Energy 346 (2026) 140239

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Scenario based comparison of alternative fuel production systems for a virtual average German farm

Lea von Rüden *, Barbara Satola, Michael Kröner, Martin Vehse, Alexander Dyck, Carsten Agert

German Aerospace Center (DLR), Institute of Networked Energy Systems, Carl-von-Ossietzky-Straße 15, 26129, Oldenburg, Germany

ARTICLE INFO

Keywords:
Biomethane
Hydrogen
Rapeseed oil
Agriculture

ABSTRACT

The German agricultural sector consumes approx. 2 billion litres of diesel annually. While sustainable fuels remain underutilised, shifting from diesel to low-emission options is crucial for achieving a climate-neutral agricultural sector as mandated by the German Federal Climate Change Act. This study therefore examines three on-farm renewable fuel production pathways - biogas from manure and rapeseed oil, as well as hydrogen - on an average German farm. The results show that hydrogen offers the most land-efficient solution, requiring less than 1 % land use of the other alternatives, whereas rapeseed oil proves the most cost-effective option, with periodical costs 26 % lower than for biomethane and 18 % lower than for hydrogen, respectively.

Abbreviations

ADAC	Allgemeiner Deutscher Automobil-Club – General German Automobile Club
AfA Table	Depreciation Table for General Purpose Assets
CAPEX	Capital Expenditures
CBC	COIN-OR Branch and Cut
CHP	Combined Heat and Power Plant
DM	Dry Mass
GHG	Greenhouse Gas
HVO	Hydrotreated Vegetable Oil
IBC	Intermediate Bulk Container
JCB	J.C. Bamford Excavators Limited
KTBL	Kuratorium für Technik und Bauwesen in der Landwirtschaft – Association for Technology and Engineering in Agriculture
Lt	Lifetime
Oemof	Open Energy Modelling Framework
OPEX	Operational Expenditures
PCo	Periodical Costs
PV	Photovoltaics
SCIB	Solving Constraint Integer Programs
WACC	Weighted Average Cost of Capital

1. Introduction

German agriculture, forestry and fishery collectively consumed over 79 TWh in 2022 [1]. The energy demands of individual farms vary significantly depending on their specific activities. For instance, dairy farms primarily rely on electricity for milking and cooling operations [2], whereas, piglet breeding farms require both electricity and heat [3,4]. Arable farming, meanwhile, is characterised by high fuel consumption for operating agricultural machinery such as tractors [5,6]. Notably, many animal husbandry farms engage in arable or grassland cultivation, necessitating the use of agricultural machinery for tasks like harvesting and feeding. Germany's agricultural sector utilizes approx. 2 billion litres of fossil fuels per year [7]. Given the German government's goal of achieving climate neutrality by 2045, as outlined in the Federal Climate Change Action Act [8], the agricultural sector must reduce its greenhouse gas (GHG) emissions. Especially considering that agricultural activities occupy approx. 50.4 % of the land area in Germany [9], this highlights not only the significance of farming in terms of GHG emissions but also presents a substantial opportunity to meet local energy demands through decentralized energy production – minimizing additional land use impact [10]. While certain aspects of farming are more challenging to mitigate, such as those related to animal husbandry or land use change, transitioning to alternative fuels presents a feasible opportunity for reducing GHG emissions.

The replacement of diesel-fuelled utility vehicles with alternatively fuelled ones is a gradual process, as agricultural machinery often remains in use for extended periods (8–12 years) [11]. In future, retrofitting diesel-fuelled agricultural machinery to accommodate

* Corresponding author.
E-mail address: lea.vonrueden@dlr.de (L. von Rüden).

https://doi.org/10.1016/j.energy.2026.140239
Received 17 November 2025; Received in revised form 23 January 2026; Accepted 28 January 2026
Available online 29 January 2026

sustainable fuels may be an option. Most alternative fuels require specific technical systems, such as electric motors [12] or adapted combustion engines [13,14]. Various alternatives exist, including electrically driven agricultural machinery (powered by batteries or cables), plant-based oil derived fuels (e.g. rapeseed), biomethane or hydrogen (pure or processed into synthetic fuels) [15]. Each option has its advantages and disadvantages. For instance, synthetic fuels and biodiesel can be used in existing machinery, but are complex to produce and less efficient compared to other alternatives [15]. This study aims to investigate these options further by evaluating the self-production of hydrogen, biomethane from manure and rapeseed oil. The study focusses on self-production, as farms have multiple options for decentralized renewable energy generation. However, due to their remote locations, they face limited prospects for connection to a hydrogen grid. The advantages and disadvantages of on-site versus centralized hydrogen production are discussed in detail by Jordan (2022), including considerations of economies of scale and the logistical and energetic challenges associated with transporting hydrogen in centralized systems [16]. The self-production cost calculated in this study provide insights into potential market prices and the maximum feasible transportation costs for a centralized production. Furthermore, on-farm hydrogen production enhances energy independence, reducing reliance on external energy providers.

Battery electric and cable bound vehicles [17] are not considered due to the occasional high energy demands (e.g. ploughing and harvesting), which would require large batteries. Due to the energy requirement of conventional ploughing, which is approx. 44 MJ/ha [18], lithium-ion battery with a specific energy of around 150–200 Wh/kg would require a loaded battery with a mass of approx. 64 kg/ha [19]. Assuming a truck-mounted battery with a capacity of 400 kWh [20] this corresponds to a battery mass of about 2 tons, increasing the tractors weight by approx. 50 % [21]. However, increasing vehicle weight has a detrimental effect on the soil compaction [22], which may compromise long-term soil health and crop productivity. Electric connections are typically unavailable at arable fields, making charging and cable-bound machinery impractical. Synthetic fuels and biodiesel are also excluded. Their production goes beyond production of hydrogen and biogenic fuels discussed here. Further research on these options can be based upon the findings of this study.

Thoughts on alternative fuels in agriculture are not new, as evidenced by previous studies. Remmele et al. (2014) conducted a comprehensive review of various propulsion systems through expert interviews [23]. Their study found that experts generally favour combustion engines powered by biodiesel and plant oil. In the middle of the ranking, they placed agricultural machinery with batteries and combustion engines fuelled with biomethane, while hydrotreated vegetable oils (HVO) and electric engines powered with hydrogen were ranked at the bottom. The present study evaluates the production of hydrogen, rapeseed oil and biomethane from a simulative point of view, not only by expert opinions.

Several options for agricultural machinery running on plant oil already exist, including John Deere tractors that can operate with plant oil under warranty [24]. Additionally, diesel engines can be retrofitted to use plant oil; however, these modifications are not always successful due to issues such as fuel injection systems plugging or combustion system problems caused by unsuitable fuel [25]. Research has shown that the operation of tractors from Deutz, Fendt and John Deere with rapeseed oil is feasible, with very little differences in emissions between diesel and rapeseed oil [26]. However, it was also found that more frequent engine oil exchanges are necessary due to the accumulation of rapeseed oil in the engine [27]. Studies have not only investigated the use of rapeseed oil as a fuel for agricultural machinery but also for vehicles such as a retrofitted VW Golf [28], with problems arising from low-quality rapeseeds and poorly conducted pressing. A comparison of the environmental impacts of sunflower, rapeseed and soybean oil production found that sunflower oil has the highest impact, while those of soybean and rapeseed oil are similar in magnitude [29]. Given these findings, and considering that rapeseed is a locally sourced crop in Germany, this study focuses on rapeseed as a fuel source and excludes other oil plants. Furthermore, rapeseed is the primary feedstock due to its dominant share in German oil crop cultivation. On average, it accounts for over 90 % of the cultivated area for oilseed crops in Germany, with regional shares reaching 99 % in Schleswig-Holstein (around Kiel) and 80 % in Bavaria (around Munich) [30].

A recent study by Mathur et al. (2022) compared various biogenic fuels and provided an overview of current research in the field [31]. The authors noted that biofuels from food and non-edible sources have major limitations primarily due to concerns over land use. However, algae and microalgae-based fuels are found a promising option for future biofuel production.

Besides plant oil, biogas is another potential source for biogenic fuel in agricultural machinery. Biogas can be converted into biomethane, which has more consistent properties and is better suited for use in combustion engines [32]. Several companies have already developed or are testing biomethane fuelled tractors, including New Holland, which introduced a pilot series tractor that runs on liquid biogas [33]. They also produce a series of tractors powered by compressed biomethane [33,34]. Valtra has produced a small series of biomethane tractors since 2011. Testing by two Bavarian research centres demonstrated that these tractors can provide the necessary power [35].

The topic of biofuels elicits differing opinions among authors. Graham-Rowe (2011) expresses concerns about biofuels regarding the need for water of the plants and the competition between food and fuel production [36]. Similarly, Monbiot (2023) emphasises the importance of agricultural land use in contributing to GHG emissions and suggests that renaturing used fields and meadows could have a positive impact [37]. Woods et al. (2010) conclude that biofuels can be viable if the energy generated by the plant is greater than the energy required for its production [38]. However, when comparing the land use and global warming potential across photovoltaics (PV), wind and biogas, Böhm et al. (2024) found that wind has the least impact, followed closely by PV, with biogas consistently ranking last [39]. It must be noted that this study is focused on electricity production, but since green hydrogen production relies on electricity, the results of Böhm et al.'s study can be applied to the hydrogen context as well.

Research on using hydrogen in agricultural machinery is ongoing, but commercial solutions are not yet available. Several companies have experimented with hydrogen-powered tractors and other equipment. Fendt took part in the "H2Agrar" project and produced two prototypes of hydrogen powered tractors, mechanized with fuel cells which are currently being tested on farms in Lower Saxony (Germany) [40]. However, J.C. Bamford Excavators Limited (JCB) and New Holland have also experimented with fuel cells but concluded that they are not suitable for agricultural machinery due to their complex cooling system, sensitivity towards dust and vibrations and high costs [40]. Deutz offers a hydrogen combustion motor, which is not yet used in agricultural machinery [41] while Liebherr introduced a 6-cylinder hydrogen engine for a 50 t dredger, which is most likely suitable for agricultural machinery [40,42]. JCB has constructed prototypes of hydrogen-powered dredgers and tele hoist load luggers. Furthermore, they developed a mobile tanking station to address the challenges of infrastructure and large storage sizes [43]. Additionally, Rolls-Royce developed a hydrogen combustion engine and plans to offer retrofits of existing gas engines for hydrogen combustion [44]. Generally, hydrogen is emerging as a promising fuel for agricultural machinery with a growing trend towards combustion engines being preferred over fuel cells.

Research is ongoing regarding the use of hydrogen, beyond the industrial development. A literature review by Maganza et al. (2023) examined the possibilities of using hydrogen in greenhouses and on animal farms, concluding that it is a promising technology with a low technology readiness level [45]. A study by Janke et al. (2020) integrated hydrogen into a Swedish farm using historic wind and electricity price data to simulate energy demand and electrolyser integration. The study utilized all aspects of the hydrogen production including fuel, waste heat for stables and oxygen to improve water quality in a rainbow trout pond [46]. Additionally, Zhao et al. (2024) evaluated the load profiles of fuel cell tractors, focusing on construction methods to optimize fuel cell performance through batteries and supercapacitor integration [47]. Other studies have been conducted on the production of various alternative fuels focusing on a single fuel without comparison [48–50], while this study focuses on the comparison of the different alternative fuels, hydrogen, rapeseed oil and biomethane.

The GHG emissions associated with fuel production are assumed to be similar across various fuels, as they all require machinery and building construction. Fossil fuels such as diesel are produced in industrial facilities. The production facilities simulated in this study are decentralized and thereby may be more material intensive. However, decentralized production can still offer benefits by reducing transportation related emissions compared to centralized production and distribution of fossil fuels [51]. Rapeseed oil, a renewable resource, releases CO_2 during combustion, but this CO_2 was previously taken from the atmosphere through photosynthesis. However, fertilization of rapeseed crops generates additional emissions [52]. Biomethane production involves processing manure into a higher-quality fertilizer, which can lead to methane emissions, estimated at around 2 %, as methane can leave the processing units/storages or during combustion into the atmosphere unwantedly [53]. Methane has a global warming potential 25 times of that of CO_2 [54]. Additionally, concentrated feed for dairy cattle often relies on external nutrients, disrupting the nutrient cycle and creating further emissions. In operation, hydrogen produces no GHG emissions, as it recombines with oxygen to water [55]. However, similarly to biomethane, there can be leakages and hydrogen itself has a global warming potential of 7.1–9.3 compared to CO_2 [56]. A detailed assessment of the GHG emissions of the distinct systems is beyond the scope of this paper.

This study aims to conduct a comparative analysis of economics and land use associated with three alternative fuels produced on farms for the usage in agricultural machinery: biomethane from manure, plant oil from rapeseed and hydrogen. Specifically, it seeks to answer the following research questions.

1. Which fuel type can be produced most economically, and how do changing environmental parameters of crop rotations, cultivation (organic or conventional), location in Germany, influence the profitability?
2. How do the fuels differ regarding land use?

This study differs from previous ones by comparing three sustainable fuel options specifically for self-production on farms, rather than focusing on a single fuel type. Most previous studies neglected comparison between different fuels, while Böhm et al.'s (2024) [39] work focused on electricity production options, not fuels, considering GHG emissions and land use. Also, agricultural machinery producers do not follow one single direction and did not collectively decide on one future fuel. Therefore, this study can help to determine the future pathway.

2. Methods

To compare the self-production possibilities of renewable fuels on farms, a simulation using the open energy modelling framework (oemof) was conducted [57,58]. Oemof is an open-source software which can be used to optimize energy systems based on defined "costs". These costs can include financial costs, GHG emissions, land use or any other parameter. The framework offers flexibility in modelling, allowing users to adapt predefined component types (e.g. sources, sinks, converters) to specific needs. Thereby the simulation can optimize the sizing of the components and/or optimize the energy flows between the components. Previous studies have already utilized oemof for similar simulations, e.g. including an optimized coupling of a local grid and a cable bound agricultural machine [17].

To investigate the influence of various parameters on fuel costs, a scenario analysis was conducted. Fig. 1 shows an overview over the different scenarios considered. The study integrates two locations in Germany: Kiel (northern region) and Munich (southern region), which have distinct environmental conditions such as higher wind speeds in Kiel and higher solar irradiation in Munich. The location is crucial for the production of renewable electricity from PV and wind power plants as it affects investment decisions [10]. Furthermore, the cultivation method (organic or conventional) was also examined, as organic farming requires diesel for mechanical weed control (like harrowing) and close to none for fluid herbicide application [59], while for conventional farming, it is the other way round. Different crop rotations were considered, including rapeseed, maize and winter wheat plus additional grassland, which require different fostering steps and influence fuel consumption (in total and timewise) [59]. The scenarios were analysed from multiple perspectives including investment and operational costs and land use for the different investigated inputs (PV, wind, rapeseed and manure from dairy cattle kept on the farm) and the comparison with diesel as conventional fossil fuel.

2.1. Assumptions

Different assumptions were made for the simulation of the different scenarios (Fig. 1), which will be described in the following sections.

2.1.1. Assumed farm

It is assumed that the farm has 100 ha of agricultural land, which is the average size of farms in Germany [60]. The agricultural land is divided according to the cultivation method [60]: for organic farming 50 % is used for grassland and 50 % for arable land [61], while for conventional farming 70 % is used for arable farming and 30 % for grassland [62]. The different crop rotations are based on maize, rapeseed and winter wheat, as proposed by Mohr and Ehmcke-Kasch (2017) [63]. The distribution of these crops is shown in Table 1. Crop rotations can be viewed from two perspectives: in a single field, where the crop sequence changes each year, or at the farm level, where multiple fields bear the different crops. For the first rotation, four equal-sized fields are

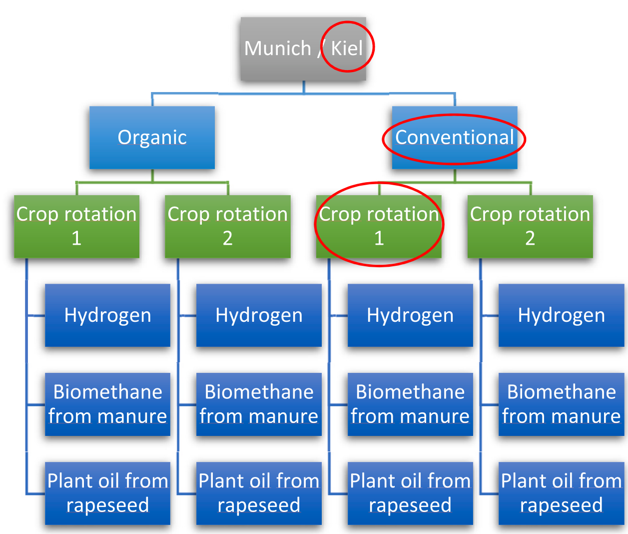

Fig. 1. Overview on the different scenarios considered in this study. For all the types of variations two options are assumed, for the location (grey) Kiel and Munich, for the cultivation (light blue), organic and conventional, and for the crop rotations (green), one with four and another with six elements. On the last level the three fuel options (dark blue) are depicted. The basis scenario is highlighted with red circles.

Table 1
Overview on the areas used for the different crops (rotating) and grassland (permanent on one site) for the different crop rotations and cultivation methods.

Conventional				Organic			
Crop rotation 1		Crop rotation 2		Crop rotation 1		Crop rotation 2	
Field size [ha]	Cultivated plant	Field size [ha]	Cultivated plant	Field size [ha]	Cultivated plant	Field size [ha]	Cultivated plant
30.0	**Grass**	30.0	**Grass**	50.0	**Grass**	50.0	**Grass**
17.5	**Rapeseed**	11.6	**Rapeseed**	12.5	**Rapeseed**	8.3	**Rapeseed**
17.5	**Maize**	11.6	**Winter wheat**	12.5	**Maize**	8.3	**Winter wheat**
17.5	**Maize**	11.6	**Maize**	12.5	**Maize**	8.3	**Maize**
17.5	**Winter wheat**	11.6	**Winter wheat**	12.5	**Winter wheat**	8.3	**Winter wheat**
		11.6	**Maize**			8.3	**Maize**
		11.6	**Winter wheat**			8.3	**Winter wheat**

assumed, each following the same sequence. The same principle applies to the second rotation, which uses six fields instead of four. The cultivated amount of rapeseed is also considered as the amount available for oil production in the simulation.

Additionally, it is assumed that the farms use their own manure to produce biogas, which means that animals are kept on the farm. The animals are assumed to be dairy cattle. The feed requirement of dairy cattle consists of two types: basis feed and concentrated feed. Basis feed includes locally produced hay, grass silage or maize silage, while concentrated feed is high-energy feed from soybean and typically purchased. The amount of feed required depends on whether the cow is in her lactation phase and whether it is her first lactation phase. In the simulation it is assumed that the cows are in their first lactation phase and require 3.99 t dry mass (DM) of basis feed and 2.31 t of concentrated feed per cow [64]. However, the costs of purchasing concentrated feed are not considered in the simulation as these expenses are not directly linked to fuel production (the primary focus of this model) but rather to maintain dairy cow nutrition – the cows' central function being milk production. The share of DM of silage maize is assumed to be an average value of 32 % [65]. The number of cows kept on the farm depends on the amount of basis feed available from its own production (silage from maize and grass) and thus depends on the type of cultivation and crop rotation. Furthermore, it is assumed that each cow produces 17 m^3 of manure per year [66]. An overview on the calculations can be found in Table 2. It is worth noting that there is no relationship between the cultivation method and the ratio of maize to grass silage fed [67].

2.1.2. Weather data

The weather has a significant impact on the yield of renewable energies, particularly solar irradiation for PV production and wind hours and speed for wind power plants. Additionally, the weather affects agricultural operations. Weather data was obtained from "onebuilding" [68], which provides typical meteorological years (TMYs) of locations worldwide. TMYs are synthesized datasets designed to represent typical meteorological conditions of a specific geographic zone by aligning with long-term statistical averages. Unlike historical records TMYs are constructed to exclude exceptional weather events and to mitigate the representativeness bias inherent in individual years. To account for different German weather conditions two locations were chosen: Kiel in the north, known for high winds and proximity to the sea and Munich in the south, characterized by high solar irradiation. To verify the data, the amount of rainfall from "onebuilding" was compared with published rainfall data for Munich [69]. The results showed a deviation of around 5 % from the ten-year average. This suggests that the weather data is reliable. The weather not only affects the production of renewable energies, but also crop development and yield. However, individual crop yields were not simulated in this study. Instead, German averages were assumed, as other parameters like soil quality can significantly impact yields. These parameters are strongly localized and difficult to assume for indistinct locations. Furthermore, the comparative analysis of rapeseed yield data across the federal states of Schleswig-Holstein (Kiel) and Bavaria (Munich) reveals only minor fluctuations, with no consistent interannual or regional productivity advantage. Specifically, yields in Schleswig-Holstein demonstrated a 20 % reduction relative to Bavaria in 2016, whereas by 2022, the trend reversed to a 12 % higher production level in Schleswig-Holstein. Overall, these variations do not support a sustained unidirectional yield disparity between the two regions [30].

2.1.3. Fuel demand based on fossil diesel demand

To estimate the fuel demand for agricultural machinery, crop rotations and field sizes were used as a basis. However, the yearly sum of fuel demand is not sufficient; the timing of different cultivation procedures is also crucial. Therefore, weather data was combined with data from the KTBL using their procedure calculator for individual crops [59]. This calculator provides information on diesel demand per hour, operation hours of the individual agricultural machinery, and other relevant details for each step of the cultivation process, including the first or second half of the month when they are typically performed. The following assumptions were made.

- Distance from farm to field: 3 km
- Mechanical power output of the standard tractor used: 67 kW
- In the organic maize cultivation, no diesel demand was provided for chopping in the KTBL data, as it is usually done by a contractor. Therefore, in this study it was adopted from conventional farming.

The simulation was conducted in hourly time steps, so the data from the operation calculator needed to be distributed over the hours of the year. It is necessary to employ distinct, equal timesteps for the simulation to work. The simulation employs hourly time steps to mitigate computational bottlenecks, acknowledging that finer temporal resolution would significantly escalate runtime without proportional gains in output precision for this application. Every farm is different, so the assumptions may not be valid for every farm. However, slight changes with earlier starting times or work in later evening hours do not have large influences on the simulation results. Multiple assumptions were made: During normal operation, working days are from Monday to Friday, with working hours from 8 a.m. to 12 p.m. and 1 p.m. to 6 p.m.

Table 2
Overview on the number of dairy cattle and amount of manure production per year.

Cultivation	Crop Rotation	Maize DM [t/a] [59]	Grass DM [t/a] [59]	Feed requirement [t/cow]	Number of cows	Manure Production [m^3/a]
Organic	1	280	160.35	3.99	110	1870
	2	185	160.35	3.99	86	1463
Conventional	1	560	120.15	3.99	170	2890
	2	371	120.15	3.99	123	2091

However, during harvest, the day of the week is irrelevant. The working times are adjusted to 9 a.m. to 10 p.m. Harvesting will only proceed if there is less than 0.1 mm of rain recorded the day before and during harvest. Transportation of the harvest begins 1 h after the harvesting process and lasts for an additional hour. Silage compaction, on the other hand, starts 2 h after the chocking and continues for 2 h longer than the chocking process itself. During the harvest, an unlimited number of tractors are available, unlike the normal operation in which only two tractors are utilized. The rotation of the grass silage begins 1 h after mowing starts, while swathing occurs a day later and pressing takes place two days after mowing begins.

2.1.4. Modelling approach

The modelling of the alternative fuel production systems is performed using oemof [57]. Oemof and its sub-package, oemof.solph, offer the possibility of creating linear optimization problems based on the represented energy system, which are described in more detail in the following sections. The package is useable in Python. Optimization was conducted using open-source solvers, like the COIN-OR Branch and Cut solver (CBC) and Solving Constraint Integer Programs (SCIP). CBC was prioritized here as it is recommended by oemof.solph and is established in energy system modelling. The optimization is performed over a defined timeframe, with a fixed timestep length; in this case the timeframe is one year with hourly timesteps. A model built in oemof.solph consists of multiple components, including transformers, storages, sinks and sources, which are connected via buses. Buses and components are linked through flows, which can have multiple properties assigned, such as costs, minimal and maximal flow rates. The minimal system consists of a source, a sink and a connecting bus, allowing energy to enter, leave and flow through the system. Transformers can be used to convert the energy from one type to the other, e.g., a biogas plant converts the manure fed into the system, using electricity, into biogas. The input and output flows can change units, provided the implemented conversion factors account for these changes.

Oemof.solph can be employed for various types of optimizations. One option is the investment optimization, realized in this paper, where several components are optimized in terms of size, depending on demand and the investment costs of individual components (detailed in Appendix 1). In this study, the components are optimized for self-consumption, as the sale of products while dimensioning the components through the investment optimization led to infeasibilities, likely due to the infinite sale of the products resulting in an infinitely large size. Furthermore, the goal of this study is to examine the options of in-house production of the self-consumed fuel. The term “size” refers to the unit of input/output flow, not area or volume. In a second simulation, actual selling prices are considered, allowing the system to produce fuel both for self-consumption and market sale. To facilitate comparison, the different fuel demands are calculated in kWh, considering the efficiency of each engine (diesel, biomethane and rapeseed oil) or fuel cell (hydrogen). The assumed conversion factors for the simulated system are presented in detail in Appendix 2. Some simplifications were made during the dimensioning process, which include neglection of distinct component sizes or minimal capacities, as well as necessary refuelling stations.

2.1.4.1. Hydrogen system. The simulated hydrogen system consists of multiple components, as shown in Fig. 2. The system set up is adopted from Nnabuife et al. (2024) [70]. To produce hydrogen, the system relies on renewable energy sources, specifically PV and wind power plants. It is assumed that the renewable energies cover the electricity demand and no grid connection is available for buying. The PV and wind inputs are based on the weather data retrieved in section 2.1.2, taking into account the efficiencies of PV plants (20 % module efficiency [71and95]% inverter efficiency [72]) to convert global irradiation into electricity. Similarly, the efficiency of wind power plants is considered, calculated based on wind speed and the performance curve of an assumed small wind power plant produced by Halbes Energji [73]. This approach is also applied to the implementation of PV and wind power plants as well as in the two other energy systems regarded in this study. These renewable energy sources generate electricity, which flows into the “electricity bus”. This bus is connected to two main components: an electrolyser and a battery. The electrolyser uses purified water (0.5 L/kWh [74]) and electric energy (1 kWh electricity for 0.65 kWh hydrogen [75]) to convert it into hydrogen. The purification process of the water is included in the system, having an efficiency of 80 % of water usage [74], while the electricity demand is incorporated in the

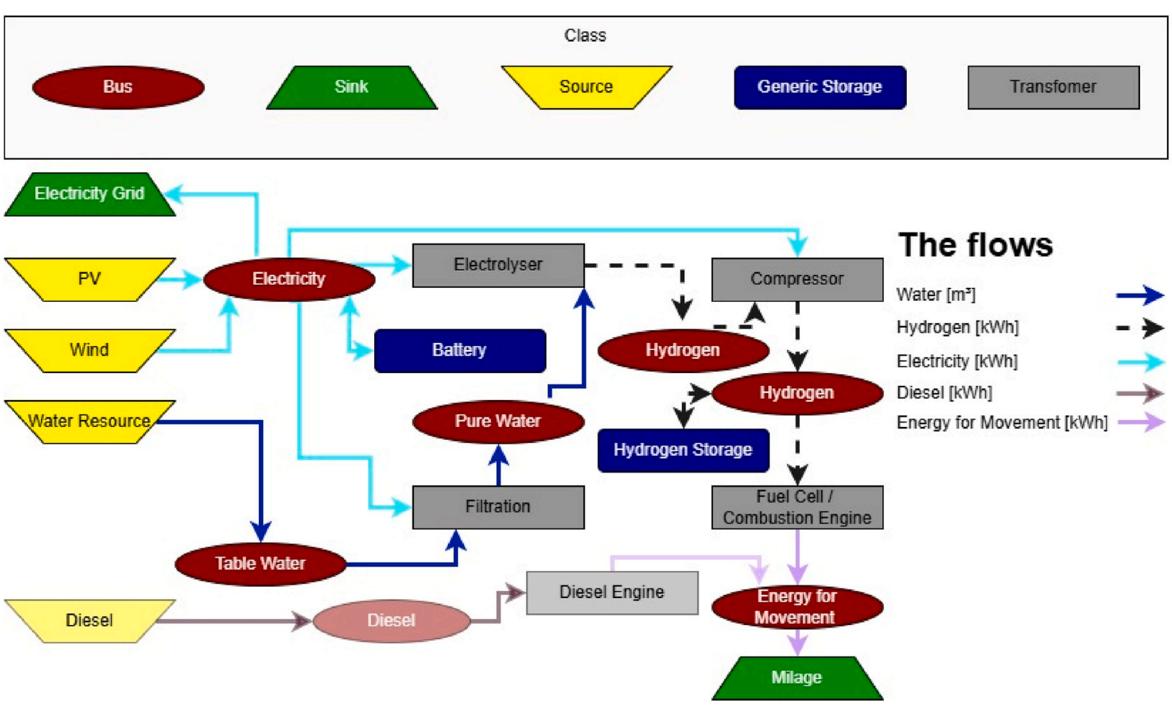

Fig. 2. Schematic depiction of the simulated hydrogen production system in oemof [58].

electricity demand of the electrolyser [75]. Following production, the hydrogen is compressed to 350 bar using 0.09 kWh of electricity to compress 1 kWh of hydrogen [76] and stored for later use in a 350 bar storage with an assumed loss of 2 % during charge and discharge. Losses of hydrogen storages are strongly dependant on the infrastructure available [77]. This assumption needs to be adapted when a specific system is simulated. The diesel option is not considered in this simulation but is compared in section 3.1.

2.1.4.2. Biomethane system. The biomethane system is also depicted in oemof [57] and its schematic representation can be found in Fig. 3. The input to this system is the manure produced by the assumed number of dairy cattle on the farm, as described in section 2.1.1., flowing into the system with a continuous flow. The time spent by the cows on the meadow during summer, which reduces the manure input to zero during daytime, are neglected. The system set up is based on the one shown by Stinner et al. (2015) [78]. The manure can be either stored, where no loss rate is assumed, or excess manure can be removed from the fuel production system and directly used as fertilizer. After that it is processed in the manure biogas plant, converting 1 m^3 of manure and 3.4 kWh of electricity [79] into 256 kWh of biogas [78]. The produced biogas can be stored, with an assumed loss of 2 % during discharge or directly treated in a scrubber, which removes CO_2 and impurities from the biogas, leaving only methane [80] while getting 0.96 kWh methane from 1 kWh biogas using 0.0001 kWh of electricity. The purified biomethane is used as fuel in the combustion engine of the tractor. Additionally, PV and wind power plants provide the energy required for the production processes, such as fermentation stirring like described in the previous section. The grid is only available for selling excess energy and not to buy electricity. As without sink, the linear equation system would not prove feasible.

2.1.4.3. Rapeseed oil system. In addition to biomethane and hydrogen, plant oil produced from rapeseed is also considered as renewable fuel in this study. The simulated model, depicted in oemof [57], is shown in Fig. 4. The model is based on the system described by Remmele et al. (2009) [81]. The rapeseed is assumed to be stored in a silo throughout the year under beneficial conditions, maintaining consistent energy content. From this silo, rapeseed is extracted for pressing and post processing, which involves multiple filtering steps to achieve the necessary level of purity. This entire process is incorporated into the "rapeseed oil production" component, where 1 kg of rapeseed is converted to 3.5 kWh of oil and 0.66 kg of press cake [82] using 0.06 kWh of electricity [83]. After production, the oil can be stored and used as needed to meet the fuel demand. Oil as liquid is much easier to store than biomethane or hydrogen. Here the usage of Intermediate Bulk Container (IBC) is assumed. No losses are assumed. Notably, the energy required for pressing etc. is sourced from PV and wind power plants, rather than generated by using the rapeseed oil itself or taken from the grid as already described in section 0.

2.2. Economic methods

The economic analysis of the different options (biomethane, rapeseed oil, and hydrogen) is conducted from one perspective. The investment costs in the form of periodical costs (PCo) are compared directly to analyse the influences of individual components and their shares. For calculation, formula (1) is used [57], which considers *PCo*, weighted average cost of capital (*WACC*), investment costs (*CAPEX*), costs for operation and maintenance (OPEX) and lifetime (*lt*).

$$PCo = CAPEX + (OPEX*lt)*\frac{WACC*(1+WACC)^{lt}}{(1+WACC)^{lt}-1} \quad (1)$$

It is assumed that the *WACC* is 2 %, which corresponds to the interest

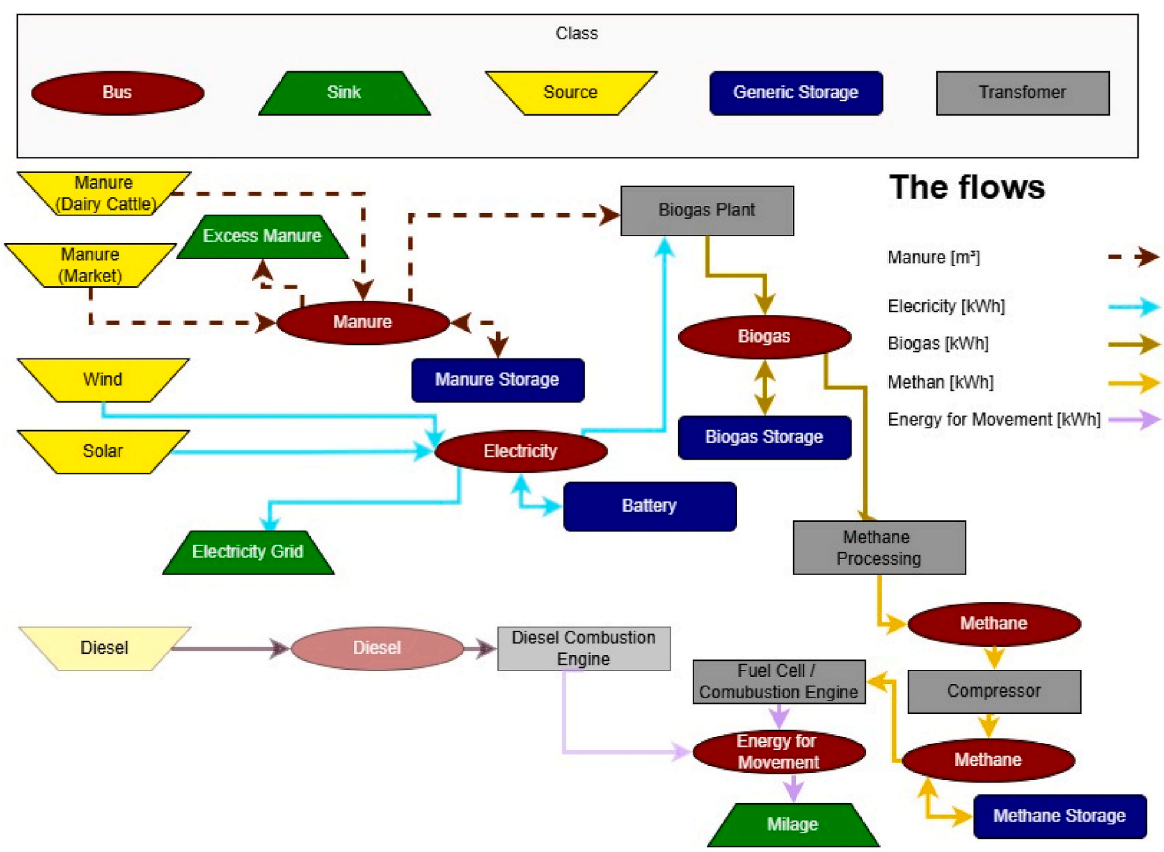

Fig. 3. Schematic depiction of the simulated biomethane production system in oemof [58].

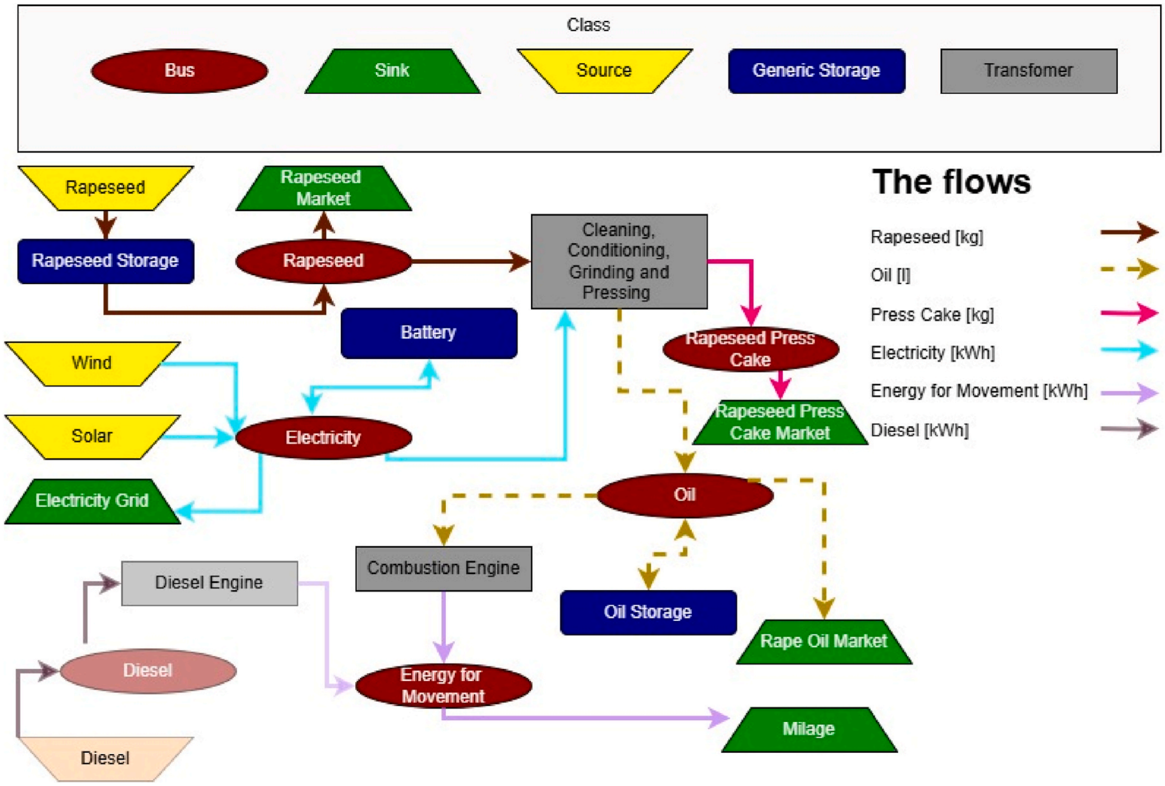

Fig. 4. Schematic depiction of the simulated rapeseed oil production system in oemof [58].

rate of the European central bank, currently at 2.25 % since April 2025 [84]. Subsidies for individual components or systems are not integrated into the calculation of the component/system costs.

2.3. Sensitivity analysis

A sensitivity analysis evaluates how variations in inputs influence model outputs [85]. The most important and uncertain inputs of this simulation are the assumed costs. Here, each component's cost is individually adjusted by increasing from 10 % to 200 % in 10 % increments, and the simulation's resulting component sizes are recorded. To explore interdependencies, the analysis also examines how cost changes of the electrolyser – an exemplary component – affect the sizes of the other components in the system.

2.4. Land use

In addition to the economic analysis, land use is also examined in this study. The specific area used on each farm is considered, not considering the land area required for the biogas plant, electrolyser, and oil press, as it is considered insignificant compared to the land required for energy inputs. Therefore, the focus is laid on comparing the inputs required for production, including electricity from PV and wind power plants, rapeseed, and manure, which are determined by the optimization process instead.

3. Results and discussion

This study provides a comprehensive scenario analysis. However, the presentation of each single scenario in detail would go beyond the scope of this paper. Therefore, the main trends and findings have been pointed out and are reflected here.

To facilitate comparison and analysis, a base scenario was established as a reference point (see Fig. 1). It serves as a standard against which other adapted scenarios can be compared. The base scenario is set in Kiel, where conventional farming is practiced employing the four-element crop rotation. The specifications are applied to all three renewable fuels which are being examined.

3.1. Periodical costs

For a first assessment, the periodical costs of each alternative fuel option are compared to each other, as well as to changes in input parameters (location, cultivation and crop rotation). Fig. 5 provides an overview on the effects of the parameter variations for each fuel type. The figure is divided into three parts: a) rapeseed oil, b) biomethane and c) hydrogen. The costs are presented as PCo, which consider the total investment costs, the costs for operation and maintenance, lifetime, and split the costs into the costs per year (see formula (1)). Upon examining the differing scales and base scenario lines, it is evident that the annuities for rapeseed oil production fall within the lowest range (13–15 T€/a), followed by biomethane with annuities ranging from 50 to 57 T€/a. Hydrogen has the highest PCo, ranging from 75 to 88 T€/a. The dash-dotted line in the figure illustrates the costs that would have been incurred if the fuel demand had been met with conventional diesel fuel, assuming a price of 1.7 €/l [86], resulting in total costs of approx. 6360 €/a. Notably, diesel can be purchased at this price at a standard gas station. Although German farmers are entitled to a rebate of approx. 21 cents per litre, as subsidy from the state [40]. This analysis does not consider such or other subsidies. Should the state opt to support one technology, this would necessitate adjusted simulations.

A comparison of the cost ranges of the alternative fuels analysed in this study with the current diesel expenses reveals that the alternatives are not yet competitive. Notably, the use of diesel would be approx. 58 %, 89 %, and 92 % less expensive than constructing in-house fuel production systems for rapeseed oil, biomethane, and hydrogen respectively, when compared to the base scenario costs. Furthermore, the potential revenue generated from the sale of additional products produced by these facilities would not significantly alter the economic landscape. The rapeseed oil price is so low, that any potential earnings

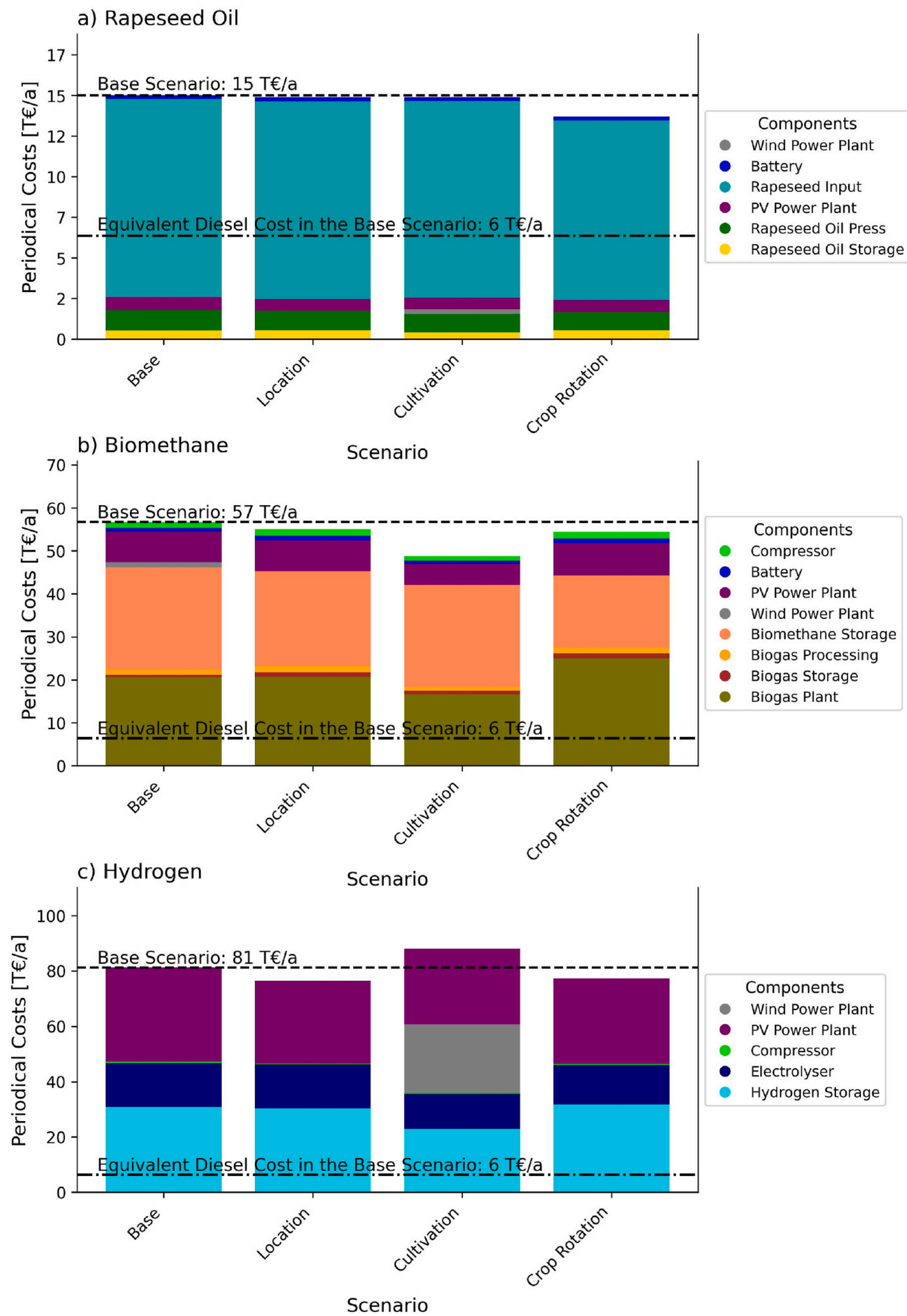

Fig. 5. Fuel and scenario-specific PCo for rapeseed oil, biomethane and hydrogen, including the cost distribution of the fuel specific components for the base scenario (location: Kiel, cultivation: conventional, crop rotation (rapeseed, maize, maize, winter wheat) and the adapted scenarios where one parameter is altered. Location: changed from Kiel to Munich, Cultivation: modification from conventional to organic, crop rotation: adaption from the crop rotation with four elements to the crop rotation with six elements as shown in Table 1. Please be aware of the varying scales of the subfigures.

from its sale would be negligible. In the case of biomethane, annual earnings of approx. 1800 € could be realized, but this would not substantially alter the picture. Similarly, the sale of additional hydrogen would only generate around 730 € per year.

3.1.1. The base scenario

Analysing the individual components reveals the primary cost drivers for each fuel option. The leftmost bars in Fig. 5 represent the base scenario in its most cost-effective configuration.

The PCo of rapeseed oil production in the base scenario are primarily driven by the cost of rapeseed, which accounts for approx. 81 % of the total costs. Although not a component itself, the rapeseed inputs are considered as costs, as when they are used for fuel production the revenue for sale is lost. In total 39 % of the rapeseed harvested are consumed by the fuel production. Looking at the remaining PCo, the press has the highest share with approx. 8 %, followed by the PV power plant (5 %), the oil storage (4 %) and the battery (2 %). It needs to be considered that the actual sizes of the components are small. The press is able to produce approx. 22 kWh/h (2.6 l/h), which is very little and not available on the industrial market [81]. As the electricity is only used for the operation of the press, a PV power plant with a capacity of in total 11.5 kWp combined with a 3-kWh battery storage is the optimum in the base case. In comparison, the oil storage is quite large with a capacity of 3.6 m^3. However, as the storage is assumed to be made of intermediate bulk containers (IBC), the periodical costs of approx. 240 €/container [87], are low in comparison to the other components. To be cost comparative with diesel, the annual rapeseed oil production costs would need to reduce by approx. 60 %. As the main cost driver is the rapeseed input, a falling rapeseed price would be the only option to make this system competitive, if there is no increase of the current diesel price, due to shortages, rising CO_2 prices etc.

For biomethane production, manure is a necessary input that is assumed to be freely available from the dairy cattle on the farm as a by-product of milk production. The biogas plant's processing converts this manure into a more valuable fertilizer, achieving a higher nutrient retention [88]. The two key components are the biomethane storage (42 %) and the biogas plant (36 %) followed by smaller investments in PV (12.5 %) and wind power plants (2.3 %), biogas processing to methane (2.2 %), battery (1.5 %), biogas storage (1 %) and a compressor (2.5 %). Similarly to the oil scenario, the sizes of the individual components are small. The biogas plant produces approx. 19.4 kWh/h of biogas. Biogas plants sizes are usually measured in kW of the connected combined heat and power plant (CHP), not giving the amount of biogas produced. Therefore the size of this biogas plant is converted into kW producible by an imaginary CHP, which is, depending on the efficiency of the CHP a 5.4 kW_e to 9.1 kW_e plant [66]. A 507-kWh biogas storage is implemented. Therefore, the biogas processing unit can wash 51 kWh of biogas per hour, with a downstream compressor, which can compress the same amount of biomethane. The biomethane storage is large and can store 23,901 kWh of biomethane. Regarding the renewable energies, a 100 kWp PV and a 1.4 kW wind power plant in combination with a 10-kWh battery storage complete the biomethane production system. To be a cost competitive solution compared to diesel, the costs of the components would need to reduce by approx. 90 % or the price to purchase diesel would need to rise by 9.5 times.

For the hydrogen production system, renewable electricity plays a crucial role. As such, the PV power plant has the highest share of the PCo at 42 % with an approximate size of 480 kWp. Surprisingly, in the high wind area of Kiel in this scenario the optimal solution does not consider the build-up of wind turbines. The second highest PCo is associated with the hydrogen storage, accounting for 38 % of the total PCo and having a capacity of approx. 20,600 kWh, which is equivalent to a volume of 26 m^3 at 350 bar (800 kWh/m^3 [89]). The electrolyser accounts for 19.6 % of the PCo and has a capacity of 41 kW electric producing approx. 26 kWh of hydrogen per hour. The remaining components play a minor role in terms of PCo. The water filtration system is not shown in Fig. 5 as it accounts only for 0.07 % of the PCo while processing 10.4 L per hour. The compressor can process approx. 26 kWh of hydrogen per hour and accounts for 0.4 % of the total PCo. As hydrogen is the most expensive technology in this comparison, the annual production costs would need to be reduced by 93 % or the diesel price would need to increase by 13.5 times. However, the PV power plant is the highest cost driver, and many farms already have a PV power plant installed, which is currently losing the compensation for electricity fed into the grid by the German state, as it is only temporary. These power plants could be used for hydrogen production and thereby significantly reduce the total investment costs.

3.1.2. Location

One variation of the base scenario is the change in location from the area around Kiel, a city in northern Germany, to Munich, which is approx. 850 km south. This alteration in location leads to different weather conditions, integrated in the simulation. The irradiation in Munich is increased by 16 % compared to Kiel, while the amount of wind is reduced by approx. 44 %. As a consequence, new optima emerge for investments in PV and wind power plants as well as batteries. The annuities for this scenario are depicted in Fig. 5 with the second bars from the left, for the respective fuel in a) to c).

Regarding rapeseed oil production, a change in location has only a minor influence on the PCo. The share of renewable energies in overall PCo is small, and reducing PV by 1 kWp has no significant impact as well as the reduction of press size by 5 %, due to the more constantly available irradiation and thereby electricity. The amount of rapeseed needed for production remains the same, but weather conditions differ between locations. This leads to varying rapeseed yields per ha. However, there is no clear picture showing an increased yield at one location compared to another, when averaging yields from 2018 to 2023 [90].

Fig. 5 b) shows the biomethane production system PCo for two scenarios: the base scenario (leftmost bar) and the scenario in which the farm is located in Munich. The location of the farm has little influence on the optimal sizing of the system, but does lead to some changes due to the electricity usage in the compressor etc. Overall, costs are reduced by approx. 2.8 %. A key difference between the two scenarios is the size of the methane storage, which is reduced by 7 % in the Munich scenario. This is because the higher availability of solar irradiation allows for better timing of biogas plant operation, making a smaller methane storage sufficient. Additionally, there is no wind power plant in the Munich scenario, and the PV power plant has a similar size to the base scenario but with a 36 % increased battery size.

When producing green hydrogen, the renewable power plants play a significant role, and therefore, the location of the farm has a major impact on the total PCo. In the case in which the farm is located in Munich the total PCo are reduced by 7.5 % compared to the base scenario. This reduction is mainly caused by the decrease in size of the PV power plant by 13 %. The higher solar energy production during spring and autumn allows for a better adaptation of hydrogen production to demand, resulting in a reduction of approx. 2 % in the size of the hydrogen storage. Notably, no battery is used in either of the scenarios.

3.1.3. Cultivation

The second variation of the base scenario is a change in cultivation method, which has a minor impact on the total amount of fuel needed, with a slight decrease of approx. 0.5 %. However, this change affects the timing and peak demands of the fuel and particularly during harvest time the peak is lower. The demand in spring and autumn time becomes more continuous. The influence on the respective investments per fuel is depicted in the third bar from the left in Fig. 5.

When comparing rapeseed oil production under conventional versus organic cultivation methods, there are only minor changes in the PCo. The main differences are a 0.5 % reduction in the amount of rapeseed needed for the production in the organic case, and an investment in a wind power plant combined with a reduction in the PV power plant and battery size. This is most likely due to the higher demand for electricity during spring and autumn months under organic cultivation. However, the share of the respective components is minor, meaning it has no major influence on the total PCo.

For biomethane production, switching to organic cultivation has a significant impact, reducing the total PCo by approx. 14 %. The biomethane storage and the biogas plant are the main cost drivers, and their sizes are affected by this change. The size of the biogas plant decreases by 19 %, while the methane storage is not influenced. However, the lower peak demands allow for a smaller biogas plant to meet these needs. Furthermore, the organic cultivation method eliminates the need for a wind power plant as the fuel consumption aligns better with solar irradiation, while the PV plant can be reduced by 32 %.

For hydrogen production, switching to organic cultivation has the opposite effect compared to biomethane production, increasing the total PCo by 15 %. This increase is mainly due to the addition of a small wind power plant with a capacity of 27.5 kW, which is necessary to account for the changed energy demands. As renewable energy is the only input for the electrolyser, the production is dependent on weather conditions. The organic cultivation method leads to higher demand in spring and autumn, and reduced peaks in summer. As a result, the sizes of the electrolyser and PV power plant are reduced by 20 %, while the hydrogen storage is even reduced by 26 %. However, the reductions in PCo are outweighed by the increased costs of the additional wind power plant.

3.1.4. Crop rotation

The last variation of the base scenario involves changing crop rotation from four elements (rapeseed, twice maize and winter wheat) to a new crop rotation with six elements (rapeseed, thrice winter wheat and twice maize). This change has a significant impact on the fuel needed for cultivation, as each crop has specific fostering demands. The second crop rotation results in approx. 9 % lower fuel demand due to slightly shifted and lower peak demands. The harvesting periods of rapeseed, winter wheat, and maize are staggered throughout July and September. As a result, the PCo for all three fuel production systems decrease in this scenario (see Fig. 5, rightmost bar).

For rapeseed oil production this has the highest impact on the calculated PCo. The reduced fuel consumption leads to a corresponding decrease in the amount of rapeseed needed for production, with a linear reduction of 9 %. However, since all components of the system account for less than 20 % of the annual costs, due to the high influence of the rapeseed need, the adapted investments are not significant.

For biomethane production, the total PCo are reduced by approx. 4.5 %. The most significant reduction is seen in methane storage size, which decreases by about 30 %, due to the reduced peak fuel consumption and changed fuel consumption distribution throughout the year. Other components also change, with a notable increase of 118 % in the biogas storage size, but this has a minor impact on the overall periodical costs.

For hydrogen the total PCo are reduced by 5 %. This reduction is due to the linear decrease of 9 % in all components except for the hydrogen storage. The hydrogen storage size increases by 2 %, which has a significant influence on the overall PCo. The reason for this increase is the misalignment between consumption and solar irradiation, when no battery is used. This leads to a need for a larger hydrogen storage to ensure that production can keep up with demand.

3.2. Range of the component sizes

In the previous section, the influence of individual parameters was described in detail. However, the simulation was conducted for a much broader range of options. Fig. 6 provides an overview of the component size ranges for each energy system, highlighting the most crucial components. The red point indicates the size of the respective component in the basis scenario, while the black point represents the average size of the component across all scenarios. If the black point is not visible, it is because it overlaps with the red point. The grey bar illustrates the range of component sizes, with percentages at the edges of the bar indicating

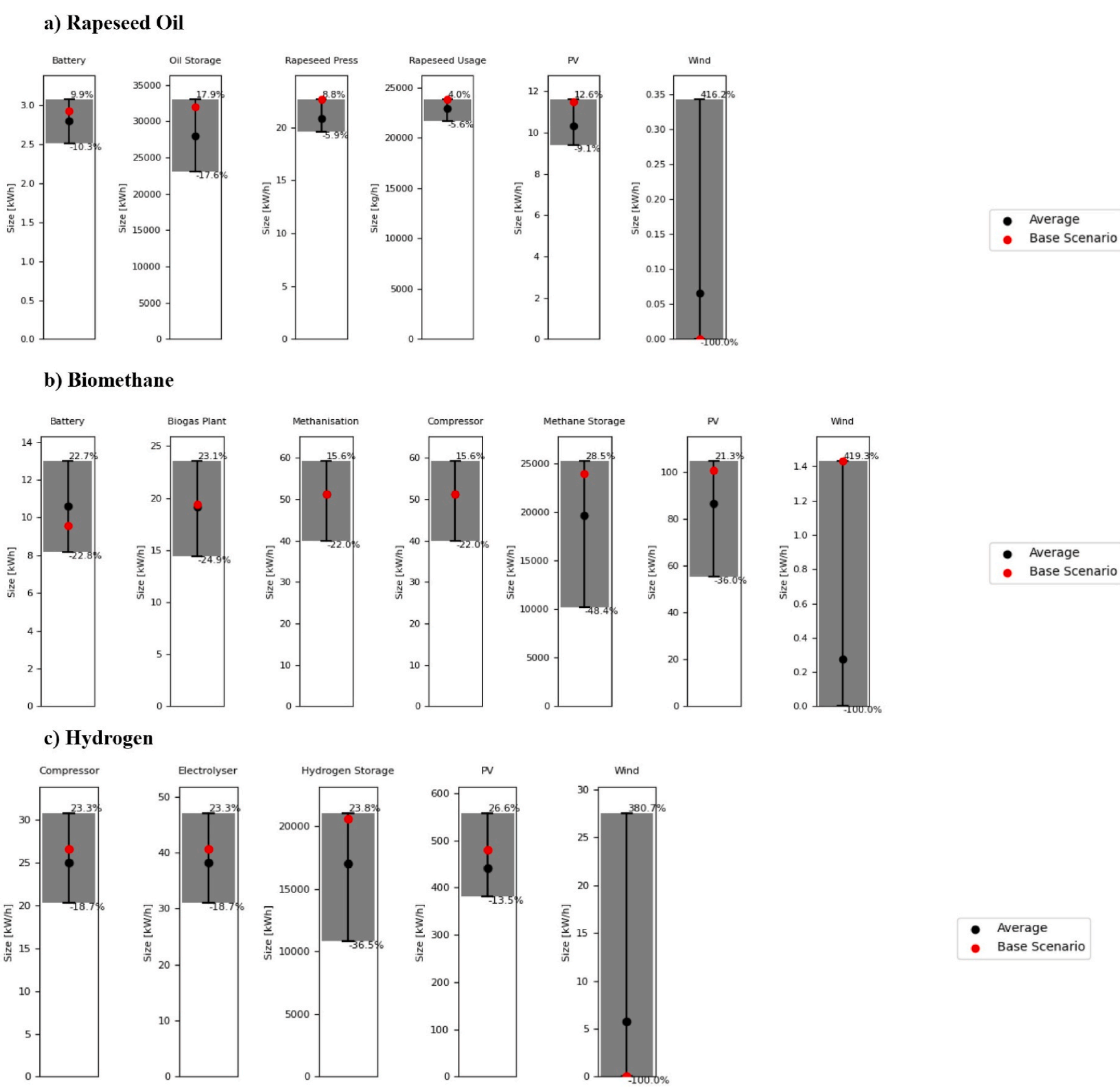

Fig. 6. Overview on the component sizes variation regarding all simulated scenarios. The red point depicts the base scenario and the black point the average over all the scenarios. The grey bar shows the variations, while the percentages give an indication of the minimal and maximal deviation from the average. The size refers to the respective provided energy of the component per hour or the storage capacity.

the deviation of the minimum and maximum size from the average. The size refers to the respective provided energy of the component per hour or the storage capacity.

Fig. 6 reveals that, across all examined scenarios, all depicted components are consistently used, except for the wind power plant, which is rarely invested in, as indicated by the low average point. However, when an investment in wind power does occur it tends to be at the upper end of range, which is, when looking at the scales, with a maximum of 27 kW in the hydrogen scenario, very small.

Examining the rapeseed oil figures in section a) of Fig. 6, it is evident that the base scenario consistently exceeds the average point, with the notable exception of no investment in a wind power plant. The component size ranges are relatively narrow, particularly for the rapeseed input, which is considered as component and is linearly dependant on the fuel demand. Similarly, for the PV, battery, oil storage and press exhibit limited variability, with a maximum deviation of 18 % from the average. The oil storage component displays the highest variability. Likely due to its status as the cheapest component per unit in this energy system.

In the biomethane scenario, the most striking observation is that the base scenario and average values coincide for the biogas plant, the biogas processing and the compressor. In contrast, the base scenario values for methane storage, PV and wind size exceed the average, likely due to the high fuel demand in this scenario. The battery size in the base scenario is below the average, as the relatively large PV and wind power plants reduce the need for electrical storage.

In the hydrogen system, a pattern similar to the other scenarios emerges, with the base scenario component sizes exceeding the average values across all scenarios. Notably, the hydrogen storage size is nearly at the maximum of the range. No wind power plant is used in this scenario.

3.3. *Sensitivity of the model to periodical cost adaptations*

The PCo are assumed based on various literature sources. However, in real-life, a price reduction (e.g. due to economies of scale) or increases in PCo (e.g. due to rising material costs or to inflation) can occur. Therefore, an analysis of the reaction of the optimization system's response to changes in prices of single components (ranging from −90 % to +100 % of the assumed price, in 10 % increments of the assumed PCo) is conducted. All components that are available for investment across all systems (PV, wind and battery) are analysed as well as core components of the systems. For the oil production, these include the oil press and oil storage; for the hydrogen systems the electrolyser and hydrogen storage; and for the biomethane system the biogas plant, biogas cleaning unit, and biogas and methane storage. The main goal of the optimization is in the sensitivity analysis as well as in the other simulations to meet the assumed fuel demand. The respective sensitivities are depicted in Fig. 7 a) to c), while d) illustrates the effects of changing the PCo of one component (exemplified by the PCo change of the electrolyser) on other important components of the system.

Regarding rapeseed oil, as depicted in Fig. 7 a), it is evident that the battery, PV and oil press exhibit similar behaviour. A 90 % cost reduction leads to an increase in size ranging from 90 % to 120 %, whereas a

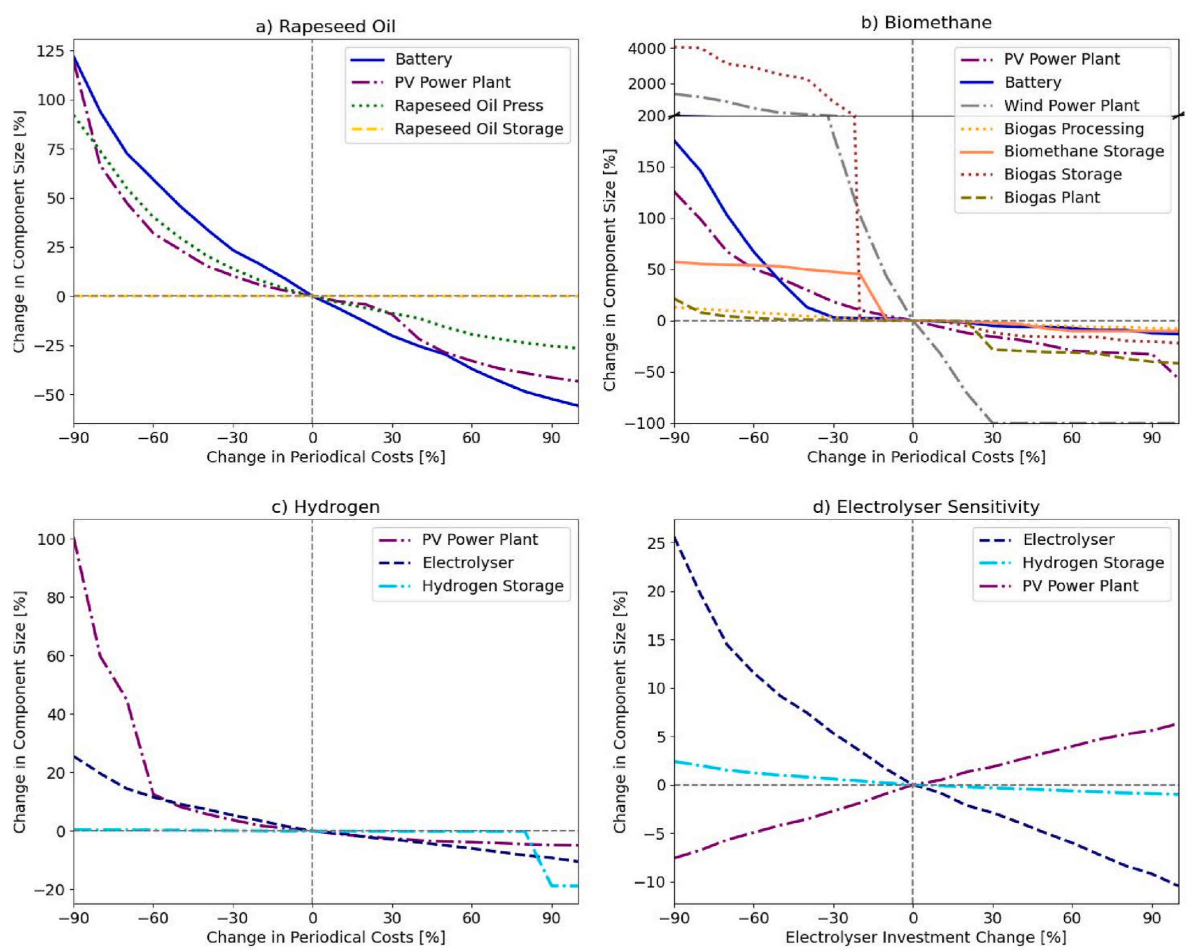

Fig. 7. Sensitivity analysis for the variation of periodical costs regarding the different fuel types a) rapeseed oil production b) biomethane production and c) hydrogen production whereas d) represents exemplary the effects of the periodical cost variation of the electrolyser in the hydrogen production on the other components in the respective system. Please be aware of the varying scales of the subfigures.

100 % increase in cost results in reduced sizes of 25 %–55 %. In contrast, the oil storage is relatively economical, and the percentage change in costs does not lead to a noticeable change in size. The wind power plants behaviour could not be displayed, as there is no wind power plant constructed at the assumed costs. Nonetheless, when the costs are sufficiently low, a wind power plant is indeed built. Specifically, at 10 % of the original costs, a 4-kW plant is constructed, whereas no wind power plant is built when the costs reach 90 % of the original PCo or higher.

The biomethane system is illustrated in Fig. 7 b). To enhance the figures expressiveness, the y-axis has been broken to display two different scales. Notably, the wind power and biogas storage exhibit extremely large sizes, exceeding 1000 %, when the costs are reduced by 90 %, as they are dimensioned very small in the first place. As the wind and PV power plants are the two alternatives for electricity production, this significant increasement in the size of the wind power plant leads to a corresponding 70 % reduction in PV capacity. Conversely, when the PCo are 30 % higher than assumed, the optimal system no longer includes a wind power plant. The biogas storage serves as buffer between the biogas plant and biogas processing into biomethane. Interestingly, when the costs are reduced to 10 % of the original value, the biogas storage's increased size results in a 50 % smaller biogas plant and a more continuous biogas production throughout the year. In contrast, the remaining components exhibit much lower inclinations, with the biogas processing and the biogas plant demonstrating a relatively minor response to price reductions.

Examining the hydrogen system (Fig. 7 c)), it is evident that the PV power plant exhibits the highest inclination rate. Notably, the wind power plant as well as the battery are not depicted, as they are only constructed, when the prices reach 40 % or 80 %, respectively, of the assumed prices. In contrast, the hydrogen storage is relatively insensible to changes in PCo, similar to the oil storage. A size reduction of 20 % occurs only when the PCo are increased by 90 %.

The effect of electrolyser size on other system components is illustrated in Fig. 7 d). As the electrolyser size increases, the required PV capacity decreases. This is because the electrolyser can more efficiently utilise periods of high solar irradiation, resulting in a slight increase in storage requirements.

It is striking to note that cost reductions generally have a more significant impact than equivalent cost increases. This suggests that the system components are already near their minimum required size to meet the demand, indicating, that further reductions in size would not be feasible without compromising performance.

3.4. Degree of utilization of the components

While the previous sections focused on investment optimization, this does not provide insight into the degree of capacity utilization throughout the year. Table 3 provides an overview of the percentage of the hours per year during which the core components of each system are utilized, as well as the percentage of the capacity utilization when in use. This is presented for both options: self-consumption and additional selling.

An examination of Table 3 reveals that the hours of usage and capacity utilization of the production units increase when the fuel is produced not only for self-consumption but also for sale on the market. This trend is most pronounced for the biogas plant, where manure is constantly supplied at no cost and electricity demand is relatively low. Additionally, the presence of a battery allows for bridging periods with no solar irradiation or wind. This usage pattern appears more realistic, as biogas plants cannot be started up quickly or frequently due to the fact that the microorganisms involved in the process cannot be simply switched on and off [91]. The electrolyser's operating hours are constrained due to the absence of wind power plants and the reliance on PV power plants without battery storage. Consequently, hydrogen production is limited to the periods with solar irradiation, which account for approximately 52 % of the hours in a year. In the two other scenarios (biomethane and rapeseed oil) there are batteries and partially wind power plants available to extend the operating hours.

Table 3
Overview on the capacity utilization of the single components as comparison between the only self-consumption and the surplus selling for the basis scenario.

	Self-Consumption		Self-Consumption and Sale	
	Hours in use during the year [%]	Mean capacity utilization [%]	Hours in use during the year [%]	Mean capacity utilization [%]
Oil Press	51 %	84 %	57 %	84 %
Oil Storage	82 %	47 %	48 %	23 %
Battery	31 %	42 %	33 %	60 %
Biogas Plant	57 %	57 %	94 %	80 %
Biogas Storage	54 %	54 %	42 %	76 %
Biogas cleaning	34 %	34 %	57 %	55 %
Methane Storage	57 %	57 %	42 %	39 %
Electrolyser	46 %	50 %	52 %	56 %
Hydrogen Storage	82 %	39 %	58 %	32 %

Fig. 8 shows the hydrogen storage levels throughout the year for the self-consumption-only scenario.

It is evident that the storage is necessary, particularly during harvest time when fuel demand is high. The figure illustrates that this is a long-term storage with minimal fluctuations. High seasonal peaks in hydrogen demand occur during autumn, particularly coinciding with harvest activities, when solar irradiation has already declined. Consequently, energy must be stored over extended periods – often several months – requiring seasonal storage capacity. In contrast, battery storage is typically used for daily charge and discharge cycles, enabling more stable, day-to-day hydrogen production. However, batteries alone cannot address the seasonal imbalance between solar availability and demand. Therefore, even with battery integration, a hydrogen storage system remains essential for seasonal buffering. This explains the absence of battery investment in the hydrogen-based scenario, as the primary storage challenge is seasonal rather than daily. In contrast, the battery storage in the oil system is subject to daily charging and discharging, depending on the photovoltaic electricity production. Connecting to the grid would make hydrogen production less weather-dependent, potentially leading to reduced storage capacity requirements and increased electrolyser usage times.

3.5. Land use

In addition to economic aspects, other factors such as land use are crucial when evaluating fuel alternatives. Fig. 9 provides an overview of the land needed for production, focusing only on the land used directly at the farm, including e.g. PV power plants or the area used for rapeseed cultivation. Land use is considered in relation to the total land available per farm, which is 100 ha.

For the hydrogen production option in the base scenario, very little land is required, with about 2570 m^2 needed for PV power plants. This represents a relatively small percentage of the total land available, around 0.26 %. Additionally, previous research [10] shows that many farms already have existing PV power plants (e.g. on rooftops) or potential ones, without reducing their agricultural area.

For the biogas scenario, the land needed for PV is lower compared to other options, as it is not the main driver of land use. The production of manure has the highest influence on land use in this scenario. The calculation of the area needed to produce manure is based on the number of dairy cattle required to generate that amount of manure, assuming that the manure itself is the primary product of interest. The analysis only considers the area needed on the farm to produce the basic

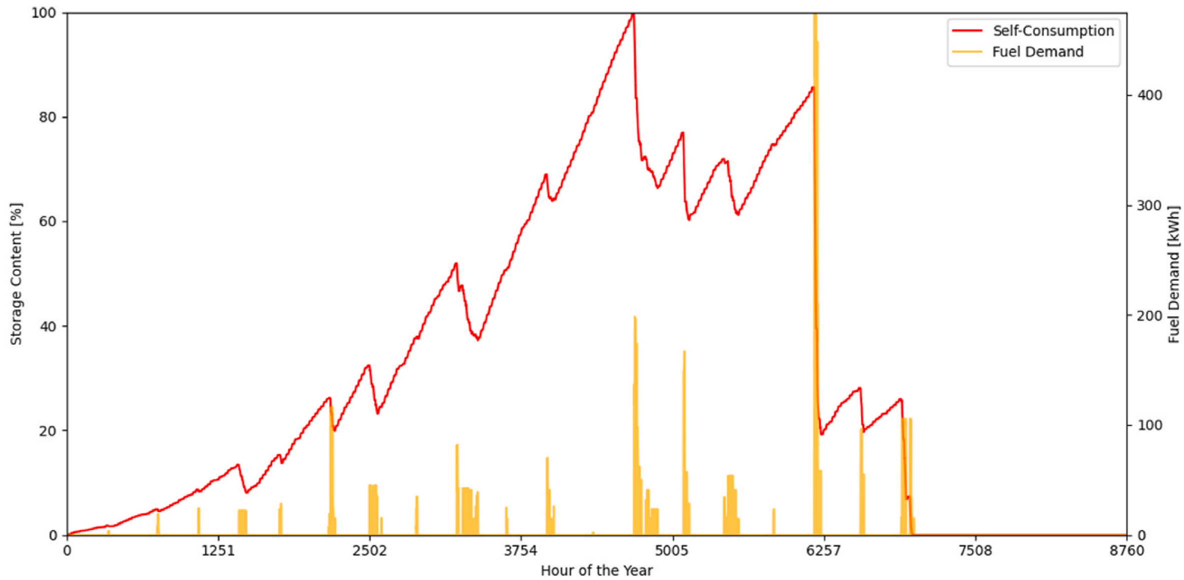

Fig. 8. Hydrogen storage content and fuel demand of the base scenario in the course of the year (starting at the 01st of January) for the self-consumption of hydrogen.

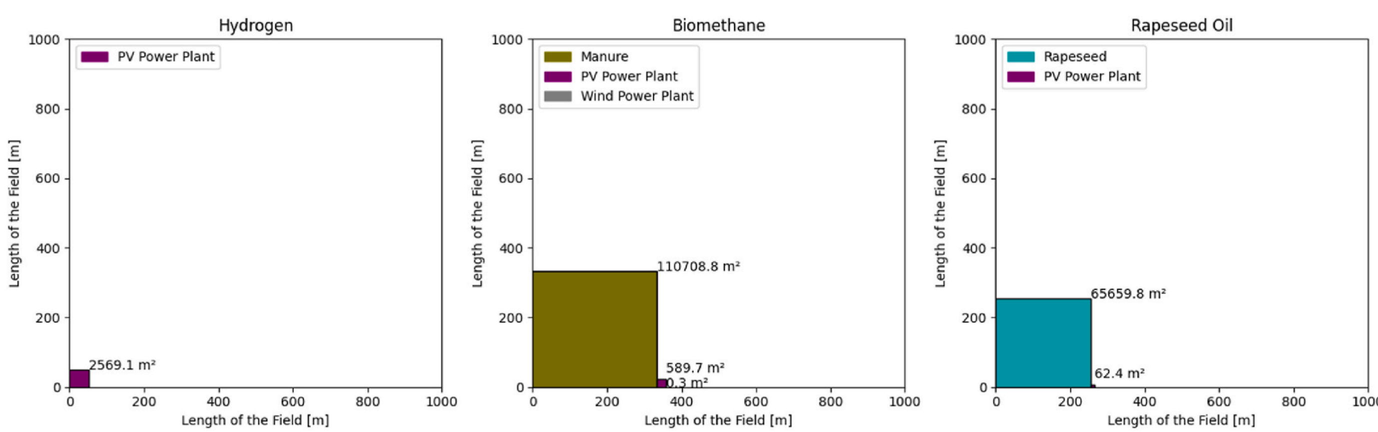

Fig. 9. Land use comparison of the average of all scenarios for the three fuels, hydrogen, biomethane and rapeseed oil.

feed for the dairy cattle, and does not account for areas in other parts of the world where the raw material for concentrated feed is produced. Taking this into consideration, biogas emerges as the least area-effective option, with a total area usage of approx. 11 % of the available land.

For the rapeseed oil scenario, the largest land requirement is the cultivation of the rapeseed, accounting for approx. 6.5 % of the total farm area. In all scenarios the land required can be met with the rapeseed production, without needing to buy additional rapeseed. The area needed for solar energy production is negligible at 62 m^2.

Comparing the three fuel options shows that hydrogen has the least impact on the land use. When the PV is built for example as an agri-voltaic system, the land use minimizes even further [92]. This is particularly important to consider, as studies indicate that suitable land for agriculture is not uniformly available across all regions [93].

3.6. Discussion

A review of the research question reveals that for economic aspects, oil produced from rapeseed is consistently the most profitable alternative to diesel in all scenarios. This aligns with the existing number of decentralized rape oil mills in Germany, which was at 585 in 2007 [94]. Additionally, retrofitting tractors to use rapeseed oil is already a viable option in practice [25]. However, the tax reduction of agriculturally used diesel is not accounted for in this study, which would further reduce the diesel price by an average of 21 cents per litre [95]. This advantage is unique to diesel and not applicable to other fuels like rapeseed oil. Furthermore, Germany currently imports rapeseed, as consumption exceeds production. This means that an increased demand from farmers producing their own fuel could drive up rapeseed costs, making the use of this fuel less advantageous or reduce the available land for the production of other crops.

Fig. 5 highlights the influence of the location, cultivation and crop rotation on the PCo of the different fuel options. Looking at the rapeseed oil PCo, they are influenced only slightly by these factors. The most important cost driver is the rapeseed input, which remains constant as long as fuel consumption does not change. Therefore, crop rotation has the greatest impact on rapeseed PCo. Regarding hydrogen, the location has the highest influence on the PCo, primarily due to high electricity needs and the differing efficiency of the renewable energies due to changes in weather conditions. For biomethane, cultivation is the most significant factor, driven by the reduced peak demands.

The land required for hydrogen production is extremely small, mainly due to the fact that only land is needed for PV and wind power plants. In comparison, the area required for hydrogen production is less than 1 % of the areas needed for the other alternatives. The area needed in biomethane production is based on the amount of basis feed produced on the farm to feed dairy cattle, where the focus is on manure as the primary product.

Other studies have typically focused on a single fuel concept without comparing different diesel-replacing fuel options. However, some studies like Remmele et al. (2014) [23] have explored expert opinions, which suggest that combustion engines using biodiesel and plant oil are seen as the future. This is consistent with the present study's findings on economic aspects, which show that rapeseed oil is the most economical alternative. Additionally, Böhm et al. (2024) [39] found that wind and PV have the least impact on the land use and GHG emissions compared to biogas. These findings are confirmed by the present study, which extends the analysis to include rapeseed oil and focuses specifically on fuel production.

The simulation presented in this study employs oemof, a linear optimization framework, to determine the optimal system configuration. The model calculates this configuration based on demand profiles, which are derived from the assumptions regarding the farm's operational schedule and the diesel calculations provided by the KTBL [59], as well as the assumed cost parameters. Variations in these cost parameters may influence the selection of component sizes, as demonstrated in section 3.3. However, the simulation does not explore alternative system designs – such as varying types of rapeseed presses or different electrolyser configurations – primarily because incorporation of such variations would extend beyond the scope of this study. While such alternatives exist, their inclusion would not significantly alter the core findings, as the optimization remains constrained by the fixed demand requirements and the absence of external fuel sources. Consequently, the results exhibit only marginal variability, as the system must fulfil demand under the given assumptions without relying on supplementary inputs.

The results of this study are based on various assumptions, particularly regarding costs. The assumed costs are today's costs, as predicting cost development in future years is challenging due to uncertainty and variability of market conditions. The large consequences of changes in cost of the single components were analysed in section 3.3. Where the sensitivity analysis shows, that cost reductions generally have a higher impact on the component sizes than equivalent cost increases. This suggests that the system components are already near their minimum required size to meet the demand, indicating, that further reductions in size would not be feasible without compromising performance and the fulfilment of the fuel demand.

Some market trends could be observed apart for the results of the study: biogas and oil plants have already been built and are operational. In contrast, hydrogen technology is still in earlier stages and has not yet achieved widespread adoption, so it is expected to benefit from economies of scale as the industry grows [96]. In terms of economic aspects, there are further opportunities for cost reduction: oil production generates press cakes as a by-product (this would reduce the PCo by approx. 3600 €/a, when assuming a selling price of 250 €/t [97]), which can be sold as protein feed for animals. However, the transport can reduce the profit. Similarly, hydrogen production generates oxygen as a by-product, which could also be used or sold to reduce costs. Nevertheless, there are no oxygen demands on the farm site and transportation is very expensive so most oxygen usages focus on the on-site usage [98]. Furthermore, subsidies by the state could also shift the picture.

Farms already have experience with collaborative arrangements, such as machinery rings, in which they pool resources to purchase expensive equipment and share its use. A similar concept could be applied to renewable fuel production. This collaboration could lead to several benefits. Increased demand would drive up production volumes and reduce costs per kWh. Larger system sizes can be more efficient and cost-effective than smaller ones. Additionally, higher utilization rates for machinery would be achieved, as the optimal sizes calculated by the simulation are relatively small compared to typical system sizes.

The optimal system sizes calculated by the simulation may not be readily available on the market, so in a real-life implementation, it would be necessary to adapt the sizes to larger and more realistic values. This could increase PCo. Additionally, some environmental aspects were not considered, as for example the usage of water, e.g. the water consumed by the plants. This aspect requires further investigation, as highlighted by Azma et al. (2021) [99], who emphasise the importance of locally specific groundwater availability in assessing the feasibility of such systems.

Additionally, the analysis of storage usage in section 3.4 reveals that the final product storages are long-term storages, providing the opportunity to store the required fuel for peak demands during harvest time. Integrating the fuel production system into the farm's overall energy system, taking into account electricity and heat demand, or collaborating with another entrepreneur with a more consistent fuel demand could significantly increase the utilization of the production units and lead to lower prices per unit.

This study focussed on a single average farm, but it is also important to consider the applicability of these fuel concepts for the entire country. In Germany, approx. 2 billion litres of diesel are used every year in the agricultural sector [15]. Converting this to alternative fuel concepts, when incorporating the efficiency of the respective fuel, we get: 2.07 billion litres of rapeseed oil, 20.4 billion kWh of biogas or 12.2 billion kWh of hydrogen. This would translate into a significant increase in land use for rapeseed production, exceeding the current amount of rapeseed produced in Germany by approx. 35 % and covering more than 1.6 million ha [90]. The PV required for hydrogen would cover around 61, 250 ha, while biomethane would require around 70 % of Germany's dairy cattle manure (considering the calculations of section 3.5, this is equivalent to 2.5 million ha of land for basis feed of the cattle, with conventional farming and 2.3 times the size for organic farming), with Germany having a total agricultural area of approx. 17 million ha for agricultural usage [100].

This leads to the conclusion that rapeseed oil might seem to be the most cost-effective option, but it is no feasible solution for every farm as the demand would exceed the produced amount and lead to shortages e.g. for rapeseed in nutrition and land transformation towards monoculture. Thereby, the assumed prices are expected to increase as well. This would lead to considerable discussion about plants used for nutrition versus plants used for transportation purposes. This could especially be the case as the demand for rapeseed oil could only be met with German production by 48 % in 2022 [101].

Regarding biomethane, if effectively used, the amount of dairy cattle in Germany could meet the demand of the agricultural machinery and would simultaneously upgrade the manure. However, there is a trend towards a decreasing number of cattle [102], which could lead in future to a gap between production and demand for manure. Additionally, arable farms without animals do not have the option to use their own manure and would need to buy the required biogas. Approximately one third of the manure produced in Germany is already used in biogas plants. Currently, there are 9600 biogas plants operating in Germany, producing 5600 MW of electricity [103]. However, retrofitting these existing plants to produce biomethane for fuelling purposes seems unlikely, especially considering that many of them already have accompanying CHP plants to produce electricity.

For hydrogen production, less area is needed. Furthermore, the simulation mostly considered electricity production via PV power plants, but wind is even more land efficient [39]. In addition to that, there are many old and new PV concepts that do not or only minimally use agricultural land – usage on rooftops, agrivoltaics [104], floating PV [105] etc.

4. Conclusion

In a nutshell, either a mixture of all the three renewable fuel options should be used or the focus should be upon biomethane and hydrogen, as hydrogen is very land efficient and there is enough manure at the moment to meet the fuel demand with biomethane. Rapeseed oil is the most economic option; however, the demand could not be met with the existing rapeseed production. None the less, a system with one single fuel, as it is right now with diesel, has several advantages, e.g. compatibility between different farms, as well as single structures for exchange and transportation. Therefore, hydrogen seems to be the best option as it is producible by any farm type (with animals or without) and faces the smallest land competition due to efficient PV and wind power plants. However, battery storages are important to increase the operating hours of the electrolyser during the year and make it more independent of the irradiation and wind available. With economies of scale and rising prices for fossil fuels, it can become more economically attractive in future. Furthermore, it can be post processed into synthetic fuel. This approach would allow for a gradual transition to a more sustainable energy source while minimizing disruptions to existing infrastructure and operations.

5. Outlook

This research provides a solid base for future studies, which could extend the topic in several ways. For instance, the simulation could be expanded to include not only fuel demand but also heat and electricity, creating a more comprehensive, sector integrating concept. Additionally, by focusing on individual farms, this study provides a valuable basis for exploring community-based energy production concepts with shared resources, which could potentially lead to higher profitability.

CRediT authorship contribution statement

Lea von Rüden: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Barbara Satola:** Writing – review & editing, Project administration, Conceptualization. **Michael Kröner:** Writing – review & editing, Supervision, Project administration, Conceptualization. **Martin Vehse:** Writing – review & editing, Supervision, Conceptualization. **Alexander Dyck:** Supervision. **Carsten Agert:** Supervision.

Usage of generative AI

The authors utilized Generative AI technologies for language optimization during the preparation of this work. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix 1. Overview on the periodical costs of the different components of the systems and the costs for the fuels

Component	CAPEX Source	Unit	OPEX Source	Unit	Year	Source	Lifetime [years]	Source	Factor	Unit	Source	Cost [€/kWh] Reference year	Cost [€/kW] 2020	Cost [€/kW] 2024
Diesel	–	–	1.771	€/l	2024	[86]	–	–	9.96	kWh/l	[106]	0.18	0.14	0.18
Green Hydrogen 350 bar	–	–	9	€/kg	2023	[107]	–	–	33.33	kWh/kg	[108]	0.27	0.22	0.28
PV	900	€/kW	13.3	€/kW	2024	[109]	30	[110]	–	–	–	913.30	737.03	913.30
Wind	6250	€/kW	3750	$€/kW_{lifetime}$	2021	[111]	20	[112]	–	–	–	10,000.00	9690.00	11,560.17
PEM Electrolyser	2503	€/kW	50.06	$€/kW_{year}$	2024	[96]	20	[113]	–	–	–	3504.20	3146.77	3504.20
Li-Ion Battery	1000	€/kWh	0		2022	[114]	12.6	[115]	–	–	–	1000.00	898.00	1071.31
Compressor	3800	€/(kg/h)	114	€/(kg/h)a	2024	[116]	20	[116]	33.33	kWh/kg	[108]	182.42	147.21	182.42
Hydrogen Storage	450	€/kg	–	–	2024	[116]	20	[116]	33.33	kWh/kg	[108]	13.50	10.90	13.50
Rape Oil production - decentral	1320.416	€/(kg/h)	26.40832	€/(kg/h)	2007	[81]	14	[117]	3.5	kWh/kg Raps	[81]	1690.13 [€/kg]	1948.72 [€/kg]	2324.83 [€/kg]
Rape oil storage	0.41	€/l	–	–	2024	[87]	14	[117]	11.316	kWh/l	[81]	0.04	0.03	0.04
Manure Storage	136	€/m^3	–	–	2024	[118]	20	[119]	–	–	–	136.00	109.75	136.00
Manure Biogas Plant	7100	€/kW	284	€/kW	2017	[79]	16	[119]	–	–	–	11,644.00	12,063.18	14,391.38
Biogas Storage	450	€/kg	–	–	2024	[116]	20	[116]	33.33	kWh/kg	[108]	13.50	10.90	13.50
Methane	0.1197	€/kWh	–	–	2024	[120]	–	–	–	–	–	0.12	0.10	0.12
Biogas Processing	1300	€/Nm^3	39		2022	[121]	16	[119]	6.25	kWh/m^3	[66]	307.84	276.44	329.79
Methane Storage	450	€/kg	–	–	2024	[116]	20	[116]	33.33	kWh/kg	[108]	13.50	10.90	13.50
Water Filtration	45900	€/m^3	–	–	2020	[75]	20	–	–	–	–	45,900.00	45,900.00	54,758.70
Water Storage	410	€/m^3	–	–	2024	[87]	14	[117]	–	–	–	410.00	330.87	410.00
Rape Oil	1095	€/t	–	–	2024	[122]	–	–	10443841	kWh/t	[81]	0.000105	0.000085	0.000105

Appendix 2. Efficiencies of the utilized components

Component	Bus	Conversion factor	Unit	Source
Electrolyser	electricity	1	kWh	[75]
Electrolyser	hydrogen	0.6529	kWh	[75]
Electrolyser	Clean water	0.0005	m^3/kWh_e	[74]
Battery	inflow	1		[123]
Battery	outflow	0.8600		[123]
Water filtration	Tab water	1	m^3	[74]
Water filtration	Clean water	0.8	m^3	[74]

(*continued on next page*)

(*continued*)

Component	Bus	Conversion factor	Unit	Source
Water filtration	electricity	0		incorporated in electrolyser [75]
Water storage	inflow	1		
Water storage	outflow	1		
compressor	electricity	0.09	kWh	[76]
compressor	Hydrogen in	1	kWh	[76]
compressor	Hydrogen out	1	kWh	[76]
Hydrogen storage	inflow	1	kWh	
Hydrogen storage	outflow	0.98	kWh	
Fuel cell	hydrogen	1	kWh	[124]
Fuel cell	Fuel kWh	0.6	kWh	[124]
Diesel engine	Fuel kWh	0.4	kWh	[124]
Diesel engine	diesel	1	kWh	[124]
Manure storage	inflow	1		
Manure storage	outflow	1		
Biogas plant	manure	1	m^3	[78]
Biogas plant	electricity	3.44	kWh	[79]
Biogas plant	biogas	156.25	kWh	[78]
Biogas storage	inflow	1	kWh	
Biogas storage	outflow	0.98	kWh	
Methanisation	biogas	1	kWh	[80]
Methanisation	electricity	0.0001	kWh	[80]
Methanisation	methane	0.96	kWh	[80]
Methane storage	inflow	1	kWh	
Methane storage	outflow	0.98	kWh	
Methane engine	methane	1	kWh	[125]
Methane engine	Fuel kWh	0.42	kWh	[125]
Rapeseed storage	inflow	1		
Rapeseed storage	outflow	1		
Rape oil production	rapeseed	1	kg	[82]
Rape oil production	oil	3.5	kWh	[82]
Rape oil production	Press cake	0.66	kg	[82]
Rape oil production	electricity	0.06	kWh	[83]
Oil storage	inflow	1		
Oil storage	outflow	1		
Oil engine	oil	1	kWh	[126]
Oil engine	Fuel kWh	0.4	kWh	[126]

Data availability

Data will be made available on request.

References

[1] Bundesamt Statistisches. Primärenergieverbrauch. https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Umwelt/Glossar/primaerenergieverbrauch-inland.html; April 29, 2024.

[2] Crosson P, Shalloo L, O'Brien D, Lanigan GJ, Foley PA, Boland TM, et al. A review of whole farm systems models of greenhouse gas emissions from beef and dairy cattle production systems. Anim Feed Sci Technol 2011;166–167:29–45.

[3] Blázquez CS, Borge-Diez D, Nieto IM, Maté-González MÁ, Martín AF, González-Aguilera D. Geothermal heat pumps for slurry cooling and farm heating: impact and carbon footprint reduction in pig farms. In: Borge-Diez D, Rosales-Asensio E, editors. Heat energy recovery for industrial processes and wastes. first ed. Cham: Springer International Publishing; Imprint Springer; 2023. p. 221–43.

[4] Licharz H, Rösmann P, Krommweh MS, Mostafa E, Büscher W. Energy efficiency of a heat pump system: case study in two pig houses. Energies 2020;13(3):662.

[5] Ahlgren S, Baky A, Bernesson S, Nordberg Å, Norén O, Hansson P-A. Tractive power in organic farming based on fuel cell technology – energy balance and environmental load. Agric Syst 2009;102(1–3):67–76.

[6] Azizi K, Heidari S. A comparative study on energy balance and economical indices in irrigated and dry land barley production systems. Int J Environ Sci Technol 2013;10(5):1019–28.

[7] information.medien.agrar e.V. Der Treibstoff, der die Landwirtschaft am Laufen hält. https://www.ima-agrar.de/wissen/nachrichten/1159-der-treibstoff-der-die-landwirtschaft-am-laufen-haelt; July 10, 2025.

[8] Deutscher Bundestag. Bundes-Klimaschutzgesetz: KSG; 24.06. 2021.

[9] Statistisches Bundesamt (Destatis). Flächennutzung: bodenfläche insgesamt nach Nutzungsarten in Deutschland. https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Landwirtschaft-Forstwirtschaft-Fischerei/Flaechennutzung/Tabellen/bodenflaeche-insgesamt.html; February 08, 2024.

[10] Rüden L von, Satola B, Reininghaus N, Kröner M, Vehse M, Dyck A, et al. GIS-based technical analysis of the local renewable energy production potentials of farms in Germany. Renew Sustain Energy Rev 2025;212:115412.

[11] Bundesministerium der Finanzen. AfA-Tabelle für den Wirtschaftszweig "Landwirtschaft und Tierzucht". https://www.bundesfinanzministerium.de/Content/DE/Standardartikel/Themen/Steuern/Weitere_Steuerthemen/Betriebspruefung/AfA-Tabellen/AfA-Tabelle_Landwirtschaft-und-Tierzucht.html; April 15, 2024.

[12] Liu M, Li Y, Xu L, Wang Y, Zhao J. General modeling and energy management optimization for the fuel cell electric tractor with mechanical shunt type. Comput Electron Agric 2023;213:108178.

[13] Labeckas G, Slavinskas S. Performance of direct-injection off-road diesel engine on rapeseed oil. Renew Energy 2006;31(6):849–63.

[14] Labeckas G, Slavinskas S. Comparative performance of direct injection diesel engine operating on ethanol, petrol and rapeseed oil blends. Energy Convers Manag 2009;50(3):792–801.

[15] Remmele E, Eckel H, Pickel P, Rathbauer J, Reinhold G, Stirnimann R, editors. Alternative Antriebssysteme für Landmaschinen. Darmstadt: kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. (KTBL); 2020.

[16] Jordan T. Hydrogen technologies. In: Hydrogen safety for energy applications. Elsevier; 2022. p. 25–115.

[17] Stöhr M, Hackenberg B. Auslegung (semi-) stationärer Energiespeicher für leitungsgeführte vollelektrische Landmaschinen. München. 2018.

[18] Mileusnić ZI, Petrović DV, Đević MS. Comparison of tillage systems according to fuel consumption. Energy 2010;35(1):221–8.

[19] Khan FNU, Rasul MG, Sayem A, Mandal N. Maximizing energy density of lithium-ion batteries for electric vehicles: a critical review. Energy Rep 2023;9:11–21.

[20] Truck MAN, Bus SE. Powerful, versatile, quiet: the new MAN eTGS. https://www.man.eu/global/en/truck/all-models/the-man-tgs/the-man-etgs/overview.html; January 08, 2026.

[21] John Deere (Pty) Ltd. 6B series: tractors. https://www.deere.com/assets/pdfs/region-1/products/tractors/6B%20Brochure%202023.pdf; January 08, 2026.

[22] Kukharets S, Zabrodskyi A, Sheludchenko B, Jasinskas A, Domeika R, Šarauskis E. Assessment of changes in soil contact stress depending on tractor tire parameters. Sci Rep 2025;15(1):172.

[23] Remmele E, Eckel H, Widmann B. Regenerative Energieträger und alternative Antriebskonzepte für mobile Arbeitsmaschinen. 2014. p. 256–9. Seiten/LANDTECHNIK, Bd. 69 Nr. 5.

[24] Union zur Förderung von Oel- und Proteinpflanzen e.V. Pflanzenöl-Traktor mit Werksgarantie. https://www.ufop.de/biodiesel-und-co/rapsoel-kraftstoff/technik-und-infos/pflanzenoel-traktor-mit-werksgarantie/; June 19, 2024.

[25] Voegelin D. Dipl. Ing. Dieter Voegelin Bundesverband Pflanzenöle e.V. 2006. https://www.bv-pflanzenoele.dedv@landenergie.

infoUmrüstkonzeptefürTraktoren–StanddderTechnikundPerspektiven. BadSassendorf.
[26] Ettl J, Bernhardt H, Huber G, Thuneke K, Remmele E, Emberger P. Evaluation of pure rapeseed oil as a renewable fuel for agricultural machinery based on emission characteristics and long-term operation behaviour of a fleet of 18 tractors. SN Appl Sci 2020;2(10).
[27] Thuneke K, Gassner T, Emberger P. Rapeseed oil fuelled tractors - operation and emission characteristics. In: Kosutic S, editor. Actual tasks on agricultural engineering. PROCEEDINGS; 2009. p. 57–66.
[28] Dukulis I, Birkavs A, Birzietis G, Pirs V. Adapting of automobile VW golf for using pure rapeseed oil as fuel. In: Malinovska L, Mezote A, Kronbergs E, Nulle I, editors. International scientific conference. ENGINEERING FOR RURAL DEVELOPMENT; 2009. p. 141–7.
[29] Sanz Requena JF, Guimaraes AC, Quirós Alpera S, Relea Gangas E, Hernandez-Navarro S, Navas Gracia LM, et al. Life cycle assessment (LCA) of the biofuel production process from sunflower oil, rapeseed oil and soybean oil. Fuel Process Technol 2011;92(2):190–9.
[30] Bundesministerium für Landwirtschaft. Ernährung und Heimat. Ölsaaten. https://www.bmel-statistik.de/landwirtschaft/bodennutzung-und-pflanzliche-erzeugung/oelsaaten; January 07, 2026.
[31] Mathur S, Waswani H, Singh D, Ranjan R. Alternative fuels for agriculture sustainability: carbon footprint and economic feasibility. AgriEngineering 2022;4(4):993–1015.
[32] Muratcobanoglu H, Mert RA, Muratcobanoglu F, Gokcek OB, Demirel S. Biogas upgrade techologies and biomethane utulization oportunities. In: Bilgili MS, Demir A, editors. Proceedings of the 6TH eurasia waste management symposium. EWMS; 2022; 2022. p. 409–14.
[33] Göggerle T. Weltneuheit LNG-traktor tankt flüssiges biogas. https://www.agrarheute.com/technik/traktoren/weltneuheit-lng-traktor-tankt-fluessiges-biogas-601230; June 19, 2024.
[34] New Holland Agriculture a brand of CNH Industrial N.V. T6 Methane Power: Kraftvoll und Umweltfreundlich. New Holland DE, https://agriculture.newholland.com/de-de/europe/produkte/traktoren/t6-methane-power; June 19, 2024.
[35] Neuer Valtra. Biomethan-Traktor von VALTRA im Test bei LfL und TFZ. https://press.lectura.de/de/article/neuer-biomethan-traktor-von-valtra-im-test-bei-lfl-und-tfz/9138; May 13, 2025.
[36] Graham-Rowe D. Agriculture: beyond food versus fuel. Nature 2011;474(7352):S6–8.
[37] Neuland Monbiot G. Wie wir die Welt ernähren können, ohne den Planeten zu zerstören. first ed. München: Blessing; 2022.
[38] Woods J, Williams A, Hughes JK, Black M, Murphy R. Energy and the food system. Philos Trans R Soc Lond Ser B Biol Sci 2010;365(1554):2991–3006.
[39] Böhm J, Holzheid FM, Schäfer M, Krexner T. Life cycle assessment of electricity from wind, photovoltaic and biogas from maize in combination with area-specific energy yields – a case study for Germany. Environ Res Commun 2024;6(10):105022.
[40] Eder J. Agrardiesel: Können Traktoren auch mit Wasserstoff fahren?. https://www.agrarheute.com/technik/traktoren/agrardiesel-koennen-traktoren-wasserstoff-fahren-616294; June 19, 2024.
[41] Deutz AG. Technologie der Zukunft - in Serie: Deutz TCG 7.8 H2 - Wasserstoffmotor. https://www.deutz.com/de/produkte/wasserstoffmotoren/; March 24, 2025.
[42] Liebherr-International Deutschland GmbH. Liebherr-Raupenbagger mit Wasserstoffmotor feiert Weltpremiere. https://www.liebherr.com/de-de/n/liebherr-raupenbagger-mit-wasserstoffmotor-feiert-weltpremiere-27130-3704916; March 24, 2025.
[43] J C Bamford Excavators Ltd. Immer Auf Der Such Nach Noch Besseren Lösungen. https://www.jcb.com/de-de/campaigns/hydrogen; March 24, 2025.
[44] Süß H. Wasserstoff für Traktoren: was kann der alternative Treibstoff?. https://www.wochenblatt-dlv.de/feld-stall/energie/wasserstoff-fuer-traktoren-alternative-treibstoff-573043; June 19, 2024.
[45] Maganza A, Gabetti A, Pastorino P, Zanoli A, Sicuro B, Barcelò D, et al. Toward sustainability: an overview of the use of green hydrogen in the agriculture and livestock sector. Animals an open access journal from MDPI 2023;13(16).
[46] Janke L, McDonagh S, Weinrich S, Nilsson D, Hansson P-A, Nordberg Å. Techno-Economic assessment of demand-driven small-scale green hydrogen production for low carbon agriculture in Sweden. Front Energy Res 2020;8.
[47] Zhao S, Gao Z, Li X, Li Y, Xu L. Research on energy management strategy of fuel cell tractor hybrid power system. WEVJ 2024;15(2):61.
[48] Palmieri N, Forleo MB, Suardi A, Coaloa D, Pari L. Rapeseed for energy production: environmental impacts and cultivation methods. Biomass Bioenergy 2014;69:1–11.
[49] Eftaxias A, Kolokotroni I, Michailidis C, Charitidis P, Diamantis V. Techno-economic assessment of anaerobic digestion technology for Small- and medium-sized animal husbandry enterprises. Appl Sci 2024;14(11):4957.
[50] Bhandari R, Adhikari N. A comprehensive review on the role of hydrogen in renewable energy systems. Int J Hydrogen Energy 2024;82:923–51.
[51] Clarke-Sather AR. Decentralized or centralized production impacts to the environment, industry, and the economy. 2009.
[52] Borzecka M, Faber A, Jarosz Z, Syp A, Rafał P. Greenhouse gas emissions from rape seed cultivation for FAME production in Poland. J Food Agric Environ 2013;1111:1064–8.
[53] Garderer M, Lautenbach M, Fischer T, Ebertsch G. Wärmenutzung bei kleinen landwirtschaftlichen Biogasanlagen. Augsburg; 2007.
[54] Umweltbundesamt. Die Treibhausgase. https://www.umweltbundesamt.de/themen/klima-energie/klimaschutz-energiepolitik-in-deutschland/treibhausgas-emissionen/die-treibhausgase; April 17, 2025.
[55] Fan L, Tu Z, Chan SH. Recent development of hydrogen and fuel cell technologies: a review. Energy Rep 2021;7:8421–46.
[56] Derwent RG. Global warming potential (GWP) for hydrogen: sensitivities, uncertainties and meta-analysis. Int J Hydrogen Energy 2023;48(22):8328–41.
[57] Krien U, Schönfeldt P, Launer J, Hilpert S, Kaldemeyer C, Pleßmann G. oemof.solph—A model generator for linear and mixed-integer linear optimisation of energy systems. Software Impacts 2020;6:100028.
[58] Hilpert S, Kaldemeyer C, Krien U, Günther S, Wingenbach C, Plessmann G. The Open energy modelling framework (oemof) - a new approach to facilitate open science in energy system modelling. Energy Strategy Rev 2018;22:16–25.
[59] Kuratorium für Technik und Bauwesen in der Landwirtschaft e. V. (KTBL). Verfahrensrechner Pflanze. https://daten.ktbl.de/vrpflanze/home.action;jsessionid=8AC32723B0E6C5E5E9E0A4A312942460; May 22, 2024.
[60] Bundesministerium für Ernährung und Landwirtschaft. Statistisches Jahrbuch über Ernährung, Landwirtschaft und Forsten 2022. 2023. Frankfurt am Main.
[61] Statistisches Bundesamt (Destatis). Ökologischer Landbau in Deutschland: ackerland und Dauergrünland. https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Landwirtschaft-Forstwirtschaft-Fischerei/Feldfruechte-Gruenland/Tabellen/oekologisches-dauergruen-ackerland.html; October 08, 2024.
[62] Statistisches Bundesamt (Destatis). Feldfrüchte und Grünland. https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Landwirtschaft-Forstwirtschaft-Fischerei/Feldfruechte-Gruenland/_inhalt.html; October 08, 2024.
[63] Mohr R, Ehmcke-Kasch T. Rapsfruchtfolgen mit der neuen Düngeverordnung. 2021. Hannover.
[64] Gruber L, Pries M, Schwarz F-J, Spiekers H, Staudacher W. Schätzung der Futteraufnahme bei der Milchkuh. 2006.
[65] Herrmann C, Heiermann M, Idler C, Hertwig F. Einfluss von Trockenmassegehalt (Abreife), Häcksellänge und Silierung auf die Biogasausbeute. Agriculture and Forestry Research 2009;331.
[66] Fachagentur nachwachsende Rohstoffe e. V. (FNR). Faustzahlen. https://biogas.fnr.de/daten-und-fakten/faustzahlen; October 14, 2024.
[67] Schulz F, Warnecke S, Paulsen HM, Rahmann G. Unterschiede der Fütterung ökologischer und konventioneller Betriebe und deren Einfluss auf die Methan-Emission aus der Verdauung von Milchkühen. In: p. 189–205..
[68] Eslaminezhad SA, Eftekhari M, Azma A, Kiyanfar R, Akbari M. Assessment of flood susceptibility prediction based on optimized tree-based machine learning models. J Water Clim Change 2022;13(6):2353–85.
[69] Lawrie L, Crawley DB. Development of global typical meteorological years (TMYs). http://climate.onebuilding.org; June 19, 2024.
[70] Fischer B, Doll C. Niederschläge in München von 1955 bis 2020: Niederschlagsmengen und Tage mit Niederschlägen, 2021. Münchner Statistik; 2021. p. 40–55.
[71] Nnabuife SG, Hamzat AK, Whidborne J, Kuang B, Jenkins KW. Integration of renewable energy sources in tandem with electrolysis: a technology review for green hydrogen production. Int J Hydrogen Energy 2024.
[72] NREL. Best research-cell efficiency chart. https://www.nrel.gov/pv/cell-efficiency; September 03, 2025.
[73] photovoltaik.org. Photovoltaik wirkungsgrad. https://photovoltaik.org/photovoltaikanlagen/solarzellen/photovoltaik-wirkungsgrad; August 26, 2024.
[74] www.wind-turbine-models.com. Halbes 1 kW. https://www.wind-turbine-models.com/turbines/2596-halbes-1-kw; [August 26, 2024.
[75] Nowega GmbH. Factsheet Wasserhaushalt Elektrolyse. https://www.get-h2.de/wp-content/uploads/geth2_factsheet_wasserverbrauch_elektrolyse.pdf; October 02, 2024.
[76] Holst M, Aschbrenner S, Smolinka T, Voglstätter C, Grimm G. Cost forecast for low temperature electrolysis – technology driven bottom-up prognosis for pem and alkaline water electrolysis systems: a cost analysis study on behalf of clean air task force. Freiburg 2021.
[77] Franco A, Giovannini C. Hydrogen gas compression for efficient storage: balancing energy and increasing density. Hydrogen 2024;5(2):293–311.
[78] Al Kareem SSA, Hassan Q, Fakhruldeen HF, Hanoon TM, Jabbar FI, Algburi S, et al. A review on physical and chemical hydrogen storage methods for sustainable energy applications. Unconventional Resources 2025;8:100235.
[79] Stinner W, Stur M, Paul N, Riesel D. Gülle-Kleinanlagen. 2015. Rostock.
[80] Messner J, Dederer M. Kleine Biogasanlagen bis 75 kW für den landwirtschaftlichen Betrieb: Erfahrungen und Empfehlungen. Aulendorf; 2017.
[81] Ghafoori MS, Loubar K, Marin-Gallego M, Tazerout M. Techno-economic and sensitivity analysis of biomethane production via landfill biogas upgrading and power-to-gas technology. Energy 2022;239:122086.
[82] Remmele E, editor. Herstellung von Rapsölkraftstoff in dezentralen Ölgewinnungsanlagen: handbuch. second ed. Gülzow: Fachagentur Nachwachsende Rohstoffe; 2009.
[83] Fachagentur Nachwachsende Rohstoffe e. V. (FNR). Pflanzenölkraftstoff. https://biokraftstoffe.fnr.de/kraftstoffe/pflanzenoel/; April 14, 2025.
[84] Dressler D, Engelmann K, Serdjuk M, Remmele E. Rapsölkraftstoffproduktion in Bayern: analyse und Bewertung ökologischer und ökonomischer Wirkungen nach der ExpRessBio-Methode. Straubing..
[85] European Central Bank. Key ECB interest rates. https://www.ecb.europa.eu/stats/policy_and_exchange_rates/key_ecb_interest_rates/html/index.en.html; May 20, 2025.
[86] Tarantola S, Ferretti F, Lo Piano S, Kozlova M, Lachi A, Rosati R, et al. An annotated timeline of sensitivity analysis. Environ Model Software 2024;174:105977.

[87] Allgemeiner Deutscher Automobil-Club e.V. (ADAC). Spritpreis-Entwicklung: Benzin- und Dieselpreise seit 1950. https://www.adac.de/verkehr/tanken-kraftstoff-antrieb/deutschland/kraftstoffpreisentwicklung/#spritpreise-die-letzten-24-monate; August 27, 2024.
[88] Jungheinrich PROFISHOP AG & Co. KG. IBC-Container, standard-ausführung. https://www.jh-profishop.de/IBC-Recobulk-Gefahrgut-Ausfuehrung-UV-Schutz-229660-232575/; June 27, 2024.
[89] Zietz R. Düngung: Gärreste statt Gülle einsetzen. https://www.agrarheute.com/energie/strom/duengung-gaerreste-statt-guelle-einsetzen-555953; May 16, 2025.
[90] Landesagentur für neue Mobilitätslösungen und Automotive Baden-Württemberg. Baisiwissen Wasserstoff; July 11, 2025. https://www.plattform-h2bw.de/qualifizierung/wasserstoff-faq/basiswissen-wasserstoff.
[91] Bundesministerium für Ernährung und Landwirtschaft. Erntebericht 2023. https://www.bmel.de/DE/themen/landwirtschaft/pflanzenbau/ackerbau/ernte-2023.html; April 25, 2025.
[92] Al-Wahaibi A, Osman AI, Al-Muhtaseb AH, Alqaisi O, Baawain M, Fawzy S, et al. Techno-economic evaluation of biogas production from food waste via anaerobic digestion. Sci Rep 2020;10(1):15719.
[93] Trommsdorff M, Gruber S, Keinath T, Hopf M, Hermann C, Schönberger F, et al. Agri-Photovoltaik: eine Chance für Landwirtschaft und Energiewende: Ein Leitfaden für Deutschland. Freiburg; 2022.
[94] Akbari M, Tahmoures M, Azma A, Kiyanfar R, Shahdost F. Land capability assessment by combining LESA and GIS in a calcareous watershed, Iran. Arab J Geosci 2022;15(5).
[95] Haas R, Remmele E. Status quo der dezentralen Ölgewinnung: bundesweite Befragung. Straubing..
[96] Thurow J. Agrardiesel: comeback einer klimaschäflichen Subvention?. https://www.br.de/nachrichten/bayern/agrardiesel-comeback-einer-klimaschaedlichen-subvention,UfzKrRR; April 22, 2025.
[97] European Hydrogen Observatory. Electrolyser cost. https://observatory.clean-hydrogen.europa.eu/hydrogen-landscape/production-trade-and-cost/electrolyser-cost; April 07, 2025.
[98] Belthle J. Rapspresskuchen trester schweine rind Eiweiß Eiweissfutter. https://www.agrarboerse.eu/inserat/31990-rapspresskuchen-trester-schweine-rind-eiweiss-eiweissfutter-beuron-baden-wuerttemberg; January 07, 2026.
[99] Eckl F, Moita A, Castro R, Neto RC. Valorization of the by-product oxygen from green hydrogen production: a review. Appl Energy 2025;378:124817.
[100] Azma A, Narreie E, Shojaaddini A, Kianfar N, Kiyanfar R, Seyed Alizadeh SM, et al. Statistical modeling for spatial groundwater potential map based on GIS technique. Sustainability 2021;13(7):3788.
[101] Umweltbundesamt. Fläche. https://www.umweltbundesamt.de/daten/flaeche-boden-land-oekosysteme/flaeche/struktur-der-flaechennutzung#die-wichtigsten-flachennutzungen; September 05, 2025.
[102] Bundesanstalt für Landwirtschaft und Ernährung. Versorgungsbilanz 2022: selbstversorgungsgrade von Raps- und Sonnenblumenöl steigen weiter leicht an. https://www.ble.de/SharedDocs/Pressemitteilungen/DE/2023/230524_Versorgung_Oele-Fette.html; April 25, 2025.
[103] Statistisches Bundesamt (Destatis). Agrarstrukturerhebung 2023: zahl viehhaltender Betriebe zwischen 2020 und 2023 um 4% gesunken: Rinder- und Schweinebestände rückläufig, dagegen Anstieg ebi Legehennenhaltung. Wiesbaden..
[104] Bundesministerium für Landwirtschaft. Ernährung und Heimat. Biogas, https://www.bmel.de/DE/themen/landwirtschaft/bioeokonomie-nachwachsende-rohstoffe/biogas.html; May 22, 2025.
[105] Goetzberger A, Zastrow A. On the coexistence of solar-energy conversion and plant cultivation. Int J Sol Energy 1982;1(1):55–69.
[106] Garrod A, Neda Hussain S, Ghosh A, Nahata S, Wynne C, Paver S. An assessment of floating photovoltaic systems and energy storage methods: a comprehensive review. Results Eng 2024;21:101940.
[107] Liang J, Wu S, Lu T. Portfolio selection and optimal planning for hydrogen energy storage systems composed of heterogeneous electrolyzer and fuel cell technologies in industrial park multi-energy systems. Appl Energy 2026;403:127001.
[108] Bundesamt für Wirtschaft und Ausfuhrkontrolle (bafa). Merkblatt zur Ermittlung des Gesamtendenergieverbrauchs: Informationen für die Ermittlung des Gesamtendenergieverbrauchs für nach § 8 EDL-G sowie §8, 9 und 17 EnEfG verpflichtet Unternehmen. second ed. 2024.
[109] electrive.net. H2 Mobility stellt auf neues Preismodell um. https://h2.live/news/3139/; April 04, 2025.
[110] Kabza A. Wasserstoff: eigenschaften und physikalische Daten von Wasserstoff. https://www.pemfc.de/hydrogen.html; August 28, 2024.
[111] Kost C, Müller P, Sepulveda Schweiger J, Fluri V, Thomsen J. Levelized cost of electricity: renewable energy technologies. Freiburg; 2024.
[112] Mayer JN, Philipps S, Hussein NS, Schlegl, Thomas, Senkpiel, Charlotte. Current and future cost of photovoltaics: Long-term scenarios for market develpoment, System prices and LCOE of utility-scale PV systems..
[113] Jüttemann P. Wie man beim Kauf eine gute Entscheidung trifft. https://www.klein-windkraftanlagen.com/allgemein/preise-fuer-kleinwindkraftanlagen-fehlinvestitionen-vermeiden/#t-1615197408706; August 27, 2024.
[114] Crawford RH. Life-cycle energy analysis of wind turbines—an assessment of the effect of size on energy yield. In: Brebbia CA, Popov V, editors. Energy and sustainability. Southampton, UK: WIT Press; 2007. p. 155–64.
[115] Smolinka T, Wiebe N, Sterchele P, Palzer A, Lehner F, Jansen M, et al. Studie IndWEDe: Industrialisierung der Wasserelektrolyse in Deutschland: Chancen und Herausforderungen für nachhaltigen Wasserstoff für Verkehr, Strom und Wärme. Freiburg; 2018.
[116] Bielewski M, Pfrang A, Bobba S, Kronberga A, Georgakaki A, Letout S, et al. Batteries for energy storage in the European Union: status report on technology development, trends, value chains and markets 2022. Luxembourg: Publications Office of the European Union; 2022.
[117] Kebede AA, Coosemans T, Messagie M, Jemal T, Behabtu HA, van Mierlo J, et al. Techno-economic analysis of lithium-ion and lead-acid batteries in stationary energy storage application. J Energy Storage 2021;40:102748.
[118] Eißler T, Schumacher G, Behrens J, Mendler F, Voglstätter C. Detailed cost analysis of hydrogen refueling costs for fleets. Chem Ing Tech 2024;96(1–2):86–99.
[119] Bundesministerium der Finanzen. AfA-Tabelle für den Wirtschaftszweig "Ölmühlen- und Margarineindustrie". https://www.bundesfinanzministerium.de/Content/DE/Standardartikel/Themen/Steuern/Weitere_Steuerthemen/Betriebspruefung/AfA-Tabellen/AfA-Tabelle_Oelmuehlen-und-Margarineindustrie.html; 1995. September 19, 2024.
[120] Hofmann G. Baukosten von Milchviehlaufställen. 2024.
[121] Bundesministerium der Finanzen. AfA-Tabelle für den Wirtschaftszweig "Landwirtschaft und Tierzucht". https://www.bundesfinanzministerium.de/Content/DE/Standardartikel/Themen/Steuern/Weitere_Steuerthemen/Betriebspruefung/AfA-Tabellen/AfA-Tabelle_Landwirtschaft-und-Tierzucht.html; 1996. October 14, 2024.
[122] Green Navigation GmbH. Biomethan preisreport. Unna; 2025.
[123] Sánchez-Martín L, Ortega Romero M, Llamas B, Del Suárez Rodríguez MC, Mora P. Cost model for biogas and biomethane production in anaerobic digestion and upgrading. Case Study: castile and Leon. Materials 2022;16(1).
[124] Union zur Förderung von Oel- und Proteinpflanzen e.V. Marktinformation Ölsaaten und Biokraftstoffe. Dezember; 2024.
[125] Nadeau M-J, Kim YD, Al Neyadi M, Baikeli N, Barbknecht K-D, Birnbaum L, et al. E-Storage: shifting from cost to value wind and solar applications. 2016. London.
[126] Nord TÜV. Nutzung von Wasserstoff: was macht eine Brennstoffzelle?. https://www.tuev-nord.de/de/unternehmen/energie/wasserstoff/wasserstoff-brennstoffzelle/; June 19, 2025.