A Mapping of Technology Options for

Sustainable Energies and Powertrains for Road Transport

Towards Electrification and other Renewable Energy Carriers

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Disclaimer

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Summary

With the document here, ERTRAC provides the perspective of the research community over the different technology options to address the environmental and energy challenges for road transport. As a technology platform, the work of ERTRAC is focussed and limited to technical aspects. Whilst acknowledging the high importance of socio-economic aspects for policymaking and market success, these are out of scope of ERTRAC; therefore, aspects such as costs, investment and user acceptance are only mentioned as key factors but are not elaborated upon in this document. This document should, therefore, only be read as a reference, mapping the potential research needs for all the options of road transport with sustainable energies and powertrains. It is acknowledged that European policies addressing energy and mobility also investigate and weigh social, economic and political aspects, therefore that European policies are set as a balance of these various criteria. As a technology platform, ERTRAC is not involved in EU regulatory processes and only provides a mapping of the efforts taking place in the research community: it is the role of the policymakers, not of ERTRAC, to assess the technology options and make decisions in the wider framework of social, economic and political conditions.

Recently, the European Commission has developed its “Fit for 55” policy[1] related to the decarbonisation of transport in general. As a consequence, the research needs given in this document, specifically related to road transport, have been identified as being, either <u>completely in line</u> (topic and timing, including the internal combustion engine (ICE) ban) with that policy, <u>required to be in line</u> (e.g. for the same goal of decarbonisation, but with possibly different technology and/or timing), <u>or beyond the scope</u> (i.e still related to improvements in road transport in general, but beyond the scope of the proposed policy). This categorisation is given as an aid to understanding, both of the policy but also of the industrial recommendations for European road transport research in relation to sustainable energies and powertrains within the global, industrial context.

For the last fifteen years, two objectives at the European level have been of importance for the development of road transport technology: minimizing pollutant emissions and reducing greenhouse gas (GHG) emissions. The recent progress made in reducing pollutant emissions together with the introduction of “real driving emissions” (RDE), along with the foreseen new CO_2 targets triggered by the European Green Deal, shift the development efforts towards GHG emissions reduction now more than ever.

This document concludes that a rapid and effective reduction in GHG emissions, as targeted in the European Green Deal, can be achieved in an optimal way via a simultaneous, ambitious, electrification of road traffic and the development of renewable fuels. To avoid any loopholes in the efforts, GHG emissions must be accounted for at each stage of their life-cycle, using the methods of life-cycle assessment (LCA). This means that not only must GHG emissions be monitored at the tailpipe (tank-to-wheel emissions, TtW) but also that the emissions related to the production of the energy carriers (well-to-tank emissions, WtT), the emissions related to the production of the vehicles, their end-of-life and recycling, and the emissions related to the infrastructures must be monitored. Several extreme scenarios were analysed, as shown in this document, for which different shares are allocated to electrification, hydrogen and renewable fuels, yet each scenario could reach net GHG-neutrality in 2050 on a well-to-wheel (WtW) basis. The contributors have accounted for greenhouse gasses emitted from WtW (emission related to the infrastructure and the vehicle production were not considered) and assessed the emissions offsetting mechanisms (e.g. bioenergy carbon capture and storage (BECCS)) that need to be used to reach net GHG-neutrality.

GHG-neutral mobility fosters the development of a solution-oriented choice of technologies and the use of renewable energies. Electrification is a core element of GHG reduction but is not limited to battery electric

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[1] See https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/#:~:text=The%20European%20climate%20law%20makes,EU%20climate%20neutral%20by%202050

vehicles. Also important is a technical supplement to traditional powertrain systems, i.e. plug-in hybrid electric vehicles, increasing application of renewable fuels, or the use of hydrogen as an energy carrier and the introduction of fuel cell powertrains.

Following the above considerations, whilst recognising that this technology document does not go into detail about aspects such as economic (e.g. investments) and societal acceptance, and not yet going into the specific research needs, some key messages arise, upon which such needs should be framed. In summary, these might be expressed as:

1. ERTRAC is committed to develop a net-GHG-neutral road transport system and shares the vision of Europe becoming a climate-neutral continent by 2050. To achieve this, all stakeholders in road transport have to bring substantial contributions: the Automotive Industry, Energy Providers, Transmission System (or Service) Operators (TSO) and Distribution System (or Service) Operators (DSO), public and private (Charging) Infrastructure, the Fuel Industry and Regulators.

2. Developing a net-GHG-neutral transport by 2050 represents a tremendous amount of work: it is nothing simple. Not only does one need to check that GHG-neutrality is ensured but also the availability of the considered solutions at scale (e.g. the availability of critical minerals, the availability of electricity or of biomass etc.), the customer acceptance (ease of use, cost etc.), the compatibility with biodiversity, the available water supply and land use, the inclusion within a system (e.g. dealing with daily and seasonal intermittency), the management of waste etc. In other words, one needs to “tick all the boxes” to ensure that the whole system is viable. As all of these “boxes” could not be ticked in this document, the authors cannot provide definitive conclusions regarding the most suitable energy and powertrain mix for a GHG-neutral road transport in 2050. ERTRAC and within this document is not analysing the costs, return on investment nor affordability of the proposed solutions because of compliance, competition regulation; yet we acknowledge that economic factors will play a key role in the implementation of the solutions. Thus, all considerations might need to be revised in light of these relevant aspects. However, this document can, hopefully constitute a technical reference on possibilities towards the ultimate GHG-neutrality goal.

3. In the context of this uncertainty, complexity and difficult-to-predict systemic effects, it might be more careful and wise not to bet on a single, “silver bullet” technology, so as to reduce the risks of harmful societal effects. Given the challenge represented by reaching a net-GHG-neutral transport, a multi-technology strategy is preferable, especially during research and development and the transition period, where reality can significantly deviate from the initial plan. When deploying infrastructure, such as public or dynamic recharging infrastructure, harmonisation across member states is important to avoid fragmentation of the market.

4. To achieve net-GHG-neutral road transport (WtW) in 2050, drastic changes are needed in three areas:
   - Energy and energy carrier production (electricity, hydrogen and renewable fuels);
   - Vehicle fleet and efficiency, powertrains and traffic technology;
   - Infrastructure, especially the charging infrastructure, related to both static and dynamic charging

   This technology document has been structured along these three main areas.

5. From a technical perspective, the complete and robust net-GHG-neutrality of road transport could be achieved with a mix of vehicle technologies, where electrification is the key element for the reduction of the GHG emissions:
   - Battery electric vehicles (BEV);
   - Fuel cell electric vehicles (FCEV);
   - Advanced hybrid powertrains, including plug-in hybrid electric vehicles (PHEV), mainly driven in electric mode. Only on long-distance trips will they use a highly efficient auxiliary drive, using net-GHG-neutral fuels.

6. The overall “clean” energy demand (WtW) decreases drastically with fleet electrification. Furthermore, the energy efficiency measures identified (vehicle efficiency improvements, traffic conditions optimisation and traffic reduction technologies) reduce the energy demand in a very significant way. Yet, depending on the scenarios, considering the additions due to road transport only, the total demand for electricity in Europe, compared to 2019, increases by between 20% and 160% in 2050; in parallel, the demand for liquid fuels in road transport decreases by between 55% and 98%.

7. The largely net-GHG-neutral production of electricity is a prerequisite for net-GHG-neutral road transport: cooperation globally, throughout the energy production, storage and distribution system is needed to ensure the supply.

8. Hydrogen could play a key, three-way role in the energy system as:
   - A final energy carrier (e.g. its direct use in a fuel cell or in an internal combustion engine);
   - A chemical intermediate (e.g. as a feedstock to produce e-fuels or other chemical compounds, such as fertilizers for the agricultural sector);
   - An energy storage vector (e.g. as seasonal storage to balance the electricity grid).

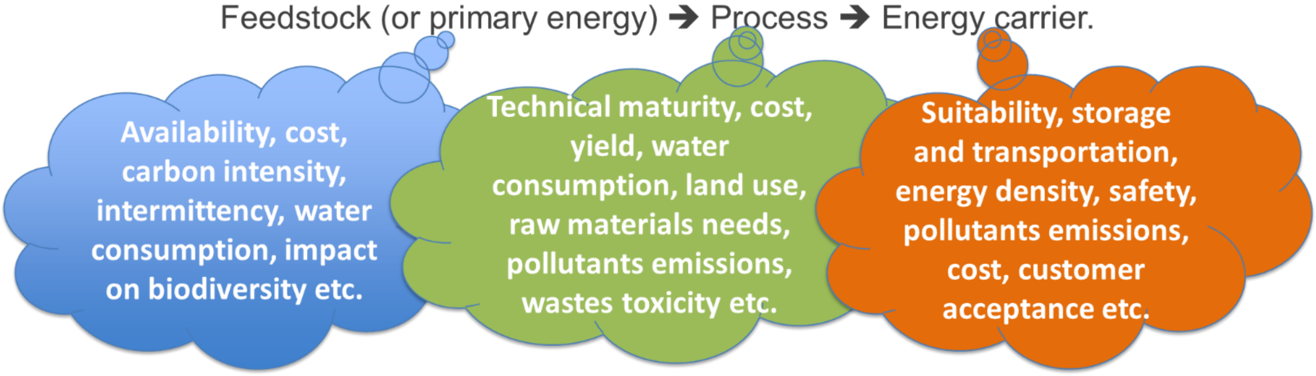
9. Tailpipe emissions-free, zero-emission in urban areas: all vehicles in urban areas can use emission-free powertrains, for example by driving 100% in electrical mode, whilst being highly efficient through the use of recuperation. To further reduce the impact of road transport on air quality, there are specific powertrain and non-powertrain related emissions which continue to require research.

10. Given the significant changes in the energy carriers used for new vehicles and for the existing vehicle parc, similarly significant changes in the infrastructure provision will be needed: for example, charging (at various rates, across multiple locations and in a possible variety of forms) together with securing supply plus adaptations for the existing liquid and gaseous fuels supply network.

Energy Carriers for Mobility

Energy carriers are intermediates that “carry” energy from the primary energies to their final use – road transport in this instance – following three universal steps:

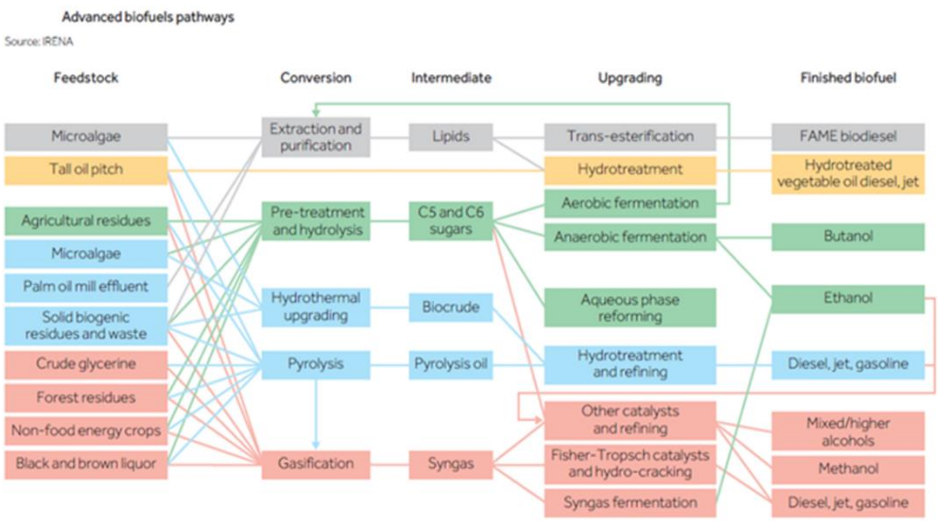
Feedstock (or primary energy) ➔ Process ➔ Energy carrier.



Today and in the foreseeable future, there is no identified single energy carrier that has the best-in-class properties in each of these three steps. When compared to each other, they each have their relative pros and cons, more or less acceptable depending on the specific transport needs. This is the reason why the expression, “there is no silver bullet” is so often used when considering the future energy carriers for road transport. It is likely that a wide variety of energy carriers will be required to feed road transport in 2050, grouped into three categories: electricity, liquid fuels and gaseous fuels.

Electricity provided approximately 23% of the final energy consumption in the EU in 2017, 31% of which was of renewable origin (RES). The rest of the electricity was produced in nuclear power plants (25%) and from fossil thermal power plants (44%). The shares of the main renewable energy sources (RES) for power generation were wind (11%), hydropower (10%), biofuels (6%) and solar (4%). According to a recent ERTRAC study[2], the transition of a 95% oil-based road transport to electrification will increase the electricity production demand for road transport by 20% to 160%, depending on the selected technological pathway. In the central scenario (1.5 TECH), electric power capacity comes from 83% RES in 2050 (12% nuclear and 4% natural gas with carbon capture and storage (CCS)), and it is still unclear whether RES will be able to increase at the required pace within a 25-year timeframe, whilst providing enough additional power to the road transport sector and to the other sectors, which would also to switch to electrification. This important question is beyond the scope of ERTRAC and of this document. Traditional operation of the power system is based on electricity production meeting electricity demand on a real-time basis. With the progressive introduction of RES, power systems are evolving in order to be ready to balance a highly variable renewable energy production by using digitalisation tools, upgrading electricity networks, increasing cross-border connections, developing storage capacities, more dynamic demand response and energy conversion, and providing new sources of flexibility to complement the flexible generation.

Liquid fuels are, today, mostly fossil-based; their renewable share, called biofuels, is mostly from food and feed crops (also known as ‘first generation’), dominated by 62% biodiesel with 18% bioethanol in second place, and 17% hydrotreated vegetable oil (HVO) third. The use of biofuels from food and feed is capped at 7% (on an energy basis) according to the Renewable Energy Directive (RED), in order to avoid competition with the food and feed industry. This triggers the development of numerous advanced biofuels (biomass-to-liquids, cellulosic ethanol etc.), using various sustainable feedstock and processes, and having typical GHG emissions reductions of more than 90% compared to a fossil basis. In addition, power-to-liquids fuels (also called e-fuels), made from renewable electricity and CO_2 captured from the air or from flue gases, are expected to develop. Whilst biofuels will continue to be used by all road transport modes, e-fuels could be targeted towards the hard-to-abate sectors, such as long-distance freight transport, as their relative high price (not discussed in this paper) could hardly compete with direct electrification, when it is easily accessible. It is an on-going debate within the research community whether all of long-distance heavy-duty freight transport could, should be electrified, using high-capacity batteries. Activities for electrification of, for the development of zero-emission of heavy-duty trucks have been started and create related research needs.



2 “Well-to-Wheels Scenarios for 2050 Carbon Neutral Road Transport in the EU”, Krause et al., 2022, to be published in the journal “Fuels” or “Technical Scenarios for the Decarbonisation of Road Transport from a Well to Wheels Perspective”, Neugebauer and Edwards, 22nd International Stuttgart Symposium, March 2022.

Concerning **gaseous fuels**, when looking to the long-term objective in 2050, one refers to renewable gas: both compressed and liquified natural gas (CNG and LNG) can be produced from a variety of renewable, scalable and very low carbon intensity energy sources, such as organic waste and biomass produced through anaerobic digestion, thermal gasification or by directly converting carbon dioxide (CO_2) into synthetic methane by using hydrogen produced from renewable electricity. With renewable gas being practically identical in composition to natural gas, moderate to high blend levels are able to further enhance the effects of using natural gas, which is already a type of lower-carbon fuel, providing substantial reductions (CNG (EU mix): 67.6 $gCO_{2eq.}$/MJ versus 92.1 $gCO_{2eq.}$/MJ for Diesel, WtT with combustion assessments) of total GHG emissions. Today, the road transport sector in EU is consuming 2.3bcm of natural gas, where 17% is renewable.

Concerning **hydrogen**, today worldwide it is produced mainly from the thermochemical conversion of natural gas ("grey" hydrogen), whilst approximately 5% is produced via electrolysis ("green" hydrogen when using renewable electricity). Several demonstration projects are underway for hydrogen production via steam methane reforming (SMR) coupled with CCS (referred to as "blue hydrogen"). Potentially, blue hydrogen production from natural gas can be coupled with a share of biomass feedstocks that could bring the overall hydrogen greenhouse gas footprint to net-zero or even negative. In a scenario with an increasing share of low-cost renewable electricity, green hydrogen production via electrolysis could be a promising contribution to decarbonization.

Powertrain Technologies for Road Mobility

Net-GHG neutrality in a complex road transport system can be reached with a new mix of powertrain technologies, with a clear focus on electrical propulsion. Beside BEVs, which are the most energy-efficient technology, also PHEVs or Electric Vehicles (EVs) in combination with fuel cells are viable technologies, depending on the market-related and political boundary conditions[1] in the different regions in the world. The ICE, as part of a PHEV, running on a fully renewable hydrocarbon or hydrogen fuel, could be a choice for some users in passenger car applications and continue as a prime mover in some heavy-duty applications. These powertrain technologies must also include on-vehicle adaptions to the refuelling or recharging requirements of the relevant energy carrier: for example, the dynamic charging of an xEV has implications for the vehicle powertrain system.

Depending on the vehicle type and energy carrier, the possible mix of powertrain technologies is shown in the following overview.

Vehicle powertrain options in 2050 for energy and vehicle types

Energy Category	Aspect	L-category (2 wheelers etc.)	Passenger Cars	Light-duty Vans (LDV)	Commercial Vehicles (truck, bus etc.)
Electricity	Battery	BEV	BEV	BEV	BEV
Liquid Fuel	Diesel-like		PHEV	PHEV	HEV PHEV
	Gasoline-like	HEV	PHEV		
Gaseous Fuel	Methane		HEV PHEV	HEV PHEV	HEV PHEV
	Hydrogen		HEV FCEV	HEV FCEV	ICE HEV FCEV

Battery Electric Vehicles (BEV). Battery electric propulsion offers two main advantages: zero emission propulsion (i.e. no tailpipe emissions) plus the lowest overall energy demand due to high efficiencies[1]. The main challenge is the energy and power density of the batteries, plus the charging to enable the required trip range and travel convenience.

Batteries. The battery is the core component of electric mobility since it defines the limits of power and energy (range) as well as, to a significant degree, the overall weight and cost of the vehicle.

The functional requirements for the battery are defined at a system level within a vehicle application. Requirements for the battery arise from its operating temperatures, charge/discharge power, energy capacity and, also, from its integration into the powertrain and vehicle (Battery Management System (BMS), Thermal Management System (TMS), packaging and chassis design). Whilst research activities are related to new cell technologies, chemistries, materials etc., it is important to realize, that improvements at a cell level do not automatically result in the same improvement at a pack level, due to additional effects inside a battery pack. The breathing and/or swelling of battery cells is only one of the well-known challenges for a battery pack. Additional challenges arise from inherently increased losses at high charging/discharging powers, due to heat generation in the cell, the module and the battery pack connectors, contactors and cables. Improvements are envisaged for all mentioned technical aspects, as well as for safety, durability and recyclability, all in combination with new digital solutions for each stage of the battery life (development, design, production, operation and end of life).

Two, main, overarching elements of the BEV, which need intense research and development, are the BMS and the TMS. The BMS directly influences actual driving performance by controlling the battery to fulfil its primary function of supplying the demanded energy for propulsion and, in combination with the TMS, maintain favourable operating conditions. The TMS, in cooperation with the BMS, is a vital overarching topic for all components, it controls the temperature of all sensitive powertrain components.

Many different **technologies for charging**, e.g. with low or high power, direct current (DC) or alternating current (AC), wireless or plugged, robotized, including bidirectionally connected (V2G) and even dynamic, continuously whilst driving (on Electrified Road Systems (**ERS)**), are currently considered in research and development. The charging technology affects the related powertrain components, such as the inverters, battery, BMS and TMS. For example, since an xEV using an ERS receives power whilst driving, the energy being used for propulsion or recharging, the vehicle's battery can be smaller than in a non-ERS EV.

Since **electric motors** are already capable of reaching peak electric efficiencies of up to 97% at high loads, the focus of research is on cost, weight and size reduction, whilst retaining efficiency improvements. Reducing energy losses will also have a direct impact on the requirements of the vehicle TMS.

Besides the motor, other electrical **high voltage (HV) components** in the powertrain, especially the power electronics, need to be optimised to reduce energy losses, since the overall powertrain efficiency depends on the individual performance and efficiency of each component in the system. This is a major challenge due to the characteristics of the HV components involved (motor, inverter, battery etc.) depending on the supplied power.

ERTRAC proposes to focus research on holistic approaches within electrical powertrain projects, to consider all elements of the system. Additionally, the development and usage of several digital technologies (simulation, digital twins, monitoring etc.) is key to accelerate the successful deployment of future BEVs, fulfilling the demanded variety of propulsion tasks.

Fuel Cell Electric Vehicles (FCEV). Hybrid propulsion, involving a fuel cell as a power conversion unit for renewable chemical energy vectors, is a solution for travelling long distances and offering zero-tailpipe emission propulsion.

The FCEV is a possible powertrain option for heavy-duty vehicles (trucks, buses etc.) and, in certain cases, also for light-duty vehicles. The current challenges are the cost and the fuelling infrastructure; additionally, the operating boundaries of the fuel cell also present some challenges.

Plug-In Hybrid Electric Vehicles. The advanced ICE, as a core component of PHEVs and HEVs when operated with renewable fuels, remains relevant beyond 2030. Dedicating the ICE to using different, low carbon fuels and within a hybrid powertrain, includes various technical measures for the engine itself, as well as for the powertrain architecture.

PHEVs and range extended electric vehicles (RExEVs) represent suitable ICE equipped vehicle concepts for those entering urban areas with access restrictions. PHEVs with renewable (CO_2-neutral) fuel offer both zero tailpipe-emissions in electric mode within city limits (and/or warranted by air-quality conditions) and long-distance travelling in hybrid (electric + ICE) mode.

Whilst PHEVs are seen as a transitional technology for passenger cars, they are a valid and sustainable technology for heavy-duty applications, addressing the conflict of long-distance transport and local zero emissions at the destination.

Hydrogen Fuelled Internal Combustion Engines (H_2 ICE). A viable way for decarbonisation is the application of green hydrogen in ICEs, being a GHG-neutral fuel from a WtW perspective. NOx emissions can be significantly reduced by a (lean) H_2-combustion in combination with emissions aftertreatment systems. Compressed (C-H_2) or liquid (L-H_2) hydrogen enable long-range operation along with brief refuelling times. The current challenges are, similarly, economic and infrastructure related.

The **recycling and reuse of materials** is recommend to be a major focus of research. Recycling and reuse solutions will be of tremendous importance to limit the depletion of scarce materials, at least when higher market shares of BEV (e.g. more than 25%) are to be achieved.

Complimentary Driveline Aspects. Non-powertrain sub-systems or components, mainly tyres and brakes, as well as some infrastructure aspects, e.g. the use of conductive dynamic charging (since this has wear mainly through the abrasion of the sliding contact surfaces), will continue to contribute to particle emissions. This issue becomes more relevant with the higher weight and torque of electrical powertrains. Accordingly, brake dust has become an important topic to study, in order to understand brake particle behaviour: it is necessary to start implementing measurement methods which may lead to future test standards and brake component approval regulations. The impact of TRWP (Tyre and Road Wear Particles) is not yet fully measured nor understood. Even if the tyre industry already conducts crucial scientific work on tyre abrasion through the TIP (Tyre Industry Project), it is still necessary to characterize more precisely TRWP (composition, quantify, biodegradability etc.) and adapt tyre concepts to lower their impact.

Infrastructures for Road Mobility

Charging management systems and platforms are important tools to meet and steer the demands of the EV market. They are one of the most decisive factors to optimise the grid connections to the charging stations, i.e. by short-term and long-term demand prediction for charging and provision. It is important to grow the infrastructure faster than the EV market. This is a challenge since the two markets have very different factors that influence the decisions for implementation. Thus, in a strongly increasing EV market with strongly increasing power demands, comprehensive, reliable and highly scalable charging systems are mandatory to cover the needs of the market in the future.

Fast charging is based on DC-charging. Different modes of transport and grid supply will foster different solutions, but efficiency will be key. It is expected that fast charging will be available in different power classes, including, for example, low voltage direct current for electrified powered two wheelers (ePTWs).

The current standard for charging stations refers to 500A, enabling 350kW charging power. Additionally, there is a new global plug standard in preparation. The “Megawatt Charging System” will enable power levels of more than 3MW, in order to enable long distance freight transport use cases with heavy-duty battery electric trucks.

Accessibility is an important point for high-power charging. It can be assumed that conductive plug charging is limited to 350kW, and to achieve this power rate, cable cooling is essential. Therefore, in order to facilitate recharging and reduce recharging duration, different interfaces should be considered. It is also important to recognize that it is difficult to imagine older or disabled people being able to handle these heavy charging cables, so the accessibility for high power charging should be improved.

However, fast charging at high charging currents increases the power losses, these are being addressed with recent developments. The impact of high-power charging on the LCA of BEVs should be investigated more deeply. Moreover, the limitations of the electric grid in cities could create restrictions for the installation of a dense network of charging stations. This interaction should be further investigated.

Today, the natural **gas infrastructure** represents an important asset in Europe: it is composed of approximately 200,000 km of high-pressure pipelines for gas transmission, and more than 2,200,000 km of low-pressure pipelines for gas distribution. The natural gas infrastructure and vehicle technologies are fully compatible with renewable gas, when the appropriate purity is controlled, thus offering a wide flexibility in managing the progressive injection of methane produced from different pathways. Anaerobic digestion processes, thermal gasification and Power-to-Methane pathways are all leading to the same molecule, which can be both injected into the grid or used in vehicles.

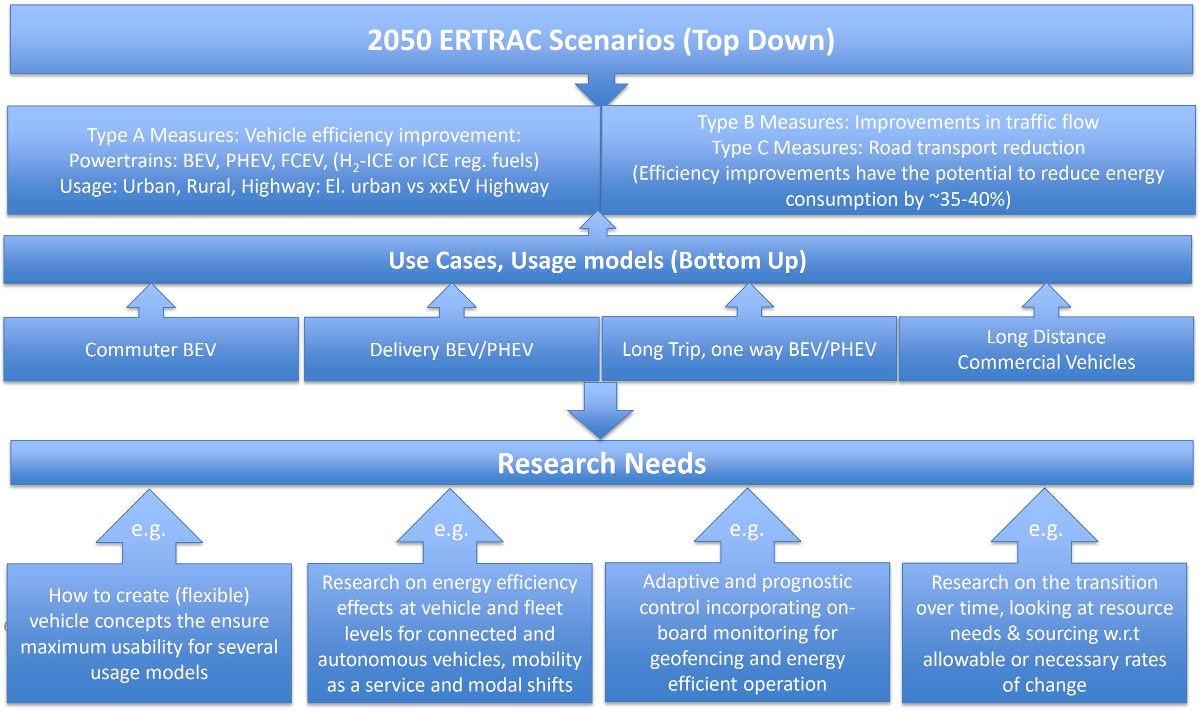
The contribution of **hydrogen**-based powertrains to decarbonisation in all modes of transport can only be realised if an appropriate refuelling infrastructure is established. Therefore, the rapid expansion of hydrogen refuelling stations is needed. Thus, the hydrogen can either be used in fuel cells or in combustion engines and, in addition, offers an opportunity to store energy seasonally. Hydrogen blending in the natural gas grid is an interesting transitional option, providing that the challenges related to using mixtures in a grid originally dedicated to natural gas can be overcome.

Infrastructures for **liquid fuels** are well developed in Europe, with 120,000 service stations available to consumers, refuelling more than 25 million vehicles on an average day. 36,000 km of pipelines ensure the efficient movement of crude oil and refined products across Europe. Shifting this system to renewable fuels is not expected to require any major modifications.

Systemic Aspects

Given the overall goal of net-zero CO_2 emissions road mobility by 2050, possible scenario solutions for that time have been considered, based upon the workings and findings of the ERTRAC CO_2 Evaluation Group[2]. Whilst a scenario-based assessment is useful to evaluate whether the road transport system can achieve a net-zero CO_2 emissions status, in reality it is likely that each individual user will choose their means of mobility, as a consequence their own needs and constraints, whilst considering the boundaries imposed by the regulations. This individual, bottom-up optimisation is not the same as the top-down, system optimisation (as illustrated below): there may be significant divergence for the end result, the products, mobility modes and infrastructure needs. As such, improved understanding of the individual compared to the system behaviour in a net-zero carbon road mobility situation is needed. It is important to better understand how these behaviours will change in the future, together with what factors will influence the change.

Further, the divergence may be more acute along the route towards net-zero carbon mobility at 2050, when the possible rates of change of the related infrastructure industries, regulatory limits and societal behaviours may become bottlenecks. Questions arise related to how much incentives will be used to encourage the change, increase the rate of change, whilst at the same time retaining social equality. Alternatively, or perhaps consequently, the rate of change is unlikely to be continuous, monotonic. Rather, particularly as a consequence of the allowable carbon budget, significantly increased rates of change, varying at any single point in time between different types of road transport, are likely to be necessary and experienced. As such, an understanding of the achievable rates of change in any single parameter related to the road mobility system needs to be reached.



Whilst the possible risks related with individual use cases, usage models have not been (yet possibly should be) derived, it was found that some research needs are identified beyond the usual ERTRAC vehicle technology related areas. What becomes clear from this consideration of use cases, usage models, is that, especially for individual mobility, we should ensure we always have a choice (with varying costs) even as the system changes: the mobility needs have to be met. Further, that connectivity (analogous to perfect information supply in commerce), through digitalisation and, possibly realised through automation, gives the opportunity to optimise both the individual mobility efficiency and mobility system efficiency concurrently (relative to what parameters we determine most appropriate in any incidence, e.g., energy efficiency). Moreover, that such connectivity gives us a means to investigate, to practice adaptive and prognostic control within the system. A systems approach via connectivity will realise, thus demand system changes, for example, modal shifts and mobility as a service. Hence, connected, collective mobility should cost less (given an equal basis for energy and investment costs) and service costs should reduce, utility factors should improve. One might consider this a move towards rational mobility, analogous to the ideal of the rational consumer.

The ERTRAC CO_2 Evaluation[1] acknowledged that the question, "What is the best fuel/fleet combination?" (which, from a system perspective, is equivalent to the question posed often by individual users and in such use cases), could not be answered by the study. Specifically, system optimisation cannot be based on an extreme scenario approach. Therefore, further research, innovation and development work will be needed to assess and establish the optimal solutions, on the basis of various criteria. Such criteria were identified as:

- Energy production and storage capacity;
- LCA to account for the emissions and energy required for infrastructure and vehicle production;

- Investments in infrastructure and energy production facilities;
- Cost of energy production and distribution, as well as vehicle technology development;
- Land use, water use and other resources needed; plus their allocation between different sectors;
- Different locations for energy production (EU or MENA-Region);
- Customer acceptance of specific vehicle types and fuels;
- The acceptance of CCS.

Furthermore, research needs from other aspects were derived, for example:

- Determination of the balance between technical and societal matters, their allowable rates of change;
- Societal acceptance, given future scenarios, of other sources of decarbonised electricity, energy, such as nuclear power compared to longer term issues (e.g. waste management);
- System second order sensitivities, rates of change possible, and the rates of change of these that are acceptable;
- Societal TCO aspects of and solutions and pathways thereto.

Overall Recommendations for research activities

According to the wide range of challenges in all technical areas on the way to GHG-neutral mobility, many different research needs have to be addressed within the next decade. An overview of the most important topics linked with a timeline proposal and technology readiness level (TRL) correlation is summarised in the following tables. The research needs identified, each in relation to the GHG-neutrality objective and air quality targets compliance, are colour coded in line with the following definition:

- Blue, in line with a full ban of internal combustion engine sales:
  - This colour code covers research needs related to zero-tailpipe emissions technologies, in a scenario where internal combustion engines would be banned from sales for all categories of vehicles (including passenger cars, light commercial vehicles and heavy-duty vehicles);
- Yellow, required to achieve the objective and by some legislation (e.g. the Renewable Energy Directive or Euro 7) whilst including the sale and continued use of internal combustion engined vehicles:
  - This colour code covers two categories of research needs:
    - A first category corresponds to developments required by some existing pieces of legislation. For instance, according to the Renewable Energy Directive (RED), advanced biofuels and e-fuels (RFNBOs) will need to be supplied by 2030, which requires research and development to ensure the solutions are available. Another example is Euro 7, which triggers research and development needs for passenger cars, light commercial vehicles and heavy-duty vehicles, notwithstanding a partial of full ban on internal combustion engines which might happen later on. Independent of an ICE-ban, these research needs are required at least during a period of transition;
    - A second category corresponds to the achievement of climate goals. For instance, independent of an ICE-ban, GHG-neutral fuels are required to meet climate goals (and they help reaching net GHG-neutrality sooner), as they act on the legacy fleet. In some scenarios that do not include a full ICE-ban, ICE could be used in the longer term (i.e. post-2050) and still comply with the climate targets. These could also require the further development of adapted powertrain technologies;
- White, additional topics, beyond the objective and targets above but related to the topic of this document, these topics are often transversal:
  - This colour code covers research needs not directly covered by the EU Green Deal nor the Fit-for-55 Package, related or not related to climate goals.

More detailed descriptions can be found in the related Chapter 6 of this document.

Table. Research needs for Energy Carriers

	Research Needs for Energy Carriers	2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035
Electricity	Carbon-neutral electricity generation and balanced grid	Research recommendations out of the scope of this document (see ETIP SNET reports)
Biofeedstocks	Biomass availability for biofuels production Impact of biomass cultivation and collection on biodiversity Mobilisation of biomass to biorefineries Waste availability for renewable fuels	Continuous evaluation
	Optimized practices for crops and forestry	Mature, with continuous improvements
	Algea & micro-organisms	TRL 2-3 → TRL 4-6
Green H_2	Alkaline electrolyser	Mature, with continuous improvements
	Polymer-electrolyte membrane electrolyser (PEM)	TRL 7-8
	High temperature (co-)electrolyser cell (SOEC)	TRL 6-7 → TRL 7-8
CO_2	Direct capture from air (DAC)	TRL 4-6 → TRL 7-8
	CO_2 from biomass upgrading	Mature, with continuous improvements
	CO_2 from flue gas (concentrated source)*	TRL 6-9 → TRL 7-9
Biofuels	Transesterification	Mature, with continuous improvements
	Hydrotreatment	Mature, with continuous improvements
	Biomass to Liquids via Gasification + FT	TRL 7-8
	Hydrothermal Liquefaction + upgrading	TRL 5-6 → TRL 7-8
	Pyrolysis + co-processing / upgrading*	TRL 5-9 → TRL 7-9
	Alcohol to synfuels*	TRL 6-9 → TRL 7-9
	Sugar-to-Diesel	TRL 2-3 → TRL 4-6 → TRL 7-8
	Algae to liquid	TRL 2-3 → TRL 4-6
	Biotechnological fuel production	TRL 2-3 → TRL 4-6 → TRL 7-8
	Bio-DME and bio-OME	Mature, with continuous improvements
E-fuels	Paraffinic e-fuels through Reverse Water Gas Shift (RWGS) and Fischer-Tropsch**	TRL 5-6 → TRL 7-8
	e-methanol synthesis e-DME synthesis through e-methanol pathway e-olefins synthesis through e-methanol pathway Oligomerization of e-hydrocarbons through e-methanol pathway Hydrotreatment through e-methanol pathway	Mature, with continuous improvements
Gaseous fuels	Carbon-neutral production of biogas and power-to-gas	Research recommendations out of the scope of this document (see Gas for Climate report)

* *Several technologies having different maturities*

** Only RWGS is not a mature technology in this process

Table. Research needs for Powertrain Solutions

	Research Need for Powertrains	2022–2035
	Modelling and Simulation	Continuous Improvement
	Connectivity and Data Management	TRL 4-6 › TRL 7-8
	Recycling, Materials for New Powertrains	Continuous Improvement
	Availability/ Sustainability of Resources	Continuous Evaluation
BEV	Advanced Components, Materials and Processes	TRL 2-3 › TRL 4-6 › TRL 7-8
BEV	Connected and AI-based systems (BMS, TMS etc.)	TRL 2-3 › TRL 4-6
BEV	System approach, vehicle integration	TRL 4-6 › TRL 7-8
BEV	Safety test procedures and technologies	TRL 4-6 › TRL 7-8
BEV	Charging technologies (bidirectional, comfort-charging, robotic)	TRL 4-6 › TRL 7-8
BEV	Battery Swapping technologies	TRL 4-6 › TRL 7-8
BEV	Data acquisition and AI supported development	TRL 7-8
BEV	Implementation of eco-design principles	TRL 7-8
FCEV	Stack Technology	TRL 2-3 › TRL 4-6 › TRL 7-8
FCEV	System Technology	TRL 2-3 › TRL 4-6 › TRL 7-8
FCEV	Storage Technology	TRL 2-3 › TRL 4-6 › TRL 7-8
FCEV	System adaption and integration to vehicle types	TRL 4-6 › TRL 7-8
Hybrids incl. ICE	Dedication of ICE to renewable fuel including H_2	2-3 › TRL 4-6 › TRL 7-8
Hybrids incl. ICE	New sensors (physical, virtual) for engine control	TRL 4-6 › TRL 7-8
Hybrids incl. ICE	Improved thermal behaviour at cold start	TRL 4-6 › TRL 7-8
Hybrids incl. ICE	Dedication of ICE to hybridisation incl. simplification	TRL 4-6 › TRL 7-8
Hybrids incl. ICE	EATS and OBD, OBM for ren. Fuels, H_2 and RDE+	TRL 4-6 › TRL 7-8
Hybrids incl. ICE	Minimisation of oil consumption	TRL 7-8
Batteries	Advanced virtual development tools	TRL 2-3 › TRL 4-6 › TRL 7-8
Batteries	Increase of energy density (cell, pack, system level)	TRL 2-3 › TRL 4-6 › TRL 7-8
Batteries	Improve fast charging while avoiding degradation	TRL 2-3 › TRL 4-6 › TRL 7-8
Batteries	Optimise TMS, BMS for better efficiency and safety	TRL 2-3 › TRL 4-6 › TRL 7-8
Batteries	Recyclability, producability and circular economy	TRL 2-3 › TRL 4-6 › TRL 7-8
Batteries	Smart functionalities, monitoring, AI	TRL 2-3 › TRL 4-6 › TRL 7-8
Batteries	Regulatory activities for testing and safety	TRL 4-6 › TRL 7-8
Batteries	Advanced materials, combinations, treatments	TRL 2-3 › TRL 4-6
ERS	Safety concepts for ground based power supply	TRL 4-6
ERS	Adaption of powertrain components to ERS	TRL 7-8
Other Emission	Develop tyre-road-interaction models, basics	TRL 2-3 › TRL 4-6
Other Emission	Improvement of rolling resistance, tyre wear	TRL 4-6
Other Emission	Recycling of tyres, raw material reduction	TRL 4-6
Other Emission	Optimisation of road formulation	TRL 2-3 › TRL 4-6 › TRL 7-8
Other Emission	Technologies to reduce/ avoid brake dust: -brake dust particle filters (active/ passive) -new materials with less abrasion -recycling, reusage -braking strategies, usage of drum brakes	TRL 2-3 › TRL 4-6 › TRL 7-8
Other Emission	Reduction of harmful electromagnetic radiation	TRL 2-3 › TRL 4-6
Other Emission	Technologies for reduction of particles from ERS	TRL 2-3 › TRL 4-6 › TRL 7-8

Table. Research needs for Infrastructure

	Research Need for Infrastructure	2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035
Roads for ERS	Road durability due to embedded ERS	TRL 2-3 › TRL 4-6 › TRL 7-8
	Alignment of standards for roads and electrification	TRL 7-8
	Optimisation of ERS installation procedure	TRL 4-6 › TRL 7-8
	Development of adapted maintenance technologies	TRL 4-6 › TRL 7-8
	ERS affection by climate (snow, temperature etc.)	TRL 2-3 › TRL 4-6 › TRL 7-8
	Impact of ERS on environment/ health (EMF, particles etc.)	TRL 2-3 › TRL 4-6
	Integration of ERS roads into energy system	TRL 2-3 › TRL 4-6 › TRL 7-8
	Legal implication: European standards for ERS	TRL 7-8
	Safety: emergency strategies (helicopter access etc)	TRL 4-6 › TRL 7-8
Road Construction	Improved road mixes for less drag and better durability	TRL 4-6 › TRL 7-8
	Improved road construction methods (e.g. connected and autonomous plant)	2-3 › TRL 4-6 › TRL 7-8
	Develop European Road Quality Label/ CO2	TRL 4-6 › TRL 7-8
	Increase degree of recycling for lower CO2-footprint	2-3 › TRL 4-6 › TRL 7-8
	Carbon absorbing surfaces in road construction	2-3 › TRL 4-6 › TRL 7-8
	Impact of adjacent furniture/ vegetation	TRL 4-6 › TRL 7-8
	Biomaterials in road construction (e.g. bio-binders instead of bitumen)	2-3 › TRL 4-6 › TRL 7-8
	Use of bio-fuels and alternative powertrains in machinery	TRL 4-6 › TRL 7-8
Energy supply	European standardization of charging economics and user interface (billing, taxes etc.)	TRL 7-8
	Fast charging for solid-state batteries with higher power	TRL 2-3 › TRL 4-6 › TRL 7-8
	European strategy for energy policy and distribution	Contnuous Evaluation
	Grid balancing and smart charging (V2G etc.)	TRL 4-6 › TRL 7-8
	Standards for liquid and gaseous fuels to integrate alternative fuel components into the grid	TRL 7-8
	Adaption of gas-grid to hydrogen	TRL 7-8

Table. Research needs from a System Perspective

	Research from the System Perspective	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
System Change	Fleet mix change for minimum CO_2 budget expenditure to 2050			TRL 4-6			TRL 7-8								
	Realizing efficiency improvements methods A, B and C.		TRL 4-6				TRL 7-8								
	International CO_2 neutral energy supply optimisation	TRL 2-3				TRL 4-6					TRL 7-8				
	CCS and DAC realisation at scale		TRL 4-6				TRL 7-8								
System Appraisal Methods	RT system dynamic modelling for the transition, prediction capability thereto	TRL 2-3				TRL 4-6					TRL 7-8				
	LCA for the whole RT system & its transition			TRL 4-6				TRL 7-8							
	Economic analyses for the whole RT system transition			TRL 4-6				TRL 7-8							
	Resource use (land, water etc.) minimisation and distribution between sectors	TRL 2-3				TRL 4-6					TRL 7-8				
	Societal acceptance prediction and appraisal methods		TRL 2-3				TRL 4-6					TRL 7-8			
	RT system robustness and second order sensitivity methods		TRL 2-3				TRL 4-6					TRL 7-8			
Use Cases	Commuter & Urban Delivery in 2030 - implications for smart low power & fast charging - relevant battery improvements - vehicle concepts - societal acceptance		TRL 4-6			TRL 7-8									
	Delivery in 2030 - implications for smart low power & fast charging - relevant battery improvements		TRL 4-6			TRL 7-8									
	Longer one-way trips in 2030 - increasing the rate of climate neutral energy carriers for ICE, supply & infrastructure - ZE range segmentation - future services for vehicles and users		TRL 4-6			TRL 7-8									
	Long distance commercial vehicle operation in 2030 - increasing the rate of climate neutral energy carriers for all powertrains, supply & infrastructure - Improvements in powertrain energy density and reliability - Smart energy management possibilities at all CV energy refilling opportunities		TRL 4-6			TRL 7-8									

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1 Introduction

The road to GHG-neutrality[3] is long and intertwined between vehicles, energy and infrastructure technologies. Naturally, whilst the goal of GHG-neutrality is given[4], full clarity of the route ahead is not yet available. What is clear, however, is that this route requires the contributions from many stakeholders and much investment. The negative impacts of making possibly wrong decisions, too early, are significant.

Therefore, it is worthwhile now, to consider the research needed to reach that goal. Such research can give, with technical neutrality and a long-term perspective, insight into further open questions, risks and rewards along the route. Hence, through undertaking that research, the impacts of reaching the milestones along the road to GHG-neutral mobility might be better understood by all, decisions made upon firmer foundations.

Such research needs to relate to the broad perspective, road transport as a system within a European energy and infrastructure network. Therefore, consideration of the state of the art in relation to energy carriers, vehicle powertrain technologies and infrastructure capability is given in this document; this is followed by an assessment based upon a selected number of use-case scenarios; hence recommendations for the research needed are presented at the end.

This roadmap should not be read in isolation: there is much previous and work on-going to suggest the research needed, quantify the consequences of possible routes and of different scenarios. Of particular importance for the short-term (this decade) are the strategic research and innovation plans made in preparation for the Horizon Europe framework programme[5]. In addition, given the broad nature of this document, reference is given to many sources at the end of this paper. Furthermore, this document should not be considered definitive nor set-in-stone: the suggested research needs are open for adjustments, as more is learned as we transition towards GHG-neutrality. Similarly, the research needs can be review in line with existing and future policy within Europe.

Finally, it is also important to realise what this document is not. The document looks at technical aspects to determine research needs, from a holistic perspective but without direct considerations of the social, societal or economic aspects thereto. Clearly, these are important aspects but ones which are beyond the immediate scope of ERTRAC, ETIP-SNET and CONCAWE activities.

1.1 Regulatory Aspects

For the last decades, two objectives at a European level have been of importance for the development of powertrain technology: minimizing exhaust emissions and the reduction of CO_2 emissions to meet European and global regulations. ERTRAC keeps track of regulatory efforts and decisions[6][7]. On the other side, regulatory targets need to reflect the technological realities and possibilities. Therefore, this

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[3] See the ERTRAC document, “The Timeline to Carbon Neutrality in Road Transport – a long-term effort, with different phases, multiple technologies and interdependences”

[4] See the ERTRAC 2050 Vision documents and “Well-to-Wheels Scenarios for 2050 Carbon Neutral Road Transport in the EU”, Krause et al., 2022, to be published in the journal “Fuels” or “Technical Scenarios for the Decarbonisation of Road Transport from a Well to Wheels Perspective”, Neugebauer and Edwards, 22nd International Stuttgart Symposium, March 2022. In the original documentation and presentation of the ERTRAC 2050 Vision and ERTRAC CO_2 Evaluation Group work, the wording “carbon-neutrality” was used. However, based on the definitions used within this document (see Appendix) actually GHG-neutrality is appropriate to reflect the extent of the studies.

[5] See the 2Zero SRIA, but also those from linked organisations, for batteries, hydrogen, CCAM etc.

[6] ACEA’s progress report “Making the transition to zero-emission mobility”, 2019. https://www.acea.be/uploads/publications/ACEA_progress_report_2019.pdf

[7] ACEA’s report on “CO_2 emissions from heavy-duty vehicles”, 2020. https://www.acea.be/uploads/publications/ACEA_preliminary_CO2_baseline_heavy-duty_vehicles.pdf

technology and research oriented document tries to contribute to a qualified discussion among all relevant stakeholders.

On 17th April 2019, the European Parliament and Council adopted Regulation (EU) 2019/631 introducing CO_2 emission standards for new passenger cars and light commercial vehicles in the European Union. This regulation set targets for the reduction of tailpipe CO_2 emissions of newly registered passenger cars by 15% and 37.5% for the years 2025 and 2030 respectively. These targets follow from that of 95gCO_2/km for the year 2021, as set in 2013. Using laboratory test (WLTP) results, the progress of manufacturer, is monitored each year by the Member States, based on new car registration data.

The “Fit for 55 Package” Proposal from the European Commission (July 2021) goes far beyond these CO_2 reduction targets and proposes an additional one: from 2035 onwards, only “Zero-Emission” passenger cars should be allowed for new registration. In reality, this limits the powertrain options to BEV (Battery Electric Vehicles) and FCEV (Fuel Cell Electric Vehicles) only.

In 2023, the European Commission will review the regulation, reporting to the European Parliament and Council on the progress made towards reaching the passenger car CO_2 targets. Amongst other things, this ‘mid-term review’ will take stock of the roll-out of charging and refuelling infrastructure for alternatively powered vehicles, their market uptake, as well as CO_2 reductions from the car fleet.

The regulation setting CO_2 standards for trucks obliges manufacturers to reduce their average fleet emissions across the regulated vehicle groups by 15% (by 2025) and 30% (by 2030) compared to the baseline. Possible further regulatory limits, beyond 2030, are currently under discussion and a first proposal is expected during 2022.

The EU is seeking to reduce CO_2 emissions from road traffic primarily through fleet limits for new vehicles based on a “tank to wheels” (TtW) perspective. However, between 1990 and 2017 the efficiency gains enforced by regulatory limits were outweighed by increased traffic volume: in 2017, CO_2 emissions from road transport amounted to 543 million tons, 18% higher than in 1990, virtually unchanged over the fifteen years.

In this decade Europe will probably see a significant ramp-up of electrified vehicle sales (BEV and PHEV) with a significant reduction of the CO_2 emissions from the new vehicle fleet. But several scientific studies have elaborated, that the cumulative Greenhouse Gas (GHG) Emission from road transport will be dominated for many years by the existing vehicle fleet. The effective reduction of GHG-Emissions requires also ambitious measures for the vehicle stock. An effective technical measure to reduce the in-use CO_2 emissions of a conventional ICE powered vehicle is the use of low-carbon fuels. The introduction of low-carbon fuels to the market would have a complimentary impact on the cumulative CO_2 emissions from Road Transport in the next decades together with the introduction of Zero-Emission-Vehicles in the New Vehicle Fleet[8].

Whilst it is not the purpose of this document to suggest regulatory measures, in any way, it is important to realise that the discussions leading to the definition of the research needs has been made not only from the holistic perspective of road transport as a system within a bigger energy supply and infrastructure provision network but also with regard to possible future measures and assessment methods for overall system climate neutrality. Hence, life-cycle analysis assessment methods and circular economy aspects are inherent features of the research needs identified.

[8] See, for example, Kramer, “FVV Fuels Study IV – Transformation of Mobility to the GHG Neutral Post Fossil Age”, SIA Powertrain & Energy, June 2022

1.2 Use Cases and Fleet Scenarios

Although pure battery electric vehicles are expected to be a major pillar for achieving the Green Deal objectives in 2050, these can only be achieved robustly with an intelligent mix of technologies, one that satisfies the needs of the users and fulfils local environmental requirements. This will require a holistic approach.

The vehicle powertrain technology variations that are considered within this roadmap are BEV, FCEV, as well as PHEV and HEV, operated with sustainable electricity and/or fuels (including hydrogen). Today, what the precise share between these technologies will be is unknown, but it is clear that the split will help to ensure that every user can meet nearly all their needs, is willing to purchase and use the solutions as designed.

Furthermore, it is unknown how the mobility models will develop and evolve over the next thirty years. Similarly, it is unknown how the regulations that actually apply in the urban areas and the user's preferences for ownership or willingness and openness for concepts, such as the shared economy, will develop. Mobility will be a key pillar for economic success and societal satisfaction even in 2050: so the critical question is, "how is it possible to achieve the environmental, Green Deal objectives in parallel with other socio-economic objectives?".

The realisable rate of change, for both new and existing technologies is a challenge and vital consideration when regarding future scenarios. For example, how fast can Europe build-up a completely new infrastructure for electric charging and hydrogen? The "new" technologies, such as BEV and FCEV, will also face shifts in the access and allocation of resources (e. g. increasing access needed for lithium, cobalt, catalysts etc.). On the other hand, how soon can the production and supply of renewable fuels be scaled-up? Hybrid solutions may be vital to bridge the gaps that may appear during the transition: specific solutions will be optimised, fit-for-purpose, yet may be very different from what we see on our roads today.

Nevertheless, even if the detailed path is unclear, we can try to describe possible milestones for the next decades:

Milestone 2030: Air quality limits related to road transport are achieved, as far as possible, all across Europe (even in hotspots). Alternative technologies for CO_2 reduction are pushing strongly into the market. The climate relevant (CO_2 and equivalent) emissions from road transport are decreasing but slowly, for example, possibly due to the low rate of vehicle stock turnover yet growing road transport, and the levels of investment in the energy and infrastructure aspects needed.

Milestone 2040: Since the vehicle stock is renewed, air quality relevant emissions from road transport are no longer an issue. Whilst the mobility of people and goods continues to grow, climate change relevant emissions (CO_2 etc.) from road transport are decreasing rapidly within Europe, by tens to hundreds of millions of tonnes per year. Significant infrastructure and energy production changes, in particular related to renewable sources and chemical storage, have enabled this.

Milestone 2050: All of road transport, throughout Europe is climate-neutral and air-quality is not affected by vehicle powertrain emissions anymore.

However, the number of unknowns, projecting a step-by-step approach to 2050 and determining the research needs thereto, is extremely difficult. Hence, to assist in this process, "corner-point" scenarios at 2050, which by definition meet the Green Deal targets, might be envisaged. From these, use-cases can be conceived, as a means of visualising possible final constellations of the vehicle parc, its energy supply and infrastructure requirements.

Such “corner-point” scenarios have been created as part of the ERTRAC 2050 Vision[9] and evaluated for their energy needs through the work of the ERTRAC CO_2 Study group[1]. Figure 1 illustrates the market split per powertrain in the different scenarios:

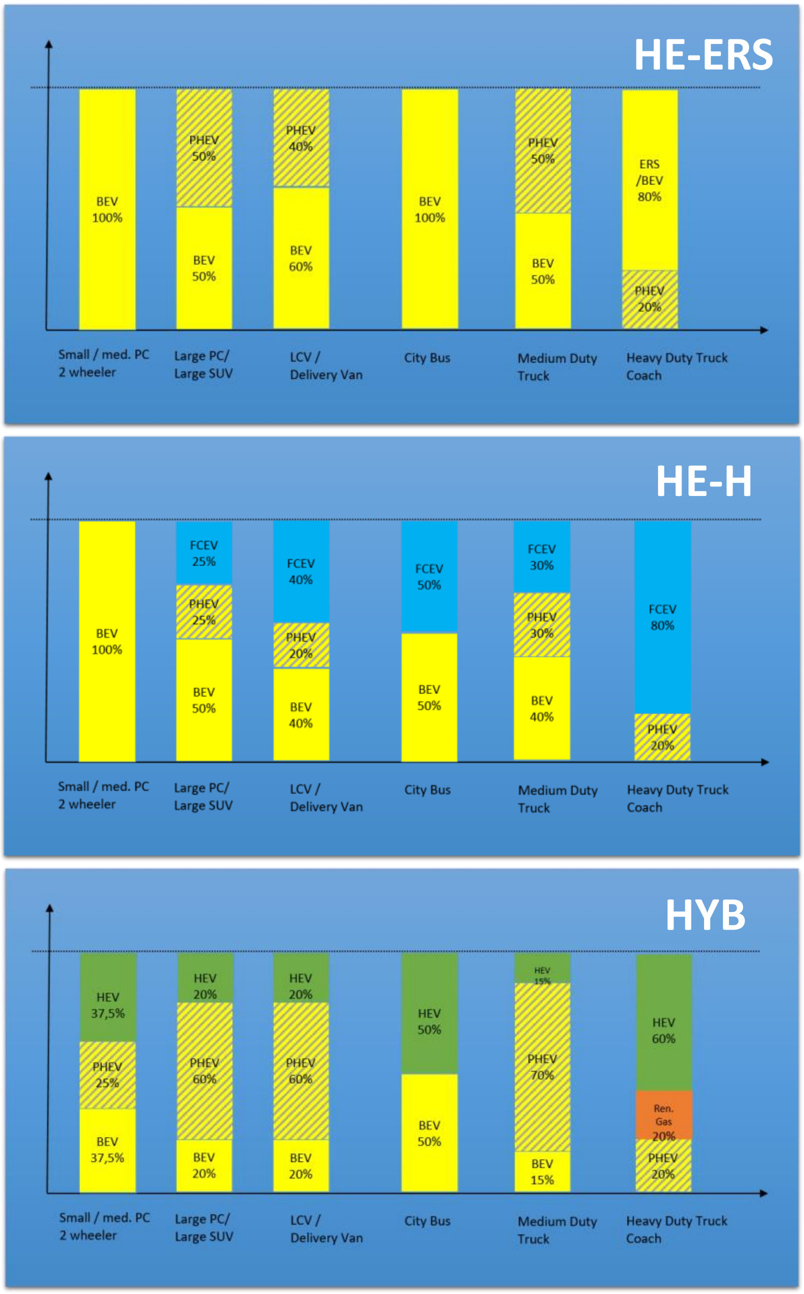


Figure 1. Scenario data from the ERTRAC CO_2 Evaluation Group
(the graphs show, for each of the scenarios, the proportion of the powertrain technologies in the different vehicle classes of the projected 2050 European vehicle parc)

The “**Highly Electrified including Electrified Roads Systems (HE-ERS)**” Scenario, represents the use using electrification to a very significant degree. Passenger cars and vehicles for urban use have a battery electrified powertrain or a plug-in hybrid powertrain. Heavy-duty trucks can also use electrified roads over long distances.

[9] See https://ertrac.org/uploads/images/1.%20ERTRAC%20Vision%202050_ERTRAC%202017.pdf

The “**Highly Electrified including Hydrogen (HE-H)**” Scenario represents the use of fuel cell technologies for long distance journeys, in addition to the presences of BEV and PHEV.

The “**Hybrid (HYB)**” Scenario describes a fleet mix in a situation where the infrastructure for charging, electrified roads or hydrogen is not fully developed. For that reason, there is a relatively large use of combustion engines with renewable fuels in this scenario.

Even if the scenarios are quite different, they each include a significant share of fleet distance travelled electrically (see Figure 2) and are all GHG-neutral by using renewable energy carriers or using additional Carbon Capture and Storage (CCS) technologies if needed. Thus, the first important message is, that GHG-neutrality can be achieved by different pathways, but the consequences for the energy supply and the infrastructure needs are quite different. If life-cycle aspects, such as land use, water use, materials or economic aspects such as investments or costs, are considered, the system analysis becomes highly complex. Therefore, it is very difficult to determine which scenario is the “best”.

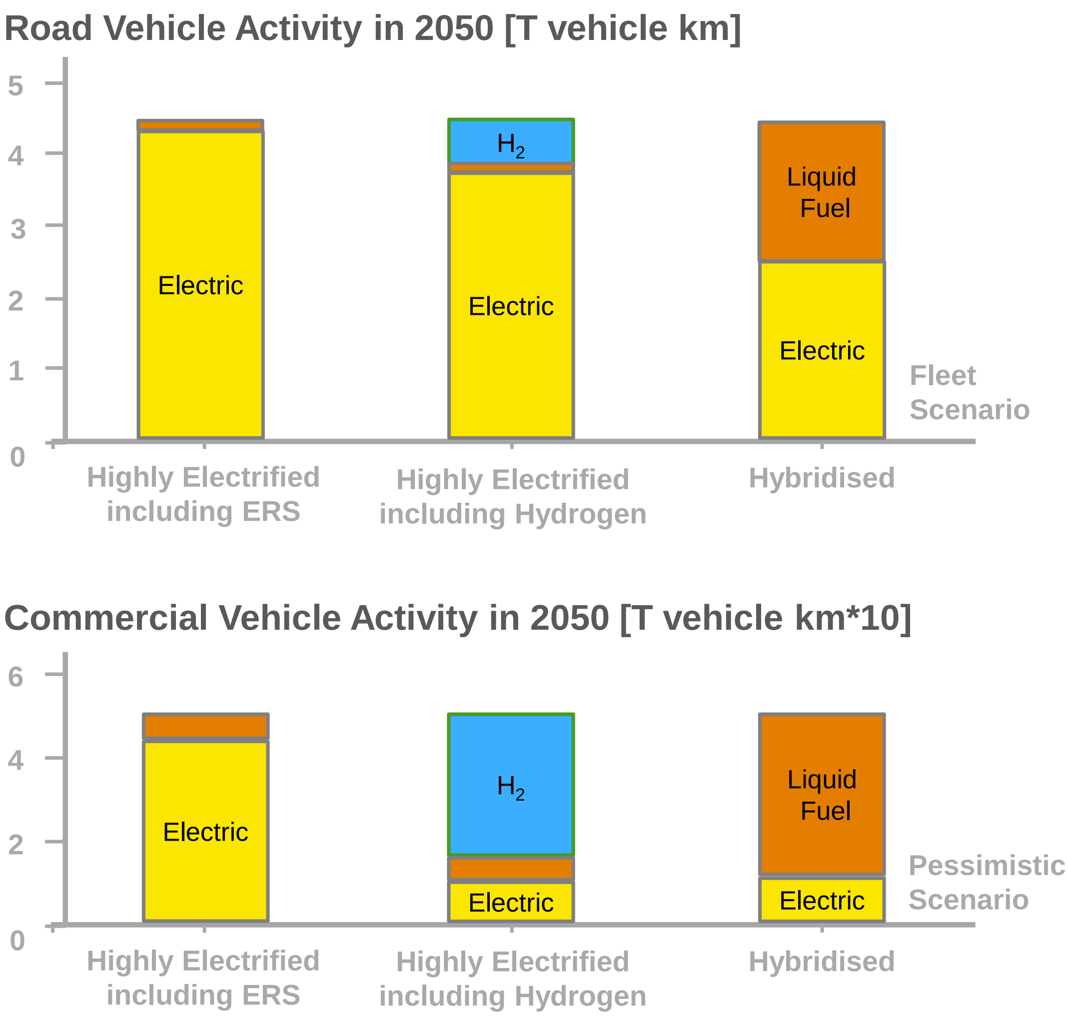


Figure 2. Road vehicle activity rates (per scenario and energy carrier) from the ERTRAC CO_2 Evaluation Group study[10]

[10] “T” relates to “tera”, i.e. one trillion. The “liquid fuel” use comes from that within the PHEV vehicles. See the ERTRAC CO_2 study[1] for further information.

1.3 Key Messages for a Climate Neutral Road Transport System in 2050

Following the above considerations whilst not yet going into the specific research needs, some key messages arise upon which such needs should be framed. In summary, these might be expressed as:

0. **A climate-neutral road transport system is possible!** ERTRAC is committed to use 100% renewable energy carriers for road transport and to end the dependency on fossil fuels. ERTRAC shares the vision of Europe becoming a climate neutral continent in 2050. To achieve this, all stakeholders in road transport have to bring substantial contributions: the automotive industry, energy providers, electric grid operators (TSO and DSO), public and private (charging) infrastructure, the fuel and regulators.

1. **The electrification of powertrains** is the key element for climate neutrality. These powertrains include those in BEV, future PHEV and FCEV.

2. **Emissions free in urban areas:** All vehicles in urban areas have to use emission free powertrains. They will drive by 100 % in electric mode (geofencing for PHEV) and will be highly efficient including using recuperation.

3. A 100% BEV scenario including long distance transport raises **significant environmental, economic and social challenges:**
   - scalability must be ensured: availability of critical resources;
   - charging infrastructure is needed all over Europe, including areas of lower population density;
   - the energy supply and distribution must be secured at all times, in spite of intermittent RES, a diversity of energy carriers is needed to increase the system resilience;
   - customer acceptance is key: ease of use, availability, cost etc.;
   - a systemic evaluation is needed to ensure that the whole system is viable.

4. **The future PHEV** will drive mainly in electric mode (circa 100 km customer range), so the e-mode will cover most of the daily trips. Only on long distance trips will it use a highly efficient, emissions neutral, fuel auxiliary drive.

5. **Renewable fuels are needed.** Thanks to the high electrification of all powertrains, the demand for fuels will be significantly reduced. This amount can be covered by renewable fuels. Renewable fuels are the only option to decarbonize the older conventional vehicles in the fleet.

6. **Global energy partnership:** Europe is not able to produce the needed energy in a renewable way internally. Despite effective energy saving programmes, Europe will still need to import energy. The energy could be produced outside Europe and transported, most likely, via chemical energy carriers (gas and fuels) to Europe. The existing fuel infrastructure could still then be used. This could offer a specific opportunity for an economic collaboration between Europe and Africa, due to the potential for renewable energy production in this continent.

7. **The fossil fuelled ICE, as the main propulsion system in road transport, will phase out by around 2040 in most areas of the world**. In highly electrified powertrains, the ICE will take on a new role. The ICE will be GHG-neutral when powered by renewable fuel: it will be a GHG-neutral auxiliary drive with negligible emissions.

8. **The technical leadership of Europe, jobs and mobility for all** will be secured by the mix of technologies: BEV, future PHEV and FCEV.

9. **A truly open research programme** covering all GHG-neutral technologies is needed.

1.4 The Structure and Content of this Document

The Chapters 2, 3, 4 and 5 give an outline of the state of the art with respect to their subject matter: “Renewable energy carriers”, “Vehicle powertrains”, “Infrastructure” and “A systemic view and impacts”. A brief vision of a possible solution, situation in 2050 will be given along with an indication of the developments needed to realise this. Consequently, the recommendations for needed research are made in the last chapter (Chapter 6).

For assistance, a table of definitions is given in the appendices. Similarly, a list of notes is given in the document and a list of references at the end of document.

The work on this document was performed between January 2020 and November 2022: the document is a snapshot of what was observed during this period. In a fast moving and highly uncertain environment, valid observations made at that time might become obsolete in the coming years.

2 Renewable energy carriers for mobility

Introduction

“Energy carriers for mobility”: what exactly are we talking about? The wording “energy carriers” means that these are not energy sources in themselves (often referred as “primary energies”) but are intermediates which “carry” energy from the primary energies to their final use – road transport in this instance.

Primary energy refers to energy available on Earth without any transformation. Most of time, primary energy cannot be used as such in its final application. The most used primary energies today are fossil-based: coal, crude oil and natural gas. Primary energies can also be “renewable”: wind, sun, crops, wood, potential energy of water (stored in a lake or in a river), geothermal heat etc. Another well-known primary energy is not fossil-based nor renewable: the potential energy of fission reaction from a nucleus (mainly uranium 235).

Before becoming energy carriers, these primary energies undergo a set of transformations, called “process(ing)”. After this step, they will become final energies that can immediately be used for transport purposes. Each energy carrier comes with its own characteristics, making it more or less suited for a given transport application. Hence, it can be observed that any energy carrier comes with three universal steps:

Feedstock (or primary energy) ➔ Process ➔ Energy carrier.

Each of these three steps comes with its own characteristics. Some of them are listed below for the purpose of illustration:

- Feedstock (or primary energy)
  - Availability, cost, carbon intensity, intermittency, water consumption, impact on biodiversity etc.
- Process
  - Technical maturity, cost, yield (or energy expanded), water consumption, land use, raw materials needs, pollutants emissions, wastes toxicity etc.
- Energy carrier
  - Suitability to be used in a powertrain, ease of storage and transportation, energy density, safety, pollutants emissions, cost, customer acceptance etc.

Today, and in the foreseeable future, there is no identified single energy carrier that has the best-in-class properties in each of these three steps. When compared to each other, they each have their relative pros and cons, more or less acceptable depending on the specific transport needs. This is the reason why the expression “There is no silver bullet” is so often used when considering the future energy carriers for (road) transport. With this in mind, it is indeed likely that a wide variety of energy carriers will be required to feed transport in 2050: this is the purpose of this chapter, to describe these different energy carriers. For this purpose, this chapter is divided in three categories of energy carriers, each of them corresponding to a dedicated section: electricity, liquid fuels and gaseous fuels.

For the sake of clarity, each of these paragraphs has the same structure:

- First, the panel of solutions considered for the production of the energy carrier is listed. Here, the three aforementioned steps (feedstock, process and energy carrier’s properties) are described with the aim to give the reader a broad understanding of their status, their specific needs, gaps and constraints to make them GHG-neutral, and their foreseen evolutions for the decades to come.
- Then, energy mix scenarios are described. These scenarios represent a range of different assumptions regarding the mix of feedstock and processes which could be used to produce each energy carrier family by 2050, with a view of reaching GHG neutrality for transport. They have been

designated by the ERTRAC CO_2 Evaluation Group and will be used for the evaluation of the use cases (see Chapter 5).

- Finally, an environmental assessment of the energy mix is given. In this document, its scope is limited to GHG intensity of the energy carriers (How much GHG is emitted when 1kW.h of energy carrier is used?) and their energy expanded (How much energy is needed to produce 1kW.h of energy carrier?). These values will also be important inputs to the Chapter 5 on use cases. However, it is important to keep in mind that these two indicators only represent a relatively small share of what a holistic environmental assessment could be, including also other parameters such as water consumption, land use, raw material needs, impact on biodiversity, pollutants emissions, waste toxicity etc. The authors would certainly not pretend that the latter are less important than the former; they simply were not in a position to give this holistic view, regularly because the data is not easily available. In some cases, it can trigger further research needs, which will be described in Chapter 6.

Developing renewable energy carriers for a GHG neutral transport by 2050 represent a tremendous amount of work: it is nothing but simple. Not only one needs to check that GHG neutrality is ensured, but also the availability at scale, the customer acceptance (ease of use, cost etc.), the compatibility with the available water supply and land use, the inclusion within a system (e.g. with spinning reserves or storage availability or transmission capacities allowing to compensate intermittency) etc. In other words: one needs to “tick all the boxes” to ensure that the whole system is viable. As all of these “boxes” could not be checked in this document, the authors cannot provide definitive conclusions regarding the most suitable energy mix for a GHG neutral transport by 2050. However, this document will hopefully constitute a good first step towards this ultimate goal.

2.1 Electricity

Approximately 23% of the final energy consumption in the EU in 2017 was based on electricity, 31% of which was from renewable origin (RES). The rest of the electricity was produced in nuclear power plants (25%) and from fossil thermal power plants (44%). The shares of main RES were wind (11%), hydropower (10%), biofuels (6%) and solar (4%).

The energy mix across EU countries differs. For example, 71% of electricity in France comes from nuclear, whilst other countries (such as Italy or Austria) do not have any nuclear power plants at all. The share of fossil fuels spreads from 91% in Cyprus to just 3% in Sweden.

The timetables for the phase-out of coal are set between 2025 and 2038. Natural gas appears as a transitional fuel, that will be replaced mainly with renewable solutions like solar and wind, but that could be partially replaced with green and renewable gas as well.

Traditional operation of the power system is based on electricity production meeting electricity demand on a real-time basis. With the progressive introduction of variable RES, power systems are evolving in order to get ready to balance up to 100% variable renewable energy production, see Figure 3. To date, this has been possible by using digitalisation tools to promote efficient cooperation between system operators, by upgrading electricity networks, and by increasing cross-border connections. Balancing markets are incentivising the development of new storage capacity, more dynamic demand response and energy conversion, providing new sources of flexibility that complement flexible generation.

The electricity sector is fully prepared to face into this future; one in which it shall be the pivoting factor in decarbonisation given that it has already embarked on the wide-scale development of renewable energies and the modernisation and reinforcement of electricity grids, among other actions aimed at providing business solutions aligned with climate goals.

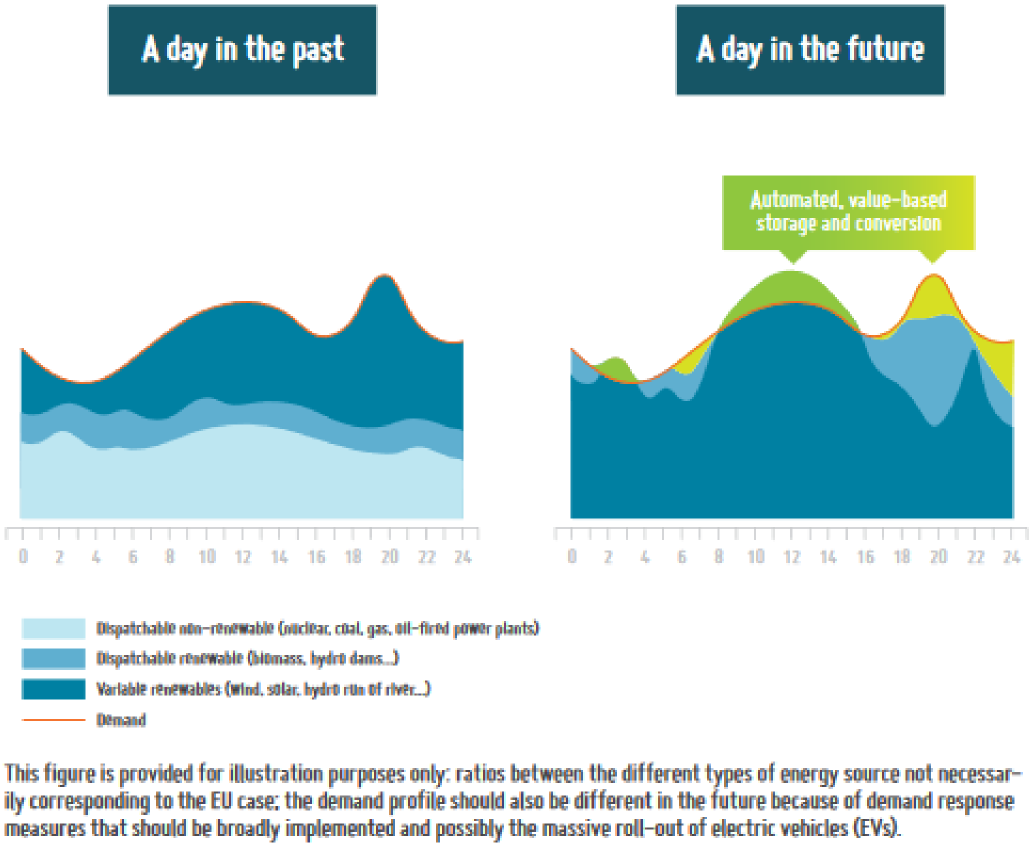


Figure 3. Illustration of daily variation in primary energy carriers. Source [2.1]

2.1.1 Panel of solutions considered for the production of decarbonized electricity

Both wind and solar photovoltaic energy have achieved drastic reduction in costs over the past decades. In the future, as will be detailed in this document, it is expected that the increase of flexibility that smart grids, distributed generation and storage, and demand-side management will provide to the system would compensate for a loss of flexibility on the generation side of intermittent renewable sources, such as wind or solar.

Wind energy is a mature and competitive[11] technology, being a key part of Europe´s industrial base, with 260,000 quality high skilled jobs. The European wind industry has a 40% share of all the turbines sold worldwide, exporting technology and services. According to the IEA, wind will become the primary source of electricity generation in Europe in 2030.

EU offshore wind resource is much greater and more stable than onshore, which is driving the growth of offshore wind installed capacity. Due to this higher resource, wind turbines are currently reaching nominal ratings of 8-9MW, with some designs reaching 12MW and expectations to reach even bigger machines (15MW expected in 2030). Additionally, the increase of the rotor size, due to the use of stronger materials and aerodynamics improvements, will significantly increase the turbine load factor. In 2019, the average load factor for new offshore wind capacities reached 44%, continuously increasing over the past decades (see Figure 4). In comparison, the new capacities of onshore wind load factor reached 31%, also continuously increasing over time. The offshore wind industry is currently dominated by the use of foundation structures. For this reason, the projects are limited to shallow water areas (<~50m deep).

[11] Based on LCOE

Floating offshore wind technology, in an incipient phase of development, will allow the locations to be extended to deeper waters, potentially accessing locations with greater numbers of wind hours. Most importantly, offshore wind has the potential to deliver the bulk power needed to deliver the EU transition in the power sector, on time.

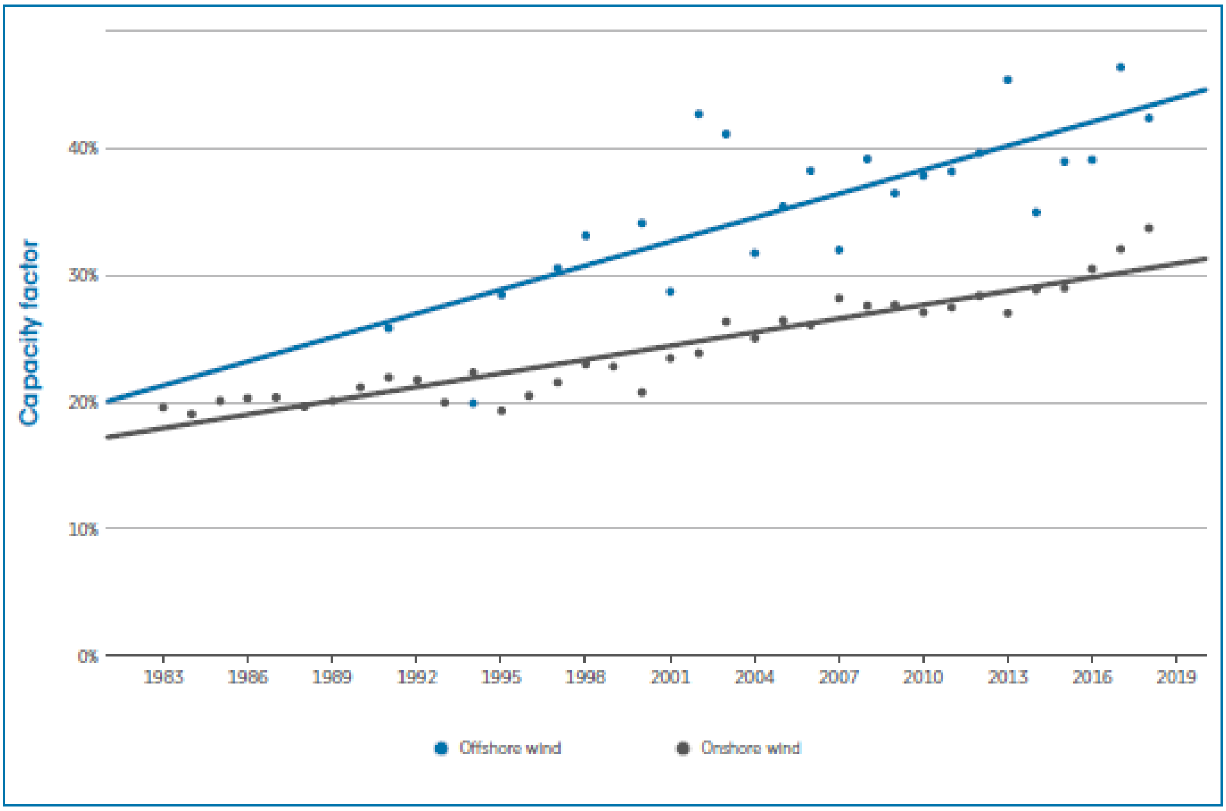


Figure 4. Global weighted-average capacity factors for new onshore and offshore wind capacity additions by year of commissioning, 1983-2018. Source [2.2]

Global **Photovoltaic** installed capacity has been increasing at an average 46% yearly during the last decade, with modules being the component with faster cost decrease: 24% less every time cumulative capacity doubles. Portugal has unveiled the final results of the solar auction held over the Summer 2019, which made global headlines as reports emerged of bid prices of €14.76/MW.h (around US$16/MW.h)[12]. The increasing investment in R&D of manufacturers is making possible the emergence of technologies for the best use of the solar resource, less degradation with the passage of time, smaller resistance to the passage of electric current and in general increased energy output electric from the same solar spectrum. The load factor for new utility-scale solar photovoltaic has increased regularly from 14% in 2010 to 18% in 2018, as the share of deployment in sunnier locations has risen (see Figure 5).

[12] In order to visualize how competitive solar prices are already today, and assuming an average consumption of an electric car of 20kW.h/100km, the marginal cost of "fuel" for an electric car using directly this electricity would be of just 0.28€ every 100km (taxes and transport costs excluded). In comparison, a car equipped with an internal combustion engine with a consumption of 5 litre/100 km would have a marginal cost of fuel of 2€ every 100km (Diesel price at 0.40€/litre, taxes and transport costs also excluded).

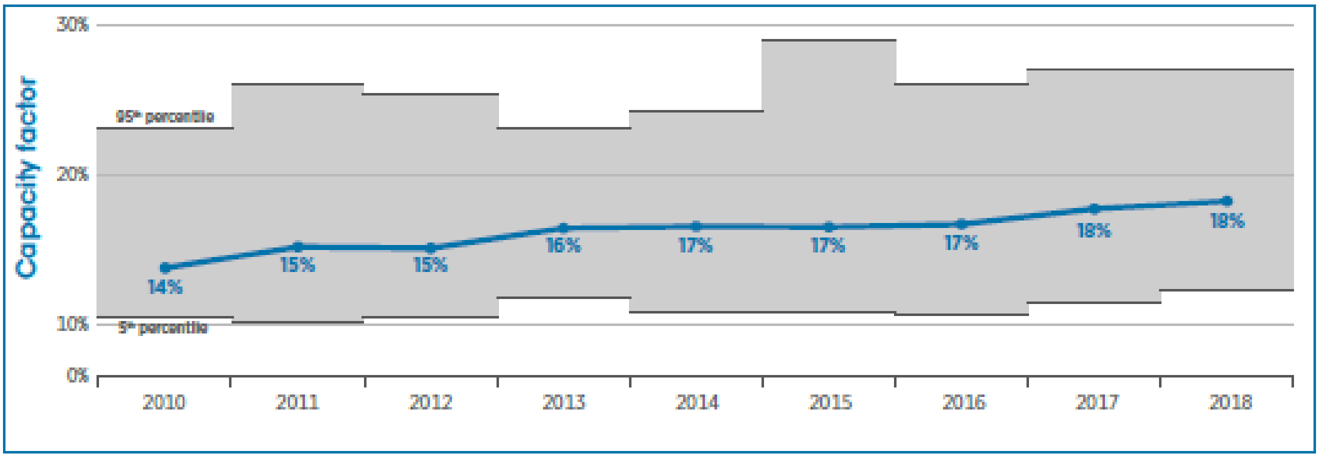


Figure 5. Global weighted-average capacity factors for utility-scale PV systems by year of commissioning, 2010-2018. Source [2.2].

Hydropower is a versatile, flexible technology that, at its smallest, can power a single home and, at its largest, can supply industry and the public with renewable electricity at a national, even cross-border scale. In terms of generation capacity, hydro accounts for eight of the world's ten biggest existing power stations. There are four broad hydropower typologies: **Run-of-river hydropower; Storage hydropower; Pumped-storage hydropower; and offshore hydropower,** a growing group of technologies that use tidal range, tidal currents or the power of waves to generate electricity from seawater. The global potential of ocean energy resources is very large but most tidal and wave energy devices are still in the research and development phase. Cumulative installed capacity in the EU in 2030 is expected to be between 1.3 to 3.9GW, depending on the scenario considered (Source: EC).

Nuclear Power Plants have been, over decades, the basis for reliable, emission-free power generation. At the end of 2017, 448 nuclear reactors with 393GW_{el} in 31 countries were in operation, and 59 units were in construction worldwide (Source: IEA). Most nuclear power generation is based on three reactor types: pressurized water reactors, PWR (63.2%); boiling water reactors, BWR (18.3%); and pressurized heavy water reactors, PHWR (6.5%) – in total representing 88% of the nuclear fleet[13]. Being used most of time as base power, nuclear power plants benefit from the highest load factor, reaching an average of 90% in Europe[14].

In a system with a high penetration of variable renewable energy, **energy storage** of short, medium and long durations will be necessary. There are multiple storage technologies with different power characteristics and storage capacity (duration), see Figure 6. Each technology is determined to provide a concrete application by its technical suitability, as well as its cost. Until today, only one technology of large energy volume and long-lasting storage has proven to be technically and economically viable so that it can be exploited massively in the electricity sector: pumped storage. As an example, lithium-ion batteries are on their part able to store medium volumes of energy during 4 to 6 hours, providing back-up capacity in periods of peak demand, regulating the network frequency in milliseconds or optimising the integration of renewables in the system. The high demand for batteries for EVs could lead to important economies of scale and investments on this technology, which could be definitely the storage technology with the greatest evolution until 2030. However, it should be clear that there is another type of technology in development.

[13] Nuclear Power Reactors in the World - 2015 Edition. International Atomic Energy Agency (IAEA). Retrieved 26 October 2017
[14] Source: Foratome

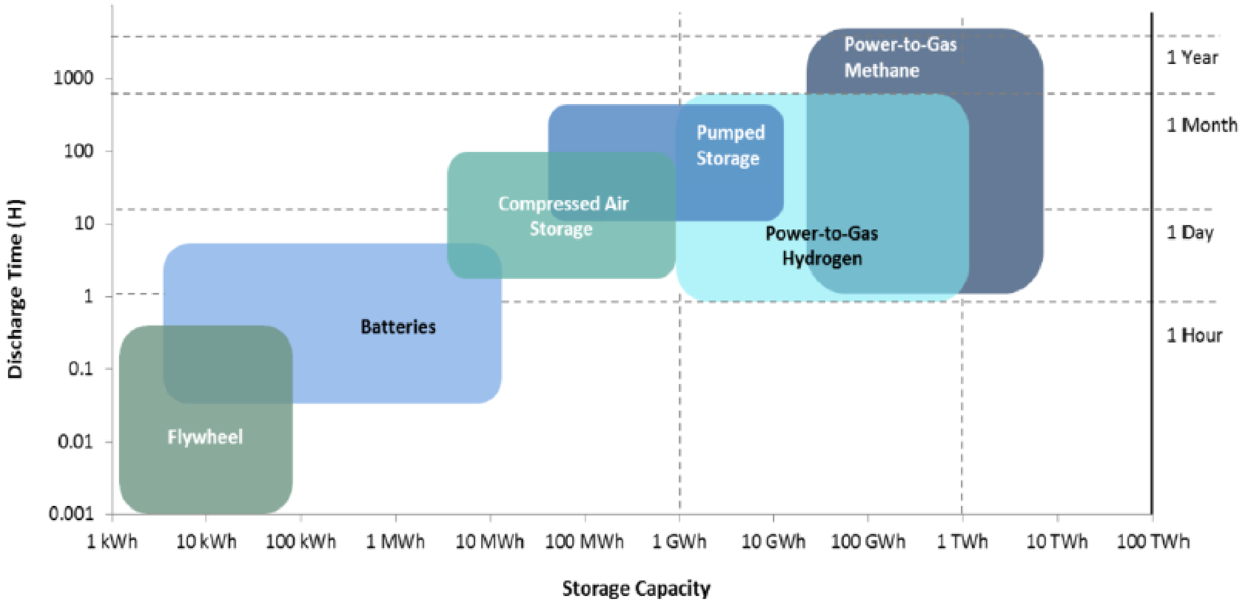


Figure 6. An overview of different energy storage technologies. Source [2.3]

Investments in electricity networks will be necessary **for the deployment of new infrastructure and the digitalisation plus automation of the existing one,** so as to ensure that the **electricity system is sufficiently robust and flexible in order to:** Integrate a large amount of intermittent renewable production, manage the growing demand for electricity and maintain the current quality of supply.

2.1.2 Energy mix scenarios

In November 2018, the European Commission presented its strategic long-term vision for climate neutrality by 2050, 'A Clean Planet for all' [Source 2.4]. The strategy shows how Europe can lead the way to climate neutrality by investing in realistic technological solutions, empowering citizens and aligning action in key areas, such as industrial policy, finance, or research – while ensuring social fairness for a just transition. The Commission's strategic vision provides a detailed analysis of eight pathways for a possible future EU economy. The scenarios rely on both existing and emerging technological solutions, citizen empowerment and alignments across policy, finance and research.

1.5TECH scenario – Power generation capacity / shares

The 1.5TECH scenario is one of the two proposed by the EC that reaches net-zero GHG emission by 2050. This scenario is based on "energy efficiency first" principle, balanced with the augmented need to produce renewable electricity for the production of green hydrogen (P2X). This scenario builds on two trends that have already started:

- Decarbonization of electricity, due to the massive introduction of competitive[15] RES.
- Electrification of the demand in transport, buildings and industry allows a strong reduction in the primary and final energy demand.

Under this scenario, total installed capacity for electricity generation in Europe would grow from 985GW in 2015 to 2800GW in 2050, see Figure 7.

[15] According to LCOE

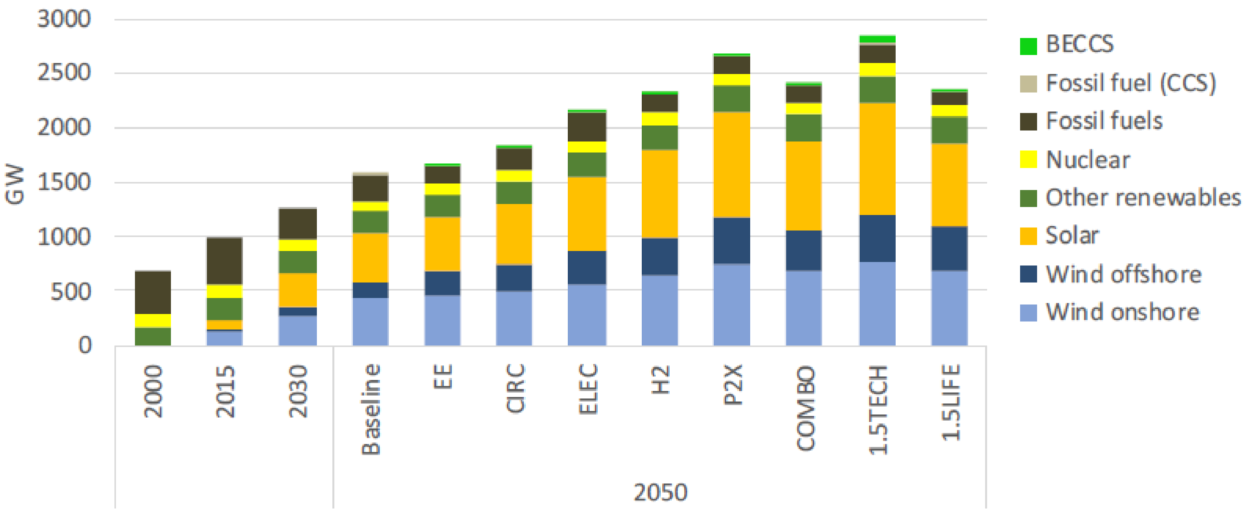
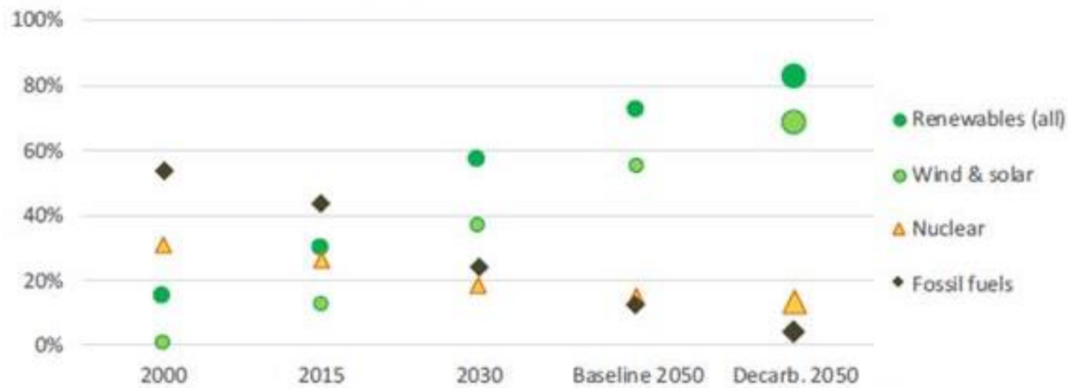


Figure 7. Power generation capacity. Sources [2.5 & 2.6]

Electricity demand in 2050 will be 2.5 times that in 2015 (from 3,000 to 7,200TW.h) which makes the electricity share of final energy consumption grow from 23% in 2017 to over 50% in 2050. Most of the increase in demand comes from the electrification of transport. 45% of the electricity demand, in the scenario, is dedicated to the production of green hydrogen via electrolysers.

As illustrated in Figure 8 below, the 1.5 TECH scenario ("Decarb. 2050") envisions an electricity mix based on the following share of power generation capacity[16]:

- Renewables (RES 83%)
  - Wind+ Solar: 69%
  - Biomass with CCS: 10%
  - Hydro: 4% (versus 12% in 2016)
- With contribution of nuclear (12%) and natural gas with CCS (4%)
- Others (e.g. fossil without CCS).



Notes: 1. The shares of renewables, nuclear and fossil fuels sum to 100%. Wind & solar is a component of renewables. 2: The "Decarb. 2050" points are the averages across all decarbonisation scenarios per category. These scenarios provide very similar power mix in 2050, with renewables ranging from to 81% to 85% (wind & solar alone from to 65% to 72%), nuclear from 12% to 15% and fossil fuels from 2% to 6%.

Figure 8. Shares in power generation. Source [2.5 & 2.6]

[16] This is the power generation installed capacity (expressed for instance in GW). The share of power generation (expressed for instance in TW.h) is different.

1.5TECH scenario – Carbon intensity of the electricity mix

Under this scenario, the electricity sector will be able to reach net zero GHG emissions in 2050 due to the massive use of renewables and CCS with biomass. Biomass with CCS generate negative emissions that compensate positive emissions in other sectors (such as industry) with emissions harder to abate.

In the 1.5TECH scenario and for the purpose of this 2050 Roadmap, the residual CO_{2eq} intensity of the electricity mix has been estimated in 5.2gCO_2/kW.h[17].

1.5TECH scenario – Storage needs

As illustrated in Figure 9 below, 1.5 TECH provides figures for storage in the electricity sector. Pumping hydro (48TW.h) and batteries (128TW.h), on top of the EV batteries. Hydrogen production (105TW.h) will as well be a source of storage for the electricity system[18].

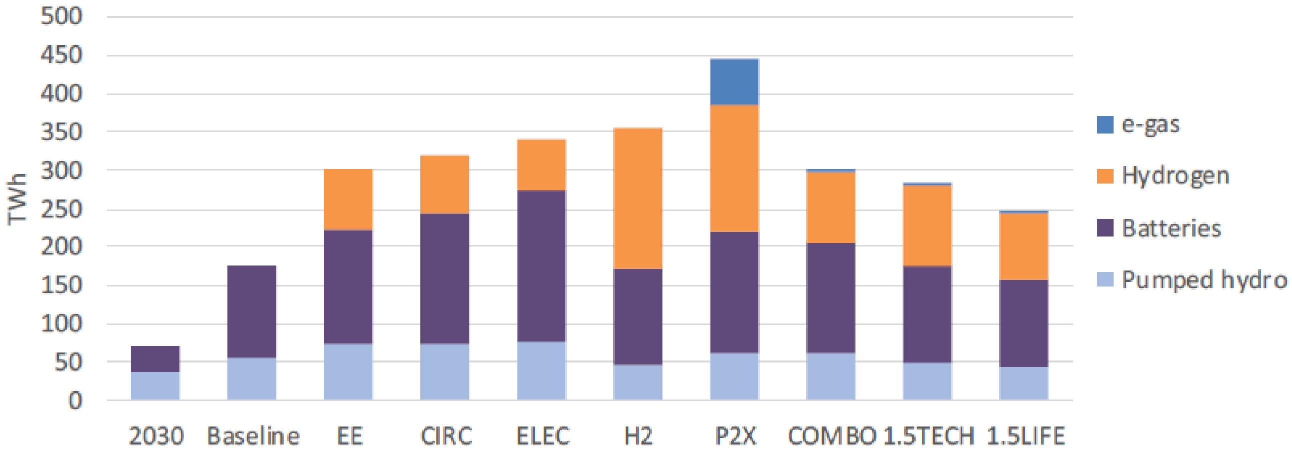


Figure 9. Electricity Storage in 2050. Source [2.6]

Neither hydrogen nor synthetic methane or fuels are used to generate electricity in EC scenarios, although this would be technically feasible[19].

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[17] Source: ERTRAC, based on A Clean Planet for all [ACP4A 2018]. CI of electricity mix – Details: Step 1. Gross electricity generation in 2015 baseline: 3,234TW.h (Figure 8 from ACP4A - Appendixes). Step 2. 7,955TW.h generation in 2050 (1.5TECH scenario) (Note. 146% of additional gross electricity compared to 2015 baseline (Figure 22 from ACP4A - Appendixes)). Step 3. Assumption: 10% losses due to transmission /storage → Gross electricity supply in 1.5TECH 2050: 7,159 TW.h. Step 4. Emissions from the power sector: 37.5MtCO_{2eq} (1.5TECH 2050 - as reported in page 113 of ACP4A). Carbon intensity: GHG emissions/gross electricity demand: 5.2gCO_{2eq}/kW.h.

[18] To be more accurate, storage can be seen as a topic with 3 levers:

1. The power capacity of the storage capacities (expressed in GW): this is the instantaneous power that you can get (or which can be absorbed) by the storage capacities to equilibrate the grid;
2. The energy capacity of the storage capacities (expressed in TW.h): this is the sum of the energy capacities which can be stored simultaneously at a given point in time;
3. The total energy which is taken from storage capacities each year (also expressed in TW.h). This value (3) can (or cannot) differ significantly from the previous one (2) depending on the needs. For instance, pumping hydro storage can have relatively small storage capacities compared to the total energy which they can deliver each year as they can theoretically be emptied and filled every day. The same approach can be used for batteries. But for hydrogen, the situation is likely to be different as it would ensure inter-seasonal storage: in this case, the ratio between total energy taken from storage (3) and storage capacity (2) should be lower than for pumping hydro and batteries.

The authors did not manage to clarify whether the storage values mentioned in the text and in the figure refer to storage capacities (2) or to total energy taken from the capacities (3).

[19] As electricity is getting decarbonized, it can be used to produce green hydrogen and e-fuels which are derived from it. Technically speaking, it would be possible to store and use these fuels to produce electricity when intermittent sources are not sufficient to supply electricity to the grid; however, this pathway is not considered in the EC scenarios, and these fuels are used by other sectors instead.

While 1.5 TECH assumes a percentage of fossil fuels and nuclear in the electricity mix, other studies such as the NET ZERO 2050 TOWARDS FOSSIL-FREE ENERGY IN 2050[20] from Cambridge Econometrics and Element Energy or the one from Energy Watch Group and LUT University provide different scenarios that show that 100% RES energy systems in Europe and worldwide would be feasible by 2050.

The Energy Watch Group finds,
- The report confirms that a transition to 100% renewables would be possible across all sectors. The transition to 100% renewable energy would require comprehensive electrification in all energy sectors. The total electricity generation would be four to five times higher than the electricity generation in 2015. Accordingly, electricity consumption in 2050 would account for more than 90% of the primary energy consumption. At the same time, consumption of fossil and nuclear energy resources in all sectors would cease completely.
- The global primary energy generation in the 100% renewable energy system would consist of the following approximate mix of energy sources: solar energy (69%); wind power (18%); hydropower (3%); bioenergy (6%); and geothermal energy (2%).
- By 2050, wind and solar power would account for 96% of the total power supply of renewable energy sources. Renewable energies would be produced virtually exclusively from decentralised local and regional generation.

2.1.3 Environmental assessment

The summary of the GHG intensity of the electricity mix used in the ERTRAC 2050 roadmap is detailed below. This electricity mix will be used in both direct use (e.g. BEVs) as well as in indirect ones (e.g. production of H_2 or e-fuels). The industrial processes required to convert waste or biomass into biofuels are also deemed to use this low carbon electricity mix.

Table 1. Summary of energy expended and GHG emissions for the 2050 electricity mix scenarios considered in the ERTRAC roadmap (JEC 2030 WTT v5 values are included for comparison purposes).

Electricity mix (WTT)	**Description**		
Timeframe	2030 JEC WTT v5 (EMEL3b) EU-mix / LV	2050 ERTRAC 1.5TECH (Base case)	2050 ERTRAC 100% RES (Sensitivity)
GHG ($gCO_{2eq}/kW.h_{electricity}$)	268	5.2	0
Energy expended, $MJ/MJ_{electricity}$	1.33	0.13	0.07
RES in mix	45%	83%	100%

[20] https://europeanclimate.org/wp-content/uploads/2019/11/14-03-2019-towards-fossil-free-energy-in-2050-executive-summary.pdf

2.2 Liquid fuels

2.2.1 Panel of solutions considered for the production of low-carbon liquid fuels

2.2.1.1 Biofuels

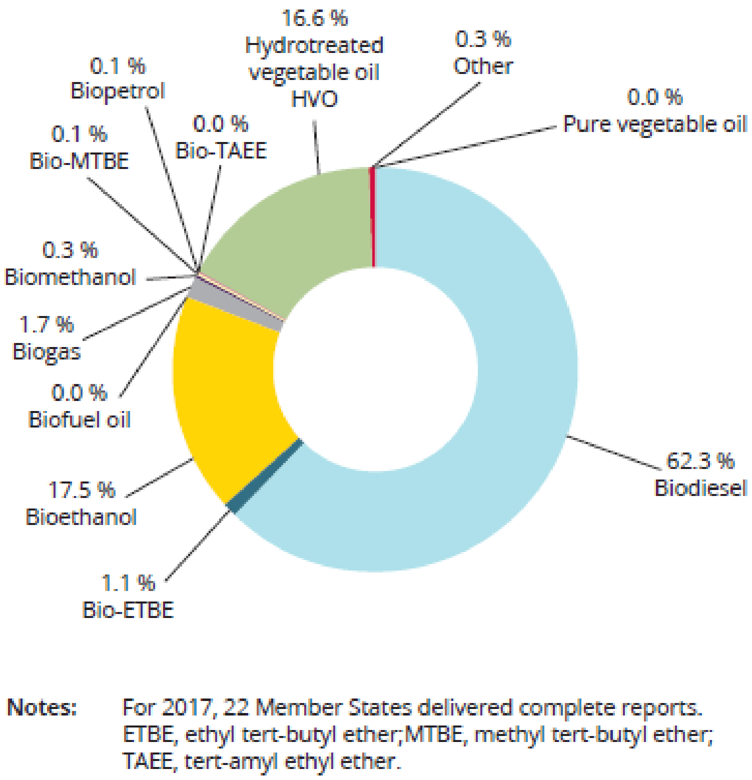


Figure 10. Overview of the biofuel supply (by type) in Europe in 2017. Source [2.7]

'Food & Feed' / 'First generation' / 'State of the art' biofuels

Biofuels from food and feed (also known as 'first generation') are based on agricultural commodities such as cereals, sugar beet and sugar cane, as well as vegetable oils. They use well-established conversion technologies. Consumption in EU28 in 2018 amounted to 19Mtoe, dominated by 62.3% biodiesel with 17.5% bioethanol on 2nd place, and 16.6% hydrotreated vegetable oil (HVO), see Figure 10. The use of biofuels from food and feed is capped at 7% (on an energy basis) according to the Renewable Energy Directive (RED II – 2018/2001/EC), in order to avoid competition with the food and feed industry. To be eligible for the status of biofuels, the corresponding feedstock must comply with a number of sustainability criteria, amongst which is the reduction of GHG emissions compared to a fossil basis, or the forbidding of deforestation.

From the end-use point of view, the use and blending ratio of biofuels from food and feed, such as ethanol (EtOH) and conventional esterified biodiesel (FAME), is often limited for technical reasons (incompatibility issues with mainstream vehicles).

The most used biogenous component in gasoline engines is **ethanol** (EtOH). It is already introduced in many European countries up to 10%v/v of ethanol in gasoline fuel grades, while modern 'flex-fuel vehicles' (FFV) can run on any gasoline-EtOH mixture up to 85%v/v EtOH (E85). EtOH is a naturally widespread chemical, which can be produced from any feedstock containing appreciable amounts of sugar or materials that can be converted into sugar. Fermentation (biotechnology) is the predominant pathway for EtOH production. EtOH has technical advantages as a fuel for spark-ignition engines, including its high Octane Number. This gives the fuel a strong resistance to knock which translates into increased efficiency on adapted engines.

FAME, or biodiesel, is produced from vegetable oils, animal fats or waste cooking oils by trans-esterification and esterification. In the trans-esterification process a triglyceride reacts with an alcohol in the presence of a catalyst (liquid or solid), forming a mixture of fatty acids esters and an alcohol, whereas the esterification process is necessary to convert free fatty acids of oils or fats to fatty acid esters and water. Using triglycerides result in the production of by-product glycerol. The physical characteristics of fatty acid esters are closer to those of fossil diesel fuels than pure vegetable oils, but properties depend on the type of vegetable oil. A mixture of different fatty acid methyl esters is commonly referred to as biodiesel, which is a renewable alternative fuel. It is also non-toxic and biodegradable. Some properties of biodiesel are different from those of fossil diesel, thus for correct low temperature behaviour and for slowing down oxidation processes biodiesel requires a different set of additives than fossil diesel.

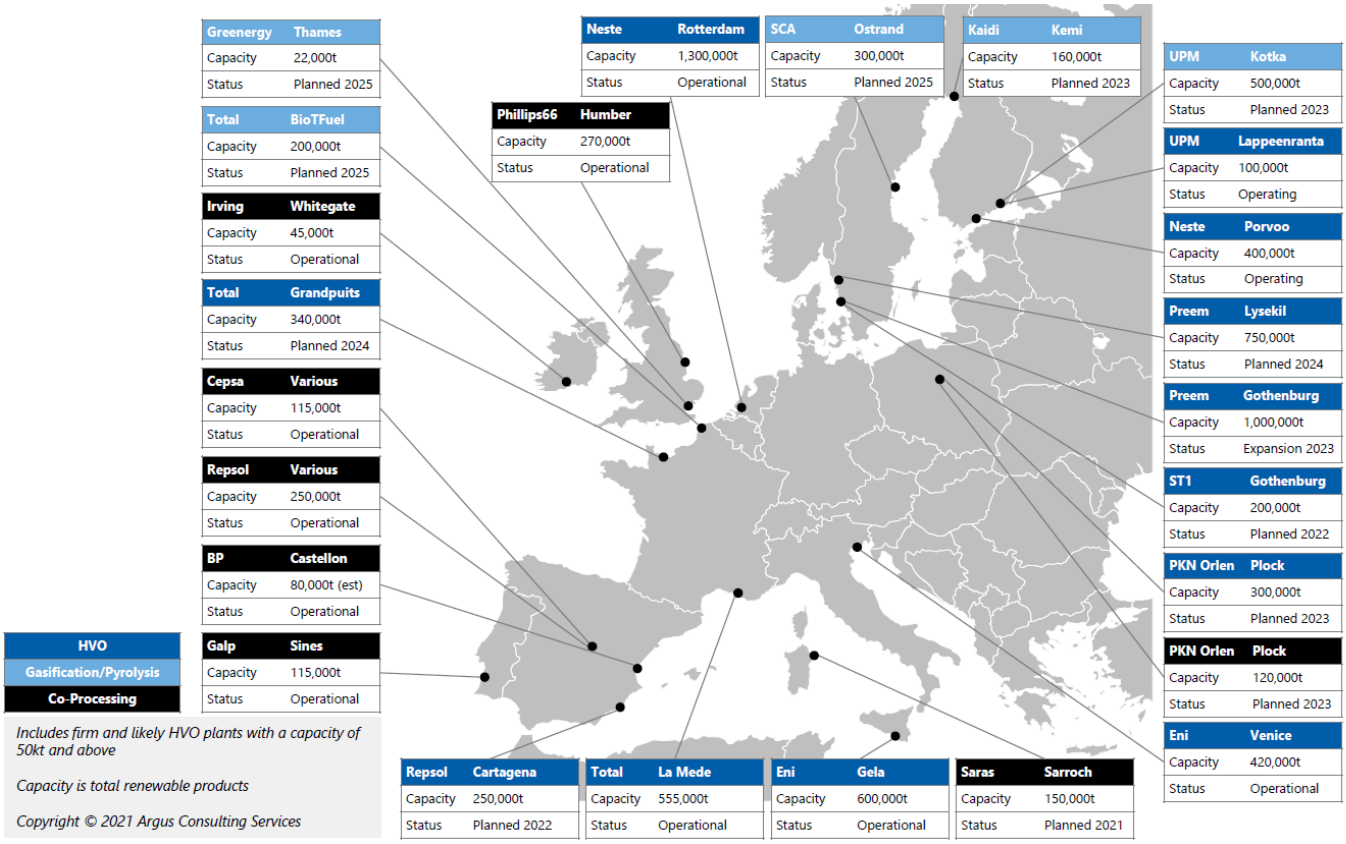


Figure 11. Operating and Planned HVO and BTL plants in Europe. Source [2.8] Copyright © Argus Consulting Services.

HVO which can be made also from vegetable oils, waste animal fats or new alternative oil production pathways is a renewable paraffinic diesel fuel which complies with the EN 15940 standard. HVO can be blended, as a drop-in fuel, without a fixed 'blending wall' into conventional (EN 590) diesel fuel, fitting any existing diesel vehicle, any aftertreatment system and any existing infrastructure. Up to about 80% blending ratios in diesel fuel were shown achievable, and up to 100% in vehicles compliant with EN 15940 paraffinic fuels. HVO, with its paraffinic nature, high cetane number and good winter properties, achievable thank to hydro-isomerisation production step, is a very suitable fuel to be used in compression ignition engines. Its high-energy content is similar to the one of diesel fuel, reaching the best value among renewable components. This means that the current storage tank and vehicle fuel tank sizes as well as the wide driving range of diesel vehicles can be maintained. HVO production technology, relying on hydrotreatment process, is ready and used in large commercial scale. HVO production is estimated to reach 5.6Mt/y by 2023 in Europe, with existing and planned production capacities given in Figure 11 above. The technology is in many respects similar to catalytic processes used in traditional oil refining; it is available from many process technology suppliers. The main product of a HVO process is diesel paraffinic fuel, in addition some volumes of aviation kerosene can be produced. Minor amounts of renewable hydrocarbon gasoline and renewable LPG are produced as side products. The limiting factor for the maximum HVO volume is the availability of sustainable feedstock, since HVO competes with the same sources as FAME, especially with the frame of the cap on biofuels from food and feed imposed by RED II. In particular, HVO production (and FAME production) is criticized for relying heavily on palm oil as a feedstock, which is suspected to cause indirect land use change (ILUC), and for which regulation already foresees a cap and a complete ban in 2030.

'Advanced' biofuels

General introduction: The production of advanced biofuels always follows three main steps, see Figure 12:

- After the feedstock is collected, it goes through a pre-treatment stage;
- Then the feedstock is deconstructed, either through a thermochemical or a biological route, resulting in intermediate products such as sugar or lipids;
- Finally, these intermediate products are refined before obtaining final products.

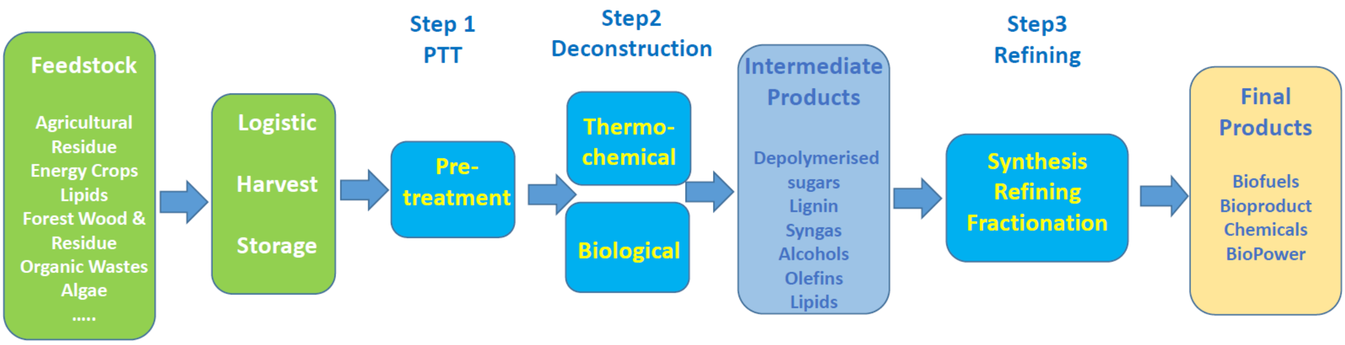


Figure 12. The main stages of biofuel production

Biomass to liquid (BtL). Synthetic fuels from biomass are a more recent development, not yet available on the market at scale. At the moment, there are small research and pilot plants but great expectations are linked with the fuel designated as biomass-to-liquid (BtL), one reason being that they can offer outstanding GHG reductions (up to 90%) while complying with all the sustainability criteria. A great advantage of BtL fuel is that many different sustainable feedstocks can be used. The range extends from waste materials already produced, such as straw, biological wastes and wood offcuts, to energy crops which can be specially cultivated for fuel production and fully utilised.

BtL fuels can be produced from biomass in a two-stage process. In the first stage (gasification), a synthetic gas is produced, composed mainly of hydrogen, carbon monoxide and carbon dioxide. For this purpose, the biomass is placed in a reactor and broken down in the presence of heat, pressure and a gasification agent, for example oxygen. In the second stage, fuel components are synthesised from this, which can be processed to the BtL end-product, optionally with diesel or petrol properties which can be 'fine-tuned'. The best-known synthesising process is the Fischer-Tropsch (FT) synthesis: in this case, BtL (as HVO) can be used without major technical modifications to the engine, and logistics is possible using the existing infrastructure; the methanol-to-synfuels synthesis is also regarded as a promising option. Several companies and research institutes in Europe are co-operating to test the production of BtL fuels on a pilot scale.

Another production pathway of BtL is Hydrothermal liquefaction (HTL). It is a thermal depolymerisation process used to convert wet biomass into biocrude under moderate temperature (250°C-550°C) and high pressure (5-25MPa). In this process, long carbon chain molecules in biomass are thermally cracked and oxygen is removed in the form of H_2O (dehydration) and CO_2 (decarboxylation). These reactions result in the production of biocrude, typically with a lower heating value of 33.8-36.9MJ/kg and 5-20wt% oxygen. The reaction usually involves homogeneous and/or heterogeneous catalysts to improve the quality of products and yields. Depending on the processing conditions, the fuel can be used as produced for heavy engines or upgraded to road transportation fuels such as diesel or gasoline.

Pyrolysis can also be used for producing fuel from lignocellulosic biomass. In this case, the temperatures used can be much higher, ranging from 210°C to 1000°C, depending on the composition of the biomass (hemicellulose, cellulose or lignin). Pyrolysis oils are of low quality, they typically have a density of 1100-1200kg/m^3, a lower heating value of 17-20GJ/m^3 and a water content of 20-30wt.%[21]. They can be improved either by co-processing in a refinery or by upgrading (e.g. hydrotreatment).

Sugar to Diesel. The conversion of sugar to ethanol is a very well-known process. More recently, some research projects have also produced renewable diesel components from sugar. The potential pathways are as follows: heterotrophic organisms, microbes such as bacteria, yeasts and fungi are unable to synthesize organic compounds themselves and need to feed on organic material, such as sugars, to multiply. By feeding sugars these types of microbes are capable of storing large quantities of lipids in their cells, typically over 50% of their mass. They produce alkanes, alkenes and lipids, and multiply very rapidly, typically achieving maturity in a couple of days to a week. Oil-producing microbes can be grown in conventional bioreactors of the type used in the brewing and biotechnology industries. Agricultural and industrial by-products represent a possibility as suitable and sustainable raw materials for sugars for industrial-scale production. These alkanes and alkenes from sustainable renewable sources are well suited for further (co)processing in existing refinery infrastructures.

Microbial oil produced from waste or residue based sugars using yeasts and moulds is ideal for production of HVO. Microbial oil consists of triglycerides, such as vegetable oils, and animal fats. Its fatty acid distribution can be adjusted and optimised. Diesel from sugar can be used immediately and without technical modifications to the engine as drop-in fuel.

Advanced sugar to ethanol (or higher alcohols) pathways. Glucose, as one molecule from the wide field of sugars, is ubiquitous, found mostly as a polymer in cellulose and hemicellulose. Glucose metabolism can be found in nearly any form of organisms and is leading to the same intermediates, which can be coupled by modern biology, to virtually any type of product. Amongst them is the formation of alcohols, especially ethanol. Ethanol formation is among the oldest and best surveyed biotechnological processes for mankind.

Thus, the technology is established at industrial scale and spread worldwide. Ethanol is produced currently mainly on basis of, e.g., corn, wheat or sugar beet, with cellulosic ethanol being now introduced in industrial scale. Furthermore, butanol and its isomers are very interesting fuel components. Especially with butanol, an increasing number of companies are investing due to its interesting properties (e.g. lower oxygen content than ethanol and easier management of volatility while keeping a high Octane Number). Butanol formation is achieved, nowadays, through fermentation by specially adapted microorganisms.

Butanol can be introduced into existing gasoline fuels already today, within the boundaries of current European and U.S. specifications. Its production processes using sugars from sustainable, renewable sources or even waste streams are highly attractive for fuels with reduced GHG footprint. Enabling an ethanol industry on the basis of cellulosic sugars is allowing butanol production from these sources.

[21] Advanced biofuels from fast pyrolysis bio-oil, K. Overwater, 2nd EU-India Conference on Advanced Biofuels, March 2019.

Higher alcohols, including pentanol and its isomers upwards, have not been proven today in a semi-technical or technical scale. For these alcohols, all the advantages for butanol compared to ethanol will also be in place. With an increasing C-number, one must take into account that these molecules will show degraded cold flow properties.

Long chain alcohols, such as 1-octanol, 1-nonanol or 1-decanol, are also considered for use in a compression-ignition (Diesel) engine. Thanks to their oxygen content, they show a capacity of lowering engine-out soot emissions. However, the assessment of their life cycle GHG emissions shows limited benefits compared to fossil fuels. The compatibility with some rubbers currently used in engines may also be questioned, although it is likely that alternatives could be found if dedicated engines were designed.

Algae to liquid technologies. Algae are a very large and diverse group of unicellular and multicellular atrophic organisms. Particularly microalgae have been in the focus of the biofuel industry because of their high lipid content and very fast growth rates. It has been estimated that microalgae could produce between 25 - 30t oil per hectare and year, which could be used as basis for the production of biodiesel, HVO and kerosene. The yield depends on the strain's genetics, the growth method, assess to key nutrients and location (Rösch & Posten, 2012). Microalgae of microscopic size can be grown in seawater and on land unsuitable for cultivation. Microalgae produce sugars, lipids and proteins from CO_2, water and nutrients using photosynthesis. They can make use of the nutrients contained in wastewater, for example. As they also bind CO_2, they also offer a number of exciting possibilities in helping meet tomorrow's energy needs. Under favourable conditions, microalgae can produce lipids year-round, and offer a dramatically higher production potential than oil plants.

The production pathways of drop-in fuels from algae oil follow similar production pathways as other biofuels pathways using, e.g., vegetable oils as feedstocks. However, different measures have to be applied to harvest the algae biomass in the first place (e.g. centrifugation, sedimentation and filtration) and to extract the oil from the algae (e.g. using organic solvents or supercritical CO_2). Depending of the algae species, the oil will be characterized by a high degree of unsaturation, which will cause problems in the production process of biodiesel if the unsaturated fatty acids are not at least partially saturated beforehand. For the conversion into biodiesel the lipids need to undergo two processes: esterification and hydrogenation. About 12kg of dry algal biomass are needed to produce 1kg biodiesel (Petkov et al., 2011). An alternative way of producing fuels from algae would be to produce in a first step biocrude from algae, which then could be processed or co-processed in a traditional refinery. However, this process has not yet been demonstrated as there are still questions regarding the compatibility of the refining process with the impurities contained in biocrude. Today, using algae exclusively for energy purposes is economically not viable.

Biotechnological fuel production. The idea of biotechnological fuel production originates from the thousands of years old principle of microbial fermentation of sugar-rich raw materials. The microorganism itself represents the central conversion unit, e.g. eukaryotes like yeast, prokaryotes like bacteria (Escherichia coli) and archaea bacteria, could act as small factories. Within a cell multiple synthesis steps occur, numerous subsequent chemical reactions which convert the nutrition material via metabolic pathways into various products, as the cell needs to multiply itself and assembles energy from the substrate. In the case of the yeast the cell metabolises sugar performing cell-internal fermentation and produces ethanol as product. From this start point the idea of microbial fuel production extends to the target of a designed biofuel production to get a variety of gasoline and diesel fuel compatible components which offer the potential of biofuel production.

Another example is photosynthetic microorganisms, which are able to collect solar radiation (sunlight) and take up carbon dioxide as nutrient and convert it into components that show compatibility as fuel. The photosynthesis precedes the conversion to chemical energy which the cell uses in metabolic pathways to synthesize products. For example, cyanobacteria transform the collected light and CO_2 in a direct, two-step pathway into fuel products, ethanol and in the future to diesel products. Because of their ecological origin the cyanobacteria can also produce in extreme environments, so they can tolerate for example brackish and saltwater. Photosynthetic produced fuels would not require agricultural land within the production time – and would not directly compete with biofuels based on sugar or lignocellulosic biomass.

Biomethanol. With the chemical structure CH_3OH, methanol is the simplest alcohol, with the lowest carbon content of any liquid fuel. As a basic alcohol, methanol is today a transportation fuel due to its efficient combustion, ease of distribution and high level of availability around the globe. Methanol is used today in transportation in four main ways:

- Directly as fuel or blended with gasoline in captured fleets and niche markets
- Converted in dimethyl ether (DME) to be used as a diesel replacement
- Converted to Methyl-tertiary-butyl ether (MTBE)
- As a part of the biodiesel production process.

Methanol is a liquid fuel that is currently mainly made from natural gas and coal. It can also be made from biogas instead of natural gas, using renewable resources like wood, agricultural or municipal waste[22]. In this case, it reduces greenhouse gases emissions. Alcohol fuels have been used widely in transport ever since the invention of the internal combustion engine, they continue to be employed today as an alternative to gasoline derived from oil in different part of the world.

Methyl-tertiary-butyl ether (MTBE). Methyl-tert-butyl ether (MTBE) is a blend component of gasoline fuel. MTBE has a high Octane Number, which improves the knocking behaviour. MTBE is manufactured via the chemical reaction of methanol and isobutylene.

Dimethyl Ether (DME) and oxymethylene dimethyl ether (OME). DME is a synthetic fuel that can be produced in a number of pathways, with both fossil and renewable feedstock. DME is primarily produced by converting hydrocarbons sourced from natural gas or coal via gasification to synthesis gas (syngas). Synthesis gas is then converted into methanol in the presence of catalyst (usually copper-based), with subsequent methanol dehydration in the presence of a different catalyst (for example, silica-alumina) resulting in the production of DME. As described, this is a two-step (indirect synthesis) process that starts with methanol synthesis and ends with DME synthesis (methanol dehydration). The same process can be conducted using organic waste or biomass. DME can also be produced from biomethanol via dehydration to form DME.

DME can be used as a transportation fuel as diesel substitute. DME is a gas at atmospheric pressure, boiling point is minus 25°C, but it condenses to a liquid at low pressure 5.1bar @ 20°C. Physical properties and handling are very similar to LPG. DME has been commercially used as a high-grade propellant for various health care products, and its ‘environmental, health and safety’ (EHS) characteristics are better than conventional petroleum-based fuels. The LPG infrastructure for vehicle fuel currently exists in many countries in the world. The same technology can be used for DME with only minor modifications, mainly change to DME compatible sealing materials.

Polyoxymethylene dimethyl ethers (also called OME) are polymers of DME with the molecular formula $H_3CO(CH_2O)_nCH_3$ where n is typically about 3 to 8. When n is between 3 and 5, OME are liquid and can be considered as additives to diesel fuel.

Tailor made fuels from biomass (TMFB). As conventional biofuels use feed and food crops, the Cluster of Excellence ‘Tailor-Made Fuels from Biomass’ was established in 2007 at RWTH Aachen University to address this problem and improve the whole process chain from biofuel production to its utilization in the engine. The long-term target is to derive new, biomass-based, synthetic fuels with optimised properties for use in vehicle applications. These properties do not only include the physical and chemical combustion properties of the fuel as the final product but, at the same time, take the biomass conversion and fuel

[22] Methanol can also be a power-to-fuel (e-methanol). See detailed description in the next section.

production by (bio-) catalysis into account, thereby optimising the fuel production along the whole process chain from biomass to fuel to combustion products. It is important to point out that this research project has been set-up in an iterative way, meaning that neither the fuel production pathways from biomass nor the final fuels have been defined a-priori. Instead, by combining the production and the fuel combustion research iteratively, the pathways as well as the produced fuel are altered as the project evolves.

The competition to, e.g., the food chain is being avoided by considering lignocellulosic biomass in general – which describes the whole plant rather than just the fruit or the oil – as input product for the fuel production process. First of all, the lignocellulose must be split up into its components, cellulose, hemicellulose and lignin. Innovative reaction media such as ionic liquids are used to break up the linkages between these components and to separate the respective fractions. Using various catalytic conversion methods, the individual components can then be converted into the desired fuel molecules. Figure 13 shows possible methods of converting the lignocellulose fractions via selected intermediates into the desired fuel components. The pathways represented in Figure 13 form only a small group of the thousands of combinations possible to transform lignocellulosic biomass into fuel molecules.

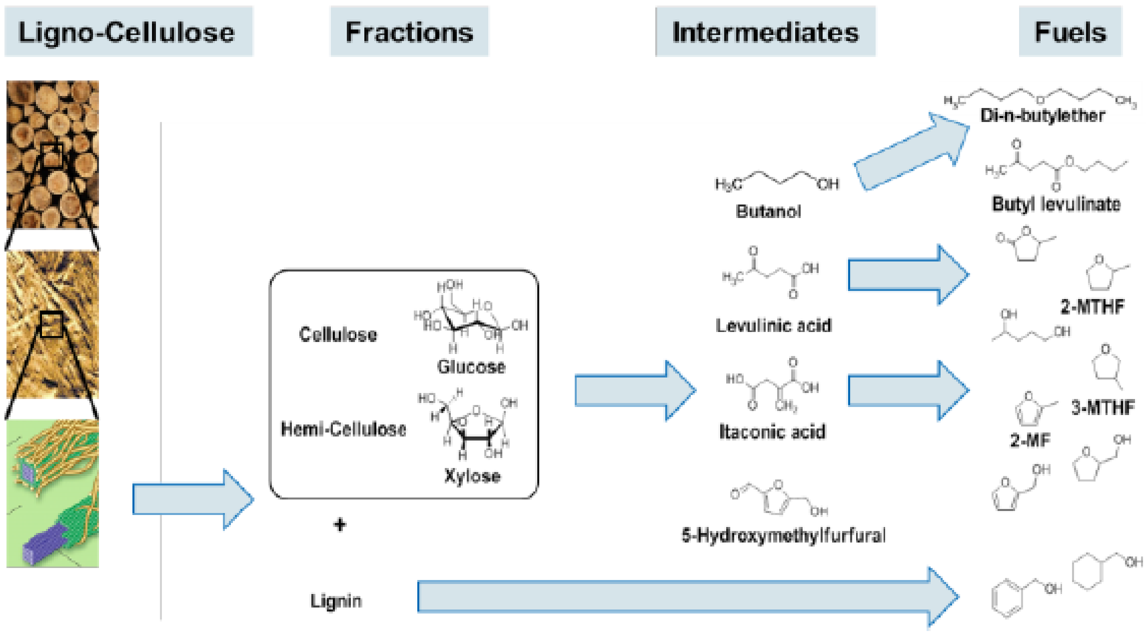


Figure 13. Possible production pathways for tailor-made fuels. Source [2.9]

According to the pathway shown by Figure 13, three molecules, which meet the requirements for clean diesel combustion, have been derived:

- 2-methyl tetrahydrofuran (2-MTHF)
- Di-n-butylether (DNBE)
- 1-Octanol

As it is publicly funded, (DFG – Deutsche Forschungsgemeinschaft) the Cluster of Excellence can be considered a fundamental research project. The scales of TMFB production at the moment do not exceed laboratory to small pilot plant scale. Nevertheless, the fuel design process as it has been developed within the cluster as strong unifier between fundamental natural sciences (chemistry & biology) and applied engineering research (process and chemical engineering & mechanical engineering) has to be considered as valuable method for future fuel development activities.

Co-optimisation of fuels and engines (Co-Optima). The U.S. Department of Energy (DOE) Co-Optimisation of Fuels & Engines (Co-Optima) initiative was created in 2016 and brings together scientists, from nine national laboratories (e.g. Argonne, Lawrence Livermore, Oak Ridge and Sandia national laboratories, plus the National Renewable Energy Laboratory); with more than twenty university and industry partners to investigate fuels and engines as dynamic design variables that can work together to boost efficiency and performance, while minimizing emissions. Applications include the entire on-road fleet, from light-duty (LD) passenger cars to heavy-duty (HD) freight trucks. Research is mainly focused on identifying blendstocks that can be added to conventional liquid fuels to tailor the fuel properties. Considered blendstocks can be produced from a wide variety of resources, including non-food biomass such as forestry and agricultural waste. Research explores options that pair these blendstocks with combustion solutions including:

- Turbocharged (or "boosted') spark-ignition (SI)
- Mixing-controlled compression ignition (MCCI) for medium-duty (MD) and HD trucks
- Advanced compression ignition (ACI) for the full range of vehicle classes targeting 60% brake thermal efficiency.

The Co-Optima approach starts by establishing compounds properties and molecular structure relationships. The most interesting compounds follow a retrosynthetic analysis leading to biofuel process development. Finally, experimental and theoretical developments are performed, related to the fuel-air mixture preparation (e.g. sprays) and combustion (e.g. auto-ignition behaviour or soot formation).

In 2018, the Co-Optima project completed the research on fuels for SI engines. It developed a merit function which proved that Research Octane Number (RON), octane sensitivity (S), and heat of vaporization (HOV) are the fuel properties with the greatest impact on boosted SI engine efficiency, see Figure 14. The project then identified ten blendstocks from four chemical families (alcohols, olefins, furans and ketones) with the greatest potential to increase boosted SI efficiency.

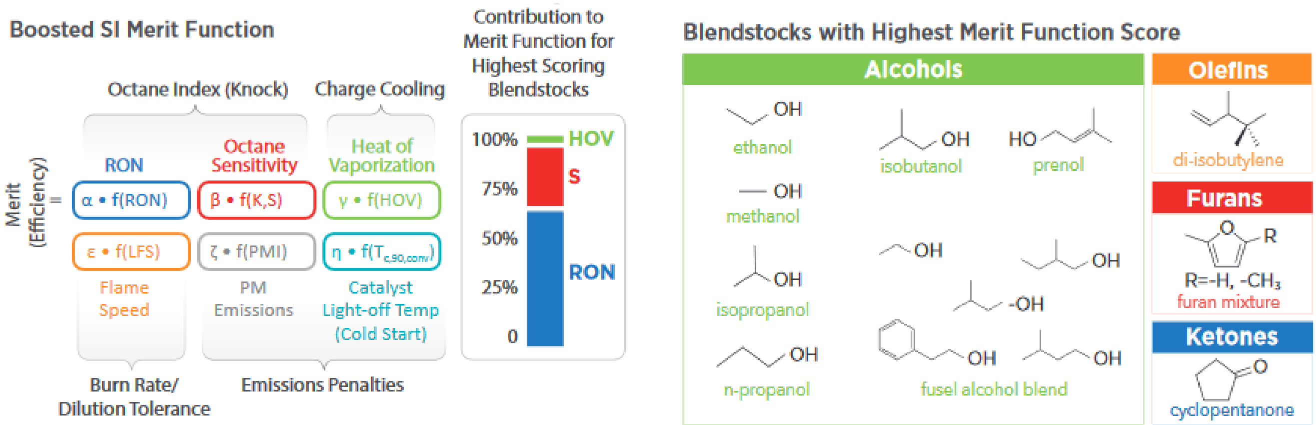


Figure 14. Fuel Merit Functions

The research on fuels for CI (Diesel) engines is still on-going. Thousands of mixtures and molecules were screened via fuel property experimental or *in silico* tests (thousands in silico), comprising a wide range of hydrocarbon and oxygenate chemistries. For instance, all candidates offer a Cetane Number greater than 40, an energy content (LHV) greater than 28MJ/kg, GHG emissions reduced by at least 60% on a well-to-wheel basis compared to a fossil reference etc. At this stage, as can be seen in Figure 15, five blendstocks were identified and met these criteria with no adoption barriers (upper left), and seven others have the potential to reduce emissions with some adoption barriers (upper right). Eight other blendstocks are still undergoing evaluation regarding their technical-economical assessment (TEA) and their life-cycle assessment (LCA) (lower).

The evaluation of the blendstocks' physical-chemical properties has revealed performance advantages for some ethers, esters and hydrocarbons, as illustrated in Figure 16 below. The blendstocks of interest were also evaluated regarding their technology readiness level (how far along is the blendstock on the path to commercialization and is it scalable?), their economic viability (what is it going to cost to produce and are the economics favourable?) and their environmental impact (what will be the environmental impacts of blendstock production compared to fossil fuels?). The results given in Figure 17 show that many of blendstocks are at a relatively low TRL: there is still a lot of uncertainty regarding blending metrics, testing, and legal limits of these blendstocks. On a more positive note, the feedstock changes typically have little to no impact on the fuel production process. The economic viability metrics show mostly positive outcomes: Diesel via HTL of wet wastes and hydroxyalkanoate-based ether-esters offer the lowest potential target costs. Feedstock cost is mostly favourable and market competition is low for most pathways. Environmental impact metrics are more uneven: they show positive outcomes for fatty acid ethers and HTL pathways. Figure 18 shows that seven blendstock pathways show significant reduction in GHG emissions (> 60% compared to a fossil reference); sodium hydroxide and imported process electricity are major contributors to GHG emissions explaining the bad performance of long chain primary alcohols.

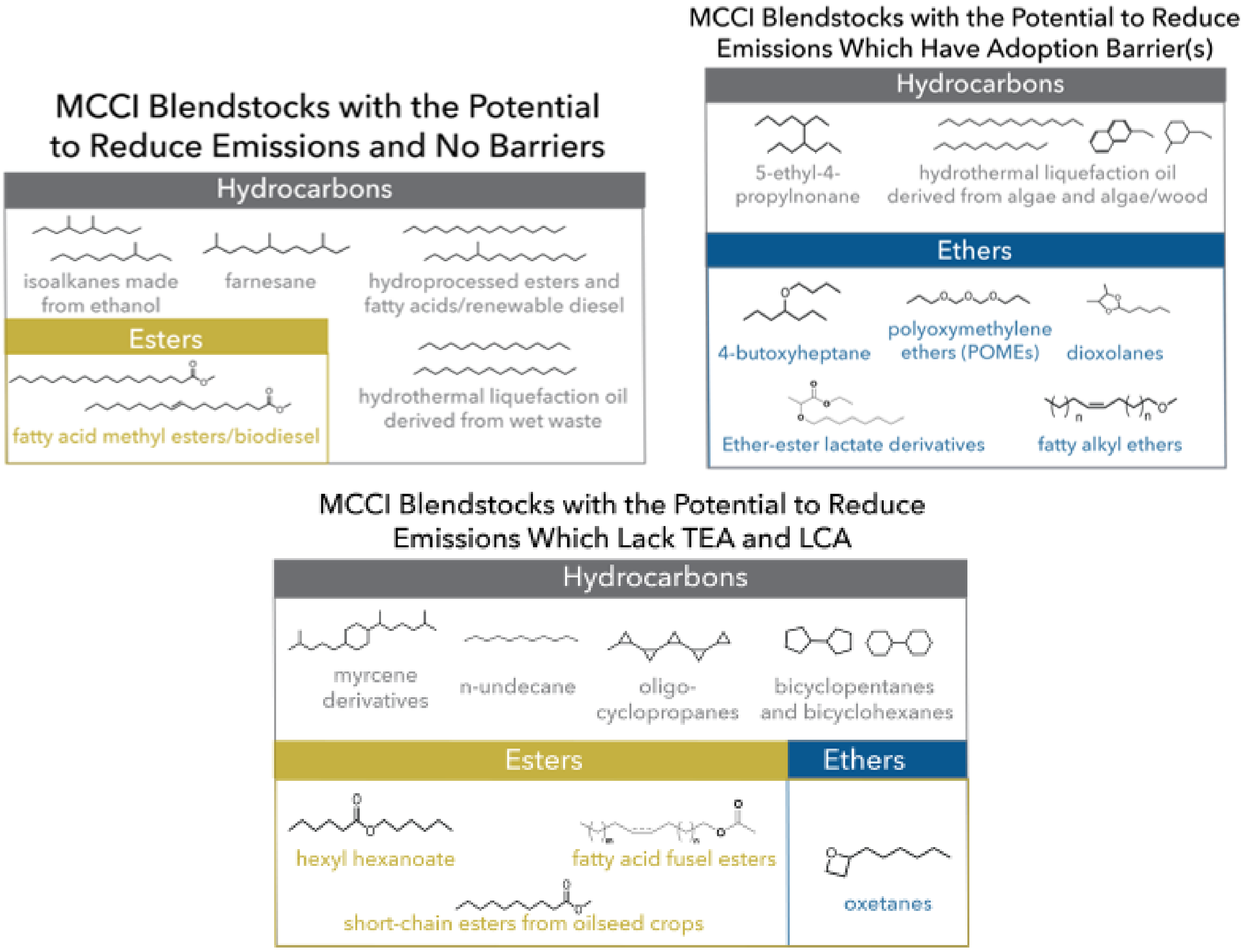


Figure 15. Blendstocks identified by the co-optima project, with a potential to reduce emissions

Tier Criteria	2-Nonanol	Farnesane	n-Undecane	Hexyl Hexanoate	Methyl Decanoate	Butylal	Renewable diesel	Soy biodiesel	5-ethyl-4-propyl-nonane	4-Butoxyheptane	4,5-deimethyl-2-(pentan-3-yl)-1,3-dioxalane	2-(heptan-3-yl)-4,5-dimethyl-1,3-dioxolane	4,5-deimethyl-2-pentyl-1,3-dioxolane	2-heptyl-4,5-diemthyl-1,3-dioxolane	Dipentyl ether
Cetane	40	59	71	40	52	70	80	52	48	80	45	64	48	69	111
Flash Pt (°C)	96	101	65	99	111	62	>52	>93	62	64	54	58	70	80	57
Melting Pt (°C)	-36	-73	-26	-55	-18	-58	-7	-1	<-80	<-80	<-100	<-100	<-100	<-100	-69
Water Sol (g/L)	0.5*	<0.1*	0.04	<0.1	<0.1	<0.1*	<0.1	<0.1	BDL	0.02	<0.04	<0.04	<0.04	<0.04	0.03
LHV (MJ/kg)	32	34	33	35	30	28	34	33	44	39	33	34	33	34	31
YSI	47	110	65	67	50	48	N/A	N/A	100	58	58	69	49	63	44
	Prior to Fuel Property Prediction								Utilizes Fuel Property Prediction						

* Indicates predicted fuel property value
BDL = below detectable limit

Figure 16. Physical-chemical properties of the blendstocks identified by the Co-Optima project (colour code: green: exceeds criteria; blue: meets criteria; orange: barriers exist)

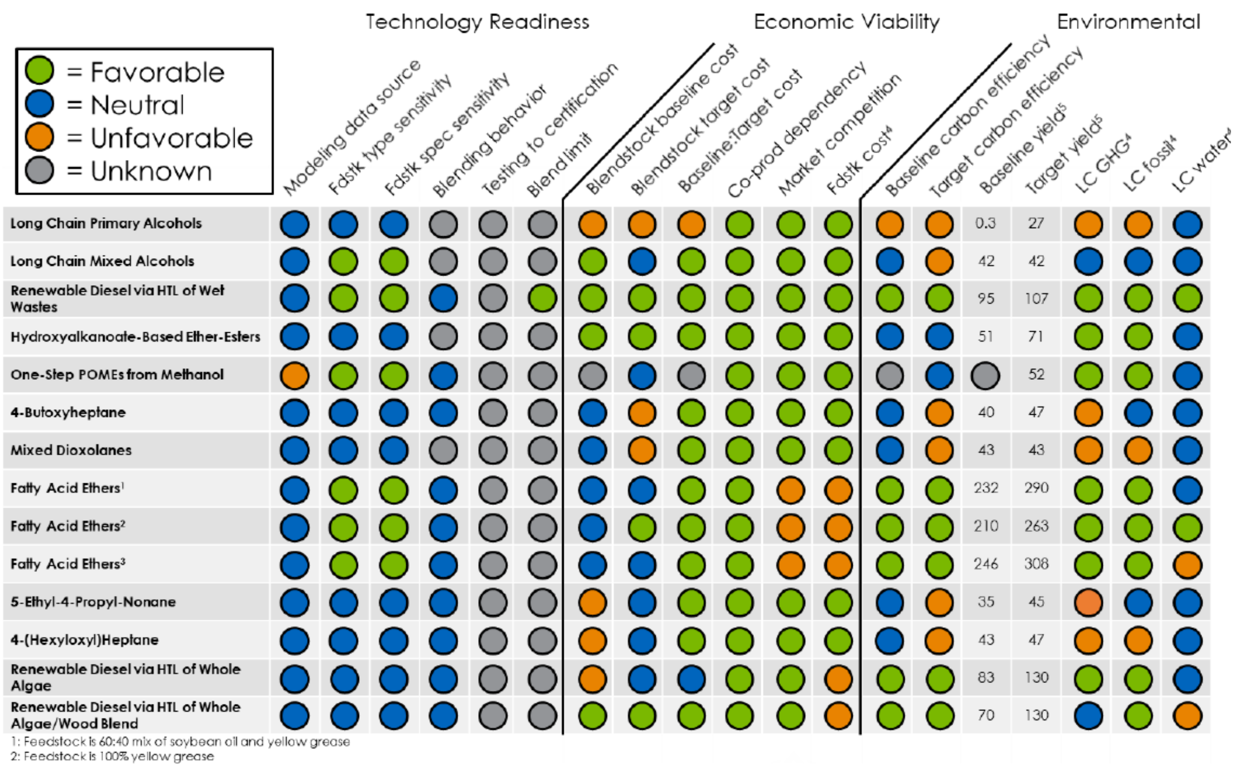


Figure 17. Techno-economic properties of the blendstocks identified by the Co-Optima project

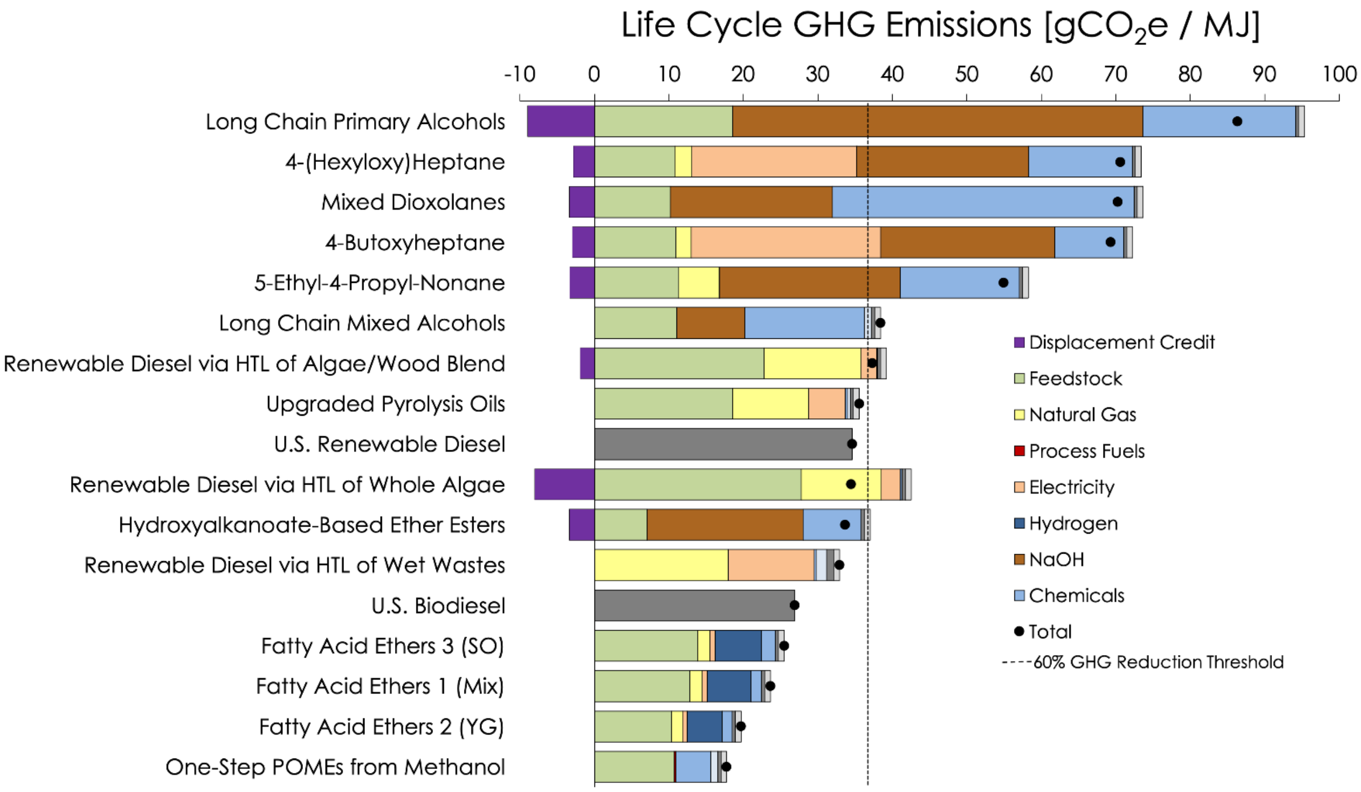


Figure 18. Life Cycle GHG emissions of the blendstocks identified by the Co-Optima project

Summary of the advanced biofuels production pathways (Figure 19) and their associated technology readiness level (TRL), Figure 20.

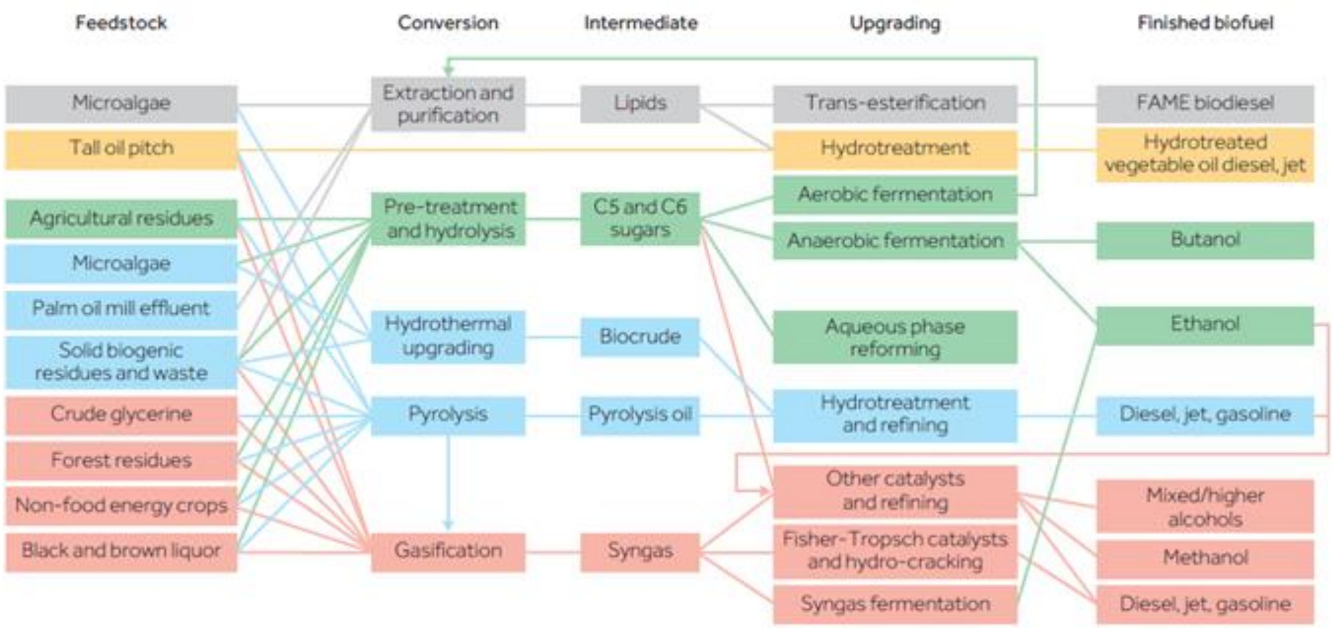


Figure 19. Advanced bio-fuel pathways. Source [2.10]

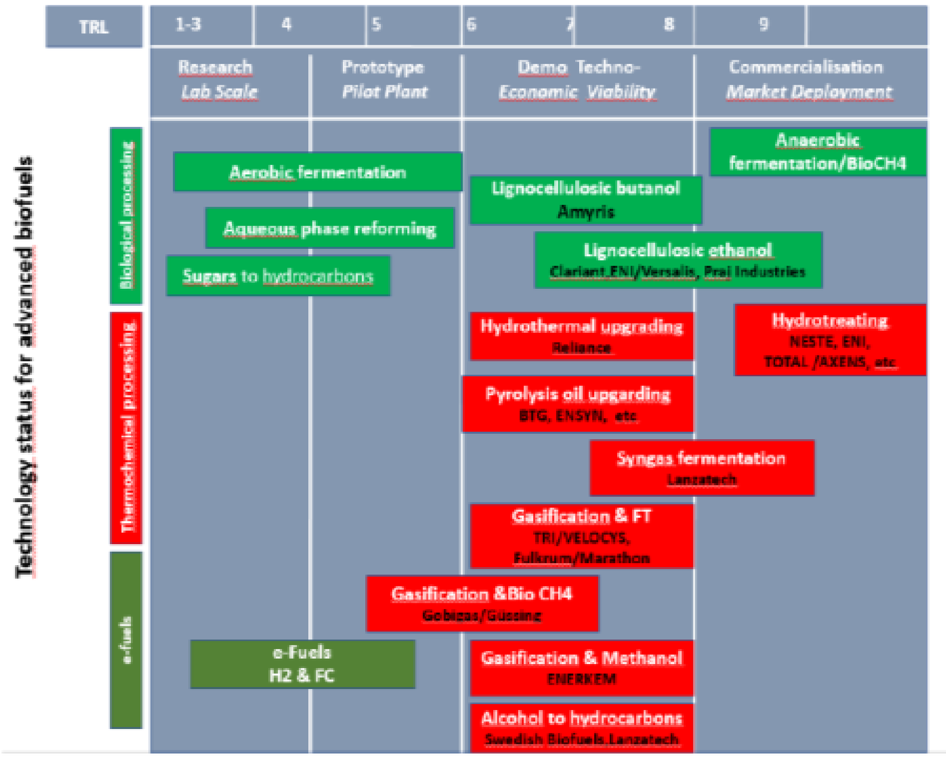


Figure 20. Advanced Fuels Conversion Technologies. Sources [2.10 & 2.11]

Potential primary use of biofuels (Table 2).

Table 2. Potential primary uses of biofuels

	Biofuels	Passenger Cars	Heavy Duty	Maritime	Aviation	Other sectors (not transport)
Gas	Biomethane	X	XX	XX		XXX
Liquids	FAME	XXX	XXX			
	HVO / HEFA	XXX	XXX	X	XXX	
	Ethanol / alcohols	XXX	X	X		
	Synthetic Fuel (Gasification + FT, pyrolysis, HTL, etc)	XXX	XXX	XXX	XXX	

(no 'X' = no envisaged potential).
Green = compatible use; blue = moderate potential; yellow = uncertain/limited role. 'Other sectors' include industry, building and power

2.2.1.2 Fuels from power-to-liquid

Fuels from power-to-liquids (or e-fuels) are synthetic fuels, resulting from the combination hydrogen produced by the electrolysis of water with renewable electricity and CO_2 captured either from a concentrated source (e.g. flue gases from an industrial site) or from the air (via direct air capture, DAC). The Tables 3 and 4 summarise the potential primary uses of e-fuels across different transport segments, and a qualitative overview of lower heating value, storability, infrastructure and powertrain development (Table 4).

Table 3. Potential primary uses of e-fuels

	E-fuels	Passenger Cars	Heavy Duty	Maritime	Aviation	Other sectors (not transport)
Gas	e-Methane (CH_4)	X	XX	XX		XXX
	e-Hydrogen (H_2)	XX	XX	X	X	X
Liquids	e-Ammonia (NH_3)		X	XXX		
	e-Methanol (CH_3OH)	XX	X	X		
	e-DME / e-OME	X	XX	XX		
	e-Gasoline	X				
	e-Diesel	X	XXX	XX		
	e-Jet				XXX	

Xs as an initial estimate of the potential role of different e-fuels in transport segments (no 'X' = no envisaged potential).
Green = compatible use; blue = moderate potential; yellow = uncertain/limited role. 'Other sectors' include industry, building and power

Table 4. Qualitative overview of e-fuels. Source [2.12][23]

	E-FUELS	LOWER HEATING VALUE (LHV), MJ/kg / MJ/litre	STORAGE	ADDITIONAL INFRASTRUCTURE	POWERTRAIN DEVELOPMENT
Gas	e-methane	46.6 / 0.04	Medium[a]	No	No
	e-hydrogen	120 / 0.01	Difficult	Yes	No[b]
Liquid	e-ammonia	18.6 / 14.1	Easy	Yes	Yes
	e-methanol	19.9 / 15.8	Easy	No	Yes
	e-DME	28.4 / 19.0	Easy	Yes	Yes
	e-OME	19.2 / 20.5	Easy	Yes	Yes
	e-gasoline[c]	41.5 / 31.0	Easy	No	No
	e-diesel[c]	44.0 / 34.3	Easy	No	No
	e-jet[c]	44.1 / 33.3	Easy	No	No

[a] E-methane could use most of the existing logistics, including transportation, storage and distribution systems of natural gas, but storability is not as easy as for liquid molecules.
[b] FCEVs (fuel cell electric vehicles) are commercially available, but are limited in number and it is difficult to assess whether they will become a mainstream option.
[c] Properties refer to conventional fossil fuels due to lack of publicly available properties for e-fuels (properties are expected to be similar although more research is needed).
Green = positive characteristics; yellow = negative characteristics.

Hydrogen (as an unavoidable first step)

E-hydrogen is used as a feedstock for producing e-fuels. It can also be a final product in itself. It is produced by electrolysis from water. Different electrolysis technologies can be used for producing hydrogen. These include low-temperature (50 to 80°C) technologies such as an alkaline electrolysis cell (AEC), proton exchange membrane cell (PEMC) or high-temperature (700 to 1,000°C) processes using a solid-oxide electrolysis cell (SOEC). The efficiency of electrolysis is today between 60-70% and has the perspective to reach 70-75% for alkaline and PEM electrolysis and 80% for high temperature electrolysis in the midterm. Additionally, prices for these devices are forecast to drop significantly as installations all over the world are taking up speed.

[23] https://www.concawe.eu/wp-content/uploads/Rpt_19-14.pdf

As a massive production of green hydrogen (at least 40GW renewable hydrogen electrolysers and the production of 10 million tonnes of renewable hydrogen by 2030[25]) is foreseen in the next two decades, also road transport could benefit from this transfer. In road transport (passenger cars and trucks), hydrogen can be used in fuel cells and for heavy and large application also the use in combustion engines could play a significant role.

CO_2 capture

The production of e-fuels requires CO_2 (except e-ammonia), which can be obtained from various sources including biomass combustion, industrial processes (e.g. flue gases from fossil oil combustion), biogenic CO_2, and CO_2 captured directly from the air.

E-fuels related technologies

E-fuels production routes, see Figure 21, consist of e-hydrogen reacting with captured CO_2, followed by different conversion routes according to the final e-fuel: methanol synthesis for e-methanol, e-DME, e-OME or e-liquid hydrocarbons; or the reverse water-gas shift (RWGS) reaction to produce syngas + Fischer-Tropsch synthesis to produce e-liquid hydrocarbons, such as e-gasoline or e-diesel; E-ammonia does not require CO_2 and is synthesised from e-hydrogen through a Haber-Bosch reaction.

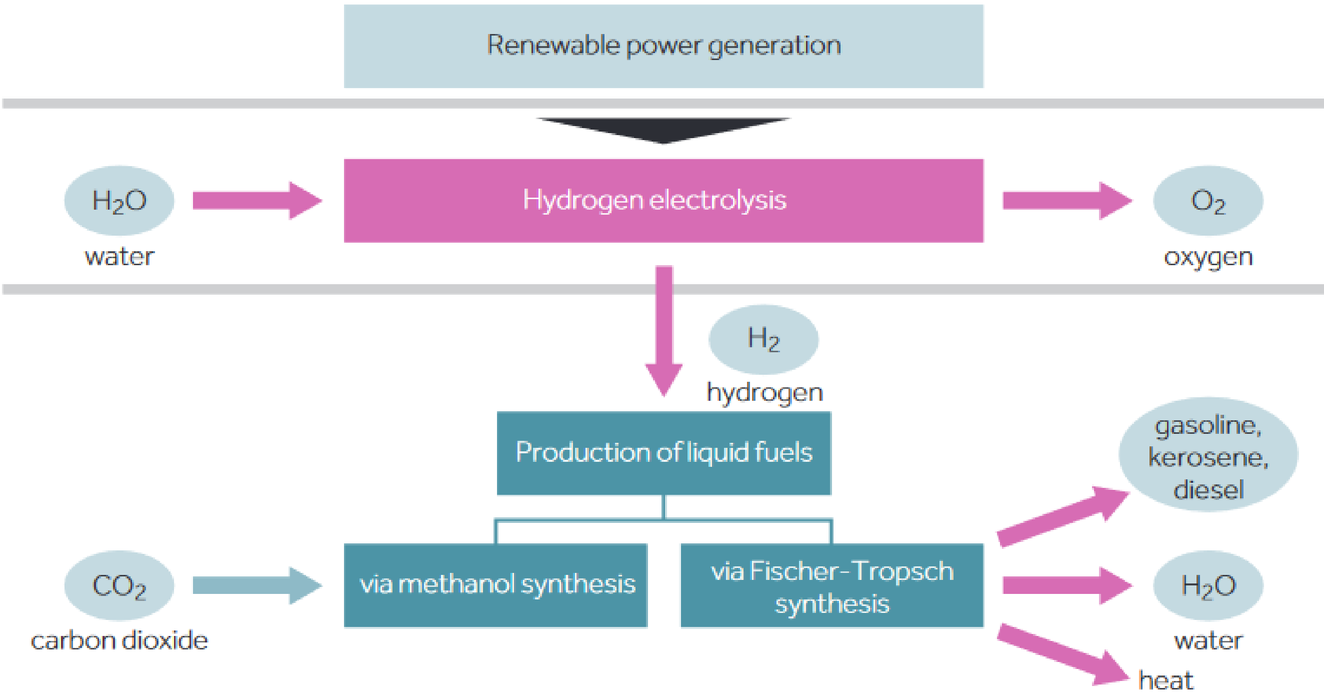


Figure 21. E-fuels production routes. Sources [2.13 & 2.14]

E-Methanol and its derivatives:

- Methanol (as pure and as drop in component)
- Dimethyl Ether (DME) and OxyMethylene dimethyl Ether (OME)
- Synthetic gasoline (through Methanol to Gasoline process) (EN228)
- MTBE
- Methanol to Kerosene / Diesel

[25] COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS: A hydrogen strategy for a climate-neutral Europe.

e-Methanol is a simple to generate base chemical which is built from e-Hydrogen and circular (re-used from carbon capture, biomass based or air captured) CO_2. Methanol production from these components is, generally speaking, state of the art and methanol is in the moment (mainly from fossil sources: natural gas and coal) produced and shipped at around 90Gt scale p.a. There are already larger scale demonstration plants on renewable methanol such as CRI in Iceland. Furthermore, there are seven ships for methanol transport running on methanol already in operation.

The production of methanol from hydrogen and CO_2 can reach efficiencies of up to 85-90%, which is much higher than the liquefaction of hydrogen with an efficiency of roughly 70-75%.

Besides the use of neat methanol (M100), methanol is used as blend component (up to 3% in EN228 gasoline, in Europe, as regulated by Directive 200/30/EC) and higher blend rates are and have been tested around the world.

Furthermore, methanol has some efficient ways to generate derivatives such as DME and synthetic gasoline or kerosene. DME is a rather easy to use liquid gas (such as LPG) for CI engines. Synthetic gasoline, e.g. generated by the Methanol to Gasoline process (which is existing in large scale demonstration and commercial size), is able to fulfil the EN228 specification and, therefore, can also help to decarbonize the existing vehicle fleet as pure or drop-in component.

Additionally, there are other efficient production routes through Ethylene which can enable Kerosene or more Diesel-like products based on Methanol as a feedstock.

Fischer-Tropsch products (with focus on paraffinic Diesel)
Liquid e-fuels production via the Fischer-Tropsch reaction (same process as for the BtL related technology) results in a mix of fuel gases, naphtha[26]/gasoline, kerosene, diesel/gas oil, base oil and waxes. Figure 22 shows a typical distribution of total e-crude product leaving the Fischer-Tropsch reactors before they are separated or converted by further processing steps. The product distribution is a function of many factors, including the catalyst composition (e.g. iron versus cobalt) and the operating conditions.

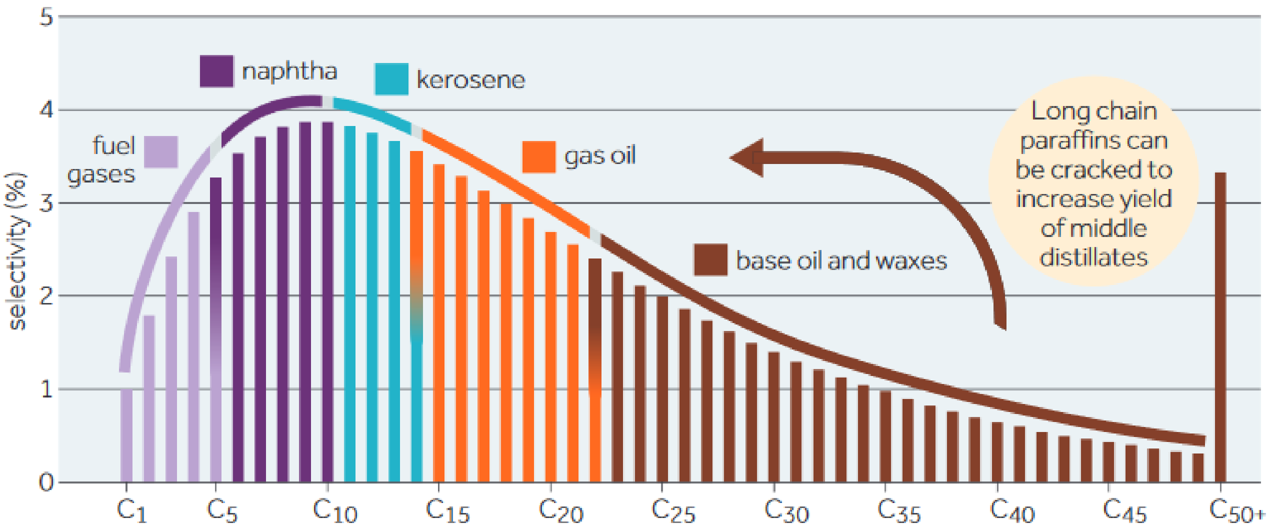


Figure 22. Fischer-Tropsch liquid e-fuel products. Source [2.15]

[26] Naphtha is a cut of hydrocarbons, mainly composed of alkanes and cyclo-alkanes in the C_5-C_{10} range. It can either be used directly in the gasoline pool (straight-run naphtha), be incorporated in the gasoline pool after going through further step of refining (e.g. isomerization or reforming) or be used as feedstock for the chemical industry.

The resulting 'e-crude' from the Fischer-Tropsch reaction, which can be a single stream or several separate streams, could be fed to a hydrocracking unit. The intermediate wax molecules are hydro-processed within a hydrocracker into shorter 'middle distillate' molecules, which are then purified by distillation into naphtha, kerosene and gas oil fractions. The mass balance to produce 1 litre of liquid e-fuel (~34MJ/litre) is 3.7–4.5 litres of water, 82–99MJ of energy (heat or) electricity[27] and 2.9–3.6kg of CO_2 (see Figure 23).

The Fischer-Tropsch products produced through this process have the advantage of being 'drop-in', which means that they immediately can be used with the existing infrastructure and the existing vehicles fleet. They also can reach GHG neutrality on a well-to-wheel basis if the electricity used is renewable (e.g. from wind turbines or solar panels) or carbon-free (e.g. from nuclear) and if the CO_2 is captured from the air or captured from flue gases, providing that the flue gases are considered as waste[28]. However, they have the drawback of being thermodynamically extremely inefficient: for instance, as illustrated in Figure 24, if one considers the production pathway using Direct Air Capture, the efficiency of e-fuels production is down to 35%. The efficiency drops even more, to roughly 10-12%, once the overall well-to-wheel pathway is taken into account, given that these fuels are to be used in internal combustion engines having a limited efficiency as well.

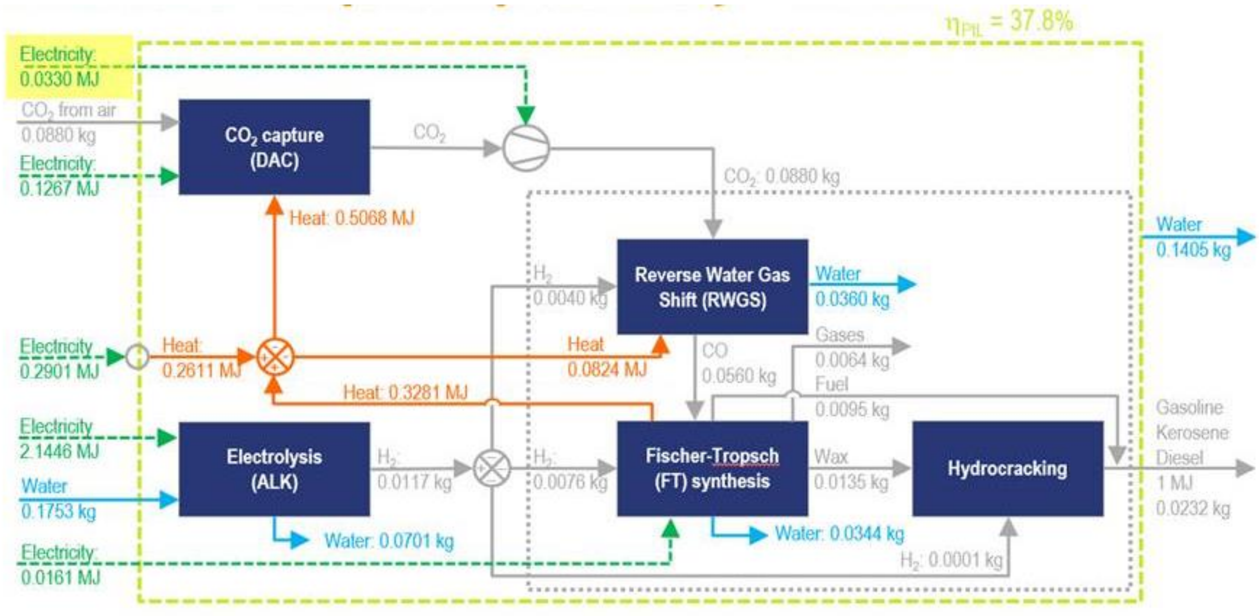


Figure 23. Resources required for liquid e-fuel production (e-Fischer-Tropsch pathway)[29]

[27] This includes the energy required for CO_2 capture. This does not include the energy needed for water desalination (if required), knowing that it is a minor contribution to the energy needed (< 1%).
[28] Depending on the accounting mechanism, the CO_2 captured from the flue gases can either be subtracted from the emissions of the process which created the flue gases, or from the process which utilizes it (to produce e-fuels in this instance), but it cannot be both. Under this provision, as flue gases are considered as a waste, it is assumed that the CO_2 emissions are subtracted from the well-to-wheel analysis of e-fuels, which allows them to reach GHG neutrality.
[29] CONCAWE E-fuels techno-economic assessment (to be published).

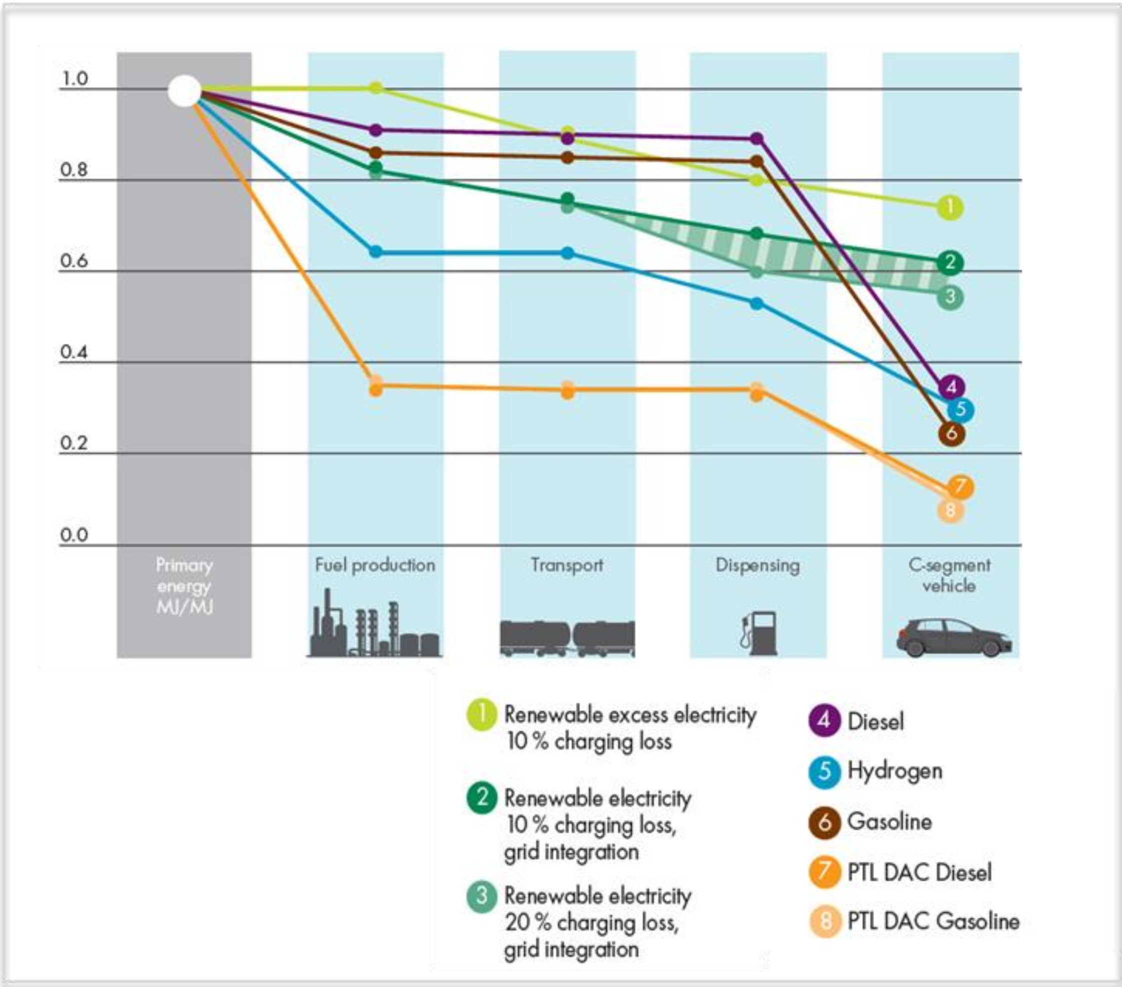


Figure 24. The Well-To-Wheel efficiency of various fuel and powertrain combinations. Source [2.15]

E-Olefin to Alcohol

Olefins are part of the Fischer-Tropsch product mixture and are quite valuable base chemicals. They are also used for production of synthetic base oils and the shorter chain paraffins can also be used to generate alcohols through hydroformylation. These alcohols are in generally capable of being used as blend components in high amounts to gasoline (C_2-C_4) and Diesel (C_5-C_{11}). Such blend components have in general a positive impact on the combustion and emission behaviour of the engines (such as improved NOx/PM trade-off[30]) and can also help to bring paraffinic products closer to the existing fuels standards (especially EN590).

Besides the processes and fuels described above, which are already today foreseeable and most of them highly probably candidates to transform the world's energy system to GHG neutrality, also new routes such as direct H_2O and CO_2 co-electrolyzers and others are being developed and have the potential to significantly increase the efficiencies of the chemical energy storage and fuel production in the midterm.

2.2.2 Liquid fuels mix scenarios

The future fuel mix in 2050 is expected to be a combination of different feedstocks and conversion technologies, producing different types of either **drop-in fuels** (with similar characteristics to the

[30] Mixing-Controlled Compression Ignition (MCCI) Fuel Property Effects, NREL, 2020.

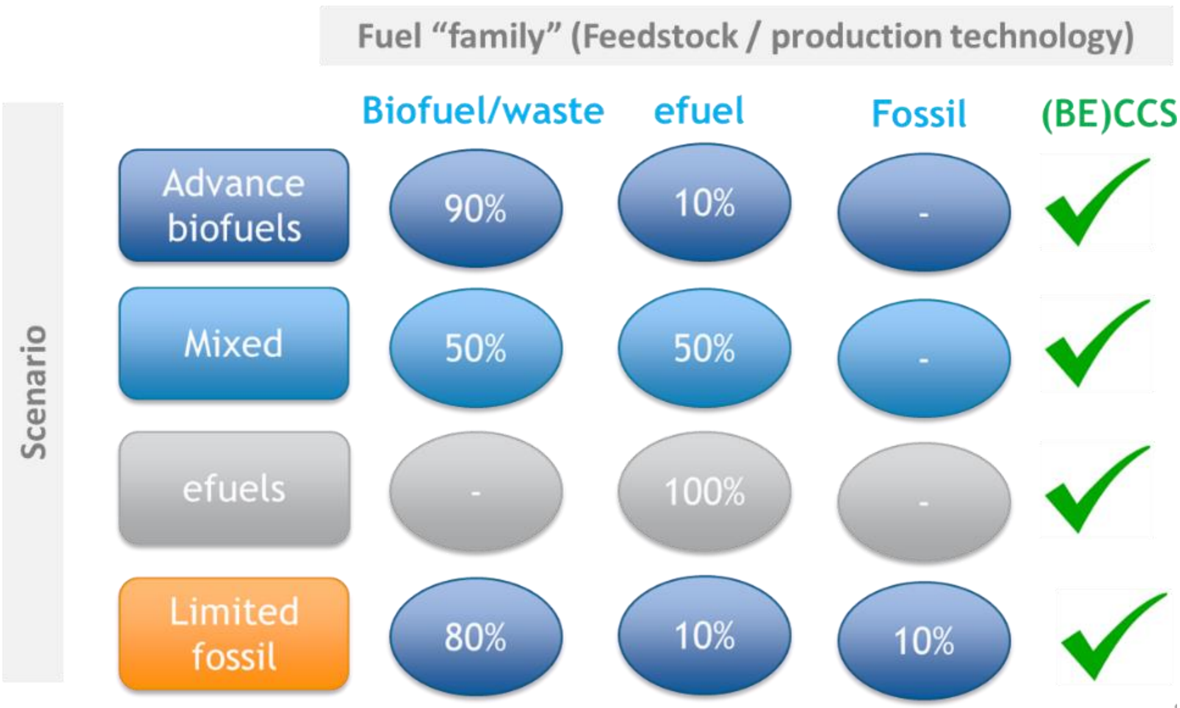
conventional fossil based gasoline/diesel benefiting from total compatibility with engines and existing infrastructure) or **blending components** limited by future blending walls (difficult to foresee at this stage).

Within ERTRAC Roadmap 2050, it is important to note that:

- Total **demand** for fuels (as energy carriers) is defined by the fleet scenarios described in Chapter 5: it will be determined by the share and fuel efficiency of internal combustion engines powered vehicles (including HEV and PHEV) in 2050
- Within each fleet scenario, the fuel mix scenarios:
    - explore different combination of fuel pathways (from different feedstock & production routes) with focus on drop-in fuel routes (**Well-to-Tank**)
    - assess their implications in terms of, amongst others, GHG emission savings, feedstock and electricity demand
    - reach Well-to-Wheel CO_{2eq} (i.e. GHG) neutrality. Therefore, the additional negative emissions requirements are estimated to compensate the potential remaining CO_2eq emissions.

Depending on the scenario, negative emissions could be achieved by either coupling Carbon Capture and Storage with Biofuel production plants (BECCS) or combining Direct Air Capture (DAC) technologies where the captured CO_2 is permanently stored underground).

Due to the complexity and uncertainty around the 2050 future fuel mix, four fuel mix scenarios have been explored in this report, summarized as follows, see Figure 25.



(BECCS refers to biofuel production routes coupled with CCS (allowing negative emissions)).

Figure 25. Fuel share scenarios (2050)

Note on the scenarios:

- **Advanced biofuels**: this scenario considers that 90% of the production of fuels in 2050 will be composed of **advanced biofuels** from either lignocellulosic material, residues or waste (no food/crop-based fuels included in the assessment). The remaining 10% of the demand will be satisfied by e-fuels.
- **Mixed**: A mix scenario increases the role of e-fuels and explores a case with an equal share of both advanced biofuels and e-fuels to meet fuel demand.

- **E-fuels:** This scenario pushes the limits for e-fuel deployment in transport (100%). For this scenario, as no biofuels are produced, direct air capture plants (DAC) will be the technology used to create negative emissions.
- **Limited fossil:** This scenario builds on the *advanced biofuel* one, where the majority of the fuel demand is satisfied through advanced biofuels (80%) by considering some remaining fossil derived fuels in the fuel mix (10%).

2.2.3 Environmental assessment

In the JEC Well-To-Tank (WTT) v5 report, the complexity of the future alternative fuel mix is clearly represented by more than 250 different fuel pathways modelled as combination of different feedstocks and conversion technologies, all of them at different stages of technology and commercial readiness levels. For the purpose of this report:

- Some JEC WTT v5 routes have been selected as **indicative values** representing the different big clusters of the type fuels mentioned above.
  - The JEC Well-To-Tank data, used as the basis for the ERTRAC assessment, includes **producing, transporting, manufacturing and distributing to the final consumer (retail station) a number of fuels suitable for road transport powertrains** (Figure 26).
  - The fuel related pathways proposed in this section should not be taken as ERTRAC's view on one single feedstock/pathway but as **illustrative examples** of future carbon intensities of different fuels which could become available in the market[31].

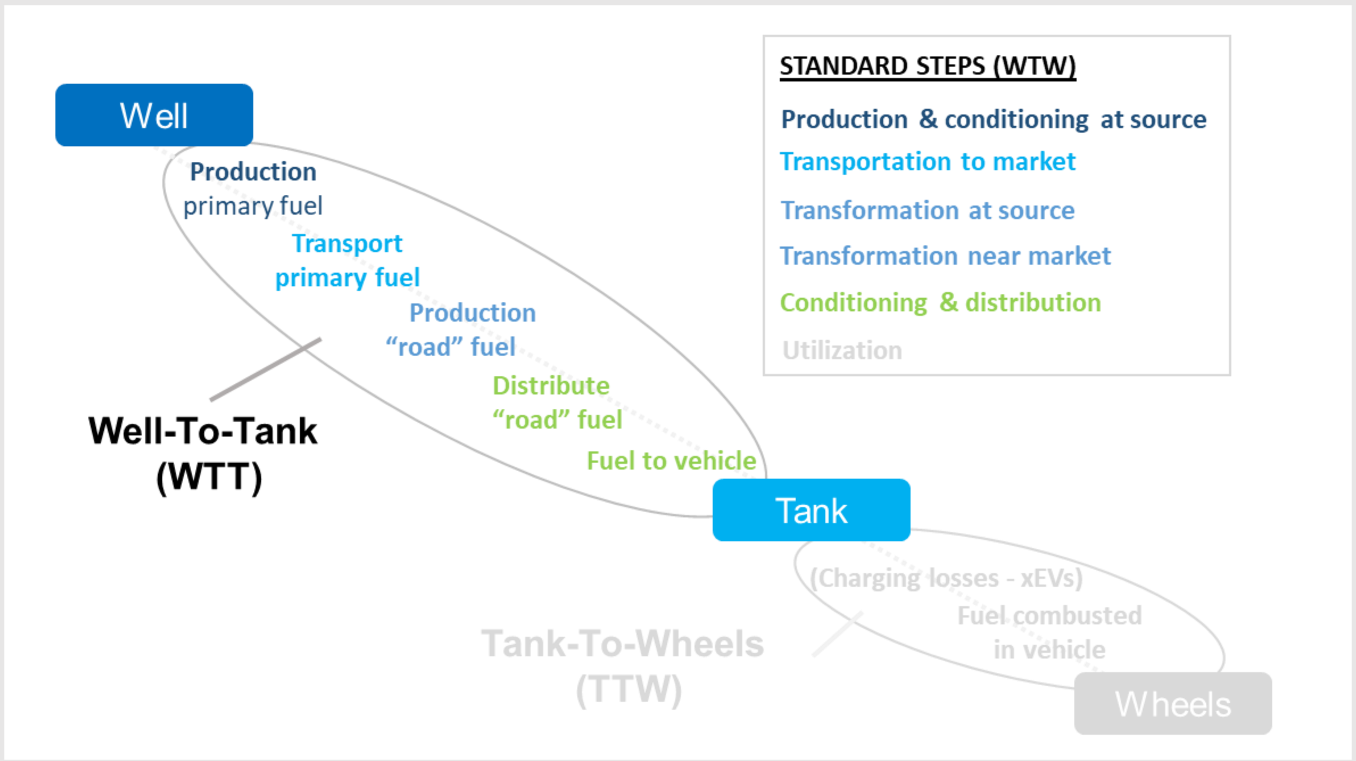


Figure 26. Scope of the JEC Well-To-Tank analysis v5 (WTT)

[31] For example, the fact that only Diesel pathways were modelled for the sake of simplification does not mean that gasoline pathways will not exist.

- Building on the JEC WTT v5 data, the following major modifications have been conducted to derive ERTRAC 2050 values:
  - **Timeframe**: extension towards 2050 pushing the limits for process electrification
    As the JEC WTT v5 values refer to the 2030 timeframe, the ERTRAC 2050 figures:
    - Increase the level of electrification in the conversion processes (replacing thermal energy when possible[33]).
      Heat and steam for process chemicals have also been replaced by electricity sources.
    - Assess two different 2050 electricity scenarios – as defined in Section 2.1.3:
      - The **1.5TECH** scenario as the **reference case** (with a carbon intensity of 5.2gCO_{2eq}/kWh)
      - One 100% renewable scenario with no residual CO_{2eq} emissions in the generation phase, as a sensitivity.

      Note. For the e-fuel production process, 100% renewable electricity will be assumed in both scenarios. A sensitivity on the production of e-fuels with electricity from the grid (carbon intensity as in the 1.5TECH scenario) will also be explored.
    - Replace fossil fuels usage by biofuels in some processes (e.g. collection, chopping) where limited electrification is foreseen.
  - JEC *State-of-the-art technology* as average energy consumption in 2050.
    No additional energy efficiency improvement versus the JEC WTT v5 figures has been considered assuming that average plants in 2050 would expend a similar amount of energy per MJ of fuel produced than the state-of-the-art technologies modelled in JEC (with the only exception of the use of highly efficient turbines when required).
  - Transport:
    - Out of Europe: the CO_{2eq} emissions due to transport of feedstocks to Europe will be significantly reduced according to some on-going international initiative, e.g. GHG emissions related to maritime transport reduced by 50%, following IMO's long term strategy.
    - Logistics/Intra-Europe: All the emissions from the domestic transport are already included within the fleet emissions (so deleted from the JEC fuel transport to avoid duplication).
  - As a proxy, N_2O and CH_4 emissions linked to the biofuel production processes are kept as in JEC WTT v5.

The following table summarizes the values used for the ERTRAC 2050 Roadmap, as illustrative examples of liquid diesel/gasoline-like fuels, based on the considerations described above:

[33] Totally within Europe and partially in the upstream steps – when produced out of Europe

Advanced biofuels

Table 5. Advanced biodiesel figures to ERTRAC model (WTT, 2050)

Diesel-like	**Wood residue**			**Wood via black liquor**			**Waste**		
Feedstock/ Process	**Waste wood to gasification/synthesis plant (Fischer-Tropsch)[i]**			**Waste wood via black liquor[i]**			**Waste cooking oil to HVO[ii]**		
Timeframe	2030 JEC (WWS D1a)	2050 ERTRAC 1.5TECH (Base case)	2050 ERTRAC 100% RES (Sensitivity)	2030 JEC (BLS D1a)	2050 ERTRAC 1.5TECH (Base case)	2050 ERTRAC 100% RES (Sensitivity)	2030 JEC (WOH Y1a)	2050 ERTRAC 1.5TECH (Base case)	2050 ERTRAC 100% RES (Sensitivity)
GHG (gCO_{2eq} /MJ_{fuel})	9.7	0.06	0.05	5.3	0.05	0.04	11.1	0.34	0.09
Energy expended (MJ/MJ_{fuel})	1.21	1.16	1.15	0.11	0.05	0.05	0.16	0.20	0.14
Share in the 2050 biofuel mix - ERTRAC[iii]	-	80%		-	10%		-	10%	

Notes:

(i) Including forest residue collection, seasoning, chipping, gasification or synthesis plant and dispensing at retail site.

(ii) Includes HVO production and dispensing at retail site.

The 2050 ERTRAC roadmap does not attempt to estimate the potential sustainable availability of the biomass/waste required for the realisation of the different scenarios explored. As a reference for the discussion and according to the ENSPRESO REPORT [JRC 2019[34]], the total sustainable bioenergy supply potential at European level (2050) could range from to ~190Mtoe/y (<> 8,000PJ) up to 500Mtoe/y (~21,000PJ) with the major share of the potential from agricultural/forestry biomass and a small proportion of waste-based biofuels in all the scenarios. Additional investigations will be needed to verify the sustainable potential with no biodiversity impact for transport, considering also the needs of other sectors (out of the scope of this report).

[34] https://www.sciencedirect.com/science/article/pii/S2211467X19300720?via%3Dihub

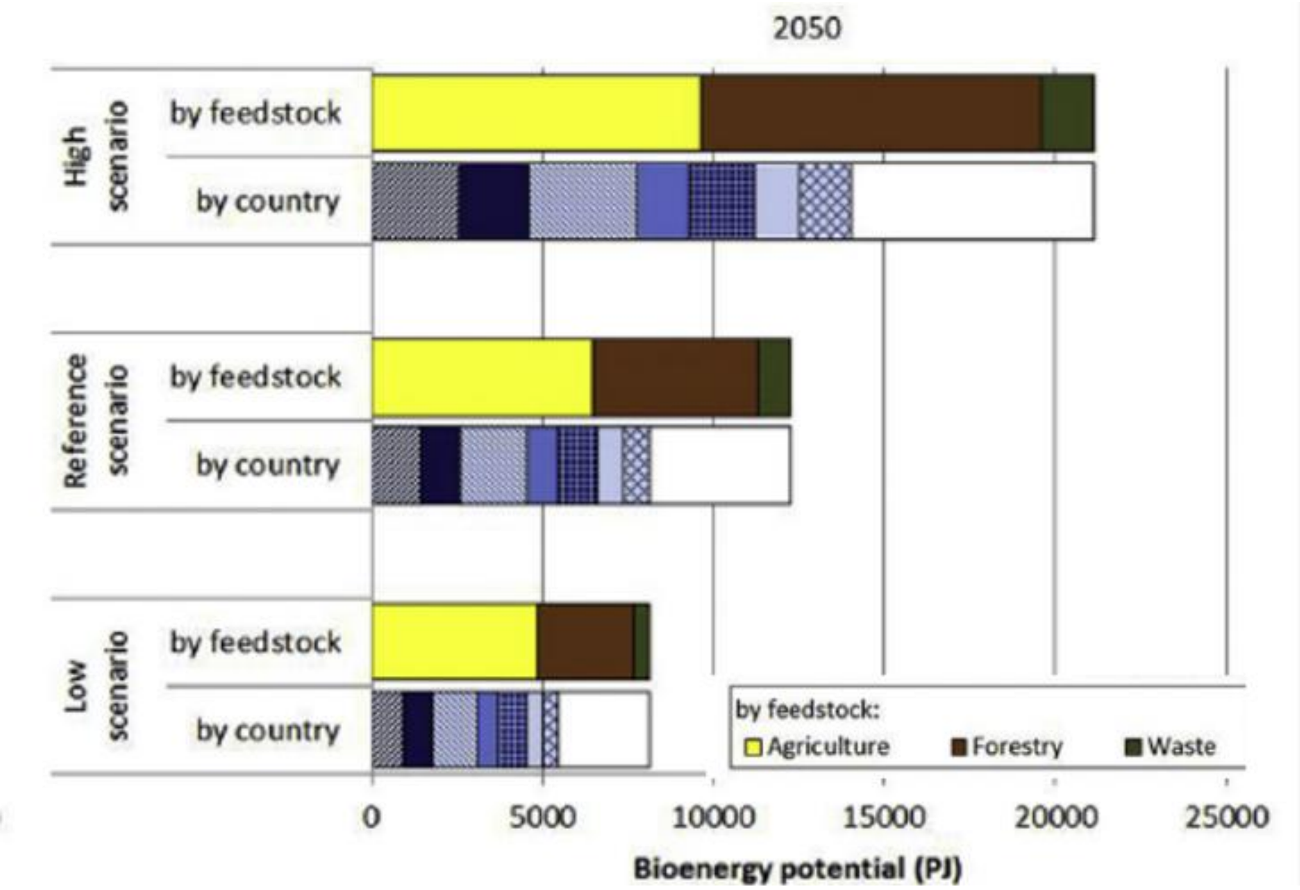


Figure 27. Bioenergy potential [ENSPRESO]

Table 6. 2050 values used for ERTRAC modelling purposes – Advanced liquid biofuel mix (WTT).

Liquid biofuel mix* (ERTRAC 2050)	ERTRAC 1.5TECH (Base case)	ERTRAC 100% RES (Sensitivity)
GHG (gCO_{2eq}/MJ)	0.086	0.053

*As a simplification, the values presented above are considered as a proxy for both gasoline and diesel-like fuels in 2050.

E-fuels

The e-fuel production pathways presented below have been defined based on the following considerations:

Table 7. E-fuels figures to ERTRAC model (WTT, 2050)

	e-Diesel								
Feedstock/ Process(i)	**H_2 from high temperature water electrolysis based on SOEC (100% RES) + Fischer-Tropsch route + CO_2 from flue gases (industrial site)**			**H_2 from high temperature water electrolysis based on SOEC (100% RES) + Fischer-Tropsch route + CO_2 from flue gases (biomass upgrading)**			**H_2 from high temperature water electrolysis based on SOEC (100% RES) + Fischer-Tropsch route + + CO_2 from Direct Air Capture (DAC)**		
Timeframe	2030 JEC (RES D2a)	2050 ERTRAC 100% RES (Base Case)	2050 ERTRAC 1.5 TECH (Sensitivity)	2030 JEC (RES D2b)	2050 ERTRAC 100% RES (Base Case)	2050 ERTRAC 1.5 TECH (Sensitivity)	2030 JEC (RES D2c)	2050 ERTRAC 100% RES (Base Case)	2050 ERTRAC 1.5 TECH (Sensitivity)
GHG (gCO_{2eq}/ MJ_{fuel})(ii)	0.73	0.08	3.8	0.73	0.08	3.2	0.73	0.08	4.2
Energy expended (MJ/MJ_{fuel})(iii)	1.5	1.5	2.53	1.1	1.1	1.94	1.8	1.8	2.92
Share in the 2050 biofuel mix - ERTRAC(iv)		12.5%			12.5%			75%	

Notes:

(i) Source of hydrogen: water electrolysis with 100% renewable electricity. For the production processes, 100% renewable electricity is also used as the main reference through either direct connection between electricity generation /production facilities or the purchase of Guarantees of Origin. A sensitivity on the use of the electricity mix is also explored (1.5TECH).

(ii) For the purpose of this exercise, CO_2 is considered as a waste and, in this sense, CO_2 burden free. Therefore, as in the JEC WTT v5, the GHG intensity values remain invariable regardless of the point of source.

(iii) The main difference between the pathways modelled is the energy requirement to capture CO_2 for e-fuel production which varies depending on the level of concentration of CO_2 in the flue gases or air.

(iii) In 2050, all sectors in the economy are deemed to have reduced their CO_2 emissions significantly. In the present study, 25% of the CO_2 is considered to come from flue gases (either from bioenergy or industrial processes) and 75% from direct Air Capture to satisfy the feedstock for e-fuel production at mass scale.

Table 8. 2050 values used for ERTRAC modelling purposes– Advanced liquid biofuel mix (WTT)

Liquid e-fuel mix(*) - (ERTRAC 2050)	**ERTRAC 100% RES**	**ERTRAC 1.5 TECH (Sensitivity)**
GHG (gCO_{2eq}/MJ)	0.08	4.0
Energy expended (MJ/MJ_{fuel})	1.7	2.7

*As a simplification, the values presented above are considered as a proxy for both gasoline and diesel-like fuels in 2050.

Fossil fuels

Despite the limited contribution of fossil fuels included in the ERTRAC fuel mix scenarios, the potential of these pathways towards 2050 has been investigated, both in terms of energy consumption and GHG emissions:

Table 9. Fossil fuels figures to ERTRAC model (WTT, 2050)

Diesel	**Oil based**			
Feedstock/Process	**Oil (EU mix) processed within the EU refining system(i)**	**Oil (EU mix) processed within the EU refining system + Carbon Capture**		
Timeframe	2030 (JEC COD1)	2030 JEC (COD1C)	2050 ERTRAC 1.5TECH (Base case)	2050 ERTRAC 100% RES (Sensitivity)
GHG (gCO_{2eq}/MJ_{fuel})	18.9	13.7	7.83 (iii)	7.82
Energy expended (MJ/MJ_{fuel})	0.26	0.32 (ii)	0.30	0.30

Notes:

(i) Crude oil from typical EU supply, transport by sea, refining in EU (marginal production), typical EU distribution and retail.

(ii) The addition of the Carbon Capture and Storage technology increases the energy requirement to produce a MJ of fuel.

(iii) Besides the general criteria behind the 2050 ERTRAC values, in this specific case, a ~40% reduction in the upstream value (crude oil extraction) has estimated as an average improvement ratio due to zero flaring and venting initiatives worldwide [ICAO seminar 2019[35]].

[35] M.S. Masdani, H.M. El-Houjeiri et al., Science, 361 (6405), 851-853.

Biofuel processes with Carbon Capture (BECCS) – Negative emissions

As mentioned earlier in the document, the number of biomass conversion facilities coupled with carbon capture and storage (CCS) solutions are explored in the ERTRAC study to compensate the residual GHG emissions in all scenarios when reaching GHG neutrality. As a proxy, a biofuel production pathway based on wood gasification have been used as the point of source for biogenic CO_2. A CCS scheme has been integrated within this fuel production pathway as detailed below:

Table 10. Figures for biofuel processes with Carbon Capture (BECCS) to ERTRAC model (WTT, 2050)

	Wood residue	
Feedstock/Process	Waste wood to gasification/synthesis plant + Carbon Capture and Storage	
Timeframe	2030 JEC (WWSD1aC)	2050 ERTRAC 1.5 TECH / 100%
GHG (gCO_{2eq}/ MJ_{fuel})	-105.1	-119.4
Energy expended (MJ/MJ_{fuel})	1.31	1.26

Besides this route, the Direct Air Capture technology has also been investigated. Due to the early stages of development of the technology, there is a big uncertainty around the energy consumption when developed at scale. Different sources show a range between 0.5 to 2.7MW.h electricity/tCO_2 [ICEE 2019[36]]. For the purpose of this study, an energy expended of 1.6MW.h/tCO_2 has been used.

2.3 Gaseous fuels

Gaseous fuels represent a key element to support the transport decarbonization process. In this subchapter, a perspective from methane and hydrogen is presented.

Concerning methane, when looking to the long-term objective in 2050, we mostly refer to renewable gas: both CNG and LNG can be produced from a variety of renewable, scalable and very low carbon intensity energy sources, such as organic waste and biomass produced through anaerobic digestion, thermal gasification or by directly converting carbon dioxide (CO_2) into synthetic methane by using hydrogen produced from renewable electricity. With renewable gas being practically identical in composition to natural gas, moderate to high blend levels are able to further enhance the beneficial effects of using natural gas, which is already a type of low-carbon fuel, providing substantial reductions (CNG (EU mix): 67.6gCO_2eq/MJ versus 92.1gCO_2eq/MJ for Diesel, Well-to-Tank with combustion assessments[37]) of total GHG emissions. Today road transport sector in EU is consuming 2.3bcm natural gas, where 17% is renewable[38].

[36] The Potential Role of Direct Air Capture in the German Energy Research Program—Results of a Multi-Dimensional Analysis. Peter Viebahn, Alexander Scholz and Ole Zelt.
Wuppertal Institute for Climate, Environment and Energy, Doeppersberg 19, 42103 Wuppertal, Germany (6th September 2019)
[37] JEC WTT v5 report.
[38] Source NGVA Europe/EBA: https://www.ngva.eu/medias/the-european-green-deal-in-the-fast-lane-with-biomethane-in-transport/

Concerning hydrogen, today it is produced worldwide mainly from the thermochemical conversion of natural gas (“grey” hydrogen) and approximately 5% is produced via electrolysis (“green” hydrogen when using renewable electricity). Several demonstration projects are underway for hydrogen production via steam methane reforming (SMR) coupled with carbon capture and storage (CCS) - referred as “blue hydrogen”. Potentially, blue hydrogen production from natural gas can be coupled with a share of biomass feedstocks that could bring the overall hydrogen greenhouse gas footprint to net zero or even negative. With the assumption of an increasing share of low-cost renewable electricity, green hydrogen production via electrolysis could be a promising decarbonization option.

2.3.1 Panel of solutions considered for the production of low-carbon gaseous fuels

Looking to the different production pathways for **biomethane**, **Anaerobic Digestion** (AD) is a naturally occurring, microbial process used to produce biogas from wastewater, waste or dedicated biomass. Biogas is primarily composed of methane (CH_4; 40 to >70%) and carbon dioxide (CO_2; <25-55%). Fertiliser is a second, often underestimated product of AD which can be used to replace chemical fertiliser. Via this closed nutrient loop, AD contributes to fulfil a circular economy, becoming more economic viable and ecologically interesting.

The biogas can be used on site to generate heat and electricity in a combined heat and powerplant (CHP unit) or as process energy in industry. If the use of biogas is not located on the production site, purification (removing impureness) and upgrading (removal of CO_2) processes are applied resulting in the so-called biomethane, a product whose quality allows the injection into the natural gas grid or the direct utilisation on natural gas vehicles. The evolution of the EU production of biomethane is shown in Figure 28.

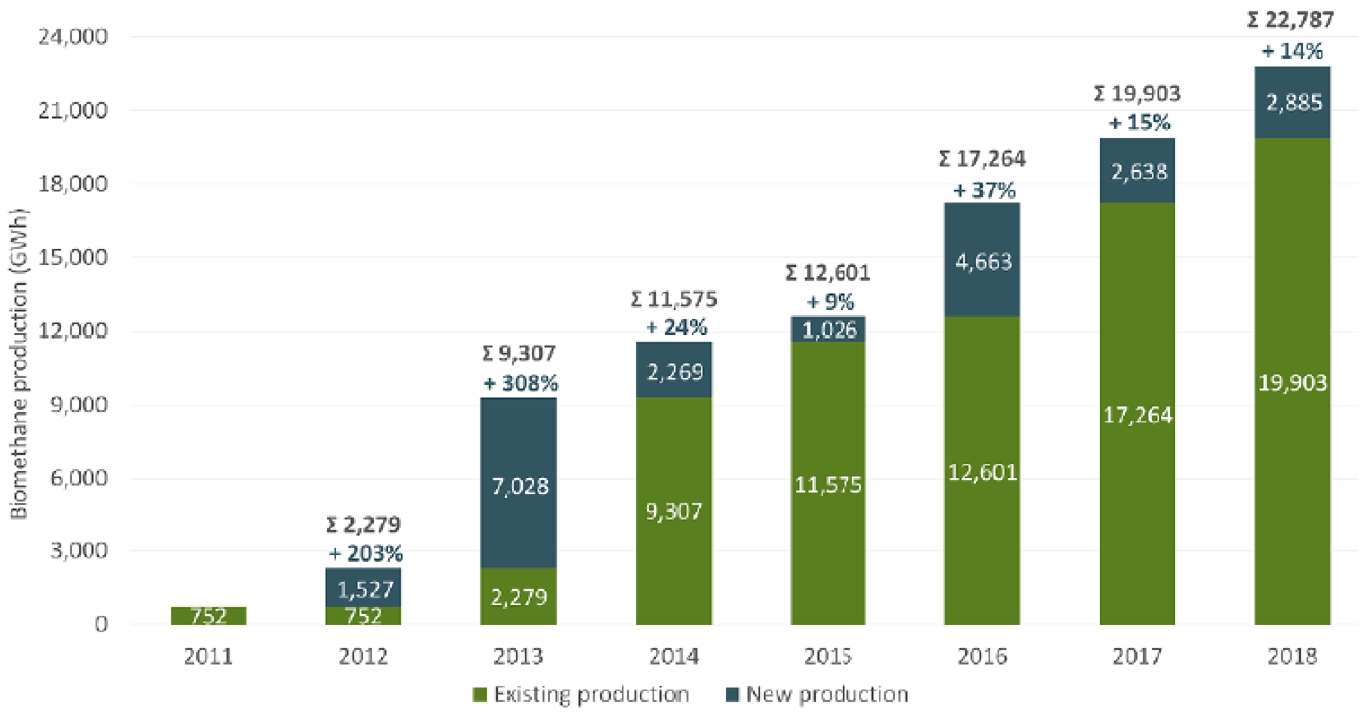


Figure 28. Evolution of the AD biomethane production in EU. Source [2.16]

A second way is represented by the **Thermal Gasification** (TG), which is performed in an enclosed reactor (gasifier) under high-temperature conditions (700-1000°C). The heat to drive the process is provided by the combustion of part of the char produced during gasification (autothermal) or from an external heat source (allothermal); for this reason, TG plants are very often integrated with Combined Heat and Power

(CHP[39]), The basic steps from solid fuel to product gas are drying, pyrolysis and gasification. The main desired product is a combustible gas called producer gas or syngas, a mixture of CO, CO_2, H_2O, H_2, CH_4. A methanation step follows gasification converting the raw syngas (carbon monoxide and/or carbon dioxide) into synthetic natural gas (SNG) which has equal chemical and technical conditions as biomethane or natural gas. Thermal Gasification plants are in the bigger scale above 20MW as the plant realized in Sweden within the GobiGas project. The projected capacity of production of SNG from TG in Europe is estimated at 880TW.h in 2030[40], but today more than 95% of renewable gas is based on AD processes[41].

The third pathway refers to **Power to Gas** (PtG) processes, often seen as a way to convert and store surplus from renewable electricity production. Excess renewable electricity is used to split water into oxygen and hydrogen. Therefore, it undergoes a methanation process (conversion of hydrogen and carbon dioxide into methane) either electrochemically (Sabatier process, TRL 8) or microbiologically (anaerobic digestion, TRL 7). Today, in Europe, Germany has the most important installed capacity with more than 20MW (electrolysis capacity) over more than 30 pilot projects, but also other countries like Switzerland, Austria, France, Spain, Sweden, Italy are realizing PtG plants for both synthetic H_2 and SNG production[42].

The carbon dioxide reacting with hydrogen for the methanation step can be derived from industrial processes (off gas) or from a biogas or syngas upgrading system providing a highly enriched CO_2 source. In biological methanation, microorganisms metabolise hydrogen and carbon dioxide to methane in a dedicated facility or directly in the biogas digester. The catalytical methanation or Sabatier process is an alternative to produce methane from carbon dioxide and hydrogen, as is also applied in the upgrading of syngas from gasification to bio-SNG.

Hydrogen can facilitate the large-scale integration of renewables, enabling grid balancing and seasonal storage as well as the decarbonisation of natural gas through innovative technologies. It is important to remember that hydrogen is not a primary energy. Therefore, hydrogen is an energy carrier which is as “clean” as the primary energies used to produce it. This is why hydrogen produced from renewable electricity (‘green’ hydrogen) or from Steam Methane Reforming associated with Carbon Capture and Storage (SMR + CCS, ‘blue’ hydrogen) is favoured in this roadmap. Hydrogen represents a solution for the decarbonisation of hard-to-abate sectors of the economy, such as transport, especially heavy-duty vehicles. Hydrogen, from both low-carbon content as well as renewable energy sources, can have a key role to play along the journey towards GHG neutrality. Hydrogen has an important role in each of the strategic building blocks[43] the European Commission foresees for paving the road to a net zero greenhouse gas economy by 2050.

Hydrogen is at a crossroads of several key technologies relevant to the energy transition: it can be produced via water electrolysis with low carbon or renewable power, and Steam Methane Reforming (or auto thermal reforming and/or methane cracking) with CCS/CCU. Biogas/biomethane reforming and biomass gasification or pyrolysis are other ways to produce hydrogen using renewable gases or wastes[44].

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[39] https://publications.lib.chalmers.se/records/fulltext/124695.pdf

[40] https://www.goteborgenergi.se/Files/Webb20/Kategoriserad%20information/Forskningsprojekt/The%20GoBiGas%20Project%20-%20Demonstration%20of%20the%20Production%20of%20Biomethane%20from%20Biomass%20v%20230507_6_0.pdf?TS=636807191662780982

[41] https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5c6a7adfd&appId=PPGMS

[42] https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2019/Roadmap_Power_to_Gas.pdf

[43] See COM(2018) 773 final – A clean planet for all – A European strategic long term vision for a prosperous, modern, competitive and climate neutral economy.

[44] Furthermore, where renewable energy sources are used to produce hydrogen and where carbon capture and storage in combination with biogenic carbon feedstock is applied, the resulting hydrogen could be considered as having a GHG negative impact. Note: natural gas can be used for hydrogen production via (steam) methane reforming or methane cracking (IV-H_2). In order to avoid GHG emissions, the CCS and CCU technology becomes an intrinsic part of the production processes. Similarly, coal gasification and subsequent carbon capture and storage delivering hydrogen (IV-H_2) is a relevant option here.

Electrolysis can play an important role in the future hybrid system. While Europe currently boasts a strong presence and role as a frontrunner in the electrolysis market (integrators, component providers, OEMs), this technology remains relatively expensive at this stage due to the high capital costs of the technology which require larger markets and further development to reach industrial scale-up and bring costs down. However, costs are expected to decrease dramatically with the uptake of power-to-gas/power-to-hydrogen. Furthermore, with the forecasted increase in wind energy generation for example (per IEA it is expected to reach around 40% of EU energy generation, becoming the primary source), electricity costs can also decrease, enabling a cheaper hydrogen production through renewable energy sources [2.17]. By combining renewable energy resources available to our continent and our vast geological hydrogen storage capacity, Europe can further support its path as global leadership in hydrogen.

Conversely, Steam Methane Reforming (SMR) technologies, which are today mature and widely used, when combined with Carbon Capture and Storage or Usage (CCS/CCU) could enable a fast and cost-efficient scaling up of low GHG hydrogen into the energy system, contributing to economies of scale. Low GHG hydrogen projects can facilitate a wider deployment of hydrogen and contribute to the upscaling of the market for hydrogen. In the mid-to-longer term, one could envisage a full switch to renewable and/or low GHG hydrogen in the gas grid to achieve deep decarbonisation. For example, in one study, the Hydrogen Roadmap Europe (Figure 29) represents the possible shares of the different hydrogen types and in different market segments:

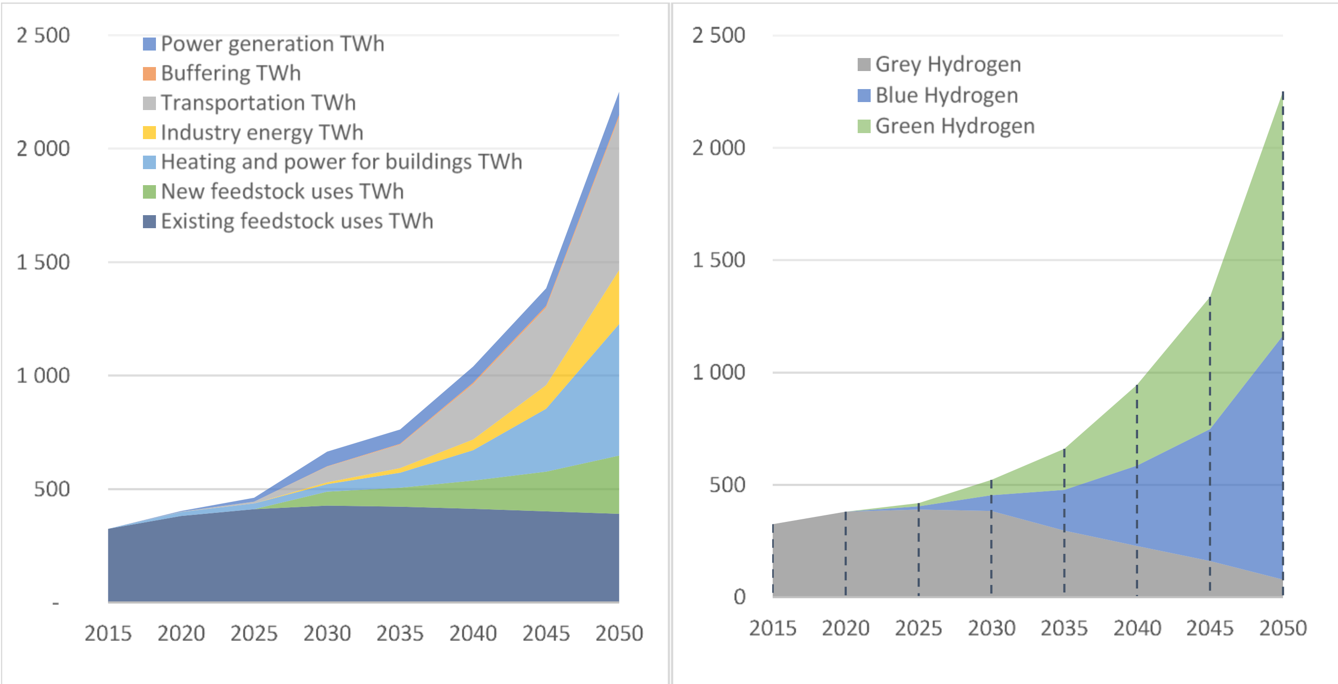

Figure 29. The possible share of different hydrogen types in different markets. Source [2.18]

Finally, and with a view to 2050, a significant cost-effective decarbonisation can only be achieved through an integrated sectoral approach using both the electricity, gas and heat infrastructures. Hydrogen and gas integration can ease the transition towards a deep decarbonisation, thanks to the ability of the gas grid to integrate varying geographies and scales (conversion of clusters for industry zone/region/country/EU) as well as admixtures of hydrogen into the grid, thereby adding to the positive spill-effects that hydrogen production deployment can have in Europe.

Table 11. An estimation of the European production capacity (TW.h). Sources [2.18 & 2.19]

	CH_4			H_2	
Year	Anaerobic Digestion	Thermal Gasification	Power to Gas (e-methane)	Green	Blue
2050	660	350	160	1087	1087

2.3.2 Gaseous fuels mix scenarios

The same approach as defined in the Liquid fuel mix scenarios is applied to the gaseous fuels in 2050, based on the proposed CO_2 Evaluation Group:

Natural Gas:

- Same scenarios as defined for liquid fuels:
  - Advanced biofuel: 90% biomethane + 10% e-methane (PtG)
  - Mixed: 50% biomethane + 50% e-methane (PtG)
  - E-fuel: 100% e-methane (PtG)
  - Limited fossil: 80% biomethane + 10% e-methane (PtG) + 10% fossil NG

Note. Due to the composition of the ERTRAC fleet, only LNG spark ignited based powertrains are included in the assessment.

Hydrogen

For hydrogen, the following scenarios have been explored:

- All fuel mix scenarios (but *limited fossil*):
  - 100% renewable H_2 produced by water electrolysis) is used (PEM technology).
  - The 1.5TECH electricity mix is used as the source of electricity (1.5TECH) with the exception of e-fuels where 100% renewable electricity is used.

Limited fossil

This scenario is used as a sensitivity on the origin of hydrogen where:

- 50% of the total H_2 demand will be satisfied as renewable hydrogen (as described above)
- 50% from low GHG routes based on fossil fuels (steam reforming of natural gas coupled with CO_2 capture and storage technologies).

2.3.3 Environmental assessment

2.3.3.1 Liquefied Natural gas-like fuels (methane)

It is worth noting that, due to the composition of the fleet as defined in the extreme cases defined for the purpose of this 2050 exercise, all the natural gas related demand will refer to Liquefied Natural Gas (LNG) routes (slightly more energy intensive process than the compressed natural gas production route due to the liquefaction process). In this context, as derived from the JEC WTT v5 values following the same logic as for liquid fuels, the figures used in the ERTRAC analysis for gaseous fuels are summarized below.

Advanced biofuels

Table 12. Liquefied biomethane (LBM) fuels figures to ERTRAC model (WTT, 2050)

Source	Wood residue			Municipal Waste			Mix advanced bio	
Feedstock/ Process	**Waste wood gasification/ methanation[(i)]**			**Upgraded biogas from municipal organic waste as liquefied biomethane (LBM)[(ii)]**			**Liquefied Biomethane (Bio) 50% wood residue + 50% municipal waste**	
Timeframe	2030 JEC (WWLG2)	2050 ERTRAC 1.5TECH (Base Case)	2050 ERTRAC 100% RES (Sensitivity)	2030 JEC (OWLG1)	2050 ERTRAC 1.5TECH (Base Case)	2050 ERTRAC 100% RES (Sensitivity)	2050 ERTRAC 1.5TECH (Base Case)	2050 ERTRAC 100% RES (Sensitivity)
GHG (gCO_{2eq}/ MJ_{fuel})	25.3	1.9	1.7	13.8	0.26	0.07	1.09	0.90
Energy expended (MJ/MJ_{fuel})	1.18	0.91	0.86	1.0	0.82	0.77	0.87	0.82

Notes:

(i) Synthetic methane (as LNG) via gasification of waste wood and methanation. Includes forest residue collection, seasoning, chopping, liquefaction (onsite refuelling station) and LBM dispensing.

(ii) Includes fermentation, upgrading as well as liquefaction and LBM dispensing (same as (i)).

E-methane (liquid)

The e-methane production pathways (sometimes referred as LSM (Liquid Synthetic Methane)) are derived from JEC WTT v5 and, as mentioned earlier, refer to the liquefied route due to the demand from the various ERTRAC fleet scenarios:

Table 13. E-methane figures to ERTRAC model (WTT, 2050)

e-methane									
Feedstock/ Process[(i)]	**H_2 from water electrolysis (100% RES) + CO_2 from industrial flue gases**			**H_2 from water electrolysis (100% RES) + CO_2 from biomass upgrading flue gases**			**H_2 from water electrolysis (100% RES) + CO_2 from direct air capture**		
Timeframe	2030 JEC (RELG1a)	2050 ERTRAC 100% RES	2050 ERTRAC 1.5 TECH (Sensitivity)	2030 JEC (RELG1b)	2050 ERTRAC 100% RES	2050 ERTRAC 1.5 TECH (Sensitivity)	2030 JEC (RELG1c)	2050 ERTRAC 100% RES	2050 ERTRAC 1.5 TECH (Sensitivity)
GHG (gCO_{2eq}/ MJ_{fuel})	6.7	0.0	2.95	6.7	0.0	2.9	6.7	0.0	3.19
Energy expended (MJ/MJ_{fuel})[(ii)]	1.14	1.0	1.81	1.11	1.0	1.77	1.82	1.2	2.04
Share		12.5%			12.5%			75%	

Notes:

(i) Refer to e-fuel Table 7 in Liquid fuels section for additional general assumptions for the e-fuel routes.

(ii) The energy use is lower mainly due to the higher efficiency of the electricity supply for CH_4 liquefaction in case of 100% RES.

Table 14. 2050 values used for ERTRAC modelling purposes – Advanced liquid biofuel mix (WTT)

e-CH_4 mix (*) - (ERTRAC 2050)	**ERTRAC 100% RES**	**ERTRAC 1.5 TECH (Sensitivity)**
GHG (gCO_{2eq}/MJ)	0.02	3.1
Energy expended (MJ/MJ_{fuel})	1.1	2.0

*As a simplification, the values presented above are considered as a proxy for both gasoline and diesel-like fuels in 2050.

(Fossil) liquefied natural gas

Despite the limited contribution of fossil fuels included in the ERTRAC fuel mix scenarios, the potential of these pathways towards 2050 have been investigated both in terms of energy consumption and GHG emissions:

Table 15. Fossil liquefied natural gas figures to ERTRAC model (WTT, 2050)

Source	Natural gas		
Feedstock/Process	Remote natural gas liquefied at source, transported and dispensed as LNG at retail point[i].		
Timeframe	2030 JEC (GRLG1) [ii]	2050 ERTRAC 1.5TECH	2050 ERTRAC 100% RES [iv]
GHG (gCO_{2eq}/MJ_{fuel})[iii]	16.6	7.15	
Energy expended (MJ/MJ_{fuel})	0.18	0.13	

Notes:

(i) Remote natural gas liquefied at source (imported from Algeria, Norway, Nigeria and Qatar), LNG sea transport, LNG distribution via truck (500km), LNG dispensing at retail point.

(ii) Pathway GRLG1C has been used as the basis for the 2050 estimate, including CCS at the liquefaction power plant (located outside EU).

(iii) Lower emissions due to different improvements in GHG reduction when looking into the 2050 timeframe. E.g. (1) reduction in non-routine flaring, minimum venting and fugitives (up to 50% assumed overall due to the implementation of on-going worldwide initiative such as the zero routine-flaring, among others). (2) less natural gas required in downstream processes inside EU versus JEC WTT v5 due to the replacement of natural gas compressors by electrically driven ones (3) electrically heated vaporization installed.

(iv) Very small (hardly detectable) differences between the two scenarios because of the small amounts of electricity required in the pathway (only for pumping at the LNG refuelling station).

2.3.3.2 Hydrogen

Table 16. Hydrogen figures to ERTRAC model (WTT, 2050)

Hydrogen	Electricity			Natural gas			Limited fossil scenario	
Feedstock / Process	Water electrolysis with low GHG electricity (renewable)			Steam reforming (SMR) of natural gas with CO_2 capture and storage (CCS)(ii)			50% Electricity + 50% NG (CCS)(iv)	
Timeframe	2030 JEC (WDE L1/LH 1)	2050 ERTRAC 1.5 TECH (Base Case)	2050 ERTRAC 100% RES (Sensitivity)	2030 JEC (GPCH2bC)	2050 ERTRAC 1.5 TECH (Base Case)	2050 ERTRAC 100% RES (Sensitivity)	2050 ERTRAC 1.5 TECH (Base Case)	2050 ERTRAC 100% RES (Sensitivity)
GHG (gCO_{2eq}/MJ_{fuel})	9.5	0.13	0	39.7	25.6	25.4	12.86	12.72
Energy expended, (MJ/MJ_{fuel}) (ii)	0.87	0.74	0.70	0.84	0.69	0.65	0.71	0.68

Notes:

(i) Electricity from wind energy. Water central electrolysis, hydrogen pipeline transport, hydrogen compression to 88MPa.

(ii) Natural gas from Russia, transport to EU by pipeline from Southern Asia or Middle East (4000km to EU), distribution through high pressure trunk lines. Central large-scale reformer, hydrogen pipeline, hydrogen compression to 88MPa at retail site with CCS.

(iii) More efficient gas turbines then have been used in the downstream long-distance pipeline transport versus JEC WTT v5 and downstream distribution conducted by means of electrically driven compressors (instead of natural gas ones).

(iv) It is worth noting that the intention of the ERTRAC scenario is not to foresee the future but to explore a limited fossil scenario, where the meaningful contribution from fossil natural gas with CCS is considered. For such a case, an even share with electrolytic H_2 has been used. Worth mentioning that, several other studies such as Navigant one[47] show a potential different ratio (35/65).

[47] https://gasforclimate2050.eu/publications/

3 Powertrain Options for Road Mobility

Introduction

Automotive powertrains are increasingly turning towards low or zero tailpipe emissions. The diversified powertrain portfolio in the future will lead to a significant reduction of greenhouse gas (GHG) emissions in agreement with the targets of the Paris climate change conference and the goals of "Fit-for-55". The future powertrain portfolio will be more diversified than today, comprising mainly BEVs and also advanced ICEs (gasoline, diesel, gaseous fuels and several renewable fuels, including green hydrogen), HEVs and PHEVs. This composition of different powertrains will be gradually complemented by FCEVs.

The automotive industry actively works on reaching cost competitiveness of novel powertrains to promote the development towards zero emission transport; however, decisions are primarily made on how to most efficiently and cost effectively meet the valid emission limits.

As described in Chapter 1 and explicitly emphasised for traction batteries, the responsible handling of resources, landscapes and related persons and a circular economy are general goals to be worked on, as well as further powertrain research.

In addition to improving BEVs with increasing achievable range, it is possible that long-distance journeys with passenger cars could still be addressed by PHEVs, HEVs and advanced ICE propelled vehicles. Whilst the majority of two-wheeler and passenger car (PC) powertrains will be electrified (BEV, xHEV), HD long haulage vehicles will see a smaller share of BEV and higher shares of ICEs with renewable fuels, H_2 (including FCEV) and hybridisation. Due to existing challenges, ICE powertrain technologies for 2030 long-distance vehicles, such as PHEVs, hybrids and advanced ICE vehicles, will be optimised for highest efficiency and increasingly supplied with renewable fuel. FCEVs, especially fuelled with green hydrogen, will be added to the long-distance powertrain options. Besides the roll-out of fast charging stations, further H_2 refuelling stations will be necessary with an increasing number of FCEVs. Smaller and lighter L-category vehicles, such as electrically chargeable powered two-wheelers (ePTWs), are very much suited to urban use and are, as such, well positioned to fully exploit the advantages of BEV, considering mobility and sustainability challenges.

Powertrain Technologies

This chapter describes the primary powertrain variations that have the potential to be operated CO_2 neutrally, hence contribute to achieving sustainable mobility. The success of these variations depends on user acceptance, minimal cost for additional infrastructure and operation at near zero-impact emissions. The variations can be classified in two basic categories: electric or internal combustion, which may also include hybrid drives. While a transformation now moves towards electrified and especially fully electric vehicles, the internal combustion engine (ICE) in a hybrid powertrain or in combination with alternative fuels still offers specific advantages, such as nearly unlimited driving range due to rapid refuelling. On the other hand, the electric drive (BEV or FCEV) offers significantly higher efficiency and zero tail-pipe emission operation. A wide range of vehicle types, vehicle sizes, transportation purposes and operation profiles in combination with the necessary energy and fuel infrastructure leads to a variety of powertrains. These can range from solutions for full electric light vehicles, such as e-scooters, ePTWs, to PHEV passenger cars, and up to fuel cell or H_2-ICE powered long haulage heavy-duty vehicles. In the future the various types of powertrains will come under closer scrutiny regarding overall energy efficiency and environmental impact, in terms of Life Cycle Analysis (LCA).

The need to approach engineering limits for new powertrain solutions and to reduce development costs and time requires further research in scalable and multi-domain models to efficiently support layout and tailoring of powertrain topology and component's as well as system's characteristics to the intended use case of the vehicle, i.e. rightsizing with regards to power and energy density. At the same time, digitalisation has become synonymous with connectivity and will be vital to support the process of using digital data for both design and operation, which will rely on advanced concepts, e.g. digital twins. Within the vehicle, this enables data collection for powertrain analysis, design and management interacting also with the thermal management strategy of the BEV or with the powertrain control of a PHEV, as well as of the hydrogen-powered long-haul truck. Apart from overall powertrain monitoring, performing specific functions, such as conditioning of the battery or accurate range prediction, are indispensable for BEVs. Applications are currently in preparation but limited to prototype testing and demonstration projects, as well as initial steps in niche products. Additionally, the interaction with a running fleet offers potential for improvements of road transport in terms of energy consumption, maintenance and repair, operation times and costs, and traffic optimisation. To address the challenges, adequate simulation capabilities and the use of data-driven, artificial intelligence (AI) techniques are promising, yet need further research.

3.1 Battery Electric Vehicles (BEV)

The following sub-chapter focusses on the battery electric vehicle (BEV) powertrain but includes related vehicle technology aspects due to the strong interaction and dependency on systems such as thermal management and especially connectivity encompassing both data and power. The traction battery will be addressed in its own sub-chapter (Section 3.2). The content is an update and complementation of the former ERTRAC Roadmap of Electrification, which is still valid for non-powertrain topics. (The aspects described below need to be interpreted individually from each application perspective. The focus may vary between different vehicle categories and applications).

VISION AND PROPOSED AREAS FOR SUPPORT

In general, BEVs are particularly attractive due to their high efficiency, very clean local operation and will be able to cover many of the road transport applications from 2030. Additionally, inherent modular aspects of powertrain offer new degrees of freedom in vehicle design and hence user experience. Focusing on these aspects, to further improve parameters such as energy density, will be needed to successfully expand the share of pure electric vehicles into mainstream usage. Rethinking and fully understanding future mobility and logistic models and expectations, as well as fit-for-purpose charging options, will also be a key element in specifying and designing innovative and affordable powertrains that optimally meet the user's specific needs and especially the economic expectations. It will be particularly novel to consider the system in which the vehicle will be operated and how connected systems can be used to benefit powertrain design and optimisation on the one hand and optimise continuously operational usage and lifetime reliability on the other. Integrated and more compact, potentially modular, powertrain subsystems and components can strongly benefit future vehicle design. In particular, the means of (physically) connecting to the power grid and the need for fast and integrated comfort charging or battery swapping are of great interest. Finally, industrialization, from manufacturing (prototyping to series) to recycling, and the responsible use of resources must be addressed.

CURRENT STATUS OF THE TECHNOLOGY AND DEPLOYMENTS

BEV powertrain technology is currently transitioning from the first generation to a second generation. As strong market growth has increased steadily, individual components, such as inverters, chargers, electric motors and battery packs, have constantly improved and been optimised for a specific electrical-network architecture and voltage level according to the vehicle category, also for larger series production. These are deployed in typical, conventional vehicles by replacing the existing ICE powertrains with an electric drive without major changes in vehicle design. Currently, the first, dedicated electric vehicle designs have successfully entered the market, but are still often based on stand-alone components, that have made very good progress over the last years yet are still considered to be in an early phase of a long development process to increase their technical level and maturity.

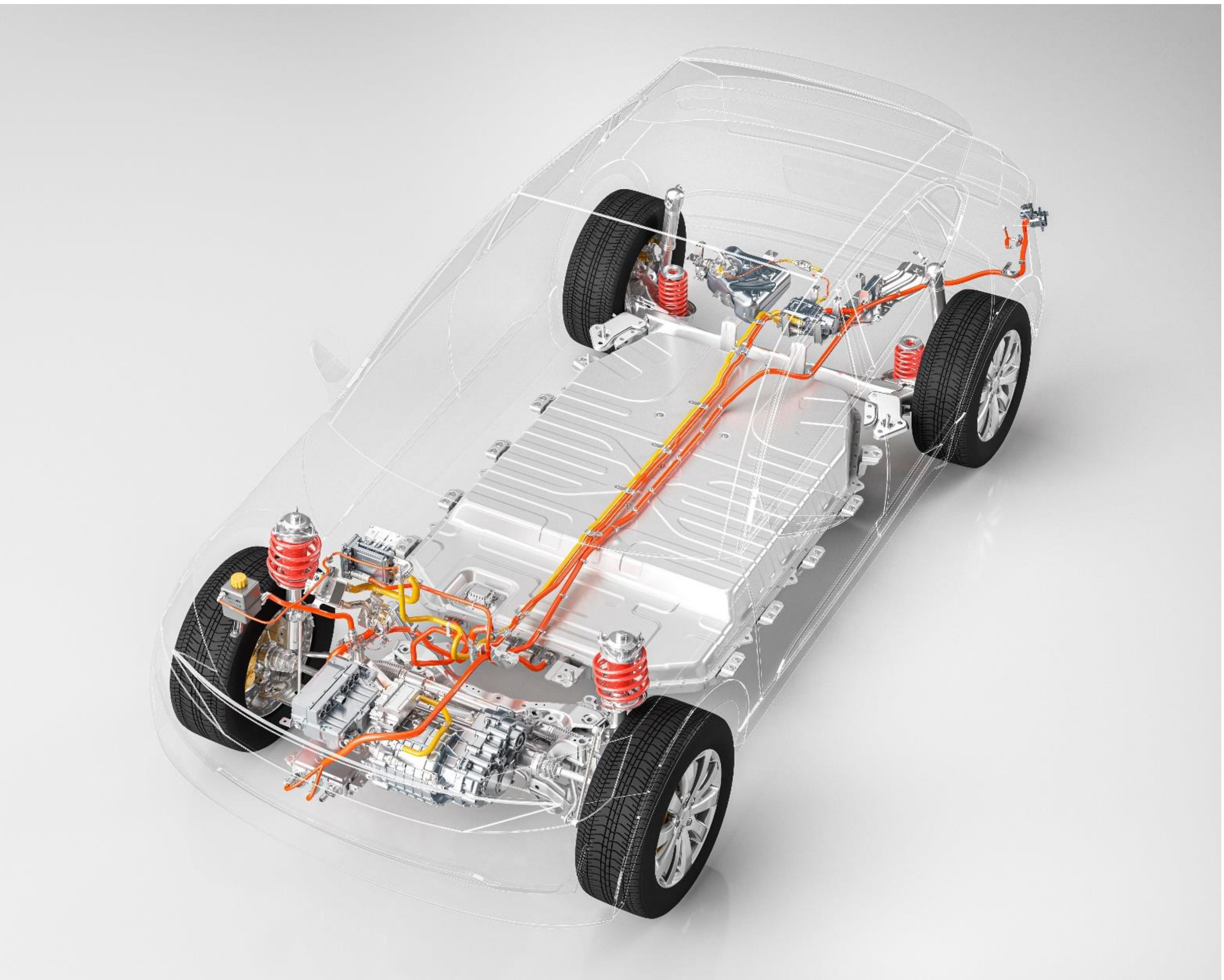

Figure 30. BEV powertrain

At the same time, the first integrated solutions and modular platforms are entering the market with power electronics, electric motors and transmissions implemented in single packages within a shared housing. Even higher degrees of integration are expected, in order to reduce cost and support novel vehicle designs. Transmissions will also be included in the trend towards integrated and modular solutions. Aspects such as voluminous space occupation, efficiency, weight, cost, noise and performance still offer potential for improvement based on today´s technological status. A variety of solutions is and will be available as required by the mass market, from current simple one-stage gears up to complex in-line-planetary layouts, eventually combining two motors and enabling torque vectoring.

The high integration of the BEV powertrain components and their modularity already starts to consider new layout opportunities for future vehicle and powertrain designs. Creating dedicated powertrains by using modules is desirable when trying to make mobility both cost efficient and desirable at the same time. This chain of opportunities of modular powertrain components starts with the research on material level over system and goes on with component research and development.

The battery itself is a dominating component of the BEV powertrain and has to be rightsized considering both vehicle category and specific or dominant application. The sizes depend on the customer's preference as well as the way to provide energy (charging versus battery swapping).
In expectation of a massively growing charging network and changing boundary conditions within the changing mobility sector, it is expected that at least two different layouts will be asked for by the customer: the fit for purpose low range vehicle (e.g. 250km) but also the long distance vehicle able to cover 500km or more. The same applies to light and heavy-duty vehicles according to their use-case. Within this framework it is worth investigating the potential of small, swappable and interchangeable batteries tailored for electrically chargeable powered two-wheelers (mopeds and small motorcycles) as they are mainly used in urban environment requiring limited amounts of energy.

Beside its size and weight, the battery is also defining the vehicle performance in two ways, the acceleration (discharging power for propulsion) and the recuperation that may be possible. Even the battery technology at the cell level can influence directly the customer value (see Section 3.2) due to the dependency on the required power and energy density, as well as on lifetime and reliability. This is especially relevant regarding the time required to recharge the battery. The key figure to compare the cell (dis-)charge performance is the C-rate, which is a normalized and quantifiable means of describing the battery capabilities even at the system level. A higher C-rate means shorter charging times. A very simplified estimation of charging time based on C-rates is to divide an hour by the C-rate value (e.g. 10-80% charge in 15 minutes equals roughly 4C).

The battery management system (BMS) also directly influences actual driving performance by controlling the battery to fulfil its primary function, and, in combination with the thermal management system (TMS), maintain favourable operating conditions. The BMS has a key role in the powertrain, research is required and ongoing to reach the desired maturity level soon, in terms of architectures and functionalities for advanced operating strategies.

The TMS, in cooperation with the BMS, is a vital overarching topic for all components. It is a challenge to keep these components within their optimal temperature limits in all operating modes, since they may have different specific temperature windows for efficient and reliable operation over their lifetime. A battery needs to be preheated at cold ambient conditions yet sufficiently cooled at high power usage or fast charging. Similar effects apply to other powertrain components. Further, there is no source of heat, as with internal combustion engine powertrains, delivering "waste"-heat which is used to condition the cabin. Within the scope of TMS, an efficient and clever reuse of heat needs to be considered, especially in a case like fast charging or high-power demand. Technologies to address the wide variety of potential needs for thermal management influence the total efficiency of a BEV. A current example on the market is the use of heat pumps for a more efficient way to supply heat, e.g. to the passenger compartment.

Charging, as described in detail in Section 4.1, is vital for the success of BEVs, but also is a very wide topic and open technological area. BEVs entering the market need to be capable of different charging options in parallel, in order to support customer's specific needs for their own usage models and to deal with the limited and diverse (but fast growing) infrastructure. Many different technologies for charging, with low/ high power, DC/AC, wireless or plugged, robotized and including bidirectional connected (V2G) and even dynamic, continuous whilst driving on "Electric Road Systems" (ERS), are currently considered in research and development. The advantages of having a range of solutions available may be particularly beneficial in terms of matching different user's needs. However, the charging technology affects the related powertrain components such as inverters, battery, BMS and TMS. High power charging leading to higher current hence increased thermal losses, cell degradation, more effort to manage waste heat and increased costs for the customer.

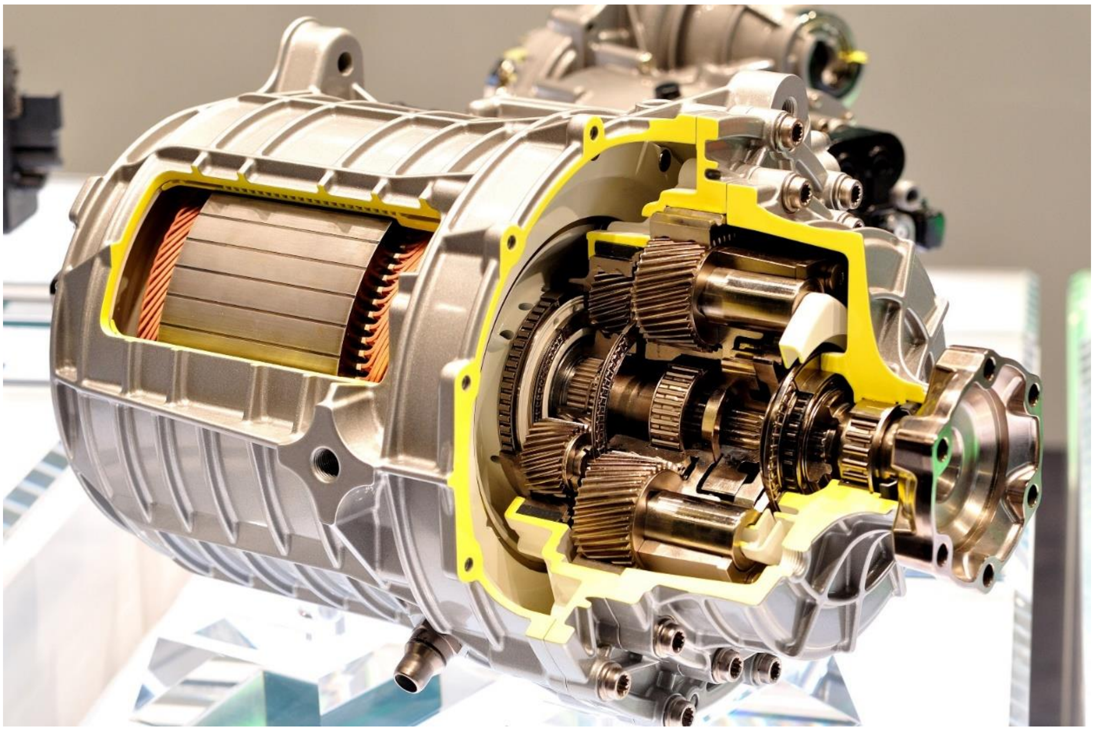

Figure 31. Integrated electric drive module

The electric drivetrain, as shown by way of example in Figure 31, provides the torque to propel the vehicle and use traction machines that already are capable of reaching peak electric efficiencies up to 97% at high loads, whilst offering > 90% over a wide range of operating points (see Figure 32). Intensive research is on-going and required in all aspects of the motor, with the focus on cost, weight and size reduction plus efficiency improvement. Reducing energy losses will also have a direct impact on the requirements on the thermal management system (TMS).

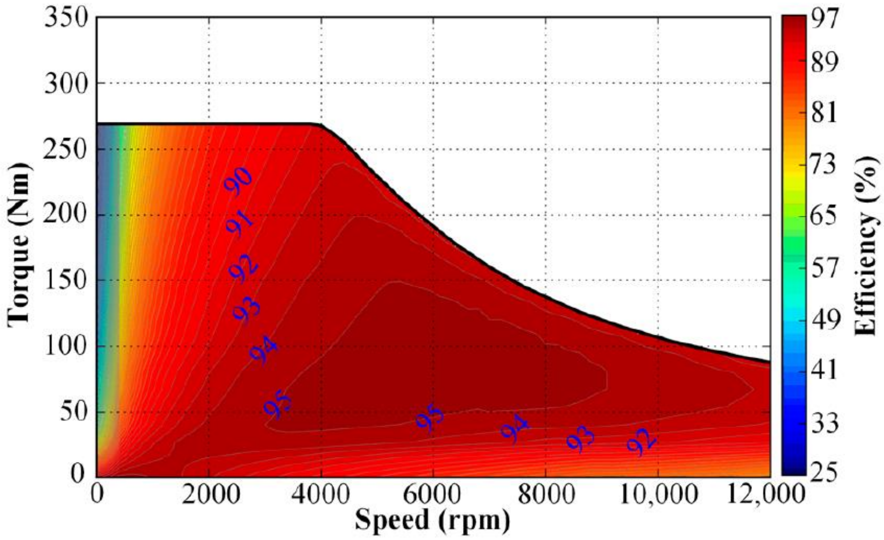

Figure 32. Typical permanent magnet synchronous traction machine (BMW i3)[48]

[48] Li, Y.; Yang, H.; Lin, H.; Fang, S.; Wang, W. A Novel Magnet-Axis-Shifted Hybrid Permanent Magnet Machine for Electric Vehicle Applications. *Energies* **2019**, *12*, 641. https://doi.org/10.3390/en12040641

Besides the motor, other electric HV components in the powertrain, especially power electronics, also need to be optimised to reduce energy losses, since the powertrain depends on the overall performance and efficiency of all components involved in the overall system and, especially, on the contradicting trends of how efficiency changes with power demand. At very low power, the efficiencies of the electric motor and inverter are low, while battery discharge efficiency is high. At higher power, efficiencies of the electric motor and inverter are high and the battery discharge efficiency decreases. Talking about powertrain efficiency always requires an overall system perspective, holistic approach and related research to balance the individual components and their properties towards a most efficient powertrain and BEV. The current state-of-the art has primarily focused on optimising the components at their own functional level and overall performance, but often with less consideration of the overall efficiency of the system.

CURRENT STATUS OF EUROPEAN RESEARCH

European funding within programs such as FP7 and H2020 have very successfully supported the initial steps of electrification within road transport, particularly for light vehicles, passenger cars and buses; further R&I efforts are needed for the electrification of heavy-duty vehicles. So far, the research has focused on component, sub-system and vehicle level improvements and addressed topics such as fast and automatic (wireless) charging, vehicle to grid capabilities, materials, light weighting, fleet management, components and their digital models, as well as vehicle technologies. There is an even higher demand for funding of the transition to the next generations of BEVs and of new electric mobility solutions, since the existing funding has been well invested, leading to the current trend of the rapidly growing market for EVs. Whilst developing the first generation of BEV powertrains, numerous new questions and technical options came up, which will enable Europe's mobility to be in the leading position in the worldwide competition. From materials over systems and components to digital elements, all aspects are important to contribute to achieve CO_2-neutral road transport and should be considered in a system perspective.

3.2 Batteries

This section is part of a European network of research and development initiatives and describes coherent content to other roadmaps while being distinguished between common battery topics and topics specially related to road transport envisaging the next steps to 2035.

VISION AND PROPOSED AREAS FOR SUPPORT

The battery (actually the accumulator) is the most efficient practical means of storing electrical energy in vehicles, aside from super-capacitors (which are inhibited, as the only means of storage, mainly by cost as well as volume and weight considerations). Every vehicle with electric drive motors will have a traction battery that is specified for the particular vehicle's needs, in terms of power and energy. It is expected that these batteries will be constantly improving: constant evolution in the areas of cost, durability, charging efficiency, safety, power and (energy) power-density (resistance of the system)[49]. In addition, the battery must fulfil a balanced and optimised combination of the following requirements as shown in Figure 33.

[49] A. König, L. Nicoletti, D. Schröder, S. Wolff, A.Waclaw, M. Lienkamp, An Overview of Parameters and Cost for Battery Electric Vehicles, World Electric Vehicle Journal, 2021, 12(1), 21; https://www.mdpi.com/2032-6653/12/1/21

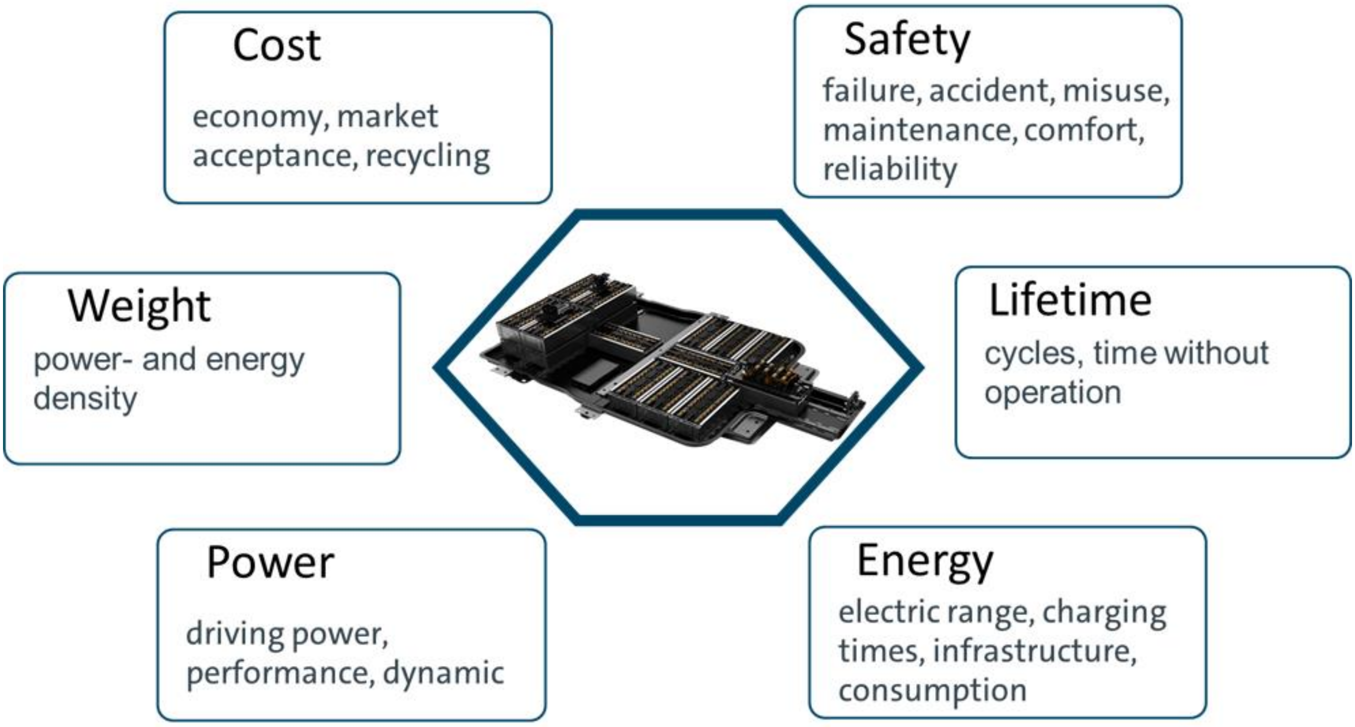

Figure 33. Requirements for batteries in road transport

A combination of chemical elements results in the theoretical energy storage potential, this is successively reduced starting with cell build-up and ending with the effort needed for the modules and packs. Envisaged improvements and innovation in cell technology will always serve as the cornerstone but will ultimately be assessed at the system level, e.g. improvements in overall battery pack energy density and the ability to charge quickly, over the entire lifetime of the battery. At the same time, the overall battery/vehicle system supports implementation, especially regarding the challenges of thermal management, which is vital for electro-chemistry and ensuring maximum lifetime from the cells to the overall system. Finally, regarding the end-of-life for batteries, it is essential to recover scarce and valuable materials, whilst keeping in mind that all these efforts must ultimately prove ethical and economically viable, both through design and through material recovery process[50].

It appears that Li-ion technology will have the greatest impact in mobility purposes for a long time to come. Other technologies, such as sodium-ion and even magnesium-ion, are under fundamental investigation and may find a market share for specific purposes mainly stationary applications or ships. Due to the far lower energy density of sodium-ion or magnesium-ion, it is unlikely that these alternatives will play a role in road transport, at least not for passenger cars.

CURRENT STATUS OF THE TECHNOLOGY AND DEPLOYMENTS

The battery is the core component of electric mobility since it defines the limits of power and energy or range as well as, to a significant degree, the overall weight and cost of the vehicle. Currently, the weight share of batteries weight is typically 20-30% for passenger cars and up to more than 40% for e-scooters: the battery can define up to 50% of the cost (not the selling price) of the vehicle, especially for small vehicle types.

[50] J. Van Mierlo et al., Beyond the State of the Art of Electric Vehicles: A Fact-Based Paper of the Current and Prospective Electric Vehicle Technologies, World Electric Vehicle Journal, 2021, 12(1), 20; https://doi.org/10.3390/wevj12010020 - 03 Feb 2021

3.2.1 Fundamentals

Battery cells are designed to fulfil the application related energy and power requirements, whilst keeping within the available space, weight and cost limitations. This typically leads to energy or power types of cell/ battery designs, sometimes also somewhat in-between (e.g. for PHEV cells). It is always a trade-off of energy versus power. It is necessary to choose one variation according to the application when designing and developing the battery module and pack. An overview of the different, most prominent cell technologies and their clustering is given in the table below:

Table 17. Battery characterization [BATT4EU, SRA for batteries 2020]

Battery Generation	Electrodes active materials	Cell Chemistry / Type
Gen 1	Cathode: LFP, NCA Anode: 100 % carbon	Li-Ion cell
Gen 2a	Cathode: NMC 111 Anode: 100 % carbon	Li-Ion cell
Gen 2b	Cathode: NMC523 to NMC 622 Anode: 100% carbon	Li-Ion cell
Gen 3a	Cathode: NMC622 to NMC 811 Anode: carbon (graphite) + silicon content (5-10%)	Optimised Li-Ion
Gen 3b	Cathode: HE-NMC, HVS (high-voltage spinel) Anode: silicon/carbon	Optimised Li-Ion
Gen 4a	Cathode: NMC Anode: Si/C Solid electrolyte	All solid-state Li-Ion
Gen 4b	Cathode NMC Anode: lithium metal Solid electrolyte	All solid-state Li-metal
Gen 4c	Cathode: HE-NMC, HVS (high-voltage spinel) Anode: lithium metal Solid electrolyte	Advanced solid state
Gen 5	Li|O2 – lithium air / metal air Conversion materials (primarily Li|S) New ion-based systems (Na, Mg or Al)	New cell gen: metal-air/ conversion chemistries / new ion-based insertion chemistries

3.2.2 Cell Technology

In general, the anode is made up of graphite or a mix of graphite and silicon, whilst the cathode active material can refer to a number of different Li metal oxide materials, depending on the final requirements of the battery for typical material combinations. In most cases these are: NMC (lithium nickel manganese cobalt oxide), NMC-LMO (NMC mixed with lithium manganese oxide), NCA (lithium nickel cobalt aluminium oxide) and LFP (lithium iron phosphate). The cathodes and anodes are kept electrically isolated by a separator, whilst the whole assembly is immersed into a liquid or gel type electrolyte. Cost has been addressed mainly by higher scale production processes, as seen in gigafactories, improving manufacturing processes and also by trying to reduce the most expensive elements (e.g. cobalt). The resulting nickel-rich electrochemistry will require more research to adequately prepare for new safety challenges.

One of the relevant factors for the lifetime of cells is the so-called 'breathing factor', which results from the change in cell volume between full charge and full discharge. This differs considerably for different cell materials. Volume change values are listed in the Table below.

Table 18: Volume change of different battery chemistries during operation

Battery chemistry	Breathing factor for 0 - 100% SoC
Lithium Iron phosphate / graphite	< 1 %
Lithium Nickel Manganese Cobalt oxide / graphite	3 %
Lithium Nickel Manganese Cobalt oxide / Lithium metal	15-25 %

Whilst the chemistry offers significant advantages in terms of energy density and performance factors, the high volume change especially of all solid state batteries containing Lithium metal anodes still has to be considered in the cell design, which is one of the biggest challenges to fulfil product requirements.

3.2.2.1 Li-Ion Cell Technology

A typical state of the art lithium-ion battery consists of two different electrodes – called anode and cathode. Those are electronically isolated via the separator inside the cell. During discharging the electrons move via the external circuit from the anode (negative electrode) to the cathode (positive electrode), whilst the lithium-ions inside the cells move, via the electrolyte, from the cathode to the anode. The liquid electrolyte is distributed homogenously over the whole cell (in porose electrodes and the porous separator. The lithium ions can diffuse unhindered through the liquid phase.

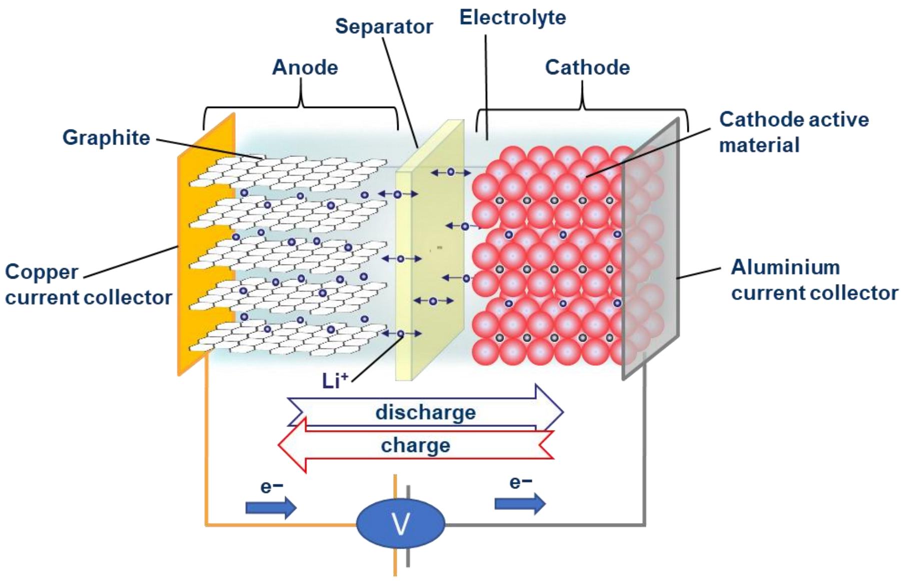

Figure 34. Structure of a Li-ion cell

3.2.2.2 Non-Lithium Alternatives

Alternatives that substitute Li-ions as the charge carrier, such as Na-ions or Mg-ions, have been considered for many years. The main advantage might be a significant cost reduction as well as the availability of materials, the diversity of sources to secure availability and even safety issues. Mg-batteries still need significant improvements concerning cell voltage, energy density and electrolyte availability. These performance issues still hinder further commercialization of this technology.

Sodium-ion technology (Sodium Ion Battery (SIB)) has made significant progress over the last decade. Energy densities are still lower compared to lithium-ion technologies but improving. Sodium-ion cells show good cycle life, longevity and safety behaviour. A large cell manufacturer announced a 2022 market entry for SIB's: the lower cost per kW.h and usage than Lithium-ion battery production technology makes this cell type interesting, at least for stationary energy storage. Assuming further technology progress, SIBs might also become post-lithium candidates for more demanding applications.

3.2.2.3 Solid State Cell

Solid state (polymer or ceramic) cells are defined by the use of solid electrolytes

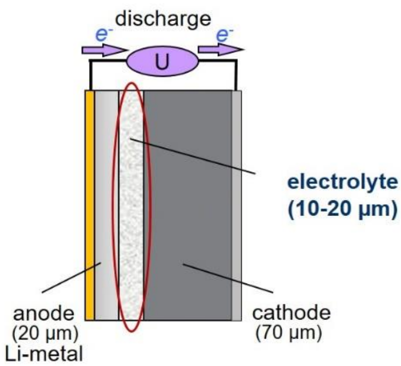

Figure 35. Scheme of one concept of a solid-state cell

The most obvious difference between solid-state cells and conventional lithium-ion cells is the fact that the electrolyte takes on the function of the separator in solid-state cells. In general, three promising types of solid electrolytes are known today, the organic electrolytes, oxidic electrolytes and the sulphidic electrolytes. It is not yet clear which of the three will best meet the requirements of the market.

Solid electrolytes generally offer the opportunity to use very thin anodes (15µm) of pure, metallic lithium because of the solid structure, which is preventing lithium dendrite growth. This leads to a higher energy density compared to Li-Ion cells. Furthermore, replacing volatile electrolytes leads to improved safety .

Pure solid-state cells require a homogeneous ionic conductivity at every position over the whole cell area from layer to layer (phase boundary) and over lifetime. This is one of the key challenges. On the other hand, the electrolyte has to be absolutely stable against lithium metal.

Oxidic and suphidic electrolytes show the highest potential to enter the battery market for the next 10 years or later.

OXIDIC CERAMIC ELECTROLYTE

The advantages of oxide ceramic electrolytes are the mechanical barriers against the growth of lithium crystals that cause short circuits (dendrites) and that they are chemically stable against lithium.

The challenges are: the lower conductivity, by one order of magnitude in relation to liquid electrolyte, (~10^{-3}S/cm @ 25°C); the hard material has a high contact resistance towards the cathode layer; the production in thin layers (<20µm) is a challenge and the low elasticity is very sensitive for micro cracks which causes shortcuts. In addition, high pressures might be needed to stabilize the solid/solid interphases.

Examples are:

- $Li_{6.06}Al_{0.196}La_3Zr_2O_{12}$, Garnet (~$10^{-3}$S/cm @ 25°C): stable against metallic lithium, but the production in thin layers often show pores. Lithium dendrites are growing immediately through the pores generating shortcuts.

SULPHIDIC CERAMIC ELECTROLYTE

The advantages of the sulphidic electrolytes are the high ionic conductivity. Some of the sulphidic electrolytes show an ionic conductivity which is almost comparable to liquid electrolytes (10^{-2}mS/cm @ 25°C). The material is soft, resulting in good contact resistances at the phase boundaries and a good resistance against cracking.

The main drawback is the chemical reaction of most sulfidic electrolytes with lithium and humidity, often leading to toxic reaction products.

Examples are:

- $Li_{10}GeP_2S_{12}$ (~10^{-2}S/cm @ 25°C): not stable against metallic lithium;
- $Li_7P_2S_8I$ (~10^{-3}S/cm @ 25°C): stable against lithium, but lower conductivity;
- 80 Li_2S & 20 P_2S_5 (~10^{-3}S/cm @ 25°C): stable against lithium, but reaction of sulfur on cathode (NCA, $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$), protection required.

POLYMER ELECTROLYTE

Polymer electrolytes are a soft and very flexible material. They can be produced in a simple manner. This enables a relatively easy cell fabrication.

On the other hand, the electrolytes have a low conductivity, 20-5mS/cm (25°C), which is three magnitudes lower than for liquid electrolytes. The cells have to be heated up to around 60°C until the operation can start. Due to the soft material, the barrier against dendrite growth is very limited. This does not allow fast charging.

3.2.2.4 Anodeless

Using solid-state electrolytes allows anodeless cell design. This is characterized by a composite-layer on the anode current collector. During the first charging procedure, the lithium (included in the cathode) is evenly deposited on the collector. The composite layer is responsible for a homogeneous lithium distribution.

This technology is in the very early stage of research. A major advantage for this concept is the avoidance of pre-lithiation of the anode, hence there is a chance for the use of less lithium. Another benefit is seen in the simplified production process and process environment of the anode.

3.2.2.5 *Battery Progress – data and time*

Table 19. Expected battery progress over time – EUCAR commonly agreed data (BEV) 2021

BEV – data cell level	unit	Condition	2019	2030 < 400km	2030 > 600 km	2030 HDV
Specific Energy	Wh/kg	1/3 C charge & discharge @ 25°C	250	450	450	450
Energy density	Wh/l	1/3 C charge & discharge @ 25°C	500	1000	1000	1000
Specific power – discharge (c)	W/Kg	180 s, SOC 100%-10%, 25°C	750	1000	1000	1000
Power density – discharge (c)	W/l	180 s, SOC 100%-10%, 25°C	1000	2200	2200	2200
Peak power – discharge (PC/CV)	W/kg	10 s, SOC 50%, 25°C / -25°C	1500/500	1800 / 600	1800 / 600	1350 / -
Peak power – discharge (PC/CV)	W/l	60 s, SOC 50%, 25°C / -25°C	3000/1000	4000 / 1300	4000 / 1300	3000 / -
Charging rate	C 1/h	SOC 0% - 80%	3	3.5	3.5	3
Self discharge	%	SOC 100%, 25°C, 30 days	1	1	1	1
Cycle lifetime WLTP (car)	MWh	25°C, DOD 90% @ SOH 80%	~ 20	22 - 24	22 - 24	N / A
Cycle lifetime bus / truck	MWh	25°C, DOD 90% @ SOH 80%	~ 20	22 - 24	22 - 24	N / A
Hazard level	-----		<= 4	<= 4	<= 4	<= 4
Cost	€/kWh		220	70	70	70
BEV – data PACK level	unit	Condition				
Cell volume – battery pack	%		60	75	75	75
Cell weight – battery pack	%		70	80	80	80
Lifetime expectation	Year / km	DOD 90%	15 / 150.000	15 / 150.000	15 / 150.000	N / A
Cost	€ / kWh	Times of cell cost	1.3	1.2	1.15	N / A

Table 20. Expected battery progress over time – EUCAR commonly agreed data (PHEV) 2021

PHEV – data cell level	unit	Condition	2019	2030 PC (100 km)	2030 CV (70 km)	2030 HDV (150 km)
Specific Energy	Wh/kg	1/3 C charge & discharge @ 25°C	200	350	350	350
Energy density	Wh/l	1/3 C charge & discharge @ 25°C	500	800	800	800
Specific power – discharge (c)	W/Kg	180 s, SOC 100%-10%, 25°C	750	1750	1750	1750
Power density – discharge (c)	W/l	180 s, SOC 100%-10%, 25°C	1500	2200	2200	2200
Peak power – discharge (PC/CV)	W/kg	10 s, SOC 50%, 25°C / -25°C	1500/500	1800 / 600	1800 / 600	1350 / -
Peak power – discharge (PC/CV)	W/l	60 s, SOC 50%, 25°C / -25°C	3000/1000	4000 / 1300	4000 / 1300	3000 / -
Charging rate	C 1/h	SOC 0% - 80%	4	5	10	10
Self discharge	%	SOC 100%, 25°C, 30 days	1	1	1	1
Cycle lifetime WLTP (car)	MWh	25°C, DOD 90% @ SOH 80%	~ 20	15 - 24	N / A	N / A
Cycle lifetime bus / truck	MWh	25°C, DOD 90% @ SOH 80%	~ 20	15 - 24	N / A	N / A
Hazard level	-----		<= 4	<= 4	<= 4	<= 4
Cost	€/kWh		220	100	120	120
PHEV – data PACK level	unit	Condition	2019	2030 = e 100km	2030 = e 70 km	2030 = e 150 km
Cell volume – battery pack	%		60	70	70	70
Cell weight – battery pack	%		70	75	75	75
Lifetime expectation	Year / km	DOD 90%	15 / 150.000	15 / 150.000	15 / 150.000	N / A
Cost	€ / kWh	Times of cell cost	1.3	1.2	1.15	N / A

3.2.3 Battery Technology

Current battery-solutions for BEVs are often designed for high energy, i.e. range, but can supply a high (peak) power only for a limited period of time (e.g. 10s depending on the SoC and temperature). Currently the battery systems offer a pack of one homogeneous type of cell technology and do not mix different cell technologies or include super-capacitors. Generation 3a is already finding widespread usage in the current initial market growth phase, which is largely driven by large state subsidies, whilst Generation 3b and 4 are just beginning to enter the market. A recent announcement promises very long ranges using advanced battery chemistries. However, this significantly increases the mass of the battery pack hence the overall vehicle weight. Also, the first heavy-duty applications with solid state batteries may soon enter some markets.

Figure 36. Battery assembly of a PC and an E-Scooter

The currently dominating battery technology in the automotive sector is lithium-ion Generation 3a, whilst other materials and chemistries, up to solid state batteries, are part of current research activities.

It is important to realise that improvements at a cell level do not automatically result in the same improvement at a pack level, due to additional effects inside the battery pack. The breathing or swelling of battery cells are only one of the well-known challenges for a battery pack. Additional challenges arise from inherently increased losses at high charging/discharging powers, due to the heat generation of cell, module and battery pack connectors, contactors and cables. As mentioned above, these effects are of particular importance in phases of high-power loads as, e.g., during fast charging and hill climbing. Increasing electrical losses and heat stress not only lead to energy losses but are relevant for ageing. Thermal management is, therefore, a key topic in the development of batteries, especially if fast charging is often used.

The sensitivity of the battery performance to temperature is a very relevant factor. Very low or very high temperatures necessarily lead to power limitations to protect the battery cells. Since this is a limiting factor for the vehicle functionality, the thermal management also has the role of ensuring the ideal conditions to achieve the best possible functionality within the current limits. Thus, the design of the battery thermal management system (BTMS) is key to keep the battery operating at high performance under safe conditions. Accurate 1D-3D thermal models are indispensable to predict the battery thermal behaviour. Optimal BTMS strategies may include active cooling systems based on air, or other liquids such as water, ethylene glycol or oil. Passive cooling systems can also be implemented, which include phase change materials and heat pipes[51]. Continuing research is needed in order to optimise the battery thermal performance in the best way suited for each end user application.

[51] H. Behi, D. Karimi, M. Behi, M. Ghanbarpour, J. Jaguemont, M.A. Sokkeh, F.H. Gandoman, M. Berecibar, J. Van Mierlo, A new concept of thermal management system in Li-ion battery using air cooling and heat pipe for electric vehicles, Appl. Therm. Eng. 174 (2020). doi:10.1016/j.applthermaleng.2020.115280.

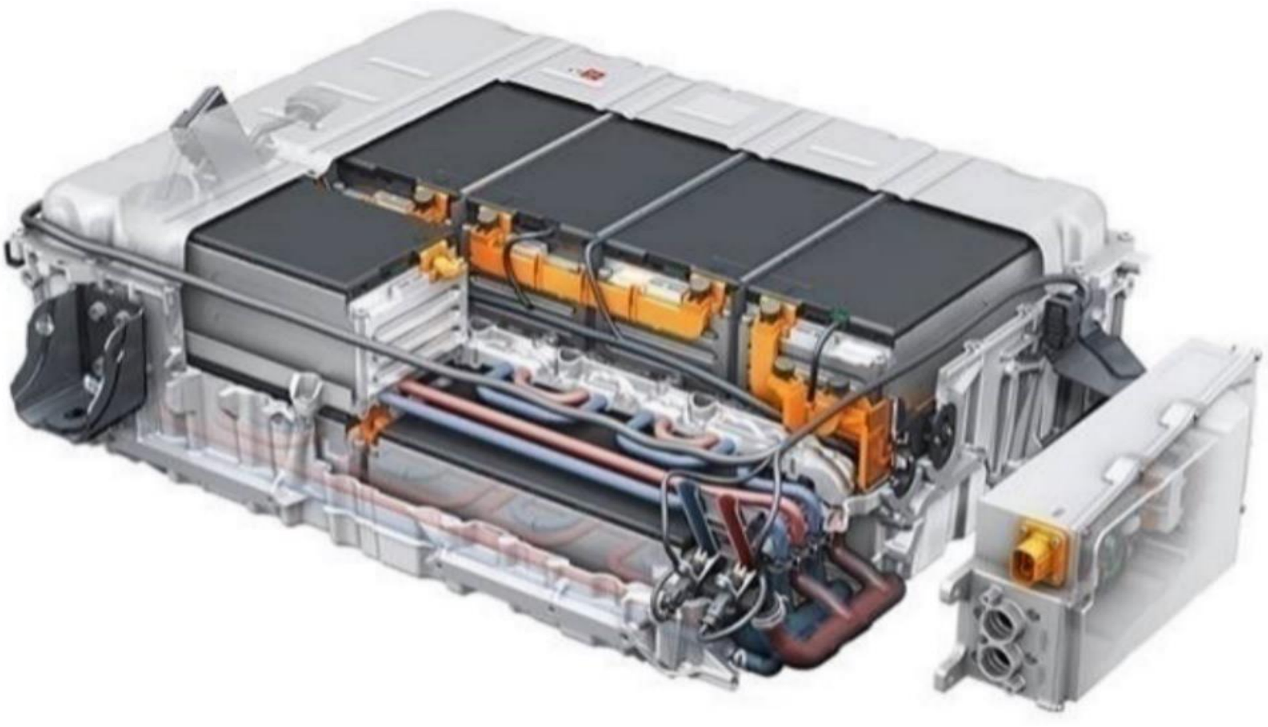

Figure 37. PC battery system with TMS (Source: Audi (website homepage))

Moreover, fast charging is known to cause lithium plating on the anode surface, deteriorating battery life and safety. In particular, heavy-duty EVs will require fast charging rates and very high charging power to reduce charging times, which will affect the lifetime of the battery even more than in passenger cars, which are expected not to fast charge as often.

EV (Lithium-ion) batteries deteriorate over time due to irreversible physical and chemical degradation that occurs naturally as well as being induced by the operating temperature, the current demand and the frequency/depth of charge and discharge cycles. The ageing phenomena influence the battery capacity, energy and efficiency, ultimately resulting in reduced performance and range of electric vehicles. Due to research efforts and improvements of charging strategies and chemical compositions the negative impact of the described phenomena could be reduced resulting in an improved suitability of BEVs for daily use. State-of-Health (SoH) is the “tracking” parameter that can be used as an indicator for battery ageing, whilst the parameter that defines the life of a battery is End-of-Life (EoL). The EoL of a battery is reached when the energy content or delivered power is not sufficient for the specific application.

The battery systems are nowadays not equipped with the necessary set of sensors to properly monitor the SoH of the battery and the BMS doesn´t have the required intelligence nor database to reliably predict the EoL.

Estimation and management are dependent upon the computational power and the storage capacity of the battery management system (BMS). With the use of machine learning and cloud computing, the capabilities of BMS can be increased[53]. Hence, adaptive models, real-time data-driven models and physics-based models, can be applied to monitor the capacity and the power fade of the cells, with increased efficiency, accuracy and reliability. Extended multi-physics and multi-scale modelling is needed to understand the basic phenomena and to act as parent models for consistently scaled reduced order models, e.g. as digital twins for BMS. Additionally, in recent studies, the possibilities of utilizing multiple

[53] Berecibar, M. (2019). Accurate predictions of lithium-ion battery life. *Nature*, *568*, 325-326.

sensor technologies, non-destructive testing probes with high frequency and knowledge of the mechanical properties of the cells, such as the internal pressure in the battery cell, are explored for SoX estimation[54].

The technology mentioned above will help to assess the durability of a battery under real-world use conditions, incorporating the calendar life as well, but this still needs to be developed. Lifetime testing until EoL, to obtain condition-based predictions, is a very time consuming and costly process that is not yet well developed. Currently, no practical method exists, in a short comprehensive test, to quantify all conditions of a battery. In order to be able to forecast the battery EoL, accelerated ageing tests are widely used; however, this method still shows a lack of reliability and reproducibility for standardization purposes.

Battery pack design for manufacturing and integration purposes is generally made up of modules that contain the cells, and are built-up depending on the type of cell being used, cylindrical, pouch, prismatic, etc. The module level would be ideal for servicing, repair and potential use in 2nd life, but no standard design exists. Furthermore, modularity always comes with an overhead (e. g. for connections) that needs to be weighed against the need to move to higher integrated systems and solutions. Modularity should attempt to find the right balance between the functional requirements and the aforementioned advantages of the module level. Nowadays there is also a trend to go away from fixed module elements in order to save space and integration effort (cell-to-chassis). Service will be more challenging here, depending on each specific concept. Alternative solutions are cell-to-pack, cell-to-car or swappable systems, which offer different pros and cons and require further research needs.

EV batteries are typically considered at the end of their first life when they can no longer meet the automotive standards: still, they retain approximately 70 to 80% of their initial capacity, although those figures can vary depending on current or planned use cases. To recover most of the residual value of disused batteries and to prevent a build-up of hazardous waste, two options are possible: reuse/repurpose or recycle the valuable materials.

3.2.4 Reuse & Recycling

It is theoretically possible and already prepared by legislation that mobile batteries could be used at the end of in-vehicle life in less demanding applications (i.e., battery cycling and environmental conditions) if the cost differential between new and reused batteries is sufficiently large to warrant the performance limitations of the latter ones. However, this might delay the ramp-up of the return rate to recyclers hence affect the economic viability of recycling in the first years. It would also require standardized pack or module designs as well as standardized interfaces to the BMS and thermal systems, that vehicle architects and developers would have to consider early in the design phase. BMS presents a further challenge since these systems have not yet been designed for individual monitoring of cell performance, from the lack of data on the performance of different battery chemistries and designs, to the assessment of the residual capacity at cell level this remains challenging. It is expected that the use of artificial intelligence (AI) will play an important role here in the future. The topic described above is addressed in several programs of European research within the related stakeholders and remains an important research topic.

Recyclers are faced with challenges ranging from the handling of high-voltage batteries with reactive components to the efficient recovery of expensive materials and rare metals under economically viable conditions. This may lead to new hazards for recyclers, due to the bypassing of battery safety precautions from the original design and deployment. It may be necessary to consider this in future designs as well as any means necessary to maximize the material recovery with minimal energy in order to minimize the CO_2-balance over the entire lifetime of the vehicle (LCA).

[54] Berecibar, M., Gandiaga, I., Villarreal, I., Omar, N., Van Mierlo, J., & Van den Bossche, P. (2016). Critical review of state of health estimation methods of Li-ion batteries for real applications. *Renewable & sustainable energy reviews*, *56*, 572-587. https://doi.org/10.1016/j.rser.2015.11.042

3.2.5 Safety

Battery technology currently offers a high safety level. Well acknowledged safety hazard levels have been defined for road transport in the past, by EUCAR and serve as a common base for international battery development.

Increasing energy densities lead to higher cathode potentials and/ or less electrochemically stable materials, which requires reassessing potential risks, to ensure at least the already achieved level of safety at the system level.

Numerous and intense testing from cell to system level and finally on vehicle level is part of the development process. Current safety concepts are based on international standards and regulations (ISO, SAE, IEC etc.) for high voltage (HV) systems, on hardware testing and on monitoring of certain critical parameters (e.g. voltage or temperature).

A variety of standards (SAE J2464; SAE J2929; ISO 12405-1/2/3; IEC 62660-2; ECER100; GB38031) for abuse testing is used on cell/module/pack level. ECER100 and GB38031 are mandatory at both vehicle (with a traction battery) and component levels. Batteries also need to be tested and approved as a separate component to be used in a system. GB38031 is not yet mandatory for 48V traction batteries. In addition, the UN38.3 transport regulation is mandatory for air transport of all Li-ion batteries.

Apart from the mandatory regulations for homologation of components and vehicles, there is no official, legal standardization of testing and risk management at present. Hence, every cell supplier is free in his safety strategy.

Current legislation, European, national and local rules, lead to expensive efforts for transport of critical/ non-operational batteries (e.g., for repairs or updates), which may preclude a viable 2nd life scenario.

Transporting Li-ion Batteries is regulated worldwide, for the battery and packaging materials, by IATA and IMDG, and in Europe falls specifically under ADR[55]. The transport of defective Li-ion batteries (either damaged or critically non-operational) that need to be returned to the supplier is a particular challenge which currently requires significant effort and needs innovative solutions to ensure economic viability. Activities about this are on-going but the topic still requires further research activities.

3.2.6 Digitalisation

The development and use of batteries in road transport nowadays are not yet highly supported by digital tools. This is reflected in the limited functionalities of lifetime monitoring and collection of data as well as in the subsequent use of AI and physics-based models for improved thermal management, safety measures, SoH monitoring and EoL prediction. Simulation has the potential to supplement the experiments on a large scale, thus save time and effort, and is very important in the value chain of battery production. Multi-physics and multi-scale modelling require further research, to boost understanding of the basic phenomena and to be able to fully use simulation for cell development and production planning. Consistent scalability of these detailed models to mechanistically based reduced order models and their integration in system level simulations enables efficient exploration of the large design space and accurate virtual assessment of the interactions between the cell, module, pack, powertrain and vehicle. Improvements in this technological field will strongly support the next generations of batteries, in terms of safety, performance, cost and reliability.

[55] ADR = Accord relatif au transport international des marchandises dangereuses par route.

CURRENT STATUS OF (EUROPEAN) RESEARCH

Since the rise of electrification, a large number of EU funded projects has investigated topics such as high-capacity anodes, high-voltage cathodes, higher voltage and environmentally friendly electrolytes, and enhanced environment-friendliness across the entire value chain, scale-up and manufacturing processes, the increase of energy density and the overall quality improvement of battery cells. Even though this research laid the groundwork for the efficient and sustainable development of batteries, further investigation is needed in, e.g., the improvement of material compositions or the recycling of battery cells, to maintain Europe's competitiveness whilst working towards the Green Deal goals.

Short- and long-term initiatives such as, e.g., BEPA/BATT4EU, Battery 2030+ or Batteries Europe, aim to contribute to the development of ultra-high-performance batteries, that are safe, affordable and sustainable. They provide disruptive technologies throughout the entire battery value chain for the European battery industry and enable Europe's long-term leadership in the field.

3.3 Powertrain adaptation for use with Electrified Road Systems

Powertrains for vehicles running on electric road systems are electrified and include the ability to receive energy whilst driving. Generally, these powertrains would be the similar to those in BEV, with additional equipment installed to transfer the energy to the moving vehicle. This energy is used for propulsion but can also be stored on-board, e.g., by recharging the vehicle's battery. This would make it possible to reduce the battery capacity in comparison to vehicles without such additional equipment (e. g. from 650kW.h to 200kW.h). Ideally, only minimal adaption of the powertrain would be necessary, to keep powertrain variations to a minimum. Power conversion would be necessary to ensure that voltage levels are compatible with the vehicle's traction power-network. The powertrain of a vehicle using an electrified road normally includes an electric drive, either solely or in a hybrid configuration with another power source, such as an internal combustion engine or a hydrogen fuel cell. This makes electrified road system adaptions a technically possible add-on to other electrified powertrains, although the cost implications need to be investigated for each envisaged combination.

Since such electrified road applications may save net cost, payload and resources on the vehicle side and, possibly, at the system level (see Chapter 4 on the electrified road system infrastructure), powertrains using such systems are of interest where large batteries (due to their cost and impact on payload) and their charging needs (high-power, for a short period of time and often simultaneously with many other vehicles) could limit the adoption of battery electric powertrains: hence long-haul heavy road freight has been a focus of this technology development. Such vehicles, however, have demanding requirements on the electrified road system. The list here covers a few key criteria, in order to ensure adequate functionality for long-haul truck operations:

- Power requirements: 200kW-450kW, with reasonable energy losses;
- Proof of concept: energy efficient transfer at 100km/h on-highway;
- Installation on a truck: need to be able to fit on an articulated truck, with a nominal minimum ground clearance of 345mm[56].

Even if these requirements have been realized in projects with the overhead contact line or ground contact rail infrastructures, there are additional topics related to the further development of powertrains using dynamic charging, particularly related to the pantograph or other pick-up devices. As with other aspects of the changes in the mobility system, the challenge of dynamic charging is to reach a high utilisation of the system, which means that many trucks need to be equipped to use it, not only domestic trucks but also trucks in international traffic, as well as, possibly, some cars or vans. This means that a European standard and initiative is needed, to enable scale-up in an effective way and to reduce the lead-time for the system.

[56] This is the example data from that one OEM. Often, one would expect about 550mm ground clearance for a truck, between 170 to 200mm for a passenger car.

The application of trucks using electrified roads is currently being tested in selected routes, at a small scale. Connecting a significant share of today's freight tractors to such systems will require large investments to retrofit highways with ERS-infrastructure and power stations nearby, injection points and conductors with suitable cross sections, the global economic and ecological impact of which is still under evaluation. Further discussion of this is given in Chapter 4.

Vehicle regulation
The current UN ECE R100 reads, "If the on-board REESS can be externally charged by the user, vehicle movement by its own propulsion system shall be impossible as long as the connector of the external electric power supply is physically connected to the vehicle inlet.". This will clearly need to be changed to allow vehicle operation with a conductive electrified road system.

The current Weights & Dimensions Directive should be updated to give the same, special extensions for trucks using dynamic charging as for other green truck concepts[57].

As with each innovation in use across Europe, the homologation and technical inspection for vehicles which use electrified road systems needs to be regulated at a European level (e.g., What requirements need to be fulfilled? Who is tasked with the inspection? How frequently is the inspection to be done?).

3.4 Fuel Cell Electric Vehicles (FCEV)

CURRENT STATUS OF THE TECHNOLOGY AND DEPLOYMENTS
Different building blocks of the FC technology have been validated in numerous European trials. Researchers have developed these components to the point where they have the operational reliability to allow them to be deployed in small series production to mainstream vehicle customers (1,000s of units in the US and Asia); the main driver for fuel cell technology in Europe is heavy-duty applications (over 1,600 buses to be deployed). The fuel cell stacks operating in London's buses since 2010 have lasted for over 25,000 hours, thereby proving their longevity for heavy-duty applications. Trials with a small fleet of L-category vehicles (two-wheelers) have also been carried out.

The challenge now is to reduce cost through a combination of increased production volume as well as technology development to improve production and automate techniques, reduce material costs per unit of output (specifically costs of precious metals used as catalysts in fuel cells and carbon fibre in tanks) and improve designs at stack (e.g. catalyst layers) and system BoP components level (e.g. air loop). Spill-overs, in terms of technology and up-scaling will be considered regarding LDV systems and are expected for other fields of HDV applications such as rail, marine or aviation. L-category vehicles face additional challenges surrounding refuelling protocols (work is on-going at vehicle manufacturer level) and face more acute cost pressures.

VISION FOR 2030 AND PROPOSED AREAS FOR SUPPORT
High level R&D, demonstrated for manufacture, has enabled fuel cell systems and hydrogen tank components to be optimised to allow FCEV vehicles to be offered on a cost competitive basis from light to regional markets. For heavy-duty applications more R&D needs to be carried out in order to meet power density requirements in the (low or high temperature) fuel cell system and in the tanks systems for the transport mission.

3.4.1 Fuel Cell Trucks

CURRENT STATUS OF THE TECHNOLOGY AND DEPLOYMENTS
There is a lot of interest from several OEMs in launching fuel cell trucks. Not just the existing players but start-ups, as well as companies that did not sell trucks in Europe before, are active in this field. Most

[57] As fully electric trucks using electrified roads, the current derogation for green vehicles does allow 1 extra tonne of GVW.

products and projects in the hydrogen fuel cell area though remain in either a limited market launch or demonstration domain (TRL 5 to 6) with rapid technological improvements needed to achieve performance required for mass market penetration.

Some demonstration activities for fuel cell trucks include the FCH JU REVIVE and HECTOR projects. The FCH JU funded project 2Haul started in 2019 and will develop and demonstrate 16 FC heavy-duty trucks up to 44 tons. One OEM has launched Europe's first mass produced fuel cell trucks starting with Switzerland mainly aimed at regional haul operations. Two other OEMs plan to launch their first products in the 2021-23 timeframe and several others will launch their products in the second half of the decade. However, the initial specifications of these vehicles may not be suitable for wide adoption and further improvements will be needed including technology improvements, cost reduction and infrastructure for hydrogen. These areas of improvements include fuel cell stacks and systems but also other parts of the FCEV including hydrogen storage, cooling systems, vehicle design, batteries, electric drives etc.

VISION FOR 2030 AND PROPOSED AREAS FOR SUPPORT

In 2030 a significant growth of FC HDV market is expected to accelerate sales after 2030 due to new CO_2 regulations and TCO competitiveness versus other zero or GHG-neutral technologies to contribute to the CO_2-neutral mobility by 2050. The FCEVs for HD long-haul trucks are still foreseen to cost more than an ICE diesel, and a sustainable policy support is needed to support the transition.

Flagship projects

With a growing need to decarbonise all areas of the transport sector, and a high focus on air quality issues in cities arising from traffic emissions, the demand for zero emission vehicles in all segments is anticipated to continue to grow over the next decade. The development and demonstration activities outlined above will lay the foundations for a larger scale FC HDV roll out programme in the mid 2020's. Key priorities in the market activation phase include developing and implementing innovative commercial models to manage risk appropriately and supply chain development to ensure that the vehicles are fully supported throughout their operational lives. Supporting such priorities entails guaranteeing customer expectations in terms of FC system reliability and driving range.

3.4.2 Fuel Cell Buses, Coaches, Minibuses & LDV

CURRENT STATUS OF THE TECHNOLOGY AND DEPLOYMENTS

The technical performance of fuel cell buses as well as light-duty vehicles and associated refuelling infrastructure has been validated via several multi-year real world trials focused on urban buses and passenger cars, which have shown that hydrogen fuel cells are capable of meeting the needs of even the most demanding bus operations. However, LDVs and fuel cell buses are not yet a fully commercial proposition, mainly due to the relatively high costs (capital and operating costs) of vehicles. This in turn is due to the limited volume production methods for the vehicles themselves and the drivetrain components. Improvements in the overall maintenance and support supply chain are also expected with volume, which will bring up the value of the vehicles for the users to a standard set by vehicles powered by combustion engines.

The latest demonstration projects (JIVE programme) are designed to allow the sector to begin to scale-up and achieve the economies of scale for the product needed for more cost-effective fuel cell buses while running costs are significantly determined by the costs of the (green) hydrogen. These activities are fully aligned with a commercialization vision set out by stakeholders in the sector, which envisaged increasing scale via joint procurement as a stepping-stone towards the potential deployment of many of fuel cell buses by the mid-2020's.

VISION FOR 2030 AND PROPOSED AREAS FOR SUPPORT

The vision for 2030 for FC HDV sketched above includes buses, coaches and minibuses. With a hydrogen infrastructure rolled out for heavy-duty applications and with a supply industry fulfilling the needs of large-scale market introduction of FC HDV, also LDV market introduction is expected to occur in the second half of the 2020s.

Fuel cell solutions for urban bus applications were successfully developed and demonstrated within the scope of activities of the FCH JU. Thus, further support should focus on adopting the FC technology for coaches and minibuses.

3.5 Plug-in Hybrid Electric Vehicles (PHEV) & Hybrids using renewable energy carriers

3.5.1 Introduction

The advanced internal combustion engine (ICE) as a core component of PHEVs and HEVs, e.g. operated with renewable fuels, maintains its relevance beyond 2030, however, as part of a multiple powertrain market scenario. In future with advanced internal combustion engines, pollutant emissions will reach near zero impact level.

Besides BEVs and FCEVs, PHEVs and RExEVs represent suitable ICE-equipped vehicle concepts for those urban areas with access restrictions. Zero pollutant emissions can be achieved in electric mode within city limits and/or warranted by air-quality conditions, whilst, alternatively, ICE might still be used outside those areas e.g. in rural surroundings, enabling customers to fulfil typical mobility demands under sustainability aspects. Sustainable alternative fuels produced from renewable sources bear the potential for a further reduction of greenhouse gas (GHG) emissions in a well-to-wheel frame. Renewable gases including methane or hydrogen can also reduce direct vehicle greenhouse gas emissions and/ or pollutant emissions towards 2030.

In contrast to vehicles with only one type of drive, hybrids have the freedom to distribute the drive requirements to one or the other drive according to any optimisation criteria. In the first development stage, the criterion was often minimal development costs, so that a hybrid was little more than the addition of an electric drive to a fully-fledged internal combustion engine drivetrain. The need to make optimum use of the energy once stored on-board, be it fuel or electrical charge, requires subsequent development stages. This involves redistributing the tasks between the combustion engine, transmission, e-drive and battery.

The selected powertrain topology essentially defines the extent to which functions are shifted between the main elements. In addition to functional considerations, economies of scale from the joint use of components with conventional ICE vehicles or BEVs are relevant to this question. This explains that today P0 and P2 topologies (the supporting e-motor is located on the belt side of the engine, P0, or on the transmission input, P2) are strongly represented in the market. In the future a shift to higher topologies or to serial hybrids (range extenders) can be anticipated, especially for HD applications, where investments are more likely to be viable.

This will very probably result in a major change to the combustion engine, which will no longer be optimised with regard to rapid torque build-up but must, above all, guarantee permanently high power with the lowest possible consumption and lowest tailpipe emissions. Similar far-reaching changes are obvious for gearboxes, as the ICE speed and load range will change. The fundamentally new functional architecture and changes to the main drive elements open up the possibility of significant cost reductions compared to hybrids of the first generations.

3.5.2 Internal Combustion Engines (ICE) for hybrid applications

This section is a complementary update to the still valid ERTRAC Roadmap “Future Light and Heavy-Duty ICE Powertrain Technology” from 05.04.2016, which describes in detail the general aspects of ICE based powertrains. The content of the mentioned roadmap will not be repeated within this ICE chapter. The chapter focusses on describing the technical possibilities linked to the ICE while being aware, that long-term decisions towards ICE investments could have a limited likelihood.

3.5.2.1 Passenger cars and motorcycles

As shown in Figure 35, below, there are customer requirements for long distance driving, so it is expected that the ICE will remain a significant (but abating) powertrain component for LD vehicles also in the next decade and for HD vehicles possibly even longer. Since it has been optimised for current fossil fuels in the past, a further step would be the optimisation for new, alternative fuels as described above. While the new fuel will provide a low or zero CO_2 footprint in combination with a unique, high-energy density, that is especially supporting the requirements of modern transportation systems, such as brief refilling time, the dedication of the ICE to the new fuel will reduce the overall demand of resources hence support economic use cases and delivering a clear advantage related to the CO_2 footprint regarding the total lifecycle.

The dedication of the ICE to the different low carbon fuels includes various technical measures, implemented as modification to current engine generations or, linked to higher invests, leading to new engines. The overall target is the increase of engine efficiency in combination with near zero impact emissions.

Different fuels (e-fuels, synthetic fuels, liquid, gaseous) have different properties and require dedicated ICE technologies. Fuels offer different knock limits, different spray and inflammation behaviours, different soot creation and many more. A current example for the need of dedicated engine layouts are renewable methane engines. The state-of-the-art solution is a bivalent concept based on the regular SI petrol engine. Gasoline determines the maximum combustion pressure by the knock limit. Since renewable methane has got a significantly higher knock limit than petrol a higher compression ratio would allow for an increased engine efficiency. This benefit cannot be used in bivalent concepts due to the lower knock limit of gasoline, even when running on renewable methane. A dedicated engine with higher compression ratio and other technical features would offer significantly higher fuel economy. Following that example all fuel properties need to be taken into account and an optimised engine needs to be developed for each relevant renewable fuel.

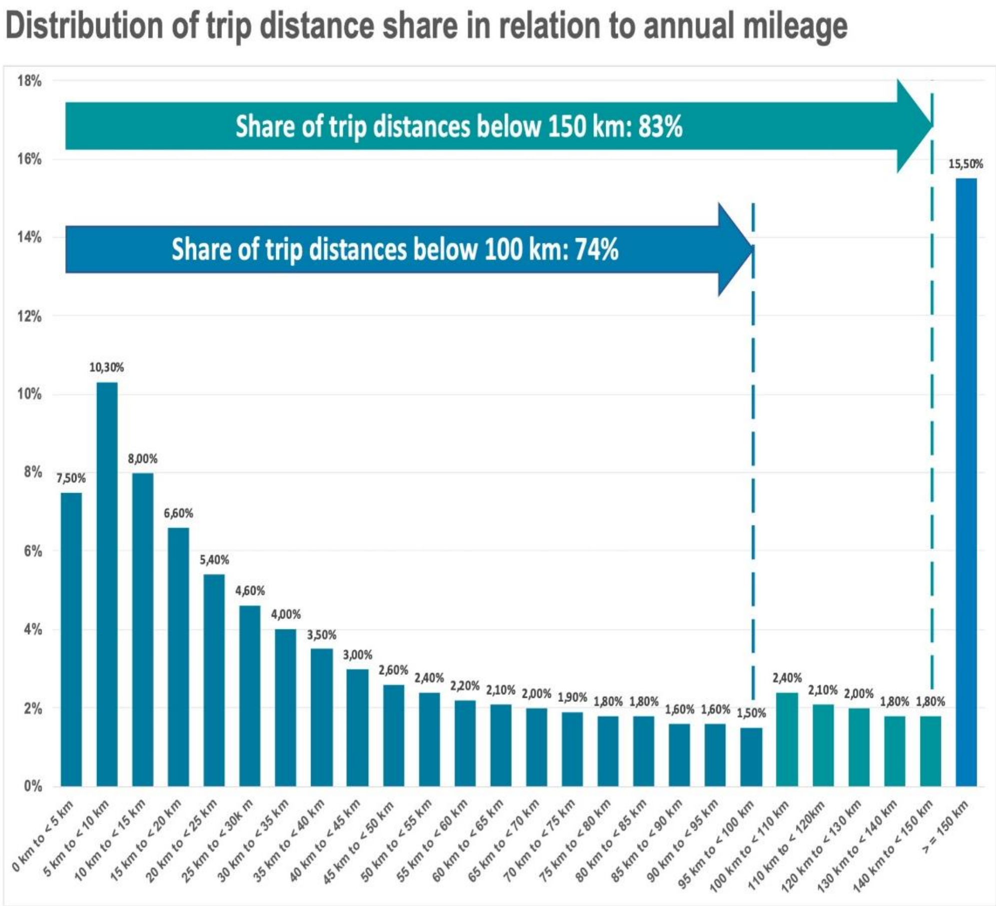

Figure 38. Share of the annual mileage for the example of a PC in Europe (Source: BMW. Sample size 200,000 BMW passenger cars in the EU market. Normally, BMW drivers are “long-distance drivers” so that an average of all brands in Europe will be more towards a higher share of trips at lower mileage)

HYDICE: Hybrid / Renewable Fuel Dedicated Combustion Engine. This needs to have the highest level of mechanical integrity (peak pressure) and thermal capability (cooling system). Furthermore, a peak efficiency optimised combustion system including air path, fuel injection and potentially exhaust gas recirculation are strictly depending on the fuel used and the operating condition. Depending on the fuel properties, the lean combustion can be used as well to increase the overall efficiency to levels above 51%, to reduce fuel cost and to reduce NOx raw emissions.

A technically even more promising (but more expensive) approach is the parallel development of fuel and related engines to reach new levels of efficiency for future hybrid powertrains with alternative fuels.

The use of an ICE in a hybrid powertrain creates higher economic challenges. Hybrids are more complex than pure ICE powertrains hence higher costs are involved. At the same time, the operating range of the ICE can be reduced within a hybrid layout by using the high voltage components for some of the tasks. Examples are idling or transient operations, which can be skipped or supported by the electric engine. Taking those two aspects together a dedication for electrified powertrains and a simplification are the necessary steps for the development of the ICE. Less complex functionality will lead to less complex and less expensive hardware.

3.5.2.2 Heavy-duty propulsion systems

In particular, on long-distance missions, the low weight- and volume-specific energy storage capacity of batteries is challenging. Hybrid propulsion involving a fuel cell or an internal combustion engine as power conversion unit for renewable chemical energy vectors (cf. Chapter 2 of this document) is a solution to travelling long distances in an ecological and economical way.

Whilst the challenges of fuel cells have been discussed in a previous paragraph in this chapter, this section focuses on the application of internal combustion engines for HD-(P)HEVs. However, it has to be noted that the ERTRAC "European Roadmap Electrification of Road Transport", the "ERTRAC Long Distance Freight Transport Roadmap", and the ERTRAC "Future light- and heavy-duty ICE Powertrain Technologies" documents available at www.ertrac.org/index.php?page=ERTRAC-roadmap are considered up-to-date and valid, and shall not be extensively quoted here.

Whilst the operation of HD-PHEVs in zero emission areas is enabled by using electricity stored in a battery and/or drawn from an electrified road (if and where dynamic charging is applicable), the battery capacity shall be limited to typical missions inside those ZE zones. Aside from investment cost related to the installed battery size, minimising its weight and size thus becomes a commercial advantage, as it maximises the usable payload. Therefore, powertrains for HDV will as an alternative to pure electric drivetrains where applicable most likely develop into PHEV architectures. The electric drive may be integrated into the drivetrain in P2, P3 or P4 positions to enable an electric-only operation with the ICE unclutched. This includes hybrid powertrain variants with one axle propelled by an EDU and the other by the conventional powertrain.

With a continued economic growth after recovery from the pandemic, the challenge to reduce GHG and pollutant emissions from freight transport remains unbroken. HDV must increase their use of renewable energy in any form significantly, to deliver their required contribution to climate and environmental protection.

As indicated in Chapter 2, drop-in renewable fuels have the potential to reduce the well-to-wheel GHG emissions of the entire fleet at large. Depending on the composition, they may further be designed to unleash efficiency increases of newly developed or retrofitted internal combustion engines. Providing them in large scale with standardised specifications rather than on request, is a matter of finding a business opportunity for fuel providers. Nonetheless, large truckage companies have their tractors mostly refuelled in the depot. Therefore, they may also deploy truck tractor units with internal combustion engines dedicated to special blends of synthetic renewable fuels to enjoy less fuel consumption and additional tax incentives from cutting their carbon footprint.

Research challenges for HD-PHEVs are there in the higher lifetime expectancies related to HD commercial vehicles, aggravating the already described challenges for PHEV powertrains. In order to use renewable fuels that are not 100% compliant with current standards, engines may need to be flex-fuel enabled, via functionalities such as variable valve actuation, variable compression ratio and electrified turbochargers. Further research on using electrically heated catalysts and special coatings for improved conversion after re-starting the engine may also be required to come to zero impact emissions of HD-PHEV.

3.5.3 Pollutant emissions

Similar to the other measures primarily targeting GHG, use of the new and alternative fuels offers further opportunities for pollutant emission abatement[58] whilst, in parallel, avoiding implications for air pollutants[59] from both new vehicles and the existing stock. Monitoring the effects of these new fuels should not be limited to those pollutants currently regulated but should also include new species that may become relevant because of the alternative fuel formulation.

In this context, the example of renewable hydrogen combustion is basically associated only with NOx emissions (generally high at engine out conditions due to the high flame temperatures but which can be lowered by lean combustion) and particle emissions (mostly originating from the lube oil), whilst, at the same time, the combustion is basically completely CO and hydrocarbon free[60]. This calls for the development and adaptation of appropriate DeNOx systems, which would include TWC in the case of stoichiometric combustion and SCR systems in the case of lean combustion, the latter offering the possibility of using H_2 itself instead of AdBlue as reagent[61,62].

The current range of air pollutants contained in the emission standards definition does not cover all relevant species. As new vehicle technologies, exhaust aftertreatment technologies and, in particular, fuels and additives are expected to be introduced in the future, the focus should move to covering these species as well. Some notable examples include formaldehyde (HCHO) from alcohol-based fuels, ammonia (NH_3) and nitrous oxide (N_2O) from sophisticated exhaust aftertreatment systems, but also brake and tyre wear particle emissions, which are emitted in lower quantities by fully electric cars as well (see Chapter 3.6), and which are not today covered by emission standards.

Recently published data indicate that current Euro 6d plug-in hybrids perform extremely well in terms of emissions and comply with the respective limits by a large margin when tested under the current RDE test conditions. Therefore, in the future, SI or CI internal combustion engines in the complex plug-in hybrid powertrains operated on tailored e-fuels, are expected to be ultra-low emitters under practically all real-world driving conditions[63]. These will include challenging situations, such as repeated cold start/short urban trips and low ambient temperatures, as well as less challenging situations such as harsh accelerations, high vehicle payload including trailer towing and filter regeneration events. Thus, they will be contributing to substantial improvements of for example urban environments where air quality is a major concern.

As already mentioned within the vehicle, connectivity and automation will enable accurate thermal management strategies in PHEVs, such as the preheating of the EATS, further contributing to a sustainable usage of the zero emission ICE.

Table 21 summarises these emission species, their mobile sources, current standards, harmfulness and preliminary priority indications.

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58 E.g. Villforth, J., Kulzer, A.C., Deeg, H.-P., Vacca, A. et al., “Methods to Investigate the Importance of eFuel Properties for Enhanced Emission and Mixture Formation,” SAE Technical Paper 2021-24-0017, 2021, doi:10.4271/2021-24-0017

59 E.g. Garcia, A., Monsalve-Serrano, J., Villalta, D., and Guzmán Mendoza, M., “OMEx Fuel and RCCI Combustion to Reach Engine-Out Emissions Beyond the Current EURO VI Legislation,” SAE Technical Paper 2021-24-0043, 2021, doi:10.4271/2021-24-0043

60 Thomas Koch, Sousa, A. and Bertram, D., "H2-Engine Operation with EGR Achieving High Power and High Efficiency Emission-Free Combustion," SAE Technical Paper 2019-01-2178, 2019, https://doi.org/10.4271/2019-01-2178.

61 Syed, Sirajuddin, Renganathan, Manimaran, “NOx emission control strategies in hydrogen fuelled automobile engines”, https://doi.org/10.1080/14484846.2019.1668214

62 Koch, D., Eßer, E., Kureti, S. et al. H2-deNOx Catalyst for H2 Combustion Engines. MTZ Worldwide 81, 30–35 (2020). https://doi.org/10.1007/s38313-020-0229-3

63 Giechaskiel, B.; Valverde, V.; Kontses, A.; Suarez-Bertoa, R.; Selleri, T.; Melas, A.; Otura, M.; Ferrarese, C.; Martini, G.; Balazs, A.; Andersson, J.; Samaras, Z.; Dilara, P. Effect of Extreme Temperatures and Driving Conditions on Gaseous Pollutants of a Euro 6d-Temp Gasoline Vehicle. Atmosphere 2021, 12, 1011. https://doi.org/10.3390/atmos12081011

Table 21. The emission species considered for emissions standards for mobile sources and their rating

	Mobile source	Current standards	Harmfulness (framework)
High priority			
NO_2	Emission control devices	With NOx, but limit may be too high.	Health, environment, ozone formation (AQ pollutant)
NH_3	Emission control devices	Only concentration limit for Euro VI engines	Health, environment. Secondary aerosols with PM. (AQ pollutant)
N_2O	Emission control devices	No	Strong GHG. Global warming (IPCC)[64] and possibly contributing to stratospheric ozone depletion
NMOG	E.g. alcohol fuels	With THC, but needs revision	Health. Ozone forming
Methane	Fuel related	For HD engines and with THC	Strong GHG. Global warming (IPCC)[50]. Ozone forming potential
Formaldehyde	Combustion (e.g. diesel engines), fuel oxygen	No	Health, environment (ozone), US EPA
Particles e.g. sPN <23nm	Fuel, lube, combustion	BC through PM, PN	See Section 3.4.
Medium priority			
Acetaldehyde	Combustion (ethanol fuels), fuel oxygen	No	Health, environment (ozone), less harmful than formaldehyde
Ethanol	Fuel related (ethanol fuels)	Partially in THC	Harmful at high concentrations
Isocyanic acid, cyanides	Emission control devices.	No	Difficult to measure (low concentrations)
Lower priority			
Ozone	VOC, NOx induced (Appendix 1)	No	Difficult to measure.
1,3-Butadiene	Combustion, emission control	No	Low ambient and exhaust concentrations. Easier to limit fuel olefin content
Acrolein	Secondary from 1,3-butadiene emission	No	Difficult to measure
Toluene, xylenes			Could be limited through fuel quality
Secondary aerosols (SOA or SIA)	PM, NH_3, SVOC, aromatics, PAH	No	Difficult to measure, could be limited thorough precursors
Dioxins and furans	Fuel and oil additives.	No	Could be limited through fuel and oil chlorine content
Benzene, PAH, metals	Fuel and oil related, engine wear metals	Partly by fuel quality standard	“Trojan horse” effect to be considered
Pb, SO_2	Fuel related	Fuel quality standard	Health, Environment

[64] In the JEC v5 report, the GHG effect of N_2O and CH_4 is not accounted for in the Tank-to-Wheel emissions. Hence, the method used in the JEC v5 report implicitly assumes a perfect combustion, where CO_2 is the only greenhouse gas present at the tailpipe. The Well-to-Wheel emissions calculated in the CO_2 study and disclosed in Chapter 5 are based on the same assumption.

3.5.4 Hydrogen Fuelled Internal Combustion Engines (H_2 ICE)

A viable way for decarbonization is application of green hydrogen, being a fuel with zero carbon footprint potential, in ICEs. As described above NOx remains one of the few harmful combustion by-products which can be minimized during combustion and, finally, removed through efficient aftertreatment concepts. In addition, the use of hydrogen in modern ICEs offers a near-term and cost-effective as well as efficient route to decarbonization.

CURRENT STATUS OF THE TECHNOLOGY AND DEPLOYMENTS

Historically, the port fuel injection engine configuration was applied for hydrogen ICEs: this suffers many limitations, including pre-ignition, knocking, backfiring and low volumetric efficiency. Hence, limiting the engine achievable specific torque and efficiency. A key step to eliminate these deficiencies is direct injection of hydrogen.

Similar to other engine types, a proper, engine operation point specific, interplay of injection pressure and timing as well as ignition timing, air-fuel ratio, EGR rate and engine including combustion chamber design is needed to optimise the trade-off between engine power output, efficiency and NOx emissions. Application of EGR and multiple injections (requiring high rail pressures) already proved as efficient measures to significantly decrease NOx emissions, however, if high specific torque needs to be achieved simultaneously with low NOx emissions, NOx aftertreatment systems need to be applied. With these measures, hydrogen fuelled ICEs can match power outputs and efficiencies encountered in modern fossil fuelled ICE counterparts, whilst eliminating tail-pipe carbon-based emissions and featuring ultra-low NOx emissions.

However, the use of hydrogen as fuel in ICEs is more challenging than using conventional fuels, requiring certain R&I activities to ensure large-scale deployment. On the component level, one of the significant challenges is availability of durable and low-cost hydrogen high-pressure injection systems, being exposed to the fuel featuring low lubricity and viscosity. In addition, hydrogen chemically interacts with metals. Fuel storage and fuel supply systems have reached higher level of maturity, whereas R&I activities are also need in this field. However, the main change in reaching engineering limits in terms of engine efficiency and emissions, whilst ensuring durable, safe and low-cost operation, is certainly holistic engine development and optimisation that ensures most adequate engine performance with respect to its intended application.

An additional challenge is the development of highly efficient exhaust aftertreatment to achieve near zero emissions. In this context both NOx and particle number emissions need to be tackled via further exploration and optimisation of existing technologies in view of the specific boundary conditions of H_2 combustion.

VISION FOR 2030 AND PROPOSED AREAS FOR SUPPORT

H_2-fuelled ICE will lead to a fast introduction and implementation of an H_2-infrastructure (carbon-free production, distribution network and filling stations). The lean combustion systems of H_2 engines for truck applications and other commercial vehicles will eliminate tailpipe NOx and particle emissions of these vehicles. Compressed (C-H_2) or liquid (L-H_2) hydrogen will enable long range operation together with brief refuelling times. In parallel, H_2-fuel cell trucks can easily be introduced to the market based on an H_2-infrastructure and H_2-tank systems available at mass production scale already. H_2-ICE propelled commercial vehicles might be used for long distance transportation as well as for shorted annual distances and lighter loads.

3.6 Complimentary Driveline Aspects

Non-powertrain sub-systems or components (the main components concerned here being tyres and brakes), contribute, on the one side, to CO_2 emissions with their specific energy consumption (either directly at vehicle level or more globally when considered through LCA approach) and, on the other side, to non-exhaust (and today mostly non-regulated) emissions. Both aspects are linked and must be tackled, in parallel, in order to achieve the overall objectives of road transport regarding impact on environment.

3.6.1 Reducing the energy consumption of non-powertrain components

Knowing that overcoming the rolling resistance alone represents 20% to 30% of the total energy used by a vehicle, whatever the propulsion mode, the first challenge for energy consumption reduction is thus linked to tyres continuous development activities in order to improve rolling resistance, combined with grip, handling, noise and wear whilst take into account real uses and new uses in tyre conception. The second challenge for energy consumption reduction, for all type of non-powertrain components, is at a more global level, along the lifecycle of the components: reducing the use of raw materials, improving health monitoring and end of life management. Specific research needs related to these challenges are given in Chapter 6.

More generally, simulation of the global system of mobility is also key to reduce the global CO_2 emission. The ecosystem is so complex that simulation is key to speed-up and improve conception and make the right design choices, either at component (like tyres or brakes) level or at system level. Furthermore, with new types of mobility solutions (e.g., automated vehicles), simulation allows to limit the number of tests while still considering all possible scenario (scenario related as an example to emergency manoeuvre, braking or also CO_2 emission).

3.6.2 Reducing non-exhaust emissions

The trend towards vehicle electrification is increasing the importance of non-exhaust emissions, with brakes and tyres wear particles being a significant part of these emissions. Accordingly, brake dust has become an important topic to study, in order to understand brake particle behaviour, start implementing measurement methods that might lead to future test standards and brake component approval regulations.

In 2014, the European Commission created the Particle Measurement Programme (PMP) Informal Working Group (IWG) to investigate this topic and provide enough data and knowledge to establish future legislation. The main objective of the PMP is to set up a commonly accepted methodology for measuring brake wear particles, with its roadmap[65] already defined. Furthermore, some European Union (EU) funded projects have been working on the issue of particles, in order to contribute to and complement PMP group activities. Other markets are also involved in this topic, such as Japan and the USA, mainly, but also India, Korea and China.

In parallel, the automotive industry is willing to reduce the emissions by applying new and inventive technologies. Different systems and innovative ideas have been used for reducing brake dust emissions, such as:

- Brake Dust Particle Filter: A new particle filter system capable to reduce fine dust coming from the brake system of the vehicles has been created. Passive systems can reduce the emissions by around 40% while active systems, with power supply to filters and sucking devices, can reduce up to 80% of the brake dust emissions, although their relative benefit is yet to be determined.

[65] 51st PMP IWG Meeting - JRC presentation. TF2 (Development of a method for sampling brake wear (BW) particles and selection of the most suitable methods for BW particles measurement and characterization) roadmap.

- Usage of drum brakes (where possible under safety aspects) help reducing the brake dust emissions and may therefore lead to smaller, lighter and cheaper filter systems or even make them obsolete
- Regenerative Brake Systems: Another solution for the brake dust emissions concern is the regenerative brake systems of all types of EV and HEV. It has been demonstrated the potential for particle reduction and it will depend on the used recuperative brake system, the foundation brake, the driving behaviour etc.
- Dedicated braking strategies actively controlling the brake force at the wheels to maintain each brake in the best possible operating window can help reducing the emissions by up to 30%.
- Low abrasion components for brake pads/ discs/ drums offer further reduction potential of up to 60%.
- Recycled brake pads: They can maintain comparable friction, wear and airborne particle emission behaviour as well as commercial virgin brake pads. However, further study of recycling into full-scale brake pad is suggested.

Brake and tyre wear are linked during the braking phase. It could be interesting to address this matter at the same time.

On tyre side emissions concern both air quality (non-exhaust emissions) and exterior noise. Different systems and innovative ideas have been used for reducing tyre emissions like electrostatic capturing. Improving the wear performance is one way to reduce the wear particles emissions but also there are other important elements to be taken into account like the road surface, driving style, traffic flow, vehicle design and weight.

The impact of TRWP (Tyre and Road Wear Particles) is not yet fully measured nor understood. Even if the international tyre industry already conducts crucial scientific work on tyre abrasion through the TIP (Tyre Industry Project) under the roof of the WBCSD (World Business Council of Sustainable Development), it is still necessary to characterise more precisely TRWP (composition, quantify, biodegradability etc) and adapt tire conception to lower their impact.

Road characteristics also have an impact on all tyre performances (rolling resistance, grip, noise, wear etc) and, since road particles are included into TRWP, it is necessary to work in parallel on road formulation to improve both tyre and road performances. Tyre design could also have a significant impact on road endurance. Sustainable roads should be a complimentary objective to sustainable road transport.

Reducing the tyre road noise generation corresponds also to one of the expectations of the city inhabitants and must be further studied and improved.

The use of a conductive electrified road system also creates emissions, mainly by abrasion of the sliding contact surfaces. Investigations[66] on overhead catenary systems have shown, that about 1000kg of copper is released over a 35-year lifetime from each kilometre of the track, this is considered environmentally harmful due to its toxic properties.

Overall, it is clear that further investigations in the coming years must be done in order to reduce non-exhaust particles emissions and, at the same time, the entire vehicle emissions.

[66] Kees van Ommeren, Peter Haanen, Martijn Lelieveld (all Decisio), Jeroen Quee, Walther Ploos van Amstel (all Sweco), Michiel Aldenkamp, Thijs van der Woude, Ruud van Sloten (all EV Consult); “Cost-effectiveness analysis Electric Road Systems (ERS) for the Netherlands”; March 2022.

4 Infrastructures supporting renewable energies

4.1 Electricity

4.1.1 Charging

Innovative transport technologies and business models have the potential to improve liveability, connectivity and sustainability in urban plus non-urban areas. However, to fully make use of their potential, the integration of new forms of transport, including electromobility, and the energy supply planning, including the deployment of the new charging infrastructure, should be made in a holistic way.

Electrification in transport has been a disruptive innovation that has led to a fast-charging market offer. However, different electric powertrains require specific types of charging (or refuelling) infrastructure: different forms of charging have penetrated the market to varying degrees. At the same time, many electric vehicle owners, especially in cities, will need to rely on access to charging stations in collective parking lots, at apartment blocks, offices or business locations; this suggests that member states focus on charging station density in urban areas. The current levels and the expected further adoption of EVs creates demand for new applications and services along the value chain, including: the charging infrastructure (charging hardware, charging services and navigation); the power sector (smart charging and/or smart grid applications, aggregated demand-side management); cars and components (e.g. battery leasing); recycling services. Standards in the charging stations networks have to be promoted in order to ensure the service compatibility. New mobility business models, especially those centred on vehicle sharing can, already in the short-term, remove barriers (e.g. range limitations and high purchase price) for the large-scale adoption of EVs as privately-owned vehicles).

Setting-up the new charging infrastructure implies high installation costs: on one side, governments cannot bear alone these costs; on the other, for companies, the sale of electric power to EV drivers by itself is not enough to generate enough revenue to repay the investments. To develop new business models for the updated charging infrastructure set-up, a participatory approach, involving all the relevant actors (e.g. local authorities, spatial planners, citizens, private investors and transporters) must be enhanced; multi-funding strategies and innovative costs plus revenue sharing approaches have to be put in place. The issue of governance is strategic because the value creation is directly derived from the proper management of inter-relationships amongst stakeholders. New participatory and multi-actor business model concepts should be accompanied by governance modes which foster embedding the stakeholders, to better manage the inter-organizational relationships in the long term.

The development of innovative business models and market engagement strategies, aimed at the implementation of economically sustainable charging infrastructure planning solutions, can be addressed by exploiting available tools or by providing incentives to the development of new tools. For instance, to facilitate the planning process, decision support tools, optimisation methods and the exploitation of available data, can accommodate forecasted trends. The use of economic assessment methods to analyse the complexity of the electromobility ecosystems can be successful, in order to understand the impact that the different types of electric vehicle charging scenarios have in different electromobility sectors. Thus, enhancing and facilitating research and studies that assess the economics behind the EV charging infrastructure would provide significant support to governments and regulators, for instance when they have to define how to structure the electricity bill or to design special subsidies or tax discounts.

4.1.1.1 *Charging from the Vehicle User Perspective*

Electric energy can be transferred in three fundamentally different ways: conductively, inductively or capacitively. **Conductive energy transfer** uses a direct conductor-to-conductor transfer of electric current from a primary source, e.g. the AC grid, to the vehicle's power system. This is the most common way used for almost all chargeable vehicles, from bicycles to heavy-duty trucks**. Wireless**[68] **energy transfer** means that the primary electric energy source is converted into a high frequency magnetic field that is transferred to the vehicle, where a receiver again converts this high frequency magnetic field into a current that can be fed into the vehicle's power system. This is usually referred to as "inductive charging" or "wireless charging", the latter due to it not needing a cable or contact for connection. **Capacitive energy transfer** converts the primary source voltage into a high frequency AC voltage that, via conductive plates in close proximity, is transferred via electric fields to the vehicle, where it is rectified and used to feed power into the vehicle's systems. This is uncommon technology that is demonstrated by research to suffer from low power density, i.e. a large space is needed even for modest charging power transfers.

Almost all types of energy transfer systems to electric vehicles are based on a sequence of energy conversions, they can take place either when the vehicle is standing still (static charging) or when moving (dynamic charging).

Static Charging

Static charging includes all technologies for transferring energy from an external energy source to an electric vehicle, in most cases to the energy storage on-board of the vehicle. The energy source can be an AC grid, an external DC source, such as a rectified AC grid voltage, or an external battery, a PV plant, or another vehicle. Since an electric vehicle usually can provide a bidirectional energy flow, it is more correct to talk about static energy transfer rather than static charging. Examples where the opposite energy flow direction may be interesting is where one vehicle provides another with energy, where a vehicle provides a house or a local grid with energy etc.

Static energy transfer takes place with the vehicle and the energy source standing still. This means that there is normally a way to force the electric potential of the chassis and any touchable structures of the involved equipment to ground potential, i.e. connecting them to Protective Earth (PE). This is very important from an electric safety point of view.

The functional blocks of almost all types of chargers can be illustrated with the block diagram of Figure 39. Note that a transformer is a part of the energy conversion chain. This is used to separate the supply side (the AC grid) from the load side (the EV battery) electrically, to provide safety and to adapt voltage levels.

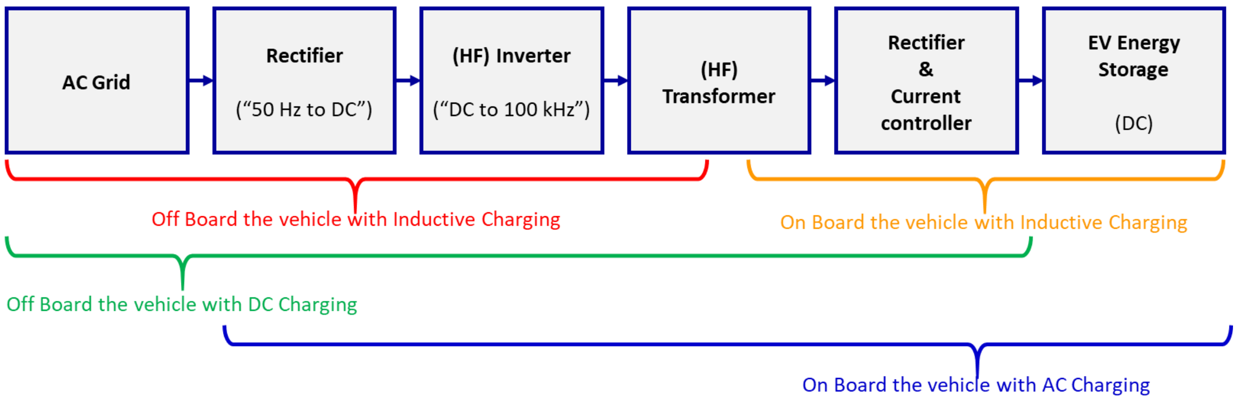

Figure 39. The functional block diagram of a generalized charger

[68] Commonly known as "inductive charging" although that term is technically incorrect.

There are several types of EV battery chargers that can be described by the block diagram of Figure 39.

The On-Board Charger
The On-Board Charger, the AC Charger, contains the five rightmost blocks of Figure 39 in the vehicle, thus only an AC voltage needs to be supplied to the vehicle. Since AC power outlets are widely available, all electric vehicles are equipped with an On-Board Charger (OBC). There are, however, two reasons why the power of OBC’s is limited: most AC power outlets are limited in power output and the size and weight of the OBC is limited by the vehicle.

AC power outlets in domestic buildings are usually limited to a few kilowatts. In Europe a 230V 50Hz 10A 1-phase outlet provides up to 2.3kW. With 3 phases and a 32A fusing the corresponding power is 22kW. Plug-in hybrid and full electric vehicles are usually equipped with an OBC that can handle an AC supply in this range, from 1 Phase 2.3kW to 3 Phase 22kW. 22 kW is a high electric power from a domestic energy use point of view, not all homes can provide that power level, but from a charging time point of view it is still a relatively slow process, providing about 100km or range per hour for a normal electric car.

One component that determines the size of an On-Board Charger is the transformer. The size of a transformer is inversely proportional to the frequency it operates at. To reduce the size of the transformer, the Rectifier and HF Inverter blocks of Figure 36 are used to increase the frequency of the power grid (50 or 60Hz) to 100’s of kHz, even MHz are possible.

The prospect of increasing this power by using a larger OBC, or parallel connections of several OBC’s, is not attractive, due to size and weight limitations. In cars the OBC power is usually limited to 22kW or less, but commercial vehicles have OBC’s with powers up to 44 or 88kW. Even so, 88kW is still a relatively low charging power for a commercial vehicle.

To increase the power without vehicle penalty on size or weight, it is necessary to move the charging components out of the vehicle, thus creating an Off-Board Charger.

The Off-Board Charger
The Off-Board Charger, the DC charger, contains the five leftmost blocks of Figure 36 not in the vehicle; thus, it supplies DC to the vehicle battery directly. Since most of the equipment needed is located outside the vehicle, the size and weight limitations are reduced. For this reason, the transformer function does not need to be minimized and the Rectifier and HF Inverter blocks of Figure 39 are often omitted, using a grid frequency transformer instead.

An Off- Board Charger can be designed to provide significantly higher powers than on-board chargers. Figure 40 shows some off-board chargers. Note that the charging stand (that looks almost like a fuel pump) does not contain the main energy conversion blocks of Figure 39; instead, these are mounted in a separate cabinet located nearby the charging stand.

Figure 40. External DC Chargers of various brands and the content of a related power cabinet

Inductive (Wireless) Charging

The inductive charger takes advantage of the possibility to split the magnetic core of the transformer in Figure 41 into two halves, one of which is mounted outside the vehicle (the primary side) and one that is mounted in the vehicle (the secondary side). It these two halves can be positioned close enough, energy transfer can be made without involving any plugs. Normally, the primary side is mounted on the ground and the secondary side in the underbody of the vehicle, see Figure 41.

Figure 41. Illustration of the inductive (wireless) charging principle

The distance between the primary and secondary side of the Inductive charger is normally equal to the ground clearance of the vehicle. From a transformer point of view, this gives a challenge to provide a reasonable charging power from a certain surface. To somewhat alleviate this challenge, a "z-mover" can be used, that either lifts the ground side part or lowers the vehicle side part before the charging starts.

Development trends in static charging

There are three main trends that describe the development trends of static charging equipment:

- The power level is increased towards levels limited by the battery and the connector plug to shorten the time spent on fast static charging.
- The need for automation is with few exceptions not accommodated by static charging systems but is expected to develop, not least due to the emerging of autonomous vehicle.
- Bidirectional capabilities, used in Vehicle-to-Grid, Vehicle-to-Infrastructure, Vehicle-to-Vehicle applications.

A large fleet of electric vehicles connected to the power grid represent a massive source of electric power and energy that, if controlled, can become an important player on the electricity market. Technologies that facilitate such operation are expected to develop significantly within the next decade.

Dynamic Charging systems

Systems that can provide a continuous electric energy supply to a vehicle while moving are referred to as "Electric Road Systems" (ERS). This is not a new type of infrastructure, it has existed for more than a century as supply to, e.g., trolley buses and even trucks in building sites. At the end of the 20th Century, companies began to look for alternatives to overhead lines as they were considered less aesthetic in urban environments, so the ground level power supply in the form of electrified rails that we see today emerged. There are several different types of electric road systems that can be used both in cities and on country roads. Further information on such systems is given in Section 4.1.1.3, below.

4.1.1.2 Fast charging

In order to increase the acceptance of e-Mobility, charging times must be drastically reduced. As a consequence, fast charging will enable new mobility modes for people and goods, to support the transformation of mobility behaviour.

Fast and super-fast charging must be an option for longer travel or emergency charging, even though the great majority of the charging procedures may be done at home or work with low-power. The required infrastructure for fast charging shall be robust, interoperable and should come with user centred services.

Fast charging is based on DC-charging. Different modes of transport and grid supply will foster different solutions, but efficiency will be key. It is expected that fast charging will be available in different power classes, including, for example, low voltage direct current for ePTWs. The current standard for charging stations refers to 500A enabling 350kW charging power. Additionally, there is a new global plug standard in preparation. The “Megawatt Charging System” will enable power levels of more than 3MW, in order to enable Long Distance Freight Transport use cases with heavy-duty battery electric trucks[69].

For a future decarbonized mobility based on electric energy, due to a higher charging rate, fast charging is an enabler for both long distances and for raising the customer’s interest for EVs.

Table 22. The definition or classification of fast charging for passenger cars

Charging mode	Power	C-Rate	Charging Rate	SoC
Standard charging	< 50 kW	< 1C	< 3 km/min.	< 90 % SoC
Fast charging	< 150 kW	< 3C	< 20 km/min.	< 80% SoC
Ultrafast charging	≤ 350 kW	> 3C	> 40 km/min.	< 70% SoC

Understanding the relationship between C-Rate and fast charging is key for any target (and limit) setting, for research and development of fast charging. C-Rate relates to the amount of time needed to reach the nominal capacity of the battery with respect to 1C achieving 100% SoC in one hour. Currently, the average C-Rate (over the capacity range) is up to 1C. For the future we expect from 1C up to 3C as normal for BEV[70], as an average C-rate during the entire charging time.

Accessibility is an important point for high-power charging. It can be assumed that conductive plug charging is limited up to 350kW, and to achieve this power rate, cable cooling is essential. Therefore, in order to reach comparable times for the “refuelling”, different interfaces should be considered. Should these cables be significantly heavier or hard to handle than existing refuelling equipment, adaptations might be needed to ensure ease of handling by disabled or older people. The availability and number of fast charging stations should also prevent delays for commercial vehicles, the charging times should be compatible with the mandatory rest periods.

Following the example of commercial heavy-duty vehicles, automated charging for opportunity charging is fully applicable for passenger vehicles. Instead of an overhead connector, underbody systems or charging

[69] Conductive plug charging is currently being standardized for power of more than 3MW (3000A @ 1000-1500V) by the CharIN truck charging workgroup, with more than 70 members across industries (truck OEMs, charging equipment manufacturer, cable and plug manufacturers, utilities, CPOs etc.).

[70] As of August 2020, the new Hyundai Iconiq 5 has a >2 C-rate, for example.

arm-robots are also under consideration: these could allow power transfer levels up to 1MW if the battery system permits higher charging rates.

On the other hand, wireless chargers (by induction) are also seen as a possible charging interface for high power charging. Nowadays, power levels up to 100kW can be reached but require a totally different system integration from that of the conductive charging system. Wireless charging is also an option for overnight charging[71], it represents a charging interface which may be shared for different vehicle typologies, from cars to trucks.

The required charging infrastructure technology and its deployment depends upon the type of EVs, their battery technology and their use. It is expected that, for the time being, EV technology will define the requirements for the infrastructure. In future, for example with solid-state batteries helping the electrification of heavier mobility applications, the power and charging process should be redefined accordingly with the technical requirements of this new technology[72].

Regarding the location and amount of fast charging infrastructure, it will depend on the specific topology of each country and city. In a city with a large percentage of private or work-place parking available, the need and, therefore, the amount of publicly available urban fast chargers will be significantly lower than a city with less private parking availability. Also, in a country with low population density and long distances between cities (for example France or Spain) an interurban fast charging network will be paramount; but not in cases of a high population density country with small distances between cities (for example The Netherlands). Thus, there will not be a “one-size-fits-all” configuration and the level of stringency of future policies regarding traffic in the centre of cities could have an impact in the urban deployment of fast chargers.

Pricing models depending on charging speed will also influence charging behaviour. Ultrafast charging will, in general, be more expensive than charging with lower power. In the end, it is the driver deciding which power best suits their needs.

Charging management systems and platforms are important tools to meet and steer the demands of the EV market. They are one of the most decisive factors to optimise the grid connections to the charging stations, i.e. by short-term and long-term demand prediction for charging and provision.

It is important to grow the infrastructure faster than the EV market. This is a challenge since the two markets have very different factors that influence the decisions for implementation. Thus, in a strongly increasing EV market with strongly increasing power demands, comprehensive, reliable and highly scalable systems are mandatory to cover the needs of the market in the future[73].

Interoperability means each vehicle can charge at each charging station. Interoperable fast charging should ensure full transparency of and interoperability for any vehicle at any charging station, to guarantee the availability of free and operable charging spaces, thus including charging power as a parameter for consistent planning is important. Or, in other words, the “ultimate goal” is to get the amount of charging that an e-Mobility customer really needs, at the right time (access), the right spot and the right charging

[71] Wireless Power Transfer (WPT) will be focussed, in the beginning, on residential and overnight charging use cases with power levels of up to 11kW. Currently there are several new passenger vehicles in preparation for large-series production at European and Asian OEM with 11kW WPT functionality.

[72] Fast charging solid-state batteries with higher power levels than today’s battery technology remains to be proven at higher TRL (see the BATT4EU SRIA, SA 7 – Advanced materials to enable ultra-fast charging has TRL5 in 2023 and TRL7 in 2027)

[73] For example, a simple estimate of the power to be delivered on the parking lots on motorways with heavy traffic use, leads to approximately 50 fast charging stations for trucks and 200 for cars every 100km, with a total power of 40 MW (assuming a flow of 5,000 trucks per day, 40% on long distance trips, i.e. 2,000 truck to be fast charged over 24 hours, twice as many vans and 5 times as many cars, with some peak loaded hours. Thus, approximately, 30 slots for trucks @ 600kW, 60 slots for vans @ 150kW and 150 slots for cars @100kW would be required on a parking lot, i.e. 42 MW, which is more power than on a large airport today.

power. Cross-border charging opportunities have to be established within Europe, ensuring charging independently of the vehicle, the country and the energy provider; roaming must support the driver's needs at both national and EU-wide levels.

In terms of the communication protocol, PLC and wireless interfaces may coexist in order to allow launching communication with the EV before it reaches the charging point, providing positioning aids (such as buses with the Oppcharge protocol). Therefore, the charging preparation process can be reduced in time (done during the EV approach), advancing the power transfer process, improving the user perception on the charge quickness. For high power charging, the communication interface (HW and SW) for the external converter control (V2G communication) will be required, in order to avoid safety issues and to ensure the compatibility with all BEVs in the market (which may be affected due to the noise induction over the CPLine causing charge abortions). At higher current, there is a higher risk of electrical noise induction over the line that contains the analogue PWM communication and the high-level PLC. WLAN communication uncouples the high-level communication from the power lines, so could be a feasible option for high power charging. However, WLAN could bring different issues related to robustness, crosstalk and a tampering and/or hacking risk.

Additionally, an in terms of charging system development, a sustained fast charge should be the main goal for the OEMs[74] to improve user's fast charging perception. Nowadays, we see very different behaviours depending on the vehicle, some of them are capable to charge at super-high rates but just for a very limited SOC window (10-25%), in other cases, there are vehicles which provide a mainly constant charge rate from 0 to 80% approximately, see for example the data in Figure 42.

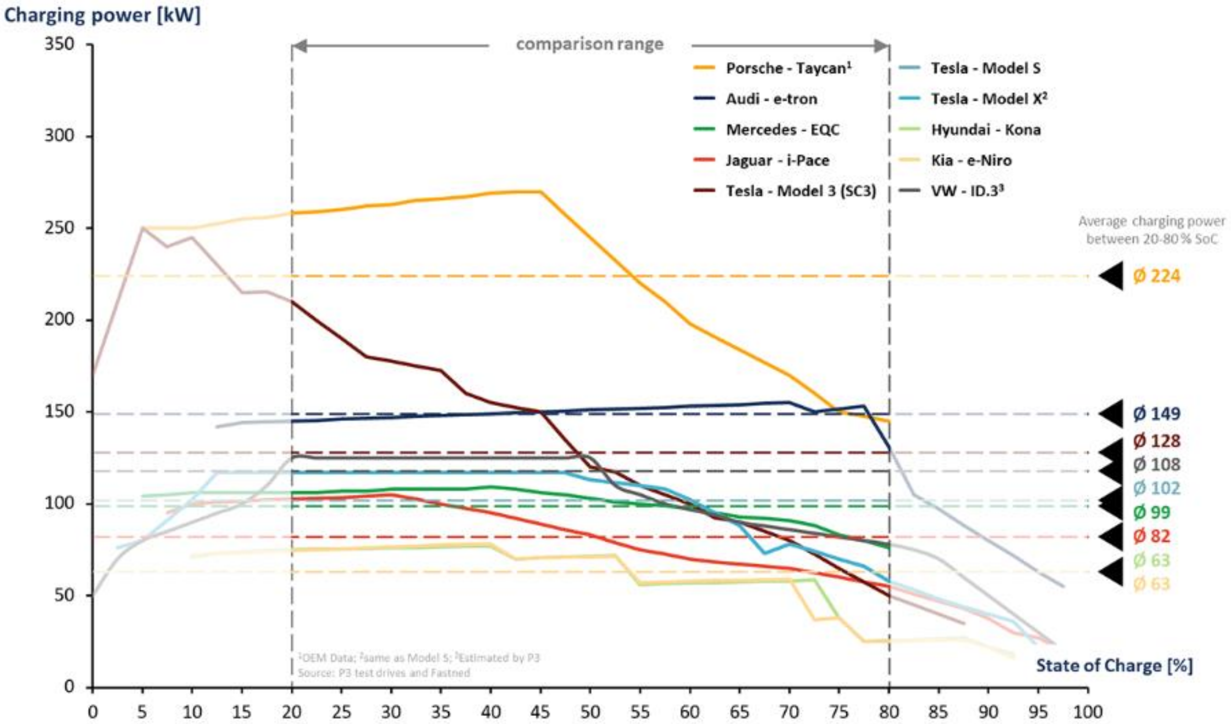

Figure 42. The different charging profiles from different BEV models (P3 study)

[74] ACEA, together with Transport & Environment have made clear statements, pushing for binding national targets in AFID, regarding the urgent need of deployment of stationary charging infrastructure (and H_2 refuelling) in Europe. https://www.acea.auto/press-release/zero-emission-trucks-industry-and-environmentalists-call-for-binding-targets-for-infrastructure/.

4.1.1.3 Electric Road System Charging

An ERS enables the transfer of electric power from the road to vehicles whilst in motion, vehicles can easily connect and disconnect to the infrastructure, running with or without using the system. ERS has seen development in the past ten years: solutions are currently being tested on several highways and municipal roads in Europe. Interest in the system is motived by its ability to achieve many of the benefits of electrification (e.g. low operating costs, low WTW GHG emission and zero tailpipe emissions), without the limitations otherwise imposed by current batteries (size, weight and cost) and stationary charging (e.g. time lost whilst standing still). This is particularly relevant for the electrification of commercial vehicles with high daily mileages, whereas the widespread application of dynamic charging to personal vehicles has yet to be shown relevant. Some analysis shows that electric road systems on the busiest motorways could be an economical alternative to diesel fuel. However, across Europe there is still discussion about a viable scale-uprate, hence the time necessary to build-up a sufficient network to realise an impact in a timely manner: this is also related to the electricity grid capability in different countries[75]. In general, electric road systems may need additional powerline infrastructure to reach remote sections of highway.

Concepts

Currently, there are three main concepts, with different degrees of maturity, as shown in Figure 43.

An **overhead contact line solution** uses conductive wires (also known as **catenaries**) above the vehicle to provide the energy. The energy is transferred to the vehicle by means of a power receiver device (called a pantograph) installed on top of the vehicle, which follows and detaches automatically from the overhead contact lines. This concept builds on expertise, components and standards from railways, light rail and trolley buses[76].

An **in-road solution** for conductive energy transfer from roadway to electric vehicles uses **conductive rails** installed in or beside the road to provide the needed energy. The energy is transferred to the vehicle via a power receiver pick-up arm installed beneath the vehicle, which follows and detaches automatically from the rail[77].

An **in-road wireless solution** uses induction via a magnetic field to transfer the energy. Electric current in primary coils installed in the roadway create magnetic fields which induce current in a secondary coil installed beneath the vehicle[78].

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[75] The German authority "The Federal Ministry of Transport and Digital Infrastructure" have made a roadmap towards climate friendly commercial vehicles. In their perspective it is clear that stationary charging is the way forward for city distribution and regional haul. For LH BEV they have a decision point for fast/ultrafast charging infrastructure in 2024; the decision for electrified road systems is expected between mid-2024 and the end of 2025. https://www.bmvi.de/SharedDocs/EN/Documents/overall-approach-climate-friendly-commercial-vehicles.pdf?__blob=publicationFile
The road transport department in Sweden have, in a recent, study clearly stated that ERS are, in almost every possible scenario, not a financially viable solution (and environmental impact low), but stationary charging is financially viable and have a higher environmental impact. This study is based on real vehicle data from Scania and Volvo. However, the interpretation of the results is still a matter of debate. http://trafikverket.divaportal.org/smash/get/diva2:1540415/FULLTEXT01.pdf (only in Swedish).
The French Ministry of Ecological Transition (in charge of transport), in 2021, committed three working groups to analyse the environmental and economic potential of ERS, the pros/cons of the available solutions etc. Reports are available: https://www.ecologie.gouv.fr/lautoroute-electrique (also available in English); An updated analysis is published in 2022: "Les routes électriques (ERS)", RGRA N°989, Mars-Avril 2022, https://www.editions-rgra.com/revue/989 .
[76] One demonstration was carried out in Sweden on an open road (2km) in 2016-2020, and three real life trials are being carried out in Germany since 2018, 2019 and 2021; trials have also taken place in the USA. Catenary systems, together with stationary chargers and hydrogen stations, are part of the German transport ministry's 4.1bn€ scaling-up effort during 2021-2023 that shall lead to one third of all HDV kilometres travelled to be powered by electricity by 2030.
[77] Tests and demonstrations have been running in Sweden: a test track was developed over a few hundred metres in 2017 with a flat rail (see Figure 40), and a demonstration project, with a hollow rail, has been running on a 2km section of a national road since 2018 and another demonstration of a different conductive rail technology has been carried out since 2020 on a 1km municipal road.
[78] A demonstration project is running in Sweden since 2020 on a 2km municipal road using a rigid truck, a 2km test track is equipped in Italy (tests are starting in 2022), and some tests are planned in France and Germany.

Figure 43. Different electric road system configurations and demonstration

Table 23. The advantages and disadvantages of different ERS. Adapted from Source [4.1] but also see[79]

Tech:	Overhead conductive	Ground-conductive	Ground-inductive
Pro's	• Medium to high power[80] transfer and efficiency, at up to highway speeds • No impact on the motorway surface and interior • Based on mature technology	• No major visual impact • Medium to high power transfer (more than some other technologies) • Technology suitable for charging all vehicles with various power needs	• Not visible for outside viewers • No interference with the road operation after installation • Potentially, no add-on technology with moveable parts • The power receiver is not subject to mechanical wear • Technology potentially suitable for charging all vehicles
Con's	• Visual impact • Allocates space over and alongside the motorway • Pylons need protection via safety barriers • Imposes an overhead obstacle • Risks should the catenary system fail[81] • Drag forces of the pantograph • Abrasion of the overhead line, generating particles • Extensive use of copper • Not suited to small vehicles	• Impact on the road structure (groove in the surface) • Adaptation of the machines to renew the pavement upper layer without removing the rail • Exposed rail in the roadway surface: provisions to be taken to ensure a good skid resistance and winter operation[82] • Need for maintenance due to dirt, snow and ice (for the hollow rail) • Risk to and of the pick-up arm in the case of accident or emergency	• Impact on road structure during installation. • Medium to low lateral tolerance • Generates magnetic field for the low to medium power transfer per coil and a lower efficiency • Limitation of the power to be transferred to the vehicle[83] • High use of copper[84]

[79] Analysis carried out in https://www.ecologie.gouv.fr/lautoroute-electrique and on-going by PIARC in the TF2.2. See also the reports of the Swedish demonstrations mentioned above.
[80] However, with some limitations for a series of trucks traveling at short distances (50 m), above all on slopes.
[81] The rate of pantographs could be approximately 100 times more than on the railway (up to 10,000 per day versus less than 100). Moreover, the high frequency dynamic variations of the altitude of the pantographs (pavement evenness plus truck suspension and tyre strains, much higher than on railways, may impose shocks on the catenary and electric arcs.
[82] The latest developments of the flat rail technologies seem to satisfy these criteria.
[83] With the current technology, induction could not feed the most demanding trucks (300kW and above), which would also refrain powering and charging the vehicles simultaneously. However, the technology is progressing.
[84] The inductive technologies may use almost as much copper as the full battery solution (https://www.editions-rgra.com/revue/989), whilst the other dynamic charging technologies would save a significant amount of this material.

Energy efficiency & TCO

Achieving a high energy efficiency is essential to realizing the potential of electric road systems[85,86], as several key benefits, such as low operating cost and low WTW emissions, stem from this. The energy efficiency, achieved in existing overhead ERS projects, whilst driving at 90km/h on motorways, is above 90% from the electric grid to vehicle propulsion (for conductive systems), and between 70 to 90% for inductive systems. For other solutions the results from real-world experiences are limited.

Since, in most European countries, a majority of the road freight transport is concentrated to a few percent of the national road network, hence limiting the needed infrastructure investment, ERS can result in a lower TCO compared with other electrification solutions, biofuels or even conventional diesel (especially on roads with high traffic volumes, as shown in some reports[87]).

Roadmap, European dimension and Standardization

To achieve the full-scale benefits of electrified road systems, the first step will be to pilot the system by electrifying shuttle routes, e.g. 20-100km long sections between ports and logistics centres, or on environmentally sensitive routes, where a high number of trucks go back and forth. Subsequently, those shuttles would be linked-up to form sections of a growing network. In that phase, the flexibility of dynamic charging, mentioned in Section 3.5, can be used together with other fuels and powertrains. Specifically, in this stage, the use of hybrid trucks enables a smooth transition from the current fossil fuel regime to an increasingly electrified one. In the last stage, the network nears completion (with links established between Member States), this acts as a catalyst to transition the truck fleet away from hybrids towards fully zero-emission vehicles, e.g. BEVs and FCEVs equipped to use the ERS[88,89]. Analysis in Germany shows that 89% of truck trips beyond the motorway are 50km or shorter, meaning that electric road trucks could have a fairly small battery and still perform nearly all missions electrically. Such a truck could be affordable, thus lowering a barrier for uptake of new truck technologies by small logistics operators.

Many European countries have expressed interest in electrified roads (including Sweden, Netherlands, France, Italy, Austria, Hungary and the UK). Although larger countries (eg. France or Germany) may be able to justify investments independently, a joint approach could achieve greater benefits economically and in terms of emissions reduction: however, this would require agreements on technical issues to be reached early on[90].

The standardisation of the various dynamic charging technologies, including the interfaces between different sub-systems, is on-going. Further attention to secure a seamless cross-border operability is essential. The remaining main challenge is legal certainty. Dynamic charging systems are related to both power grids (Directive 2009/72 /EC on the electricity market and national laws) and roads (national laws and Directive 1999/62/EC for tolls and user charges). This will have an effect on energy metering, data collection, enforcement, access control and the business model.

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85 See Bossel, "Useful Transport Energy from Renewable Electricity", 2006 and https://youtu.be/bEdcdsLC88Y?t=6158

86 The hydrogen efficiency is 27% with electrolysis (60% for the electrolysis, 90% for compression and 50% for the fuel cells).

87 Source 4.2, also BMVI, Öko-Institute, ICCT, UC Davis, IEA, French Ministry of Ecology Transition and RGRA (https://www.editions-rgra.com/revue/989).

88 Note the data shown there is from a specific study in Source [4.3], this data is different to that used in the ERTRAC study, sources [1.1] and [1.2].

89 The scenario recommended in the French report: https://www.ecologie.gouv.fr/sites/default/files/GT1%20rapport%20final.pdf is different. It is recommended, after the pilot and a choice of a harmonized technology, to develop (in France) 4,900 km of electrified roads over 5 years (by 2030) and 3,950 km by 2035. An extensive economic study was carried out to prove the advantage of such a planning.

90 In Germany, the National Platform for Mobility of the Future (the main policy advisory body for the transport ministry) in June 2020 recommended that 4,000km of highways be equipped with ERS by 2030, in order to secure reaching the 40% reduction in transport CO_2 that Germany has committed to. In France, the study carried out by the French Ministry of Ecological Transition in 2021, recommended that 4,900km of motorways be equipped with ERS by 2030, and 3,950 more km by 2035. Doing that, no location would be further than 125km from an electrified motorway, allowing covering the whole territory with a range of 250km on battery. The reduction of CO_2 for the fleet of trucks and vans would be 86% by 2040.

4.1.2 Grid integration

PEV[91] charging loads can have numerous positive and negative impacts on the distribution grid, depending on the PEVs spatial and temporal behaviour, the characteristics of the charging infrastructure and of the distribution infrastructure, including age, utilization, peak load and presence of other distributed resources, such as solar PV.

Whilst global BEV proliferation will have a relatively small impact in the global electricity demand (if all passenger cars were electric in Europe, this would represent an increase of 17% of the total electricity consumption in Europe, less than 1% yearly growth projected until 2040), uncontrolled charging would substantially increase the power peak load of the global system, potential local grid instabilities and would lead to local grid congestion, requiring further investments in grid reinforcements and in peak power plants.

Grid reinforcements associated with new electrified uses is “business as usual” to European DSOs[92] and TSOs[93]. For instance, the Spanish electricity demand grew as much as 6% per year between 1997 and 2007 and the required grid investments were carried out assuring supply security.

EVs will represent 3,955GW.h of total storage capacity in 2040, equivalent to approximately 20% of the highest power demand in EU and half of today’s daily EU electricity consumption. This storage capacity will offer new opportunities for consumers and the power system, which could benefit from a great source of flexibility (see Figure 44), under efficient market signals and based on the development of user-centric technologies such as:

- Smart charging: consumers can shift charging to other times, either through a price incentive (Time of Use (TOU) charging) or direct control (V1G)
- Vehicle to grid (V2G): consumers can use their EV batteries to provide energy and non-energy remunerated services to TSOs (frequency regulation, balancing etc.) and DSOs.
- Vehicle to home/business: consumers can use their EVs to power their homes or businesses, combined or not with self-consumption (the battery on an EV contains ~3-4 days of the electricity consumption of a normal home).

For these new opportunities, for businesses to happen, all involved stakeholders will have to work together to develop awareness and acceptance by users. The value of using EV batteries to support electricity grids will have to be shared between stakeholders, including EV owners.

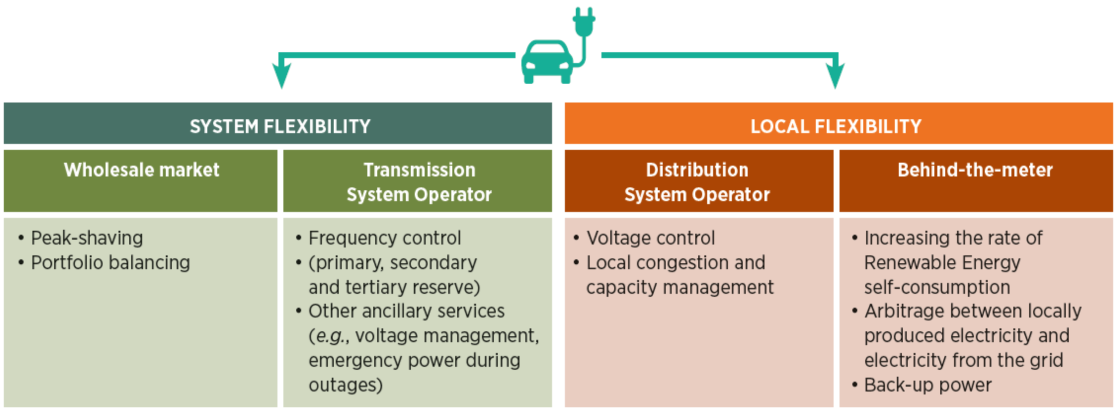

Figure 44. IRENA smart charging for the electric vehicle revolution

91 PEV stands for Plug-in Electric Vehicles, it includes BEV and PHEV.
92 DSO stands for Distribution System Operator (low and medium voltage power grids).
93 TSO stands for Transmission System Operators (high and ultra-high voltage power grids).

4.1.2.1 *Smart charging*

Smart charging, during off-peak periods and when demand and network congestion is otherwise low, means that consumers can potentially benefit from cheaper pricing when charging, future network reinforcement and its impact on electricity costs can be avoided. Smart charging might save 60-70% of the required grid reinforcement investment needed to serve a fully electrified light duty vehicle fleet (see Figures 45 and 46, for example).

There are two main types of “managed charging” for PxEVs, which adjust the time and speed of charge:

- Time-of-use (TOU) Charging: drivers are incentivized by a lower electricity rate price to charge during off-peak hours, usually pre-programming the start time through the charger or PEV. For example, day-time off-peak tariffs in Spring may be proposed by utilities to encourage charging during times of high solar PV generation.
- V1G, referring to unidirectional power flow to vehicle from grid: the PEV participates in a demand response (DR) programme that controls active charging to be on or off or at a different speed through the charger or vehicle software but does not allow for the discharging of the PEV battery back to the grid. Under a DR programme, electricity usage is adjusted (typically reducing use or shifting use to other times in the day) at certain times in response to price signals or other conditions. An aggregator (utility or private company) usually directly controls charging for many vehicles at once to shift charging to times that provide the most grid benefit when prices are low or renewable energy is abundant.

TOU charging is already used by utilities while V1G programmes are still in the pilot phase.

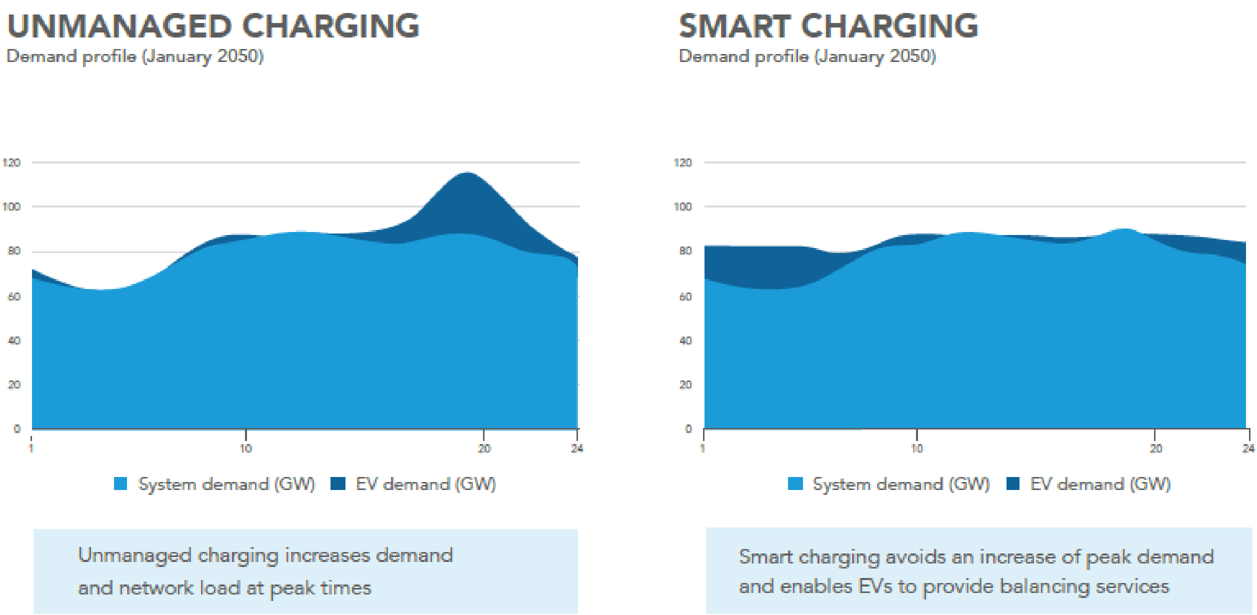

Figure 45. The profile of EV charging under both unmanaged (left) and managed (right) scenarios for a 100% electrified fleet. Source [4.4][94]

[94] The EV demand shown only applies for BEV solutions with stationary charging, it does not include the demand when using electrified road systems.

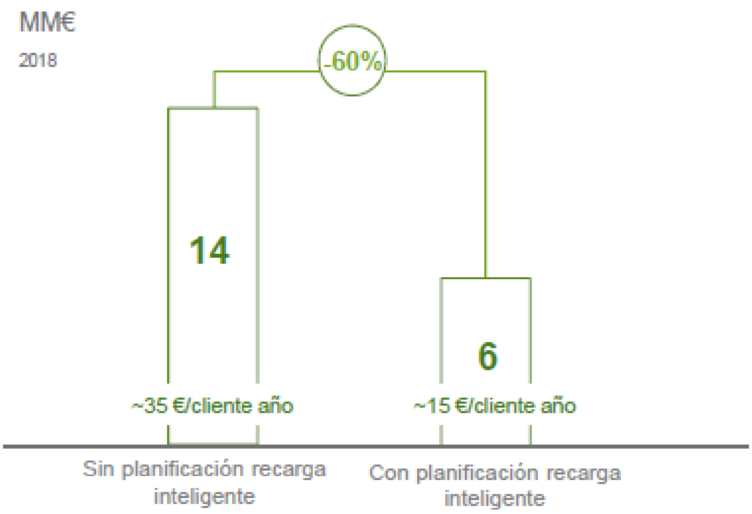

Figure 46. The investment required in Iberdrola's distribution grids in Spain, UK, USA and Brazil: unmanaged (left) and managed (right). Scenario: Full EV penetration estimated in all these regions except for Brazil (30%)[95]. Source [4.5]

Smart charging (V1G and V2G) technologies will require the development of standards, as the basis for communications between electric vehicle, charging point and DSOs that allow dynamic and advance smart charging. It will also require data sharing related to batteries between vehicles and trusted smart charging service operators, which must be made safe and secure.

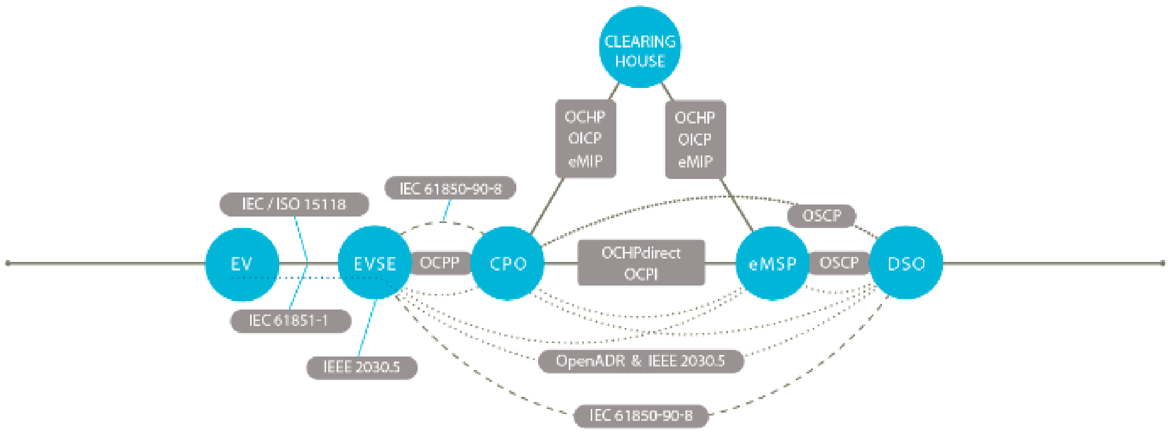

Figure 47. Standardized interface needs for smart charging. Source [4.6]

With an efficient integration, TSO and DSOs will achieve more cost-efficient operation and avoid unnecessary grid investments, whilst allowing more solar and wind power integration, reducing curtailment (wasted energy) and, ultimately, reducing the CO_2 emissions.

The net benefit of smart charging depends on the dominant renewable energy source in each country:

- In wind-dominant countries, overnight EV charging can absorb excess of renewables as well as avoid increased in peak load on the distribution network.
- In PV-dominant countries, daytime workplace charging may be the most advantageous way to absorb excess of renewables.

[95] Same conclusions are presented in the French TSO study on smart charging, May 2019.

In both cases, smart charging will prevent local grid congestions, overload or instabilities, and their associated investments.

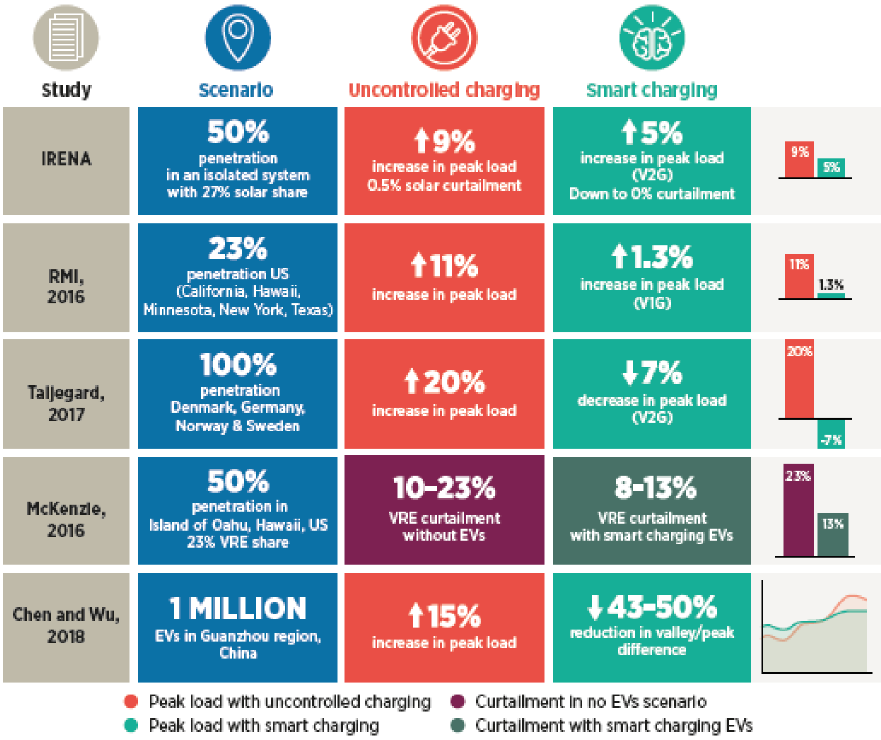

Figure 48. Smart charging for electric vehicles (IRENA: Examples of studies assessing the impact of EV charging strategies (Figure 34)). Source [4.7]

4.1.2.2 Vehicle to grid (V2G)

An aggregation of PEVs (similar to smart charging) could act as storage for the grid, by charging over some hours, storing the energy in the car battery and then discharging some energy back to the grid. Under V2G, PEVs could also provide some ancillary services to the grid, continuity of energy supply, peak load shaving, or compensation of the reactive power.

Providing flexibility services to the TSO or DSO would offer early revenues for EV owners. However, net benefits depend on flexibility services prices, which vary among Member States and are subject to regulatory changes (see Figure 49, which shows how benefits or disbenefits may arise, each as a consequence of local regulation).

Several V2G programmes are already in the pilot phase. Nevertheless, the decision to participate in grid integration will ultimately rest with the customers. EV usage profiles, user-centric technologies, regulatory measures and mobility patterns (i.e., ownership, mobility as a service) will be the key drivers to efficiently integrate BEV in the power grid[96], yet these must be balanced with the possible impacts on the vehicle battery life, hence overall benefits for the vehicle owners or users must be determined.

[96] See https://www.reutersevents.com/sustainability/why-v2g-holds-key-electric-vehicle-revolution: "Cycling the battery while the car is stationary has no negative impact and is a very stable way of removing electrons…Individual drivers are likely to be more reluctant to allow their cars to be used like this, in part because of the loss of flexibility and also because of concerns about battery deterioration from repeated discharges."

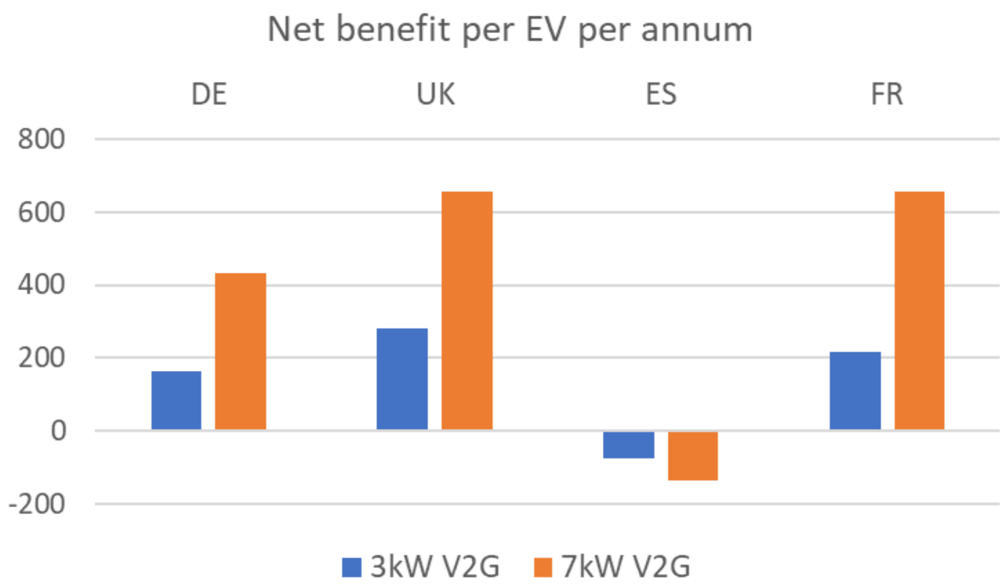

Figure 49. Vehicle to Grid net benefit (€) in Europe per PEV per annum. Source [4.8]

Vehicle to home/business
Vehicle to home is already technically feasible and has many benefits in DC houses[97]. It can be used for peak shaving, reducing the cost of the fixed part of the electricity contract in most of the EU Member States. With TOU pricing, the battery of the EV can be charged at night and used during peak pricing instead of a grid supply, also decreasing the electricity bill. Coupled with solar generation, the battery can be used to store potential excess RES electricity during the day and make it available after sunset. Business case is directly related to self-consumption regulation.

4.2 Liquid fuels

In Europe today, more than 120,000 service stations are available to consumers, often at almost every other street corner in populated areas. The most important properties of liquid fuels are well-understood by vehicle manufacturers and by consumers: their properties have been continuously improved over many years to produce high-energy, high-value, economical and trouble-free products. On an average day, more than 25 million vehicles are refuelled with approximately one billion litres of liquid fuels. These service stations are refuelled from a sophisticated and highly developed supply and distribution network that consists of refineries, blending terminals and service stations, efficiently interconnected by pipelines, barge operations and delivery trucks. Approximately 36,000km of pipelines ensures the efficient movement of crude oil and refined products across Europe. Blending terminals are typically used to mix in certain bio-components, especially ethanol because of its affinity for water, before the finished product is delivered to the service station, whilst minimizing water separation and corrosion. Similarly, conventional biodiesel components (FAME) can increase the potential for materials incompatibilities and contamination in manufacturing and distribution: fuel supply and distribution systems have been engineered to minimise these problems over a range of environmental and climatic conditions. Major research is currently not needed because most problems can be resolved through proper materials selection, quality control, and supply system housekeeping.

[97] https://www.edsoforsmartgrids.eu/wp-content/uploads/EDSO-paper-on-electro-mobility-2.pdf
ELECTRIC VEHICLES AND THE CALIFORNIA GRID, NEXT 10, JULY 2018.

Liquid renewable or synthetic fuels produced by thermochemical or catalytic processes, by hydrogenation of vegetable oils or electro-fuels undergoing a Fischer-Tropsch conversion have less of an impact on the distribution system. In the future, there may be a growing preference for these renewable or synthetic liquid fuels whose properties are similar to fossil hydrocarbons as a means to reduce system incompatibilities and improve vehicle performance. In this scenario, fuel supply and distribution system can be expected to be less sensitive to advanced biofuels and electro-fuels blends as the quality and the chemical structure of renewable components improve. In an alternative scenario, some research questions may arise as new fuel types and blends may enter the market. For example, there can be problems with spark ignition engines using blends of high biofuel content distributed by pipeline; or compatibility issues with compression ignition engines using blends with a high rate of oxymethylene dimethyl ethers (OME).

More information regarding the performance of different types of biofuels and electro-fuels in current and future vehicle technologies could help ensure the best and most economic selection of renewable components. Since service station tanks and pumps are frequently difficult to retrofit, logistics and market scale-up become increasingly difficult if new engine configurations are introduced to the market requiring a specific fuel that is not routinely available at the service station. Better integration and optimisation of fuel, engine and vehicle also requires the development of robust standards for liquid and gaseous blends.

Energy tax revenues represent an important share of total tax revenue for Member States. Fuel taxation represents between 3% and 4.5% whereas other energy taxes (such as electricity and gas) represent close to 2% (see, for example, Figure 50).

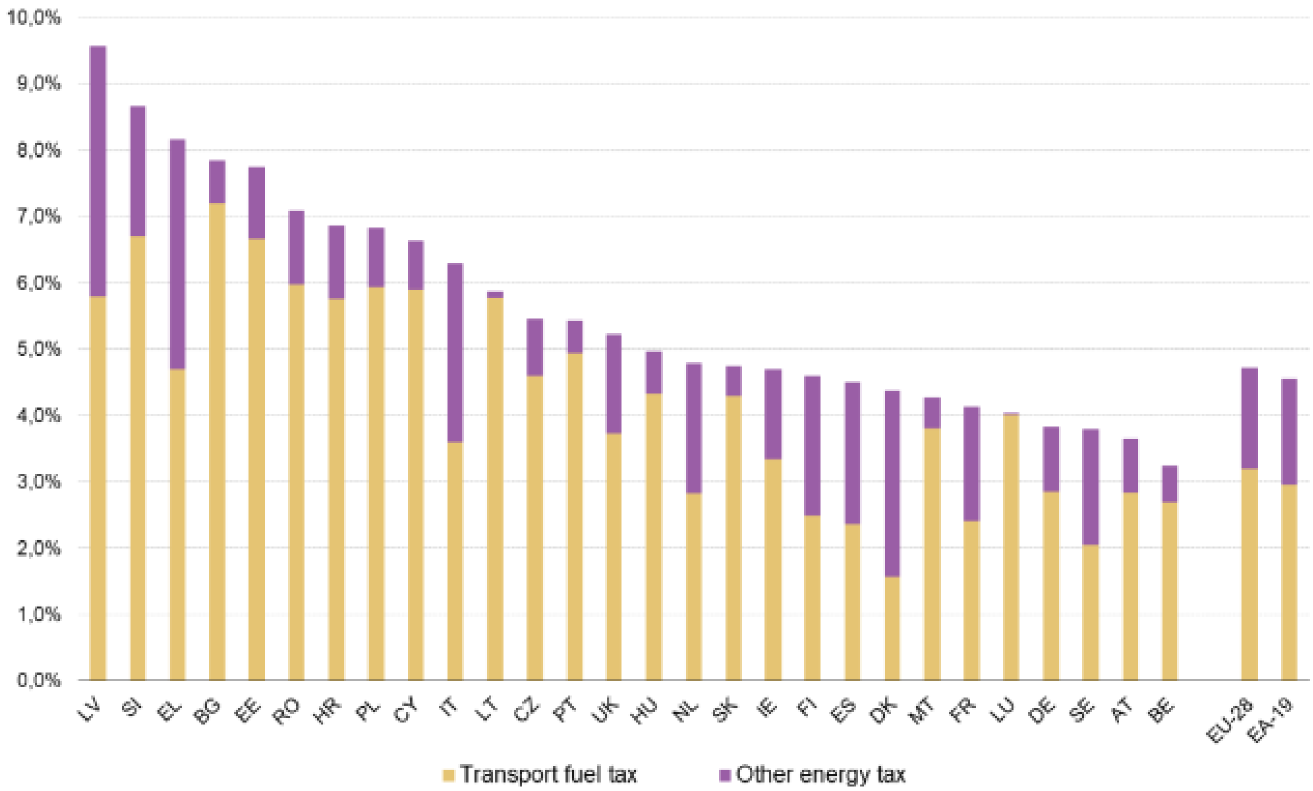

Figure 50. Energy tax revenues per Member State relative to total tax revenues, 2017. Source [4.9]

4.3 Gaseous fuels

4.3.1 Natural Gas Infrastructure

Today, the natural gas infrastructure represents an important asset in Europe: it is composed with approximately 200,000km of high-pressure pipelines for gas transmission, and more than 2,200,000km of low-pressure pipelines for gas distribution. All this system ensures the transport of a huge amount of energy over long distance in a cost-effective way.

Gas storage facilities offer the capability to manage large amounts of energy, providing flexibility to the energy system to match the seasonal demand (today energy peak demands are met by thermal and hydropower plants (up to 85%)) contributing to the security of supply and offering a low-cost storage system for a wide family of renewable energies.

On top of that, the gas infrastructure also contributes to the diversification of the energy supply (so also to the security of supply) and ensures the connection of the EU system to the global LNG market. Looking to the direct utilisation of LNG in the transport sector, this is key to support the maritime sector as well as in the heavy-duty applications (trucks and coaches).

4.3.2 CNG and LNG refuelling infrastructure

Over the last years, considering natural gas as playing a role as a transitional fuel, Europe has improved the development of the refuelling infrastructure at an average rate of 200 new CNG stations/year and 50 new LNG stations/year. The development of the LNG refuelling infrastructure is relatively recent, considering that in 2014 Europe just had a first network of just 30 stations. The refuelling infrastructure as of end 2019 is reported in Figure 51. It is important to understand how and how much renewable gas can be integrated into this infrastructure in the future.

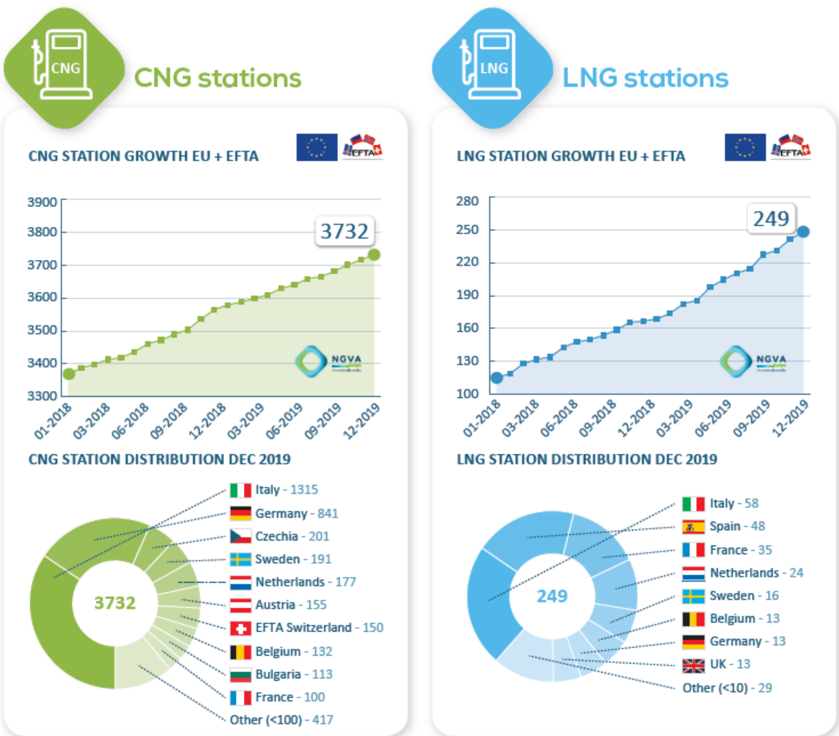

Figure 51. Development of CNG and LNG refuelling stations in Europe

4.3.3 Integrating renewable gas

The natural gas infrastructure and vehicle technologies are fully compatible with renewable gas, when the appropriate purity is controlled, thus offering a wide flexibility in managing the progressive injection of methane produced from different pathways. Anaerobic digestion processes, thermal gasification and Power-to-Methane pathways are all leading to the same molecule, which can be both injected into the grid or used in vehicles.

Hydrogen blending in the natural gas grid is an interesting additional option in the future. This will need analysis about the compatibility and the adaptability of the systems (distribution grid, station compressors and storage system, vehicle storage and feeding system, impact on combustion process) plus the maintenance of safety standards.

4.3.4 Hydrogen Infrastructure

Unlike other fuels, currently there is a lack of infrastructure and uncertainty in its deployment, in order to bring hydrogen to hydrogen refuelling stations: this should be taken into account in the evaluation of the deployment of the FCEV and H_2 ICE infrastructure.

The contribution of FCEV (and other hydrogen-based powertrains) to decarbonisation in all modes of transport can only be realised if an appropriate infrastructure is established. Therefore, the rapid expansion of hydrogen refuelling stations is needed and equivalent considerations as to the handling of the refuelling equipment (as for fast charging mentioned above) need to be made. An appropriate framework to invest in the hydrogen refuelling infrastructure should reflect the multi-faceted solutions that hydrogen technologies can bring to the transport sector's decarbonisation (i.e., multi-purpose HRS at strategic locations for several applications (e.g., airport GSE + public HRS)). The sector foresees a need for at least 3700 HRS by 2030, based on the Hydrogen Roadmap for Europe (see Figure 52). These HRS should be capable of servicing 1t H_2.

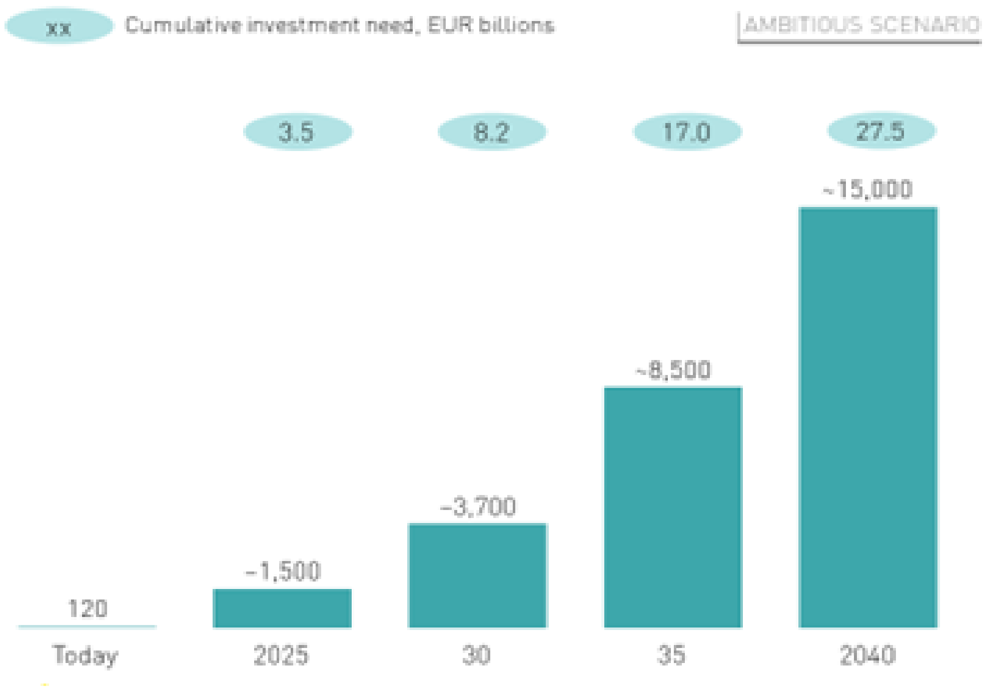

Figure 52. Hydrogen refuelling station development requirements

However, today's infrastructure is rather limited, with the majority of the publicly available stations based in Germany, France, Denmark and the UK (see Figure 53 below).

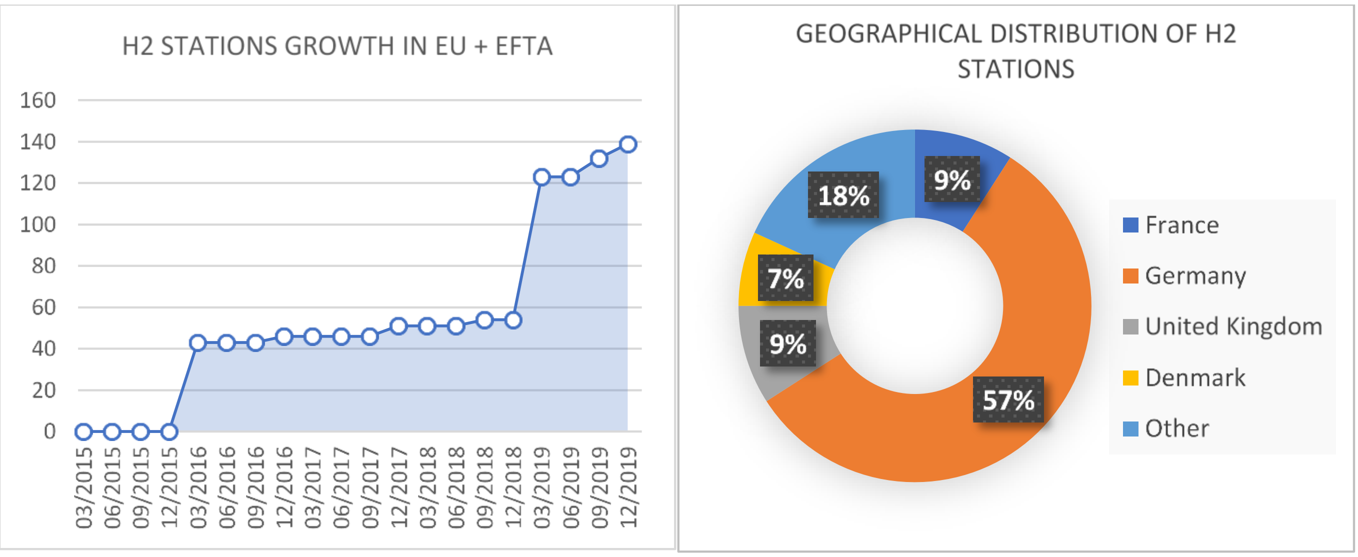

Figure 53. Hydrogen refuelling station distribution around Europe. Source [4.10]

4.4 Other infrastructure aspects supporting efficiency

4.4.1 Electric Road Systems (ERS)

Independent of which dynamic charging technology (overhead or ground conduction, or wireless (induction)) is used, the road infrastructure and the maintenance of that will be affected, although the effect varies noticeably between the options. Additional research would be needed, as listed in Chapter 6.

4.4.2 Road construction and maintenance relevant to fuel efficiency

It is known that road geometry (hills, curves etc.) has a large bearing on fuel efficiency and accordingly roads are designed in hilly areas to minimise inclines through cut and fill, travelling alongside the side of mountains of through the use of bridges or tunnels. Realistically, there is little option for retrofitting systems. Increasing the efficiency of bridge or tunnelling methods may improve the benefit cost ratio for some new schemes.

The condition of the road surface itself also plays a role in the fuel efficiency of vehicles. Bumpy and uneven roads or those with potholes are not only less comfortable for drivers and passengers, but also result in increased suspension travel than smooth roads. The net result, other than increased wear and tear on the vehicle, is increased energy use: fuel or electricity that should be used to propel the vehicle forward is being lost in the wheels moving up and down.

The case for on-going research in improved road construction and maintenance techniques remains strong. Research should be considered for areas listed in Chapter 6.

4.4.3 Alternative fuels and road construction or maintenance

The impacts, either positive or negative, of alternative fuels, such as liquid or gaseous biofuels on road construction, operation and maintenance are likely to be negligible.

The impacts of future battery powered vehicles might be more significant, given their different mass and wheel torque characteristics, hence require research. There is currently a relatively low penetration of electric cars on the road and those that are, have tended to be built on a standard vehicle chassis. For larger vehicles, the penetration level is lower still.

The loading impacts of future battery vehicles on highway infrastructure should be researched, including the vibration frequency of the powertrains. It is known for example, that road surfaces and bus bays can suffering rutting and deformation through the engine vibration of stationary buses. The vibration frequency of electric buses and other heavy vehicles will require investigation.

Research should be undertaken on the use of alternative fuels and powertrains in construction machinery and non-road machinery, taking into account current and future emission standards.

5 A systemic view and expected impacts

5.1 Introduction

In the preceding chapters, the state of the art and likely developments in three aspects of road mobility (energy carriers, powertrain technologies and infrastructure) have been presented, such that future research needs could be identified (as collated in Chapter 6) given the constraints of any technology roadmap. In this chapter, an alternative approach is taken to determine identifiable further research needs. Given the overall goal of net zero CO_2 emissions road mobility by 2050, possible scenario solutions for that time are considered, based upon the workings and findings of the ERTRAC CO_2 Evaluation Group[1]. Subsequently, specific individual uses cases are suggested: envisaging these use cases can help to identify yet more possible needs for research[98]. Finally, looking from the possible situation in 2050 back to the 2020's, helps to visualize possible issues along the route from today towards a net zero carbon road mobility system in by mid-century: such a system perspective over time can help to recognize further possible issues and the necessary research to help address them.

5.2 Net Zero GHG Road Mobility Scenarios for 2050

The ERTRAC CO_2 Evaluation Group posed and generated answers for some relevant questions using a scenario approach:

- Which technologies can support net GHG-neutral[99] road transport?
- How large is their specific effect?
- What could be the fleet and fuel impact?
- How much energy and which energy (carrier: electricity, hydrogen and or synthetic fuels) is needed for road transport?
- Which energy paths do we have and how much electricity is needed to produce the different energy carriers?

from a well to tank (WtT) plus tank to wheels (TtW) basis. The WtT basis included four extreme fuel mix scenarios, individual feedstock routes and two difference scenarios for electricity production, but not the energy needed to create a battery that is capable of storing energy. The TtW basis included rising transport demands between 2020 and 2050 as well as different activity profiles, efficiency measures (optimistic and pessimistic) and vehicle fleet (parc) compositions. The study considered three different powertrain scenarios within those vehicle fleet (parc) compositions: Highly Electrified including Electrified Road Systems (HE-ERS); Highly Electrified including Hydrogen (HE-H); Hybrids Scenario (HYB).

Some specific conclusions were drawn from this evaluation:

- To achieve GHG-neutral road transport (WtW) in 2050, drastic changes are needed in all three areas: Vehicle fleet and efficiency, powertrains and traffic technology; Infrastructure; Energy production (electricity, hydrogen and renewable fuels).
- The complete and robust GHG-neutrality of road transport could be achieved with a mix of technologies, where electrification is the key element for the reduction of the CO_2 emissions: BEV (possibly combined with electrified roads); PHEV; FCEV; and Advanced Hybrid powertrains (noting that the mix of these powertrain options will strongly depend on the development of the

[98] Since the resultant efficiency of the road mobility system is a consequence of the individual technologies, their individual usage and their interactions within the system. Further, system efficiency will depend on traffic management, resilience etc. System effectiveness will need to address the issues of system robustness and cyber-security risks for example.
[99] In the original documentation and presentation of the ERTRAC CO_2 Evaluation Group work, the wording "Carbon-neutrality" was used. However, based on the definitions used within this document (see Appendix) actually GHG-neutrality is appropriate to reflect the extent of the studies.

infrastructure (charging infrastructure, electrified road systems, hydrogen filling stations, production capacities for renewable fuels etc.)).
- The overall WtW energy demand decreases drastically with fleet electrification.
- The energy efficiency measures identified reduce the energy demand (fuel consumption) in all scenarios in a very significant way.
- The demand for fuels decreases massively in all scenarios (for example, in highly electrified scenarios by up to 95%).
- In strongly electrified scenarios, the WtW differences in energy consumption between the fuel scenarios are quite small.
- The total demand for electricity in road transport will increase (energy production + use in vehicle): equivalent to 20%-30% of the total EU28 electricity consumption in 2019 as a minimum (in the advanced biofuels or limited fossil scenarios combined with hybrid fleet; equivalent to 40%-55% of the total EU28 electricity consumption in 2019 in highly electrified scenarios; up to 1.6 times the total EU28 electricity consumption in 2019 if e-fuels are used along with a hybrid fleet).
- The largely GHG-neutral, renewable production of electricity is a prerequisite for “GHG-neutral” road transport in all fleet and fuel scenarios.

And some further research needs were presented by the ERTRAC CO_2 Evaluation group:
- Enabling fleet mix change by improving powertrain technology: cost, range, functionality etc.; and adapting infrastructure technology and concepts.
- Realising the efficiency improvements by Measure A: Vehicle; Measure B: Traffic conditions; and Measure C: Traffic Reduction Technologies.
- Beside Road Transport:
  - Realising renewable electricity generation capacity (inside and outside of Europe)
  - Realising net GHG-neutral H_2 and fuel production (inside and outside of Europe)
  - Realising the technology and capacity of CCS and DAC (which has not yet been demonstrated at large scale)
  - Determining the availability of raw materials and sustainable feedstocks (appraised in a life-cycle analysis perspective).

5.3 Use Cases

Whilst a scenario-based assessment is useful to evaluate whether the road transport system can achieve a net zero carbon status, in reality it is likely that each individual user will choose their means of mobility, as a consequence their own needs and constraints. This individual, bottom-up optimisation is not the same as the top-down, system optimisation[100] (as illustrated in Figure 54): there may be significant divergence for the end result, the products, mobility modes and infrastructure needs. As such, improved understanding of the individual compared to the system behaviour in a net zero carbon road mobility situation is needed. It is very important to better understand how these behaviours will change in the future, together with what factors will influence the change.

Further, the divergence may be more acute along the route towards net zero carbon mobility at 2050, when the possible rates of change of the related industries, regulatory limits and societal behaviours may become bottlenecks. Questions arise related to how much incentives will be used to encourage the change, increase the rate of change, whilst at the same time retaining social equality. Alternatively, or perhaps consequently, the rate of change is unlikely to be continuous, monotonic. Rather, particularly as a consequence of the allowable carbon budget, significantly increased rates of change, varying at any

[100] One can envisage that the ERTRAC CO_2 Evaluation considered “corner points” in the solution space: individual mobility usages are as likely to be somewhere “in the middle” of the solution space and, as such, may well have different, further needs for research in order to approach optimal solutions.

single point in time between different types of road transport, are likely to be necessary and experienced. As such, an understanding of the achievable rates of change in any single parameter related to the road mobility system needs to be reached.

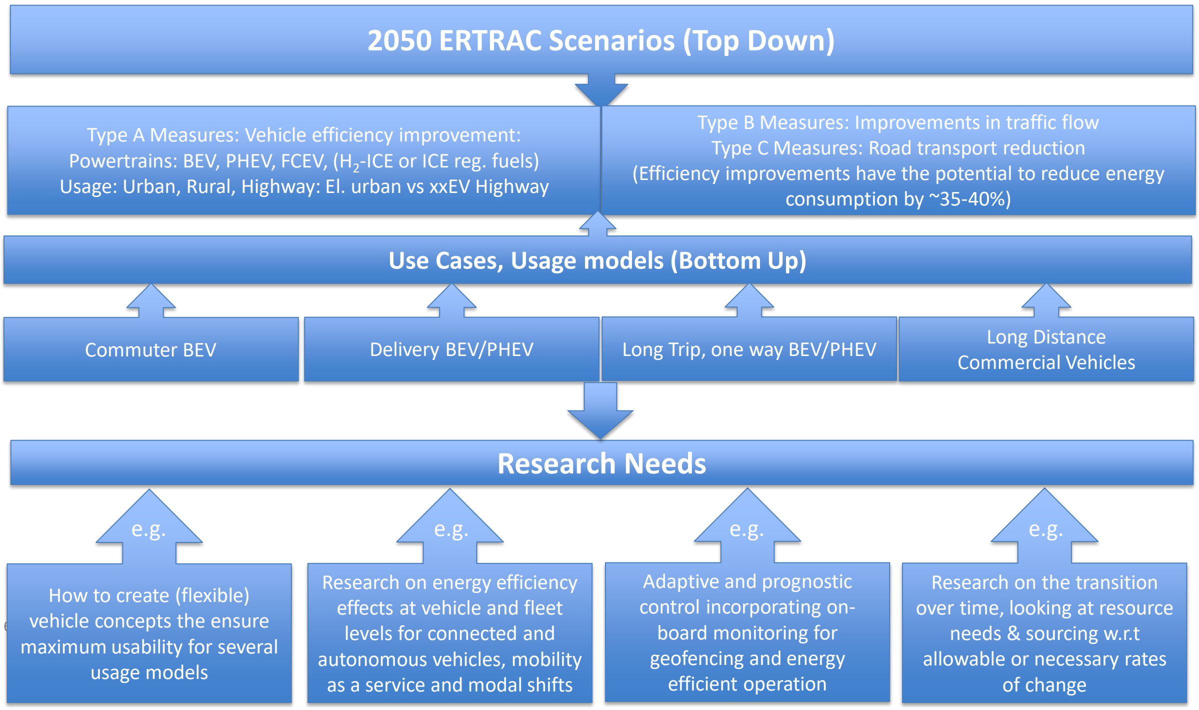

Figure 54. Different perspectives determine research needs

Hence the question arises: how can such use cases, such usage models[101] be defined? Is a use case: one vehicle, one route, one energy carrier? Or is it one technology level? One scenario? Or is it one year during the transition to net zero? Whilst the technologies discussion with Chapters 2 to 4 might imply certain use cases, usage models, a specific approach is needed here. Further, whilst the ERTRAC CO_2 Evaluation Group study considered three powertrain scenarios and two technological progress scenarios (optimistic and pessimistic) on a TtW basis, plus two electricity supply scenarios (100% RES and 1.5 Tech.) and four fuels scenarios (biofuels, e-fuels, mixed fuels and limited fossil) on a WtT basis, only the consequences of those scenarios that directly affect the user are important to generate use cases and usage models. Hence, the different vehicle types and their powertrain scenarios are of primary importance (the technology progress scenarios are too detailed to allow discrimination): what goes into the "plug" or "fuel nozzle", as long as it is compatible with the vehicle (i.e. drop-in), is mostly only of secondary importance for the user.

Hence the use of the following vehicle types must be considered:

- Two-wheelers
- Small and/or medium cars
- Large cars and SUVs
- Light commercial vehicles (LCV), up to 3.5 tonnes GVW.

[101] There is no singular definition for a comprehensive differentiation between "use cases" and "usage models", a consideration might be: "use case" - one particular trip within a usage model (or scenario), described as detailed as possible. This is not a single manoeuvre, nor a single user interaction. Since the system of interest is, principally, the energy transfer and management, a use case should consist of relevant situations for energy conversions; "usage models (or scenarios)" - could be typica profiles of how a vehicle is being used by a particular group of users, defined by statistical data (average distance, speed, mileage etc.), along with a consequential preferred type of vehicle.

- Medium Duty trucks
- City Busses
- Heavy Duty Trucks
- Coaches

where, possibly, small cars, large cars and heavy-duty trucks are of most importance from a GHG generation perspective. Further, from the user perspective, whether you fuel with fossil fuel, renewable fuel or hydrogen, as long as the range is sufficient, the refuelling time should be the same: the criteria will only be availability of fuelling station, range and cost (see Figure 55). Presuming those three are given, as a consequence of market forces etc., these collapse onto one. Hence, there are really only two primary powertrain choices: solely BEV or xEV, where x is not "B" but rather "PH or FC or H_2", hence we can represent these as "xxEV" to differentiate them from BEV.

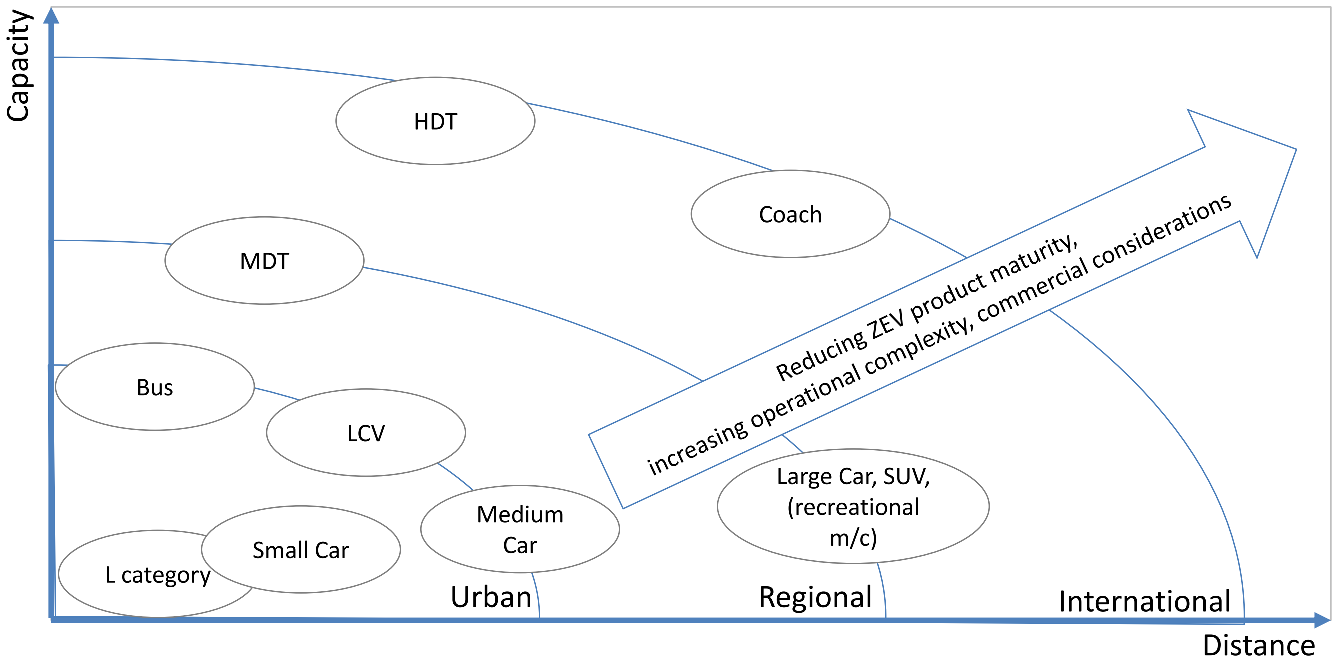

Figure 55. Different vehicle types and uses envisaged over a distance versus capacity landscape

Consequently, collating various factors related to specific use cases, usage models, based on these different vehicle types, application domains, and motivations helps to identify possible challenges, enablers or research needs for energy carriers, vehicle technologies or infrastructures specifically, as well as collectively. In addition, societal matters can be treated similarly, as can standardization or regulatory needs plus any other aspects. Such a collation for several use cases, usage models will be presented and discussed in the following section.

5.4 Results

An example of such a result is shown in Figure 56, for a commuter in 2030. Various aspects have been considered following a description of the use case: what vehicle types might be used based upon what motivation; what other aspects, including standardization or regulatory needs can be identified; hence, what research needs might be derived for the energy carriers, the vehicles, the infrastructure and the consideration of societal aspects can be identified. Thus, the use case example for a commuter in 2030 might be summarized as follows.

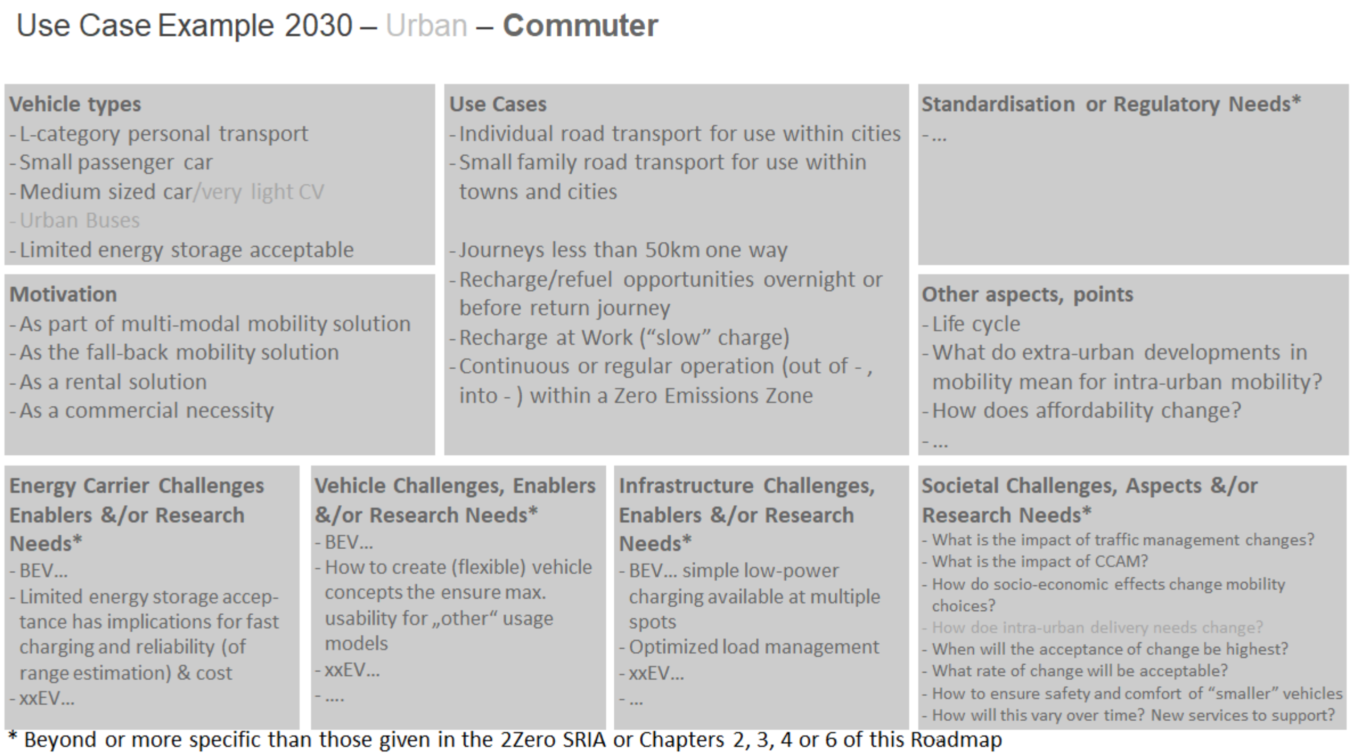

Figure 56. Example use case, usage scenario, for a commuter 2030

The **commuter in 2030** will use individual road transport within cities and as a small family means of transport within and between towns and cities. As such, the regular journey is likely to be less than 50km one way and present easily accessible refuelling or recharging opportunities: for example, overnight charging prior to the journey and a recharge opportunity during the work time (or shopping activity, for example). Much, if not all, of the operation is likely to occur within a ZE zone. Consequently, an L-category, small or medium sized car is the vehicle of choice, as part of a multi-modal journey solution, or a fall-back solution. The vehicle ownership might be private but it could also be a rental or commercially owned vehicle. Questions that might arise for the owner could be, "how will the affordability of this mode change?", "how will extra-urban mobility developments change my mode choice?", "what might the life-cycle aspects of this mode choice be?". Consequently, the following research needs and/or questions might be identified, beyond those previously recorded:

- For energy carriers, since this is mostly likely to be a BEV with limited energy storage, what are the implications of and for fast, smart charging with this usage; how might the reliability, durability of the energy carrier (the battery) be improved in this use case, and at what cost?
- For the vehicle and powertrain, how might this usage change the vehicle concept, hence the powertrain architecture?
- For the infrastructure, is sufficient low power charging available at the appropriate locations (e.g. junctions with other transport modes, workplaces, leisure venues etc.) and are these smart enough to optimise the energy management for the vehicle and the transport system?
- And, for society in general, "how will the vehicle concepts change over time?", "how will their safety, their comfort etc. be maintained?", "what will be the impacts of the use and ownership of such vehicles with CCAM developments?", "what will be the subsequent impact on mobility choices, mode usage intensities, socio-economic aspects of mobility?". Finally, "what rate of change in these aspects will be acceptable in this usage?".

Considering another use case, the **urban delivery in 2030**, this will also use individual road transport within cities and a small van within and between towns and cities. As such, the regular journey is likely to be less than 50km but in a repeated loop so as to also present easily accessible refuelling or recharging opportunities: for example, overnight charging prior to the journey and a recharge opportunity during the shift time (at the delivery depot). Much, if not all, of the operation is likely to occur within a ZE zone. Consequently, an L-category, small or medium sized car or van is the vehicle of choice, although busses services might also be used. The vehicle ownership might be private (e.g. as in some MaaS offerings) but is more likely to be a commercially owned vehicle. As such, the primary question that might arise could be, "what potential is there to limit the energy storage, to reduce the vehicle initial purchase price?". Consequently, the following research needs and/or questions might be identified, beyond those previously recorded:

- For energy carriers, since this is mostly likely to be a BEV with limited energy storage, what are the implications of and for fast, smart charging with this usage; how might the reliability, durability of the energy carrier (the battery) be improved in this use case, and at what cost?
- For the vehicle and powertrain, how might this usage change the vehicle concept (whilst still allowing other usages), hence the powertrain architecture, with frequent stop and go operation? How will cabin thermal management be made?
- For the infrastructure, is sufficient low power charging available at the appropriate locations (e.g. regular delivery venues) and are these smart enough to optimise the energy management for the vehicle and the transport system (e.g. higher power charging at depots for during breaks and shift changes)?
- And, for society in general, "how do intra-urban delivery modes change over time?", "what new business and services models might arise?".

Considering another use case, **delivery in 2030**, but this time with a different vehicle powertrain, that is a PHEV, then the following differences might be seen. The regular journey is likely to be longer up to 100km but again in a repeated loop. Much of the operation is likely to occur crossing a ZE zone, hence geo-fencing regulation will be necessary and beneficial. A medium sized car or van is the vehicle of choice. The following change in research needs and/or questions might be identified, beyond those previously recorded:

- For energy carriers, since this is to be a PHEV with limited energy storage, what are the implications of and for fast, smart charging with this usage; how might the reliability, durability of the energy carrier (the battery) be improved in this use case, and at what cost?

Retaining, now, the PHEV architecture, but considering another use case, the **longer one-way trip in 2030**, for families or deliveries between urban centres. As such, the journey is likely to be 100 to 750km one way, requiring easily accessible refuelling and overnight charging. Some of the operation is likely to occur within a ZE zone, requiring a limited ZE range, such that consideration of inter-urban mobility developments need to be considered for this extra-urban mode. Consequently, medium sized car or larger cars are the vehicle of choice. The vehicle ownership is most likely to be private (or effectively so). Consequently, the following research needs and/or questions might be identified, beyond those previously recorded:

- For energy carriers, "how might the supply and share of net-zero carbon energy carriers be most rapidly increased?"
- For the vehicle and powertrain, "how might the choice of ZE rage be segregated?"
- For the infrastructure, "how might the supply of net-zero carbon energy carriers be prioritised?"
- And, for society in general, "what potential future services (e.g. related to SOC management or comfort versus energy management) might be offered to these vehicles?".

Considering, finally, another use case, the **long-distance commercial vehicle operation in 2030**, this will include journeys between 300, often 600 and 1000km, most probably one-way, whilst running at above 16 tonnes GVW, outside of urban areas, ZE zones. As such this would include trucks and long-distance coaches. Here, the primary determinant of use will be operational effectiveness and efficiency, determined in part on a gravimetric or volumetric total cost of ownership basis. Consequently, the following research needs and/or questions might be identified, beyond those previously recorded:

- For energy carriers, “how quickly and densely can fast charging, hydrogen and net-zero carbon hydrocarbon liquid fuel refuelling capabilities be achieved?”
- For the vehicle and powertrain, “what are the limits of future powertrain component reliability, durability and safety?”, “what are the limits for the gravimetric and volumetric powertrain architectures and how might regulation be developed to recognise this whilst still enabling improvements in operational efficiency and reductions in its carbon-intensity?”
- For the infrastructure, is “what opportunities are there within depot, for charging, refuelling, energy carrier conversion and smart energy management?”.

Whilst the possible risks related with individual use cases, usage models have not been (and possibly should be) derived, it is found that through this analysis some research needs are identified that are beyond the usual ERTRAC vehicle technology related areas. What becomes clear from this consideration of use cases, usage models is that, especially for individual mobility, we should ensure we always have a choice (with varying costs) even as the system changes: the quality of mobility needs to be retained. Further, that connectivity (analogous to perfect information supply in commerce), through digitalisation and, possibly realised through automation, gives us the opportunity to optimise both the individual mobility efficiency and mobility system efficiency concurrently (relative to what parameters we determine most appropriate in any incidence, e.g. energy efficiency). Moreover, that such connectivity gives us a means to investigate, to practice adaptive and prognostic control within the system. A systems approach via connectivity will realise, thus demand system changes, realise, for example, modal shifts and mobility as a service. Hence, connected, collective mobility should cost less (given an equal basis for energy and investment costs) and service costs should reduce, utility factors should improve. One might consider this a move towards rational mobility, analogous to the ideal of the rational consumer.

5.5 Other Aspects

The ERTRAC CO_2 Evaluation acknowledged that the question, “What is the best fuel/fleet combination?” (which, from a system perspective, is equivalent to the question posed often by individual users and in such use cases), could not be answered by the study. Specifically, system optimisation cannot be based on an extreme scenario approach. Further research, innovation and development work will be needed to assess and establish the optimal solutions, on the basis of various criteria. Such criteria were identified as:

- Energy production and storage capacity;
- Life Cycle Assessment (LCA) to account for the emissions and energy required for infrastructure and vehicle production;
- Investments in infrastructure and energy production facilities;
- Cost of energy production and distribution, as well as vehicle technology development;
- Land use, water use and other resources needed; plus their allocation between different sectors;
- Different locations for energy production (EU or MENA-Region);
- Customer acceptance of specific vehicle types and fuels;
- The acceptance of CCS.

It is noted from the consideration of the electricity needs of the different scenarios in the study that there is a “Wide variation in total electricity request: Range between 600TW.h up to 4400TW.h (representing from ~20% up to ~140% of total EU-28 electricity consumption in 2019 (3220TW.h).” Further research is suggested to reduce the size of this range.

It is noted from the different scenarios that “The differences between the electricity scenarios (RES and 1.5TECH) are pretty small.” Further research might be to understand differences related to other impacts, apart from energy needs, between the two scenarios.

It is noted, from the consideration of the overall WTW energy needs of the different scenarios, that “The share of TTW in the whole WTW energy consumption varies between **~50% up to 90%,** increasing with the level of fleet electrification.” The validity of this variation needs to be established when also considering other life-cycle aspects, such as the energy needs related to the manufacturing of the vehicle, in particular how those change e.g. with the inclusion of battery manufacturing, which is not part of the existing study.

It is noted, from the consideration of the overall WTW energy needs of the different scenarios, that “E-Fuels production without 100% renewable electricity is not a reasonable scenario!”: this may be true for net-zero at 2050, but is e-fuels production earlier, without 100% renewable electricity a reasonable scenario? What do we need to know to answer this? Is it reasonable in the ramp-up phase as a long as the “long-term” pathway leads to the 100% renewable scenario? These questions could be answered with further analysis considering different parameters and perspectives.

It is noted that, “The demand for fuels decreases significantly in all scenarios” (in highly electrified scenarios up to 95%). What are the socio-economic consequences thereof? Since, for example, this can have an impact on the scale-economy of liquid fuel production that would have consequences for other sectors as well. These are also areas for further research, beyond those traditionally addressed by ERTRAC.

Similarly, it is noted that, “The total **demand for electricity** in road transport will **increase** (energy production + use in vehicle)”. What are the socio-economic consequences thereof?

Furthermore, research needs from other aspects might be derived from the considerations in Section 5.4 and beyond, for example:

- Determination of the balance between technical and societal matters, their rates of change;
- Societal acceptance, given future scenarios, of other sources of decarbonised electricity, energy, such as nuclear power compared to longer term issues (e.g. waste management);
- System second order sensitivities, rates of change possible, and the rates of change of these that are acceptable;
- Societal TCO aspects of and solutions and pathways thereto.

In addition, there were some caveats, which imply future research needs and necessary continuing reference to other studies:

- This study explored different corner scenarios based on a static fuel and fleet modelling exercise;
- The analysis does not include dynamic modelling or prediction; the results of the analysis should be considered as estimates for comparative purposes;
- The analysis does not draw conclusions on fuel and electricity availability, competition with other sectors demand, economics, societal acceptance ... especially the fundamentals of supply versus demand.

6 Research recommendations

Introduction

Based upon the review of the state of the art and the primary issues related to each of the aspects of energy carriers, powertrains and infrastructures, together with the consideration of the use cases and efficiencies in future road mobility, a wide range of needs for future research for road transport can be identified. These are listed in this chapter and represented diagrammatically, per aspect over a selection of different TRL. The research needs identified, each in relation to the GHG-neutrality objective and air quality targets compliance, are colour coded in line with the following definition:

- Blue, in line with a full ban of internal combustion engine sales:
  - This colour code covers research needs related to zero-tailpipe emissions technologies, in a scenario where internal combustion engines would be banned from sales for all categories of vehicles (including passenger cars, light commercial vehicles and heavy-duty vehicles);
- Yellow, required to achieve the objective and by some legislation (e.g. the Renewable Energy Directive or Euro 7) whilst including the sale and continued use of internal combustion engined vehicles:
  - This colour code covers two categories of research needs:
    - A first category corresponds to developments required by some existing pieces of legislation. For instance, according to the Renewable Energy Directive (RED), advanced biofuels and e-fuels (RFNBOs) will need to be supplied by 2030, which requires research and development to ensure the solutions are available. Another example is Euro 7, which triggers research and development needs for passenger cars, light commercial vehicles and heavy-duty vehicles, notwithstanding a partial of full ban on internal combustion engines which might happen later on. Independent of an ICE-ban, these research needs are required at least during a period of transition;
    - A second category corresponds to the achievement of climate goals. For instance, independent of an ICE-ban, GHG-neutral fuels are required to meet climate goals (and they help reaching net GHG-neutrality sooner), as they act on the legacy fleet. In some scenarios that do not include a full ICE-ban, ICE could be used in the longer term (i.e. post-2050) and still comply with the climate targets. These could also require the further development of adapted powertrain technologies;
- White, additional topics, beyond the objective and targets above but related to the topic of this document, these topics are often transversal:
  - This colour code covers research needs not directly covered by the EU Green Deal nor the Fit-for-55 Package, related or not related to climate goals.

6.1 Recommendations for energy carriers for road transport

6.1.1 Electricity

As research recommendation related to electricity generation are not specific to road transport (because electricity is provided to almost all sectors), they will not be detailed in this document. They can be found in the reports published by ETIP SNET[102] (European Technology & Innovation Platforms for Smart Networks for Energy Transition, whose role is to guide Research, Development & Innovation (RD&I) to support Europe's energy transition).

6.1.2 Liquid fuels

6.1.2.1 Feedstock for the production of liquid fuels

Biomass

Biomass is used as a feedstock to produce biofuels. A great diversity of biomass exists. In the Renewable energy directive (RED II) alone, more than twenty different resources are listed. Today, there is no consensus on how to regroup biomass categories. Some categories are linked to the composition of the biomass, as "Lignocellulosic", while some are linked to the origin of the biomass or their use, as "Food & Feed". In RED II categories correspond to:

- Conventional feedstock: biomass that could be used in the food & feed sector;
- Advanced feedstock: listed in the Annex IX part A of the REDII, and can be split in the following categories:
  - Agricultural & forestry residues (e.g. straw, corn stover, bagasse etc.);
  - Industrial residues (e.g. sawdust and black liquor etc.);
  - Woody and grassy energy crops (e.g. Poplar, willow, ryegrass, miscanthus etc.);
  - Algae & micro-organism (autotrophic and heterotrophic organisms);
- Others: listed in the ANNEX IX, part B, i.e. Used Cooking Oil (UCO) and animal fat.

Transport represents only a minor part of the biomass used for an energy purpose (less than 10%). It is one of the reasons why the prospective evaluation of biomass availability for biofuel production is a difficult exercise. The estimates are calculated with models based on several assumptions including:

- The usage competition;
- The yield and the available plantation area;
- The sustainable amount of residues that can be recovered;
- The food demand.

Consequently, the estimates vary greatly from one study to another. They also vary depending on the type of biomass, each type facing different challenges that can affect their availability.

Beyond the evaluation of biomass availability, further evaluations must be performed, such as:

- Evaluating the impact of biomass cultivation and collection on biodiversity;
- Evaluating the potential of actually mobilizing biomass, from its collection to its delivery in a biorefinery;
- Optimisation of practices for energy crops, algae & micro-organism.

[102] https://smart-networks-energy-transition.ec.europa.eu/publications/etip-publications

Table 24: Research needs for Energy Carriers

	Research Needs for Energy Carriers	2022 – 2035
Electricity	Carbon-neutral electricity generation and balanced grid	Research recommendations out of the scope of this document (see ETIP SNET reports)
Biofeedstocks	Biomass availability for biofuels production	Continuous evaluation
	Impact of biomass cultivation and collection on biodiversity	Continuous evaluation
	Mobilisation of biomass to biorefineries	Continuous evaluation
	Waste availability for renewable fuels	Continuous evaluation
	Optimized practices for crops and forestry	Mature, with continuous improvements
	Algea & micro-organisms	TRL 2-3 → TRL 4-6
Green H_2	Alkaline electrolyser	Mature, with continuous improvements
	Polymer-electrolyte membrane electrolyser (PEM)	TRL 7-8
	High temperature (co-)electrolyser cell (SOEC)	TRL 6-7 → TRL 7-8
CO_2	Direct capture from air (DAC)	TRL 4-6 → TRL 7-8
	CO_2 from biomass upgrading	Mature, with continuous improvements
	CO_2 from flue gas (concentrated source)*	TRL 6-9 → TRL 7-9
Biofuels	Transesterification	Mature, with continuous improvements
	Hydrotreatment	Mature, with continuous improvements
	Biomass to Liquids via Gasification + FT	TRL 7-8
	Hydrothermal Liquefaction + upgrading	TRL 5-6 → TRL 7-8
	Pyrolysis + co-processing / upgrading*	TRL 5-9 → TRL 7-9
	Alcohol to synfuels*	TRL 6-9 → TRL 7-9
	Sugar-to-Diesel	TRL 2-3 → TRL 4-6 → TRL 7-8
	Algae to liquid	TRL 2-3 → TRL 4-6
	Biotechnological fuel production	TRL 2-3 → TRL 4-6 → TRL 7-8
	Bio-DME and bio-OME	Mature, with continuous improvements
E-fuels	Paraffinic e-fuels through Reverse Water Gas Shift (RWGS) and Fischer-Tropsch**	TRL 5-6 → TRL 7-8
	e-methanol synthesis	Mature, with continuous improvements
	e-DME synthesis through e-methanol pathway	Mature, with continuous improvements
	e-olefins synthesis through e-methanol pathway	Mature, with continuous improvements
	Oligomerization of e-hydrocarbons through e-methanol pathway	Mature, with continuous improvements
	Hydrotreatment through e-methanol pathway	Mature, with continuous improvements
Gaseous fuels	Carbon-neutral production of biogas and power-to-gas	Research recommendations out of the scope of this document (see Gas for Climate report)

* *Several technologies having different maturities*

** Only RWGS is not a mature technology in this process

"Green" hydrogen is obtained through water electrolysis by means of renewable electricity. Several technologies are proposed, of which alkaline electrolysis cells are technologically mature and proton exchange membranes are technologically advanced. Other solutions are under development or research. Amongst the research needs, the literature lists the co-electrolysis with CO_2, under pressurized stack operation, aiming at the avoidance of the reverse water gas shift (RWGS) stage and the reduction of costs. Research on co-electrolysis of Solid Oxide Electrolysis Cell (SOEC) to reduce start-up time, and improve ramping flexibility is proposed, allowing for the reduction of battery size and investment cost. Process heat integration and optimisation of the operating conditions promoting internal methanation have also been proposed. Research on plasma chemical conversion aims at increasing the power density and consequent productivity and easing conditions for splitting CO_2 through vibrational excitation of the molecules. Plasma technology increases productivity by a factor of 10 by volume as compared to SOEC electro-chemical conversion. However, the technology requires the optimisation of the reduced electric field, and the reduction of the CO_2 gas temperature to increased energy efficiency.

One of the main challenges of green hydrogen generation for e-fuels production is the coupling of intermittent renewable electricity with continuous fuel production, requiring electricity and/or hydrogen storage facilities.

Table 25. TRL of processes for green hydrogen production and CO_2 capture [Cerulogy 2017][103]

Technology	TRL (today)
Water electrolysis	
Alkaline electrolyser	9
Polymer-electrolyte membrane electrolyser (PEM)	8
High-temperature electrolyser cell (SOEC)	5
CO_2 supply	
CO_2 extraction	
CO_2 from biogas upgrading, ethanol production, beer brewing, ...	9
CO_2 exhaust gas	
Scrubber with MEA	9
Scrubber with 'next generation solvent'	8
Absorption/electro-dialysis	6
Pressure-swing absorption (PSA)/Temperature-swing absorption (TSA)	6
CO_2 from air	
Absorption/electro-dialysis	6
Absorption/desorption (TSA)	6
CO_2 conditioning (liquefaction and storage)	9

Waste plastic

Waste plastic can be used for producing fuels. The use of waste plastic is governed by the EU waste management law, and the waste hierarchy must be followed. The recovery of waste for other purpose, such as the production of biobased fuel, is allowed only if prevention, reuse, and recycling are not possible. In addition, waste plastic should be used for fuel production only when the waste-to-fuel life-cycle emissions result in a GHG emissions reduction relative to fossil fuels when considering the emissions

[103] Cerulogy 2017. What role is there for electrofuel technologies in European transport's low carbon future? https://www.transportenvironment.org/sites/te/files/publications/2017_11_Cerulogy_study_What_role_electrofuels_final_0.pdf

associated with the previous disposition of the waste. This will limit the plastic quantities available for fuel production. the estimated EU volumes of non-recyclable plastic wastes is 10 Mt/y, where 37% is landfilled. This means that 3.7 Mt/y could potentially be used for the production of renewable fuels, which can be seen as a quite small potential considering that it is spread all over Europe.

6.1.2.2 Biofuels

'Food & Feed' / 'First generation' / 'State of the art' biofuels

Transesterification is an industrialised process available to produce FAME renewable fuel. It has the advantage of allowing the conversion of vegetable oil into esters under low temperature and pressure, relatively short reaction time, and to ensure a high conversion rate. The process was originally developed for the upgrading of vegetable oil and was expanded to all triglycerides, as are animal fat, used cooking oil (UCO) and dedicated energy crops for vegetable oil production. The industrialised method of transesterification is through homogeneous catalyst. Recent investment and research aims at: 1) the expansion of the process onto advanced feedstock requiring intensified pre-treatment and, 2) the technical development of new methods to improve the process selectivity and conditions.

Hydrotreatment is flexible in its feedstock requirements allowing the use of vegetable oils (HVO), waste and residue materials. Possible feedstocks are triglycerides, sourced from vegetable oil, UCO or animal fat.

The process requires a pre-treatment of the feedstock, which ensures obtaining a feedstock absent of impurities and compatible with hydrotreatment process that will not have negative effects of its operation, independently of the feedstock origin and properties. The pre-treatment steps have made significant progress over the last decade and are still evolving.

Other research activities concern the hydrotreatment process itself, which is a catalytic process. Research works on catalyst development indicate a high conversion up to 99 %, that can be deteriorated due to coke deposit, and requiring regeneration. Development of transition metal phosphides (TMPs) catalysts for the hydrodeoxygenation (HDO) has been encouraged as they are a cost-effective solution, present higher resistance to water, and do not require sulphur feed. Other developments include catalyst production to maximise conversion of specific to renewable resources as waste cooking oils. Undesired reactions as polymerisation and coke formation are to be avoided, as they can damage catalytic conversion and can count for 2 to 30 wt.% of the feed. The main challenge of hydrotreatment process is the avoidance of coke formation. For this, it is desired to minimize polymerisation and condensation reactions that occur at high temperature. Some solutions are the reduction of the HDO activation energy, the increase of HDO reaction rates, and avoid fast temperatures increase within the range of 200-250°C, above the HDO reaction rate, as polymerisation would quickly take place.

Other research needs observed in the literature are catalyst materials, catalyst suitable for hydrogenating carbonyls into alcohols, dehydrating alcohols to olefins, and saturating olefins into alkanes. Further research is proposed on catalyst surface properties affecting reaction mechanism, and technologies to reduce conventional H_2 consumption. The economic feasibility of advanced biomass pre-treatment is poorly documented.

'Advanced' biofuels

Biomass to Liquids (BtL) via Gasification + FT. Gasification followed by Fisher-Tropsch (FT) production of waxes, and upgrading to alkanes, is a proven technology that has been applied to coal since mid-twenties century. Extension to process application to lignocellulosic renewable resources has gained attention and pilot to demonstration plants have served to confirm the technology readiness. Several resources of lignocellulose composition can be used as feedstock, as are agricultural and forestry residues, woody and grassy energy crops, and industrial residues (biomass). The process counts of four main steps: pre-treatment, gasification, gas cleaning, and Fischer-Tropsch and upgrading.

The mains goals of pre-treatment techniques are to increase the volumetric energy density, to homogenise the biomass composition, and to facilitate the continuous flow of the biomass into gasifier. Research and development of dry biomass pre-treatment aims at improving the efficient and homogeneous heat transfer, the treatment of inert gas, optimising or processing gas (CO, CO_2) and particle discharges, and improving the flexibility of operation between start-up and steady-state phases.

Current research and development works related to gasification aim at adapting the bed conditions to optimise syngas composition for a FT process, improving yield, ensuring a continuous flow, and the integration onto Fischer-Tropsch stage.

Cleaning and conditioning of biosyngas is critical for correct functioning and high yield of Fischer-Tropsch stage, as impurities would result in contamination and deactivation of the Fischer-Tropsch catalyst. More specifically, a ratio of H_2:CO of 2:1 is necessary to ensure maximal conversion. Gas cleaning must be designed to allow high control flexibility as impurities are dependent on the biomass and the gasification temperature control. Gas quality control can be employed using analysers capable of detecting impurities, as for example sulphur at ppb concentrations.

The Fischer-Tropsch process is a collection of polymerisation reactions. Reactors as cobalt and iron are known to increase reaction rates, but other materials are also researched. For example, cobalt reactors are better adapted to diesel fuel, while ruthenium is most efficient (yield) catalyst but is more expensive.

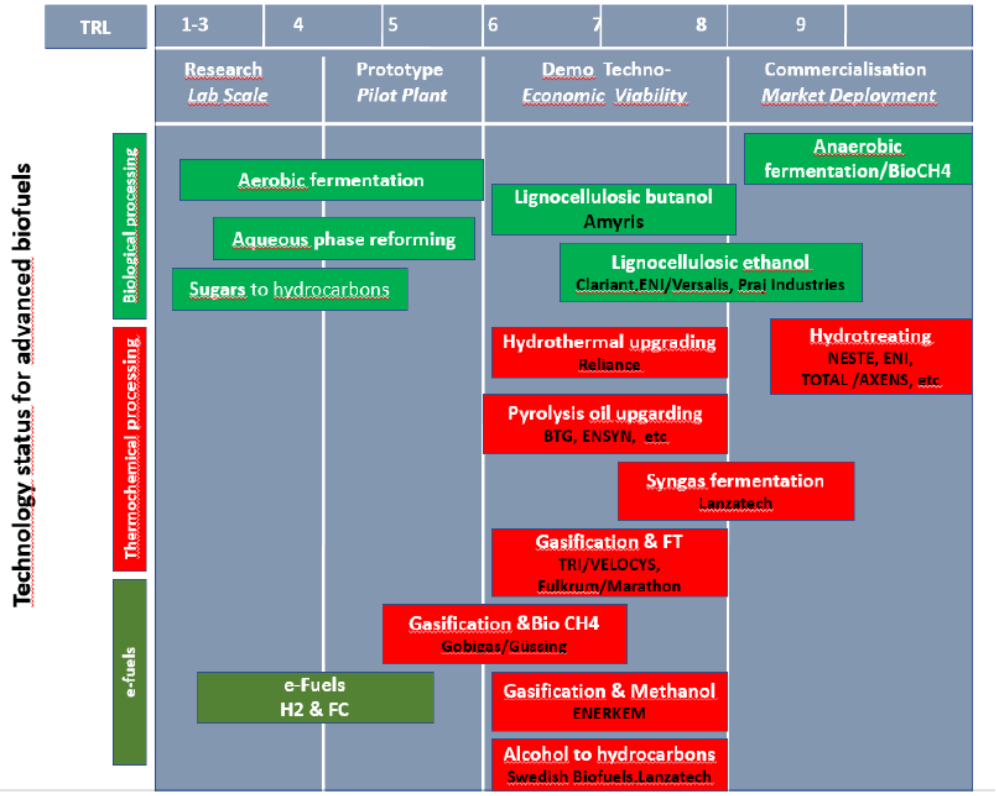

Figure 57. Summary of the TRL of processes for advanced biofuels production[104].

Reaction temperature, reactor pressure, and space velocity have a significant influence on FT catalyst activity and product selectivity. Research on Fischer-Tropsch catalysts aims at improving efficiency and

[104] Sustainable biomass availability in the EU, to 2050, C. Panoutsou, Imperial College London for Concawe, 2021. https://www.concawe.eu/wp-content/uploads/Sustainable-Biomass-Availability-in-the-EU-Part-I-and-II-final-version.pdf

material selection, and integrating Fischer-Tropsch and isomerisation reactions into one stage. Furthermore, some research works focus on efficient (mass conversion) and robust Fischer-Tropsch catalytic system for converting H_2 deficient and CO_2 containing syngas, at high C_{5+} selectivity in order to avoid the integration of a water-gas-shift stage and to reduce cost.

Hydrothermal Liquefaction (HTL) + upgrading. The R&D challenges for HTL + upgrading fuel production are:

- Co-Liquefaction, which can improve economics by enhanced feedstock availability;
- Water management;
- Co-processing with crude oil in a refinery: three European projects consider HTL biocrude co-refining: 4refinery, Waste2Road, HyFlexFuel;
- More generally, upgrading of HTL products to fuel products is an important R&D challenge;
- Biocrude fractionation;
- The aqueous phase management is one of the main bottlenecks for process scale-up.

Pyrolysis + co-processing / upgrading. Here, two different processes should be listed:

- Fast Pyrolysis: some full-scale industrial plants already exist (Green Fuel Nordic plant in Finland, Pyrocell plant in Sweden). It consists in a thermochemical decomposition of biomass residues through rapid heating (450-600 °C) in absence of oxygen. Different types of lignocellulosic biomass residues are converted into one homogeneous energy carrier: Fast Pyrolysis Bio Oil (FPBO). FPBO is "an emulsion of lignin fragments in a sugar syrup". It is a dark liquid, but not a typical refinery feedstock. It is typically co-processed with crude oil in a refinery in a FCC unit, up to 5% at industrial scale, and up to 10% at pilot scale. The R&D challenges are related to increasing the rate of co-processing and upgrading the bio-oil to fuels products through other pathways such as Hydrotreating, Hydrocracking or Gasification (+ Fischer-Tropsch).
- Slow Pyrolysis is a robust and mature technology with many reactor types available at any size. It is a multi-feedstock technology focused on solids. For this technology as well, the R&D challenges are related to upgrading the pyrolysis products to fuel products.

Alcohol to synfuels. The process is an adaption of the alcohol to jet pathway, for which the industrialised stages are readily available. The first stages concern the production of methanol (e.g. using biogas) or ethanol through fermentation from lignocellulose. Resources can be either agricultural and forestry residues, woody and grassy energy crops, or industrial residues (biomass residues). Ethanol is cleaned and subsequently dehydrated into ethylene. To ensure high purity, the product undergoes a primary separation and a purification. The stage is followed by oligomerisation into olefins, and hydrogenation and fractionation for the production of paraffins and isoparaffins. The products are renewable gasoline, diesel, jet, and naphtha in minor proportion.

Sugar-to-Diesel. A research demand towards the production of diesel fuels or of C4+ alcohols is in the engineering of organisms capable of using both C6 and C5 sugars as well as an increased product tolerance. The supply of sugars from cellulose and hemicellulose still is consuming a remarkable amount of energy during the production process, so it is vital to provide low energy intensive processes to depolymerise cellulose and hemicellulose. Separation technologies also play a major role in the production process and is energy consuming. More efficient separation techniques will thus be required for an improved sustainability.

Algae to liquid technologies. The R&D needs of algae as drop-in fuels cover the full range of topics from basic biology to engineering:

- The ecology of algae, their lipid productivity and composition, growth rates and growth control have to be developed and optimised. This does not only refer to yield rates and strain improvement towards a desired fatty acid profile but also to increased tolerance of contaminants.
- Scale up is a critical issue for algae fuel production.

- Ongoing research and cost reduction of efficient cultivation reactors is of importance.
- Low-cost, high-efficiency algae cultivation technology needs to be developed for large scale algae production.
- The energy balance of cultivation, harvesting and oil extraction must be improved.
- Facilitation of sustainable cost-competitiveness of algae fuels. This needs to include identifying algae species with high oil contents and with higher yields, but also developing and optimising different steps in the cultivation process.
- Further R&D needs to ensure a whole value-chain approach, which takes economic, socials, environmental and technological, as well as biorefining and LCA into account.

Biotechnological fuel production. The R&D challenges for biotechnological fuel production are:

- To identify and/or modify strains and species capable of producing valuable fuel components. Methods of genetic engineering could be useful to switch on or off and to regulate the desired metabolic pathways.
- To investigate cultivation needs, growth rates, growth control, substrates and energy efficient harvesting and extraction methods.
- To develop energy and cost efficient, scaled-up cultivation reactors.
- To investigate and assess fuel components on their potential to make a substantial contribution to future sustainable mobility.
- To test new fuels and components on their potential for reducing fuel consumption and lowering emissions in current and future drive trains.
- To ensure a whole value-chain approaches taking into account the stakeholders along the chain and the technological, economic, social and environmental properties.

Dimethyl Ether (DME) and oxymethylene dimethyl ether (OME). The R&D challenges for DME and OME are:

- For renewable production, gasification technology belongs to the key technologies. Black liquor gasification (and the whole chain from production to use in HD vehicles) has been successfully demonstrated in the BioDME project. Further development of direct gasification is one important field for further research.
- Increasing the production energy efficiency and the process of sourcing from both bio feedstock.

Table 26. Summary of production pathways and TRL for advanced biofuels production[105] - (MSW is Municipal Solid Waste)

Raw material	Conversion pathway	Biofuel type	Status TRL (2020)	Fuel
Waste oils & fats, Used Cooking Oil (UCO), Veg. oils (through crop rotation, cover crops), liquid waste streams & effluents	Hydrotreatment including co-processing	Hydrotreated Vegetable Oil (HVO) / renewable diesel	Commercial	Drop-in blends with road diesel or neat HVO, Sustainable Aviation Fuels
MSW, sewage sludge, animal manures, agricultural residues, energy crops	Biogas or landfill production & removal of CO2	Biomethane		Captive fleets or injected in the gas grid
Lignocellulosic, agricultural residues, MSW, *solid* industrial waste streams/residues	Enzymatic hydrolysis & fermentation	Ethanol	TRL 8-9	Gasoline blends such as E5, E10 (drop-in), E20 (minor engine modifications), E85 flexi-fuel engines), ethanol with ignition improvers for diesel engines (ED95), or ethanol/butanol upgraded to biokerosene (ATJ)
	Gasification + fermentation	Ethanol	TRL 6-8	
Lignocellulosic solid agricultural residues, MSW, *liquid* industrial waste streams & effluents or intermediate energy carriers (torrified wood or pyrolysis oils)	Gasification + catalytic synthesis (including biomethane, methanol etc.)	Synthetic fuel	TRL 6-9	Drop-in blends with diesel, gasoline, Sustainable Aviation Fuels, bunker fuel or as pure biofuel e.g. bio-SNG, DME, methanol,
Lignocellulosic, MSW, waste streams	Pyrolysis or liquefaction (i.e. HTL) + Hydrotreatment	Hydrotreated bio-oil/biocrude	TRL 5-8	Neat or drop-in diesel, bunker fuel, gasoline, Sustainable Aviation Fuels; using the less processed HPO as fuel for maritime (less costly)
Pyrolysis oils or biocrudes from lignocellulosic, MSW, waste streams	Co-processing in existing petroleum refineries	Co-processed bio-oil/biocrude	TRL 5-7	Neat or drop-in diesel, bunker fuel, gasoline, Sustainable Aviation Fuels
CO_2 from RES systems and air (fermentation)	Reaction with RES H_2	e-fuel	TRL 5-7	Depends on fuel type, i.e. methanol or DME, ATJ

[105] Sustainable biomass availability in the EU, to 2050, C. Panoutsou, Imperial College London for Concawe, 2021 https://www.concawe.eu/wp-content/uploads/Sustainable-Biomass-Availability-in-the-EU-Part-I-and-II-final-version.pdf

6.1.2.3 Fuels from power-to-liquid

Producing power-to-liquids (e-fuels) can use various processes. The most mature pathways involve e-methanol, produced from “green” hydrogen and captured CO_2, and its derivatives. The derivatives can be obtained through DME synthesis (described above) or olefin synthesis through dehydration. From olefins, hydrocarbons can be obtained through oligomerization (alcohol to synfuels pathway described above) or hydrotreating. All the processes mentioned above are technologically mature today and available at industrial scale.

Another e-fuel process is not technologically mature yet though: the one involving Reverse Water Gas Shift (RWGS) and Fischer-Tropsch to produce paraffinic e-fuel. RWGS, which is a step to produce carbon chain liquid fuels through CO_2 upgrading, is the technology bottleneck here. The reaction of CO_2 with H_2 to produce CO and H_2O must take place at high temperature to ensure CO selectivity. The process requires further research and development. For example, no pilot tests are observed in the literature, although Repsol has announced an e-fuel pilot plant involving RWGS by 2024[106]. Publications are at laboratory research and initial upscaling stage. Amongst the research needs, it is observed that the process requires development of high temperature enduring catalysts as research aims at the avoidance of severe sintering of catalysts. Avoiding thermodynamic limitations help achieve high conversion and suppress CO/CO_2 methanation. Research needs also extend to catalyst solutions to avoid the high cost of noble metal catalysts to facilitate commercialisation, andto improving process stability under real operating conditions.

Table 27. Summary of TRL Processes for E-fuels Synthesis [Cerulogy, 2017][105]

Technology	TRL (today)
Synthesis	
H_2 storage (stationary)	9
Fischer-Tropsch pathway	
Fischer-Tropsch synthesis	9
Reverse water gas shift (RWGS)	6
Hydrocracking, isomerization	9
Methanol pathway	
Methanol synthesis	9
DME synthesis	9
Olefin synthesis	9
Oligomerization	9
Hydrotreating	9

[106] Power to liquids – PTL, Repsol, 2021; https://www.concawe.eu/wp-content/uploads/Session-2-Presentation-4-Alfonso-Garcia.pdf

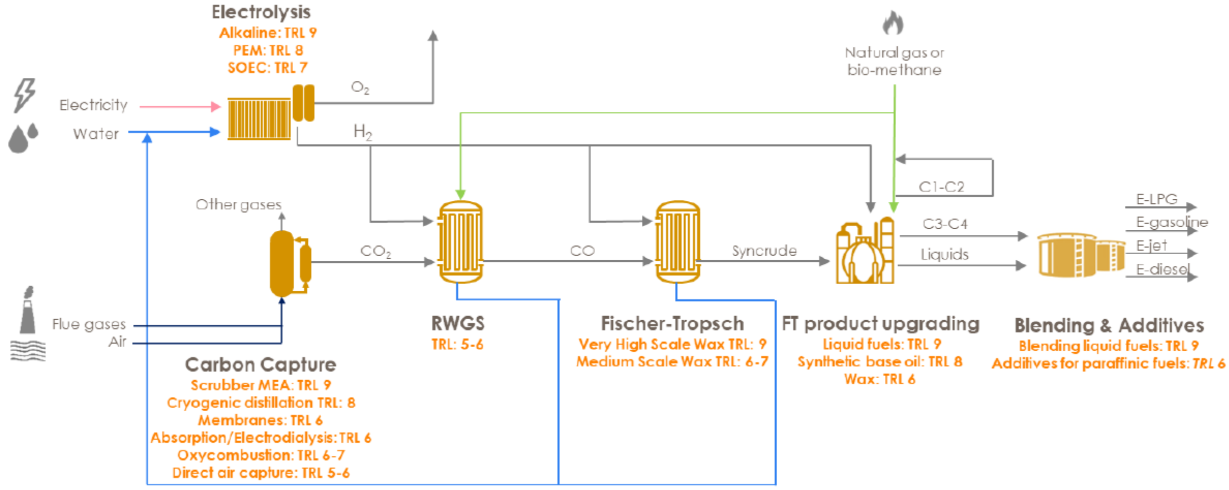

Figure 58. Summary of TRL of processes for an e-fuel synthesis via Reverse Water Gas Shift and Fischer-Tropsch[108].

6.1.3 Gaseous fuels

As research recommendation related to gaseous fuels production considered in this document (biogas, and power-to-gas) are not specific to road transport (because these gaseous components are provided to many other sectors), they will not be detailed in this document. Regarding biogas more particularly, they can be found in the reports published by Gas for Climate[107] (Association aiming at analysing and creating awareness about the role of renewable and low carbon gas in the future energy system). The document contains analysis regarding the feasibility of REPower EU 2030 targets and production potentials of biogas in the Member States and outlook to 2050.

[107] Biomethane production potentials in the EU - Feasibility of REPowerEU 2030 targets, production potentials in the Member States and outlook to 2050, A gas for Climate report, July 2022. https://gasforclimate2050.eu/wp-content/uploads/2022/10/Guidehouse_GfC_report_design_final_v3.pdf

6.2 Recommendations for Powertrains

The variety of powertrain technologies envisaged requires numerous different research needs. These are clustered below according to the related sub-chapter and TRL.

Digitalisation, as a tool, represents an overarching activity for accelerating the development of advanced powertrains and is inherent at all TRLs. Significant advancements of digitalisation call for building-up knowledge and capabilities in the areas of:

Modelling and simulation:

- Significant advancements in predictive multi-physics and multi-material models for simulating coupled transport, thermodynamics, electrochemistry, chemical kinetics, electromagnetics and material mechanics, as well as fatigue phenomena, to support the development of all types of electrified powertrains (generally applied at lower TRLs);
- Development of consistently scaled and computationally efficient models, e.g. reduced-order models, sharing as high a level of consistency with the detailed models as possible, to enable high-fidelity system layout analysis and the application of the models in cyber-physical systems, e.g. Hardware-in-the-Loop (HiL) applications, as well as for on-line monitoring (applied at higher TRLs);
- Development of innovative interactions of AI and physics-based, detailed as well as reduced-order models to further boost efficiency of the design space exploration;
- Development of advanced, physics-based and AI supported digital twins (including SoX observers and EoL prediction functionality for batteries, fuel cells, electrical motors, inverters and other relevant components of electrified powertrains), which are applicable to on-board and off-line (cloud) applications, for on-line monitoring, virtual sensor functionalities, model based fault detection, model based predictive maintenance and for supporting health-passport functionalities, with an aim to enhance reliability and safety whilst reducing TCO;
- Development of advanced, integrated and interoperable models of the entire PLM, including LCA.

Connectivity and data management:

- Development in the area of safe transmission and reliable storage of key data, which is vital for efficient data access purposes, condition monitoring, anomaly and fault detection as well as predictive maintenance;
- Development in the area of standardization of data exchange and data management procedures;
- Development of HW supporting safe and efficient data transfer and processing, including telemetry enabled functionalities.

6.2.1 Recommendations for BEV

Early-Stage Research Actions (TRL 2-3) potential market entry 2030 - 2035

- Advanced power electronics based on beyond GaN (Ultra-Wide-Band-Gap materials);
- Novel PCB concepts and materials, including additive manufacturing and 3D design;
- Extremely, highly integrated powertrain systems and components, including novel electrical connections;
- Integrate structural batteries to the vehicle chassis (e.g. as part of the body structure);
- Telemetry enabled BMS, EMS and xMS architectures;
- AI-based health management (i.e. self-updating algorithms based on in-situ data);
- 100% fossil-free energy for manufacturing and recycling;
- Recycling with the highest efficiency in material recovery, at a sensible level for LCA and economics, referring to the recycling strategy of the EC (70%), whilst acknowledging that the real goal is a circular economy.

Development Research Actions (TRL 4-6) potential market entry 2025 - 2030:

- Right-sized voltage levels in novel architectures (TRL 3 or 4);
- Modular powertrain architectures, ideally suited for right-sizing powertrain and vehicle concepts;
- Integrated electro-mechanical components and control systems functionality;
- Improvements in thermal management systems with structurally integrated liquid cooling and/or heating;
- Improvements in battery packs integrated into a full vehicle thermal management system;
- Improvements in integrated thermal management (powertrain with overall vehicle perspective) to improve overall system efficiency;
- Air-cooled powertrain systems (TRL 4);
- Lightweight powertrain components and systems for vehicle concepts;
- New testing of packs and modules for the physical investigation of safety and durability;
- Swappable batteries (harmonization across L-category vehicles and classes):
    - Identification and definition of parameters for harmonization of battery packs and battery modules for specific vehicle categories;
    - Improvement of battery recycling, refurbishing rates through shared architectures;
    - Advanced, load peak shaving and battery-to-grid techniques, based on distributed battery swapping stations;
    - Smart and predictive battery handling systems, based on usage and ageing profiles;
    - Technical improvement based on wide usage profiling and clustering.
- Research of structural measures and processes for the integration of the battery into the chassis, vehicle including new material, production options;
- Right sizing: optimising the use of resources (to achieve sustainability and reduce cost) to satisfy the most relevant use cases and user needs by tailoring performance indicators and requirements that harmonize vehicle specifications and design in a holistic manner;
- Advanced components and modules for integrated vehicle thermal management to maximise overall vehicle efficiency, designed for the adopted solutions (batteries, EM design, inverter technologies etc.) considering cost, weight and size criteria;
- Achieving, demonstrating unprecedented safety through a holistic systems approach from component to the system level, including novel sensors and observers plus digital-twins;
- Continue the research on functional integration, at the level of components, systems and systems of systems, to improve performance and affordability;
- Enabling, establishing/demonstrating of bidirectional charging systems with increased efficiency and power quality, using wide-bandgap power modules, converter topologies and control systems.
- High-power automated charging.

Innovation Actions (TRL 7-8)

- Demonstration of advanced concepts under real-world conditions (follow-up of earlier TRLs);
- Demonstration of fail-operational powertrains;
- Data acquisition (standardized) to support future AI needs;
- Developing/demonstrating comfort charging (fast, wireless, robotic etc.);
- Further investigation in optimised power management technologies for extended battery life, increased safety and reduced energy consumption;
- Implementation of eco-design principles considering manufacturing, recycling and the economics of BEV powertrain components.

Table 28. Research needs for Powertrain Solutions

	Research Need for Powertrains	2022–2035
	Modelling and Simulation	Continuous Improvement
	Connectivity and Data Management	TRL 4-6 › TRL 7-8
	Recycling, Materials for New Powertrains	Continuous Improvement
	Availability/ Sustainability of Resources	Continuous Evaluation
BEV	Advanced Components, Materials and Processes	TRL 2-3 › TRL 4-6 › TRL 7-8
BEV	Connected and AI-based systems (BMS, TMS etc.)	TRL 2-3 › TRL 4-6
BEV	System approach, vehicle integration	TRL 4-6 › TRL 7-8
BEV	Safety test procedures and technologies	TRL 4-6 › TRL 7-8
BEV	Charging technologies (bidirectional, comfort-charging, robotic)	TRL 4-6 › TRL 7-8
BEV	Battery Swapping technologies	TRL 4-6 › TRL 7-8
BEV	Data acquisition and AI supported development	TRL 7-8
BEV	Implementation of eco-design principles	TRL 7-8
FCEV	Stack Technology	TRL 2-3 › TRL 4-6 › TRL 7-8
FCEV	System Technology	TRL 2-3 › TRL 4-6 › TRL 7-8
FCEV	Storage Technology	TRL 2-3 › TRL 4-6 › TRL 7-8
FCEV	System adaption and integration to vehicle types	TRL 4-6 › TRL 7-8
Hybrids incl. ICE	Dedication of ICE to renewable fuel including H_2	2-3 › TRL 4-6 › TRL 7-8
Hybrids incl. ICE	New sensors (physical, virtual) for engine control	TRL 4-6 › TRL 7-8
Hybrids incl. ICE	Improved thermal behaviour at cold start	TRL 4-6 › TRL 7-8
Hybrids incl. ICE	Dedication of ICE to hybridisation incl. simplification	TRL 4-6 › TRL 7-8
Hybrids incl. ICE	EATS and OBD, OBM for ren. Fuels, H_2 and RDE+	TRL 4-6 › TRL 7-8
Hybrids incl. ICE	Minimisation of oil consumption	TRL 7-8
Batteries	Advanced virtual development tools	TRL 2-3 › TRL 4-6 › TRL 7-8
Batteries	Increase of energy density (cell, pack, system level)	TRL 2-3 › TRL 4-6 › TRL 7-8
Batteries	Improve fast charging while avoiding degradation	TRL 2-3 › TRL 4-6 › TRL 7-8
Batteries	Optimise TMS, BMS for better efficiency and safety	TRL 2-3 › TRL 4-6 › TRL 7-8
Batteries	Recyclability, producability and circular economy	TRL 2-3 › TRL 4-6 › TRL 7-8
Batteries	Smart functionalities, monitoring, AI	TRL 2-3 › TRL 4-6 › TRL 7-8
Batteries	Regulatory activities for testing and safety	TRL 4-6 › TRL 7-8
Batteries	Advanced materials, combinations, treatments	TRL 2-3 › TRL 4-6
ERS	Safety concepts for ground based power supply	TRL 4-6
ERS	Adaption of powertrain components to ERS	TRL 7-8
Other Emission	Develop tyre-road-interaction models, basics	TRL 2-3 › TRL 4-6
Other Emission	Improvement of rolling resistance, tyre wear	TRL 4-6
Other Emission	Recycling of tyres, raw material reduction	TRL 4-6
Other Emission	Optimisation of road formulation	TRL 2-3 › TRL 4-6 › TRL 7-8
Other Emission	Technologies to reduce/ avoid brake dust: -brake dust particle filters (active/ passive) -new materials with less abrasion -recycling, reusage -braking strategies, usage of drum brakes	TRL 2-3 › TRL 4-6 › TRL 7-8
Other Emission	Reduction of harmful electromagnetic radiation	TRL 2-3 › TRL 4-6
Other Emission	Technologies for reduction of particles from ERS	TRL 2-3 › TRL 4-6 › TRL 7-8

6.2.2 Recommendations for Batteries

Based on the explanations of Section 3.2 the following research needs can be derived:

Advanced **virtual development of batteries** is one of the key pillars for strengthening position of the EU in the battery value chain. Therefore, in addition to the overarching digitalisation topics addressed in Chapter 3, a large leap forward is required in specific areas of the virtual development of batteries[108]:

- Development of innovative, fundamental, multi-scale, multi-physics and AI supported models to enable accelerated optimisation of material combinations and interfaces, as well as for the design of electrodes and electrochemical cells;
- Development of innovative, scale-bridging approaches to successfully transfer key aspects from lower-scale models to continuum-scale multi-physics models applied in cell, module and pack engineering, as well as to advanced digital twins with an aim to boost the KPIs of prototypes and final products.

The ability to fast charge batteries (with smaller storage capacities) without impacting battery lifetime is another decisive research challenge for batteries from the system perspective. Many of the detailed aspects to tackle this challenge are included in the description of the various research actions described below:

Early-Stage Research Actions (TRL 2-3)
Cell technology:

- Increase the energy density of high-power density battery cells for recuperation and fast charging, including materials and designs for enhanced heat rejection;
- Advanced and affordable lithium-ion technologies to achieve high energy and power density, as well as high energy efficiency, at sufficiently low degradation rates and increased safety whilst operating in the desired temperature ranges (Generation 3b and Generation 4);
- Improved understanding of the root cause of battery degradation, in order to improve fast charging and V2G capabilities;
- Fundamental research on innovative battery chemistry beyond lithium cell technology (Generation 5);
- Integration of smart functionalities (e.g., sensing and self-healing);
- Increase the ratio between active to passive material in the battery to ensure low LCA footprint as well as to support efficient and cost-effective manufacturability and recyclability
- Research on swelling (over lifetime) and breathing (over charge cycle) mechanism to avoid or minimize the volume change and the related challenges on cell and system level

Module/pack system technology including BMS and TMS:

- Cell to pack integration considering design, integration, functionality, durability and safety aspects, as well as manufacturability and recycling;
- Increase system level power density for high energy density batteries through new structural materials and new thermal-rejection materials, as well as methods for passive cooling;
- Innovative TMS for enhanced temperature control of batteries at minimized energy consumption;
- Methods for detecting, preventing and suppressing thermal runaway and fire propagation, in order to increase safety;

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[108] These points are related to the battery 2030+ initiative roadmaps, see https://battery2030.eu/wpcontent/uploads/2021/08/c_860904-l_1-k_roadmap-27-march.pdf

- BMS capable of supporting physics-based SoX cell observing, as well as self-healing functionalities; including performance tracking on fleet basis (see battery directive)
- AI-based adaptive BMS (i.e. self-updating algorithms based on in-situ data); supported by cloud level solutions
- Establishing a cost-effective, circular economy for modules and packs, including techniques for material recovery (e.g. mechanical disassembly and processing);
- Post-lithium battery concepts (pack design and all technical challenges depending on the choice of cell type).

Development Research Actions (TRL 4-6)

Cell technology:

- Battery designs with an optimal trade-off between energy and power density, durability, safety, fast charge, cost and LCA-footprint, tailored to specific applications (L-category vehicles and different LDVs as well as HDVs);
- Implementation of advanced battery technologies (monitoring, sensing, data, models and passports) to boost service life and safety, as well as to enable more efficient second life use.
- Research on swelling (over lifetime) and breathing (over charge cycle) mechanism to avoid or minimize the volume change and the related challenges on cell and system level

Module/pack system technology including BMS and TMS:

- Lightweight and specific volume optimised, next generation, high-energy density battery packs, including TMS and BMS;
- Enhanced, intra-pack safety concepts through safety by design and innovative manufacturing (cell breathing/swelling compensation, crash concepts, emergency concepts etc.);
- Advanced battery pack design tailored to cell chemistries (structural integrity, thermal management and materials including multi-material structures);
- Integration of low cost and reliable HW and virtual sensors for SoX monitoring and supporting emergency functionalities;
- Apply methods and tools of battery degradation to improve fast charging and V2G capabilities;
- Research on integration of BMS, TMS etc into the overall vehicle control system
- BMS for advanced chemistries, including SW and HW enhancements to support advanced SoX and safety functionalities; supported by cloud level solutions
- Innovative, low-cost concepts for cell balancing, featuring low weight and high energy efficiency;
- Accelerated test and validation of modules and stacks for mass market applications;
- Development of innovative high-voltage electrical components;
- Activities for standardization at the module level, including sensing functionalities and communication protocols;
- Research on structural batteries (e.g. as part of a vehicle body structure);
- Research on modular pack designs to enable end-of-life management and flexible second-life usage;
- Implementation of eco-design principles for batteries on system level
- Integration of safety requirements for packs and housings, including cooling, into the battery technology.

Manufacturing/material recovery:

- Optimisation of the manufacturing process for cost reduction, minimizing environmental impact, and enhanced quality of cells and packs (quality improvement, reduction of energy consumption, minimization of the process steps, increase in process speed etc.);
- Optimisation of the entire chain from raw materials to battery pack production, to comply with the principles of a circular economy, with an aim to reduce the life-cycle impact of batteries;

- Development and optimisation of method for high volume, high efficiency and low-cost material recovery and integration into circular economy.

Innovation Actions (TRL 7-8)

- Demonstration of enhanced, lithium-ion technology (Generation 3b and Generation 4) developed with advanced simulation tools, development methods and advanced manufacturing processes;
- Demonstration and validation of novel battery concepts under real-world conditions;
- Confirming that the KPIs (technical, durability, safety, economic and financial) can be met whilst providing compelling economic and environmental cases for the end users of the technology.
- Research on swelling (over lifetime) and breathing (over charge cycle) mechanism to avoid or minimize the volume change and the related challenges on cell and system level

6.2.2.1 For Battery Materials

In general, in relation to materials, specifically the provision thereof, there is a research need to decrease the use of rare materials (e.g. recycling, improving designs) or the need to find suitable replacements.

Generation 3: Advanced Lithium

For the **Generation 3a** research topics are:

- At the cathode, NMC 811: promised higher capacity, as well as higher safety aspects, however the manufacturing and the fast-ageing property is today a challenge;
- At the anode side: carbon (graphite) + silicon component (5-10%) are research topics for cycling stability and corrosion stability.

Generation 3b:

- At the cathode side: HE-NMC needs further research for stability, manufacturing and lifetime, also HV-spinel systems are under consideration for a higher cell voltage (5V), however the expense of energy content is today under intensive research to get the same values as the NMC 811 material.

Generation 4: All solid state, lithium ion or lithium-metal

Solid-state technology: Generation 4a is dealing with polymer solid; Generation 4b is dealing with all solid-state Li metal:

- Research is needed so that Europe is not losing competitiveness to other regions.
- Research to decrease the tendency to build dendrites and inhomogeneous plating
- Gen4c: research on creating/ enabling an electrolyte being stable at higher voltage
- Research on technologies for the production of separators

Generation 5: Lithium Air, Lithium Sulphur

Further research needs will be identified in the future.

- Research on active electrolytes to minimize/ avoid unwanted reactions with contact partners (e.g. lithium vs sulphur)

Beyond Generation 5, post-lithium technologies need to be researched.

6.2.3 Recommendations for vehicles using Electric Road Systems

The research need on the vehicle side is about adapting BEV to dynamic charging applications, which requires systems solutions of the kind already mentioned in Section 3.3. In relation to catenary systems, the technology is already at a higher TRL, the challenges are further optimisation of the cost, weight, volume, standardization, regulation etc. Hence, the following are suggested, particularly related to the other types of electrified road systems:

- TRL 4-6: Research on safety solutions for grounded supply;

- TRL 7-8: Development and adaption of specific onboard systems;
- TRL 4-6: research on safety measures for different kind of possible failures (such as cable breakages);
- TRL 7-8: research on smart energy management to avoid a lack of power supply when many vehicles are using the system at the same time and close together.

6.2.4 Recommendations for Fuel Cells

Early-Stage Research Actions (TRL 2-3)
Fundamental improvements are available for all of the fuel cell vehicle components. Key areas of research include:

Fuel cell stack technology:
- Development of new technologies towards improved area and volumetric power density, increased reliability and extended lifetime validation at the single cell and short stack level;
- Increase the efficiency through design and materials to reduce thermal losses, hence minimise the cooling effort;
- Technologies to enable cost reductions;
- Technologies to allow operation at higher temperatures (100C) so as to reduce the cooling system (packaging etc.) requirements in vehicles.

Fuel cell system technology:
- Improvement or development of strategic BoP components and design of systems for low cost and scaled-up manufacturing;
- Development of new, disruptive concepts towards improved volumetric and gravimetric power density and increased durability of HDV systems.

On-board storage technology:
- Development of new materials for high pressure tanks, enhancing the properties of the liner and targeting cost reduction of the reinforcement;
- Development of novel storage concepts to improve storage density, including solid carriers, pressurized tanks and liquid hydrogen;
- Development of recycling technologies thereto.

Recycling (LCA, Circular Economy approach):
- Recycling for FC Stacks to regain Pt, Au, all precious metals in general;
- Recycling for H_2 storage, tackling carbon fibre recycling, which has complexity due to the resins used.

Attention will also be paid to developing systems for scaled-up fuel cell manufacturing plants. Due to the high technical maturity of FCEVs, there is not a case for early phase development projects at the whole vehicle level.

Development Research Actions (TRL 4-6)
Development projects will work on existing technologies deployed in real systems, including:

Fuel cell stack technology:
- Stack level improvements for higher system performance, durability and reliability (including game changing concepts for core components);
- Developing low-cost concepts and improving manufacturability (processes, automation, quality control tools, in line and end of line diagnostics).

Fuel cell system technology:
- Improving system manufacturability;

- Optimisation of the system to different use cases (e.g. within heavier commercial vehicles), targeting improved performance and durability (e.g., hybridized powertrains, range extender, advanced tools and methods for improving control and strategies.

On-board storage technology:

- Development and validation of integrated mounting concepts, safety by design and innovative manufacturing techniques;
- Integration of low cost and reliable safety sensors for structural health monitoring and fire detection.

Integration:

- System integration into different vehicle types (classes), development of BoP components, bench test validation of complete drivetrains, packaging and vehicle integration;
- Supplier identification, benchmarking and standardisation at a component level.

Innovation Actions (TRL 7-8)

Due to the support of the FCH JU and Horizon2020 funding, multiple demonstration projects have already been able to prove the reliability and technical readiness of FCEVs. As a result, the only demonstration projects needed over 2021-2027 will be demonstrating less developed use cases, such as heavy-duty long-haul FC trucks, heavy-duty off-road FC vehicles and, to a lesser extent, FC vans.

6.2.5 Recommendations for Fuel Cells for Commercial Vehicles

As above, reference should be made here to the Clean Hydrogen Europe Partnership SRIA and the research projects from the preceding JU[109].

Development Research Actions (TRL 4-6)

Building on the development work already underway in this sector, a targeted programme of support can help to cover the costs of further development activities and attract a growing number of suppliers. There is a case for funding to support non-recurring engineering costs and prototyping/development activities, including:

- Establishing FC HDV specifications required to meet user's needs and regulation constraints for a range of truck sizes, duty cycles and auxiliary units (e.g., refrigerated food transport) power demand. Modelling, optimisation and life cycle cost analysis tools are essential to suitably address optimal HDV and coach powertrain designs and energy management, as well as determining the FC related recycling potential;
- Prototyping activities, development of control, diagnostic and prognostic procedure, interfaces between sub-systems and integration of FC systems and on-board hydrogen storage into FC HDV. Investigation of future usage of liquid hydrogen. Development of health of state monitoring concepts for service and maintenance.

Coaches:

Adapting fuel cell systems from other vehicles (urban buses or cars) for long distance coaches, developing solutions for integrating fuel cell-based powertrains into coaches without compromising the utility of the vehicles and certifying hydrogen-fuelled coaches in line with existing regulations governing conventional coaches.

[109] See https://www.clean-hydrogen.europa.eu/about-us/key-documents/strategic-research-and-innovation-agenda_en

Minibuses:

Adapt fuel cell systems from other vehicles (cars and vans) for minibuses, developing solutions for integrating fuel cell-based powertrains (including FC system, electric drivetrain, hydrogen tanks etc.) into minibuses, whilst maintaining passenger carrying capacity, range etc.

LDVs:
Cost reduction and specific performance improvements via reduced need for platinum group materials, higher functional integration at a component level and standardization of components, as well as sub-systems.

Innovation Actions (TRL 7-8)
Given the similarities and synergies between the FC HDV (including coaches) and the marine or railway sectors, demonstration projects in this area can learn from previous real-world trials. Further demonstrations in the post 2020 period should focus on:

- Validating the performance of the technology in a range of real-world operations, specifically KPIs such as availability, lifetime, efficiency and ownership costs;
- Preparing the market for wider roll-out, e.g. by training technicians to maintain the vehicles etc.;
- Collecting and analysing empirical evidence on performance (technical and commercial) of vehicles and associated refuelling infrastructure. Exploiting the promising synergies between hydrogen based renewable distributed energy systems and the transport sector;
- Ensuring the range of truck types are trialled (e.g., different weight classes and niches such as refuse trucks);
- Ensure the safety issues associated to the significant amount of on-board stored pressurized hydrogen are fully addressed.

Support for deployment of European heavy-duty fuel cells in the bus market, and support for new entrant bus OEMs and novel drivetrain concepts. Demonstration will be required for new entrant OEMs, fuel cell coaches, minibuses and LDVs during the period until 2030. The scope of these activities will include:

- Validation of technical performance in real world operational environment;
- Optimising solutions and modifying designs based on feedback from trials;
- Confirming that KPIs (technical and economic) can be met, providing compelling economic and environmental case for end users of the technology.

6.2.6 Recommendations for PHEV and alternative fuels

Internal Combustion Engines:

Early-Stage Research Actions (TRL 2-3)
Measures to increase engine efficiency and minimize exhaust emissions:

- Basic research on the combined optimisation of the properties of renewable fuels and tailored combustion modes, to explore the design space and reach engineering limits, in terms of maximized efficiency and minimized exhaust emissions;
- Development of new materials to reduce heat transfer, minimize friction and wear.

Development Research Actions (TRL 4-6)
Measures to increase engine efficiency and minimize exhaust emissions:

- Technology to maximise the benefits of low carbon fuels (“Dedication to low carbon fuels”);
- Determine the highest injection pressure for CI (2000++ bar) and SI engines for renewable fuels, to optimise combustion.
- Create a fully variable and dynamic airpath to optimise transient engine operation;

- Increase the performance of ignition systems when running with renewable fuels and high EGR, dilution, so as to reduce the cyclic variability;
- Dedicated combustion strategies (lean, stratified, controlled autoignition (CAI) etc.) tailored in combination with renewable fuel(s);
- Characterisation of fuel properties and tailored combustion modes by laboratory engine (and other) tests to deliver data for digital models;
- Advanced physical and/or virtual sensors (e.g. fast lambda control) and closed-loop combustion control to tailor combustion to engine operating point and fuel properties;
- Detection and usage of fuel quality (sensors, electronics, digital models);
- Optimisation of thermal behaviour (fast heating-up, optimised heat flux, minimum thermal losses, thermal isolation/storage etc.) including system level optimisation;
- Tribology:
    - Improve the lifetime of the engine oil by dedicated lubrication-oils for renewable fuels (acid, ashes etc.) under consideration of unregulated emissions (NoLims category);
    - Holistic, system level optimisation dedicated to electrification including simplification and phlegmatization.

Innovation Actions (TRL 7-8)
Demonstration at the system level:
- Boosting efficiency (maximizing compression ratio, variable compression ratio, Atkinson or Miller Cycle, large stroke/bore ratio, minimized heat transfer etc.);
- Electrically driven accessories (larger potential for DHE);
- Sweet spot optimisation and operation (larger potential for DHE);
- Increase structural strength and thermal properties to cover higher combustion pressures and thermal loads linked to renewable fuels;
- Dedication to electrification including simplification in operation strategies and hardware.

6.2.7 Recommendations for ICE pollutant emissions

Research targets
- Development of exhaust aftertreatment systems for all types of engines and fuels able to achieve the above objectives;
- Development of sensor and OBM and/or OBD technologies to secure monitoring of vehicle performance under all driving conditions and over its entire useful life;
- Development of emission and consumption optimised control systems through geofencing;
- Development of powertrain non-exhaust emission control systems.

Development of exhaust aftertreatment systems for all types of engines and fuels capable of:
- Ultra-fast light-off under extremely low temperatures;
- Maintaining high conversion efficiencies under the zero flow conditions due to frequent and intermittent engine start-stop and under ageing effects;
- High filtration efficiencies for all levels of particle loading for any type of engine and fuel;
- High filtration efficiencies for particles down to nanoparticles
- High filtration efficiencies for solid particles with a specific attention to semi-volatile particles;
- Focus on secondary aerosol and VOC production potential as well;
- Negligible back-pressure thus minimizing the fuel penalty and associated CO_2 emissions;
- Reduction of all (today) non-regulated pollutants (NO_2, NH_3, NMOG and Formaldehyde) and GHG gases (CO_2, N_2O and CH_4);
- Material compatibility and efficiency of aftertreatment systems with sustainable bio and synthetic fuels, considering LCA issues as well;

- Measurement tools development for data recording and analysis to address tailpipe emission for non-regulated pollutants, PM and PN;
- Research on the health effects from non-soot particles, such as those from urea and ash;
- Research on the effects of particle emissions from alternative fuels on health;
- Robust simulation models for insights on performance and methods of optimising configurations;
- Multiple exhaust aftertreatment functionalities into a single unit;
- Surface chemistry and physics for high-efficiency, low-temperature catalysis and filtration.

Development of sensor and OBM, OBD technologies for the accurate, continuous and secure monitoring of vehicle performance under all driving conditions and its entire useful life

- Including energy consumption;
- Optimise diagnostic capabilities and functionalities.

Development of emission and consumption optimised control systems through geofencing

- Eco-routing, eco-driving impact assessment;
- Cloud-connected next generation vehicles for real-time co-optimisation to minimize real driving emissions and local pollution.

Development of powertrain non-exhaust emission control systems to address

- Particles from electrical machines etc.;
- Fuel evaporation losses or leaks that result in VOC emissions;
- Electromagnetic emissions.

6.2.8 Recommendations for H_2 ICE

Early-Stage Research Actions (TRL 2-3)

H_2 fuel system:

- Durable and low-cost hydrogen high-pressure injection systems (including the pump and the nozzles), enabling multiple injection including material and tribology related research;
- Highly under-expanded H_2 jets with shock formation downstream of the injector nozzle to optimise injection and mixture formation.

H_2 combustion system:

- Basic combustion analyses at ICE relevant conditions, including stratified and/or highly diluted mixture, to expand the knowledge base on combustion kinetics and the behaviour of the relevant regulated and unregulated emissions (also forming the basis for highly precise modelling);
- Development of spray driven (diffusion controlled) H_2 combustion.

Exhaust gas aftertreatment:

- Focusing on cold start operation and on highly efficient nanoparticle filters yet also addressing non-volatile components;
- Innovative techniques, such as the use of H_2 as reductant in aftertreatment devices.

Development Research Actions (TRL 4-6)

H_2 fuel system:

- Optimisation of the injector design, the operating parameters of the injector and the injection strategies to the targeted geometrical constraints of the combustion chamber, to ensure proper mixture formation, enabling highly efficient and low emission combustion;
- H_2 pre-conditioning (pressure, temperature);
- Indirect H_2 injection (H_2-metering under special consideration of low volumetric H_2 density, air-H_2 mixture preparation, elimination of backfire);
- Direct H_2 injection (pressurizing, injection nozzle, spray pattern and multiple injection) optimisation.

H_2 combustion system:

- Optimisation of the entire process from injection, mixture formation to combustion, leading to specific optimal trade-offs for specific power, efficiency and low emissions at full and, in particular, at part loads, by exploring the potential of multiple injection, charge stratification and dilution;
- In-cylinder charge motion and turbulence, considering the high combustion speed even under lean operation, as well as the effect on wall heat losses;
- In-cylinder mixture preparation considering the gas properties of H_2 and the expected long injection durations (due to low densities and low specific volumetric heating values of H_2);
- Ignition systems with a special focus on the very low energy activation and short ignition delay, leading to low energy ignition systems but causing high risk for irregular combustion initiated by hot spots in the combustion chamber;
- Control of burn rates under consideration of the low ignition delays, the high flame velocities and combustion speeds for Air+H_2 mixtures, as well the avoidance of knocking combustion.

H_2 ICE control, sensors and OBD functions:

- Closed-loop injection/combustion-control to achieve the targeted optimal specific trade-offs between power, efficiency and emissions, as well as cylinder balancing and engine durability.

H_2 ICE oil consumption optimisation:

- Engine design for the lowest possible oil consumption, for efficiency improvement and emission reduction without negative effects on durability and reliability. Minimization of oil consumption to minimize unwanted emission by (partly) burned oil and other effects on combustion ignition through engine oil.

Exhaust gas aftertreatment

- Lean deNOx aftertreatment;
- SCR aftertreatment;
- Presence of unburned H_2 with the need of a specific aftertreatment system;
- Soot emissions from oil combustion due to H_2 burning very close to walls (cylinder liner) and, consequently, the need of particle filtration;
- Management of the complete aftertreatment system, focusing on efficiency at low temperature, thermal management and transition mode (stochiometric/lean) if needed.

6.2.9 Recommendations for Complimentary Driveline Aspects

Improve tyre rolling resistance combined with grip, handling, noise and wear
20% to 30% of the energy used by a vehicle is dissipated into its tyres (elastic deformations). Reducing the tyre rolling resistance without sacrificing safety is key to achieve the objectives of energy efficiency and CO_2 emissions reduction. This leads to the following research needs:

- Developing new and innovative technologies (architecture, materials etc.) and systems to reduce the rolling resistance (for all applications, from micro-mobility to heavy trucks);
- Developing new tyres for new vehicles to improve their energy efficiency but also to retrofit existing vehicles (this could hasten the transition to lower CO_2 mobility).

Tyre performance (rolling resistance, grip, noise, wear etc.) is always a compromise, improvement of one performance is most often on detriment of others. Tyre use on future vehicles (e.g., electric or autonomous) will be slightly different than today's classical vehicle usage, leading to different or new constraints (e.g. mechanical solicitations or dimensional constraints) for tyres. This leads to the need to improve tyre performance (rolling resistance, grip, noise, wear etc.) regarding the new applications:

- Characterize the different or new uses and their impact for tyres;
- Develop dedicated tyres adapted to specific vehicle and uses with enhanced specific performance.

Take into account real use (including fuel consumption): (tyres better optimised to real use)

- Characterise uses and impact on tyre performance;
- Develop real-use models, including components (tyres) specificity.

Reduce use of raw material

Tyres are still mainly produced using fossil raw materials. Reducing the use of this type of raw material is necessary for environmental benefits. Hence, research and developments needs are:

- Develop new technologies to reduce tyre mass;
- Use of recycled materials as raw materials;
- Maximise the tyre re-use.

Use biomaterials as raw materials

Raw materials for tyres are today, in the majority, still coming from fossil resources. Replacing these raw materials by renewable and/or biomaterials is a necessity.

- Develop biopolymers, bio-components etc.

Recycle tyres

Even if part of today's End of Life Tyres (ELT) are recycled into other applications with granulates, part of them is still burned in cement kilns. Better uses for ELT, into high value products or processes, is needed, especially to feed the tyre industry in secondary raw materials.

- Develop processes to recycle ELT into reusable raw materials for the tyre industry.

Reduce the tyre impact (non-exhaust emissions to improve air quality and exterior noise)

Improving the wear performance is one way to reduce the wear particles emissions but there are other important elements to be taken into account, such as the road surface, driving style, traffic flow, vehicle design and weight.

The impact of TRWP (Tyre and Road Wear Particles) is not yet fully measured and understood.

- Characterise more precisely TRWP (composition, quantify, biodegradability etc.);
- Adapt tyre conception to lower impact of TRWP.

Reducing the tyre noise generation correspond to the expectations of the city inhabitants.

Develop sustainable roads (also relevant for Infrastructure aspects)

Roads are usually made from fossil raw materials. ELT (End of Life Tyre) granulates can be part of road formulation, but regulations differ from country to country (allowed in US, Australia yet forbidden in the EU). Road characteristics have an impact on all tyre performance (rolling resistance, grip, noise, wear etc.)

- Work on road formulation to improve tyre and road performance
- Demonstrate the benefit of ELT granulates into road formulation to change EU regulation
- Improve road formulation to transfer a part of tyre performance (e.g. better grip coming from road would allow to focus more on rolling resistance on the tyre side);
- Improve the road endurance to limit the impact on the traffic when a maintenance is needed.

Develop new tyres concept adapted to new usages (urban fleet, new type of mobility)

Achieving ambitious objectives in term of environment goals and CO_2 reduction may require complete rethinking of the tyre design and manufacturing:

- Development of new tyre concepts: airless, 3D printing of treads etc.;
- Develop complementary micro-mobility solutions associated to new types of ‘’tyre type’’ solutions.

Develop tyre telematics

The tyre is the only vehicle component in contact with the road. Sensors in tyres will enable crucial functionality and services for safety, predictive maintenance, autonomous vehicle behaviour etc.

- Develop sensors around tyres and associated mobility services (predictive maintenance and tyre health);

- Develop new types of smart material.

Develop innovative and efficient manufacturing processes
As a consequence of the new uses, dedicated specific tyres will induce even more diversity and small series production volumes. This will affect the competitiveness of the existing factories. Knowing that tyres performance and manufacturing processes are closely linked, it is necessary to develop innovative manufacturing processes for those new tyres, taking into account the range of diversity whilst minimising energy consumption.

- Develop new process to take into account more diversity and small series, to ensure competitiveness of the existing factories and to reduce their global environmental footprint;
- Develop alternative processes to minimise energy consumption.

Develop simulation
Simulation of the global system of mobility is key to achieve the global CO_2 emissions targets. The ecosystem is so complex that making the right design choices should be supported by a simulation approach. Simulation is key to speeding-up and improving conception, either at a component (tyre) level or a system level. Furthermore, with new types of mobility solutions (e.g. automated vehicles), simulation allows to limit the number of tests while still considering all possible scenarios. Scenarios related, as an example, to emergency manoeuvre, braking but also CO_2 emission.

- Develop simulation at tyre and system level.

Technologies to reduce brake dust particles:

- Develop the use of brake dust particle filters (active and/or passive);
- Enhance the performance of regenerative braking (for xEVs) to further reduce the use of foundation brakes;
- Re-consider the usage of drum brakes (where acceptable);
- Further development of low abrasion components;
- Develop smart braking strategies for xEVs;
- Enhance the recycling and/or reusage of raw materials.

Technologies to reduce particle emission when using conductive electrified road systems:

- Research on the mechanisms and/or mitigation of the environmental impact from the abrasion of sliding contact materials (e.g. copper from catenary systems).

6.3 Recommendations for Infrastructure

Enhancing and facilitating research and studies that assess the economics behind the EV charging infrastructure would provide significant support to governments and regulators, for instance when they have to define how to structure the electricity bill or to design special subsidies or tax discounts.

More information regarding the performance of different types of biofuels and electro-fuels in current and future vehicle technologies could help ensure the best and most economic selection of renewable components. Since service station tanks and pumps are frequently difficult to retrofit, logistics and market scale-up become increasingly difficult if new engine configurations are introduced to the market requiring a specific fuel that is not routinely available at the service station. Better integration and optimisation of fuel, engine and vehicle also requires the development of robust standards for liquid and gaseous blends.

6.3.1 Recommendations for roads

Additional research related to **Electric Road Systems Infrastructure** would be needed on:

- Road construction durability;
  - More research is needed on what will happen with the durability of the road during accelerated loading, when there are materials embedded in the road that have different characteristics than the road (all embedded technologies including all inductive technologies).
  - More research is needed to assess the durability of a catenary system under a high number of pantograph crossings and their dynamics, under extreme weather events (storms, strong wind, ice and snow etc.), road works requiring dump trucks, emergency rescue, the maintenance and the visual acceptance.
  - A potential solution for both systems could be for prefabricated pavement surfaces integrated with dynamic charging channels and conduits to connect to the electricity supply. This could extend the lifetime of the pavement and ensure the performance of the dynamic charging system, however, the resolution of the known problems associated with prefabricated road surfaces, e.g. transverse joints, will also be essential.
  - It is not investigated what impact roadside installations will have on the road surface; road surface damage might be generated by installations too close to the road. Further investigations are needed to understand how such installations impact the slope stability and, subsequently, the road due to, for instance, vibrations from wind or passing vehicles, and how such risks might increase with increased amount of precipitation in a changed climate.
  - The differences between standards for roads and standards from the electrification field need to be further investigated, there could be differences both when it comes to construction and use of the systems.
  - How the installation procedures can be optimised (regarding all electrified road technologies) to
    - cause as little impact on traffic as possible during the installation phase;
    - being able to make adjustment already in the installation phase to make the electrified roads more sustainable in the future and thereby reduce the amount of maintenance operations.
  - The effects of ambient climate and temperature need further studies. For example:
    - Snow on the road could have an impact on the positioning of the vehicles (through ADAS) thus interfere with the proper connection, if ADAS is used by the ERS vehicle when connecting.
    - Snow and ice may have an impact on catenaries (overweight). However, neither the catenaries nor rails in pavement would not be affected too much by ice and snow as long as the traffic flows; if the traffic is stopped, it is not an issue. Inductive solutions may not be impacted.

- The large temperature variation between a Nordic Winter and a southern European Summer could have an effect on both material and electronics. For example, high temperatures may limit the power delivered.
- Research may be required for methods to isolate the differences in thermal expansion and contraction of the metal rail or inductive coil and the surrounding asphalt or concrete, should expansion joints be insufficient.
- Research is required for methods to thermally isolate embedded elements, should those elements increase the temperature of surrounding temperature-sensitive paving materials.

- Road maintenance (all dynamic charging technologies);
  - For all dynamic charging systems, there will be two major implications for the maintenance regime. Firstly, methods for standard maintenance will need to be revised and the equipment must be adapted to avoid damage to the charging system, through activities such as resurfacing. Secondly, there will be additional maintenance requirements associated with the charging system itself, ranging from testing for currents, performance of the systems, cleaning (e.g. leaves in the rail, removing icicles from overhead cantilevers or cables).
  - For all dynamic charging systems the impact of winter maintenance (e.g. snow ploughing and salting) will need to be understood and optimised and possibly amended.
  - For all dynamic charging systems, there will be additional maintenance inspections.
  - Regular maintenance operations on the road and in the roadside areas will be needed and affected by having roadside installations.
  - For all systems, there will be traffic management requirements and lane closures; systems should be developed to undertake maintenance of the systems as quickly and remotely as possible.
  - For all systems, there will need to be significant staff training and standards as road workers are not familiar with working in and around high voltage installations.
  - Cost estimations are needed on how maintenance activities will be affected by dynamic charging systems and the changes made to maintenance activities.
- Impact on environment, natural and cultural landscape;
  - All systems will have some roadside infrastructure, such as control boxes and connection points. Systems to the side of the road and above the road, in particular, will have greater visual impact which may restrict their use in certain situations. Research should be undertaken to minimise the impact, e.g. through using materials that enable the function with a lower visual profile, or otherwise improve the aesthetic impacts. Research should be undertaken to determine the amounts of ERS required for given traffic loads, to determine if it is needed constantly for heavily used motorways or a certain percentage of the route length for other roads. This could enable visually intrusive systems to be sited according to local landscape considerations.
  - More research is needed on the wear of the system most importantly the overhead conductive techniques. The difference to the railway is that particles coming from above on a road will be spreading on the road or in the air above the road. The potential use of the system will be more frequent than that of the railway and people will travel on the roads. These questions will be very important to investigate further. Conductive rail technologies will also generate particles. Accelerated tests are needed, the spreading distance from the road is important.
  - Investigation on EMF emission from the whole system, should follow new EU directives. The effects on humans are not sufficiently investigated at this time. Investigate EMC and/or EMI standards that are specific to ERS-road-vehicle-human interaction.
- Research the potential extension of ERS to a whole system approach, to use the road as part of the energy transmission network. Also seek to integrate energy harvesting from the roadside and/or infrastructure into this and assess the business case with these areas included;
- Better understanding the efficiency limits of the ground-inductive compared to ground-conductive dynamic charging systems;

- Legal implication (obstacles and opportunities) in the areas of road law and electric laws, and the impact on the road planning process;
  - Develop common European standards for electrified road systems to maximise economies of scale, as well as the chance to set the global standard.
- Safety implications;
  - Understand how emergency vehicles, including helicopters, can retain access to the road.
  - Understand how secondary, exceptional uses of road, e.g. emergency aircraft landing, is affected.
  - Understand the skid resistance (for all vehicles but particularly motorbikes) when crossing the rail(s).[110]

Research related to **Road Construction** should be considered for the following areas:

- Improved road mixes for smooth, low rolling resistance and long-life roads;
  - Determine which parameters and indices have the most impact on energy efficiency and fuel consumption.
  - Determine how IRI, MPD and megatexture contributes to the overall energy efficiency on roads for all vehicle types.
  - Determine the actual relationship between traffic speed and road condition. Research has shown decreased speeds with more uneven roads (less fuel consumption).
  - Long term functional requirements based on energy consumption on newly build roads.
  - Balance between safety, low texture and a maintained durability.
  - Research how improving IRI, MPD and megatexture contributes as a maintenance parameter serving to retain road energy efficiency at a high level throughout the entire life span.
- Studies have shown that improved methods for road construction and maintenance, assisted by the new range of smart and digital technologies fuelled by big data, machine learning, artificial intelligence, blockchain, internet of things, etc. can significantly contribute to increase the efficiency and quality at every stage of the process, from the production plant, transport and on-site paving operations, to the continuous monitoring and decision making during the road service life. However, more needs to be done in this area;
- Develop and implement a standard or labelling of road quality for enhanced energy consumption across Europe to collectively improve and document CO_2 saving potential;
- Increased use of recycled material and bio-based binders to reduce the carbon footprint of the road;
- Consider potential for research into carbon absorbing surfaces so roads are carbon-neutral or carbon positive, from a construction point of view, over their lifetime;
- Investigate impacts of enhanced road efficiency specifically for EVs;
- Can adjacent road furniture and/or vegetation be implemented as an efficient mean of enhancing energy efficiency by lowering road wind gusts, and contribute to improving road aesthetics?;
- Further investigation into the use of alternative fuels (e.g., bio-binders) to replace standard bitumen in road construction;
- Research should be undertaken on the use of alternative fuels and powertrains in construction machinery / non-road machinery, taking into account current and future emission standards.

6.3.2 Recommendations for the energy supply infrastructure

Research needs in general related to the energy supply structure are noted here:

- European standardisation of charging economy and use interfaces (billing, taxes etc.);
- Fast-charging infrastructure (e.g. for solid-state batteries) with higher power (towards megawatt);
- A European strategy for energy policy and distribution related to road transport;

[110] Some studies have been carried out in France on one technology, suggesting no loss of adhesion, but more work is needed.

- International standardization for information exchange in the charging value chain (e.g. between CPO and EMSP);
- Infrastructure automated charging solutions;
- Grid balancing and smart charging (V2G etc.);
- Local energy storage concepts to handle peak power need;
- Sector coupling and synergies with other industries and energy sectors to capture excess of energy;
- Standards for liquid and gaseous fuels, including alternative fuel components, within the grid;
- Adaption of the gas supply grid to hydrogen.

Table 29. Research needs for Infrastructure

	Research Need for Infrastructure	2022 – 2035
Roads for ERS	Road durability due to embedded ERS	TRL 2-3 → TRL 4-6 → TRL 7-8
	Alignment of standards for roads and electrification	TRL 7-8
	Optimisation of ERS installation procedure	TRL 4-6 → TRL 7-8
	Development of adapted maintenance technologies	TRL 4-6 → TRL 7-8
	ERS affection by climate (snow, temperature etc.)	TRL 2-3 → TRL 4-6 → TRL 7-8
	Impact of ERS on environment/ health (EMF, particles etc.)	TRL 2-3 → TRL 4-6
	Integration of ERS roads into energy system	TRL 2-3 → TRL 4-6 → TRL 7-8
	Legal implication: European standards for ERS	TRL 7-8
	Safety: emergency strategies (helicopter access etc)	TRL 4-6 → TRL 7-8
Road Construction	Improved road mixes for less drag and better durability	TRL 4-6 → TRL 7-8
	Improved road construction methods (e.g. connected and autonomous plant)	2-3 → TRL 4-6 → TRL 7-8
	Develop European Road Quality Label/ CO2	TRL 4-6 → TRL 7-8
	Increase degree of recycling for lower CO2-footprint	2-3 → TRL 4-6 → TRL 7-8
	Carbon absorbing surfaces in road construction	2-3 → TRL 4-6 → TRL 7-8
	Impact of adjacent furniture/ vegetation	TRL 4-6 → TRL 7-8
	Biomaterials in road construction (e.g. bio-binders instead of bitumen)	2-3 → TRL 4-6 → TRL 7-8
	Use of bio-fuels and alternative powertrains in machinery	TRL 4-6 → TRL 7-8
Energy supply	European standardization of charging economics and user interface (billing, taxes etc.)	TRL 7-8
	Fast charging for solid-state batteries with higher power	TRL 2-3 → TRL 4-6 → TRL 7-8
	European strategy for energy policy and distribution	Contnuous Evaluation
	Grid balancing and smart charging (V2G etc.)	TRL 4-6 → TRL 7-8
	Standards for liquid and gaseous fuels to integrate alternative fuel components into the grid	TRL 7-8
	Adaption of gas-grid to hydrogen	TRL 7-8

6.4 Recommendations from the System Perspective

Some research needs were identified by the **ERTRAC CO_2 Evaluation Group**, following their study for 2050:

- How to enable fleet mix change by improving powertrain technology: cost, range, functionality etc.; and adapting infrastructure technology and concepts.
- How to realise the efficiency improvements by Measure A: Vehicle; Measure B: Traffic conditions; and Measure C: Traffic Reduction Technologies.
- Beside Road Transport:
  - How to realise renewable electricity generation capacity (inside and outside of Europe);
  - How to realise net GHG-neutral H_2 and fuel production (inside and outside of Europe);
  - How to realise the technology and capacity of CCS and DAC;
  - How to determine the availability of raw materials and sustainable feedstocks (appraised in a life-cycle analysis perspective).

However, specifically it was noted that system optimisation cannot be based on an extreme scenario approach. Further research, innovation and development work will be needed to assess and establish the optimal solutions, on the basis of various criteria. Such criteria were identified as:

- Energy production and storage capacity;
- Life Cycle Assessment (LCA) to account for the emissions and energy required for infrastructure and vehicle production;
- Investments in infrastructure and energy production facilities;
- Cost of energy production and distribution, as well as vehicle technology development;
- Land use, water use and other resources needed; plus their allocation between different sectors
- Different locations for energy production (EU or MENA-Region);
- Customer acceptance of specific vehicle types and fuels;
- The acceptance of CCS.

Furthermore, research needs from other aspects were derived, for example:

- Determination of the balance between technical and societal matters, their allowable rates of change;
- Societal acceptance, given future scenarios, of other sources of decarbonised electricity, energy, such as nuclear power compared to longer term issues (e.g. waste management);
- System second order sensitivities, rates of change possible, and the rates of change of these that are acceptable;
- Societal TCO aspects of and solutions and pathways thereto.

In addition, there were some caveats, which implied future research needs:

- The study explored different corner scenarios based on a temporally static fuel and fleet modelling exercise;
- The analysis does not include dynamic modelling or prediction; the results of the analysis should be considered as estimates for comparative purposes;
- The analysis did not draw conclusions on fuel and electricity availability, competition with other sectors demand, economics, societal acceptance, especially the fundamentals of supply versus demand.

Considering the **use case assessment**, the follow aspects were identified.
The **commuter in 2030** and **urban delivery in 2030**: the following research needs and/or questions were identified:

- For energy carriers, since this is mostly likely to be a BEV with limited energy storage, what are the implications of and for fast, smart charging with this usage; how might the reliability, durability of the energy carrier (the battery) be improved in this use case, and at what cost?

- For the vehicle and powertrain, how might this usage change the vehicle concept, hence the powertrain architecture?
- For the infrastructure, is sufficient low power charging available at the appropriate locations (e.g. junctions with other transport modes, workplaces, leisure venues etc.) and are these smart enough to optimise the energy management for the vehicle and the transport system?
- And, for society in general, “how will the vehicle concepts change over time?”, “how will their safety, their comfort etc. be maintained?”, “what will be the impacts of the use and ownership of such vehicles with CCAM developments?”, “what will be the subsequent impact on mobility choices, mode usage intensities, socio-economic aspects of mobility?”. Finally, “what rate of change in these aspects will be acceptable in this usage?”.

Delivery in 2030, but this time with a different vehicle powertrain, that is a PHEV, the following change in research needs was identified, beyond those previously recorded:

- For energy carriers, since this is to be a PHEV with limited energy storage, what are the implications of and for fast, smart charging with this usage; how might the reliability, durability of the energy carrier (the battery) be improved in this use case, and at what cost?

Retaining, now, the PHEV architecture, but considering the **longer one-way trip in 2030**, for families or deliveries between urban centres, the following research needs and/or questions were identified, beyond those previously recorded:

- For energy carriers, “how might the supply and share of net-zero carbon energy carriers be most rapidly increased?”
- For the vehicle and powertrain, “how might the choice of ZE range be segregated?”
- For the infrastructure, “how might the supply of net-zero carbon energy carriers be prioritised?”
- And, for society in general, “what potential future services (e.g. related to SOC management or comfort versus energy management) might be offered to these vehicles?”.

Considering **long distance commercial vehicle operation in 2030**, the following research needs and/or questions were identified, beyond those previously recorded:

- For energy carriers, “how quickly and densely can fast charging, hydrogen and net-zero carbon hydrocarbon liquid fuel refuelling capabilities be achieved?”
- For the vehicle and powertrain, “what are the limits of future powertrain component reliability, durability and safety?”, “what are the limits for the gravimetric and volumetric powertrain architectures and how might regulation be developed to recognise this whilst still enabling improvements in operational efficiency and reductions in its carbon-intensity?”.
- For the infrastructure, is “what opportunities are there within depot, for charging, refuelling, energy carrier conversion and smart energy management?”

Table 30. Research needs from the System Perspective

	Research from the System Perspective	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
System Change	Fleet mix change for minimum CO_2 budget expenditure to 2050			TRL 4-6			TRL 7-8								
	Realizing efficiency improvements methods A, B and C.		TRL 4-6				TRL 7-8								
	International CO_2 neutral energy supply optimisation	TRL 2-3				TRL 4-6					TRL 7-8				
	CCS and DAC realisation at scale		TRL 4-6				TRL 7-8								
System Appraisal Methods	RT system dynamic modelling for the transition, prediction capability thereto	TRL 2-3				TRL 4-6					TRL 7-8				
	LCA for the whole RT system & its transition			TRL 4-6				TRL 7-8							
	Economic analyses for the whole RT system transition			TRL 4-6				TRL 7-8							
	Resource use (land, water etc.) minimisation and distribution between sectors	TRL 2-3				TRL 4-6					TRL 7-8				
	Societal acceptance prediction and appraisal methods		TRL 2-3				TRL 4-6					TRL 7-8			
	RT system robustness and second order sensitivity methods		TRL 2-3				TRL 4-6					TRL 7-8			
Use Cases	Commuter & Urban Delivery in 2030 - implications for smart low power & fast charging - relevant battery improvements - vehicle concepts - societal acceptance		TRL 4-6			TRL 7-8									
	Delivery in 2030 - implications for smart low power & fast charging - relevant battery improvements		TRL 4-6			TRL 7-8									
	Longer one-way trips in 2030 - increasing the rate of climate neutral energy carriers for ICE, supply & infrastructure - ZE range segmentation - future services for vehicles and users		TRL 4-6			TRL 7-8									
	Long distance commercial vehicle operation in 2030 - increasing the rate of climate neutral energy carriers for all powertrains, supply & infrastructure - Improvements in powertrain energy density and reliability - Smart energy management possibilities at all CV energy refilling opportunities		TRL 4-6			TRL 7-8									

7 Appendices

7.1 Definitions

In this section, some relevant terms used in the document, which have been previously defined in other activities, are given here for reference (listed alphabetically).

CO_2 neutrality or carbon-neutrality
Technical process with CO_2 emissions but compensated by a carbon removal, offsetting mechanism (e.g. growth of biomass, Carbon Capture Use and Storage (CCUS), Direct Air Capture (DAC) etc..), knowing that the carbon cannot come from fossil resources (e.g. the carbon is derived from renewable biological resources or the atmosphere).

Climate neutrality
Emissions levels allowing stable concentration levels of GHG in the atmosphere.
(GHG emissions from human activities) + (GHG emissions from carbon sinks) = 0

Fuels

Renewable hydrocarbon fuels
Chemical energy vectors or carriers (such as advanced biofuels, e-fuels etc.) to be used in powertrains, produced from renewable resources without using fossil resources. Combinations of biofuels and e-fuels will also fall into this category.

Advanced biofuels
Renewable fuel produced from biomass (biofuel from food or feed crops is excluded).

Renewable e-fuels
Hydrocarbons to be used in combustion engines, produced from water, CO_2 and renewable electricity only. The CO_2 is provided by closed carbon cycles such as direct air capture (no fossil resources).

Renewable non-hydrocarbon fuels
Chemical energy vectors or carriers (hydrogen, ammonia etc.) to be used in powertrains, produced from renewable resources without using fossil resources.

GHG neutrality
Technical process with GHG emissions but compensated by a GHG removal, offsetting mechanism (e.g. growth of biomass, Carbon Capture Use and Storage (CCUS), Direct Air Capture (DAC) etc.), knowing that the carbon cannot come from fossil resources (e.g. the carbon is derived from renewable biological resources or the atmosphere).

Decarbonisation
Is a part of the process of moving towards GHG neutrality.

Vehicles[111]

Conventionally powered vehicles

Conventional vehicles use liquid fuels, from fossil or renewable origin (typically diesel and petrol) to power an internal combustion engine (ICE). Both compression ignition ('Diesel') and spark ignition ('petrol') engines convert fuel into work via combustion, with the main difference being the way the combustion process occurs.

Alternatively powered vehicles

Alternatively Powered Vehicles (APVs) are vehicles powered by technologies alternative to, or supplemental to, conventional internal combustion engines using fossil fuels. The main types of APVs, and how they differ from each other, are explained below:

Electrically Chargeable Vehicles

Electrically chargeable vehicles (ECVs) include full battery electric vehicles and plug-in hybrids, both of which require recharging infrastructure that connects them to the electricity grid.

- **Battery electric vehicles** (BEVs) are fully powered by an electric motor, using electricity stored in an on-board battery which is charged by plugging into the electricity grid.
- **Plug-in hybrid electric vehicles** (PHEVs) have an internal combustion engine and a battery-powered electric motor. The battery is recharged by connecting to the grid as well as by the on-board engine and/or regenerative braking. Depending on the battery state of charge, the vehicle can run on the electric motor and/or the internal combustion engine.

Fuel cell electric vehicles

Fuel cell electric vehicles (FCEVs) are also propelled by an electric motor, but their electricity is generated within the vehicle by a fuel cell system that typically uses compressed hydrogen (H_2) plus oxygen from the air. So, unlike ECVs, they are not recharged by connecting to the electricity grid. Instead, FCEVs require dedicated hydrogen filling stations.

Hybrid electric vehicles

Hybrid electric vehicles (HEVs) have an internal combustion engine (typically running on petrol or Diesel) and a battery-powered electric motor. Electricity is generated internally from regenerative braking or during cruising from the combustion engine, so HEVs do not need recharging infrastructure. The hybridisation level ranges from mild to full.

- Mild hybrid electric vehicles are powered by an internal combustion engine, but also have a battery-powered electric motor that supports the conventional engine. These vehicles cannot be powered by the electric motor alone.
- Full hybrid electric vehicles are powered by both an electric motor and a combustion engine, each of which (or together) can power the wheels.

xEV

Together ECV and HEV are known as by the abbreviation xEV.

Natural gas vehicles

Natural gas vehicles (NGVs) run on compressed natural gas (CNG) or liquefied natural gas (LNG), the latter mainly being used for commercial vehicles such as trucks, the former for passenger cars. NGVs are based on mature technologies and use internal combustion engines. Dedicated refuelling infrastructure is required. Recently gas vehicles running on hydrogen instead of natural gas are being

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[111] ACEA's report: Making the Transition to Zero-Emission Mobility, 2019. https://www.acea.be/uploads/publications/ACEA_progress_report_2019.pdf

considered as an option for CO_2-neutral mobility. These vehicles should be considered independently from their fuel production path, which may involve renewable or fossil sources.

Zero emission vehicles (ZEV)
These are vehicles which are considered to have zero tailpipe emissions.

Zero emission in urban areas
All vehicles with local zero tailpipe emission, that is BEV, FCEV and PHEV in a mandatory e-mode.

Net zero emission
There are still some tailpipe emissions but the resultant impact for Nature (including human beings) is negligible given compensation activities. This term is often used only in relation to CO_2 emissions but is applicable to all tailpipe emissions, however the term ZIE, below, is perhaps more precise thereto.

Zero Impact Emissions (ZIE)
These are discussed and defined in “What are Zero-Impact Emission and how can they be achieved in road transport?”, Transportation Research Part D, 102 (2022) 103123. The average fleet emissions required to achieve ZIE, as given in this reference, range from 6mg/km to 33mg/km NOx, for a variety of different road operation conditions.

The definitions from Directive 2009/72/EC may apply, specifically the following:
Distribution System Operator
Means a natural or legal person responsible for operating, ensuring the maintenance of and, if necessary, developing the distribution system in a given area and, where applicable, its interconnections with other systems and for ensuring the long-term ability of the system to meet reasonable demands for the distribution of electricity.

Transmission System Operator
Means a natural or legal person responsible for operating, ensuring the maintenance of and, if necessary, developing the transmission system in a given area and, where applicable, its interconnections with other systems, and for ensuring the long-term ability of the system to meet reasonable demands for the transmission of electricity.

As may the definitions from Directive 2018/2001 from 11th December 2018, such as:
Advanced biofuels
Means biofuels that are produced from the feedstock listed in Part A of Annex IX.

Agricultural biomass
Means biomass produced from agriculture.

Biofuels
Means liquid fuel for transport produced from biomass.

Biogas
Means gaseous fuels produced from biomass; 21.12.2018 EN Official Journal of the European Union L 328/103.

Biowaste
Means biowaste as defined in point (4) of Article 3 of Directive 2008/98/EC.

Biomass
Means the biodegradable fraction of products, waste and residues from biological origin from agriculture, including vegetal and animal substances, from forestry and related industries, including fisheries and aquaculture, as well as the biodegradable fraction of waste, including industrial and municipal waste of biological origin.

Energy From Renewable Sources or Renewable Energy
Means energy from renewable non-fossil sources, namely wind, solar (solar thermal and solar photovoltaic) and geothermal energy, ambient energy, tide, wave and other ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas, and biogas.

Food and feed crops
Means starch-rich crops, sugar crops or oil crops produced on agricultural land as a main crop excluding residues, waste or ligno-cellulosic material and intermediate crops, such as catch crops and cover crops, provided that the use of such intermediate crops does not trigger demand for additional land.

Forest biomass
Means biomass produced from forestry.

Ligno-cellulosic material
Means material composed of lignin, cellulose and hemicellulose, such as biomass sourced from forests, woody energy crops and forest-based industries' residues and wastes.

Low indirect land-use change-risk biofuels, bioliquids and biomass fuels
Means biofuels, bioliquids and biomass fuels, the feedstock of which was produced within schemes which avoid displacement effects of food and feed-crop based biofuels, bioliquids and biomass fuels through improved agricultural practices as well as through the cultivation of crops on areas which were previously not used for cultivation of crops, and which were produced in accordance with the sustainability criteria for biofuels, bioliquids and biomass fuels laid down in Article 29.

Recycled carbon fuels
Means liquid and gaseous fuels that are produced from liquid or solid waste streams of non-renewable origin which are not suitable for material recovery in accordance with Article 4 of Directive 2008/98/EC, or from waste processing gas and exhaust gas of non-renewable origin which are produced as an unavoidable and unintentional consequence of the production process in industrial installations.

Renewable liquid and gaseous transport fuels of non-biological origin
Means liquid or gaseous fuels which are used in the transport sector other than biofuels or biogas, the energy content of which is derived from renewable sources other than biomass.

Residue
Means a substance that is not the end product(s) that a production process directly seeks to produce; it is not a primary aim of the production process, and the process has not been deliberately modified to produce it; L 328/104 EN Official Journal of the European Union 21.12.2018.

Waste
Means waste as defined in point (1) of Article 3 of Directive 2008/98/EC, excluding substances that have been intentionally modified or contaminated in order to meet this definition.

Reference might also be made to the PIARC Road Dictionary, see here: https://www.piarc.org/en/activities/Road-Dictionary-Terminology-Road-Transport which has definitions for some 16,300 concepts in English and French, as well as synonyms for some other countries or languages.

7.2 Abbreviations

Terminology

AC	Alternating Current
ACI	Advanced Compression Ignition engine
AD	Anaerobic Digestion
ADAS	Advanced Driver Assistance Systems
AEC	Alkaline Electrolysis Cell
AI	Artificial Intelligence
AQ	Air Quality
ATS	Aftertreatment System
BC	Black Carbon
BECCS	Bio-Energy with Carbon Capture and Storage
BEV	Battery Electric Vehicle
BMS	Battery Management System
BoP	Balance of Plant
BtL	Biomass to Liquid
BTMS	Battery Thermal Management System
BWR	Boiling Water Reactor
CCAM	Cooperative and Connected Automated Mobility
CCS	Carbon Capture and Storage (System(s))
CCU	Carbon Capture and Usage
CHP	Combined Heat and Power
$C\text{-}H_2$	Compressed Hydrogen
CI	Compression Ignition
CNG	Compressed Natural Gas
CP	Constant Power
CPO	Charging Point Operator
DAC	Direct Air Capture (of carbon)
DC	Direct Current
DHE	Dedicated Hybrid Engine
DME	DiMethyl Ether (Ester)
DNBE	Di-n-Butylether
DR	Demand Response
DSO	Distribution Service Operator
EATS	Exhaust Aftertreatment System(s)
EC	European Commission
ECU	Electronic Control Unit
ECV	Electrically chargeable vehicles
EDU	Electrical Drive Unit
EGR	Exhaust Gas Recirculation
EHS	Environmental, Health and Safety
ELT	End of Life Tyres
EM	Electric(al) Motor
EMC	Electro-Magnetic Compatibility
EMF	Electro-Magnetic Flux
EMI	Electro-Magnetic Interference
EMS(P)	Energy Management System (Provider)
EoL	End of Life
ePTW	Electrically Powered Two (and Three) Wheelers
ERS	Electric(al/fied) Road System(s)
EV	Electric Vehicle

FAME	Fatty Acid Methyl Esters
FC	Fuel Cell or Fuel Consumption
FCEV	Fuel Cell Electric Vehicle
FFV	Flex-Fuelled Vehicles
GHG	Greenhouse Gas(es)
GRLG1	Remote natural gas liquefied at source, LNG sea transport, distribution by road as LNG, use as LNG in vehicle
GSE	As in airport GSE
H2-ICE	Hydrogen fuelled Internal Combustion Engine (also H_2 ICE)
HD	Heavy-Duty
HDV	Heavy-Duty Vehicles
HE-ERS	Highly Electrified Electric Road System scenario in the ERTRAC CO_2 study
HE-H	Highly Electrified including Hydrogen scenario in the ERTRAC CO_2 study
HE-NMC	High Energy Nickel Manganese Cobalt
HEV	Hybrid Electric Vehicle
HF	High Frequency
HiL	Hardware in the Loop
HOV	Heat of Vaporisation
HRS	Hydrogen Refuelling Station(s) (System(s))
HTL	Hydrothermal liquefaction
HV	High Voltage
HVO	Hydrogenated (hydrotreated) Vegetable Oil(s)
HW	Hardware
Hyb	Hybrid scenario in the ERTRAC CO2 study
ICE	Internal Combustion Engine
ILUC	Indirect Land Use Change
IRI	International Roughness Index
KPI	Key Performance Indicator
LBM	Liquified bio-methane
LCA	Life Cycle Assessment (Analysis)
LCOE	Levelized Cost of Energy
LD	Light-Duty
LDV	Light-Duty Vehicles (or Vans)
LHV	Lower Heating Value
L-H_2	Liquified Hydrogen
LNG	Liquified Natural Gas
LPG	Liquid Petroleum Gas
LSM	Liquid Synthetic Methane
MCCI	Mixing-Controlled Compression Ignition Engine
MENA	Middle East, North Africa
MPD	Mean Profile Depth
MTBE	Methyl-Tertiary-Butyl Ether
MTHF	Methyl TetraHydroFuran
NMC	Nickel Manganese Cobalt
OBC	On-Board Charger (Charging)
OBD	On-Board Diagnostics
OBM	On-Board Monitoring
OEM	Original Equipment Manufacturer
OME	OxyMethylene di-methyl Ether
Px	Position in the powertrain of the electrical machine, e.g. P0, P2 etc., where x is a number.
P2X	Power to X, where X is an energy carrier
PAH	Polyaromatic Hydrocarbons

PC	Passenger Car
PCB	Printed Circuit Board
PE	Protective Earth
PEM	Proton Exchange Membrane
PEMC	Proton Exchange Membrane Cell
PEV	Plug-in Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
PLC	Programmable Logic Controller
PLM	Produce Lifecycle Management
PM	Particulate Matter
PMP	Particle Measurement Programme
PN	Particle Number
PtG	Power to Gas
PTT	Pre-Treatment (of biomass)
PV	Photovoltaic
PWHR	Pressurise Heavy Water Reactors
PWM	Pulse Width Modulated
R&D	Research and Development
R&I	Research and Innovation
RDE	Real Driving Emissions
RED	Renewable Energy Directive
RExEV	Range Extended Electric Vehicle, where x denominates the range extender type
REESS	Range Extending Electrical Sub-System
RES	Renewable Energy System(s)
RON	Research Octane Number
RWGS	Reverse Water-gas Shift
SCR	Selective Catalytic Reduction
SI	Spark Ignition
SIA	Secondary Inorganic Aerosol
SMR	Steam Methane Reforming
SNG	Synthetic Natural Gas
SOA	Secondary Organic Aerosol
SoC	State of Charge
SOEC	Solid Oxide Electrolyser Cell
SoH	State of Health
SoX	State of X, where X is a characteristic
SW	Software
TCO	Total Cost of Ownership
TEA	Techno-Economic Assessment
TECH	A climate change mitigation scenario
TG	Thermal Gasification
THC	Total Hydrocarbons
TIP	Tyre Industry Project
TMFB	Tailor-Made Fuels from Biomass
TMS	Thermal Management System
TOU	Time of Use
TRL	Technology Readiness Level (see below)
TRWP	Tyre and Road Wear Particles
TSO	Transmission Service Operator
TTW	Tank to Wheel (also TtW)
TWC	Three Way Catalyst
V1G	Electricity flow from vehicle to grid

V2G	Vehicle to Grid (bi-directional electricity flow)
V2X	Vehicle to X, where X is, e.g., another vehicle or infrastructure
VOC	Volatile Organic Compounds
WLAN	Wireless Local Area Network
WLTP	World Light-duty harmonised Test Procedure
WPT	Wireless Power Transfer
WTT	Well to Tank (also WtT)
WTW	Well to Wheel (also WtW)
xMS	Management System of X, where X is a variable parameter
ZIE	Zero Impact Emission

Organisations

BEPA	Batteries European Partnership Association
BMVI	German Ministry for the Economy (BMWi)
DFS	Deutsche Forschungsgemeinschaft
DOE	Department of Energy
EBA	European Biogas Association
EC	European Commission
EPA	Environment(al) Protection Agency
ETIP.SNET	European Technology and Innovation Platform “Smart network for energy transition”
EU	European Union
EUCAR	European Council for Automotive R&D
FCH JU	Fuel Cell and Hydrogen Joint Undertaking
IATA	International Air Transport Association
ICCT	International Council on Clean Transportation
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IMDG	International Maritime Dangerous Goods
IMO	International Maritime Organisation
IPCC	Intergovernmental Panel on Climate Change
JEC	JRC EUCAR Concawe
JRC	European Commission’s Joint Research Centre
RGRA	Revue générale des routes et de l'aménagement
SAE	Society of Automotive Engineers
WBCSD	World Business Council of Sustainable Development

Technology Readiness Levels[112]

Where TRL is mentioned, the following definitions apply, unless otherwise specified:

TRL 1 basic principles observed
TRL 2 technology concept formulated
TRL 3 experimental proof of concept
TRL 4 technology validated in lab
TRL 5 technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 6 technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 7 system prototype demonstration in operational environment
TRL 8 system complete and qualified
TRL 9 actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies).

[112] https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf

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