basis via the production of biomass and the downstream process engineering or it directly provides electricity of high thermodynamic value (= 100 % energy) as shown in the right part of **FIGURE 1**. Another way is to use renewable electricity to synthesize power-to-methane or power-to-liquids, that means energy-dense fuels for vehicle propulsion with the help of internal combustion engines. The advantage of the use of hydrocarbons from renewable energy sources is the timely closed carbon cycle. In the synthesis process the same amount of carbon dioxide is bound as will be emitted later on in the combustion process. Of course, the electricity gained by the use of regenerative primary base can be directly used in battery electric vehicles or to produce hydrogen for fuel cell vehicles. However, one disadvantage of the battery electric vehicle is that it has no volumetric and gravimetric energy density comparable to hydrocarbons and only limited storage capacity – the vehicle's real operating range is thus limited. The fuel cell vehicle is still in an early stage of commercialization.

TRANSPORT FUEL – THE BIG PICTURE

The portfolio of energy carriers for transport which will be increasingly based on pure regenerative primary energy in the future could be represented as in **FIGURE 2**. The Federal German Environment Agency (UBA) has indicated a mix of electricity, hydrogen and hydrocarbons, the target area with focus on hydrocarbons in its study, published in October 2013.

A fundamental analysis shows that a 100 % regenerative primary energy base is reasonable. The energy balance of our planet shows that the short-wave solar radiation, the direct reflection and the longwave radiation from surface is balanced in a seasonal-on-year average. This is in accordance with the first law of thermodynamics, as otherwise an imbalance would result in either heating or cooling. If one takes the average hourly solar radiation on the earth's surface from about 123,000 TWh and relates it to the global annual primary energy consumption of about 155,500 TWh (IEA 2012), one realizes that solar energy from one hour of global surface solar radiation is the energy equivalent to what mankind consumes in one year.

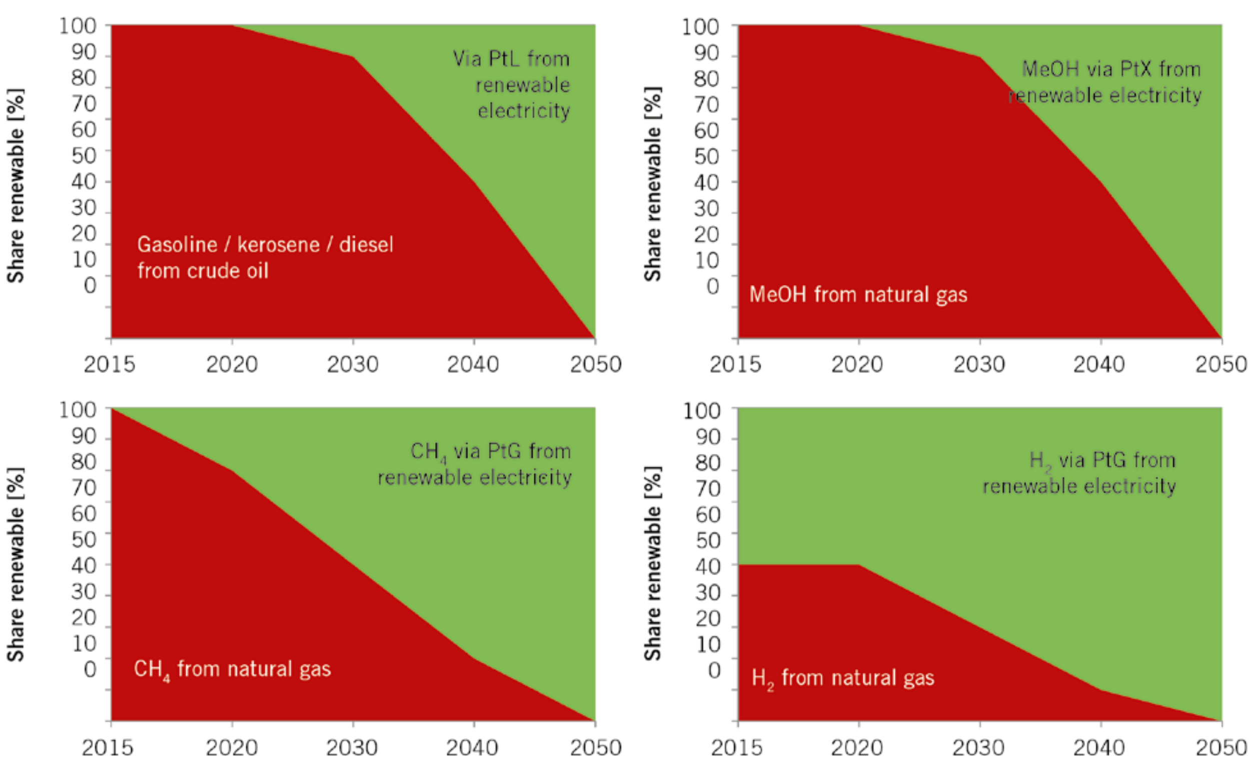


FIGURE 3 Target scenario of an energy transition in fuel by 2050 in ten year steps (© FVV)

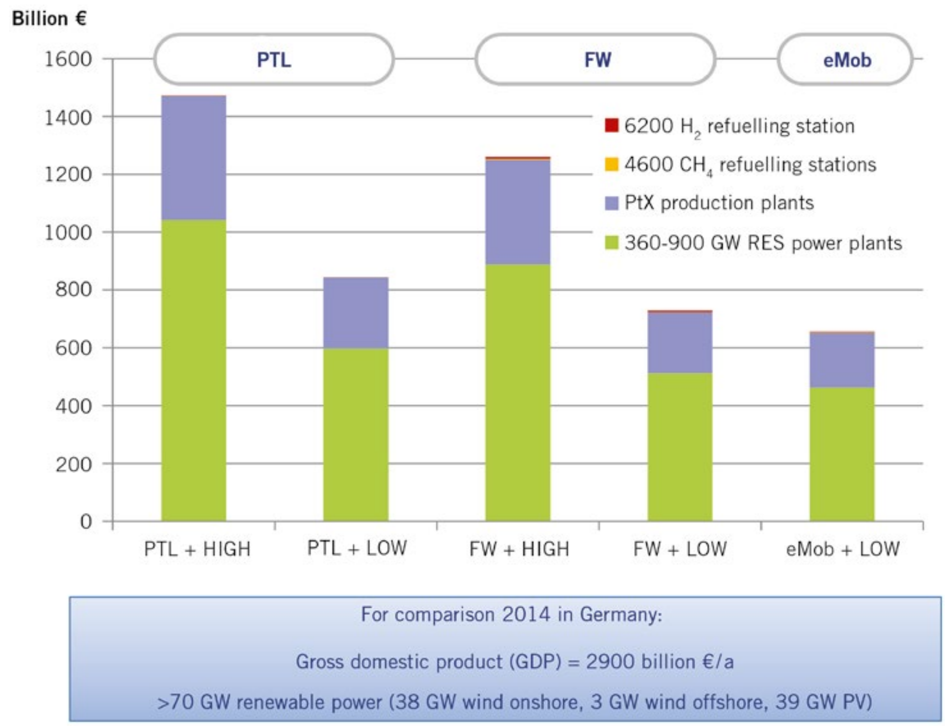


FIGURE 4 Cumulative investment needs for the various scenarios for Germany till 2050 (© FVV)

Conversely, this means that we have no problem of energy shortage in itself, but a challenge of energy conversion, that means transferring the regenerative primary energy into the energy carriers desired as for example future transportation fuels.

In a study, which was conducted by the Ludwig-Bölkow-Systemtechnik (LBST) on behalf of the Research Association for Combustion Engines (FVV) an estimate for the representation of a pure regenerative energy supply of the transport sector in Germany is shown for the year 2050. Based on different demand scenarios for the transport of persons and goods, the resulting power-to-liquids (PtL), power-to-gas (PtG) and electricity for fuel demands were calculated till 2050. In **FIGURE 3**, a target scenario for the conversion of various fuels into 100 % regenerative primary energy base is sketched. Today, hydrogen (PtH_2) for transport use is already produced with about 50 % renewable electricity, albeit starting from low absolute amounts yet. For synthetic methane ($PtCH_4$) several demonstration and pilot plants have been put into operation in the last two years. With regards to PtL, first initial demonstration / pilot plants are in operation, too; key components of PtL processes have been established on an industrial scale in the fossil energy supply; availability of large-scale plants based on renewable electricity can be expected from 2020 to 2030.

To estimate the bandwidth of necessary infrastructure investments more reference scenarios were assumed. The transportation demand has been divided into a high and low variant. The low demand variant is based on the eMobil study scenario "Regional" by Öko-Institut (2014) for the Federal Ministry for the Environment (BMUB). The high demand variant assumes further growth of passenger air and cargo transportation as stipulated by the official traffic forecast 2030 by the Federal Transport Ministry and their extrapolation to 2050 in the context of Fuel and Mobility Strategy (MFS) of the Federal Government.

With regard to the different fuel / powertrain scenarios – that means the assumed vehicle mix and corresponding fuel/energy carriers –for the "PtL" scenario of today´s vehicle type composition as well as conservative efficiency improvements through for example mild hybridization was assumed; the "eMob" scenario was derived from above captioned BMUB investigation, anticipating a widely use of electrical drives (BEV and FCEV). The "FVV" scenario assumes an increased conversion to electrified drives with internal combustion engines (REEV), but also takes into account the use of battery and fuel cell electric vehicles.

In **FIGURE 4** the cumulated investment required for PTX production plants, renewable electricity generation plants, methane and hydrogen filling stations are depicted for the entire period up to 2050. Also learning curves have been taken into account in the calculations. It can be seen that all assumed scenarios are dominanted by the share of cumulated investments into power generation plants (some 70 to 80 % of overall cumulated investments). The share of cumulated investments into fuel distribution systems is almost negligible. A transformation of the transport sector to 100 % renewable energy base requires cumulated investments of around 600 to 1400 billion euro, depending on the transportation demand and fuel / powertrain scenario. Considering an average investment of 1000 billion euro cumulated over 35 years until 2050 (that means some 28 billion euro per year in average) against the gross domestic product in Germany (that means some 2,900 billion euro GDP in 2014), it is evident that a full energy transition of the transport sector is in the order of a low single-digit percentage range of GDP. Such an infrastructure measure is certainly manageable from an economic perspective , even more as a considerable part of the investment contributes to the local value creation. The 360 to 900 GW of renewable electricity generation capacity to be installed for the transportation sector corresponds to about 5 to 15 times of today's installed renewable power plant capacities in Germany. Renewable power plant capacities of this magnitude present no knockout criterion from a technical standpoint in the EU. However, for public acceptance reasons some fuel imports may be desirable, notably of PtL in the high demand scenarios (PtL + HIGH, FVV + HIGH) for its ease of transportation by existing crude oil and minerals products logistics.

COST CONSIDERATIONS

In order to develop an indication of the expected cost levels of different transportation fuels, a cost perspective for 2050 was worked out by Ludwig-Bölkow-Systemtechnik GmbH based on published specifications and technology learning curve extrapolations. Here, all values were converted to the energy content of a liter of diesel equivalent. The summary values are shown in **FIGURE 5**.

For the fossil fuels reference, IEA takes 100 US-Dollar per barrel of oil in 2050 into account which corresponds to about 0.61 euro per liter liquid fuel (diesel equivalent, excluding taxes). The electricity generating costs are conservatively assumed at 8.2 ct/kWh including the costs of transporting electricity. The annual equivalent full load hours of renewable electricity production is considered 4000 hours/a. The carbon dioxide is completely extracted from ambient air (conservative assumption without potential restrictions). From **FIGURE 5** it can be seen that the various PtG and PtL products are all in the similar range by 2050 with some 2.5 euro per l of diesel equivalent. The fuel costs are determined by the electricity costs, which account for about 80 % of total costs ex filling station. Further evaluations with the use of renewable electricity power in countries with high solar / wind supply and 6500 hours of equivalent full load production per year including fuel transportation and distribution show a cost saving potential of about 20 % compared to Germany. The difference between fossil and renewable hydrogen production costs is significantly lower compared to more complex hydrocarbons. Further short- to middle-term cost reducing potentials are thinkable on the basis of business case analyses, for example the usage of concentrated CO_2 (for example from biogas upgrading), or additional revenues from electricity grid services (for example flexible electrolyser operation). Feasible reductions in costs achieved in this way depend on the site selection and the development of regulatory frameworks in the power system.

REVIEW OF THE FUEL PATHS

A transition from presently mostly fossil-based mobility of people and goods to a purely regenerative primary energy base is reasonable. This does not necessarily require pure electric vehicles only. Depending on the modal requirements, model strategies, especially in road transport, may draw from a host of powertrain options including battery-electric components, fuel cell-electric components as well as hybrid systems operated with differently sized internal combustion engine components. All these options have

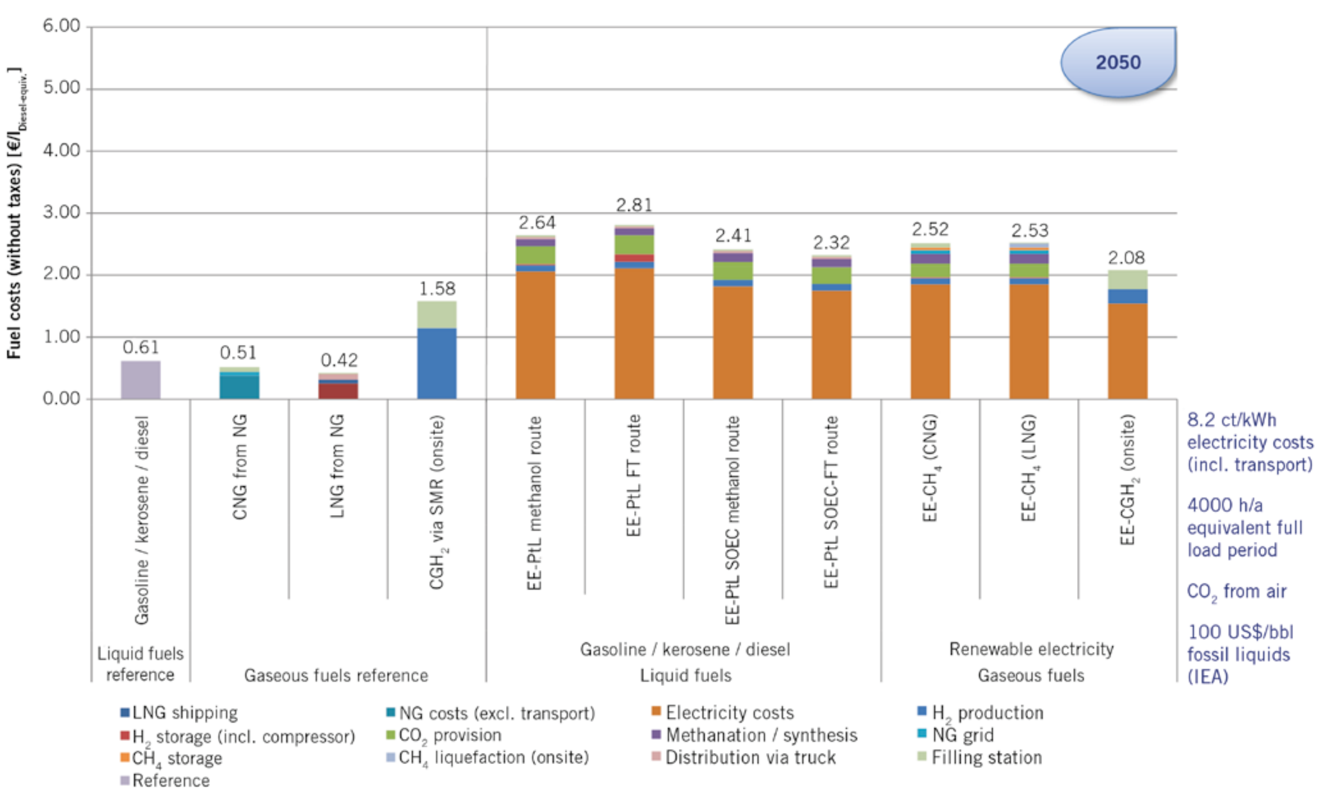
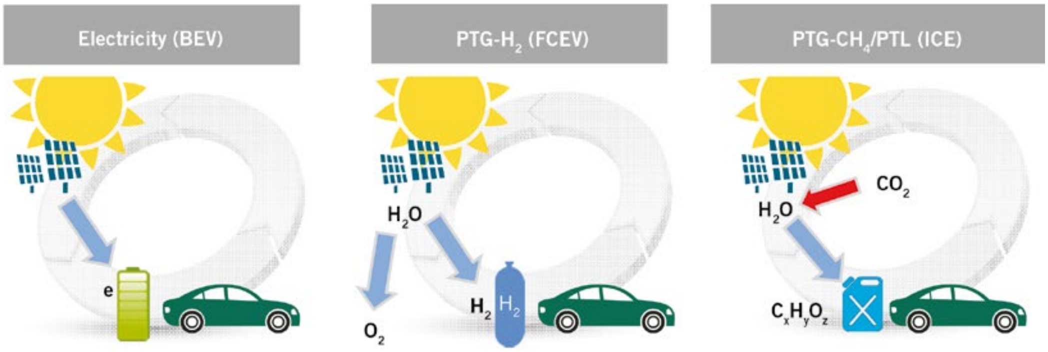


FIGURE 5 Full cost analysis of transportation fuels for the year 2050 with PTX production in Germany (© FVV)

FIGURE 6 Comparative overview of vehicle fuel/powertrain options (© APL)



	Electricity (BEV)	PTG-H_2 (FCEV)	PTG-CH_4/PTL (ICE)
Vehicle costs	-	-	+
Storage density	-	∘	+
Range	-	∘	+
Primary energy use	+	∘	-
Infrastructure	-	-	+
Emissions* (tank-to-wheel)	+	+	-
Emissions (well-to-wheel)	+	+	∘

** Criteria air pollutants*

in common that they are increasingly operated with renewable electricity, hydrogen or hydrocarbons.

FIGURE 6 shows a summary of the advantages and disadvantages of different fuel / powertrain options. The battery-electric option has significant advantages in the short-distance mobility. The high storage densities of hydrocarbons make them an especially good fit for long-distance and high-performance transport applications. The fuel cell-electric option plays a robust midfield role tapping into small, medium and heavy-duty applications.

The identified cost and investment comparisons show that a transition to a purely regenerative primary energy supply base is not a fast-selling item. As long as the added environmental value (that means sustainability) of renewable fuels is not attributed an economic value, renewable fuels remain more expensive than fossil fuels in the foreseeable future. To make this transition happen, a societal will and facilitating framework is needed in order to achieve the 2050 objectives.

The presented results are based on conservative assumptions for specific energy needs and costs. Political framework and business-opportunities may allow for lower renewable fuel costs, for example if regenerative electricity could initially be used at reduced tax rates or the use of carbon dioxide from "grey sources", such as cement works or furnaces. Rules for environmental accounting of CO_2 from grey sources would be helpful to this end, thus avoiding CO_2 extraction from ambient air, increasing the fuel production efficiency and preventing carbon leakage between sectors. If the transport sector increasingly requests more regenerative power supply, these requirements are not least to be considered in policy roadmaps and regulatory frameworks for the integration of (fluctuating) renewable electricity generation. The key to business decisions however, is sufficient security of investment. The current 2020-targets (EU FQD, EU RED, German BImSchG) should thus be further developed with a view to achieving 2050 targets.

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