Fraunhofer UMSICHT takes a stand

In Focus: Fuels of the Future

With the format "Fraunhofer UMSICHT takes a stand," we address topics that concern society, business, and science. As researchers, we want to take a stand and contribute to objectivity in emotional debates. At the same time, we highlight where we as an institute can offer solutions to societal challenges.

Our positions are developed through collegial exchange and reflect the opinion-forming process within Fraunhofer UMSICHT. We present different views transparently.

Background and context

By 2045, the German transportation sector is supposed to become largely greenhouse gas neutral. To achieve this goal, greenhouse gas emissions must be reduced by more than 40 percent compared to 1990 levels by 2030. The current German federal government's plan, as outlined in the coalition agreement, is based on EU "Renewable Energy Directive III" (RED III) [Koalitionsvertrag-2025]. The directive sets binding targets and measures to promote renewable energy in the EU in order to increase the share of sustainable energy sources and accelerate climate action. Currently, Germany has achieved a reduction of less than 20 percent compared to 1990 – meaning it has not even reached half of the target set for 2030.

The transformation process required must not be viewed as a challenge that can be solved by technology alone. As far as the transportation sector is concerned, we need to rethink concepts that reduce traffic volume and shift it toward more efficient modes of transport. Technological strategies focus primarily on electrification. Battery-electric powertrains offer the highest energy efficiency compared to other options and are considered the preferred solution, particularly in the passenger car market. At the same time, there are transport sectors where full electrification is not possible, or only to a limited extent, for various reasons. These include, among others, air and maritime transport, parts of heavy-duty transport, and mobile machinery such as excavators or combine harvesters. For these applications, energy-dense, storable energy carriers will continue to be needed.

Against this background, there is ongoing discussion about which alternative fuels low in CO_2 can complement the direct use of electricity. In principle, hydrogen and fuels produced from biomass or from CO_2 are viable options.

Fraunhofer has already addressed the role hydrogen can play in the mobility transition in other publications [e.g., Fraunhofer-2024, Fraunhofer-2025]. This paper therefore focuses exclusively on the latter two types of fuel. These include methanol, ammonia, and Fischer-Tropsch-based fuels. They are usually in liquid form, and some are comparable to today's fossil fuels as regards their properties. It should be noted that the production of a large part of these liquid fuels requires hydrogen, which is also needed for other industrial applications and is expected to be available only in limited quantities. This creates competition for its use. Sustainable biomass is also available only in limited quantities and is in demand across various sectors. The use of CO_2 as a feedstock is subject to technological, energy and infrastructure requirements, requiring significant amounts of renewable energy.

Questions and positions

1. Will fuels still be needed in the future?

Even with the consistent expansion of electric mobility, there will still be sectors where battery-electric powertrains are not a viable solution in the foreseeable future—whether for technical or economic reasons. For these applications, particularly in aviation and maritime transport, heavy-duty transport, military and mobile machinery, storable energy carriers with high energy density are required.

→ *In the future, there will be a need for low-CO_2 fuels with high energy density for various applications that cannot be electrified.*

2. Criteria for future fuels

Future fuels must make a substantial contribution to reducing greenhouse gas emissions while also meeting the specific requirements of their respective applications. These include, in particular, a high energy density, good storability and transportability, and compatibility with existing vehicle and infrastructure systems, at least in part.

→ *Future fuels should be largely CO_2 neutral and resemble today's liquid energy sources. For CO_2 neutrality, it is not only the raw material that is crucial but also the production process, which should emit as little CO_2 as possible, making direct use of as much renewable energy as possible.*

3. Which raw materials should be used to produce fuels in the future?

Carbon-containing, low-CO_2 fuels can be produced both from sustainable biomass and biogenic residues, as well as from CO_2 in combination with renewable energy. Both feedstock pathways offer specific opportunities but are available only to a limited extent.

→ *High-quality fuels can be produced, in combination with renewable energy, from CO_2 and hydrogen as well as from sustainable biomass or biogenic residues.*

4. How readily available is biomass for fuel production?

The amount of biomass available for the production of high-quality fuels is limited both nationally and globally. It is often available and economically usable in significant quantities only in certain countries or regions. When cultivating biomass, priority must be given to food security, and sustainability criteria must be observed, taking into account aspects of biodiversity conservation and social factors.

→ *Residual materials of biological origin and biogenic waste streams, e.g., sewage sludge or biowaste fractions, should preferably be used as feedstocks for fuels, as regulated, among other things, in the EU's Renewable Energy Directive (RED). The scale and type of energy crop cultivation must be socially responsible and must not jeopardize food supply or existing ecosystems. This also applies to imported biomass. A market economy alone cannot ensure this kind of control, which is why appropriate regulatory instruments are needed.*

5. How readily available is CO_2 for fuel production?

After a medium-term phase-out of fossil fuel power plants, steel[1] and cement mills as well as waste-to-energy facilities will remain as the main CO_2 sources in the long term. From an energy perspective, CO_2 from biomass is particularly interesting because it has already been removed from the atmosphere by plants and stored as carbon in the biomass.

Whether it will be possible in the future, while taking sustainability criteria into account, to capture CO_2 directly from the air (Direct Air Capture, DAC) on a scale that allows the economically viable production of sufficient fuel quantities is a much-debated question that requires technological innovations and developments. A key issue is that the CO_2 concentration in industrial point sources, such as the processes mentioned above, can be in the single- to double-digit percentage range—significantly higher than in ambient air.

→ *It can be assumed that, for the time being, primarily unavoidable exhaust gases from industrial processes will serve as the CO_2 source and biomass as the carbon source.*

6. Where will the renewable energy needed to produce future fuels come from?

The energy requirements for producing future fuels are substantial, particularly for the production of green hydrogen, which is a prerequisite for many fuel synthesis processes and will primarily be generated through water electrolysis in the future. For the conversion of CO_2 into fuels, even larger amounts of electrical energy are required, since not only hydrogen but also CO_2 in synthesis quality must be provided. In addition, conversion losses occur at every step along the synthesis pathway.

The economically exploitable potentials for wind and solar energy in Germany are limited and will continue to be needed primarily to meet electricity demand and, increasingly, heating demand – keyword: heat pumps. There are countries and regions around the world with far greater potentials, meaning that renewable energy can be provided more cost-effectively there. Therefore, a part of the required energy sources or intermediate products will have to be imported from these countries in the future.

→ *In the future, we will need more energy than we do today. The expansion of renewable energy must therefore be accelerated. Furthermore, we must prioritize the purposes for which the renewable energy potential that can be harnessed in Germany should be used. Energy and fuel supply requires international cooperation. For reasons of supply security, these international partnerships must be diversified.*

7. Which procedures are available?

Fuel production from biomass can be carried out using processes such as fermentation, gasification, and pyrolysis. In pyrolysis processes, biomass is heated in the absence of oxygen to produce a high-energy liquid that can be processed into fuels. Gasification processes initially yield a product known as “synthesis gas” that consists mainly of CO, CO_2 and hydrogen. This can be converted into fuels using catalysts.

There are two approaches for converting CO_2 into methanol: It can either be produced directly from CO_2 and hydrogen obtained in the first instance through electrolysis, or via the intermediate product “synthesis gas”. Similar to biomass-derived synthesis gas, the latter method can also be used to produce Fischer-Tropsch fuels.

→ *Technological processes for producing fuels from biomass or CO_2 are well established. Their implementation is often hindered less by technical barriers than by economic, regulatory and logistical ones. The availability of raw materials is often a major obstacle.*

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[1] *If steel mills succeed in using hydrogen instead of carbon to convert iron ore into pig iron, the amount of CO_2 emitted and made available by steel mills will be reduced accordingly.*

8. Is a single technology sufficient to meet fuel demand?

Given regional variations in resource availability and application requirements, it is unlikely that a single technology will be able to meet future fuel demand. Different production processes and feedstock pathways complement one another.

→ *Technologies that use biomass or CO_2 as feedstock for carbon-based fuels complement one another and enable not only diversification of feedstock sources but also country-specific solutions. Renewable fuels of the future will therefore draw on both feedstock sources. It is therefore advisable to continue developing several technologies for the production of renewable fuels in parallel.*

Necessary steps and recommendations

In general, the following steps are relevant for the mobility sector:

1. **Development of technologies for renewable fuels**

Since not all modes of transportation can be powered by battery-electric vehicles, the development of renewable fuel technologies must be advanced in addition to electric mobility.

2. **Clear prioritization of applications**

Since renewable energy and sustainable carbon sources are limited resources, priority must be given to applications for which no more efficient electrical alternatives are available.

3. **Accelerated expansion of renewable energy**

Renewable energy plays a key role—not only in the production of fuels. The expansion of these energy sources must therefore be accelerated as far as possible. Both battery-electric powertrains and synthetic fuels can only help mitigate climate change if sufficient renewable energy is available.

4. **Establishing international energy and feedstock partnerships**

To secure Germany's position as an industrial location, fair and long-term partnerships must be developed with countries that have significant potential for cost-effective renewable energy. An efficient infrastructure for electricity and hydrogen must be established to facilitate the import and distribution of such energy. This effort must take into account sustainability standards, local value creation and geopolitical resilience.

5. **Keeping traffic reduction and efficiency improvement in mind**

Technological solutions alone are not enough to achieve climate goals in the transportation sector. They must be supplemented by strategies to reduce traffic volume, shift to more efficient modes of transportation and make better use of existing infrastructure.

The following steps are particularly relevant for alternative liquid fuels:

1. **Promoting technology and feedstock diversity**

Biomass and CO_2 are limited resources that can be used in varying quantities depending on the respective country or region. To avoid over-reliance on any single source, different technologies are needed that must be developed in parallel.

2. **Efficient and sustainable synthesis pathways**

Both the feedstock and the processes used to produce alternative fuels must be sustainable and likewise efficient. This requires high-performance, stable catalysts and processes that utilize green electricity as directly as possible to provide the energy needed for the synthesis steps. At the same time, these processes should be capable of being operated dynamically and flexibly, thus allowing adaptation as required according to the availability of feedstock and energy.

3. Scaling up and demonstrating market-ready technologies

Technologies with a high technological readiness level must quickly be scaled up and demonstrated under real-world conditions. This is necessary to reduce costs, gain operational experience and ensure investment security.

4. Establishing a reliable regulatory framework

Since renewable fuels cannot compete with fossil fuels in the short term, appropriate policy instruments are needed. These include quota systems, effective CO_2 pricing and targeted support mechanisms. In the long term, a stable, predictable regulatory framework is essential to enable investment in production facilities and infrastructure.

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About Fraunhofer UMSICHT

Fraunhofer UMSICHT is pioneering the way to a sustainable world. We support industries and society in the transfer to a climate-neutral and circular economic system. Our research focuses on Circular Economy, Green Hydrogen, Carbon Management and Local Energy Systems.

We develop materials and processes for the circular use of resources and for the electrochemical production, use and storage of green hydrogen. We also offer solutions for the sustainable use of carbon and develop energy concepts for climate-neutral residential, commercial and industrial sites.

We combine expertise in process engineering, energy technology and materials development with a comprehensive view of the challenges facing large-scale industry, SMEs and society. We provide holistic utilization advice, point out options for action, weigh them up and develop the best solution in each case.

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