RENEWABLE ENERGY AND SYNTHETIC FUELS IN AGRICULTURE

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Abstract

A climate-friendly and CO_2-neutral energy supply for agricultural farms concerns the electricity used for buildings and animal husbandry as well as the production of synthetic fuels for cultivating the fields. This strategy is in demand with many customers, e.g., the dairy cooperative Arla Foods, whose goal is the production of cow's milk with net-zero CO_2 emissions by the year 2050. The operational energy system considered here included renewable electricity generation, covering electricity consumption in the cowshed, battery storage for times without electricity generation, the production of synthetic fuels and electricity feeding into the public power grid. Fluctuations depending on the day and the season were taken into account for electricity at 15-min intervals and for fuel per calendar week for one year. The aim was to determine the necessary capacities and the costs for renewable electricity and for synthetic fuel production of a survey dairy farm. The results showed that a farm's own electricity production is currently profitable; however, a farm's production of synthetic fuel still has comparatively high costs and therefore is not yet profitable. Further technical advances, rising prices of fossil fuels and economies of scale, e.g., larger cooperatively-operated plants, could help new technology to make a breakthrough.

Keywords: synthetic fuels; combustion engines; photovoltaic; wind turbines; batteries; economy

1 Introduction

In order to ensure the goal set by the European Union to achieve climate neutrality by 2050 and thus limit global warming to 1.5–2 °C, according to the Paris Climate Protection Agreement of 2015 (UNFCCC, 2017), most countries, including Germany, still make great efforts in the use of renewable energies (RE). Agriculture must also make its contribution to the energy transition in two ways. On the one hand, farms have good prerequisites for the production of RE, especially electricity, owing to their roofs (rooftop solar) and fields (offsite solar) for the construction of photovoltaic systems (PV) and wind turbines. On the other hand, the largest share of energy consumption in agricultural operations is the fuel requirement of fieldwork in the form of diesel. This raises the question of whether the drive energy for fieldwork can be generated again using renewable power to liquid, as was the case with hay and oats for horses 80 years ago.

In principle, future CO_2-neutral mobility can be achieved through battery-based electric vehicles or internal combustion engines, the latter being powered by synthetic fuels. With regard to agriculture, the electrification of tractors for fieldwork is currently impractical due to the large and heavy batteries required for this. In addition, due to the changing weather, it is difficult to plan the operating times of the tractors and very fast refuelling is necessary at peak times. Another possibility is the conversion of green electricity, water and CO_2, the latter from the air, into synthetic fuels for field work. In a special electrolysis process, CO_2 and water vapour are chemically split using electricity and the so-called synthesis gas, a gas mixture of hydrogen (H2) and carbon monoxide (CO), is generated. It serves as the basis for the Fischer–Tropsch synthesis, which uses it to form hydrocarbon chains of different lengths, comparable to fossil fuels (Rozzi et al., 2020; Meurer and Kern, 2021; Samavati et al., 2018; Özcan and Kayabasi, 2021). After a further processing step, the formed hydrocarbon chains can be used as a liquid synthetic fuel in conventional internal combustion engines. In addition, the advantages of fuels, e.g., high energy density and fast refuelling, can be utilized.

The pressure to develop new sustainable technologies comes not only from politics, but also from the market, i.e., processors and consumers. For example, the Arla Foods dairy carried out a climate check on dairy farms in 2020 in order to identify potential for CO_2 savings (Arla Foods, 2020). By 2050, the milk should be produced with net zero CO_2 emissions and the payment could be based on the respective CO_2 balance (IPCC, 2001). Using the example of a typical supplier to this dairy located in northern Germany, a survey dairy farm's own production and storage of electrical energy and fuel is simulated and economically assessed in the present work. The survey dairy farm in question with a total usable agricultural area of 235 hectares and 150 dairy cows has an annual energy consumption of around 80,000 kWh of electricity and 35,000 L of diesel with an energy content of around 350,000 kWh. In 2008, the first PV system was installed on the roofs of the farm, and in 2019 another system was added to the dairy barn with battery storage; thus, the farm already supplied it-self with electricity. The replacement of fossil diesel used in fieldwork, i.e., crops and grassland, with synthetic fuels from RE has not yet been resolved, and is the main research question in this article. The source of all RE for internal and for field work in agricultural operations is initially electrical power from wind and sun. Since the selected survey dairy farm uses typical production technologies, the results can also be scaled to other farm sizes.

The aim of the investigation is, on the one hand, to present the technical possibilities of self-production of synthetic fuels on the survey dairy farm and, on the other hand, to provide an economic assessment by determining the break-even point for the corresponding investments. The analysis of the synthetic fuel supply will be carried out in a first step as an isolated solution for a farm, whereby at the end we will discuss how economies of scale may be achieved through scaling or cooperative organization.

2 Methods

The technical energy system (mass model) includes the renewable electricity generation for the entire operation, the coverage of the electricity consumption in the cowshed, the battery storage, the production of synthetic fuels and an integration into the public electricity network. The aim is to use the model to simulate, as realistically as possible, an independent and regenerative energy supply to cover one's own requirements for electricity and fuel. Fluctuations depending on the day and the season are taken into account for electricity at 15-min intervals and for fuel per calendar week for one year.

For the economic objective, the costs of the energy supply are determined in scenarios and the break-even for investments in RE generation is calculated by comparing it with the status quo (baseline). From this, the opportunities and risks of an operationally self-sufficient energy system are to be derived, the further development assessed and recommendations given as to how agriculture could contribute to climate protection through the use of synthetic fuels. In the conclusion, it will be explained to what extent individual farm solutions, or at least cooperative or cross-company approaches, would be necessary in order to achieve a CO_2-neutral energy supply.

The agricultural operation from northern Germany under consideration aims to use regenerative energy to cover its electricity and fuel requirements in the future. The required electricity production and conversion steps will take place on farm. The energy system includes renewable electricity generation covering electricity consumption in the cowshed, battery storage for times with no electricity generation, the production of synthetic fuels and integration into the public electricity grid (Figure 1). The current flow in the model, and thus in the energy system, took place in a cascade. This meant that the electricity generated flowed to the first stage of consumption, and the electricity that was not consumed there flowed to the next stage.

The system for synthetic fuel production (Karlsruher Institut für Technologie (KIT), 2021) is not operated in a constant load range but adapts to the fluctuating electricity supply from wind and solar energy. Thus, the local energy system has the properties of a microgrid (Klausmann and Zhu, 2018). For this planned energy system, a model that simulates the processes and electricity flows for one year was developed in the spreadsheet program Microsoft Excel (2016). An annual simulation was necessary because there are seasonal fluctuations in the generation of electricity from wind and solar energy, as well as in the fuel requirements of a farm. With the help of the simulation, the necessary electrical performance of the technical systems, e.g., for electricity or fuel production, was determined. Furthermore, the utilization of the technical systems and the current flows were shown, which finally allowed for an economic assessment. This included the calculation of the maximum capital exenses (CapEx) in a system for synthetic fuel production as well as the necessary operating costs, mainly in the form of renewable electricity.

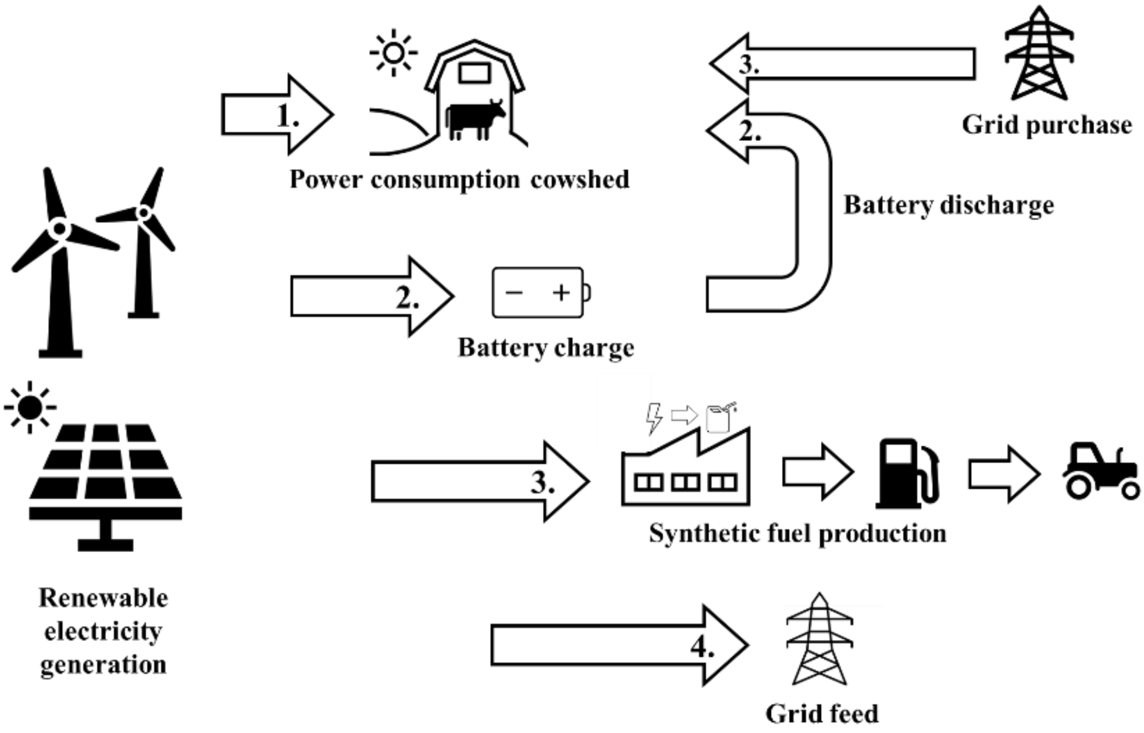

Figure 1. Scheme of a regenerative energy supply from self-power generation in the survey dairy farm.

Farm vehicles, such as tractors, combine harvesters, forage harvesters, wheel loaders, trucks, etc., need fuel for fieldwork. The annual diesel demand in the example operation showed seasonal fluctuations (Figure 2) and was approximately 35,000 l (approx. 150 l/ha) with a calorific value around 350,000 kWh. This meant that the energy requirement was about three times as high as the electricity requirement in the cow barns (about 80,000 kWh). At the baseline, the annual costs for energy from fossil resources amounted to 24,128 € for electricity purchase (market price: 0.30 € per kWh) and 45,066 € for diesel purchase (market price: 1.25 € per l). In the break-even calculation for the scenarios with renewable resources, the sum of these two amounts, 69,194 €, should be matched by the value search of the maximum investment for the synthetic fuel production plant.

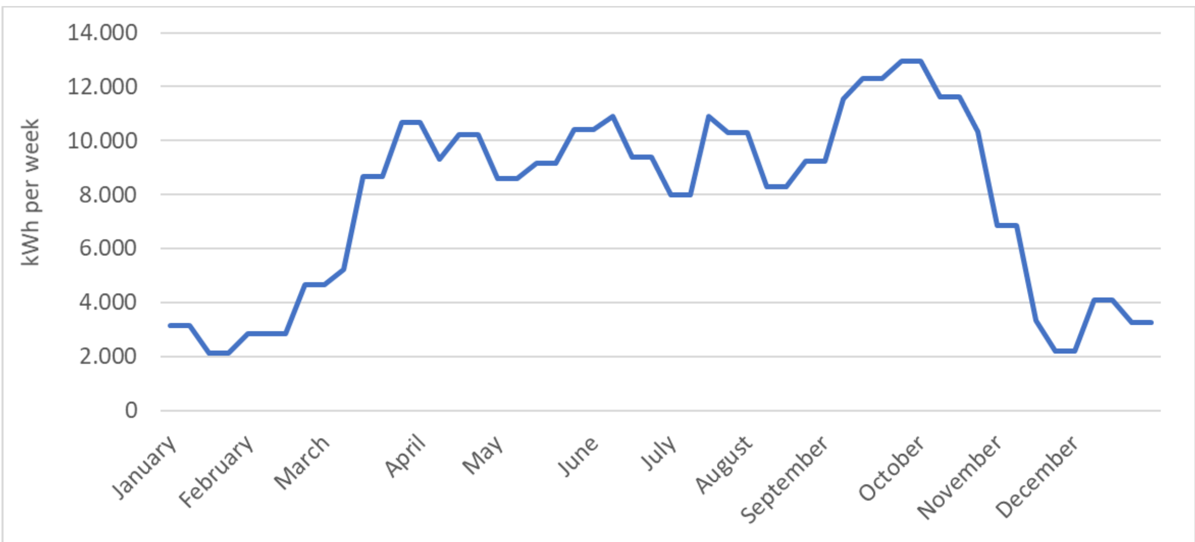

Figure 2. Annual distribution of fuel requirements in a dairy farm with crop and forage production. Source: survey dairy farm 2020.

The self-generated electricity that did not flow off at the stages of direct consumption and battery charging was used for synthetic fuel production. The input of the technical system for the production of synthetic fuel was electricity in kWh. The output was the synthetic fuel produced, the unit of which is also given in kWh. The fuel was temporarily stored in a fuel store until it is needed. The model envisages that only as much energy as is necessary is converted into fuel and that the system is utilized as evenly as possible. In order to guarantee this, the fuel requirements of an agricultural farm with arable and fodder cultivation were calculated in the model for the individual weeks of the year.

Only when the power generation exceeded the sum of the power consumption from the cowshed, battery charge and fuel production, the surplus was fed into the public power grid. Electricity purchases from the public grid only occurred if the power demand of the cowshed could not be covered by renewable power generation and battery discharge. In the model, electricity purchases were not used for battery charging or synthetic fuel production. Downtimes or maintenance times for the entire technical equipment of the energy system were not taken into account.

The establishment of a farm's own CO_2-neutral energy supply depends not only on the technical options described and the cost-price ratios, but also on the farm's capacities and a building permit. In order to be able to map different operational starting situations on the one hand, and possible future price developments on the other hand, two scenarios for different technical solutions for renewable electricity generation were created. In Scenario 1, electricity was generated with a PV system on the roof and a wind turbine. Scenario 2 only produced the required electricity with PV systems, but this time on the roofs (rooftop solar) and in the open fields (offsite solar) of the farm. Furthermore, sensitivity analyses for the current and rising energy prices for electricity and diesel were simulated. Both scenarios were compared with the status quo, the baseline where energy is gained exclusively from fossil resources, which causes annual costs of 69,194 €.

3 Results of the Model Simulations

The results show the technical and economic differences between the two scenarios explained above: electricity production with wind turbines and PV systems (Scenario 1) or production only with PV systems on the roofs and in open fields (Scenario 2).

The amounts of electricity that are required to supply the survey dairy farm with electricity and fuels from renewable sources are shown in Figure 3. In addition, in both scenarios, around 10,000 kWh (1.4% to 1.6% of total electricity) was drawn from the public power grid to cover the power consumption of the cowshed in times when there was no self-generation of renewable power. Thus, the degree of self-sufficiency of the cowshed was around 87% in both scenarios. Most of the electricity generation was carried out by the wind turbine, with 84% in Scenario 1, and the open field PV system with a share of 74% in Scenario 2. The additional electricity was generated by the PV system on the roof.

The use of the electricity was the same in both scenarios, with the grid feed-in at 9%, the synthetic fuel production at 81% and the electricity consumption in the indoor economy at 10%, mainly in the cowshed. In Scenario 2, the latter was divided again into electricity that was directly consumed (5%) and that which was temporarily stored in the battery with (5%).

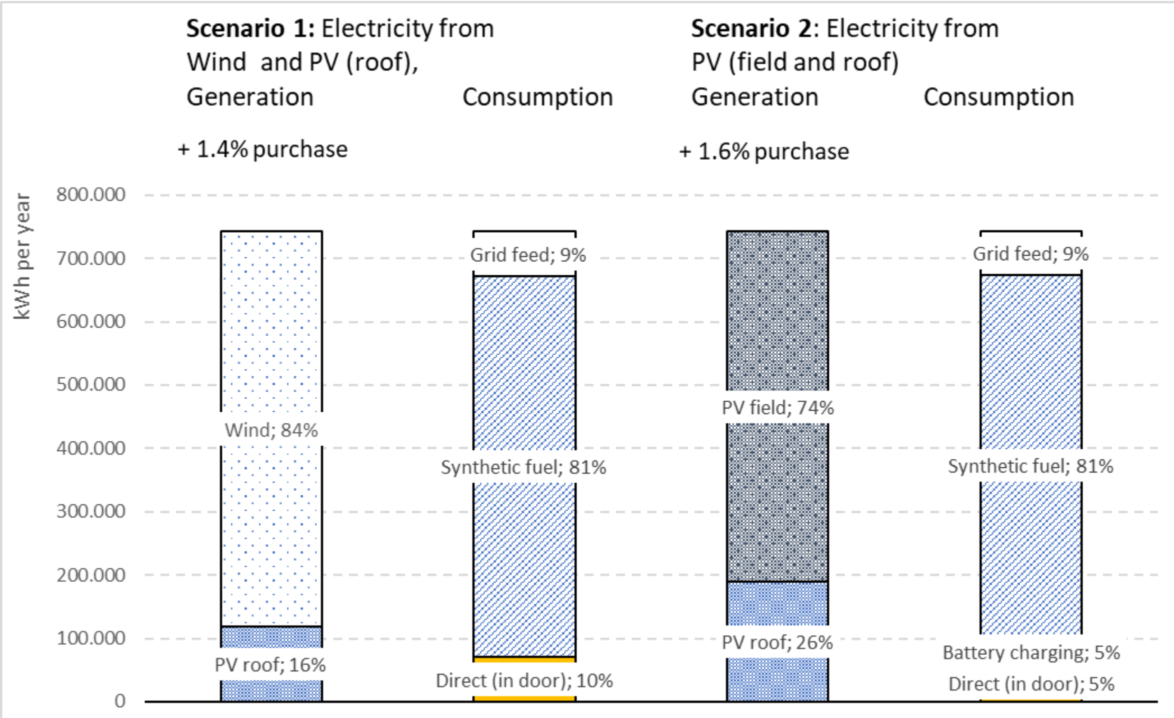

Figure 3. Annual electricity generation and comparison of the consumption of electricity generated (Scenario 1 and Scenario 2).

The influence of the various properties of the power generation systems on the fuel store, the grid feed-in and the grid purchase in the energy system over the course of a year is shown in Figure 4. The blue line shows the current synthetic fuel inventory for Scenario 1 (PV and wind) and Scenario 2 (PV). Over the course of both curves, the weekly fuel consumption for tractors for fieldworks was observed as a more pronounced decrease in the inventory, which was built up again in the following days due to the synthetic fuel production at the farm. Diesel consumption was at a consistently high level from March to October (Figure 2).

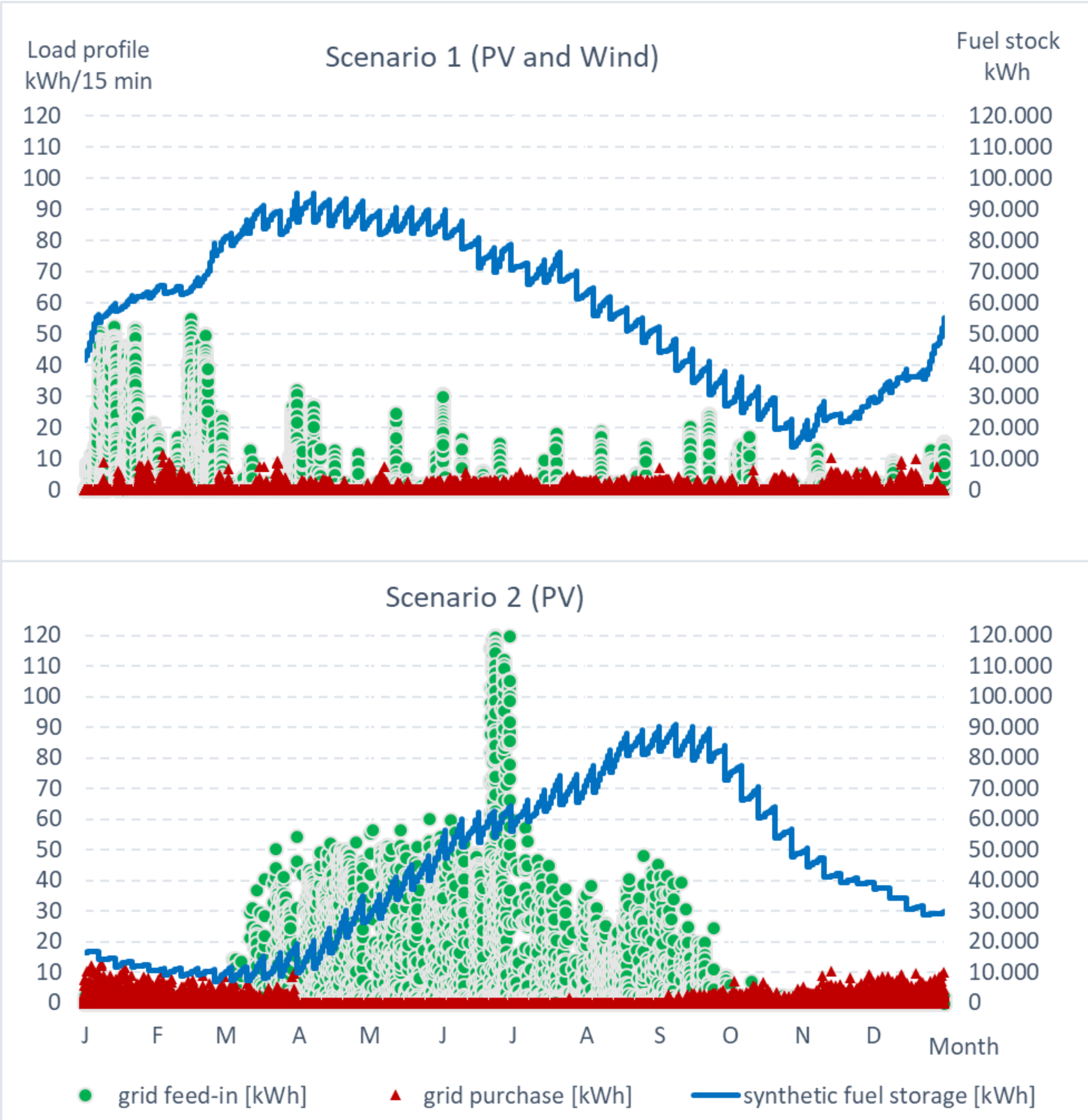

Figure 4. Load profile of grid feed-in and purchased electricity, as well as stocks of synthetic fuels for both scenarios (1 and 2) over the course of the year.

The production of electricity in the summer months, which was restricted in Scenario 1 due to the lower amount of wind, along with the simultaneous high fuel consumption, led to a constantly dwindling fuel inventory from April to November. In December, the inventory rose sharply again, such that electricity was fed into the public grid at the beginning of the year, since the target minimum stock of the fuel store had been reached. The grid purchase was similarly low over the entire year. It became clear that in Scenario 1, a fuel reserve had to be built up over the winter months in order to have enough diesel in storage for the maize harvest at the end of autumn.

In Scenario 2, the increased electricity production of the PV system in the summer months led to an increase in fuel stocks, even with the increased consumption of diesel at the same time. It turns out that a fuel reserve had to be created over the summer months in order to be able to start the fieldwork at the beginning of March. The grid feed-in load profile of approximately 50 kWh/15 min was due to the peak load times of the PV system over midday. The electricity generated exceeded the installed consumption of synthetic fuel production. In July, the feed-in was more than twice as high, as the fuel production system did not consume any electricity. The fuel store was sufficiently full at this point. From April to September, there was a small amount of electricity drawn from the grid due to the battery storage system. In the winter months, there were higher purchase shares due to the reduced electricity production from the PV systems.

The lower load hours of a PV system per year not only require a larger battery storage system, but also energy generation and energy conversion systems if a similar amount of energy is to be used over the course of the year. The power generation systems in Scenario 2 (PV) had an output of 1210 kW, almost twice as high as in Scenario 1 (PV + wind) with 587 kW. There were similar differences in the installed capacity between the systems for synthetic fuel production.

At the baseline (fossil market resource) with an electricity price of 0.30 €/kW and a diesel price of 1.25 €/l, the survey dairy farm had energy costs totalling around 70,000 €, where around two-thirds of this was spent on buying diesel.

The average electricity costs that the survey dairy farm had in the two scenarios were between 0.13 and 0.16 €/kWh. The reason for the cost reductions compared to the initial situation (0.30 €/kWh) are the additional investments in large-scale PV systems or wind turbines, which are necessary, among other things, for synthetic fuel production. In contrast, the cost of synthetic diesel increases when investments are made in more expensive systems.

In order to avoid the total annual costs exceeding approximately 70,000 €, in the energy system of Scenario 1 and 2, which generates the required electricity exclusively with RE systems, the investment in the synthetic fuel production plan must not be higher than € 821/kW for Scenario 1 or € 482/kW for Scenario 2 (Figure 5). This amount is far below the current market values of approximately € 4000/kW. Therefore, in the assessment at the end of the article, the statement is made that it is currently not economically viable.

In a direct comparison of the scenarios, the capacity for the synthetic fuel production plant in Scenario 2 was nearly doubled in size. This was due to the lower load hours of a solo PV system (Scenario 2) compared to the combination with a wind turbine (Scenario 1); thus, electrical power is available to the subsequent consumers for fewer hours per year.

When the highest energy price level of 0.45 €/kW for electricity and 2.00 €/l for fossil diesel was reached, Scenario 1 allowed a maximum acquisition cost of 2798 €/kW for the fuel production system. In Scenario 2, this figure was only € 1552/kW (Figure 5).

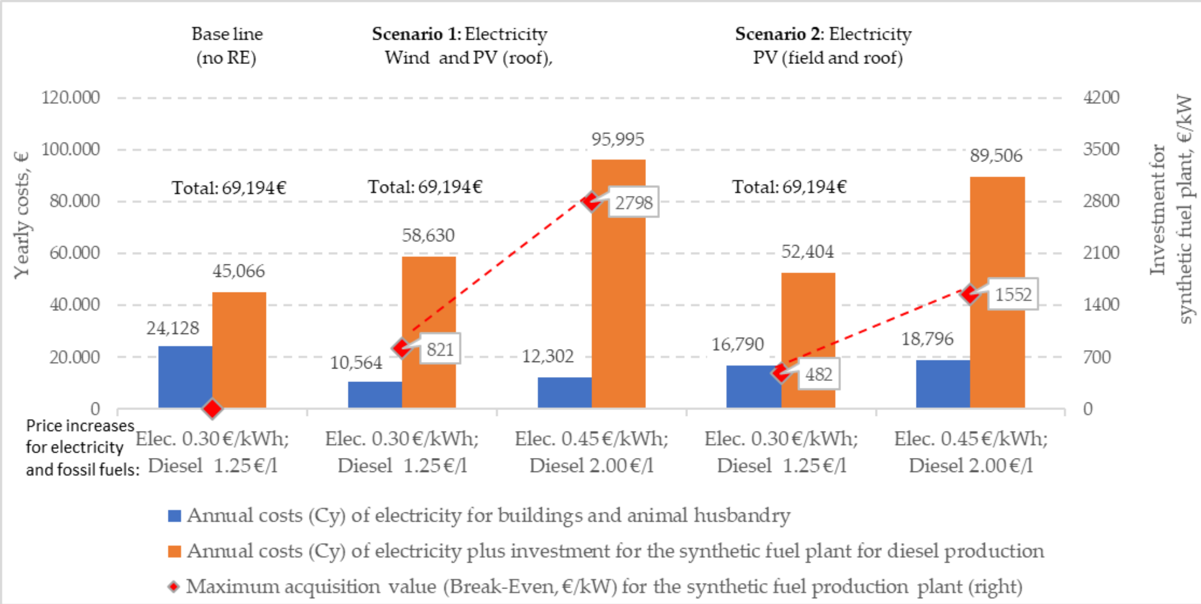

Figure 5. Annual costs for providing electricity to the barn and for producing synthetic fuel, comparing baseline, Scenario 1 and 2 (according to Equations 4a and 4b) and the maximum acquisition values (€/kW) for the synthetic fuel production plant to meet the total annual costs Cy of the baseline scenario.

4 Conclusion and Recommendation

The energy requirements of an agricultural operation, which is to be replaced by a regenerative energy supply with synthetic fuels and renewable electricity, do not make up the largest share of the greenhouse emissions that come from agriculture. The main sources of emissions are agricultural soils and ruminant digestion (BMU, 2019). The present work clearly shows that it is possible to increase the efficiency of a farm's energy system if synthetic fuel production takes place on the farm.

According to the literature, today's capital expenses (CapEx) per kW for a synthetic fuel production system would cost around 4000 €/kW of installed capacity in 2020. According to the current status, these acquisition costs would not be profitable even for Scenario 1 with a large wind turbine at the highest energy price level of 0.45 €/kW electricity and 2.00 €/l diesel fuel. For Scenario 1, the cost should be a maximum of € 3810/kW.

Due to increased demand and thus an increased production volume of systems for synthetic fuel production, the acquisition costs could be reduced to 3000 €/kW by 2050. In this case, Scenario 1 (large wind turbine) could profitably produce synthetic fuel on its own at an energy price level of 0.40 €/kW electricity and 1.75 €/l diesel fuel to cover personal needs. In Scenario 1, with a small wind turbine, and Scenario 2, with only electricity generated from PV systems, it is not profitable to produce synthetic fuel in operations under the given circumstances, even at the highest assumed fossil energy price level. Another argument against this is the fact that the container systems for synthetic fuel production have not yet reached market maturity. In a few years, the potential investment could be profitable if the energy price level rises sharply, as assumed, and the required renewable electricity is produced inexpensively by a large wind turbine.

The limitations of the simulation model could be seen in the negation of other means of energy management on a farm, as there are additional load shifting possibilities for electricity consumers, such as controlling the operation hours of manure pumping or a grist mill. Such possibilities have been modelled in previous research (Schock et al., 2015). Compared to the flexible electricity consumer considered here (the production of synthetic fuels) the expected effects of other additional direct load shifts are estimated to be comparatively small; nevertheless, direct additional load shifts should also be investigated in the forthcoming research projects.

As a positive aspect of synthetic diesel production, the means of temporary self-sufficient energy supply for crisis protection should be noted. With the synthetic diesel produced, it is conceivable to use a diesel generator for a regenerative emergency power supply on the farm. Should there be a power failure, e.g., in the public power grid, important electricity consumers, such as the milk tank cooling and the milking robot or ventilation systems in pig and chicken coops, can continue to be operated. Such a power failure would also occur if the public grid, and thus the connection to regional wind parks or PV systems, was temporarily switched off due to repair work. An emergency power generator is even a legal requirement for larger livestock facilities.

Another advantage of the technology presented is the lower land consumption compared to the production of biofuels, e.g., bio-diesel from rapeseed oil (Gradziuk et al., 2021). Here, even with open field PV systems, the land consumption was only 10% of a comparable vegetable oil production.

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