Use of renewable drive energy in agricultural machinery

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Publisher

Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. (KTBL) | Darmstadt

Technical support

KTBL-Working Group on Drive Systems for Agricultural Machinery

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Please quote this document or parts thereof as follows:
KTBL (2023): Use of renewable drive energy in agricultural machinery. Darmstadt, Kuratorium für Technik und Bauwesen in der Landwirtschaft (KTBL)

This brochure is a translation of the German-language publication published in 2023.

Publisher and distribution
Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. (KTBL)
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Published with funding from the Federal Ministry of Food and Agriculture based on a decision of the German Bundestag.

Cover photo

Foreword

Around 100 years ago, the motorization of agriculture picked up speed: Tractors made work easier and henceforth increasingly replaced the tractive power of humans and animals.

With the Great Depression of 1929, fossil fuels became expensive and the search for alternatives began. Trials with wood gasifiers were started and a few years later during the Second World War intensified. The Reichskuratorium für Technik in der Landwirtschaft (RKTL), the predecessor of the KTBL, supported the efforts, while at the same time it created a distribution key for the quota diesel fuel for the German Reich.

After 1945, the West German Board of Trustees for Technology in Agriculture (Kuratorium für Technik in der Landwirtschaft e.V.) accompanied trials with biogas-powered tractors. In the following years, there was no shortage of diesel on the world market, biogas engines did not prevail. Tractor registrations reached their peak in the mid^{-1}950s. From 1967 onwards, agriculture benefited from a reduction in gas oil taxation, which is now an agricultural diesel subsidy.

The oil price crisis from 1973 prompted the KTBL to focus once again on alternatives to diesel. In numerous projects, possibilities were discussed to reduce the demand and consumption of diesel. The potential of oilseeds has been intensively investigated.

Why this historical excursus? It shows that fossil fuels have been questioned in agriculture since the beginning of motorization. This is especially true in times of crises.

Currently, it is not only the energy crisis, but also climate change that is causing the industry and with it the KTBL to look for alternatives to fossil fuels: In 2013, the KTBL organised a technical discussion with the Technologie- und Förderzentrum, Straubing (TFZ) on alternative energy sources and drive concepts; Further events followed in 2020 and 2022. These projects have resulted in the KTBL working group on drive systems for agricultural machinery, which presents its results with this special publication to the ministries dealing with the topic, but also representatives of industry, associations, and research institutions.

I would like to thank the members of the working group and all authors for their voluntary work, which made this publication possible. It gives me confidence that we can sustainably reduce the need for fossil diesel fuel and emissions in the climate crisis. To anticipate the content of this book: Technically, this is feasible.

Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. (KTBL)

Dr. Martin Kunisch
Managing Director

Darmstadt, October 2023

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Summary

In agriculture and forestry in Germany, an average of around 2.1 billion litres of fuel were consumed annually between 2016 and 2020, which corresponds to an energy equivalent of 74.4 PJ. Less the estimated share of 12 % from forestry, the energy equivalent of fuels used in agriculture is reduced to around 66 PJ/a, almost exclusively using B7 or B0 fossil diesel. From this diesel fuel consumption, at least 3.8 million tonnes of carbon dioxide (CO_2) equivalents are to be allocated annually to the German greenhouse gas inventory for agriculture. Greenhouse gas emissions from diesel fuel use must be reduced to zero within the next 20 years, at the latest by 2045, the target year for national greenhouse gas neutrality. This can be done by saving fuel and by substituting fossil fuel with renewable drive energies.

Agricultural machinery – from tractors to harvesters to feed mixers

Mobile agricultural machines are designed for the respective purpose and their setup is primarily determined by the agricultural conditions and requirements. This distinguishes them from vehicles for pure use in road traffic. Agricultural machinery includes universal mobile traction machines such as tractors and specialized self-propelled machinery such as combine harvesters. In addition, there are transport vehicles, vehicles for loading and handling, such as telescopic and farm loaders, as well as machines used in animal husbandry, such as feed mixers. The machines differ mainly in terms of their intended use and the performance they can provide, the place of use, whether close to or further away from the farm, and the frequency of use, which can vary between daily and seasonal as well as between a few hours per day up to 24 hours during harvesting operations. This determines the amount of energy that must be carried on the respective machines to carry out the work and the time periods that are available for refuelling or battery charging.

Machine stock and new registrations

As of 1 January 2022, the Federal Motor Transport Authority (KBA) quantifies the stock of agricultural tractors (tractors) in the owner group 'Agriculture, Forestry and Fisheries' at around 340,000 machines. In addition, there are also commercially approved tractors, for example from agricultural service providers. Self-propelled machines form a separate vehicle class, and KBA has published no figures on their stock. A considerable proportion of the machines is significantly older than 10 years. On average, around 32,000 tractors are newly registered each year. Due to the long service life of the machines, it is necessary to create solutions for the switch to renewable drive energies not only for new machines, but also for existing ones.

Agriculture in transition

Recent developments indicate a decline in livestock numbers, an increasing number of field crossings for care measures in land management. This is a result of a reduction in plant protection products, greater farm-field distances, and an increasing use of autonomic systems. Most of the changes have an impact on the energy demand of the agricultural machinery. However, a certain statement on how this will change by 2045 is currently not to be made.

The diversity of agricultural work requires adapted drive energies

A quarter of the fuel consumption of mobile machinery is currently accounted for by livestock farming and three-fourths by crop production. Within crop production, around one third of the fuel is used for light work with a fuel consumption of less than 5 l/ha, for medium work with a fuel consumption of between 5 and 15 l/ha and for heavy work with a fuel consumption of more than 15 l/ha. From this distribution of the current fuel input, an energy demand of 10 to 15 PJ for the electrified machines expected in 2045 can be derived, considering the lower losses of the electric drives. Additional energy demands in upstream and downstream processes are not considered. A further 30 to 42 PJ must still be provided in 2045 in the form of sustainable fuels for internal combustion engines. The total energy demand for the agricultural machinery can be estimated at 45 to 52 PJ for the year 2045, which corresponds to a reduction of around 22 to 33 % compared to today's energy use. In addition, there are possible efficiency gains due to optimised drive systems and modified production processes.

There are a variety of technological pathways for the provision of renewable drive energies, some of which can be synergistically linked and have different levels of technology and fuel maturity. The availability of renewable fuels for agriculture should therefore be assessed on a case-by-case basis, taking into account demand competition from other transport sectors. Agriculture can participate in the production of vegetable oil-based fuels and methane, in the provision of drive energy with self-generated renewable electricity and also of its own agricultural raw materials and agricultural residues. In some cases, valuable co-products are generated during fuel production. There is an opportunity to make a significant contribution to an import-independent energy supply on the basis of a regional circular economy in the production and use of renewable drive energies in agriculture. This can increase the resilience of food production.

Fuels must meet quality requirements which, like placing on the market, are set out in the 10th Directive BImSchV (2010). Exceptions for use in self-owned vehicles are possible in the case of type approval by the manufacturer and in the case of in-house refuelling infrastructure in accordance with § 16. Energy densities related to volume and weight are important distinguishing features of various gaseous and liquid fuels as well as electrical current stored in a battery. Due to the limited installation space on mobile machines, but also due to the weight and the associated risk of soil compaction, energy density is often a limiting factor for the use of certain drive energies in specific machines. Electrical energy stored, for example, in lithium-ion batteries, possesses a low gravimetric and volumetric energy density. The volumetric energy density of gaseous fuels is significantly lower than that of liquid fuels. Further differences exist in the human- and environmental-hazardous properties of the energy sources. In addition, the drive energies differ in the production costs and finally also in the market prices. Market prices for renewable propulsion energies are not only influenced by competition, but also by political framework conditions such as energy tax, VAT, CO_2 pricing, greenhouse gas quota trading revenues, etc.

In addition to the operating costs of the machine, the investment or conversion costs for the machines as well as charging and refuelling infrastructure also account for an economic consideration.

Conclusion and options for action

The authors evaluated drive systems with different drive energies for use in agriculture for the year 2030 and, in the future, for 2045 based on 12 criteria in a five-level gradation. This led to the following result:

- Electrification of the drive systems of machines for light work, possibly also for heavy but time-limited work, is already possible on a pro rata basis for new vehicles by 2030, so that the machines for this work could be almost completely electrified by 2045. Due to the lower losses compared to combustion engine drives, the energy demand of mobile machines in agriculture can be reduced by about 22 to 33 %.
- In the long term, vegetable oil fuel and biodiesel can prove to be the preferred and suitable energy carriers for non-electrifiable work, such as medium to heavy and time-consuming work. Excessive production of biofuels from cultivated biomass due to demand from agriculture, which could lead to undesirable land-use changes, is not to be feared, as the consumption volumes in the sector are known and are comparatively low in relation to other transport sectors. In addition, electrification, e.g. of passenger cars, will no longer require significant amounts of biofuels for blending and could specifically replace diesel fuel as pure fuels in the agricultural sector.
- Paraffinic diesel fuels such as HVO diesel and Fischer-Tropsch diesel from biomass (BtL) or on the basis of electrical energy (PtL) are very suitable renewable energy sources for today's diesel-powered vehicles in use. New vehicles should preferably be powered by the fuels that are well available in agriculture to defuse competition for paraffinic fuels and to take advantage of the benefits that vegetable oil fuel and biodiesel can bring to agriculture.
- Renewable compressed methane (CNG) and liquefied methane (LNG) are evaluated as a sensible alternative, especially for agricultural farms with their own or with nearby biomethane plants, in the case of LNG with a liquefaction plant. A nationwide application is not possible due to the low supply density. Hydrogen in combustion engines or fuel cells in agricultural applications are not yet preferred options from today's perspective.

To initiate and accelerate the transition from fossil fuels to drive systems with renewable drive energies in agricultural machinery, immediate action is required. Intermediate goals should be agreed and communicated by politicians and monitoring should be established. The long service life of agricultural machinery means that the vehicle fleet is replaced only slowly. Resulting from this, in many cases, the next purchase decision must be made for a machine that can be operated with climate-friendly energy sources. Market participants are required to have long-term planning security through stable framework conditions for the success of a market ramp-up. Instruments with an economic impact such as emissions trading, taxes, levies, and investment promotion, as well as political guidelines and accompanying measures such as best practice examples and knowledge communication can prove to be guidelines for future action. These instruments and measures should not lead to an increase in bureaucratic procedures for market players, but on the contrary, a reduction in bureaucracy should be sought.

1 Introduction

Climate protection is one of the central tasks of our society. To achieve the targets for reducing greenhouse gas emissions, the machines used in agriculture will also have to be operated without fossil diesel fuel in the future. The possibilities for this are described in this publication and evaluated regarding their level of development and usability in agricultural practice – this includes machines in horticulture and viticulture. This provides all actors involved in politics, agricultural practice and consulting, research, development, and trade with a guideline for action on the way to the use of renewable, environmentally friendly drive energies.

For the sensible use of energy sources and the associated drive systems in agriculture, some basic requirements must be met. For example, systems with renewable drive energies must meet current and future functional and performance requirements with regard to production procedures, farm structures and farm sizes for agricultural machinery. In addition, they must be practical, i.e. usable on farms and by agricultural service providers. In addition, the costs must not go beyond what is realistic for agricultural operators. In addition, the selected drive systems must ensure a high degree of resilience for food, raw material, and energy production. This includes exploiting opportunities for energy self-sufficiency to reduce import dependency and integrate the provision of energy sources into value chains in the sense of the bioeconomy. The key requirement is that the solution serves the national climate protection targets for the agricultural sector.

The transition to climate-friendly drive systems has multiple impacts on agriculture, but also on the achievement of the United Nations Sustainable Development Goals, as set out in the 2030 Agenda (United Nations 2015). Any solutions that are considered must promote these objectives. In addition to the Sustainable Development Goal on Climate Action (Goal 13), other goals of the 2030 Agenda are closely linked to the issue of the energy supply of mobile machinery. These include in particular:

- Ensure access to affordable, reliable, sustainable, and modern energy for all (Objective 7),
- Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation (Objective 9), and
- Ensure sustainable consumption and production patterns (Objective 12).

2 Status quo and perspective

2.1 Technical development of agricultural machinery

Agricultural machines are designed for the respective application. Their design is influenced by the agricultural conditions and requirements, the technical possibilities, and the regulatory framework. The use depends on the respective operational orientation – such as arable farming, animal husbandry, horticulture, orchard, and viticulture – with the associated process chains and processes to be carried out. The technology is oriented towards functionality, interaction with the user and the environment as well as overall economic efficiency.

There are very different universal as well as application-specific machine concepts in use on farms. These can essentially be subdivided into

- self-propelled machinery (e.g. combine harvesters or mixer feeders),
- mobile traction machines
- (mainly tractors),
- externally propelled machinery (e.g. seed drills or mowers); and
- carrier vehicles (e.g. loading/unloading vehicles).

The drivetrain concepts are as different as the machines themselves. Taken as a whole, these are made up of the provision of useful energy on the machine side (energy storage and converters combined), energy transmission and, if necessary, further conversion stages as well as the utilisation for work, drive and auxiliary functions (Fig. 1).

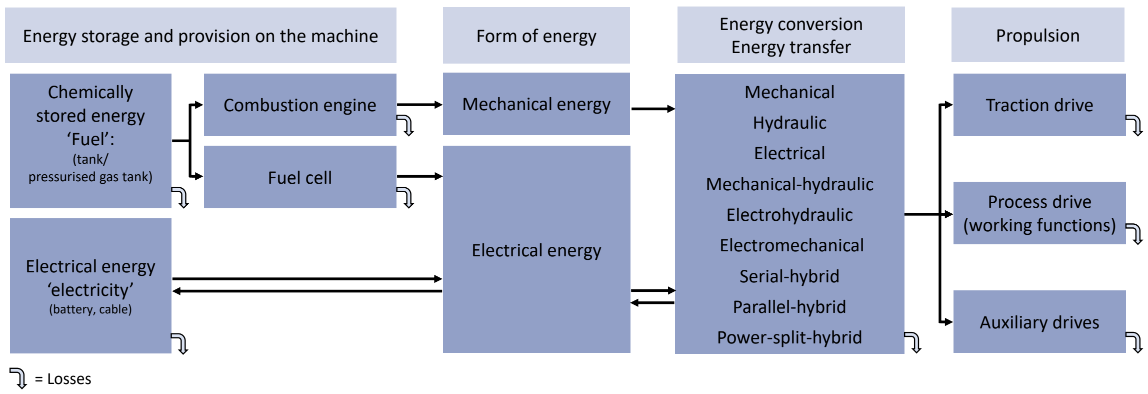


Fig. 1: Structure and overview of powertrain concepts for mobile machinery as used in agriculture (© L. Frerichs, modified)

Although in the development process modular concepts are sought, the specific process aggregates on the one hand and the primary energy supply on the other hand determine the respective basic concepts of the drive systems and the machines. KTBL (2020), Frerichs and Buck (2022), and Geimer (2020) present concrete implementation examples.

In today's agricultural machinery there are mainly internal combustion engines with a fuel tank as energy storage, sufficient for at least one working day. The liquid energy carrier can be transported to the place of use for refilling, using technical aids. The ability to carry large amounts of energy in conjunction with increasingly efficient process and machine technology has made it possible to keep up with the continuous increase in productivity in plant production. This finds visible expression in the powerful and efficient machines which are necessary today to ensure the production of food and raw materials. In addition, agriculture is characterized by many medium-sized and smaller agricultural machines and tractors. While stationary machines in the domestic industry have been largely electrified in this category, limited availability and economic reasons have almost exclusively led to drive systems with combustion engines for mobile machines. Alternatives such as electric drives, even though solutions were available, could not be implemented in the past with the required energy and power densities, necessary for agricultural applications.

In mobile machines mainly diesel engines are used. Due to the higher efficiency compared to other engine concepts, but also because of the favourable torque behaviour and for other reasons, this type of engine is preferred. The expenditure for the increasingly efficient reduction of pollutant emissions has led to a system cost increase especially relevant in the case of low engine power machine categories.

So far, the standard fuel is fossil diesel with its high energy density. The aim to replace this has a long history and has always accompanied engine development. The different alternative fuels and their availability are covered in Chapter 2.4. It is important to recognize that not all fuels are equally suitable for all engine types and injection systems. For example, for gaseous fuels such as natural gas or hydrogen gasoline engines are usually required. Many bio-based fuels in the different forms (biodiesel, HVO diesel, vegetable oil fuel) are suitable for diesel engines. There are also various technical developments that allow – more or less costly – bivalent forms of operation, i.e. several fuels can be used alternatively or at the same time (KTBL 2020).

Due to the focus on a single engine concept and only one fuel type in agricultural machinery, significant systemic advantages have been achieved. Motors are developed across products and markets and produced in large quantities, efficient and fast service networks are installed, and the energy infrastructure is technically and economically manageable for agricultural operations.

Synthetic fuels can be produced in liquid or gaseous states and for diesel and gasoline engines. Liquid synthetic fuels suitable for the diesel engine would require the least amount of adaptation in terms of engine and machine technology, would be compatible with machines already in use and would enable rapid defossilisation.

Provided that hydrogen could also be made sufficiently available for agriculture, it would be possible to use it in internal combustion engines and fuel cells. Research and development work is ongoing for both paths. Operating combustion engines with hydrogen is highly developed – gas exchange processes and material issues are currently still the subject of research. The drive train behind the engine does not have to be extensively adapted. On the machine side, hydrogen storage, i.e. the tank concept and the integration of the tanks, is the most complex task. Tank concepts, suitable for serial production (pressure, cooling, materials, etc.) and refrigeration concepts (gas station, field refuelling, etc.) have yet to be developed, just as the integration of fuel tanks into the available installation space of the machines has yet to be optimised. The lower energy density is expected to result in shorter daily service life and longer refuelling times. The effects and adaptations in technology and processes are still unclear. In addition, questions about the function and safety as well as the leakage of hydrogen during longer times of standstill of agricultural machinery needs to be clarified.

These open points of hydrogen storage apply equally to hydrogen use in fuel cell systems. In addition, in agricultural machinery, where surplus heat has to be actively dissipated due to the missing head wind – unlike in the case of trucks – a cooling system adapted to the temperature levels and the agricultural environmental conditions would still have to be implemented. Furthermore, ammonia, as it occurs in livestock houses, has a life-span-reducing effect on fuel cells, which must also be considered technically. Another current limitation is the performance of conventional proton exchange membrane (PEM) fuel cell systems. If more than 150 to 200 kW of power is required, several individual fuel cell systems are currently to be combined.

Since fuel cells provide the useful energy on the machine in electrical form, another significant difference from conventional systems lies in the required electrification of the subsequent drive train. The complexity of supplying and regulating process, travel and auxiliary drives was pointed out at the beginning. This also means that an individual solution must be created for each individual agricultural machine, whether tractor, combine harvester or feed mixer. The development cycles for agricultural machinery are often 8 years, the development times are often 3 to 5 years. Significant market penetration can therefore only be expected in the 2030s.

These statements apply generally and equally to the other drive systems in which energy is provided in electrical form or carried in a battery. In addition to fuel cells, the most well-known are battery-electric systems. There are also concept studies on mobile agricultural machines supplied directly via cable. Due to the low energy density, batteries in the agricultural environment are limited in usability, but promising developments can already be seen today, especially with machines of small to medium power, currently up to about 100 kW. Machines that do not permanently require large amounts of energy resulting from their application profile and therefore have time for charging, e.g. feed mixers between feeding times, or that are used close to the farm and therefore only have to cover short distances for charging or changing batteries, are very well suited for battery electric systems. They also bring with them various benefits, such as the absence of local air pollutant emissions.

This is different for machines that, for example, must deliver continuously high capacities for field work. Here, the required battery sizes would not be manageable in terms of installation space and weights. This also applies to charging times. Whether battery replacement systems can remedy this is the subject of research. For this, not only the machines, but also the infrastructure, logistics and consequently the production system would have to be adapted. Extensive systemic developments of this kind would also be required for the introduction of cable-bound machines. Such systems are in principle known from mining. Innovative solutions for use in agriculture are currently being investigated with regard to technical feasibility, acceptance, and sustainability.

Hybrid combinations of different forms of energy, energy storage and energy converters are conceptually also conceivable for agricultural machinery. However, they have been little used so far because they often lack the potential for recuperation, the recovery of energy used, and thus a significant factor in economic efficiency is missed. Approaches such as those being investigated for electrified trucks, to extend the range and usability by means of range extenders, could be applied to a certain extent, in terms of transferability of experience and technology.

Regarding the variety of suggested solutions, attention must be paid to the real feasibility. Not only that viable solutions are created in all aspects of sustainability, but also that the framework conditions and manageability must be ensured. As things stand at present, electrification of the machines would not be feasible on some farms because the electrical networks could not cover the peaks in power.

Tractors are universally used machines. Electrification or the use of alternative fuels here presupposes that the broad functionality is maintained on farms that do not have a specific machine for each application but use the tractor variably for a variety of tasks.

The specific example may make it clear; it will not be practicable to operate the farm loader electrically, the feed mixer with biogas, the tractor with synthetic liquid diesel fuel and the combine harvester with hydrogen.

2.2 Fuel requirements for agricultural production

Most of the energy demand in agriculture is generated using mobile machines in field work, transport, handling operations and animal husbandry, especially in cattle feeding. A smaller part is related to the drying of agricultural goods and the provision of heat for livestock housing. Table 1 shows the diesel requirements for the cultivation of the main crops according to KTBL (2022b), divided into light, medium and heavy work. The classification is based on the diesel demand per hectare (< 5 l/ha, 5–15 l/ha, > 15 l/ha) for the individual operations of the respective production process. The crops under consideration cover around 90 % of the agricultural area in Germany.

Table 1: Diesel demand in crop production and animal husbandry

Area of application	Acreage 2021	Diesel demand[4]							
		Total demand		of which					
				light work < 5 l/ha		medium work 5–15 /ha		heavy work > 15 l/ha	
	1,000 ha	l/ha	1,000 l/a	1,000 l/a	%	1,000 l/a	%	1,000 l/a	%
Crop production									
Cereals[1) including grain maize	6.064	78	476,000	75,000	16	178,000	37	223,000	47
Rapeseed	997	74	74,000	13,000	18	24,000	32	37,000	50
Silage maize, field grass/arable grass	2,543	138	314,000	45,000	14	103,000	33	166,000	53
Total arable crops	**9,604**		**864,000**	**133,000**		**305,000**		**426,000**	
Meadows and pastures	4,482	108	485,000	268,000	55	216,000	45		
Total crop production	**14,086**		**1,349,000**	**401,000**	**30**	**521,000**	**39**	**426,000**	**32**
Total crop production including correction[2]			**1,438,000**	**428,000**	**30**	**555,000**	**39**	**454,000**	**32**
Total agricultural area	**15,697**								
	%								
Share of main crops in total area under cultivation	90								
livestock									
Feeding of cattle			325,000						
Removal of manure			60,000						
Distribution of bedding material			33,000						
Total animal husbandry[3]			**418,000**						
	%								
Share of livestock in total demand	23								
Total demand including correction			**1,856,000**						

[1] Winter wheat is representative of all cereals.
[2] The correction reconciles the difference between the calculation according to KTBL planning data and the consumption recorded via the tax refund.
[3] The demand for diesel in the other production directions of animal husbandry is low and is not considered in this calculation.
[4] Deviations of the sum values due to rounding are possible.

In terms of agricultural area, 31 % of the fuel used in agriculture is used for heavy work, 39 % for medium- work and 30 % for light work. If only arable land is considered, the proportion of heavy work increases to 49 %, while heavy work in grassland management does not play a role in the definition chosen here (Fig. 2).

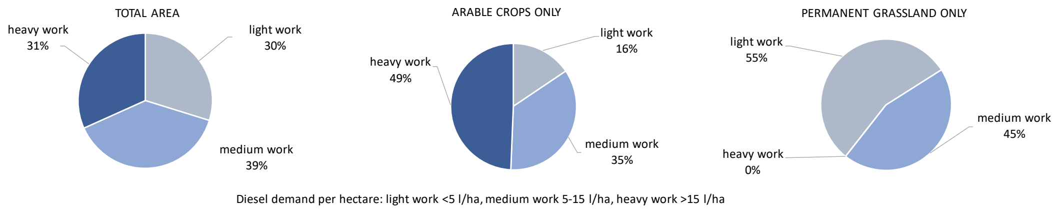


Fig. 2: Distribution of diesel use by diesel demand in the management of arable and grassland areas (© KTBL)

In animal husbandry, most of diesel consumption is accounted for by feeding, manure removal and handling of bedding material. About 418,000,000 litres per year are used here, which corresponds to 23 % of the total diesel demand in agriculture. The high consumption results from the daily use of the machines for several hours all year long.

Figure 3 shows the diesel demand for typical agricultural operations using the example of the production of silage maize and the feeding of dairy cattle, including manure removal and handling of bedding material. In contrast to Table 1, the diesel demand here is related to the time (litres/hour) instead of the area.

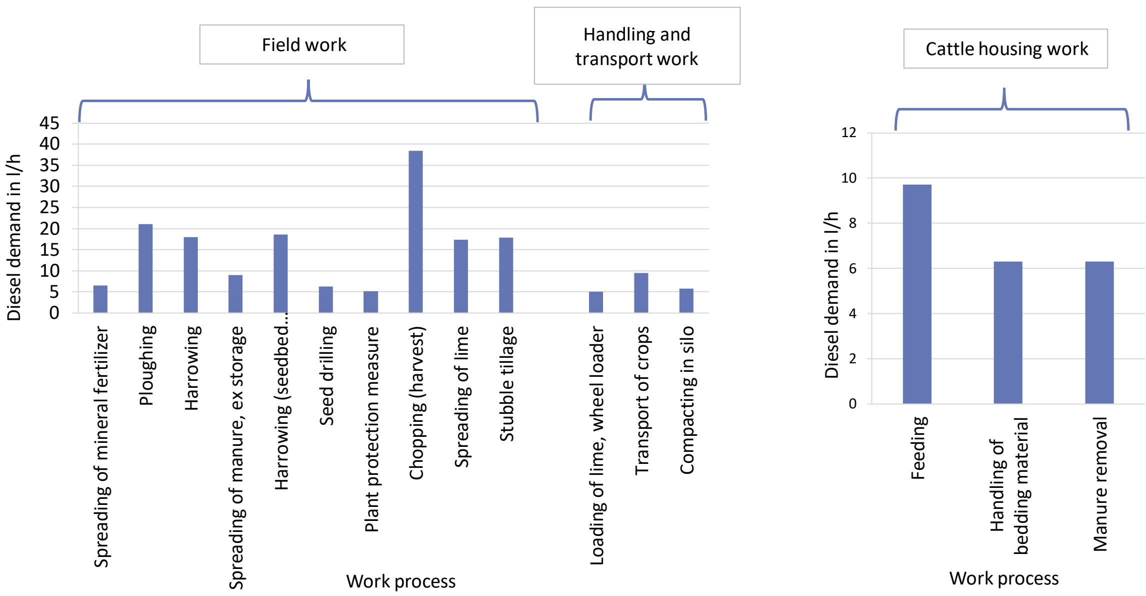


Fig. 3: Diesel demand (l/h) for typical agricultural operations using the example of the production of silage maize (left) (plough, seedbed preparation, seed, field size 10 ha, yield level medium, medium soil, 102 kW mechanization, yard-field distance 2 km) and indoor work in cattle husbandry (right) (box-running stable, solid manure, 120 cow places) (© KTBL)

To estimate which runtimes without refuelling or recharging would be feasible with alternative drive systems to cope with the different work processes, the efficiency of the respective drive systems and the available storage capacity on the machine (tank, battery) must be taken into account (KTBL 2020). A comparison of the required storage volume for energy carriers in relation to diesel fuel and in consideration of the efficiencies of the various drive systems is shown in Table 2.

Tab. 2: Required storage volume and weight for energy carriers compared to diesel fuel

1 l diesel fuel B7 corresponds to 35.6 MJ in the tank and 14 MJ on the wheel. (Efficiency of drive 32 %)

corresponds to

Energy sources	Wirkungsgrad Antrieb	Energie im Tank	Benötigter Speicher	
	%	MJ	l	kg
Vegetable oil fuel (diesel engine)	32	36	1.03	0.95
Biodiesel (diesel engine)	32	36	1.09	0.96
HVO (diesel engine)	32	36	1.03	0.81
Paraffinic diesel fuel (FT diesel (diesel engine))	32	36	0.99	0,83
CNG, 200 bar (Gas-Otto engine)	29[1]	40[1]	4.88[1]	0,79[1]
LNG, -162 °C (Gas-Otto engine)	29[1]	40[1]	1.86[1]	0.79[1]
Electricity (battery, electric engine)	81	14	12,78	20,08
Hydrogen, 700 bar (fuel cell, electric engine)	49	23	5,58	0.20

[1] Values updated February 2025

In addition to the switch to renewable drive energies, the reduction of fuel demand is also an essential lever for climate protection in agriculture. In the project 'EKoTech – Efficient use of fuel in agricultural engineering', the effect of various measures to reduce the demand for fuel in agriculture was considered (Götz and Köber-Fleck 2019, Trösken et al. 2020). Significant saving potentials therefore lie in the combination of operations to save on field crossings, machine efficiency, optimisation of the interaction between tractor and implements, and machine operation.

Figure 4 describes the development of the process efficiency of the machines compared to 1990 and 2015 as well as simulation scenarios for 2030. The calculated simulation models consider changes in the farm structure and machine equipment as well as process changes (e.g. reduction of soil cultivation depths or change in plant protection intensity). For future scenarios that concern the year 2030, assumptions have been made with agricultural technology manufacturers and farmers of the respective model region. Even with conservative assumptions, the scenario predicts reductions in fuel consumption for the year 2030 compared to 2015, which can be between 9 and 26 % for the process step 'harvest', for example.

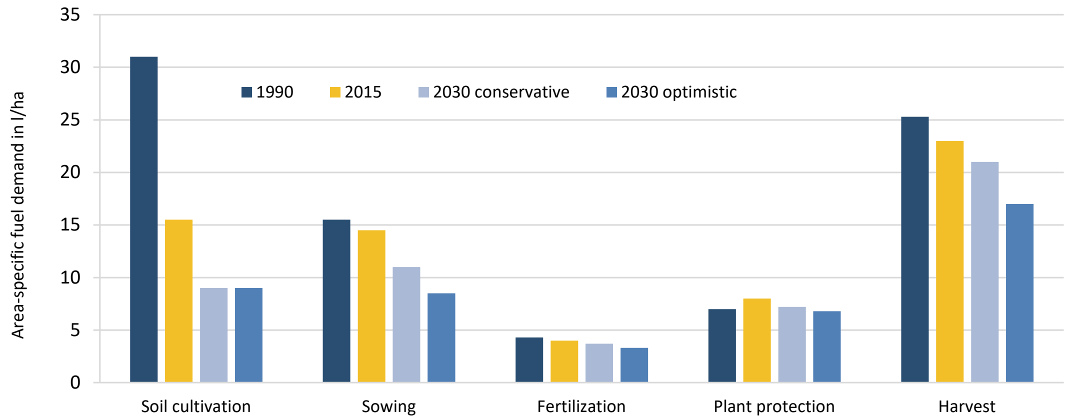


Fig. 4: Area-specific fuel demand for individual process steps of wheat cultivation in the region Südhannover (Götz and Köber-Fleck 2019, modified)

2.3 Performance requirements for agricultural machinery

The performance requirements for agricultural machinery vary greatly depending on the intended use. High continuous power outputs with correspondingly high energy demand are required, especially for soil cultivation and harvesting. Here, operating times of 12 hours and more must be guaranteed. For the timely and productive execution of field work, a certain energy autonomy must be guaranteed. The fields in rural areas are often far away from public and company-owned charging and refuelling infrastructure. Nevertheless, according to the agricultural necessity, the work must be carried out in the right time window and then, if necessary, continuously at daytime as well as at nighttime.

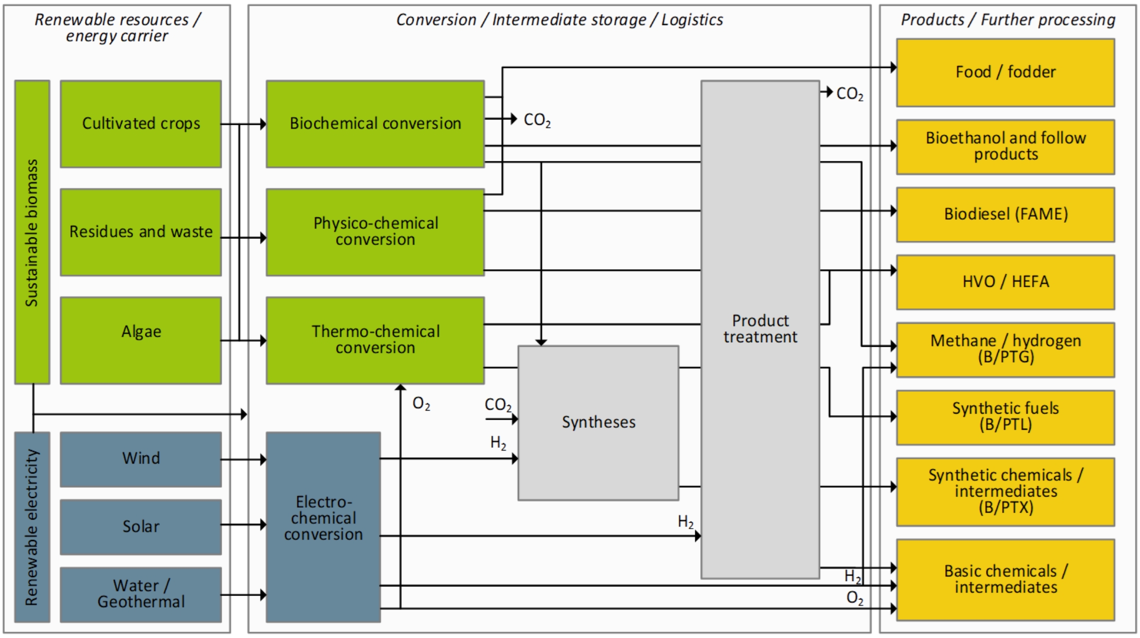
Due to the tight time slots for many agricultural tasks and the high costs that arise from the use of machines, travel times and idle times for refuelling or recharging must be minimised.

The parallel use of different drive systems and fuels on the farm increases the effort and costs.

Interval work is often carried out in livestock farming and in areas close to the farm, e.g. feeding of farm animals. Here the performance requirements are lower compared to field work and longer time slots for refuelling or loading are available.

2.4 Provision of energy sources and electrical energy

A wide range of technology options is available for the defossilisation of fuels and electrical energy for drives on the basis of renewable resources. In addition to the direct use of electrical energy from renewable sources, several liquid and gaseous fuels are currently in focus. As a rule, these are produced together with other co-products and by-products that can be used in different value chains in renewable (bio) refineries. A simplified overview of these options and possible synergies of biomass and electricity-based technologies are shown in Figure 5. Details on the individual technologies can be found in Schröder and Naumann (2022).



SynBioPTX ©DBFZ 11/2021 (w/o entitlement of completeness)
B/PTG – Biomass-/Power-to-Gas, B/PTL – Biomass-/Power-to-Liquids, B/PTX – Biomass-/Power-to-products X; FAME – Fatty acid methyl ester; HEFA – hydrotreated esters and fatty acids; HVO – hydrotreated vegetable oils;

Fig. 5: Simplified overview of technology options and synergies (© DBFZ)

An important indicator for the classification of the state of technical development and thus also the availability of the respective options is the so-called 'Technology Readiness Level' (TRL). It was originally developed by NASA for space travel and expanded by the International Energy Agency (IEA). If aspects of market introduction, including fuel certification and fit-for-purpose testing, are also to be mapped, the so-called

Fuel Readiness Level (FRL) developed by the Commercial Aviation Alternative Fuels Initiative (CAAFI) is a suitable instrument. Both indicators, TRL and FRL, can be used complementarily, as shown in Figure 6.

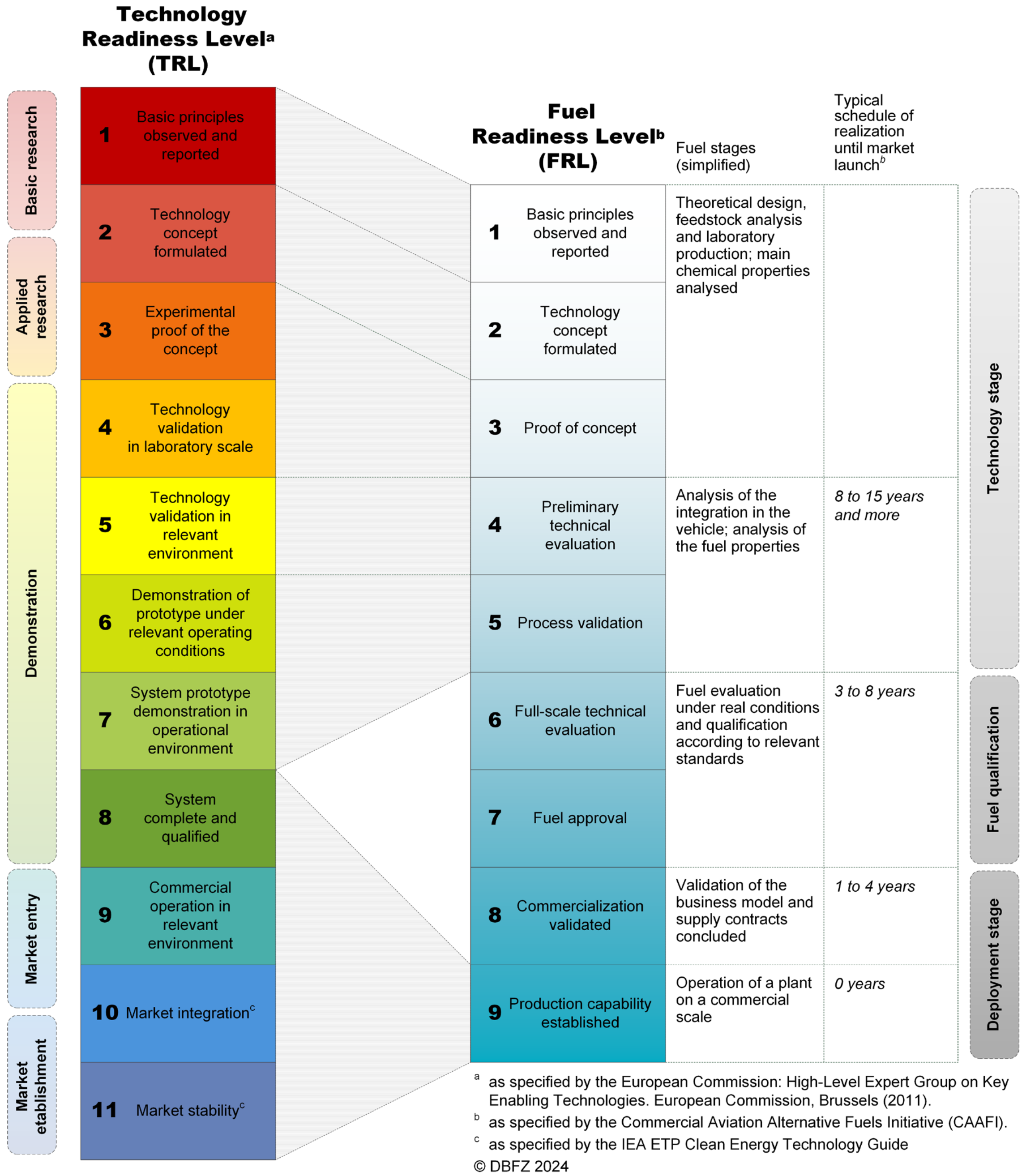


Fig. 6: Overview of Technology Readiness Level (TRL) and Fuel Readiness Level (FRL) (© DBFZ)

Infrastructural prerequisites are required to establish value chains from resources to application. This concerns many aspects:

- the provision of resources (including the production, storage, and transport of biomass as a renewable carbon carrier via crop biomass, waste and residues or electrical energy from renewable sources),
- fuel production (including production, storage and transport of process energy and auxiliary materials, as well as wastewater and waste),
- product distribution (including storage and transport for fuels, by-products, and co-products) and product application (here agricultural machinery).

Both the resources and the products are often part of an international trade with respective import and export possibilities and associated opportunities and risks. Against the background of supply chains, which are sometimes vulnerable and more unsafe worldwide, the aspect of national security of supply is of particular importance and thus also the energy sources that can be provided regionally and used there.

The status quo is assessed for the production technologies of the most common renewable energy sources in Table 3. In addition to renewable electricity, which is currently only used to a small extent in transport, energy sources based on cultivated biomass, waste and residues are established on the market. Electrolysis hydrogen and bioethanol from lignocellulose-containing waste and residues are on the way to market-relevant production. For all other options, plants are at maximum available on a demonstration scale and require appropriate investment in development to enter the market. In the short term, especially the capacities of renewable electricity and fuel options from advanced resources (resources according to RED II Annex IX A (EU Directive 2018/2001 2018)) will grow strongly, only in the medium to long term additional electricity-based fuel options will come up (RFNBOs, short PtX). According to the current situation, the projects planned worldwide until 2035 to produce electricity-based fuels can only cover a fraction of the demand for Germany alone (Odenweller and Ueckerdt 2023).

Tab. 3: Classification of the status quo of renewable energy sources (Schröder and Naumann 2022)

Energy source/ form of energy	State of development (TRL/FRL)	Current plant capacity DE	Current plant capacity EU	Fuel standard	Energy density	Classification as a hazardous substance
Electricity[1] (battery)	11	894 PJ	5,344 PJ	-	Li-ion battery 1 $MJ/l_{Li\text{-}ion\ battery}$	
Vegetable oil	11	188 PJ rapeseed, soy sunflower	677 PJ	DIN 51605 (rapeseed) DIN 51623	35 MJ/l (rapeseed)	-
Bioethanol (E85)	11 (saccharides) 8 (lignocellulose)	23 PJ < 1 PJ	202 PJ 3 PJ	DIN EN 15293	23 MJ/l (E85)	
Biodiesel (FAME)	11 (plant oils, residual and waste oils, animal fats) 4 (algae)	144 PJ -	714 PJ -	DIN EN 14214	33 MJ/l	-
Paraffinic Diesel (HVO)	9–11 (plant oils, residual and waste oils, animal fats) 4–9 (algae, biocrudes such as tall oil/ pyrolysis oil)	- -	149 PJ -	DIN EN 15940	34 MJ/l	
Paraffinic diesel (FT diesel)	6–7 (BtL, PtL)	< 1 PJ	< 1 PJ	DIN EN 15940	34 MJ/l	
Methane	9–11 (anaerobic/biogas) 6–7 (BtG, PtG)	36 PJ < 1 PJ	68 PJ -	DIN EN 16723-2	8 MJ/l (200 bar) 23 MJ/l (LNG)	
Hydrogen	9–11 (electrolysis/PtG) 5–8 (BtG)	< 1 PJ -	1 PJ -	DIN EN 17124	3 MJ/l (350 bar) 5 MJ/l (700 bar) 9 MJ/l (LH2)	
Reference: diesel	11	unknown	DIN EN 590	35 MJ/l		

[1] Electricity plant capacity corresponds to the amount of renewable electricity produced in Europe in 2019. Electricity is not a hazardous substance, but in combination with traction batteries there is an electrical hazard.

All options listed in Table 3 feature appropriate fuel standardisation and are approved for public service stations. An exception is currently (as of June 2023) paraffinic diesel fuels such as HVO and FT diesel. For agricultural use, however, only the options for paraffinic diesel fuel, methane, and biodiesel as well as vegetable oil fuel have (partially) been cleared by vehicle manufacturers.

The large differences in energy density are striking in the options described, which require correspondingly larger tank volumes or more frequent refuelling for a range comparable to conventional diesel. In addition, different motor combustion processes are to be used depending on the fuel. While the energy density of vegetable oil, biodiesel and paraffinic diesel is comparable to conventional diesel, it is only 65 % for E85 and liquefied methane and less than 25 % for all other options as compared to diesel fuel. The lowest energy density is currently achieved with electricity in a traction battery (lithium-ion battery) for electric vehicles.

Due to their chemical and physical properties, the diesel-like fuels are very well suited for storage and refuelling on site, on the farm or in the field. If there are increased requirements for

the protection of soil and water – for example in water protection areas or nature reserves –, preference should be given in particular to vegetable oil fuel, biodiesel, methane, hydrogen and electricity.

In compliance with the applicable safety requirements, electricity and hydrogen are additionally suitable as energy carriers for work in enclosed spaces or confined working conditions since no air pollutants are emitted during machine operation.

According to the state of technical development, without considering the respective field of application, in addition to renewable electricity plant capacities in the European Union are currently high for plant oils, biodiesel, hydrogenated vegetable oils and biomethane from anaerobic digestion (biogas). Development trends for Europe are strongly influenced by the legal framework and developments in the international markets. Overall, it can be assumed that demand for renewable fuels will increase sharply, in particular through binding targets in the aviation and shipping sectors. Another strong expansion is also expected for biomethane, which will be used in various applications. A simplified overview for the global production of renewable fuels, as well as capacities under construction and planning, is given in Figure 7.

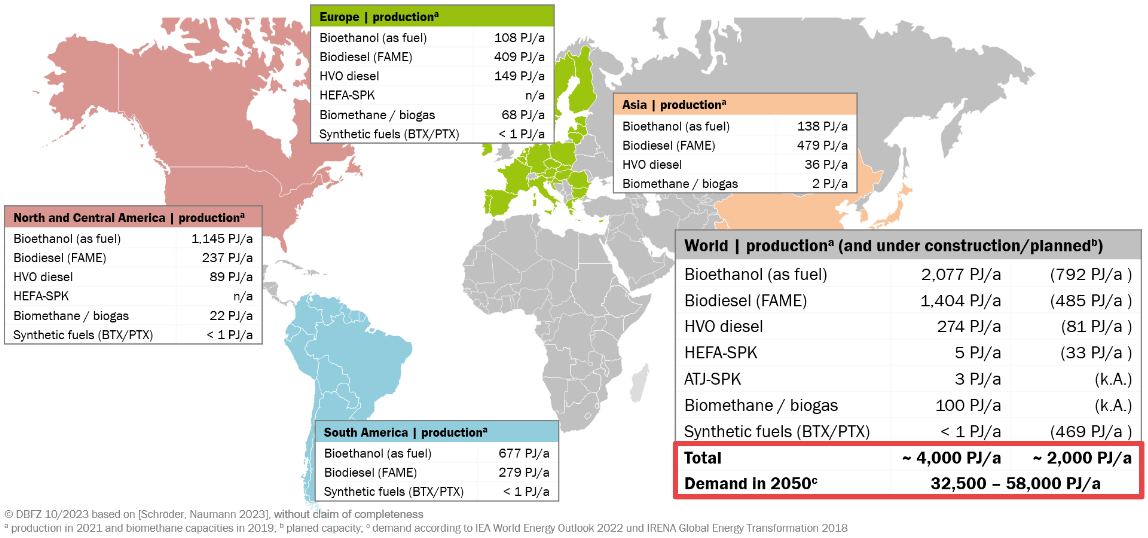


Fig. 7: Overview of global production of renewable fuels (© DBFZ)

Biofuels for agriculture

With regard to biomass-based regional value-added cycles, agriculture has a special role, as it is both a producer of renewable raw materials and a user of the products produced from them in biorefineries (BMEL 2020). Of the currently utilised agricultural area in Germany (approximately 16.6 million ha, around 46 % of the land area), 80 % is devoted to the cultivation of fodder and food, 13 % to energy crops (of which around 29 % for vegetable oil/biodiesel, i.e. 4 % of the total area and around 9 % for bioethanol, i.e. 0.6 % of the total area), 2 % to industrial crops and 5 % to other crops (FNR 2023a, 2023b).

The production of biofuels is, via co-products, closely linked to material uses in different value chains (e.g. feed/food, chemical industry).

For example, the processing per tonne of rapeseed produces not only 400 kg of rapeseed oil, but also around 600 kg of rapeseed press cake as an important protein feed. If rapeseed oil is further processed into biodiesel, around 100 kg of glycerine per tonne is produced for the pharmaceutical industry and lecithin for e.g. foodstuffs (VDB 2022). In 2022 alone, this was around 1.2 million tonnes of feed protein for around 1.9 million tonnes of rapeseed biodiesel produced in Germany and around 0.35 million tonnes of glycerine in relation to the total of around 3.5 million tonnes of biodiesel produced in Germany (VDB 2022).

Depending on the accounting methodology or selected system boundaries, the emission-reducing effect varies compared to fossil fuels. In particular, the limited availability of agricultural land and the resulting competitive situation to the production of food and feed (food-fuel competition) and nature conservation objectives is the reason for critical considerations of the cultivation of oil crops and other crops for energy use. Biomass residues and waste materials for fuel production are also limited resources, which are subject to high demand from various sectors.

All biofuels placed on the market must meet defined sustainability requirements (Biokraft-NachV 2021, see Chapter 2.8). Since 2022, in order to consider indirect land-use change, the share of so-called conventional biofuels in Germany has been limited to a maximum of 4.4 % (energy-related) within the GHG quota (see Chapter 2.8). This means, based on an average of the quantity of fuel subject to quota between 2015 and 2021 in the transport sector of 2,176 PJ/a, a maximum amount of conventional biofuels of around 96 PJ/a. In agriculture, around 66 PJ/a of fuel is consumed, which would be around 3.1 % in relation to the quantity of fuel subject to quotas in transport.

Depending on the assumptions made, in particular on electrification, between 28 and 40 % of the currently blended amount of biofuels to fossil diesel would be sufficient to meet the demand for liquid fuels in agriculture in 2045.

Linked to available plant capacities in Germany (e.g. for biodiesel alone of approx.

144 PJ (Tab. 3)) self-sufficiency of agriculture would be possible in principle. Excessive demand from agriculture for biofuels from cultivated biomass is nothing to be afraid of, as the consumption volumes in the sector are known and are comparatively low in relation to other transport sectors. The pro-rata use of crop biomass for fuel supply to ensure low-greenhouse gas food production is therefore responsible.

2.5 Costs of climate-friendly drive systems

Renewable energy sources

Production costs for renewable fuels are generally higher than for fossil fuels. A simplified presentation comparing the production costs evaluated from various publications (normalised for the reference year 2020) for so-called advanced biofuels and PtX fuels from renewable electricity is shown in Figure 8. These have large bandwidths. In addition to the TRL/FRL (Fig. 6), the respective regional framework conditions and, depending on the business model and operation, investment expenditure and operating expenditure also have an influence on production costs. For biomass-based plants, in addition to the regionally sometimes very different costs for the resource biomass, the investments have a significant influence on the production costs. For PtX fuels, in addition to the electricity price, the investments for the electrolysers and – depending on their origin – for the provision of the necessary carbon dioxide are the most important factors.

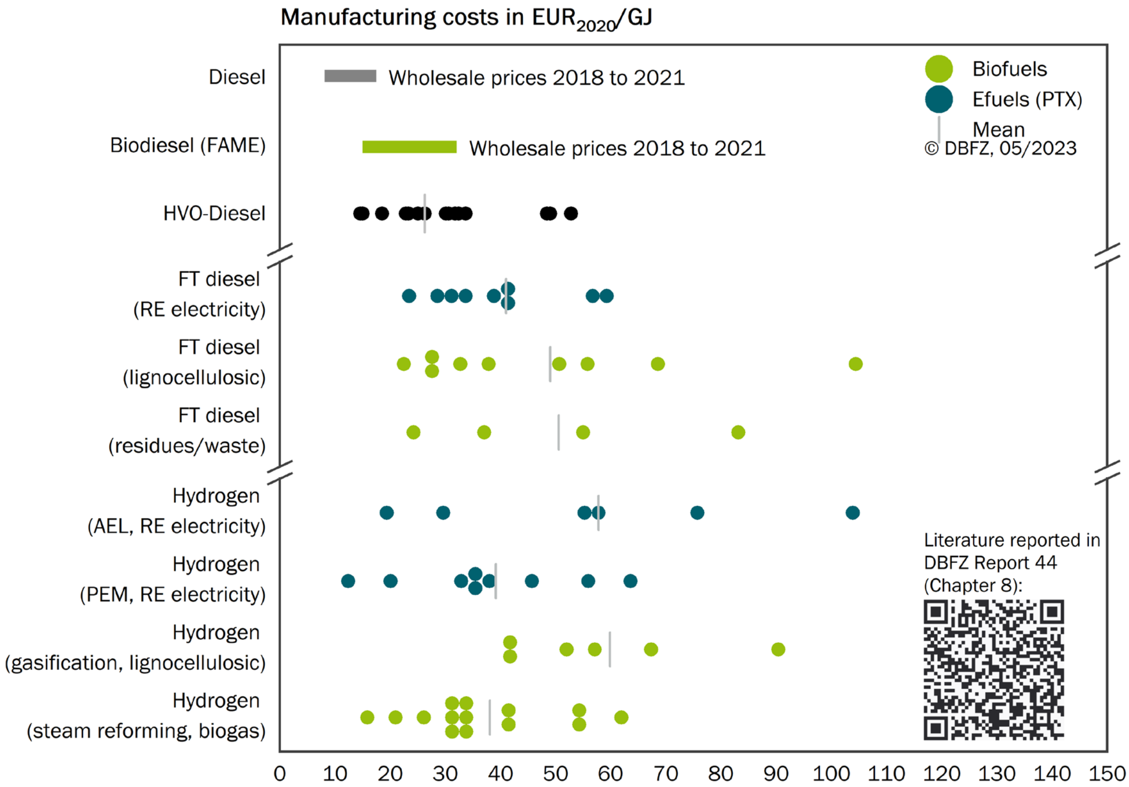


Fig. 8: Production costs for advanced biofuels, PtX fuels and HVO diesel and price levels (2020) (excluding taxes) for diesel and biodiesel (FAME) (Schröder and Naumann 2022)

In the case of fuels which are accounted for within the greenhouse gas quota in Germany (see Chapter 2.8), the specific greenhouse gas emission reductions and the revenues for greenhouse gas savings that can be achieved in quota trading also have an influence on the prices, to be distinguished from costs, and their formation on the market. In addition, price formation is influenced by many other factors, which typically lead to price developments that are sometimes very volatile.

The price trend for electricity in Germany is equally volatile; in this case, prices for non-households averaged EUR 1.79/GJ in the second half of 2019 and increased to a level of EUR 5.08/GJ by the second half of 2022 (average prices of all annual consumption classes excluding taxes and levies; Federal Statistical Office of Germany (Destatis), Genesis-Online 2023). In 2023, there was a slight easing in electricity price developments.

Investment and conversion costs

As there is currently no market for different machines from several suppliers due to a lack of supply and demand, no reliable market prices for machines with renewable drive energies are known. On a larger scale and without a surcharge only new engines are offered with an additional approval for paraffinic diesel fuel in addition to the approval for diesel according to DIN EN 590. After evaluating an investment support program of the Federal Agency for Agriculture and Food for new machines and conversions to renewable drive systems, it can be determined because of the small sample that machines with electric drive are about 30 to 40 % more expensive than comparable machines. Machines suitable for the use of CNG were sold with a surcharge of about 25 %. No data are available for machinery suitable for vegetable oil. Machines with hydrogen combustion engines and hydrogen fuel cells have so far only been known as prototypes for research and development purposes.

Storage and refuelling costs

Storage and refuelling systems for paraffinic diesel fuel, biodiesel and vegetable oil fuel do not differ in purchase price from those for conventional diesel fuel. Tanks and tank systems for diesel fuel can also be used for biodiesel and vegetable oil fuel after a recommended cleaning. If necessary, special requirements, such as calibration, must be met in individual cases, which can then lead to further costs. Many times more expensive than storage and refuelling systems for liquid fuels are those for gaseous fuels such as CNG, hydrogen and LNG. Additionally, for the storage of gaseous fuels, e.g. in gas cylinder bundles, recurring safety inspection costs of the storage facilities must be considered.

2.6 Machinery stock

The stock of motorized machines used in agriculture consists mainly of mobile machines such as tractors and self-propelled machines such as combine harvesters and corn shredders. In addition, there are transport vehicles, vehicles for loading and handling work, such as telescopic and farm loaders, as well as special machines used exclusively in livestock farming, e.g. feed mixers. Many of these machines have low annual runtimes due to the seasonality of field work. In many cases, this means that the machines remain in use for a very long time. If 750 operating hours are assumed annually, a tractor can be operated for more than 13 years until the end of its theoretical service life.

In addition, many tractors will continue to be used domestically in a second and sometimes third operating environment after being sold. Figure 9 (left) shows the tractor stock in the agricultural and forestry sector in Germany for the years 2010 to 2022, broken down by performance class. Tractors registered for commercial use, for example from contractors, are not included here. Figure 9 (right) shows the total stock of tractors of all holder groups by power and age. This figure also includes machines that are commercially registered and used in the agricultural sector or other applications. Machines with an output of less than 30 kW or more than 14 years of age are not included here.

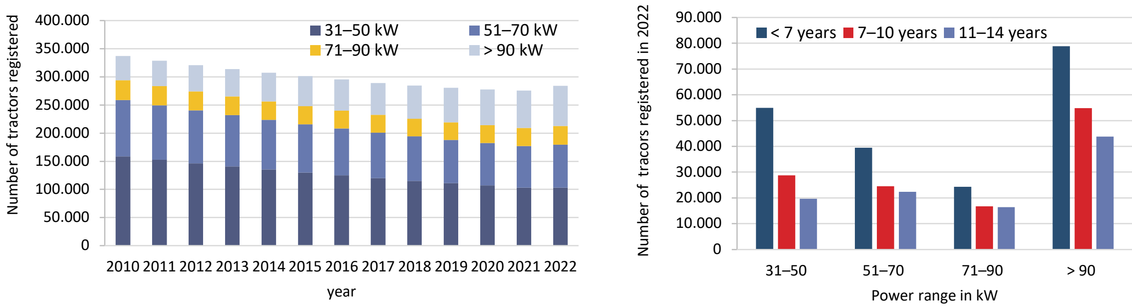


Fig. 9: Development of the fleet in use – Number of tractors registered in the agricultural and forestry owner group by power class (from 31 kW) in Germany (left); Number of tractors registered in 2022 in all holder groups by power class (from 31 kW) and vehicle age (up to 14 years) (right) (© KTBL; Source: VDMA tractor report (unpublished) and Federal Motor Transport Authority (KBA 2022))

In comparison, Figure 10 shows the number of new registrations by performance class for the years 2020 and 2021. This shows a high demand for tractors of both small and high-performance classes for Germany. The new registrations in the agricultural and forestry holder group also include tractors that are used in sectors outside agriculture. A numerical delimitation is not certain to be derived from the registration statistics.

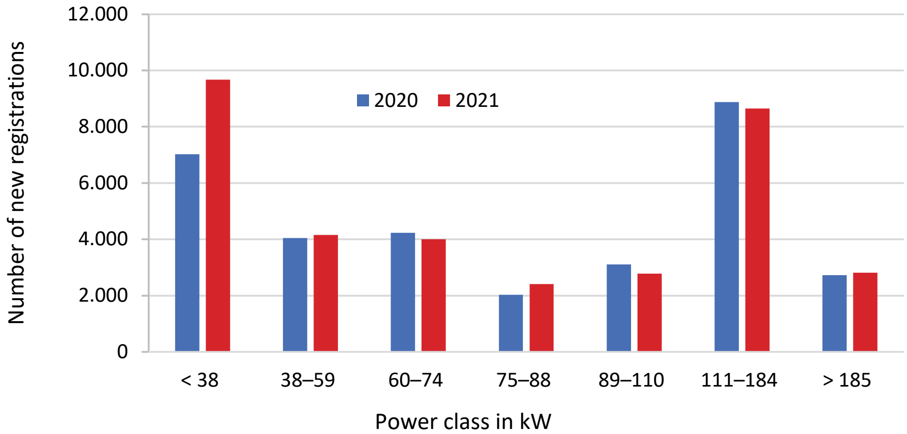


Fig. 10: New registrations of tractors in Germany in 2020 and 2021 by power class (© KTBL; Source: VDMA tractor report (unpublished))

The figures do not give any indication of the specific use of the individual machines. Particularly low-power tractors are sometimes also used outside agriculture in private environments.

This contrasts with many new registrations of tractors of high-performance classes. These machines are used in agriculture for heavy work in the fields and for transport. Here, a drive system is required that meets the requirements for a high-power density and fast on-site refuelling according to the purpose and process.

Figure 11 shows the sales figures of combine harvesters and forage harvesters for the financial years 2019 to 2022. The focus here is on local independence and seasonal and temporal flexibility. The machines are only used seasonally, usually in the range of about 250 to 300 h/a (KTBL 2022a).

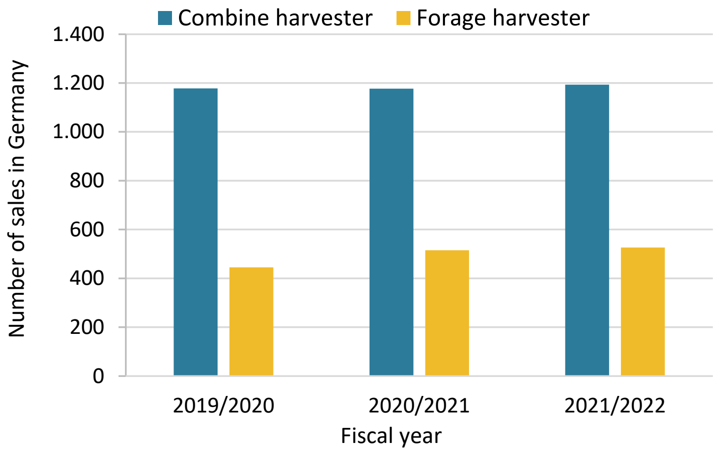


Fig. 11: Sales figures for combine harvesters and forage harvesters by financial year (© KTBL; Source: VDMA tractor report (unpublished))

2.7 Final energy demand and related greenhouse gas emissions

Fuel consumption in agriculture and forestry is well documented through the application procedure for agricultural diesel relief pursuant to Section 57 of the Energy Tax Act (EnergieStG 2018). Figure 12 shows the tax-privileged quantities of biofuels and conventional fuels used in agriculture and forestry.

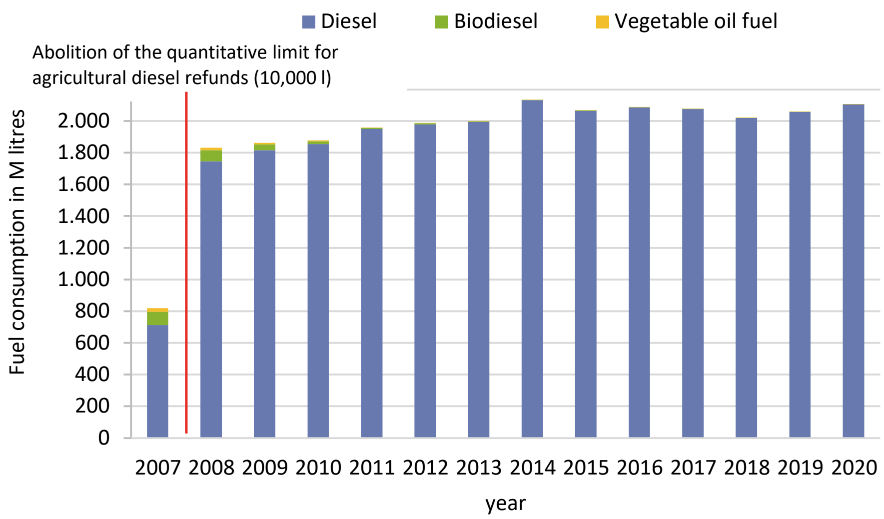


Fig. 12: Fuel consumption of agriculture and forestry in Germany – tax-privileged quantities of biofuels and conventional fuels (agricultural diesel relief according to § 57 EnergieStG) from 2007 to 2020 (© TFZ; Source: General Customs Directorate, Neustadt a.d. Weinstraße 2018 and 2022 (unpublished))

In agriculture and forestry in Germany, around 2.1 billion litres of fuel were consumed annually on average between 2016 and 2020, which corresponds to an energy equivalent of 74.4 PJ (own calculations according to data from the General Customs Directorate, Neustadt a. d. Weinstraße 2018 and 2020, unpublished). Less the estimated 12 % from forestry (calculated according to UBA (2022)), the energy equivalent of the fuels used in agriculture is reduced to around 66 PJ/a. With an energy share of 99.94 %, diesel fuel of grades B7 or B0 was used. The pure fuels biodiesel and vegetable oil fuel were used in total to an energy content of 0.6 per thousand.

In the CRF 1.A.4.c source group for the agricultural sector, 4.2 million tonnes of CO_2 equivalents (own calculations according to data from UBA 2022) are reported in the German greenhouse gas inventory of the Federal Environment Agency in the National Emissions Inventory (UBA 2022) for agricultural and forestry transport in Germany between 2016 and 2020. This value only considers direct emissions from combustion (tank-to-wheel), excluding upstream emissions for the provision of energy sources. 3.8 million tonnes of CO_2 equivalents are allocated to fuel consumption exclusively in agriculture. This corresponds to approximately 5 % of total greenhouse gas emissions in the agricultural sector in Germany. UBA (2022) provides guidance on the methodology for determining activity data and emission factors. Fuel quantities are calculated using the transport emission model TREMOD-MM (Heidt et al. 2020).

If the greenhouse gas emissions for agricultural and forestry transport in Germany are calculated on the basis of the quantities of fuel declared for tax relief for a B7 fuel quality, at least 5.1 million tonnes of CO_2 equivalents (own calculations: Emission factor for diesel fuel B0 (tank-to wheel) is 74,0 g CO_2/MJ, energy density of B0 is 35,87 MJ/l). This estimate suggests that the fuel consumption for agricultural and forestry transport may have been underestimated in the inventory reporting. The distribution of emissions between different operations for field work and livestock farming is shown in Figure 13. This is based on the distribution of fuel consumption between different operations as shown in Table 1 and Figure 2 and the emission factor of 74 g CO_2/MJ diesel fuel.

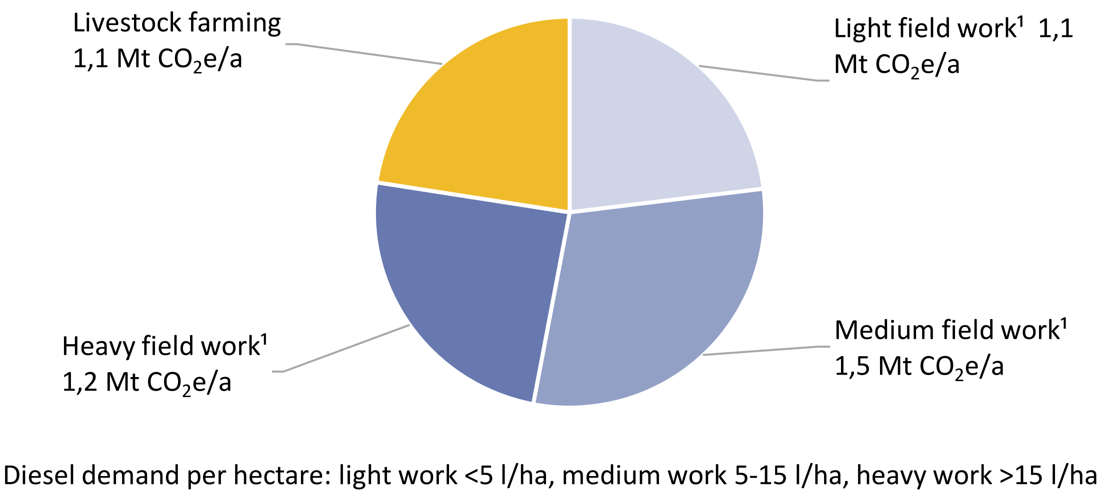


Fig. 13: Allocation of greenhouse gas emissions from fuel use in German agriculture to different work processes in millions of tonnes of CO_2 equivalents per year – estimation based on fuel consumption in 2020 on agricultural diesel relief pursuant to Section 57 of the Energy Tax Act and KTBL planning data, excluding forestry (© KTBL)

2.8 Legal framework

The greenhouse gas reduction targets for the agricultural sector are laid down in the Federal Climate Protection Act (KSG 2021). The agricultural sector must reduce annual emissions to a maximum of 56 million tons of CO_2 equivalents by 2030. Energy-related greenhouse gas emissions (source category CRF 1.A.4.c Combustion of fuels in agriculture, forestry, and fishery), e.g. from heat supply and fuel use, are attributed to the agricultural sector in accordance with Annex 1 of the Federal Climate Protection Act. About two thirds of the greenhouse gas emissions from source group 1.A.4.c originate from the combustion of fossil fuels. Reducing fuel consumption and substituting fossil fuels with renewable fuels and electricity therefore contribute to reducing greenhouse gas emissions associated with the agriculture sector. In addition to the Federal Climate Protection Act, the federal states have defined their climate protection goals in their own laws.

The competitiveness of renewable energy sources vis-à-vis fossil fuels depends on the price, which is determined, among other things, by production costs, but also by taxes and subsidies. A new directive on the taxation of energy production and electricity is being prepared at European level. The draft of 14 June 2021 provides that lower minimum levels of taxation may be set by Member States for both fossil diesel and renewable fuels for fuels used for agricultural, horticultural and forestry. What is new is that the tax amounts refer to the energy content and not to the volume. The minimum levels of taxation also vary within fuel types. Pursuant to paragraph 57 of the EnergieStG (2018), agricultural and forestry undertakings are granted, upon request, an energy tax relief on diesel fuel 'gas oils' of 21.48 Eurocent per litre. This aid for gas oil must be exempted by the EU Commission in accordance with Regulation (EU) No 651/2014 (EU Regulation 651/2014) (EnergieStG § 57(9)). The Energy Tax Act also provides for relief of 45.03 Eurocent per litre for fatty acid methyl esters and 45.00 Eurocent per litres for vegetable oil. However, since 2022, this energy tax relief on fatty acid methyl esters and vegetable oil is no longer granted. Aid is also governed by the Guidelines on State aid for climate, environmental protection, and energy (KUEBLL) (European Commission 2022/C 80/01 2022). This stipulates that biofuels can only be supported if they comply with the sustainability criteria of the EU Renewable Energy Directive (EU Directive 2018/2001 2018) (margin number 80). In addition, the caps for biofuels from food and feed crops are addressed (margin number 130). The need, maintenance, and level of tax relief for biofuels must be assessed by the Member States (margin number 303). On 27 February 2022, the KUEBLL replaced the Guidelines on State aid for environmental protection and energy 2014–2020 (UEBLL) (European Commission 2014/C 200/01 2014). The Fuel Emissions Trading Act (BEHG 2020) provides greenhouse gas emissions resulting from the use of, for example, fossil fuel (petrol, gas oils), a price derived from the prices for emission allowances. As biofuels are exempted from the BEHG, there is a cost advantage over fossil fuels.

The Federal Immission Control Act (Bundes-Immissionsschutzgesetz, BImSchG 2023) regulates the reduction of greenhouse gases and lays down gradual reduction targets for greenhouse gas emissions (greenhouse gas reduction quota) by 2030, which arise from the placing on the market of fossil petroleum and fossil diesel fuels. Distributors of fuels acting on a commercial basis are obliged to satisfy the quota. An incentive to place climate-friendly energy products on the market arises from the fact that levies are due in the event of non-compliance with the quota. In the regulation laying down further provisions to reduce greenhouse gas emissions from fuels in § 13 of the 38th BImSchV (2017) an annual limit of 4.4 %, based on energy content for the creditability of biofuels from food and feed crops is set, and in § 13a a limit of 1.9 % is set for the creditability of waste-based biofuels. Since 2023, biofuels from raw materials with a high risk of indirect land-use change, such as palm oil, are no longer eligible (§ 13b).

The EU Directive 2018/2001 on the promotion of the use of energy from renewable sources 'EU RED II' (EU Directive 2018/2001 2018) and, in future, the 'EU RED III' or the national Biofuel Sustainability Ordinance (Biokraftstoff-Nachhaltigkeitsverordnung, Biokraft-NachV 2021) regulate that the use of biofuels reduces more than a minimum level of greenhouse gas emissions and that there are no conflicts in land use for food, feed and raw material production as well as environmental protection. There is no comparable sustainability regulation for fossil fuels, electricity as drive energy or the extraction of rare earths to produce batteries. An annual 'Evaluation and Experience Report' according to the Biofuel Sustainability Ordinance submitted by the Federal Agency for Agriculture and Food provides information on the types of biofuels which were placed on the market, the respective quantities, which raw materials were used for their production, where the raw materials came from geographically and how many greenhouse gases were emitted or saved as a result.

Vehicles of category T (tractors) must comply with the requirements of Regulation (EU) No 167/2013 (EU Regulation 167/2013 2013) on the approval and market surveillance of agricultural and forestry vehicles and the associated delegated and implementing acts to obtain an EU type-approval valid throughout Europe. This includes Delegated Regulation (EU) 2018/985 (EU Regulation 2018/985 2018) as regards the environmental and performance requirements for the drive trains of agricultural and forestry vehicles and their engines. Mobile machinery placed on the market must therefore also comply with the emission requirements. This is based on type approval. Until 31 December 2016, type approval was governed by Directive 97/68/EC (EC Directive 97/68 1997), after which Regulation (EU) 2016/1628 (EU Regulation 2016/1628 2016) entered into force. Regulation (EU) 2016/1628, for example, provides in Article 25 the performance of measurements and tests and requires that the engine type or engine family operated with the reference fuel and with all specified fuels, fuel mixtures or fuel emulsions that are included in an application for EU type approval by an engine manufacturer comply with the specified exhaust emission limits. Testing additional fuels besides the reference fuel therefore involves considerable effort and costs for the engine manufacturer.

The Tenth Ordinance on the implementation of the Federal Immission Control Act (10. BImSchV 2010) regulates which fuels may be placed on the market at public service stations, which minimum quality requirements they have to meet and how the fuels must be labelled. Exemptions are possible in accordance with § 16 of the 10. BImSchV in the case of existing type approvals by the manufacturer, for own use and in the case of in-house refuelling infrastructure.

The goal is to achieve greenhouse gas neutrality by 2045. For this purpose, the transport system should be electrified as much as possible. The electrification of passenger cars and commercial vehicles is mainly driven by regulatory requirements, which are reflected in the EU by regulations on CO_2 fleet target values. However, the latter relate only to the vehicle (tank-to-wheel) and make no statement about the actual greenhouse gas reduction, as greenhouse gas emissions from the provision of electricity are not taken into account. Comparable requirements, which, for example, promote the electrification of non-road mobile machinery, do not yet exist at national or EU level.

2.9 Suitability and availability of energy sources and drive technologies for agricultural machinery

Today, agricultural machines are mainly operated with commercially available diesel fuel according to DIN EN 590 (fossil diesel with a maximum of 7 percent FAME by volume). To a small extent, machines are already operated with renewable fuels, such as vegetable oil fuel, biodiesel, HVO and biomethane or they are electrically driven.

The suitability of renewable energy sources for agricultural machinery depends on a variety of factors and should mostly be assessed in combination with the drive system used (electric motor – battery or fuel cell as well as internal combustion engine). Relevant influencing factors are

the use profile of the machines (power requirement, duration of use, place of use),

the interaction of the work done with the environment (climate, soil, water, air) and

the feasibility of establishing new drive and energy carrier concepts on the market (legal framework, infrastructure, availability of energy carriers and vehicles, acceptance).

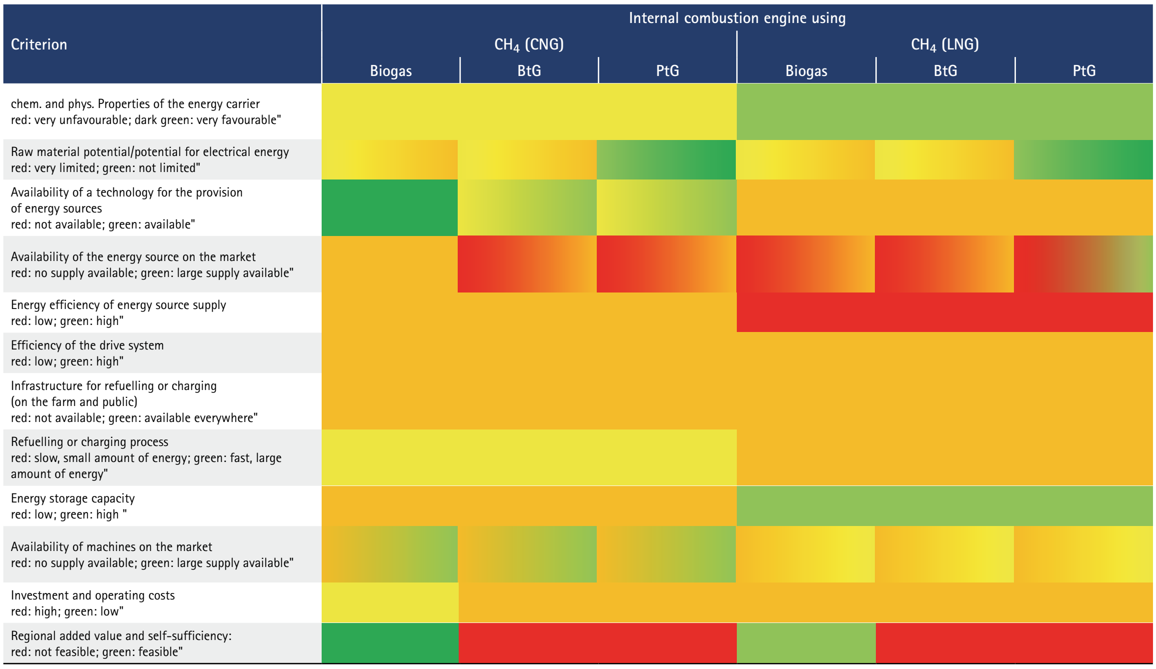
A detailed assessment of drive systems based on these factors is given in KTBL-Schrift 519

'Alternative drive systems for agricultural machinery' (KTBL 2020) and in DBFZ Report No 44 'Monitoring renewable energies in transport' (Schröder and Naumann 2022).

Figure 14 shows an evaluation of the main criteria for assessing drive systems for the years 2030 and 2045. Where a change is expected between these years, this is represented by a colour gradient. To the left of the cell, the estimate for the year 2030, to the right for the year 2045 is given.

Criterion	Internal combustion engine using						Electric engine using	
	Vegetable oil fuel	Biodiesel	paraffinic-diesel			H_2 (ICE)	Electric engine using:	Strom (Batterie)
	Rapeseed	various1)	HVO	FT (BtL)	FT (PtL)		Elektrolyse	Wind/PV
chem. and phys. Properties of the energy carrier red: very unfavourable; dark green: very favourable"								not rateable
Raw material potential/potential for electrical energy red: very limited; green: not limited"								
Availability of a technology for the provision of energy sources red: not available; green: available"								
Availability of the energy source on the market red: no supply available; green: large supply available"								
Energy efficiency of energy source supply red: low; green: high"								
Efficiency of the drive system red: low; green: high"								
Infrastructure for refuelling or charging (on the farm and public) red: not available; green: available everywhere"								
Refuelling or charging process red: slow, small amount of energy; green: fast, large amount of energy"								
Energy storage capacity red: low; green: high "								
Availability of machines on the market red: no supply available; green: large supply available"								
Investment and operating costs red: high; green: low"								
Regional added value and self-sufficiency: red: not feasible; green: feasible"								

Table continued on next page



1) Various raw materials.

Fig. 14: Evaluation of drive systems in perspective for 2030 (on the left in the table cells) and for 2045 (on the right in the table cells) (© DBFZ)

The assessment shown in Figure 14 forms the basis on which the following short- to medium-term perspective of drive systems up to 2030 and the long-term perspective up to 2045 are derived and summarized graphically (Fig. 15). The figure shows the solutions available on the market and sensible for use in agriculture under evaluation of the above criteria for new or convertible machines and the necessary energy sources according to the authors' estimation.

Reading example for Figure 14:
The color scale has 5 levels of red (very unfavorable) to dark green (especially favorable) (see column 1 for details).
Reading example: Paraffinic diesel (Fischer-Tropsch) from renewable electricity (PtL): Availability in 2030 will be marked with 'no supply available' (red, level 1), in 2045 with 'limited' (yellow, level 3).

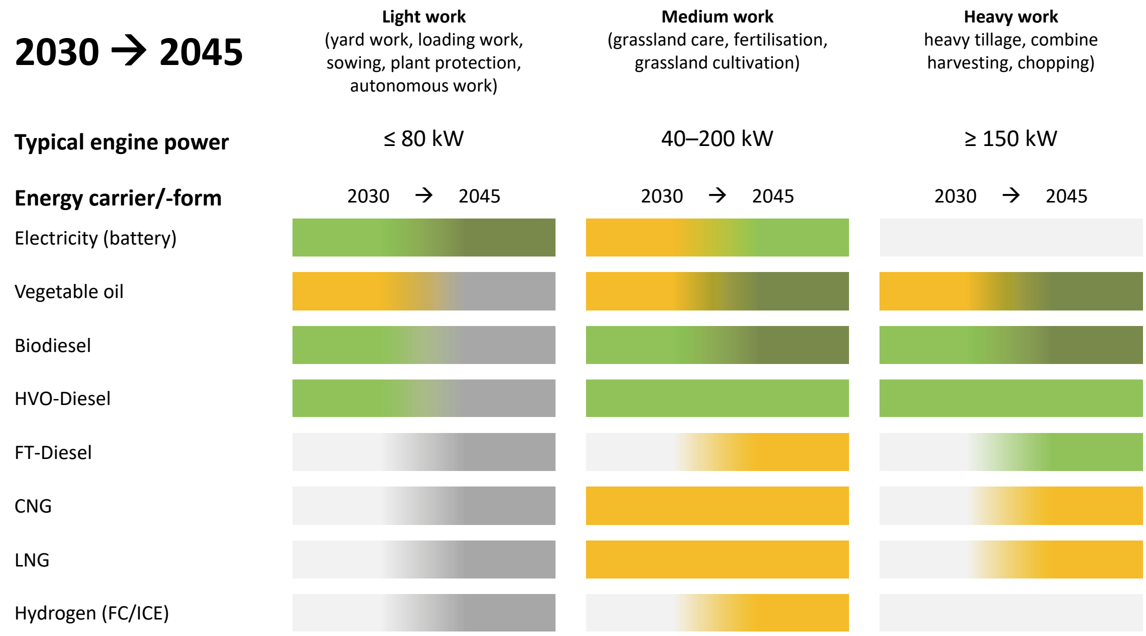


Fig. 15: Perspective 2030 and 2045 for selected renewable energy sources and drive systems in agricultural applications (© KTBL)

Legend:

Preferred options that can be implemented for agricultural machinery:
Machine and energy sources are available on the market, are suitable for the respective agricultural work, are cost-effective, the use of resources is efficient. Regional provision of energy sources is possible.

Can be implemented for agricultural machines:
Machines and energy sources are available on the market and are suitable for the respective agricultural work.

Partially implementable for agricultural machinery:
Machines and energy sources are available on the market under optimistic assumptions, the suitability for the respective agricultural work is partly given.

Can be implemented for agricultural machines:
However, more suitable alternatives are available.

Suitable renewable energy sources and corresponding drives are not available.

It should be noted that:

- Only energy sources that can be produced from renewable resources are considered.
- In 2030, the vehicle fleet will consist to a large extent of machines in use or new vehicles with already established drives.
- The expected market share 2030/2045, i.e. the penetration of a technology in practice, is not considered, only the expected availability is shown.
- Where technically sensible and practical, the electrification of the drives using renewable electricity is the preferred option due to the high energy efficiency and low energy costs, especially in the case

of power self-supply, to be able to use the scarce liquid fuels with high energy density, specifically in areas where electrification is out of the question.
- Regionally available energy sources are preferred to take advantage of the benefits in terms of security of supply and regional added value.

The main findings are that:
- electrification of the drive systems of machines for light work and heavy, time-limited work is already possible for new vehicles on a pro-rata basis by 2030, so that these machines could be almost completely electrified by 2045. In addition, new technological concepts can lead to a shift in processes and machines among the performance classes. A process division from one large machine to several small machines increases the potential for electrification but must be considered energetically holistic as well as in terms of quality and crop yield.
- the electrification of light and medium work would reduce the demand for liquid fuels by around 0.7 to 1 billion litres for the target year 2045.
- in the long term, vegetable oil fuel and biodiesel (FAME) may prove to be the preferred and suitable energy carriers for non-electrifiable work, such as medium to heavy and long-term work, to enable national security of supply with food and other agricultural products, in particular due to the regional supply possibilities.
- due to their fuel properties, paraffinic diesel fuels such as HVO diesel and FT diesel from biomass (BtL) or based on electrical energy (PtL) are very suitable renewable energy carriers for today's diesel-powered vehicles already in use. New vehicles should be powered by other fuels to defuse the competition for paraffinic diesel fuels. In the future, paraffinic fuels may receive very strong demand in other sectors, such as aviation and shipping, and are expected to be available only to a limited extent and at correspondingly high costs.
- renewable compressed methane (CNG) and liquefied methane (LNG), especially in farms with their own or with nearby biomethane plants, in the case of LNG with liquefaction plant, is evaluated as a reasonable alternative, however a nationwide application is rated as not possible due to the also low supply density in perspective. LNG is more suitable for heavier work due to the higher volumetric energy density compared to CNG. When using LNG, it must also be assured that no methane losses occur from the provision, storage, and combustion in the engine.
- hydrogen in combustion engines or fuel cells in agricultural applications is technically feasible but not a preferred option. Potential applications for hydrogen can arise, especially in the medium power range, if electrification is not possible. In particular, the low energy density compared to liquid fuels as well as the complex requirements for provision, storage and refuelling make large-scale application more difficult, so that other options are preferable. However, the biggest handicap may also lie in the subordinated availability of hydrogen over other applications.

2.10 Scenarios for the development of energy demand in agriculture

Depending on the assumptions made about the energy sources used, the energy consumption for mobile machines in agriculture can develop differently. At this point, a simplified consideration of possible developments with an estimate of the magnitudes should be made (Fig. 16).

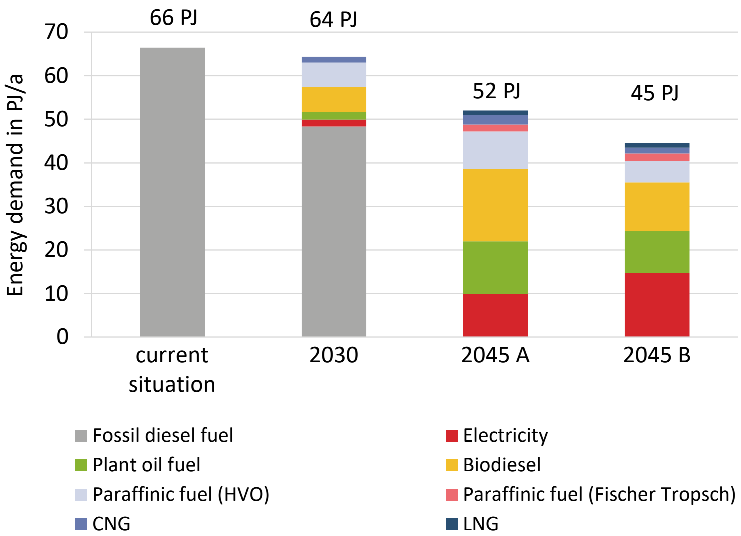


Fig. 16: Demand for energy sources for non-road mobile agricultural machinery in the scenarios 'current situation', '2030', '2045 A' and '2045 B' (© KTBL)

The future demand for energy sources depends in particular on the assumptions for electrification. A high electrification rate reduces the energy demand due to the better efficiency of the electric drives compared to combustion engine concepts. The options shown in Figure 15 assume unchanged agricultural production. Changes in land use or the size of livestock farming are not considered. Similarly, this simplified assessment does not take into account mitigation potentials as identified, for example, in the project 'Efficient use of fuels in agricultural technology – EKoTech" (Götz and Köber-Fleck 2019). For the 2030 scenario, it is assumed that only energy sources that are already available today will be used. Most of the energy demand will still be covered by fossil diesel fuel; electrification is of only minor importance, as only a limited range of machines will be available by 2030 and many existing engines with combustion engines are still in use at this time. A small part of the medium work can be covered with CNG-operated machinery, the remaining demand is satisfied by biodiesel, HVO and vegetable oil fuel.

Two different options are presented for the target year 2045. Both do without the use of fossil fuels.

In scenario 2045 A (less ambitious electrification), 70 % of light and interval work and 20 % of medium work are electrified. The remaining needs are mainly covered by biodiesel and vegetable oil fuels, supplemented by HVO diesel and a small proportion of FT-diesel for the heavy work. For medium work, CNG is also used, for heavy work also a small part LNG.

Scenario 2045 B (very ambitious electrification) assumes that 90 % of light and interval work and 50 % of medium work is electrified. The remaining needs are mainly covered by biodiesel and vegetable oil fuels, supplemented by CNG, LNG as well as HVO diesel and FT diesel as above. For the latter two fuels, a limited availability or high costs are expected, so that only needs that cannot be met elsewhere are covered, for example in the still existing older machines in use.

Tab. 4: Energy needs in the current, 2030, 2045 A and 2045 B scenarios

Energy sources used	Current situation	scenario 2030	scenario 2045 A	2045 B
	Energy demand in tank/storage in million litres/a			
Fossil diesel fuel	1,900	1,300	0	0
Vegetable oil fuel	0	100	300	300
Biodiesel	0	200	500	300
Paraffinic fuel (HVO)	0	200	200	100
Paraffinic fuel (Fischer-Tropsch)	0	0	50	50
	Energy demand in tank/storage in million kg/a			
CNG	0	30	40	30
LNG	0	0	20	20
	Energy demand in tank/storage in million kWh/a			
Electricity	0	400	2,700	4,100

The total energy demand for the mobile machinery changes in the scenarios from 66 PJ (current situation) over 64 PJ in 2030 to 52 PJ (scenario 2045 A) and 45 PJ (scenario 2045 B).

2.11 Development trends in agriculture

The change in farm sizes, farming methods and machine concepts used can influence the energy demand for farming. Changes can often not be reliably quantified, but trends can be deduced.

A management of agricultural land with a reduction in chemical plant protection changes the production processes and thus also the use of machinery and the associated fuel demand. The reduction of crop protection measures with the field sprayer towards an increased use of mechanical weed control methods requires a higher power demand and, if necessary, additional field crossings. On the other hand, if fewer ruminants are kept in Germany in the future and this leads to a shift in the cultivation of feed towards food, in particular cereals, on the arable land. This could result in a decline in fuel demand.

The continuous decline in the number of cattle in Germany, which amounted to around 14 % between 2010 and 2022 (BMEL 2022), can have a significant impact on the overall energy demand of mobile machines in agriculture. The high energy demand of mobile machines in cattle farming, due to feeding, can be easily covered by electricity. Thus, only a smaller additional reduction in the demand for scarce, liquid fuels would be expected due to the decline in stocks.

An increased use of electrically powered agricultural robots, which replace conventional machines powered by liquid fuels, would at least lead to a shift towards electricity as drive energy, but not necessarily to an overall reduction in energy demand.

The size of the farmed plots has an influence on the fuel demand as well as the farm-field distances. According to KTBL (2023) with the same mechanization level (example: 102 kW, silage maize, non-inverting tillage) the fuel demand for the management of a 1 ha plot adds up to 135 l/ha, with a plot size of 20 ha to 116 l/ha. In this case, the trend towards larger cultivation units or farm sizes can lead to a corresponding reduction in fuel demand. The division of plots through measures to increase biodiversity may prevent this reduction.

3 Possible courses of action

To initiate and accelerate the transition from fossil fuels to drive systems with renewable drive energies in agricultural machinery, supply and demand must develop as simultaneously as possible. Market participants are required to ensure long-term planning security through stable framework conditions for the success of a market ramp-up.

Measures that create a conducive framework and can prove to be a guideline for future action can be divided into policy measures to create financial incentives, further policy guidelines and measures that create or accompany the technical and logistical prerequisites for the transformation. The following is a list of options that differ significantly in terms of their impact, the burden on public budgets, etc. Prioritisation of the measures is not linked to the order in which they are listed. The measures may, individually or in combination, be conducive to a shift from fossil to renewable drive energy for agricultural machinery, following an appropriate impact assessment.

Policy options to create financial incentives

- Equal, ideally more favourable positioning of renewable drive energies in agriculture and forestry compared to fossil fuels in terms of energy taxation. The reference for the energy tax should be the energy content rather than the volume of the energy carrier. The scheme should include all renewable energy products and be open to all kinds of technology.
- Continuation of the gradual increase in the price of emission allowances in the Fuel Emissions Trading Act to increase the CO_2 levy on fossil fuels.
- Investment support for machines with renewable drive energies as well as for refuelling and recharging infrastructure, concentrating on systems with drive energies that particularly meet sustainability requirements and generate special benefits, e.g. in terms of regional circular economy, or added value.
- Implementation of the use of renewable drive energies in the national CAP Strategic Plan from 2027 onwards. The maximum amount of agricultural aid per baseline (area, livestock, etc.) will be reduced if specified quantities of renewable drive energy are not used. Additional incentives could be set for self-consumption or regional sourcing of drive energy.
- Continuation of ambitious GHG reduction targets in the transport sector resp. recast to include the drive energies used in the agricultural sector, to generate GHG quota revenues that can be priced in when supplying climate-friendly energy products for the operation of agricultural machinery.

Other policy options

- Add a greenhouse gas reduction quota for fuel-related emissions in agriculture to the Federal Immission Control Act (Bundes-Immissionsschutzgesetz, BImSchG 2023) in Part Three, Section Two, with quota obligations in accordance with Section 37a BImSchG.
- Obligation for distributors of agricultural machinery to offer only machinery which is either exclusively type-approved for renewable drive energy
- or have at least one other type of approval for renewable drive energy in addition to a type of approval for fuels in accordance with DIN EN 590 and DIN EN 15940.
- Deletion of the exemption of agricultural and forestry vehicles from the scope of application of the Clean Vehicles Procurement Act (Section 4(1)(1)), with the aim of creating an initiative market for machines with renewable drive energies through the demand of public authorities (federal, state, and local authorities).

Accompanying measures of policy and administration

- Agree on, communicate, and monitor interim targets for the transition to renewable energy sources in agriculture by 2045.
- Anchoring biofuels from cultivated biomass as well as from residual and waste materials for use in agriculture in the national biomass strategy of the Federal Government.
- Demonstrate machines with renewable drive energies, e.g. on flagship farms as part of the BMEL arable farming strategy 2035.
- Expanding the role model function of the public sector: In future, only procure machines with renewable drive systems at federal, state, and municipal level, also beyond the requirements of the Clean Vehicles Procurement Act.
- Maintaining or updating the 'Federal programme for energy efficiency and CO_2 savings in agriculture and horticulture', which currently provides funding for the retrofitting or new purchase of electric or biofuel-powered agricultural machinery or autonomous robots in the domestic sector. In the medium term, incentives contribute to reducing barriers to investment and to using agricultural machinery either electrified or with renewable drive technologies.
- Establishment of research funding programmes to support the development, testing and monitoring of alternative drive systems, including the associated energy supply infrastructure.
- Creation of framework conditions that support domestic production and, in addition, the import of renewable energy sources. The sustainability criteria, e.g. regarding the Biofuel Sustainability Ordinance, must be complied with.

Actor-specific measures of the agricultural machinery industry, agricultural technology industry and agricultural machinery trade

- Promoting the development and market introduction of agricultural machinery, operated with renewable energy sources, including infrastructure for the energy system of agricultural holdings and service providers: in particular electrified machines and equipment for indoor livestock and nearby farm applications.
- Transfer engine manufacturers' type-approvals for alternative fuels in pure form and in standardised blends by the agricultural machinery industry for new and existing machinery.
- Develop solutions for the use of renewable fuels in existing machinery: Subsequently release the use of renewable fuels as pure fuel or in standardised fuel blends as well as conversion solutions or engine control updates.
- Increased advertising of electrified and alternative fuel-compatible machines and address possible concerns of users about their practical applicability.
- Establish a network of appropriately trained agricultural machinery dealers and agricultural machinery workshops that can provide advice as well as service and repair work on site. Special courses in dealing with high-voltage systems are to be offered.
- Develop and provide uniform interfaces based on existing standards in the field of electric or semi-electric drives and trailed implements.

Actor-specific measures by fuel producers and fuel traders as well as electricity grid operators

- Provision of sufficient quantities of fuel of the required quality in the event of seasonal peaks in demand.
- Securing the geographical proximity of public service stations to agricultural customers or providing mobile refuelling systems (farm or field) if it is not possible to provide fuel for agricultural machinery via farm service stations.
- Ensuring the specific quality requirements for fuels for use in the agricultural sector, e.g. with regard to high storage stability through special additives.
- Providing sufficient electrical power on farms for the installation of charging facilities for electrified agricultural machinery.

Actor-specific measures from agricultural research and accompanying research

- Develop new technologies together with industry and agriculture and evaluate the conditions under which they can be used in agricultural practice.
- Analyse infrastructure drawbacks for the provision of energy, especially in rural areas and farms.
- Identify and clarify the legal situation and ambiguities, e.g. when refuelling vehicles already in use with renewable fuels and fuel mixtures without relevant type-approval.
- Investigation of scenarios for the increased use of renewable drive energies in agriculture and the resulting demand for energy sources and drive systems.

Actor-specific measures for agricultural holdings, machinery rings and contractors

- Switching machinery to alternative drive systems while consistently making use of electrification options.
- Participate in value creation through the production of agricultural raw materials, in particular co-products of food and feed production, for energy use – production of biofuels and electricity.
- Strengthening sectoral communication by farmers to raise awareness and identify possible solutions. This can be helped by the demonstration of individual farm solutions as best practice examples.
- Exploiting the potential of renewable drive energies in the provision of agricultural raw materials with a low carbon footprint.

Actor-specific measures from knowledge transfer and training centres

- Dissemination of information to strengthen regional circularity – use of own or regionally supplied renewable energies as a contribution to ensuring food production.
- Discuss and convey drive systems with renewable energies in vocational and university education and training.
- Continuous target group-adapted communication within the affected stakeholder groups.
- Expand the advisory services of the chambers of agriculture and state institutes as well as comparable facilities to include the aspect of low-greenhouse gas energy supply for mobile machines.
- Demonstration of machines with renewable drive systems, e.g. on inter-company training centres.

4 Communication and knowledge transfer

The transition of agricultural machinery from fossil fuels to climate-friendly and renewable drive energies is not one of the major topics that dominate discussions in agriculture, the agricultural industry, politics, and society. Therefore, for this transformation to succeed, the goals and solutions must be actively communicated. The target groups include farmers, the agricultural machinery industry, agricultural machinery dealers and workshops, fuel producers and retailers, teaching staff at universities, colleges and technical schools, political decision-makers at federal and European level, authorities, and society.

For a successful communication strategy, it is partly necessary to divide these target groups into further subgroups: The target group 'agricultural machinery industry' includes, for example, employees from management, engineering, sales, and marketing, as well as representatives of the relevant professional associations.

To initiate and accompany the transition of agricultural machinery to renewable drive energies, the following information must, inter alia, be communicated to the target groups mentioned in different widths and depths:

1. Creating Problem Awareness
   - Climate change mitigation objectives of the agriculture sector
   - Share of energy-related greenhouse gas emissions
   - Contribution of the transition to renewable drive energies for the achievement of climate protection targets
2. Acceptability
   - Availability of raw materials and energy sources
   - Material and energy cycles
   - Value added
   - Competition in use, ethical aspects
3. Technical information
   - Fuel characteristics
   - Drive system
   - Refuelling and loading technology
   - Results from field tests on the practical suitability of agricultural machinery
4. Legal provisions
   - Requirements for farm filling stations
   - Occupational safety and health
5. Environmental impacts
   - Soil and water protection
   - Greenhouse gas reduction
6. Economics
   - Costs of drive energy
   - Cost of machinery
   - Costs of refuelling and recharging infrastructure
   - Framework conditions regarding support measures, CO_2 pricing, taxation, etc.

7. Use of drive systems on the farm
   - Suitability of the different drive systems for specific operations and for specific farm structures
   - Coordination of drive system and working methods
   - Procurement of machinery, refuelling and charging infrastructure and fuels
   - Operational organisation

For the transfer of knowledge, advice and dialogue, target group-specific and oriented forms of communication should be used. These include, for example,

- conferences, lectures, lessons, training,
- publications, data collections,
- webinars, consultations,
- tutorial videos, social media as well as
- knowledge exchange and discussion at the round table.

An overview of the information content to be passed on to specific target groups and possible forms of communication is shown in Figure 17.

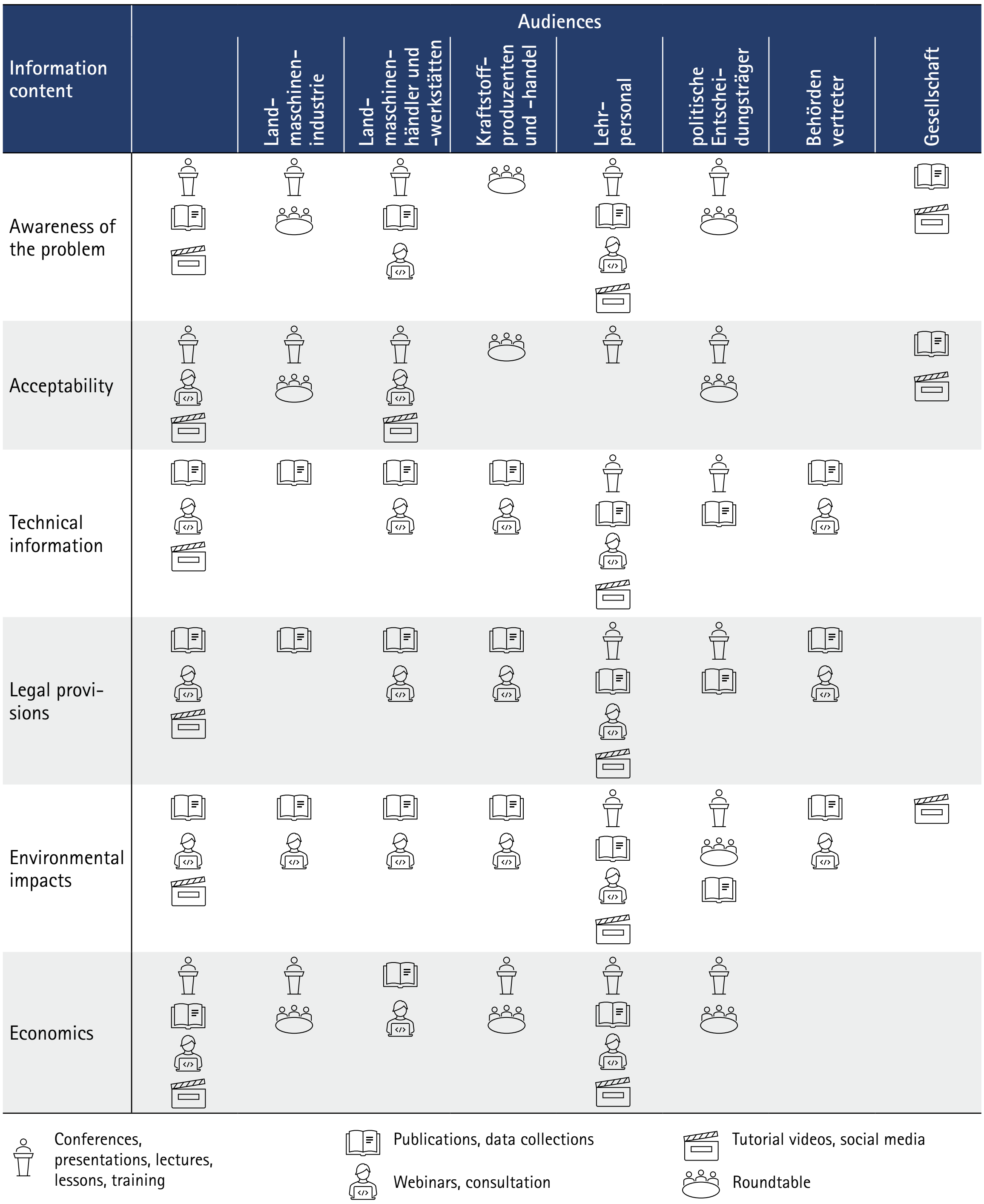


Fig. 17: Overview of the information content to be passed on to specific target groups and possible forms of communication (© TFZ, adapted)

To get the information to the target groups, a communication concept is required. The development of such a concept could be accelerated by public policies.

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Abbreviations

a	Year
AEL	Alkaline water electrolysis
ATJ	Alcohol-to-Jet (conversion of alcohols to aviation fuel)
B0	Diesel fuel without biofuel content
B7	Diesel fuel with a maximum of 7 % biofuel content
BtG	Biomass-to-gas
BtL	Biomass-to-liquid (biomass liquefaction)
BtX/BTx	Biomass-to-X (conversion of biomass into an energy source)
CAAFI	Commercial Aviation Alternative Fuels Initiative
CNG	Compressed natural gas
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CRF	Common reporting format
E-fuels	Electricity-based fuels
EUR	Euros
FC	Fuel cell
FAME	Fatty acid methyl ester (biodiesel)
FRL	Fuel readiness level
FT diesel	Fischer-Tropsch diesel fuel
gap	Common agricultural policy
GHG	Greenhouse gas
GJ	Gigajoules
h	Hour
ha	Hectares
HEFA	Hydrotreated esters and fatty acids
HVO	Hydrotreated vegetable oils
ICE	Internal combustion engine
IEA	International Energy Agency
KBA	Federal Motor Transport Authority
kg	Kilograms
KUEBLL	Guidelines on State aid for climate, environmental protection and energy (EU)
kW	Kilowatts
kWh	kilowatt-hour
l	litre

LH2	Liquid hydrogen
LNG	Liquified natural gas
m^3	cubic meter
MJ	Megajoule
NH_3	ammonia
PEM fuel cell:	Proton-exchange membrane fuel cell
PJ	Petajoule
PtG	Power to gas
PtL	Power-to-liquid
PtX/PTX/PTx	Power-to-X (electricity-based fuels, fuels, and raw materials)
RFNBO	Renewable fuels of non-biological origin
SPK	Synthetic paraffinic kerosene
t	ton
TREMOD(-MM)	Transport emission model (for mobile machines)
TRL	Technology readiness level
UEBLL	Guidelines on State aid for environmental protection and energy (EU)
VDMA	Verband Deutscher Maschinen- und Anlagenbau e.V. (Association of German Mechanical Engineering)
XtL	Paraffinic diesel fuel

Glossary

Biodiesel (FAME)	Fatty acid methyl ester produced from vegetable oils by transesterification.
CO_2 equivalent	Climate impact of various greenhouse gases, in particular methane (CH_4) and nitrous oxide (N_2O) converted to the climate impact of CO_2.
Defossilisation	Replacing fossil fuels with renewable alternatives (electricity, biofuels).
Fischer-Tropsch diesel	Fuels produced using Fischer-Tropsch synthesis to convert synthesis gas into liquid hydrocarbons.
HVO diesel	Hydrogenated vegetable oil, the properties of which are comparable to fossil diesel; is produced from fatty residues and waste materials or fresh vegetable oils.
Agricultural or forestry Tractor	Tractor or vehicle on wheels used on farms, fields, and grassland of the EC vehicle category 'T" in accordance with Directive 2003/37/EC.
Useful energy	Proportion of energy used that is available for the specific purpose, e.g. mechanical energy for the drive system.
Paraffinic diesel	Diesel fuels based on saturated hydrocarbons, the properties of which are comparable to diesel, e.g. HVO diesel and FT diesel.
PEM fuel cell	Energy converter for generating electricity from hydrogen and oxygen.
PtX fuels	'Power to X' means gaseous or liquid fuels produced on the basis of electricity.
Synthetic fuels	Fuels (e-fuels/PtX, RNFBOs), which differ from conventional fuels in terms of production or chemical structure.
GHG-quota	Obligation to reduce greenhouse gas emissions from fuels by a fixed percentage by introducing low-emission fuels. It is regulated by the Federal Immission Control Act (BImSchG).
GHG-quota trading	Transfer of compliance with the GHG-quota obligation to a third party who then places the eligible fuels on the market.

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