Energy 276 (2023) 127543

Contents lists available at ScienceDirect

Energy

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

Electrification of the agricultural sector in Norway in an effort to phase out fossil fuel consumption

Ville Olkkonen [a,*], Arne Lind [b], Eva Rosenberg [a], Lisa Kvalbein [a]

[a] Department of Energy System Analysis, Institute for Energy Technology (IFE), P.O. Box 40, 2027, Kjeller, Norway
[b] Department of Solar Power Systems, Institute for Energy Technology (IFE), P.O. Box 40, 2027, Kjeller, Norway

ARTICLE INFO

Handling Editor: G Chicco

Keywords:
Agriculture
Electrification
Energy system
Energy storage
Hybrid system
Renewable energy

ABSTRACT

The Norwegian Agrarian Association has the ambition to reduce greenhouse gas (GHG) emissions by 4–6 million tons of carbon dioxide equivalents (CO_2-eq) by 2030 in the agricultural sector. As a part of this, 10–25% is expected to come from substituting fossil fuels with renewable energy sources. This paper focuses on the effects of phasing-out fossil fuel consumption in on-field tractor operations with electrification by introducing battery-electric and/or fuel cell tractors and on-site renewable energy generation and storage. The results show that electrification of on-field tractor operations can be a techno-economically feasible pathway to reduce tractor energy-use-related CO_2 emissions in the agricultural sector. Annual CO_2 emissions are observed to reduce by 69% in 2030 and 97% in 2050. However, the CO_2 reduction potential can vary significantly based on the farm type. In this regard, the analysis revealed high sensitivity to manufacturing costs of zero-emission tractors (ZETs), which in combination with a low utilization rate can render the investment to ZETs unprofitable. Moreover, electrification increases electricity consumption, especially peak electricity demand in the agricultural sector. This effect can be reduced with on-site renewable energy generation and energy storage systems.

1. Introduction

1.1. Background

The agriculture sector has an important role towards achieving the 2030 sustainable development goals [1]. The target of UN goal number 7 is to ensure affordable, reliable, sustainable and modern energy for all, and by substituting fossil fuels with renewable energy sources in the agriculture sector, the share of renewables in the global energy mix will increase (target 7.2). Additionally, by utilising battery-electric and full cell tractors combined with on-site renewable energy generation, the agriculture sector will also contribute to technological upgrading and innovation, as included in target 8.2.

According to the Norwegian Climate Change Act [2], Norway has a target of reducing greenhouse gas emissions (GHG) by at least 50–55% by 2030 compared to the level in 1990. Additionally, the target for 2050 is to become a low-emission society, and consequently, GHG emissions should be reduced by 90–95%. In Norway, sectors that are not included in the EU Emission Trading System (ETS) have a target of reducing the GHG by 40% compared to the level in 2005 [3]. From the non-ETS sectors, transport and agricultural sectors are two major contributors to the national GHG emissions. For example, in 2020, the agricultural sector accounted around 9% of the total national GHG emissions (49.3 million tons of carbon dioxide equivalents, CO_2-eq) [4]. Consequently, The Norwegian Agrarian Association has the ambition to reduce GHG emissions by 4–6 Mt CO_2-eq by 2030 [5]. As a part of this, 10–25% is expected to come from substituting fossil fuels with renewable energy sources in the agricultural sector (e.g., agricultural machinery).

1.2. Literature review

In the agricultural sector, mechanisation has led to a substantial increase in energy consumption and CO_2 emissions [6]. Therefore, there is significant potential to rearrange the energy system of the agricultural sector by increasing the deployment of distributed energy generation with renewable energy sources. In this regard, electrification of end-use sectors is seen by many countries as a promising pathway for decreasing fossil fuel consumption, increasing energy efficiency, and hence mitigating climate change [1]. In Ref. [7], it is estimated that electrification of farms in an appropriate process with renewable energy sources can decrease the carbon footprint of farming by 44–70% depending on the farm type. In Ref. [8], it is estimated that agricultural machinery can

* Corresponding author.
E-mail address: ville.olkkonen@ife.no (V. Olkkonen).

https://doi.org/10.1016/j.energy.2023.127543
Received 18 July 2022; Received in revised form 12 April 2023; Accepted 15 April 2023
Available online 21 April 2023
0360-5442/© 2023 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

account for about 44% of the total energy inputs in farming. Reducing the demand for fossil fuels via the electrification of tractors with battery-electric, or fuel cell (hydrogen) vehicles can be a potential pathway towards more sustainable farming and contributing to the UN's sustainable goals. Policies supporting electrification can also indirectly affect food prices due to the potential to reduce pressure on global cropland [9].

Large-scale electronification may outpace the expansion of electricity supply in some regions, and thus impede reliable energy system operation. In this regard, distributing generation (and storage) technologies closer to end-users can increase energy efficiency, improve grid stability, and curtail the need for new transmission investments [10–12]. Solar photovoltaic (PV) generation, among other renewable energy (RE) sources, is considered critical to reaching global policy goals. A variety of policy instruments (e.g., feed-in tariffs, subsidies, carbon pricing, etc.) directed at distributed energy generation, e.g., from solar PV have led to significant technology improvements and module manufacturing cost reductions [13,14]. Consequently, the rate of solar PV deployment has increased exponentially during the last decades [15]. In the agricultural sector, there is a significant potential for solar PV deployment since the installation can utilize the roof area of existing buildings, and more importantly, high solar PV generation frequently coincides with the use of machinery for on-field operations and power demand in the buildings [16]. The use of agricultural fields for ground-mounted solar PV deployment can also increase the PV potential. However, this can be a non-sustainable pathway due to the possible competition between land use for energy and food production [17].

The electrification of agricultural machines can be more challenging due to the considerably higher energy demand during relatively short periods of fieldwork [18]. Moreover, RE generation and energy demands are often stochastic by nature. This can lead to a mismatch between RE availability and the energy demand of the agricultural process. Hybridization with multi-generation systems and/or energy storage systems can reduce the uncertainties related to RE generation [19]. Several studies have demonstrated the feasibility of hybrid energy systems with differing system topologies, e.g., hybrid PV-battery [20], wind-PV-battery [21], PV-hydrogen [22] and wind-PV-hydrogen systems [23]. Furthermore, hybrid storage systems can take advantage of both short-term (e.g., diurnal) and long-term (e.g., seasonal) variations in RE generation. For example, previous studies have shown that combining PV with battery electric storage can increase the self-consumption of on-site PV production [24] and reduce electricity imports from the grid [20] within a day. On the other hand, hydrogen storage systems have been demonstrated to be the most feasible option for long-term storage due to their lower loss rate [25,26]. Additionally, an increasing number of studies have investigated the synergies between hybrid energy systems and battery-electric vehicle (BEV) charging and/or hydrogen fuel cell vehicle refuelling [27–29]. In Ref. [18], it was shown that compared to a cable-oriented concept, the energy demand of a battery-electric tractor is better distributed throughout the day, which leads to improved coverage by the agriphotovoltaic[1] plant.

This paper aims to utilize the strengths of linking a model with a fine time resolution to a model with a technologically detailed representation of the technical and economic aspects of the Norwegian energy system. In Ref. [30], different methodologies to improve the representation of short-term variations of solar and wind in long-term energy system models are presented. In a recent work by Ref. [31], a hybrid modelling approach is used to assess the impact of different policy instruments for decarbonizing the energy system of an island in the northern parts of Norway. A bi-directional approach is used, where the new capacities of different technologies from the TIMES-Hinnøya models are used as input to the simulation model [32]. The latter is used to overcome the low temporal resolution limitation of the long-term energy planning model, capturing additional technical constraints needed to balance the residual hourly load variation. In Ref. [33], the authors recommend that energy systems containing large amounts of intermittent renewable energy sources should use high temporal and spatial resolutions to reflect the system's behaviour and interdependencies correctly. Similar conclusions are drawn in Ref. [34], where a MARKAL energy system model is linked to a Dutch power market model, where the results indicate that the MARKAL model is not capable of capturing the necessary investments to support a high share of renewables.

1.3. Aim, scope, and research questions

This paper aims to fill the knowledge gaps related to electrification possibilities in the agricultural sector. This study focuses especially on the effects of phasing-out fossil fuel consumption in on-field tractor operations by introducing battery-electric and/or fuel cell tractors and on-site renewable energy generation and storage. Cost-optimal transition pathways to phase-out fossil fuel consumption in the on-field tractor operations are modelled in 16 different example farms. In this regard, this paper describes a modelling framework consisting of two different technology-rich optimisation models, which differ significantly in terms of spatial and temporal resolution. Finally, an upscaling method is used to aggregate the modelled farm-level results at the national level.

Accordingly, this study aims: (i) to explore and quantify the techno-economically feasible potential to reduce CO_2 emissions in the agricultural sector by substituting fossil fuel consumption in on-field tractor operations with the electrification of tractors, using battery-electric or fuel cell vehicles; (ii) to quantify the effects that electrification of on-field tractor operations have on energy consumption and energy-use related CO_2 emissions at the farm and national level; (iii) to highlight the uncertainties related to the agricultural sector ecarbonization pathway via electrification.

2. Materials and methods

2.1. Description of studied farm types

Sixteen different example farms were included in this study (Table 1) to represent the main part of the Norwegian agricultural sector in terms of cultivated area. The characteristics of example farms including estimated energy demand and timing of on-field tractor operations are based on the data from the NIBIO report [35]. The example farms consisted of both stockless grain farms and grain farms with pork production, while all dairy farms produce forage for grazing and indoor feeding as feed for dairy cows as well as heifers and male offspring for beef production. A description of all farm types and farming operations have presented in detail in previous studies [36–39]. These studies were carried out in three regions in Norway: Østlandet (Eastern Norway), Rogaland (subregion in Western Norway) and Trøndelag (Central Norway). Since stockless grain farms are almost nonexistent in the Rogaland region, this farm type was excluded. The farming regions are referred to in this study as NO1, NO2 and NO3, respectively. This relates to the region's geographical relation to the electricity market bidding areas in Norway, as presented in Fig. 1.

2.1.1. Electricity consumption by the farm buildings

The farm buildings-related electricity consumption was also included in this study. This is since the magnitude and temporal variation of electricity consumption can affect the optimal sizing of the on-site hybrid energy system [40]. Data on electricity consumption in barns and farm buildings were measured in three different farms with similar sizes and types of operation as the example farms described in Table 1. A large grain farm had an annual electricity consumption of 28 947 kWh, including processes such as a hot air fan for drying, fans for

[1] Simultaneous use of areas of land for both solar photovoltaics power generation and agriculture.

Table 1
Overview of the different farm types, including farming area, size (small ≤40 ha, large >40 ha), tractor power output (small ≤70 kW, large >70 kW) and energy demand for on-field tractor operations [35].

Farm type	Region	Area (ha)	Size category	Power output, large tractor (kW)	Power output, small tractor (kW)	Diesel consumption, large tractor (L/year)	Diesel consumption, small tractor (L/year)	Source
Stockless grain	NO1	31	Small	90	50	1280	270	[37]
Stockless grain	NO3	28	Small	90	50	1310	400	[37]
Stockless grain	NO1	89	Large	90	50	4250	660	[37]
Stockless grain	NO3	98	Large	90	50	3090	2630	[37]
Grain and pork	NO1	31	Small	90	50	1950	240	[38]
Grain and pork	NO2	31	Small	90	50	1950	240	[38]
Grain and pork	NO3	31	Small	90	50	1950	240	[38]
Grain and pork	NO1	61	Large	135	50	3900	480	[38]
Grain and pork	NO2	61	Large	135	50	3900	480	[38]
Grain and pork	NO3	61	Large	135	50	3900	480	[38]
Dairy	NO1	25	Small	90	50	3380	30	[36]
Dairy	NO2	25	Small	90	50	4630	40	[36]
Dairy	NO3	25	Small	90	50	3380	30	[39]
Dairy	NO1	59	Large	90	50	8080	170	[36]
Dairy	NO2	48	Large	90	50	6780	290	[36]
Dairy	NO3	59	Large	90	50	7880	170	[36]

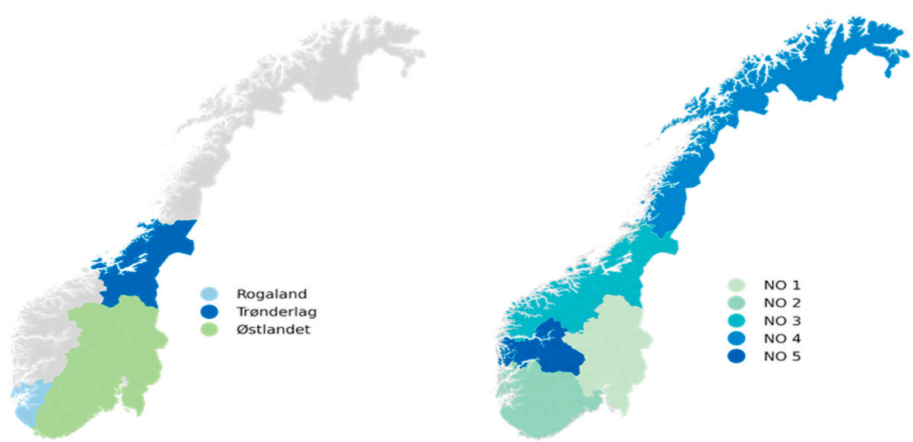

Fig. 1. Geographical relation of farming regions (left) and electricity market bidding areas (right).

drying grain bales, a workshop, and storage space for 600 tons of grain. A small combined grain and pork farm had an annual electricity consumption of 125 632 kWh, including processes such as a cold air fan for grain drying and charging of an electric vehicle. A large dairy farm large had an annual electricity consumption of 151 272 kWh, including processes such as an automatic feeder mixer, an automatic feeder and a milking robot in addition to heating and other electric loads. Since data on electricity consumption was measured only in three different farms, it was assumed that electricity consumption by farm buildings on the same farm type have the same annual electricity consumption and profile.

2.1.2. *Considered tractor fleet and energy use in on-field tractor operations*

In the reference energy system, the tractor fleet consists of one large diesel tractor, which can perform both large (>70 kW) and small (≤70 kW) tractors' on-field operations. The power output of the large tractor was assumed to be between 90 and 135 kW depending on the farm type, whereas the power output of the small tractor was assumed to be 50 kW. The large diesel tractor can be replaced with a large fuel cell tractor (FCT) and a small battery-electric tractor (BET), which can perform the on-field operations of a large and small tractor, respectively. This assumption is based on the characteristics of currently developed tractor prototypes by the major agricultural machinery manufacturers, especially regarding the vehicle energy storage capacity [41,42].

The energy demand for on-field tractor operations for large FCT and small BET were estimated based on the annual diesel consumption of large and small diesel tractors, respectively using equations (1) and (2):

$$M_{FCT} = V_{Diesel} * \frac{HV_{Diesel}}{HV_{H_2}} * \frac{\eta_{DT}}{\eta_{FCT}} \tag{1}$$

$$E_{BET} = V_{Diesel} * HV_{Diesel} * \frac{\eta_{DT}}{\eta_{BET}} \tag{2}$$

where V_{Diesel} is the annual diesel consumption, HV_{Diesel} is the energy density of diesel (10 kWh/L), HV_{H2} is the energy density of hydrogen (33.3 kWh/kg), η_{DT} is the efficiency of diesel tractor (30%), η_{H2} is the efficiency of FCT (50%) and η_{BET} is the efficiency of BET (70%) [35]. The annual diesel requirements for the on-field tractor operations were based on the estimates from previous studies [36–39]. It was assumed that the on-field tractor operations were carried out during hours between 8:00 and 18:00. For days with intensive workload (e.g., ploughing and fertilisation), the working hours could be between 4:00 and 24:00. The timing of on-field tractor operations and the related energy demand on three different example farms is illustrated in Fig. 2.

2.1.3. Assumed tractor fleet parameters

Assumed parameters for the tractor fleet are summarized in Table 2. All monetary values are presented in euro (€) using exchange rates of 1.2 USD/€ and 9.6 NOK/€ [43]. The investment cost of a large diesel tractor is based on the tractor model Fend 312 Vario S4 with an output power of 123 hp [44]. In this regard, large FCTs are assumed to have the same vehicle output power as large diesel tractors, while the output power of small tractors is based on the power output of BET Fend eVario 100 [41]. Several tractor and agricultural machinery manufacturers have developed some diesel-hydrogen and electric prototypes in the last years [41, 42], however to the best of the authors' knowledge, zero-emission tractors (ZETs) are not currently commercially available. Therefore, the investment costs of ZETs are estimated based on the investment cost of a diesel tractor and the cost ratios between a diesel heavy-duty truck and a fuel cell heavy-duty truck or battery-electric heavy-duty truck. This results in a more conservative assumption regarding the cost of investing in ZETs than what is presented in the literature, see e.g., Ref. [45]. Moreover, it is assumed that ZETs are the first available to be invested in 2030. The price of diesel is assumed to remain constant during the modelling horizon, at 0.07 €/kWh [3]. The emission factor for diesel is set to 0.25 kg/kWh [46].

2.2. Aggregating from farm to national level

The method used for aggregating the farm-level results to the national level is based on the upscaling method presented in Ref. [35]. In this regard, the total area of grain crops/forage crops (per cow) for each of the 16 example farm types and regions were estimated using statistical data regarding the total number of farms and agricultural area in Norway [51], and it was estimated to cover 50% of the fully cultivated land in Norway [35]. The total farming area per farm type and region is presented in Fig. 3. The aggregated national-level results were estimated based on the average size of each farm type presented in Table 1 and the total farming area per farm type.

2.3. Energy system modelling

In this study, the energy system models are generated by TIMES (The Integrated MARKAL-EFOM System) modelling framework [52]. TIMES is a bottom-up modelling framework providing a detailed techno-economic description of resources, energy carriers, conversion technologies and energy demand from a social welfare perspective. The TIMES model minimises the total discounted cost of an energy system to meet the demand for energy services for the regions over the period analysed.

2.3.1. Description of the IFE-TIMES-Norway model

The IFE-TIMES-Norway is a linear programming model to analyse the long-term development of the Norwegian energy system [48]. Spatially, the model covers the geographical regions in Norway, which correspond to the current electricity market bidding areas. The model provides investment and operational decisions for eight model periods starting from 2018 until 2050. To capture operational variations in energy generation and end-use, each model period is split into 96 sub-annual time slices, representing four seasons and 24-h sub-periods. The total energy system cost includes investment in supply and demand technologies operation and maintenance costs, income from electricity export and costs of electricity import from neighbouring countries. The IFE-TIMES-Norway model has a detailed description of the end-use of energy, and the demand for energy services is divided into numerous end-use categories within industry, buildings, and transport sectors. A detailed description of different sectors is presented in Ref. [48]. Each demand category can be met by existing and new technologies such as electricity, district heating, bioenergy, hydrogen, and fossil fuels. Other input data include fuel and CO_2 emission prices, exogenous electricity prices in regions outside Norway, renewable energy resources, and techno-economic characteristics such as capital and operational expenditures, efficiencies, technical lifetime, and learning curves.

Existing transmission capacity, both within Norway and to neighbouring countries,[2] is modelled exogenously and is based on the current transmission capacities (TC) and ongoing capacity expansion. The model allows new investment to TC, both on existing and new connections. The first year of investment is fixed to 2030 due to the long lead time of new transmission line projects. The electricity spot prices in the bidding areas in Norway are endogenous, as those are the dual values of the electricity balance equation, while the electricity prices in the neighbouring countries with TC to Norway are exogenous. The IFE-TIMES-Norway model has been soft-linked to various European power system models, such as EMPIRE model [53], to capture the characteristics of the European power market under different future pathway scenarios.

A two-stage stochastic framework is applied to capture the uncertainty related to solar PV production [54,55]. This is since increasing penetration of variable renewable energy can affect the short- and long-term electricity spot price level and volatility, which is often attributed to the merit-order effect and the uncertainty related to renewable electricity generation [56,57]. This will provide an investment decision under uncertainty based on the different operational scenarios and the operational decisions in each of these scenarios. In this regard, a total of 30 operational scenarios are included in the modelling runs, where each scenario has the same probability to occur. The different operational scenarios consist of different solar PV production profiles. A moment-based optimisation method described in Ref. [58] is used to select 30 days in each of the four seasons from the raw dataset obtained from renewables. ninja [59,60]. The resulting electricity spot prices and the price of delivered hydrogen in each bidding area (see Fig. 5) are used as inputs in the TIMES-farm hybrid energy system model.

2.3.2. Description of the TIMES-farm hybrid-PV-battery-hydrogen system

The TIMES-farm is a linear programming model to analyse a grid-connected distributed hybrid energy system, including on-site solar photovoltaics (PV) generation and hydrogen (H_2) production, energy storage and infrastructure for ZET charging/filling. The topology of the hybrid-PV-battery-hydrogen system is presented in Fig. 4. The model provides investment and operational decisions for ten model periods starting from 2020 until 2060. Each model period is divided into 8640 sub-annual time slices, representing 12 months, 30 days, and 24 h. The total energy system cost includes investment in supply and demand technologies operation and maintenance costs, income from selling electricity and costs of buying electricity from the grid. A description of different subsystems is presented below, while the subsystem-related parameters are summarized in Table 3.

2.3.2.1. PV system. The PV production profiles are gathered from the open data source renewables. ninja [59,60], as this was shown to give relatively high correlations with measured PV production in the Norwegian spot price regions [69]. Renewables. ninja provides hourly capacity factors from 2000 to 2018 (19 years). These data sets are used to generate averaged (arithmetic mean) capacity factor profiles and annual

[2] Countries with transmission line capacities to/from Norway include Denmark, Sweden, Finland, United Kingdom, Netherlands, and Germany.

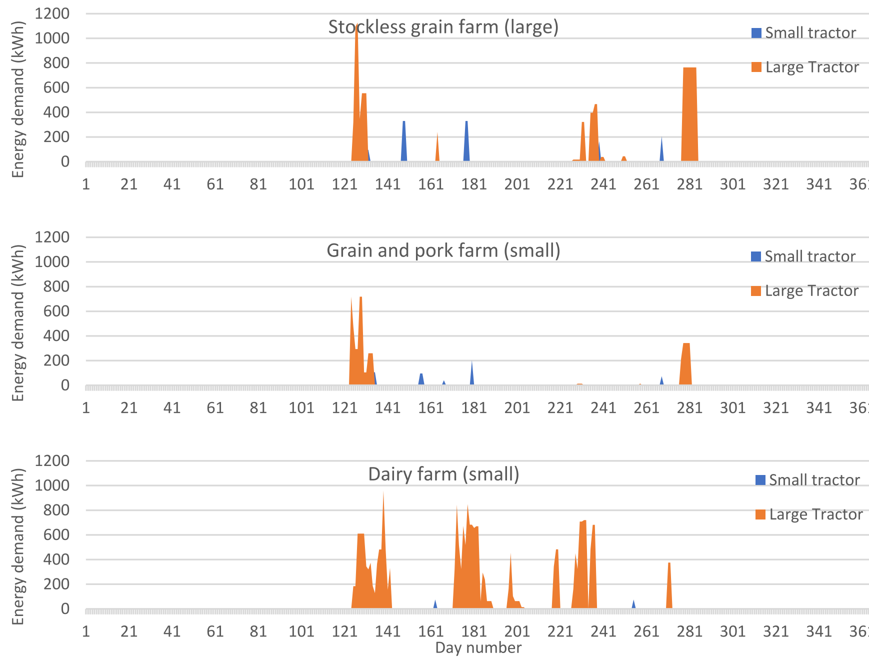

Fig. 2. Large and small tractors' energy demand related to on-field tractor operations on large stockless grain farm (top), small grain and pork farm (middle) and large dairy farm (bottom). The x-axis represents the running numbering of days.

Table 2
Tractor fleet parameters.

Subsystems	Parameter	Value				Source
			2020	2030	2050	
Diesel tractor	Investment cost (€/kW)		1300	1300	1300	[44, 47]
	Fixed O&M (% of investment cost)	10.5				
	Efficiency (%)	30				
	Lifetime (years)	15				
Battery-electric tractor (BET)	Investment cost (€/kW)[a]		3000	2190	1100	[47, 48]
	Fixed O&M (% of investment cost)	10.5				
	Efficiency (%)	70				
	Lifetime (years)	15				
Vehicle battery-pack	Investment cost (€/kWh)		155	85	40	[49]
	Roundtrip efficiency (%)	95				
	Maximum number of cycles	3700				
	Lifetime (years)	10				
Fuel cell tractor (FCT)	Investment cost (€/kW)[a]		4730	2920	1240	[47, 48]
	Fixed O&M (% of investment cost)	10.5				
	Efficiency (%)	50				
	Lifetime (years)	15				
Hydrogen storage tank	Investment cost (€/kWh)		20	17	15	[50]
	Roundtrip efficiency (%)	99				
	Lifetime (years)	15				

[a] Does not include the investment cost of vehicle battery-pack or hydrogen storage tank.

availability factors (see Table 3) for each region, using equation (3)

$$cf_{avg,t} = \frac{1}{n}\sum_{i-1}^{n} cf_{i,t} \forall t = 1, \ldots, 8760 \tag{3}$$

where $cf_{i,t}$ is the hourly capacity factor in the year I and hour t and n is the number of data sets. For all the regions, the following assumptions are made: the system is facing south with a 30-degree tilt, the system loss is set to 10% and the PV system is assumed to be a fixed-tilt system. Latitudes and longitudes for each of the regions were selected based on the largest city in the region.[3]

2.3.2.2. Battery storage system and BET charger. Battery electricity storage (BES) is modelled as a stationary storage system that can utilize the excess PV production, which can be either used as self-consumption at the farm (e.g., BET charging, electrolyzer, building) or sold to the grid in form of energy arbitrage. Moreover, it is assumed that BES is used as short-term storage to balance diurnal electricity demand variation. BES parameters are based on characteristics of the lithium-ion battery as presented in Ref. [49]. The lithium-ion battery is chosen for this application, e.g., due to its fast-charging capability, high energy density, long calendar and cycle lives and high roundtrip efficiency [70].

2.3.2.3. Hydrogen production, storage, and refuelling system. Hydrogen production, storage and refuelling system include PEM electrolyzer, stationary pressurized hydrogen gas storage tank and refuelling system. The investment cost of a PEM electrolyzer consists of three parts: electrolyzer, compressor skid and other costs (e.g., control system, installation, etc.). Furthermore, the variable cost for the PEM electrolyzer includes the costs of the hydrogen refuelling station. It is assumed that a pressurized hydrogen gas storage tank can be used as long-term storage to balance seasonal hydrogen demand variation.

2.3.2.4. Grid electricity and modelling of future energy prices. Grid

[3] NO1 = Oslo (59.91°N, 10.75°E), NO2 = Kristiansand (58.16°N, 8.02°E) and NO3 = Trondheim (63.43°N, 10.40°E).

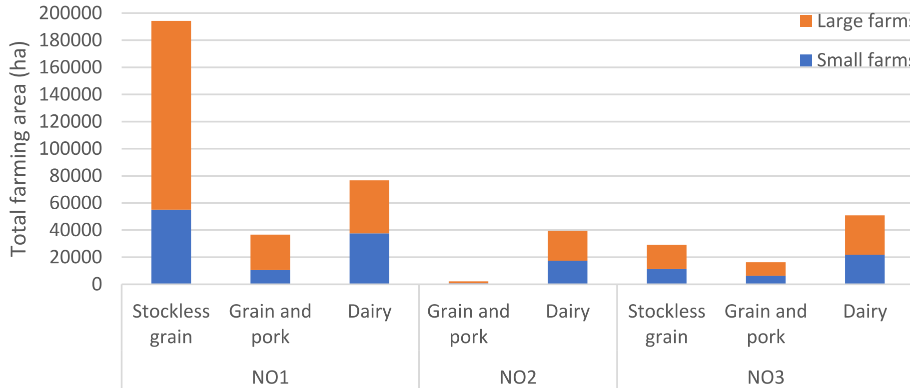

Fig. 3. Total farming area per farm type and region.

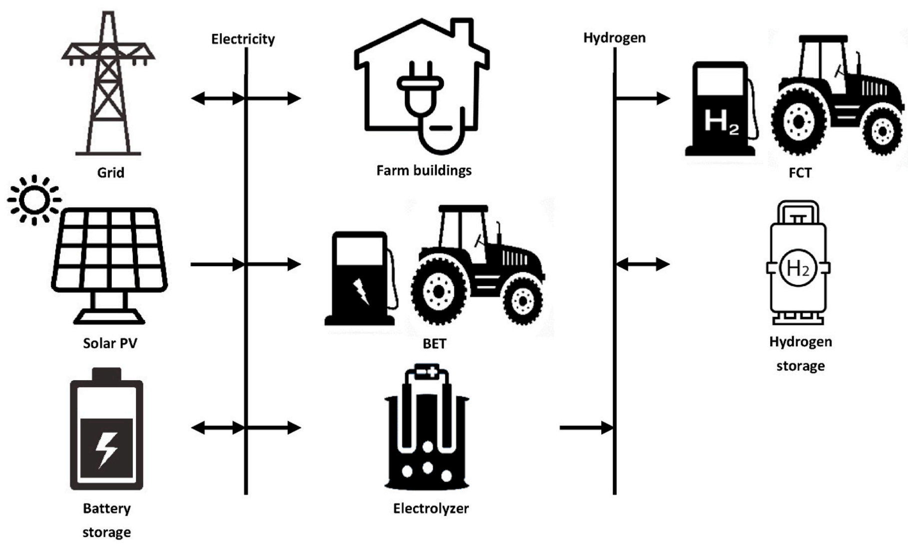

Fig. 4. Topology of the distributed energy system.

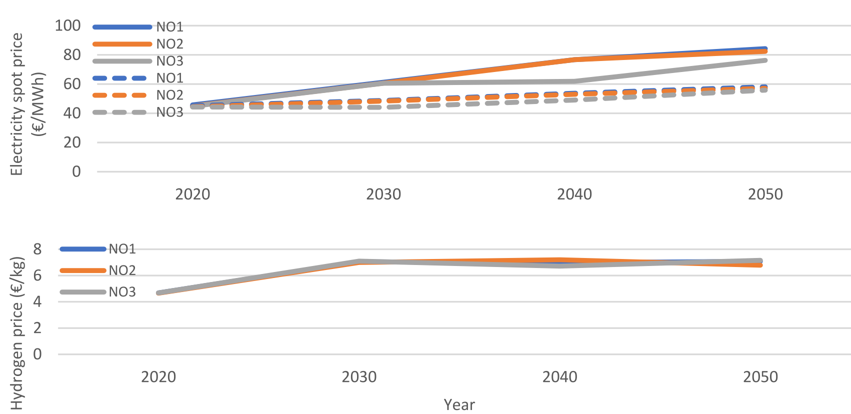

Fig. 5. Modelled future electricity spot prices (top) and the price of centrally produced hydrogen (bottom) in different bidding areas in Norway until 2050. The dashed lines correspond with the low power price scenario (S7).

electricity price is based on the current cost structure and level and consists of two parts: power charges and energy charges [71]. The power charges vary between 2.4 €/kW and 15.6 €/kW depending on the time of year. The energy charges consisted of hourly electricity spot price and an energy charge that vary with the time of year between 0.004 €/kWh and 0.007 €/kWh. Higher power and energy charges occur during the winter months (November to March). As described in Section 2.2.1, a two-stage stochastic framework was used to model future electricity spot prices and the price of centrally produced hydrogen in different bidding areas in Norway, which are presented in Fig. 5.

Table 3
Hybrid energy system parameters.

Subsystems	Parameter	Value				Source
			2020	2030	2050	
PV system	Investment cost (€/kW)		990	575	430	[61]
	Fixed O&M (% of investment cost)	0.5				
	Annual availability factor	0.11/ 0.12/ 0.11[b]				
	Lifetime (years)	30				
	Maximum installed capacity (kW_p)	80[c]				
Battery electricity storage (stationary)	Investment cost (€/kWh)		595	430	230	[49]
	Roundtrip efficiency (%)	95				
	Maximum number of cycles	4500				
	Lifetime (years)	20				
	C-rate	0.35				
Pressurized hydrogen gas storage tank (250 bar)	Investment cost (€/kWh)		20	17	15	[50]
	Roundtrip efficiency (%)	99				
	Lifetime (years)	25				
PEM electrolyzer[a]	Investment cost (€/kW)		3310	1890	1060	[62–65]
	Fixed O&M (% of investment cost)	3				
	Variable O&M (€/kWh)		0.13	0.08	0.07	
	Efficiency (%)		57	64	69	
	Lifetime (years)		7	9	15	
Charger (BET)	Investment cost (€/kW)		1040	300	300	[3,66]
	Efficiency (%)	90				
	Lifetime (years)	15				
Hydrogen dispenser (FCT)	Efficiency (%)	98				[67]
	Lifetime (years)		7	9	15	

[a] Includes the costs of a hydrogen refuelling system (e.g., hydrogen dispenser).
[b] Annual availability factor for regions NO1/NO2/NO3.
[c] With a PV module power density of 205 $W_p/m.^2$ this equates to 390 $m^2$of roof area [68], which is assumed to represent the available roof area for PV installations typical to the farms.

2.4. *Modelled scenarios and sensitivity analysis*

The reference scenarios are based on the base assumptions described above and represent the reference case for each farm type presented in Tables 1 and i.e., 16 reference scenarios in total. The sensitivity of the results is analysed for the large stockless farms located in regions NO1 and NO2 and for the small pork and grain farm located in region NO3 due to the varying level of energy demand for these farm types. Modelled scenarios and parameter changes in the sensitivity scenarios are summarized in Table 4.

3. Results

This section includes the results regarding annual energy use in on-field tractor operations, and consequent CO_2 emissions, which are first presented at the national level. Secondly, detailed farm-level results are used to describe the effects of electrification in the agricultural sector by considering the varying energy demand and timing of operations on different farm types. Finally, farm-level results are presented regarding the techno-economic sizing of the hybrid energy system at the farms. The farm-level results are presented for large stockless grain, small pork and grain and large dairy farms.

Table 4
Modelled scenario descriptions.

Scenario	Description
Reference (Ref)	Base assumptions as described in the previous sections.
CO_2 tax (S1)	The carbon tax in 2020 is set to 60 € per ton of CO_2 emitted, and then increased to 210 €/tCO_2 in 2030, 310 €/tCO_2 in 2040, and 450 €/tCO_2 in 2050.
Grid tariff (S2)	The power charges (€/kW) from April to October are increased by 50%.
Delivered hydrogen (S3)	The farms can purchase hydrogen from centralized hydrogen production plants in addition to on-site production. The cost of hydrogen delivered by gaseous tube trailers is modelled with the IFE-TIMES-Norway model (see Supplementary material).
High PV cost (S4)	Low learning rate, i.e., high solar PV costs are assumed: investment cost (and fixed O&M cost) in 2020 is set to 1250 €/kW (6.3 €/kW), 730 €/kW (3.6 €/kW) in 2030, and 540 €/kW (2.7 €/kW) in 2050.
Low PV cost I (S5)	High learning rate, i.e., low solar PV costs are assumed: investment costs (and fixed O&M cost) in 2020 are set to 730 €/kW (3.6 €/kW), 430 €/kW (2.2 €/kW) in 2030, and 315 €/kW (1.6 €/kW) in 2050.
Low PV cost II (S6)	Learning rate as presented in scenario S5. Furthermore, increased efficiency is considered by increasing the maximum installed solar PV capacity per farm type by 10% in 2030, and 30% in 2050.
Low power price (S7)	Low electricity spot prices, which are modelled with the IFE-TIMES-Norway model.
Low technology learning curve for tractors (S8)	Low learning rate, i.e., high technology costs are assumed for the BETs and FCTs: investment costs (and fixed O&M costs) in 2030 are set to 2600 €/kW (335 €/kW) and 3810 €/kW (435 €/kW), and 2185 €/kW (275 €/kW) and 2910 €/kW (335 €/kW) in 2050, respectively.

3.1. *Energy use related to on-field tractor operations*

Fig. 6 presents the aggregated annual energy use related to on-field tractor operations and on-site renewable energy generation. At the regional level, energy use in the on-field tractor operations is the highest in the NO1 region, and conversely the lowest in the NO2 region. The results show that diesel consumption in on-field tractor operations decreases significantly in 2030 and onward. At the same time, the consumption of substituting energy carriers increases. Electricity consumption increases especially due to the on-site hydrogen production in the electrolysis process, but also due to charging of small BET. The total energy use related to on-field tractor operations decreases during the modelling horizon. This is due to the improved well-to-wheel efficiency of replacing zero-emission tractors. Additionally, on-site solar PV generation starts to increase in 2030. The on-site PV generation is limited by the assumed available roof area for PV installations, hence remaining at the maximum level between 2035 and 2050. At the annual level, this is sufficient capacity to supply on-site solar PV generation to cover the increased electricity consumption due to the electrification of on-field tractor operations on all farm types. However, importing electricity from the grid is still needed to cover the electricity consumption in farm buildings. An exception to this is stockless grain farms, which are net exporters of electricity (at the annual level) due to the lower electricity demand of farm buildings.

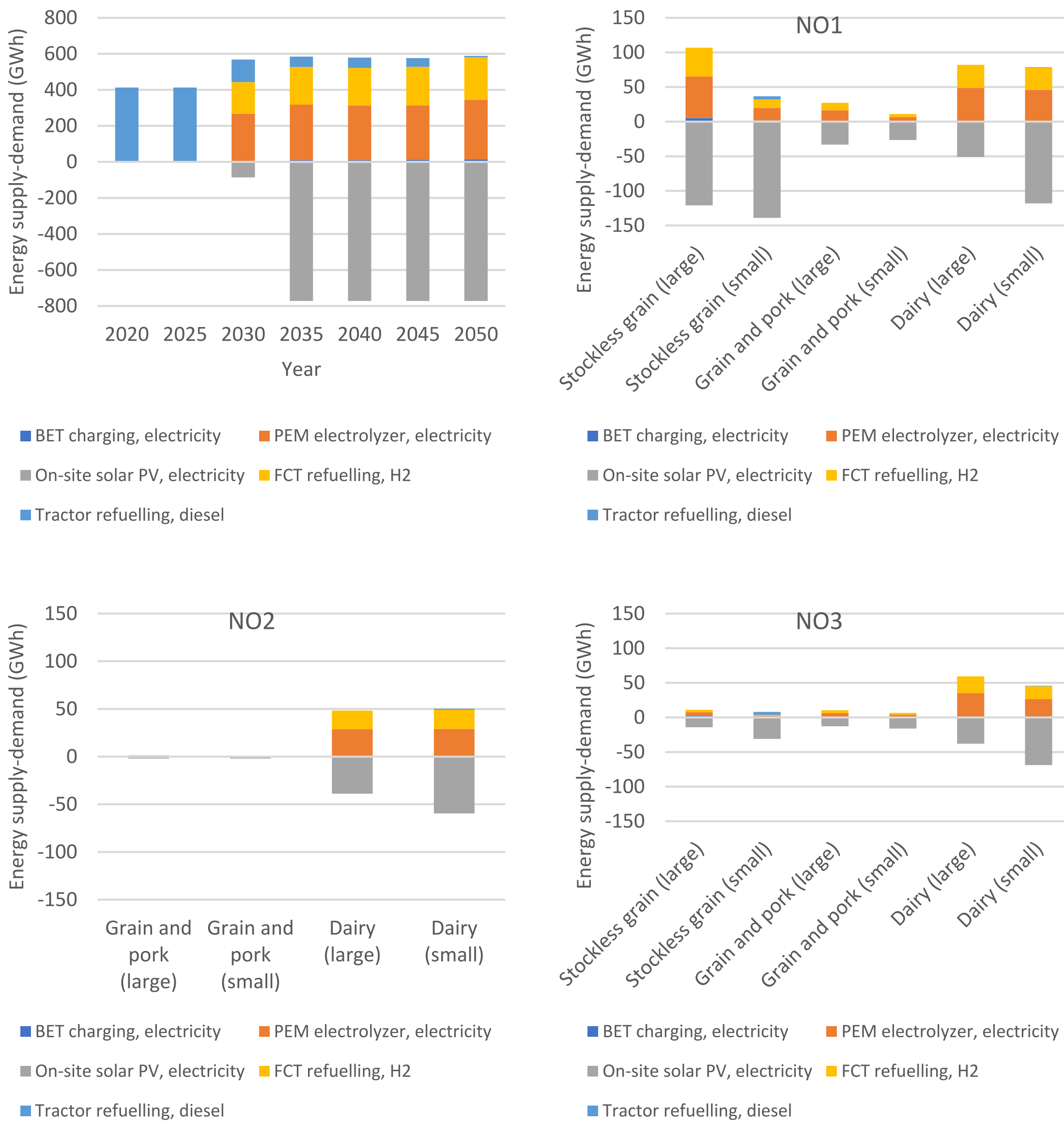

Fig. 6. Aggregated annual energy use related to on-field tractor operations and renewable energy generation at the national level (top left). Aggregated annual energy use and renewable energy generation based on farm type located in regions NO1 (top right), NO2 (bottom left) and NO3 (bottom right) in 2050.

Diesel consumption in on-field tractor operations can be observed to continue in 2050, especially at the small stockless grain and small/large dairy farms. This can be attributed to low daily working hours with the use of small tractors on these farm types (see Fig. 2). In this case, reducing operating costs are not enough to cover the higher investment costs of ZEVs, which makes investing in small BETs unprofitable.

3.2. CO_2 emission reduction potential from substituting fossil fuel consumption in on-field tractor operations

Fig. 7 presents the consequent CO_2 emissions from the energy use in on-field tractor operations that are aggregated to the farming region and farm type level. Tractor energy use-related CO_2 emissions start to decline in 2030 when diesel consumption is substituted with electricity[4] and/or hydrogen. Consequently, the tractor energy use-related CO_2 emissions are mainly phased out by 2050. At the farm type level, CO_2 emissions are observed to decline at a faster rate at pork and grain farms, and vice versa at a slower rate at the small stockless grain and small/large dairy farms, where replacing diesel tractors with small BETs is less profitable. Tractor energy use-related CO_2 emissions are observed to be most sensitive to assumptions related to a carbon tax (S1) and manufacturing costs of ZETs (S8). Currently, the use of diesel in tractors is exempt from carbon taxation in Norway. When carbon tax is applied to diesel use, the annual CO_2 emission can be observed to decline at a slightly faster rate due to a faster rate of electrification, however, a minor amount of CO_2 emissions can still be observed in 2050. Conversely, the annual CO_2 emissions related to tractor energy use decline at a slower rate when the manufacturing costs of ZETs are assumed to decline at a slower rate.

3.3. Electrification and distributed energy generation, the effects on electricity consumption on the farms

As presented in Fig. 8, total electricity consumption, and especially

[4] The CO_2 emission intensity of grid electricity in Norway and solar PV electricity generation is assumed to be zero.

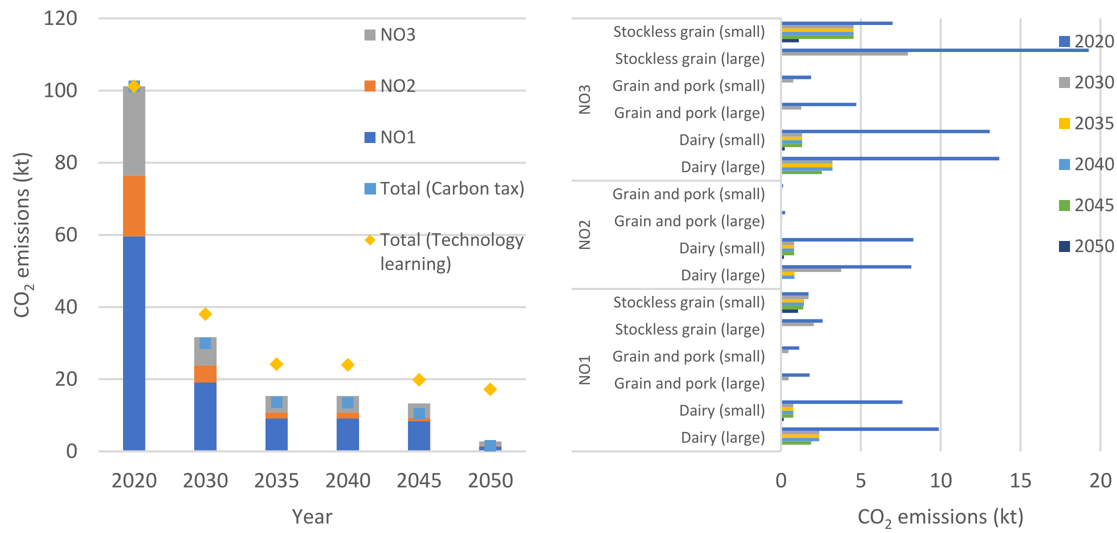

Fig. 7. Tractor energy use-related CO_2 emissions aggregated to farming region level, representing the three major farming areas in Norway (left). The sensitivity of the results is presented with square and diamond markers. The square marker represents the total CO_2 emissions in the carbon tax scenario (S1). The diamond marker represents the total CO_2 emissions in the low technology learning rate scenario (S8). Aggregated CO_2 emissions based on farm type and region (right).

peak demand, on farms is observed to increase due to the electrification of on-field tractor operations. Annual electricity consumption increases especially due to the on-site hydrogen production in electrolysis. Charging of small BETs have only a minor effect on the annual electricity demand since the BET on-field operations occur only during a few labour-intensive days (see Fig. 2). However, since the BET's battery capacity limits on-field tractor work to only a few hours, the vehicle battery needs to be recharged during the day. This is observed to have a significant effect on the increase in peak electricity demand on the farms. Peak electricity demand is observed to increase by 2–4 fold depending on the farm type. This occurs especially during the months between May and October when most of the on-field tractor work occurs. Thus, the negative effects of increasing peak demand on the Norwegian power system are reduced since at the national level peak demand occurs often during winter when heating-related electricity demand is higher.

Furthermore, on-site solar PV generation and BES systems can mitigate this effect, as presented in Fig. 9. Re-charging of vehicle batteries correlates most of the time with on-site solar PV generation. The BES system at farms is mostly utilised for reducing the need for importing electricity from the grid by shifting excess on-site solar PV generation to hours when on-site PV generation is not available. However, it is observed to be unprofitable to dimension the BES system to be able to store all the excess solar PV generation. This decreases the share of solar PV self-consumption, which is observed to be lower at the stockless grain farms.

3.4. Techno-economic sizing of the farm hybrid-PV-battery-hydrogen systems

Table 5 presents the results regarding the optimal sizing of different components of the hybrid-PV-battery-hydrogen system at large stockless grain, small pork and grain, and large dairy farms. The results show that before 2035 the cost-optimal sizing of on-site solar PV systems varies among the farm types. On-site PV system is observed to be more profitable for farm types with higher electricity demand. At the regional level, it is observed that on-site solar PV system is more profitable in NO2 and NO3 regions. However, from 2035, the optimal sizing of the on-site PV system is restricted by the available roof area, with installed capacity being 80 kW on all farm types, as presented in Table 6. Additional solar PV capacity such as building-integrated PV on facades, or as agriphovoltaics, could increase the maximum capacity beyond the assumed level. In this regard, it is observed that optimal sizing of the on-site PV system increases as the upper bound for the maximum installed PV capacity is relaxed (S6). As the capacity of the on-site PV system increases, the net imports of electricity from the electricity grid decrease, however also the share of self-consumption declines (i.e., a higher share of on-site PV generation is exported to the grid). The sizing of the on-site solar PV system, and especially the timing of the investment, is most sensitive to assumptions regarding the investment cost of the PV system. In this regard, the optimal sizing of on-site PV systems reaches the upper bound already in 2030 when it is assumed that module manufacturing costs decline at a faster rate (S5). Vice versa, the upper bound is reached in 2040 with a slower rate of module manufacturing costs decline (S4).

Battery electricity storage (BES) systems will become profitable for on-site energy storage from 2040 onward, i.e., as the cost of the BES system decreases, the cost-optimal sizing of the BES system increases. This can mostly be attributed to the declining investment cost of the BES system, but also to increasing electricity spot prices in the future. At the regional level, it is observed that BES systems are more profitable on farms located in NO1 and NO2 regions. This can be explained by higher electricity spot prices in combination with higher spot price variability towards 2050. At the farm level, the BES systems are dimensioned to meet 5–19% of the average daily electricity demand. This indicates that on-site BES is utilised to provide capacity (power) rather than energy in short-term diurnal balancing. For example, the on-site BES system reduces the need for importing electricity from the grid during the peak residual demand[5] hours. The sizing of the BES system is most sensitive to the assumptions relating to grid electricity price. In this regard, on-site energy storage becomes more profitable when the power charge is increased (S2). This is because, with a flat increase in power charges (from April to October), the on-site solar PV self-consumption becomes more valuable than exporting excess generation to the grid. On the other hand, with lower electricity spot prices (S7), profits from energy arbitrage decrease, which reduces the profitability of on-site energy storage.

[5] Electricity demand that cannot be met by renewable energy sources, e.g., on-site solar PV generation.

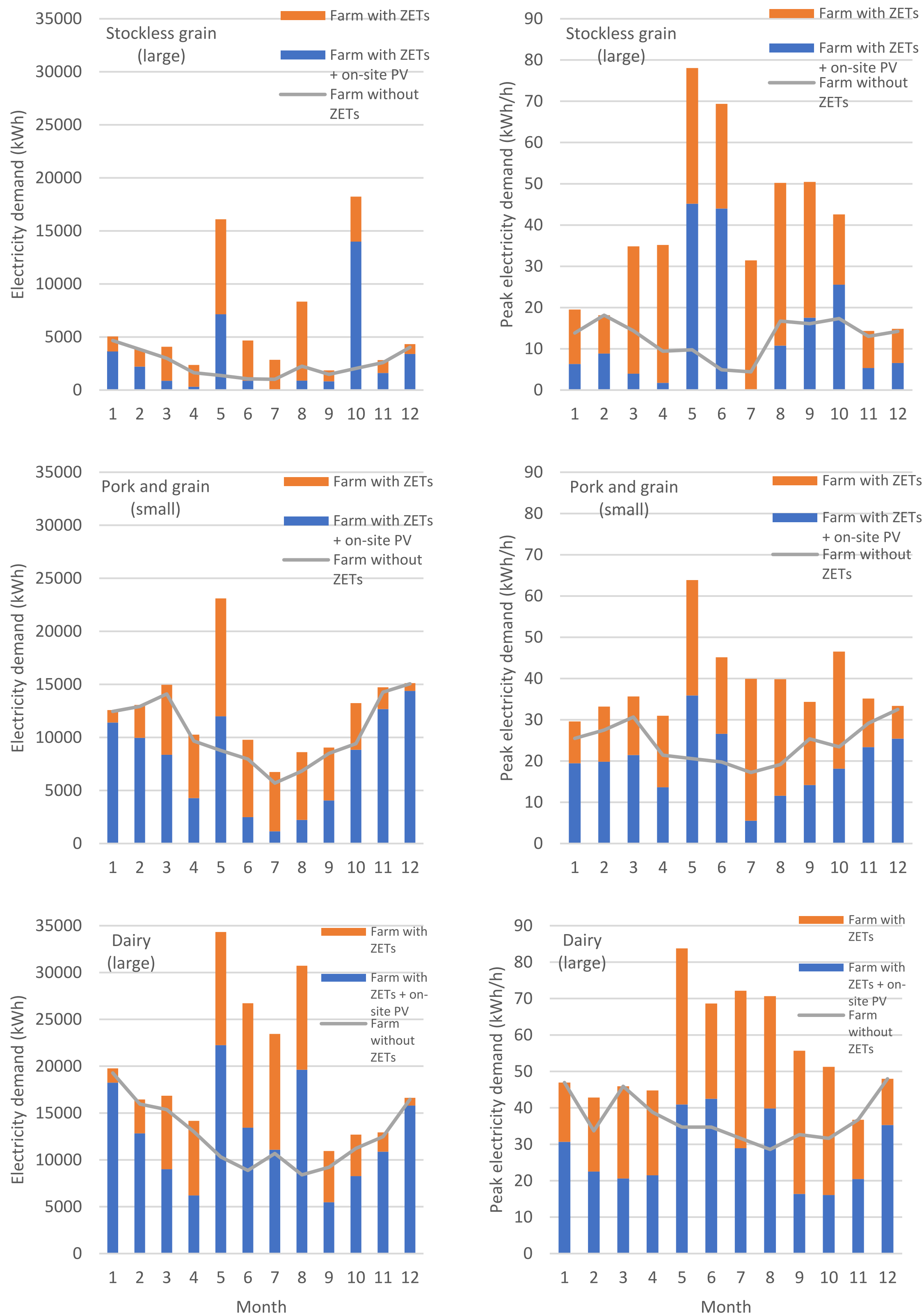

Fig. 8. The effect of electrification of on-field tractor operations with zero-emission tractors (ZETs) on monthly (x-axis, month) total (left) and peak (right) electricity consumption at large stockless grain (top), small pork and grain (middle), and large dairy (bottom) farms in 2050. The blue column represents residual electricity demand. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

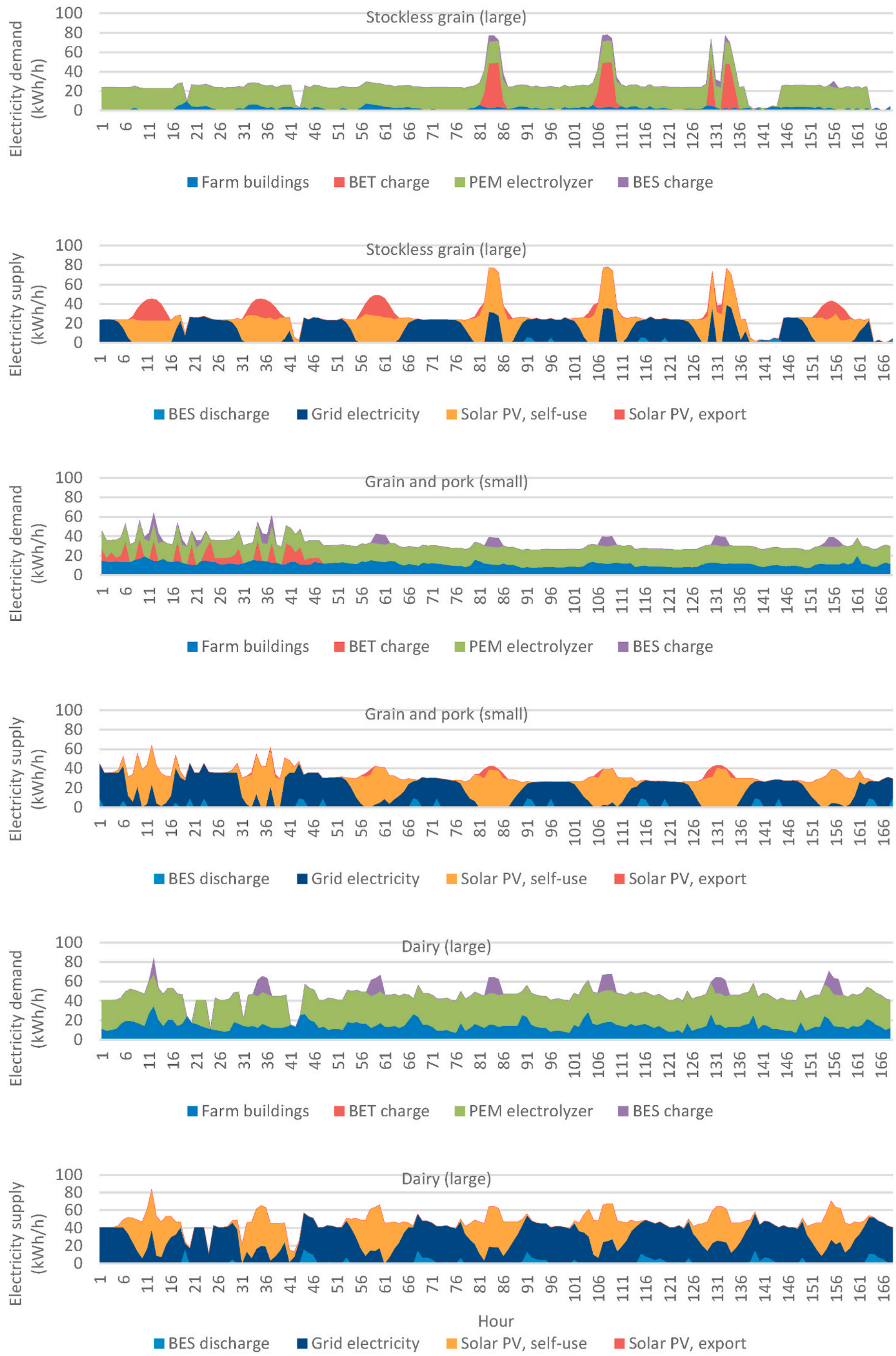

Fig. 9. Electricity supply-demand balance at large stockless grain farm (top, week 19), small pork and grain farm (middle, week 20), and dairy farm (bottom, week 19) during a week (x-axis, hour) with the highest peak electricity demand in 2050.

The cost-optimal sizing of on-site hydrogen system components is highly dependent on the hydrogen demand on the farm and the source of hydrogen (i.e., on-site vs. centralized production). The optimal sizing of the on-site hydrogen system favours utilising a larger pressurized H_2 gas storage tank as a buffer over a larger PEM electrolyzer to meet the hourly H_2 demand. This can mainly be attributed to (i) assumed costs of different hydrogen system components, and (i) high electricity demand in the electrolysis process, which increases the variability of on-site H_2 production costs, creating more opportunities for energy arbitrage. At the region level, it can be observed that this also makes the optimal sizing of the hydrogen system less sensitive to electricity price differences between the farming regions (i.e., electricity bidding areas). The PEM electrolyzer needs to operate 41–61 and 34–46 h at full capacity to fill the H_2 storage tank at pork and grain and dairy farms, respectively. However, the optimal sizing of the H_2 storage tank/electrolyzer capacity is observed to be more dependent on the large FCT's on-field operation profile rather than on the annual hydrogen demand on the farm. For example, at the stockless grain farm, a larger H_2 storage tank for buffering is more profitable than investing in a larger PEM electrolyzer due to a few days of intensive FCT on-field tractor operations with high H_2 demand. In this regard, the PEM electrolyzer needs to operate for 70–105 h at full capacity to fill the H_2 storage tank. Furthermore, the H_2 storage tank is dimensioned to meet 5–6% of the annual hydrogen demand at the stockless grain and pork and grain farms, and 2% at the

Table 5
Sizing of components in the hybrid-PV-battery-hydrogen system in large stockless grain, small pork and grain, and large dairy farms located in region NO1.

Farm type	PV system (kW)	BES (kWh)	PEM electrolyzer (kW)	Pressurized H_2 gas storage tank (kg)
Stockless grain, large (2030)	9.6	0	10.8	28.6
Stockless grain, large (2035)	80	0	15.2	32.0
Stockless grain, large (2040)	80	8.4	15.2	32.0
Stockless grain, large (2045)	80	13.1	15.2	40.4
Stockless grain, large (2050)	80	17.7	15.2	45.9
Pork and grain, small (2030)	0	0	7.7	14.0
Pork and grain, small (2035)	80	0	12.4	16.3
Pork and grain, small (2040)	80	6.1	12.4	16.3
Pork and grain, small (2045)	80	15.5	12.4	17.9
Pork and grain, small (2050)	80	28.4	12.4	18.0
Dairy, large (2030)	9.1	0	16.5	21.9
Dairy, large (2035)	80	0	16.5	21.9
Dairy, large (2040)	80	25.6	16.5	21.9
Dairy, large (2045)	80	35.0	17.5	23.3
Dairy, large (2050)	80	48.3	22.3	26.3

dairy farm. The cost-optimal sizing of the on-site hydrogen system is most sensitive to assumptions related to manufacturing costs of FCTs (S8) since it directly affects the hydrogen demand at the farm. Furthermore, on-site H_2 production and storage are observed to become unprofitable with assumed costs when delivering hydrogen by gaseous tube trailers to the farms is allowed (S3).

4. Discussion

The modelling results in this paper are in line with recent publications regarding electrification in the agricultural sector. In Ref. [18], the advantages of agriphotovoltaics and electrified agricultural machinery for sustainable transformation of the agriculture sector are discussed. In this study, only the deployment of roof-mounted solar PV was considered. However, recent studies have shown that agriphotovoltaic could also add value by enabling the simultaneous production of energy and food, which can correlate with economic benefits to farmers [72]. Similar findings regarding the economics of battery-electric tractors (BET) are presented in Ref. [45] where BETs were found to have a comparable or lower annual cost than equivalent diesel vehicle systems. Moreover, the authors highlight that battery ageing can have a significant impact on the associated costs. It was also shown that a larger battery capacity had a noticeably lower annual cost compared to an equivalent diesel system.

This study is limited in terms of geographical scope, agricultural machinery included and data availability. In this regard, the modelling results can underestimate the electrification potential in the Norwegian agricultural sector. For example, recent studies have shown that fossil fuel consumption of energy-intensive agricultural machinery could be substituted for example with hydrogen [73]. On the other hand, zero-emission tractors (ZETs) are not commercially available in the market, and hence the rate of ZET deployment and associated costs can be highly uncertain. In this regard, the sensitivity analysis revealed high sensitivity to manufacturing costs of zero-emission tractors (ZETs). This uncertainty can also lead to an alternative pathway for agricultural sector decarbonisation. Moreover, previous studies have shown that the success of renewable technologies in the agricultural sector can depend to a large extent on a proper regulatory framework and local acceptance, rather than mere techno-economic aspects [17]. Thus, agricultural sector decarbonisation could also increase the use of bioenergy in applicable processes, such as biofuels used by tractors and agricultural machinery. In this study, this is not considered since the long-term effects of global bioenergy targets on the net cumulative emissions can be uncertain, e.g., due to rotation time of biomass, production and transport of biofuels, land use and carbon stock changes, etc.) [74]. Furthermore, bioenergy is a flexible energy carrier that can be used in several processes and different sectors. Considering that bioenergy is a limited renewable energy resource, the utilization of bioenergy should be optimised for the processes where it is techno-economically most feasible. In this regard, a study of decarbonisation of road freight transport concluded that unlimited access to biofuels can delay the introduction of other zero-emission vehicles (ZEVs, e.g., battery-electric, fuel cell) [75]. Furthermore, in Ref. [76] it was found that utilising biomass in energy generation (e.g., combined heat and power) can have higher GHG emission reduction potential compared to converting biomass into biofuels that can be used in the transportation sector.

5. Conclusions

The work presented in this paper has focused on the effects of phasing-out fossil fuel consumption in on-field tractor operations in the

Table 6
Sizing of components in the hybrid-PV-battery-hydrogen system based on the farm type, size, and region in 2050.

Farm type	Region	Size category	PV system (kW)	Battery electricity storage (kWh)	PEM electrolyzer (kW)	Pressurized H_2 gas storage tank (kg)
Stockless grain	NO1	Small	80	18.6	4.1	13.0
Stockless grain	NO3	Small	80	18.3	2.5	7.8
Stockless grain	NO1	Large	80	17.7	15.2	45.9
Stockless grain	NO3	Large	80	18.3	11.1	35.4
Grain and pork	NO1	Small	80	28.4	12.4	18.0
Grain and pork	NO2	Small	80	30.6	12.4	18.0
Grain and pork	NO3	Small	80	21.3	12.4	18.1
Grain and pork	NO1	Large	80	28.4	24.9	36.2
Grain and pork	NO2	Large	80	29.8	24.8	36.1
Grain and pork	NO3	Large	80	21.3	24.8	35.8
Dairy	NO1	Small	80	48.3	9.5	11.4
Dairy	NO2	Small	80	48.8	13.4	13.9
Dairy	NO3	Small	80	42.9	8.8	11.6
Dairy	NO1	Large	80	48.3	22.3	26.3
Dairy	NO2	Large	80	48.8	20.1	21.7
Dairy	NO3	Large	80	40.8	20.6	26.6

agricultural sector in Norway. The electrification pathway was analysed by introducing battery-electric and/or fuel cell tractors and on-site renewable energy generation and storage on different farm types. The main conclusions from this paper are as follows:

- Electrification of on-field tractor operations can be a techno-economically feasible pathway to reduce tractor energy-use-related CO_2 emissions in the agricultural sector in Norway. Annual CO_2 emissions were observed to reduce by 69% in 2030 and 97% in 2050. However, the CO_2 reduction potential can vary significantly based on the farm type.
- The analysis revealed high sensitivity to the development of zero-emission tractor (ZET) manufacturing costs, which in combination with a low utilization rate can render the investment to ZETs unprofitable for some farm types. Applying carbon tax to diesel use was observed to accelerate the rate of electrification. However, substituting diesel consumption completely in the agricultural sector in Norway may require some form of additional Government policy (e.g., subsidy).
- Electrification in the agricultural sector increases electricity consumption, especially peak electricity demand during the months between May and October when most of the on-field tractor operations occur. Depending on the farm type, the peak electricity demand was observed to increase by 2–4 fold. However, in the northern European climate of Norway, the effect on the national power system is reduced since electricity demand in the national grid is typically at a lower level during the summer.
- The effect on the national power system can be reduced with on-site renewable energy generation and energy storage systems. The BES systems were found to be utilised to provide capacity (power) rather than energy in short-term diurnal balancing. On the other hand, the optimal sizing of the on-site hydrogen system was found to favour utilising a larger pressurized H_2 gas storage tank as a buffer over a larger PEM electrolyzer to meet the hourly H_2 demand. The on-site solar PV system can reduce the need for importing electricity from the grid. Moreover, excess solar PV generation can be exported to the national grid, which can have positive effects on the national power system (e.g., deferring capacity expansion). In this regard, the share of solar PV self-consumption was observed to vary significantly depending on the total electricity demand on the farm.

National long-term targets to reduce fossil energy-related GHG emissions require participation from each economic sector. In this paper, an electrification pathway to reduce tractor energy-use-related CO_2 emissions was presented, however, future research is still required. The analysis of CO_2 reduction potential in the agricultural sector can be improved by including also other agricultural machinery (e.g., combine harvesters, planters, sprayers, etc.). Recent studies have shown that fossil fuel consumption of energy-intensive agricultural machinery could be substituted for example with hydrogen [73]. Moreover, including synergies regarding available on-site energy carriers (e.g., biogas) on applicable farm types can improve the findings regarding the least-cost decarbonisation pathway. Finally, including socio-economic aspects of energy transition in the agricultural sector can improve the analysis. For example, previous studies have shown that the success of renewable technologies in the agricultural sector can depend to a large extent on a proper regulatory framework and local acceptance, rather than mere techno-economic aspects [17].

Credit author statement

Ville Olkkonen: Conceptualization, Methodology, Investigation, Data Curation, Writing - Original Draft, Writing – Review & Editing. **Arne Lind**: Conceptualization, Methodology, Data Curation, Writing - Original Draft, Writing – Review & Editing. **Eva Rosenberg**: Conceptualization, Methodology, Data Curation, Writing – Review & Editing. **Lisa Kvalbein**: Conceptualization, Methodology, Data Curation, Writing – Review & Editing.

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.

Data availability

Data will be made available on request.

Acknowledgements

The work presented in this paper is financially supported through the Solar Farm project (Research Council of Norway, grant number 280390). The authors gratefully thank Dr. Anne-Grete Roer Hjelkrem and Dr. Anne Kjersti Bakken from NIBIO for providing the data used in this paper.

References

[1] Nations U. The sustainable development goals report. 2022.
[2] Lovdata. Lov om endringer i klimaloven (klimamål for 2030 og 2050) (Act on amendments to the climate act (climate targets for 2030 and 2050). 2022 [cited 2022 21.04]; Available from: https://lovdata.no/dokument/LTI/lov/2021-06-18-129.
[3] Norwegian environment agency. Klimakur 2030-Tiltak og virkemidler mot 2030 (Climate cure 2030-Measures and instruments towards 2030). 2020. p. 1. Available: https://www.miljodirektoratet.no/globalassets/publikasjoner/m1625/m1625_sammendrag.pdf.
[4] SSB. Emissions to air [cited 2022 28.04]; Available from: https://www.ssb.no/en/natur-og-miljo/forurensning-og-klima/statistikk/utslipp-til-luft; 2022.
[5] Norges bondelag, Landebrukets klimaplan 2021-2030 (Agriculture's climate plan 2021-2030). 2020.
[6] Lin BQ, Xu B. Factors affecting CO2 emissions in China's agriculture sector: a quantile regression. Renewable Sustainable Energy Rev 2018;94:15–27.
[7] Farokhi Soofi A, Manshadi SD, Saucedo A. Farm electrification: a road-map to decarbonize the agriculture sector. Electr J 2022;(2):35.
[8] Deike S, Pallutt B, Christen O. Investigations on the energy efficiency of organic and integrated farming with specific emphasis on pesticide use intensity. Eur J Agron 2008;28(3):461–70.
[9] Dumortier J, Elobeid A, Carriquiry M. Light-duty vehicle fleet electrification in the United States and its effects on global agricultural markets. Ecol Econ 2022:200.
[10] Mulenga E, Bollen MHJ, Etherden N. A review of hosting capacity quantification methods for photovoltaics in low-voltage distribution grids. Int J Electr Power Energy Syst 2020:115.
[11] Hemmati R, Saboori H. Emergence of hybrid energy storage systems in renewable energy and transport applications – a review. Renewable Sustainable Energy Rev 2016;65:11–23.
[12] Shen X, et al. Expansion planning of active distribution networks with centralized and distributed energy storage systems. IEEE Trans Sustain Energy 2017;8(1):126–34.
[13] Renewable power generation costs in 2019, the international renewable energy agency. Abu Dhabi: IRENA; 2020.
[14] Kavlak G, McNerney J, Trancik JE. Evaluating the causes of cost reduction in photovoltaic modules. Energy Pol 2018;123:700–10.
[15] Renewable energy statistics 2021, the international renewable energy agency. Abu Dhabi: IRENA; 2021.
[16] Stohr M, Hackenberg B. Enhancing synergy effects between the electrification of agricultural machines and renewable energy deployment with semi-stationary energy storage in rural grids. In: 12th international renewable energy storage conference, vol. 2018; 2018. p. 179–87. Ires.
[17] Ketzer D, et al. Land use conflicts between biomass and power production - citizens' participation in the technology development of Agrophotovoltaics. J Respons Innov 2020;7(2):193–216.
[18] Schneider AK, et al. Drawing transformation pathways for making use of joint effects of food and energy production with biodiversity agriphotovoltaics and electrified agricultural machinery. J Environ Manag 2023;335:117539.
[19] Zhang DB, et al. Research on the configuration and operation effect of the hybrid solar-wind-battery power generation system based on NSGA-II. Energy 2019:189.
[20] Zakeri B, et al. Policy options for enhancing economic profitability of residential solar photovoltaic with battery energy storage. Appl Energy 2021:290.
[21] Khan FA, Pal N, Saeed SH. Review of solar photovoltaic and wind hybrid energy systems for sizing strategies optimization techniques and cost analysis methodologies. Renewable Sustainable Energy Rev 2018;92:937–47.

[22] Okundamiya MS. Size optimization of a hybrid photovoltaic/fuel cell grid connected power system including hydrogen storage. Int J Hydrogen Energy 2021; 46(59):30539–46.
[23] Macedo SF, Peyerl D. Prospects and economic feasibility analysis of wind and solar photovoltaic hybrid systems for hydrogen production and storage: a case study of the Brazilian electric power sector. Int J Hydrogen Energy 2022;47(19):10460–73.
[24] Klingler AL. Self-consumption with PV + Battery systems: a market diffusion model considering individual consumer behaviour and preferences. Appl Energy 2017;205:1560–70.
[25] Abdin Z, Merida W. Hybrid energy systems for off-grid power supply and hydrogen production based on renewable energy: a techno-economic analysis. Energy Convers Manag 2019;196:1068–79.
[26] Mayyas A, Wei M, Levis G. Hydrogen as a long-term, large-scale energy storage solution when coupled with renewable energy sources or grids with dynamic electricity pricing schemes. Int J Hydrogen Energy 2020;45(33):16311–25.
[27] Zandrazavi SF, et al. Stochastic multi-objective optimal energy management of grid-connected unbalanced microgrids with renewable energy generation and plug-in electric vehicles. Energy 2022:241.
[28] Xu X, et al. Risk-based scheduling of an off-grid hybrid electricity/hydrogen/gas/refueling station powered by renewable energy. J Clean Prod 2021:315.
[29] Mehrjerdi H, et al. Unified energy management and load control in building equipped with wind-solar-battery incorporating electric and hydrogen vehicles under both connected to the grid and islanding modes. Energy 2019;168:919–30.
[30] Ringkjob HK, et al. Short-term solar and wind variability in long-term energy system models - a European case study. Energy 2020:209.
[31] Zhou W, et al. Assessment of the impacts of different policy instruments on achieving the deep decarbonization targets of island energy systems in Norway – the case of Hinnøya. Energy 2022:246.
[32] Lund H, et al. EnergyPLAN – Advanced analysis of smart energy systems. Smart Energy 2021:1.
[33] Siala K, et al. Which model features matter? An experimental approach to evaluate power market modeling choices. Energy 2022:245.
[34] Brouwer AS, et al. Operational flexibility and economics of power plants in future low-carbon power systems. Appl Energy 2015;156:107–28.
[35] Hjelkrem A-GR, et al. Potential for replacing fossil energy by local PV energy for field and transport work in Norwegian farming. 2020.
[36] Bakken AK, et al. Environmental impacts along intensity gradients in Norwegian dairy production as evaluated by life cycle assessments. Agric Syst 2017;158: 50–60.
[37] Henriksen TM, Korsaeth A. Inventory of Norwegian grain production: data from three average- and three high yielding cereal farms located in the major grain producing areas of Norway. 2013.
[38] Johansen A, Hjelkrem AGR. Livsløpsanalyser av norsk svinekjøttproduksjon med og utan heimeprodusert grassaft som fôr. 2018.
[39] Roer AG, et al. Environmental impacts of combined milk and meat production in Norway according to a life cycle assessment with expanded system boundaries. Livest Sci 2013;155(2–3):384–96.
[40] Hernandez JC, Sanchez-Sutil F, Munoz-Rodriguez FJ. Design criteria for the optimal sizing of a hybrid energy storage system in PV household-prosumers to maximize self-consumption and self-sufficiency. Energy 2019:186.
[41] Fendt. Fendt FutureFarm - fendt e100 Vario [cited 2022 20.04]; Available from: https://www.fendt.com/int/e100-vario; 2022.
[42] Holland N. New holland T5.140 auto command [cited 2022 28.04]; Available from: https://h2dualpower.com/en; 2022.
[43] Norges bank. Exchange rates [cited 2022 11.07.2022]; Available from: https://www.norges-bank.no/en/topics/Statistics/exchange_rates/; 2022.
[44] Gardsdrift Bedre. Traktoroversikten (tractor overview) [cited 2022 20.04]; Available from: http://traktoroversikten.no/index.php?r=modeller/search; 2022.
[45] Lagnelov O, et al. Cost analysis of autonomous battery electric field tractors in agriculture. Biosyst Eng 2021;204:358–76.
[46] IPCC. Emission Factor Database [cited 2022 11.07]; Available from: https://www.ipcc.ch/data/; 2022.
[47] Molenhuis JR. Budgeting farm machinery costs. 2020.
[48] Danebergs J, et al. Documentation of IFE-TIMES-Norway Norway. Kjeller: IFE; 2022. ISSN: 2535-6380. ISBN: 978-82-7017-936-7. Available: https://ife.brage.unit.no/ife-xmlui/bitstream/handle/11250/2977095/IFE-E-2021-005.pdf?sequence=1.
[49] Tsiropoulos I, Tarvydas D, Lebedeva N. Li-ion batteries for mobility and stationary storage applications. EUR 29440 EN. Luxembourg: Publications Office of the European Union; 2018. https://doi.org/10.2760/87175. ISBN 978-92-79-97254-6, JRC113360.
[50] Ulleberg O, Hancke R. Techno-economic calculations of small-scale hydrogen supply systems for zero emission transport in Norway. Int J Hydrogen Energy 2020;45(2):1201–11.
[51] SSB. Statistics Norway [cited 2022 29.04]; Available from: https://www.ssb.no/en; 2022.
[52] The energy technology systems analysis Program (ETSAP). ETSAP; 2022. Available from: http://www.iea-etsap.org.
[53] Backe S, et al. EMPIRE: An open-source model based on multi-horizon programming for energy transition analyses. SoftwareX 2022:17.
[54] Seljom P, et al. Stochastic modelling of variable renewables in long-term energy models: dataset, scenario generation & quality of results. Energy 2021:236.
[55] Marti K, Kall P. Stochastic programming. Berlin, Heidelberg: Springer; 1995.
[56] Antweiler W, Muesgens F. On the long-term merit order effect of renewable energies. Energy Econ 2021:99.
[57] Rintamäki T, Siddiqui AS, Salo A. Does renewable energy generation decrease the volatility of electricity prices? An analysis of Denmark and Germany. Energy Econ 2017;62:270–82.
[58] Kaut M. Scenario generation by selection from historical data. Comput Manag Sci 2021;18(3):411–29.
[59] Pfenninger S, Staffell I. Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. Energy 2016;114:1251–65.
[60] Staffell I, Pfenninger S. Using bias-corrected reanalysis to simulate current and future wind power output. Energy 2016;114:1224–39.
[61] Nve. Norges energidager - Sesjon 5 Hvilken rolle kan solkraft spille i Norge? (Norways energydays - Session 5 What role can solar power play in Norway?). 2021 [cited 2022 20.04]; Available from, https://www.nve.no/media/12973/sesjon-5-hvilken-rolle-kan-solkraften-spille-i-norge.pdf.
[62] Elgowainy A, Reddi K. Hydrogen refueling analysis of heavy-duty fuel cell vehicle fleet. 2017 [Argonne national laboratory].
[63] Danebergs J. Techno-economic study of hydrogen as a heavy-duty truck fuel - a case study on the transport corridor Oslo – Trondheim, in *Department of energy technology Division of Heat and power technology*. Stockholm, Sweden: KTH Industrial Engineering and Management; 2019.
[64] IEA. *The Future of Hydrogen*. Paris: IEA; 2018. p. 44–5. https://www.iea.org/reports/the-future-of-hydrogen. License: CC BY 4.0.
[65] Chardonnet C, et al. Study on early business cases for H2 in energy storage and more broadly power to H2 applications. Brussels, Belgium: Tranctebel engineering S.A; 2017.
[66] Trentadue G, et al. Evaluation of fast charging efficiency under extreme temperatures. Energies 2018;(8):11.
[67] Trattner A, Klell M, Radner F. Sustainable hydrogen society – vision, findings and development of a hydrogen economy using the example of Austria. Int J Hydrogen Energy 2022;47(4):2059–79.
[68] Danish energy agency, Technology data - generation of electricity and district heating. 2022.
[69] Ortiz MM, Kvalbein L, Hellemo L. Evaluation of open photovoltaic and wind production time series for Norwegian locations. Energy 2021:236.
[70] Zubi G, et al. The lithium-ion battery: State of the art and future perspectives. Renewable Sustainable Energy Rev 2018;89:292–308.
[71] Elvia. Nettleiepriser og effekttariff for bedrifter i Oslo og Viken (Grid prices and power tariffs for companies in Oslo and Viken). 2019 [cited 2022 20.04]; Available from: https://assets.ctfassets.net/jbub5thfds15/2Mjf7J9IuatllICKBC0gUo/3f0b60d6752623c1c5c045317271c52f/Nettleiepriser_og_effekttariff_bedrift__Oslo_Viken_2020.pdf.
[72] Jain P, et al. Agrovoltaics: step towards sustainable energy-food combination. Bioresour Technol Rep 2021:15.
[73] HELIOS - a hydrogen-electric operated tractor systemPowertrain Systems in Mobile Machines. 7th International VDI. Düsseldorf; 2022. p. 95–104. Baden-Baden. 06. - 07. July 2022.
[74] Wise M, et al. Agriculture, land use, energy and carbon emission impacts of global biofuel mandates to mid-century. Appl Energy 2014;114:763–73.
[75] Danebergs J, Rosenberg E, Espegren KA. Impact of zero emission heavy-duty transport on the energy system. In: Insitute for energy technology (IFE); 2022 [Norway, Kjeller].
[76] Hedegaard K, Thyo KA, Wenzel H. Life cycle assessment of an advanced bioethanol technology in the perspective of constrained biomass availability. Environ Sci Technol 2008;42(21):7992–9.