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Potential for replacing fossil energy by local PV energy for field and transport work in Norwegian farming

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TITTEL/TITLE

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SAMMENDRAG/SUMMARY:

Sammendrag

En har i denne studien undersøkt potensialet for å erstatte fossilt drivstoff med elektrisk energi fra batterier og/eller hydrogenbrenselceller i traktorarbeidet på norske gårder. Dette ble gjort med utgangspunkt i seksten små og store modellgårder på Østlandet, i Trøndelag og i Rogaland. Disse var korngårder med og uten husdyr, og melkeproduksjonsbruk. Det årlige dieselforbruket i alle traktordrevne arbeidsoperasjoner ble beregnet og videre tidfestet og fordelt gjennom året. For alle brukstyper var det høye topper med mye traktorarbeid knyttet til pløying og/eller spredning av husdyrgjødsel om våren og til innhøsting og pløying om høsten.

Basert på effekten og kapasiteten til batteritraktorer og batterier som ble antatt å være tilgjengelige på kort sikt, ble det konkludert at maksimalt 10% av det dieseldrevne traktorarbeidet kan erstattes av batteritraktorer. Aggregert til arealet på 450 000 ha dyrket mark som nå blir drevet som modellbrukene, tilsvarer dette 3 millioner liter diesel årlig. De høye toppene i daglig arbeidsbelastning og effektbehovet for flere operasjoner begrenser ytterligere bruk av batteritraktorer. Ladetida for batteriene er for lang, og el-traktorene har ikke høy nok effekt.

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For en av de store korngårdene ble det også undersøkt om en større flåte av batteritraktorer kunne ha kapasitet til å gjøre det arbeidet som dieseltraktorer gjør i dag. En kom til at en slik flåte (0,08 traktorer per hektar dyrket mark) kunne utføre alle feltoperasjoner raskt nok og til rett tid med unntak av tresking. En slik traktorflåte med små enheter ville måtte utstyres med spesialdesignede maskiner og utstyr med tilpasset arbeidsbredde og kapasitet.

Det ble også gjort beregninger for energibruk og tidsbruk på gårdene gitt at dieseltraktorene ble byttet ut med elektriske traktorer med hydrogenbrenselsceller. Slike finnes ikke på markedet i dag, men New Holland sin prototype har høy nok effekt til å kunne gjennomføre arbeidet som var dieseldrevet på modellgårdene.

Den elektriske energien som krevdes for å erstatte fossil energi i alle traktoroperasjoner på de 450 000 ha dekket av modellgårdene, varierte mellom 445 og 465 GWh per år. Det ble da antatt at hydrogentraktorer utførte operasjoner med høy arbeidsbelastning, og den lave energieffektiviteten i hydrogenproduksjon var tatt med i beregningene. Tenkte solcelleanlegg ble dimensjonert til hver modellgård for å levere det totale årlige energibehovet for å produsere hydrogen og / eller lade batterier til traktordrift. De store gårdene måtte ha mellom 370 og 710 m^2 med PV-moduler, og det kunne være mulig å installere om en ser på tilgjengelig takareal på driftsbygninger på dagens bruksenheter.

Summary

The potential of replacing energy carriers in on-farm tractor work on Norwegian farms from fossil diesel to electric energy from batteries and/or hydrogen fuel cells has been investigated. Sixteen example farms of small and large size, covering grain production (stockless and in combination with pork) and dairy production in Østlandet, Trøndelag and Rogaland were outlined. The diesel consumption was calculated as yearly totals for single field operations and later attributed to certain day numbers. For all farm types, there were high peaks of tractor workload related to ploughing and/or spreading of animal manure in spring and to harvests and ploughing in autumn.

Based on the effect and capacity of battery tractors and batteries likely available in near future, it was concluded that maximum 10% of the diesel fuelled tractor work can be replaced by battery vehicles. Aggregated to the area of 450 000 ha cultivated land covered by our model farms, this corresponds to 3 million litres of diesel yearly. Limitations for further replacement are the mismatch between high peaks of work load and recharging time for batteries, and the high effect demand of several field operations.

The alternative of implementing a whole fleet of battery tractors was explored for one of the large sized grain farms. In theory, such a fleet (0.08 tractor units per ha farmed land) could conduct all field operations except grain harvesting. Such a fleet would, however, demand large investments in especially designed machinery and equipment with adapted working width and capacity that fit smaller tractors.

The alternative of implementing hydrogen fuel cell tractors was also investigated. Such vehicles are not commercially available on the market, but the New Holland tractor prototype would contribute effect high enough to conduct all on farm operations.

The electric energy required to replace fossil energy in all tractor operations on the 445 000 ha covered by our model farms, varied between 445 and 465 GWh per year. It was then assumed that fuel cell tractors conducted operations with high workloads, and the rather low energy efficiency in hydrogen production was accounted for. Virtual PV-systems were dimensioned to deliver the total yearly energy requirements to produce hydrogen and/or charge batteries for tractor operations on all farms individually. Large farms required between 370 and 710 m² of PV-modules, which are areas fitting quite well the roof space available on farm buildings.

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GODKJENT /APPROVED	**PROSJEKTLEDER /PROJECT LEADER**
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Preface

This study was performed within the SolarFarm-project (Exploring solar on-farm energy production combined with a fleet of electrical vehicles and precision agriculture for reduced GHG-emissions), funded by the Research Council of Norway (NFR grant number 280390).

Lisa Kvalbein and Jonathan Fagerström from Institute for Energy Technology (IFE) have contributed with calculations and evaluations of PV-systems and outputs from them. Fagerström has also taken part in discussions regarding state of the art for battery and fuel cell technology.

Anne Kjersti Bakken and Anne-Grete Roer Hjelkrem from Norwegian Institute of Bioeconomy Research (NIBIO) have designed the study and written the report. Hjelkrem is responsible for most of the calculations and results described in chapters 2 and 3. The work outlined in chapters 2.2 and 2.5 has, however, been conducted by Bakken.

Project leader Jakob Geipel and project administrator Audun Korsaeth from NIBIO have contributed substantially throughout the study.

Våler, 17.12.20

Anne-Grete Roer Hjelkrem

Content

1 Introduction

A large share of the greenhouse gas (GHG) emissions from agriculture is closely tied to biological processes, being an inevitable part of food and feed production. Measures for reduction in emissions will often come into conflict with sustained productivity.

Reducing the emissions from tractor work on farms is regarded to be among the options with lowest conflict level and as being relatively easy to achieve. In Norway, the emissions from tractors and farm machinery were estimated to be 293 000 tons CO_2-eqvivalents (CO_2e) in 2017 (SSB, cited in Kvalevåg 2019).

The farmers' associations, Norges Bondelag and Norsk Bonde- og Småbrukarlag, have recently developed their own plan for reduction in GHG emissions from agriculture (Landbrukets klimaplan 2021-2030) after they signed an intentional agreement with the Government in 2019. Replacing fossil fuel in tractors and other machinery has according to the plan a total reduction potential of 0.55 – 1.43 mill tons CO_2e for the years 2021 - 2030. This plan refers that electrification alone may contribute with a reduction of 30 000 tons CO_2e. The rest may be attained by replacing fossil diesel by biofuel or hydrogen in combustion engines.

The intrest in fossil-free electric options has increased recently in the tractor market. Electric engines have several benefits as causing no direct pollution, being more efficient, containing fewer moving parts that leads to less maintenance compared to diesel combustion engines and beeing quiet. Additionally, it is regarded to be a great potential for farmers to produce clean and renewable electricity on farm by roof mounted photovoltaic (PV) systems on farm existing buildings (Foss et al. 2016).

Both batteries and hydrogen can serve as energy carrier in electric tractors. While a fully battery powered tractor is commercially available on the market from the Californian company Solectrac, and several prototypes are developed by other companies, such as Fendt, John Deere and Rigitrac SKE, only New Holland has developed a hydrogen fuel cell powered prototype (NH2). The battery tractors are developed for lighter workloads, and can only operate over shorter distances caused by limitations in the battery technology. Hydrogen fuel cell options do in contrast have more power and operate over a longer working distance.

The estimates for annual emissions of CO_2e related to transport and soil and crop management on Norwegian farms are made by Statistics of Norway (SSB) from sales statistics of diesel in the Account statistics in agriculture and farm forestry (https://www.nibio.no/tema/landbruksokonomi/budsjettnemnda-for-jordbruket). They are totals, allowing no resolution regarding types and timing of work as well as vehicles within different production systems and operations.

A sound evaluation of the share of tractor work that could be performed with alternative energy carriers demands a detailed categorization of operations in regard to load of the work (effect demand), distance from charging/fuelling station, timing in relation to plateaus in energy use on the farm, and annual solar cycle, if solar energy captured in local PV stations is the direct source.

This approach was taken in the master theses of Alve (2015) and Skiaker (2019), where the potential for replacing diesel-powered with electrical-powered tractor work (including both battery and hydrogen fuel cell) was outlined and discussed for some example farms with grain and dairy production.

As part of the SolarFarm-project (Exploring solar on-farm energy production combined with a fleet of electrical vehicles and precision agriculture for reduced GHG-emissions, NFR grant number 280390), these studies have been expanded further to cover more operations, different fleets of vehicles, more farm types and the most important regions for agricultural productions in Norway, all to get a sound basis for upscaling the results to an aggregated national level.

The aim has been (i) to explore and quantify the potential for replacing fossil diesel with electricity from batteries and/or hydrogen fuel cells as energy carriers in field operations in Norwegian agriculture, and (ii) to outline the physical investments in batteries, charging stations, PV-systems, hydrogen plants and storage solutions that are demanded if the transformations are to be implemented.

2 Material and Methods

2.1 Description of the farms

Sixteen different grain and dairy example farms were included in this study (Table 1) to represent the main part of Norwegian agriculture in terms of cultivated area. The group of grain farms consisted of both stockless farms and farms with pork production, while all dairy farms produced forage for grazing and indoor feeding as feed for dairy cows as well as heifers and male off-spring for beef production. All farms and farming operations have been described in detail in previous studies (Roer et al. 2013, Korsaeth et al. 2014; Bakken et al. 2017; Johansen and Hjelkrem 2018) and were representative of medium and large size farms in the regions Østlandet (including Agder, Vestfold, Telemark, Buskerud, Oppland, Akershus, Østfold and Hedmark), Trøndelag and Rogaland in 2010-2015. Since stockless grain farms are virtually non-exisitng in Rogaland, this type was excluded from this study. Area per farm unit has increased almost 20% over the last ten years (SSB 2020), and the farm units previously reffered to as medium sized will in this study be reffered to as small.

Detailed inventories of the farms have been outlined previously (Table 1) and included description of the tractor fleet and energy demand for on-field tractor operations. Initially, and here regarded as a base case, the tractor fleet on all farms consisted of one large diesel tractor and one or two small diesel tractors. Additionally, four possible changes in energy carrieries from diesel to electric battery and/or to hydrogen fuel cell were outlined forming five scenarios of on-farm tractor fleets.

Tractor fleet 1: Large and small diesel tractor (base case)

Tractor fleet 2: Large diesel tractor and small battery tractor

Tractor fleet 3: Large hydrogen tractor and small battery tractor

Tractor fleet 4: Large and small hydrogen tractor

Tractor fleet 5: Fleet of small battery tractors

Tractor fleet 1 is the base case with one large and one to two small diesel tractors as outlined in the previous studies. In Tractor fleet 2, the small diesel tractors were replaced with small battery tractors assumed to have similar power output as the small diesel tractors. In Tractor fleet 3, the large diesel tractor was replaced with a large hydrogen tractor while the small tractors were replaced with small battery tractors, both assumed to have the same power output as the diesel tractors. In Tractor fleet 4, all tractors were replaced with hydrogen tractors assumed to have the same power output as the diesel tractors. Tractor fleet 5 consisted of a fleet of small battery tractors. The Fendt e100 Vario battery-powered tractor with a power output of 50 kW was the model in this scenario and the working capacity and width, and the energy demand for the on-field tractor operations were changed accordingly.

Tractor fleet 1-4 was applied at all 16 farms, while Tractor fleet 5 was only applied at the large stockless grain farm in Østlandet (Farm 3) only.

Table 1: Overview of the 16 different grain and forage farms, including area in addition to power output and diesel use for the large and small diesel tractor.

Farm	Region and type	Area (ha)	Size category	Power output large tractor (kW)	Power output small tractor (kW)	Diesel large tractor (l/year)	Diesel small tractor (l/year)	Reference
1	Stockless grain in Østlandet	30.5	Small	90	45 & 60	1 280	270	Farm 1, Henriksen and Korsaeth (2013)
2	Stockless grain in Trøndelag	28.3	Small	90	45 & 60	1 310	400	Farm 5, Henriksen and Korsaeth (2013)
3	Stockless grain in Østlandet	88.7	Large	135	45 & 70	4 250	660	Farm 2, Henriksen and Korsaeth (2013)
4	Stockless grain in Trøndelag	98.0	Large	110	70	3 090	2 630	Farm 6, Henriksen and Korsaeth (2013)
5	Grain and pork in Østlandet	30.5	Small	90	45 & 60	1 950	240	M1, Johansen and Hjelkrem (2018)
6	Grain and pork in Trøndelag	30.5	Small	90	45 & 60	1 950	240	M1, Johansen and Hjelkrem (2018)
7	Grain and pork in Rogaland	30.5	Small	90	45 & 60	1 950	240	M1, Johansen and Hjelkrem (2018)
8	Grain and pork in Østlandet	61.0	Large	90	45 & 60	3 900	480	M1 x 2, Johansen and Hjelkrem (2018)
9	Grain and pork in Trøndelag	61.0	Large	90	45 & 60	3 900	480	M1 x 2, Johansen and Hjelkrem (2018)
10	Grain and pork in Rogaland	61.0	Large	90	45 & 60	3 900	480	M1 x 2, Johansen and Hjelkrem (2018)
11	Dairy in Østlandet	24.5	Small	90	40	3 380	30	BC, Bakken et al. (2017)
12	Dairy in Trøndelag	24.5	Small	90	40	3 380	30	BC, Bakken et al. (2017)
13	Dairy in Rogaland	24.5	Small	90	40	4 630	40	SW, Roer et al. (2013)
14	Dairy in Østlandet	59.0	Large	95	60	8 080	170	CSEI, Bakken et al. (2017)
15	Dairy in Trøndelag	59.0	Large	95	60	7 880	170	CSEI, Bakken et al. (2017)
16	Dairy in Rogaland	47.9	Large	93	40	6 780	290	SWI x 1.5, Bakken et al. (2017)

2.2 Timing of on-field tractor operations

The figures for diesel consumption in different field operations as summarized in Table 1, represented yearly totals. The timing of the operations is essential information when cycles and peaks in energy demand are to be worked out. In line with this, each single tractor operation on all farm types was attributed to a certain day number. This was based on expert knowledge residing within the team of authors and their contacts within the agricultural extension service. No tractor was allowed to work for more than 20 hours per day, and all operations were assumed to go on without interruptions due to weather episodes or technical problems. In practice, there will be several intermissions during a growing season. The resulting peaks in energy demand outlined in this study might therefore be a bit exaggerated. Still, all farmers will strive to perform their field work under optimal conditions, which often occur within very narrow time windows during the growing season.

2.3 Energy sources and carriers for on-farm tractor operations

2.3.1 Diesel

Diesel fuel still powers almost every tractor at Norwgian farms. Yearly diesel consumption for on-farm field operations was estimated for different farm types in previous studies and has been listed in Table 1. Diesel combusted in combine harvesters was excluded from the given totals for grain farms. The calculations leading to these figures were based on specifications of working width and capacity of equipment and devices driven by tractors, the load of different types of work, and the effect of tractors. Further details regarding data sources and calculations can be found in Johansen et al. (2013) and Henriksen and Korsaeth (2013).

2.3.2 Solar energy

A PV-system consists of several interconnected PV-modules and an inverter. The modules deliver direct current (DC) electricity, which is, through the inverter, converted to alternating current (AC) electricity. The total energy produced by the PV-system ($E_{out,PV}$) is the total irradiation incident on the modules ($E_{inn,PV}$) multiplied by the efficiency of the PV-system (η_{PV}) (Equation 1).

$$E_{out,PV} = \eta_{PV} \cdot E_{inn,PV} \qquad (1)$$

Irradiation incident on the PV-modules, $E_{inn,PV}$, was estimated in the PV system modelling software, PVsyst (https://www.pvsyst.com/). The Meteonorm 7.2 database provided global horizontal irradiance data (time period 1986 to 2005), for the three locations: Apelsvoll in Østlandet, Kvithamar in Trøndelag and Særheim in Rogaland (Table 2). Decomposition and transposition algorithms in PVsyst were then used to translate the global horizontal irradiance into irradiance incident on the inclined PV-modules. The PV-modules were based on IBC PolySol 265 CS4 (https://www.ibc-solar.de/) with a total efficiency of 0.16. Additionally, power is lost in the inverter, due to series resistance, mismatch between modules and soiling. This is reffered to as the performance ratio, assumed to be 0.8, leading to a total efficiency of 0.13 for the PV-system. The modules are 1.92 m^2 and have a nominal capacity of 265 Wp each.

Table 2: Yearly input energy to the PV-system estimated by PVsyst and output energy from the system based on the IBC PolySol 265 CS4 PV-modules for the three locations Østlandet, Trøndelag and Rogaland.

	$E_{inn,PV}$ (kWh/m^2)	$E_{out,PV}$ (kWh/m^2)
Østlandet	1030	165
Trøndelag	1120	180
Rogaland	1060	170

2.3.2.1 Battery charging

Electricity from the PV-system may be the energy source of a battery charging station. The charger converts AC electricity to DC. Some energy is lost due to heat during charging, and the efficiency coefficient of the charger was set to η_{CS} = 0.90 (Trentadue et al. 2018). Additionally, energy is also lost within the battery (η_B = 0.95) (Pengwei and Lu 2015). The total energy delivered by the battery ($E_{out,B}$) can then be estimated from the energy delivered by the PV-system ($E_{out,PV}$) and the efficiency coefficients (Equation 2).

$$E_{out,B} = \eta_{CS} \cdot \eta_B \cdot E_{out,PV} \quad (2)$$

2.3.2.2 Hydrogen production

Electricity from the PV-system may also be the energy source in hydrogen production. Here, AC electricity from the PV-system is converted to DC (η_C =0.98). Thereafter, the DC electricity powers an electrolyser that produces hydrogen from oxygen and water. Based on the Avãlence HydroFill system which is a Proton Exchange Membrane (PEM) electrolyzer, hydrogen pressure reaches up to 400 bar (Zinola 2010), with 350 bars assumed in this study. The electrolyser requires an input energy ($e_{inn,H2}$) of 60.5 kWh per kg produced hydrogen (Ivy 2004), which equals an efficiency of about 55%. The total produced mass of hydrogen (m_{H2}) is calculated from the energy delivered by the PV-system and the required input energy per kg produced hydrogen (Equation 3).

$$m_{H2} = \frac{\eta_C \cdot E_{out,PV}}{e_{inn,H2}} \quad (3)$$

The energy needed from the PV-system to produce a certain amount of hydrogen can be derived accordingly (Equation 4).

$$E_{out,PV} = \frac{m_{H2} \cdot e_{inn,H2}}{\eta_C} \quad (4)$$

2.4 Effect and energy demand for tractors

2.4.1 Diesel powered tractor

In tractor operations, power is used for traction, for power take-off (PTO) or for both combined, depending on the operation performed. Power is sent in to the tractor in form of diesel ($P_{inn,D}$; kW), and the total power input can be calculated from the diesel consumption (C_D; l/h) and the calorific value (CV; kWh/l) according to Equation 5.

$$P_{inn,D} = C_D \cdot CV \quad (5)$$

The calorific value of diesel is CV = 10.10 kWh per litre (SSB 2020: https://www.ssb.no/a/magasinet/miljo/tabell.html) while diesel consumption (C_D) was previously calculated for the individual on farm field operations (Table 1).

A schematic overview of a diesel tractor is given in Figure 1. Diesel is converted to mechanical power through a combustion engine, and is further delivered to two shafts. One shaft delivers power to the gear box, on to the main drive and finally to the wheels for traction. The other shaft delivers power to the power take-off drive (PTOD) and on to the PTO.

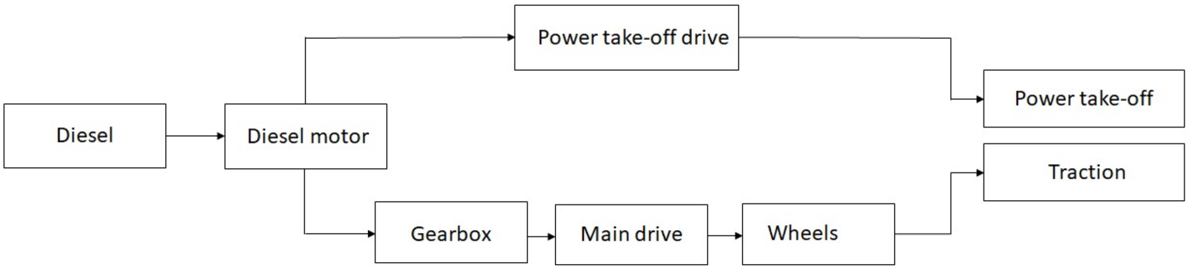

Figure 1: Schematic overview of a diesel tractor.

Power is lost during tractor operations, generally due to heat loss, friction, vibration and/or noise in the different components (Figure 1). The loss varies between tractors and tractor operations depending on torque, engine speed, the engine rated power, how the gearbox is controlled, wheel grip, rolling resistance, degree of slip and more (Bøe 2000). This variation in loss, is not included in this study, whereas an average value is used. The loss is in the following described by efficiency coefficients, which is defined as the ratio of output to input power. The total efficiency coefficient of the diesel tractor is divided between traction ($\eta_{tot,DT}$) and PTO ($\eta_{tot,DPTO}$) and is calculated by multiplying the efficiency coefficients of the separate components in Figure 1 (Equation 6 and 7).

$$\eta_{tot,DT} = \eta_{DM} \cdot \eta_G \cdot \eta_{MD} \cdot \eta_W \quad (6)$$

$$\eta_{tot,DPTO} = \eta_{DM} \cdot \eta_{PTOD} \quad (7)$$

The efficiency coefficient for the diesel motor (η_{DM} = 0.33), the gearbox (η_G = 0.85), the main drive (η_{MD} = 0.83), the wheels (η_W = 0.68) and the power take-off drive (η_{PTOD} = 0.95) were set in accordance with Alve (2015).

The power from the motor can be used (i) entirely for traction (f_{PTO} = 0, f_T = 1), (ii) entirely on PTO (f_{PTO} = 1, f_T = 0) or (iii) divided between traction and PTO. When the power is divided between traction and PTO, it is assumed that 70% is for PTO (f_{PTO} = 0.7) and 30% is for traction (f_T = 0.3) (Alve 2015). Accordingly, the efficiency coefficient is calculated from Equation 8.

$$\eta_{tot,D} = f_T \cdot \eta_{tot,DT} + f_{PTO} \cdot \eta_{tot,DPTO} \quad (8)$$

For the three options, the calculated total efficiency coefficient for the diesel tractor becomes (i) $\eta_{tot,D}$ = 0.16 (only traction), (ii) $\eta_{tot,D}$ = 0.31 (only PTO) and (iii) $\eta_{tot,D}$ = 0.27 (both traction and PTO).

The output power can then be calculated separately for traction ($P_{out,T}$) and PTO ($P_{out,PTO}$) according to Equation 9 and 10.

$$P_{out,T} = \eta_{tot,DT} \cdot P_{inn,D} \quad (9)$$

$$P_{out,PTO} = \eta_{tot,DPTO} \cdot P_{inn,D} \quad (10)$$

Similarly, the total output power (P_{out}) is found by Equation 11.

$$P_{out} = P_{out,T} + P_{out,PTO} = \eta_{tot,D} \cdot P_{inn,D} \quad (11)$$

Further, the total energy sent into the motor in form of diesel ($E_{inn,D}$; kWh) was found by multiplying the power by the period of time ($time$, h) (Equation 12).

$$E_{inn,D} = P_{inn,D} \cdot time \quad (12)$$

The output energy (E_{out}) was calculated accordingly (Equation 13).

$$E_{out} = P_{out} \cdot time \quad (13)$$

2.4.2 Electric battery tractor

A schematic overview of an electric battery tractor is given in Figure 2. DC electricity is sent from the battery into two separate inverters converting the DC power back to AC. From one inverter, power is sent to the electric motor, on to the main drive and finally to the wheels for traction. From the other inverter, power is sent through a transmission cable and to the electric PTO.

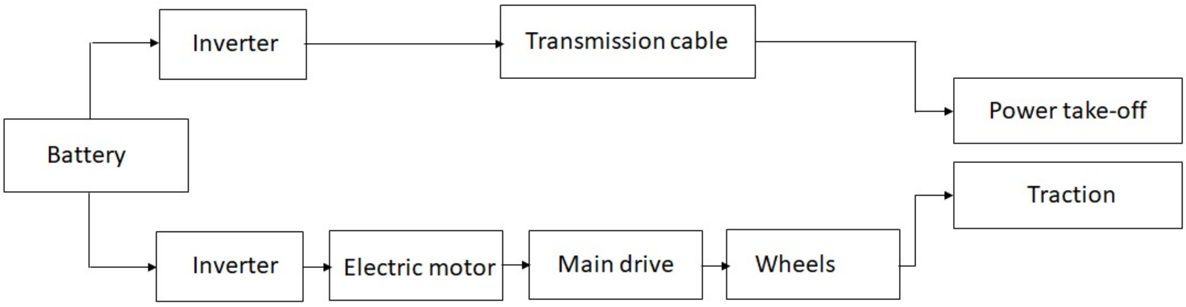

Figure 2: Schematic overview of an electric battery tractor.

The total output power from the battery in the electric tractor, used for traction ($P_{out,T}$) and for the electric PTO ($P_{out,PTO}$) during the different on-farm tractor operations is similar to the output power from the diesel tractors.

Caused by the differences in the construction, the efficiency of the two types of tractors differ (Figure 1 and 2). As for the diesel tractors, the total efficiency coefficient of the electric battery tractor is divided between traction ($\eta_{tot,EBT}$) and PTO ($\eta_{tot,EBPTO}$) and calculated by multiplying the efficiency coefficients of the separate components (Equation 14 and 15).

$$\eta_{tot,EBT} = \eta_I \cdot \eta_{EM} \cdot \eta_{MD} \cdot \eta_W \quad (14)$$

$$\eta_{tot,EBPTO} = \eta_I \cdot \eta_{TC} \quad (15)$$

The efficiency coefficient of the inverter ($\eta_I = 0.98$), the electric motor ($\eta_{EM} = 0.95$) and the transmission cable ($\eta_{TC} = 1$) were set in accordance to Alve (2015). The main drive and wheels are similar for the two tractor types, and the efficiency coefficients of these two components are therefore set similar to the one used for the diesel tractor ($\eta_W = 0.68$, $\eta_{MD} = 0.83$). In line with the diesel tractor, when the power is divided between traction and PTO assuming a 70/30 distribution (Alve 2015). The total efficiency coefficient for the battery tractor using (i) only traction is 0.53 (ii) only PTO is 0.98, and (iii) both is 0.85.

The total power sent into the tractor from the battery was thus calculated from the output power and the efficiency coefficients (Equation 16).

$$P_{inn,EB} = \frac{P_{out,T}}{\eta_{tot,EBT}} + \frac{P_{out,PTO}}{\eta_{tot,EBPTO}} \quad (16)$$

Further, the total energy sent into the motor from the battery ($E_{inn,B}$; kWh) was found by multiplying the power by the period of time ($time$, h) (Equation 17).

$$E_{inn,EB} = P_{inn,EB} \cdot time \quad (17)$$

The total energy available in a battery pack ($E_{B,pack}$) is based on the available battery pack used for Fendt e100 Vario (https://www.fendt.com/int/fendt-e100-vario), which is a lithium-ion battery with a capacity of around 100 kWh. The number of replacable batteries required, or the number of times the battery need to be charged, is estimated as follows (Equation 18).

$$n_{B,pack} = \frac{E_{inn,EB}}{E_{B,pack} \cdot \eta_B} \quad (18)$$

With the efficiency coefficient of the battery (η_B) fixed at 0.95 (Pengwei and Lu 2015). The charging time depends on the size of the battery pack and on the power of the charger ($P_{charger}$) (Equation 19). Here, both a 22 kW standard CEE socket and a supercharging option of 120 kW is assumed (https://www.fendt.com/int/fendt-e100-vario).

$$Charge_{time} = \frac{E_{B,pack}}{P_{Charger}} \quad (19)$$

This gives a charging time of 4.5 h and 0.8 h for the standard and the supercharging option, respectively. As the standard charger may be installed on the farm without major challenges, the supercharging option may require upgrade of the on farm electrical infrastructure (Berg et al. 2016).

2.4.3 Hydrogen fuel cell tractor

A hydrogen fuel cell tractor would have the same construction as a battery electric tractor, but with hydrogen as energy carrier and fuel cells included to convert the hydrogen to electricity (Figure 3). More specifically, hydrogen is sent from the hydrogen tank to the fuel cells. The fuel cells convert chemical energy into DC electricity. Further, the DC electricity is sent into two separate inverters converting the electricity back to AC. From one inverter, power is sent to the electric motor, on to the main drive and finally to the wheels for traction (in line with an electric tractor). From the other inverter, power is sent through a transmission cable and to the electric PTO (in line with an electric tractor).

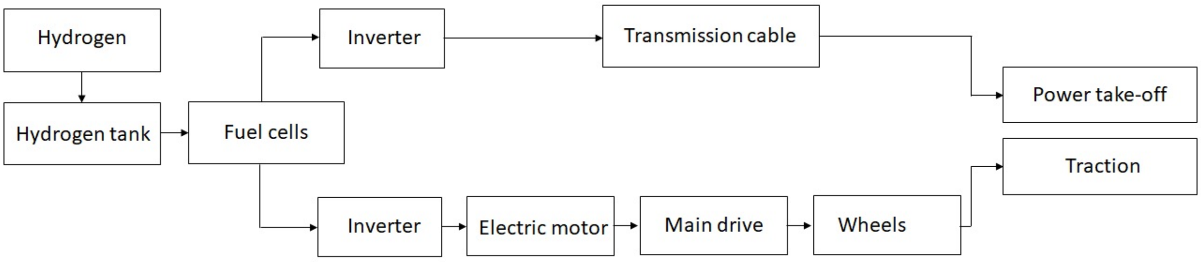

Figure 3: Schematic overview of a hydrogen fuel cell tractor.

The total output power from the hydrogen fuel cell tractor, used for traction ($P_{out,T}$) and for PTO ($P_{out,PTO}$) during the different on-farm tractor operations is similar to the output power from the electric battery and the diesel tractors.

As for the battery electric and the diesel tractors, the total efficiency coefficient of the hydrogen fuel cell tractor is divided between traction ($\eta_{tot,FCT}$) and PTO ($\eta_{tot,FCPTO}$) and calculated by multiplying the efficiency coefficients of the separate components shown in Figure 3 (Equation 20 and 21).

$$\eta_{tot,FCT} = \eta_{FC} \cdot \eta_I \cdot \eta_{EM} \cdot \eta_{MD} \cdot \eta_W \quad (20)$$

$$\eta_{tot,FCPTO} = \eta_{FC} \cdot \eta_I \cdot \eta_{TC} \quad (21)$$

The efficiency coefficient of the fuel cell (η_{FC}) is generally beween 0.4 and 0.6 (https://www.energy.gov/sites/prod/files/2015/11/f27/fcto_fuel_cells_fact_sheet.pdf), and was here fixed at 0.5 (Taner 2018). The inverter, the electric motor and the transmission cable are the same as in the battery electric tractor, and the efficiency coefficients have therefore been set equally (η_I = 0.98, η_{EM} = 0.95, η_{TC} = 1). The main drive and wheels are similar for all the tractors, and the efficiency coefficients of these two components have therefore been set similar to the one used for both the diesel and the battery tractor (η_W = 0.68, η_{MD} = 0.83). In line with the diesel and the battery tractor, when the power is divided between traction and PTO, it is assumed that 70% is for PTO (f_{PTO} = 0.7) and 30% is for traction (f_T = 0.3) (Alve 2015). The total efficiency coefficient for the hydrogen fuel cell tractor using (i) only traction is 0.26 (ii) only PTO is 0.49 and (iii) both is 0.42.

The total power sent into the hydrogen tractor from the hydrogen was thus calculated from the output power and the efficiency coefficients (Equation 22).

$$P_{inn,FC} = \frac{P_{out,T}}{\eta_{tot,FCT}} + \frac{P_{out,PTO}}{\eta_{tot,FCPTO}} \quad (22)$$

Further, the total energy sent into the motor from the hydrogen ($E_{inn,FC}$; kWh) was found by multiplying the power by the period of time (*time*, h) (Equation 23).

$$E_{inn,FC} = P_{inn,FC} \cdot time \quad (23)$$

The energy content of hydrogen (E_{H2}) is 33.3 kWh/kg. The mass consumption (m_{H2}) of hydrogen per hour is calculated by Equation 24:

$$m_{H2} = \frac{P_{inn,FC}}{E_{H2}} \quad (24)$$

The total daily mass consumption (M_{H2}) is then calculated by Equation 25:

$$M_{H2} = m_{H2} \cdot time = \frac{E_{inn,FC}}{E_{H2}} \quad (25)$$

In accordance with the NH2 tractor, a storage tank holding 8.2 kg hydrogen ($m_{H2,capacity}$) at 350 bar was assumed. The number of tanks can be estimated by Equation 26:

$$n_{H2} = \frac{M_{H2}}{m_{H2,capasity}} \quad (26)$$

A hydrogen combustion engine was developed in 2015 by modifying the John Deere 7810 tractor (http://solarhydrogensystem.com/the-system/). This tractor contained 4 tanks of 200 bar, 540 l, totaling in 36 kg hydrogen. Based on this, we will allow the hydrogen fuel cell tractor to carry up to 4 tanks.

2.5 Data sources and methods for upscaling from farm to national level

2.5.1 Principles

The 16 farm types outlined in Table 1 were chosen and designed to together represent the main part of Norwegian agriculture in terms of area, type of production and field work presently powered by fossil energy carriers.

Their respective proportions of the total consumption of fossil fuel had to be worked out as basis for further calculations and discussions. They would regard the total potential for replacement of fossil fuel by hydrogen and batteries as energy carriers, and further for those resources and investments (in physical terms) that were required to obtain the transformation.

These proportions and the total area within the 16 categories were worked out from data for 2018 available at SSB (Statistics Norway, https://www.ssb.no/en/). In a few instances, we had to go back to statistics for 2017 to get the demanded entries.

The next step was to multiply the figures for decrease in diesel consumption at farm scale by the total area each farm type occupied. The decrease was explored according to the implemented tractor fleet types (cases 2-5).

Lastly, the investments in infrastructure and batteries needed for the outlined transformations at single farms (1-16), were multiplied by the total area covered to get an estimate for demanded investments at the national scale.

2.5.2 Farms and farmland with grain crops

The total area in Norway with grain crops was 279 980 ha in 2018, distributed between 10 506 farming units (SSB). The figures for the three regions Østlandet, Rogaland and Trøndelag are given in Table 3.

Table 3: Number of farming units with grain crops and the area of grain crops in three regions.

Region	No. of farms	Area (ha)
Østlandet	8 043	230 950
Trøndelag	2 150	45 480
Rogaland	198	2 170

We could not find available statistics indicating how many of these farm units and how much of this area that were stockless. We assumed, however, that all grain cropping in Rogaland was on farms with animals.

For the other two regions, we deduced how much of the land that was on stockless farms and on farms with animals (pigs) from statistics for pork production, as described in the following section.

Table 4: Description of pork production farm units and number of animals in Østlandet, Trøndelag and Rogaland in 2017 (data for 2018 were not available).

Region	No. of farms	No. of sows	No. of slaughter pigs per sow
Østlandet	1 035	36 700	18.5
Trøndelag	367	16 300	16.5
Rogaland	618	26 000	17.9

There are in principle three types of pork farms; those keeping only sows and selling piglets, those both having sows and selling grown pigs for slaughter, and finally those buying piglets and selling grown pigs ready for slaughter.

The statistics for herd size that were available at SSB, were based on number of sows on 1 January every year and gave no information of cropped area in each farming unit. To get an estimate of the relationship between number of animals and area with grain crops, we turned to The Account Results in Agriculture and Forestry (Driftsgranskingane, https://nibio.no/tema/landbruksokonomi/driftsgranskingar-i-jordbruket).

Reference farm number 5, representing 30 farms from the whole country with combined grain/pork production, had in years 2017-2018, 49 sows, 836 pigs for slaughter and 35.7 ha grain crops, whereas farm number 24, representing 31 farms in Trøndelag with combined grain/pork production, had 23 sows, 362 pigs for slaughter and 31.3 ha grain crops. The number of slaughter pigs per sow was 17.1 and 15.7, respectively. Those ratios were not very different from 18.5 and 16.5 calculated from the gross statistics from SSB (Table 4).

Because more statistics were available for sows than for pigs for slaughter, and because there was a rather constant relationship between sows and the other animal group, we chose to scale the herd size relative to cropped area according to number of sows. The ratio for farm 5 was 1.4 sows/ha and for farm 24, 0.7 sows/ha. At the farms 11-16 in the present study (Table 1, Johansen and Hjelkrem 2018), there were 1.3 sows/ha.

From the total number of sows in the two respective regions, we deduced total areas with grain cropping that were integrated with pork production.

Instead of applying different animal densities in different regions in the calculations, we decided to use the same estimate of 1.0 sow/ha all over. One argument for choosing this rather moderate estimate is that it is common to spread some animal manure on land on neighbouring farms also. A lower ratio would lead to a higher estimate of grain crop area that is fertilized with pig slurry.

The calculations were as follows:

Area of grain crops integrated with pork production in Østlandet: 36 700 sows/1.0 sow/ha = 36 700 ha
Area of grain crops integrated with pork production in Trøndelag:16 300 sows/1.0 sow/ha = 16 300 ha

Area of stockless grain cropping in Østlandet: 230 950 ha – 36 700 ha = 194 250 ha (84% of total)
Area of stockless grain cropping in Trøndelag: 45 480 ha – 16 300 ha = 29 180 ha (64% of total)

One remark here is that some of the land in Østlandet and Trøndelag defined as stockless above, were located on farms with poultry and cattle. A consequence of not taking this fact into further consideration was that the total use of energy in field operations in grain production would be underestimated. Handling and spreading of animal manure demand more energy than applying mineral fertilizers.

The next step was to distribute the total area in each of the categories above to small and large farming units, i.e. according to model farms 1, 3, 11, 13, 15 and 2, 4, 12, 14, 16 (Table 1).

In 2018, 27% of all farming units with grain cropping (2 183 out of 8 043) in Østlandet, 27% (588 out of 2150) in Trøndelag and 12% (24 out of 198) in Rogaland were in the group of 20-40 ha, according to SSB, where the small grain farms of about 30 ha in the present study belonged (Table 1).

We assumed that all other units (smaller or larger than 20-40 ha) were managed according to the practises at our large model farms 2, 4, 12, 14 and 16 (Table 1). Land on units smaller than 20 ha is very often rented and cultivated by contractors or farmers with machinery with high working capacity.

These assumptions lead to the following calculations and results:

Area in small units in Østlandet: 2 183 units x 30 ha/unit = 65 490 ha
Area in small units in Trøndelag: 588 units x 30 ha/unit = 17 640 ha
Area in small units in Rogaland: 24 units x 30 ha/unit = 720 ha

Area in large units in Østlandet: 230 950 ha – 65 490 ha = 165 460 ha
Area in large units in Trøndelag: 45 480 ha – 17 640 ha = 27 840 ha
Area in large units in Rogaland: 2 170 ha - 720 ha = 1 450 ha

Area in stockless small units in Østlandet: 65 490 ha x 84% = 55 012 ha
Area in stockless small units in Trøndelag: 17 640 ha x 64% = 11 290 ha

Area in stockless large units in Østlandet: 194 250 ha – 55 012 ha = 139 238 ha
Area in stockless large units in Trøndelag: 29 180 ha – 11 290 ha = 17 890 ha

Area in small units with pork production in Østlandet: 65 490 ha – 55 012 ha = 10 478 ha
Area in small units with pork production in Trøndelag: 17 640 ha – 11 290 ha = 6 322 ha
Area in small units with pork production in Rogaland: 720 ha

Area in large units with pork production in Østlandet: 165 460 ha – 139 238 ha = 26 222 ha
Area in large units with pork production in Trøndelag: 27 840 ha – 17 890 ha = 9 950 ha
Area in large units with pork production in Rogaland: 1 450 ha

2.5.3 Farms and farmland with forage production

The total number of dairy farms and cows in the regions Østlandet, Rogaland and Trøndelag in 2018, given by SSB (Table 5), were together with assumptions regarding area per cow unit, the basis for estimates of forage production area in the six categories of model farms (Table 5).

Table 5: Total number of dairy farms and of dairy cows in 2018, according to region.

Region	No. of dairy farms	No. of dairy cows
Østlandet	2 395	63 900
Trøndelag	1 533	46 200
Rogaland	1 176	39 500

The forage crop area per cow unit for the medium and large farms in Roer et al. (2013) and Bakken et al. (2017) was as presented in Table 6. At these farms, the cow unit also covered all off-spring (heifers and bulls fully grown until slaughter). The area included permanent pastures, but not out-field resources.

Table 6: Area (ha) of forage crops per cow unit at six dairy farms analysed by Roer et al. (2013) and Bakken et al. (2017).

Region	Area (ha) per cow unit, small farms	Area (ha) per cow unit, large farms
Østlandet	1.25	1.18
Trøndelag	1.23	0.93
Rogaland	1.02	1.00

The area per cow unit, at these farms and in general reflects the certain yields of forage crops and the yields and feed ratio of the animals. It is not necessarily true that the largest farms have the highest yields, and the proportion of concentrate in the ratio does not depend on farm size, neither. We therefore chose to apply the means for small and large farms within each region in further calculations, i.e. 1.2, 1.1 and 1.0 ha per cow unit for Østlandet, Trøndelag and Rogaland, respectively. We differentiated between regions because yields of forage crops differ rather consistently between them.

The next step was then to distribute the total population of cows to small and large farms.

According to «TINE statistikksamling for 2018», covering more than 90% of dairy cows in Norway, 30% of the cows ("årskyrne") in the district Østlandet North were in herds of 20-35 cows, 18% in herds of 35-50 cows, 19% in herds of 50-100 cows and 2% in herds with more than 100 cows. The rest was in herds of less than 20 cows.

For the district Østlandet South, 23% of the cows were in herds of 20-35 cows, 20% in herds of 35-50 cows, 37% in herds of 50-100 cows and 5% in herds with more than 100 cows. The rest was in herds of less than 20 cows.

There were about the same number of cows in the two regions (19 600 in South and 18 900 in North)

The small and the large farms in the present study had 20 and 50 (48 in Rogaland) cows, and it was not straight-forward to group the total 2018-population based on the intervals and numbers given in «TINE statistikksamling».

We assumed that 39% (18% +19% +2%) of the cows in region North and that 62% (20%+37%+5%) of the cows in region South resided on farms of the large type. For the whole region Østlandet (where Agder was included), 51% of all cows (63 900 cows (SSB) x 51% = 32 589 cows) resided on farms of the large type and the rest (63 900 – 32 589 = 31 311) on farms of the small type.

According to «TINE statistikksamling», 27% of the cows in Trøndelag were in herds of 20-35 cows, 24% in herds of 35-50 cows, 33% in herds of 50-100 cows, and 0.3% in herds with more than 100 cows. The rest was in herds of less than 20 cows. Simplified and in summary, 57% (24%+33% + 0.3%) resided on large farms, which amounted to 46 200 x 57% = 26 334. The rest (46 300 – 26 334= 19 866) were at small farms.

According to «TINE statistikksamling», 28% of the cows (11 060, 28% of 39 500 given by SSB) in Rogaland were in herds of 20-35 cows, 25% (9 875) in herds of 35-50 cows, 27% (10 665) in herds of 50-100 cows, and 4% (1 580) in herds with more than 100 cows. The rest (6 320) was in herds of less than 20 cows. Simplified and in summary, 11 060 cows + 6 320 cows = 17 380 cows (44%) resided at small farms and 22 120 (56%) at large farms.

The number of cows within each category (farm type, six different in total) was then multiplied by the region-specific factor area/cow to get the area of forage crops according to farm type (Table 13).

3 Results

3.1 Timing and duration of on-farm tractor operations

Use of tractors for field operations in agriculture is seasonal, with high peaks of workload attributed to ploughing and spreading of animal manure in spring and harvests and ploughing in autumn (Figure 4-6), and some lower peaks in between. During winter time, tractors are often used for shoveling snow, firewood chopping/cutting/handling and some transport. These operations have not been accounted for in this study.

In Figure 4-6, the daily work hours for the large and the small (or the two small combined) tractors are given for each of the 16 farms separately. For the stockless grain farms (Farm 1-4), the daily work hours for the tractors are shown in Figure 4. Here, the total tractor work hours per season varied between 130 and 430, and on area basis from 3.2 to 4.5 hours per ha. Small and large tractors had different shares of the total work hours at the different example farms. Small tractors accounted for 31 - 33% of the total hours at the farms in Østlandet and for 46 - 61% of the hours at the farms in Trøndelag. The small tractor was in active operation for 7, 10, 10 and 24 days for Farm 1 to 4, respectively, while correspondingly, the large tractor was operating for 16, 16, 28 and 23 days, respectively.

Daily work hours for the tractors at the farms with combined pork and grain production (Farm 5-10) are shown in Figure 5. The total tractor work hours per season varied between 160 and 320, and on area basis this amounted to 5.3 hours per ha. Small and large tractors accounted for 23 and 77% of total work hours, respectively. The small tractor was in active operation for 7 days at Farm 5-7 (small farms) and 9 days at Farm 8-10 (large farms), while the large tractor was operative for 20-23 days at Farm 5-7 and 29 days at Farms 8-10.

Figure 6 shows the daily work hours for the tractors at the dairy farms (Farm 11-16). Here, the total tractor work hours per season varied between 220 and 550, and on area basis from 9 to 12.7 hours per ha. The small tractors had smaller shares of the total work hours compared to the large tractor at the different example farms. Small tractors accounted for 3 – 4% of the hours at the farms in Østlandet, 3 – 5% of the hours at the farms in Trøndelag and 3 – 9% of the hours at the farms in Rogaland. The small tractor was in active operation for 2, 1, 2, 5, 5, 9 days for Farm 11-16 respectively, while the large tractor was operative for 25, 26, 41, 59, 50 and 42 days, respectively.

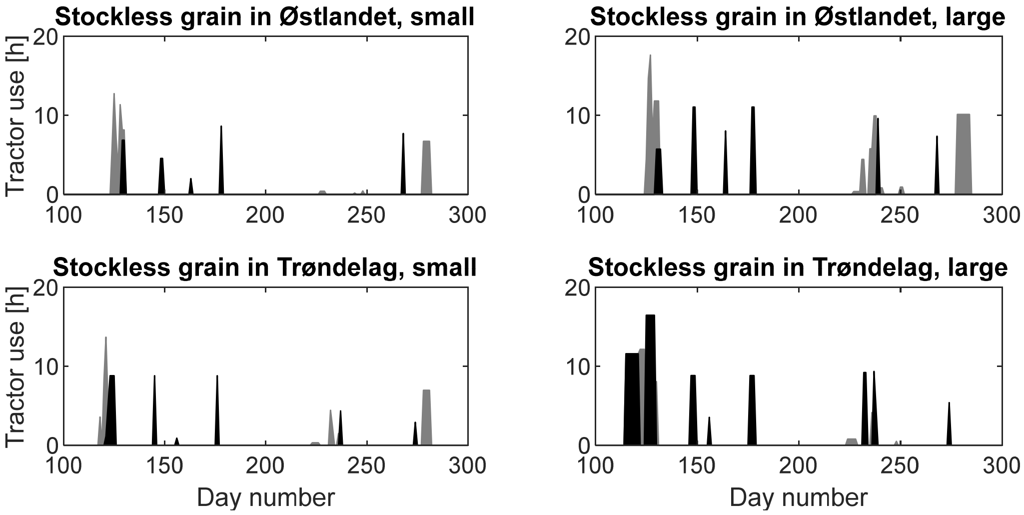

Figure 4: Daily work hours with use of the large (grey area) and small (black area) tractor at the stockless grain farms.

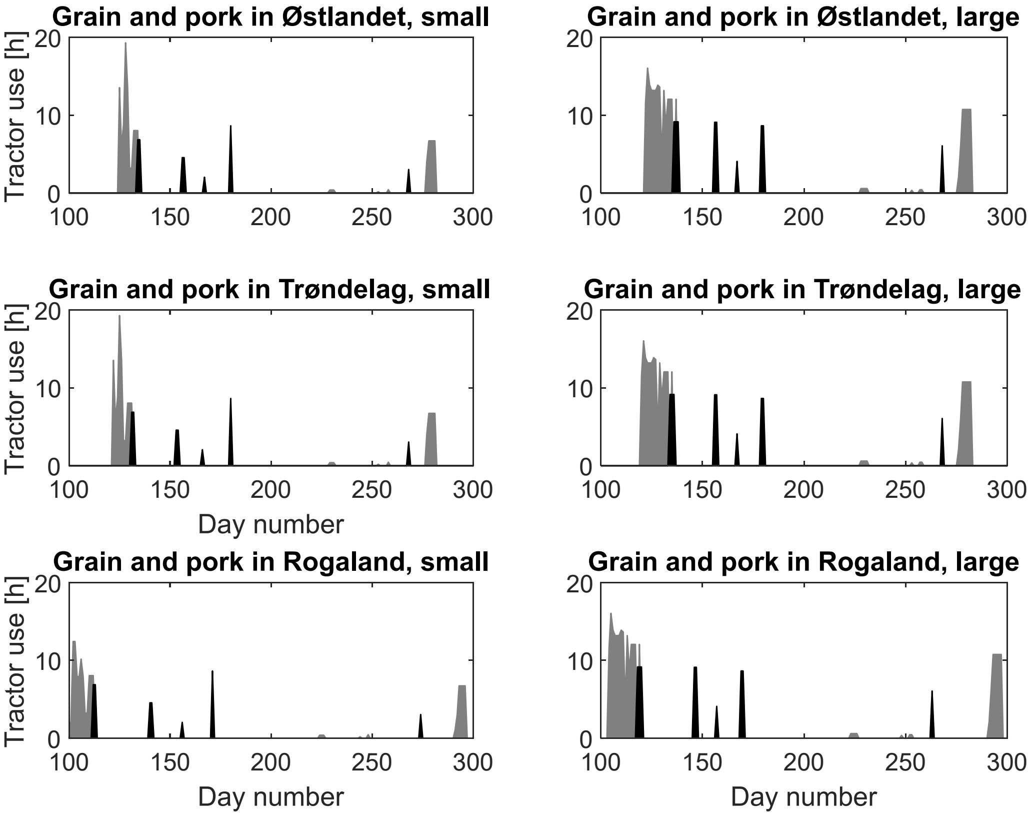

Figure 5: Daily work hours with use of the large (grey area) and small (black area) tractor at the farms with combined grain and pork production.

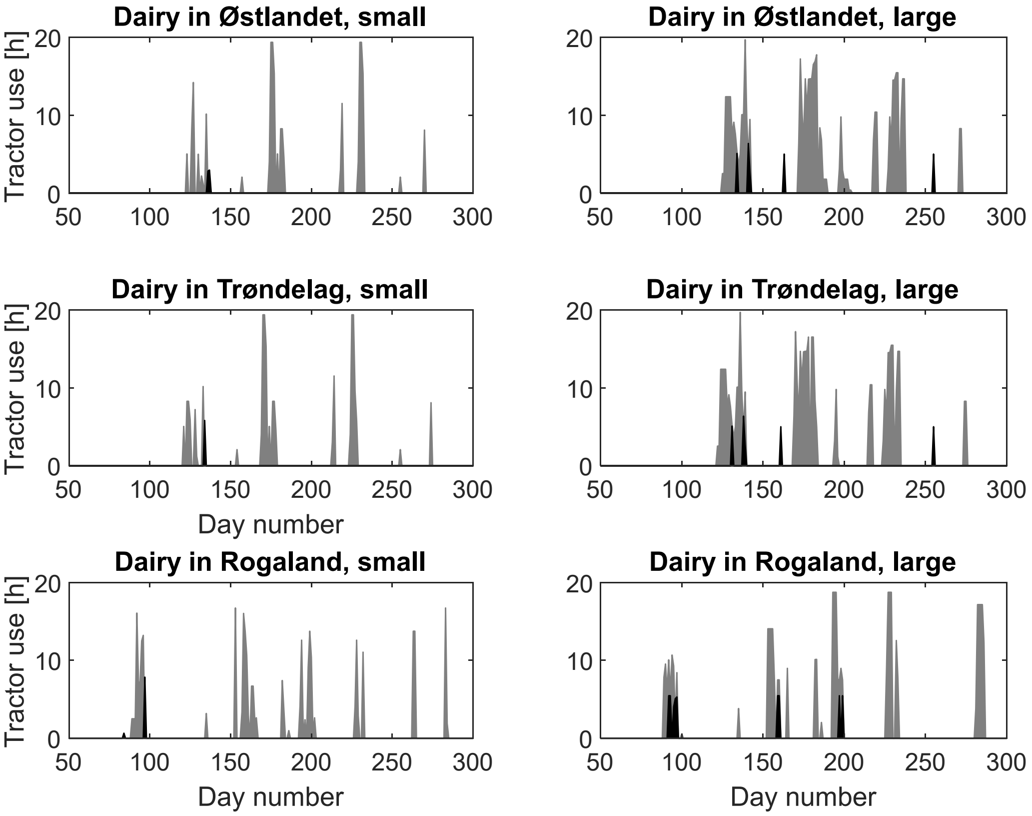

Figure 6: Daily work hours with use of the large (grey area) and small (black area) tractor at the dairy farms.

3.2 Energy use in on-farm tractor operations

3.2.1 Tractor fleet 1 (base case): Large and small diesel tractor

The between farm variation in yearly diesel consumption (Table 7) reflects varying farm sizes and differences in types and frequencies of field operations. The consumption on stockless grain farms was in the range of 50 - 60 litre diesel per ha, whereas the corresponding figures for pork+grain and dairy farms were around 70 and 130 - 190 litre per ha, respectively.

The efficiency (energy output/energy input) of the tractor operations varied between 0.17 and 0.25, with higher efficiency when PTO was used.

Table 7: Energy input to diesel tractors and output energy in form of tractor work (traction and PTO).

Farm	Region and type	Input energy in diesel ($E_{inn,D}$)		Output energy (E_{out})	
		Large tractor (kWh)	Small tractor (kWh)	Large tractor (kWh)	Small tractor (kWh)
1	Small stockless grain in Østlandet	13 000	2 700	2 200	600
2	Small stockless grain in Trøndelag	13 200	4 000	2 200	800
3	Large stockless grain in Østlandet	42 900	6 700	7 000	1 600
4	Large stockless grain in Trøndelag	31 200	26 500	4 900	4 700
5	Small grain and pork in Østlandet	19 700	2 400	4 000	600
6	Small grain and pork in Trøndelag	19 700	2 400	4 000	600
7	Small grain and pork in Rogaland	19 700	2 400	4 000	600
8	Large grain and pork in Østlandet	39 400	4 800	8 000	1 100
9	Large grain and pork in Trøndelag	39 400	4 800	8 000	1 100
10	Large grain and pork in Rogaland	39 400	4 800	8 000	1 100
11	Small dairy in Østlandet	34 100	300	7 700	50
12	Small dairy in Trøndelag	34 100	300	7 700	50
13	Small dairy in Rogaland	46 700	400	10 300	50
14	Large dairy in Østlandet	81 600	1 800	18 200	400
15	Large dairy in Trøndelag	79 600	1 800	17 600	400
16	Large dairy in Rogaland	68 500	2 900	16 800	400

3.2.2 Tractor fleet 2: Large diesel tractor and small battery tractor

The large diesel tractor and its diesel consumption were the same as in the base case (Tractor fleet 1). The electrical energy from the PV-system required for the battery tractor, replacing a small diesel tractor (Table), was calculated to lie between 100 kWh and 9 600 kWh, depending on the farm. For each farm, this is approximately 40% of the input energy required in the field operations conducted by small diesel tractors in fleet 1. The highest daily energy demand varied between 50 and 550 kWh. If such peaks were to be covered by one single battery electric tractor with a 100 kWh battery pack, the battery would need to be replaced or recharged up to 5 times a day (Table 8). The total daily charging time would be up to 4 hours and 40 minutes with a charger capacity of 40 min per battery, and 17 hours and 30 min with a standard charger with a capacity of 2 hours and 55 min. Energy needed to support the extra driving between fields and charging station is not included.

The efficiency of the small battery tractors was considerably higher than that of the small diesel tractors in fleet 1, and varied between 0.53 and 0.90, with highest efficiency when PTO was used.

If the total yearly energy demand for the small electric tractors was to be delivered from a PV-system on the respective farms, between 1 and 66 m² PV-modules would be required. The PV-system was then dimensioned in order to deliver the total yearly rquirement, and it was not taken into consideration whether energy demand coinsided with the time of capture and production.

Table 8: Energy input to a large diesel tractor and to a small battery tractor loaded by electricity from a local PV system dimensioned to cover the yearly demand. The number of batteries needed to cover the energy demand on days with peaks in work load is also given.

Farm	Region and type	Energy from diesel ($E_{inn,D}$)	Energy from PV system ($E_{inn,PV}$)	Maximum no. of batteries	Area of the PV system
		Large tractor (kWh)	Small tractor (kWh)	Small tractor	(m^2)
1	Small stockless grain in Østlandet	13 000	1 000	3	8
2	Small stockless grain in Trøndelag	13 200	1 500	3	10
3	Large stockless grain in Østlandet	42 900	2 500	4	18
4	Large stockless grain in Trøndelag	31 200	9 600	6	66
5	Small grain and pork in Østlandet	19 700	900	3	7
6	Small grain and pork in Trøndelag	19 700	900	3	6
7	Small grain and pork in Rogaland	19 700	900	3	6
8	Large grain and pork in Østlandet	39 400	1 800	3	13
9	Large grain and pork in Trøndelag	39 400	1 800	3	12
10	Large grain and pork in Rogaland	39 400	1 800	3	13
11	Small dairy in Østlandet	34 100	100	1	1
12	Small dairy in Trøndelag	34 100	100	1	1
13	Small dairy in Rogaland	46 700	100	2	1
14	Large dairy in Østlandet	81 600	600	2	5
15	Large dairy in Trøndelag	79 600	600	2	4
16	Large dairy in Rogaland	68 500	1 100	2	8

3.2.3 Tractor fleet 3: Large hydrogen tractor and small battery tractor

In Tractor fleet 3, the large diesel tractor of fleet 1 was replaced by a large hydrogen fuel cell tractor, while the small tractor was the same electric battery tractor as in fleet 2. The yearly hydrogen consumption varied between 240 kg and 1 520 kg, with the highest daily requirement calculated to be between 6 and 9 tanks of hydrogen (36 kg/tank) (Table 9). This implies that up to two refillings were needed per day assuming that the tractor could carry four hydrogen tanks. The efficiency of the fuel cell tractors varied between 0.27 and 0.39, with higher efficiency when PTO is used.

Table 9: Total energy input to a large hydrogen and a small battery tractor and the dimension of a PV-system supplying all this energy. The total yearly amount of hydrogen and the number of hydrogen tanks needed to cover the energy demand of the large tractor on days with peaks in work load are also given.

Farm	Region and type	Energy from PV system ($E_{inn,PV}$)	Energy from PV system ($E_{inn,PV}$)	Amount of hydrogen (M_{H2})	Maximum no. of hydrogen tanks (n_{H2})	Area of the PV system
		Total (kWh)	Large tractor (kWh)	Large tractor (kg)	Large tractor	(m^2)
1	Small stockless grain in Østlandet	15 500	14 500	240	5	116
2	Small stockless grain in Trøndelag	16 200	14 800	240	5	112
3	Large stockless grain in Østlandet	50 500	48 000	780	9	376
4	Large stockless grain in Trøndelag	44 400	34 800	560	6	305
5	Small grain and pork in Østlandet	23 200	22 400	360	8	173
6	Small grain and pork in Trøndelag	23 200	22 400	360	8	160
7	Small grain and pork in Rogaland	23 200	22 400	360	6	168
8	Large grain and pork in Østlandet	46 500	44 700	720	7	346
9	Large grain and pork in Trøndelag	46 500	44 700	720	7	320
10	Large grain and pork in Rogaland	46 500	44 700	720	7	336
11	Small dairy in Østlandet	39 200	39 100	630	7	292
12	Small dairy in Trøndelag	39 200	39 100	630	7	269
13	Small dairy in Rogaland	53 600	53 500	870	6	388
14	Large dairy in Østlandet	94 200	93 600	1 520	8	702
15	Large dairy in Trøndelag	91 800	91 100	1 480	8	631
16	Large dairy in Rogaland	80 200	79 200	1 282	7	581

Hydrogen production is highly energy demanding and the energy required to produce the hydrogen needed during one growing season varied between 14 500 and 93 600 kWh. Given that all energy needed for hydrogen production and battery charging was to be supplied from a local PV-system, the total demand would be in therange of 16 200 - 94 200 kWh. This corresponds to 112 to 702 m^2 PV-modules.

3.2.4 Tractor fleet 4: Large and small hydrogen tractor

In Tractor fleet 4, both the large and the small diesel tractor of fleet 1 were replaced by hydrogen fuel cell tractors. The characteristics and hydrogen consumption of the large hydrogen tractor have been outlined before (ref. Section 3.2.3).

The energy efficiency of the small hydrogen tractor varied according to field operation (if PTO was involved or not) and was between 0.26 and 0.38. Although both the battery and the fuel cell tractors were assumed to have similar electrical engines, the efficiency of the hydrogen tractor was a bit lower than of the corresponding battery tractor. This was because some of the input energy is lost in the fuel cells of hydrogen tractors. The yearly energy demand for operations conducted by small hydrogen tractors varied highly between the 16 farms (300 - 29 900 kWh) (Table 10). For each farm, the energy required to operate the small hydrogen tractor was approximately 3 times higher than what was required for corresponding operations conducted by small battery tractors (fleet 2).

The farm-wise yearly consumption of hydrogen varied between 290 and 1 550 kg (Table 10). The farm-wise consumption of hydrogen per ha was lowest for the stocless grain farms (Farm 1-4) with a variation between 9 and 11 kg per ha, followed by the grain and pork farms with 13 kg per ha (Farm 5-10). Higest values were detected for the dairy farms of 26, 26, 36, 26, 26 and 28 kg per ha for Farm 11-16, respectively. The number of hydrogen tanks required for the small tractor was between 1 and 4. Given that small tractors also could hold 4 tanks, no refilling was required on a daily basis.

If the total yearly energy demand for the electric fuel cell tractors was to be delivered from a PV-system on the farm, between 132 and 712 m^2 PV-modules was required.

3.2.5 Tractor fleet 5: Fleet of small battery tractors

A fleet consisting of only small battery tractors was applied to the large stockless grain farm in Østlandet (Farm 3), only. A total of 10 200 kWh was required to provide the fleet with energy (Table 11). Hereby, 62 m^2 PV-modules are required, if all the electricity should be produced on the farm. A total number of 7 tractors would be needed, and the extra transport required to drive each tractor to and from the field is accounted for in the calculations.

Compared to Tractor fleet 3, with a large hydrogen tractor and a small battery tractor, the fleet of battery tractors on Farm 3 only needs 20% of the energy, and the required PV-system to generate this energy is reduced from 306 to 62 m^2 PV-modules accordingly. Compared to Tractor fleet 4, with both large and small hydrogen fuel cell tractor, only 18% of the energy was needed from the PV-system, with a reduction in area from 337 to 76 m^2 PV-modules.

Table 10: Total energy input to a large and a small hydrogen tractor and the dimension of a PV-system supplying all this energy. The total yearly amount of hydrogen and the number of hydrogen tanks needed to cover the energy demand of the small tractor on days with peaks in work load are also given.

Farm	Region and type	Energy from PV system ($E_{inn,PV}$)		Amount hydrogen (M_{H2})		Maximum number of hydrogen tanks (n_{H2})	PV system
		Total (kWh)	Small tractor (kWh)	Total (kg)	Small tractor (kg)	Small tractor	(m^2)
1	Small stockless grain in Østlandet	17 700	3 200	290	50	2	132
2	Small stockless grain in Trøndelag	19 300	4 600	310	70	2	133
3	Large stockless grain in Østlandet	55 700	7 700	900	130	3	415
4	Large stockless grain in Trøndelag	64 700	29 900	1 050	480	4	445
5	Small grain and pork in Østlandet	25 100	2 800	400	50	2	287
6	Small grain and pork in Trøndelag	25 100	2 800	400	50	2	173
7	Small grain and pork in Rogaland	25 100	2 800	400	50	2	182
8	Large grain and pork in Østlandet	50 300	5 500	810	90	2	374
9	Large grain and pork in Trøndelag	50 300	5 500	810	90	2	346
10	Large grain and pork in Rogaland	50 300	5 500	810	90	2	364
11	Small dairy in Østlandet	39 400	300	640	10	1	294
12	Small dairy in Trøndelag	39 500	300	640	10	1	271
13	Small dairy in Rogaland	54 000	500	870	10	1	390
14	Large dairy in Østlandet	95 600	2 000	1 550	30	1	712
15	Large dairy in Trøndelag	93 100	2 000	1 510	30	1	641
16	Large dairy in Rogaland	82 600	3 400	1 340	60	1	597

Table 11: Total input energy to the fleet of battery tractors from the PV-system and the maximum number of batteries required for one day and size of the PV-system in order to support the requirement, and energy required from the PV-system.

Farm	Region and type	Energy from PV system ($E_{inn,PV}$)	Maximum no. of batteries/ tractors	PV system
		Small tractors (kWh)		(m^2)
3	Large stockless grain in Østlandet	10 200	7	76

3.3 Farmed land according to region, type and size of the farming units

The land with grain production in the three regions Østlandet, Trøndelag and Rogaland in 2018 was distributed to 10 farm categories as presented in Table 12. Similarly, the land with forage production on dairy farms was distributed to 6 farm categories as presented in Table 13. The total land use included in this study was 445 569 ha distributed between grain (278 572 ha) and forage (166 997 ha) production in the three regions Østlandet, Trøndelag and Rogaland.

Table 12: Area (ha) on farms with grain production in Norway in 2018 split up according to region, production type and size of farming units. Grain production in Vestlandet and Møre and Romsdal is not included.

Region and type	Small farms (ha)	Large farms (ha)
Stockless grain in Østlandet	55 012	139 238
Stockless grain in Trøndelag	11 290	17 890
Grain and pork in Østlandet	10 478	26 222
Grain and pork in Trøndelag	6 322	9 950
Grain and pork in Rogaland	720	1 450

Table 13: Estimated area (ha) with forage production (permanent pasture included) on dairy farms in Østlandet, Trøndelag and Rogaland in 2018 split up according to region and size of farm units. Area needed for production of forage fed to off-spring until slaughter is included.

Region and type	Small farms (ha)	Large farms (ha)
Østlandet	37 570	39 107
Trøndelag	21 850	28 970
Rogaland	17 380	22 120

3.4 Investments and reductions in diesel consumption after fleet transformations

Estimated diesel and hydrogen consumption, and number of required tractors were aggregated to a national level according to their share of total area and/or production as listed in Table 14. The yearly diesel consumption was reduced with 3 million litre when the small diesel tractors were replaced by electric tractors, and with 40 million litre when all tractors were replaced by electric ones (hydrogen fuel cell and/or battery).

About 7 million kg hydrogen would be required for field operations conducted by large tractors on a national level, while 7.5 million kg would be required to replace all operations.

If all large farms with grain production in Østlandet conducted their field work by use of the outlined fleet of small tractors, the diesel consumption would decrease by 7.7 million litre. Almost 11 000 battery tractors were needed to do the work.

Larger investments in tractor units would be required at a national level. Nearly 25 000 hydrogen tractors had to be avaible for total replacement of large diesel tractors. For the replacement of small diesel tractors, the same number of small battery or hydrogen tractors had to be at farmers' disposal.

Table 14: National decrease in diesel consumption and required hydrogen production and investments in batteries, charging effect and charging station etc for cases including work conducted by battery tractors.

Tractor fleet	Decrease in diesel consumption (litre)	Hydrogen (kg)	No. of large hydrogen tractors	No. of small battery tractors	No. of small hydrogen tractors
Large diesel and small battery tractor	3 026 100	-	-	24 630	-
Large hydrogen and small battery tractor	40 445 100	6 971 800	24 630	24 630	-
Large and small hydrogen tractors	40 445 100	7 539 300	24 630	-	24 630
Fleet of small battery tractors^{*)}	7 702 800	-	-	10 990	-

*) For the 120 000 ha of land farmed according to stocless grain production in Østlandet, large farm unit only

Energy demand and area of solar panels were additionally aggregated to a national level according to their share of total area and/or production (Table 15). While 11 GWh of electricity would be required to operate the small electric tractors, 441 and 465 GWh would be required to operate all tractors on the farm with large fuel cell tractors, and small battery and hydrogen fuel cell tractors, respectively. Up to 2.75 million m^2 PV-modules would be required if all the energy was to be produced by local PV-systems.

Table 5: Required investments in solar panels if all or parts of the tractors were driven by locally captured solar energy.

Tractor fleet	Energy from PV			PV-system
	Total (kWh)	Large tractor (kWh)	Small tractor (kWh)	(m^2)
Large diesel and small battery tractor	11 212 000		11 212 000	66 300
Large hydrogen and small battery tractor	441 614 000	430 402 000	11 212 000	2 609 800
Large and small hydrogen tractors	465 439 000	430 402 000	35 037 000	2 750 600
Fleet of small battery tractors*)	16 087 000		16 087 000	97 400

*) For the 120 000 ha stockless grain production in Østlandet, large farm unit only

4 Discussion

4.1 Validity of estimates for diesel consumption

Diesel consumption from on-farm field work was estimated individually for each farm type, and aggregated to a national level according to the farm types' share of total area and/or production. This totalled to a yearly use of about 40 million litre diesel, which is 30% of the total consumption estimated for Norwegian agriculture in 2017 (SSB; greenhouse production and forestry excluded). The gap between the consumption calculated in this study and totals from SSB can partly be explained by our exclusion of farms producing suckler cows, sheep, poultry, vegetables, potatoes and also dairy production in Western and Northern Norway (Vestlandet and Nord-Norge). Additionally, diesel combusted in combine harvesters was excluded in the present study, as well as diesel consumption related to transport (other than driving to the field), shoveling of snow and firewood making.

It is also possible that the fleet of tractors and the effect demand of machinery and operations driven by them have increased from 2010 - 2012 when the model farms were designed, and that this has contributed to an increase in diesel consumption per unit of work or area. For grain production without inputs of manure, DNV GL (2020) estimated a diesel consumption of 80 litre per ha, which is considerably higher than 51-60 litre per ha estimated in this study. Still, this gap can mainly be explained by the exclusion of combine harversters in this study. Further, their estimate of 133 litre per ha for consumption in forage production was lower than on the dairy farms outlined by us. The figures given for forage production in a recent study of Samsonstuen et al. (2020), who considered farms with beef production, were also lower than our estimates. As both these studies are based on older farm data as well (between 2010 and 2015), it is possible that changes in motor effects and energy demand of tractor fleets during the last ten years contribute to the discrepancy between SSB's and our figures for national totals. Another explanation for the differences might be that the area per farm unit has increased by almost 20% over the last ten years (2009 - 2019) according to SSB (2020), causing increased diesel consumption on transport work to and from the fields.

Still, it remains an open question how the diesel consumption related to farming of the 450 000 ha (50% of the fully cultivated land in Norway) covered by our model farms can be as little as 30% of the total estimated for 2017 by SSB. The consequence of a possible underestimation of diesel input (and thereby energy input) in field operations and transport work would be that our figures of the potential for reduction in CO_2 emissions and of investments and inputs needed to implement changes in energy carrieres were too low. However, an underestimation of diesel input will not bias the discussions and conclusions of which operations can be conducted with present and future non-fossile tractors, and which physical investements are demanded for shifts from fossile to "SolarFarms".

4.2 Battery tractors - potential with present and near-future technology

At the example farms outlined in this study, battery electric tractors were regarded capable of replacing the smaller diesel tractors which conducted lighter field work. This assumption is based on the battery capacity and the effect of the marketed battery tractors from Solectrac as well as the prototypes developed by the major machine manufacturers. Batteries providing the required amount of energy for heavier work or performance over longer distances are not yet available.

Aggregated to the area of 450 000 ha cultivated land covered by our model farms, it might be possible to replace in total 3 million litre diesel with electric energy if battery tractors perform the work conducted by small diesel tractors. This corresponds to a decrease of 7.5% (from 40 to 37 million litre diesel).

This reduction is far smaller than that suggested in a recent study by DNV GL (2020). The authors concluded that electrification of lighter tractor work would imply a reduction of diesel consumption by 46% and that this was achivable in 2023 based on the present development in energy density of batteries. Their study covered all production types in Norwegian agriculture though work load was not evaluated according to tractor power (effect), but to whether it was possible to operate a tractor carrying a battery of 250 kWh over at least 4 hours. On the contrary, Berg et al. (2016), discussing a scenario for 2021, stated that tractors with power above 56 kW will imply challenges with weight and volume with the presently available battery technology.

Another reason that lets the potential outlined by DNV GL (2020) appear unrealistic, is that most field work operations are performed within narrow time intervals in the growing season period, resulting in seasonal energy demand spikes. Optimal timing is determined by soil and weather conditions as well as plant development. The peaks in energy and effect demand outlined in our analyses may be a bit exaggerated, both when it comes to magnitude and narrowness, since we have not assumed any interruptions caused by non-optimal weather conditions. Still, they illustrate what will be a severe limitation for replacing diesel tractors with the battery tractors that are available on the market now and in near future. When we considered replacement of one to two small diesel tractors with one battery tractor on each of the sixteen example farms, the battery was to be recharged up to 5 times at days with maximum work loads and duration. As a standard charger requires approximately 4.5 hours to reload the battery, it would be impossible for the farmer to accomplish the work within reasonable time. A quick charger could recharge the tractor over lunch break, but still, several recharges a day would be difficult. Further, a faster recharge will cause a faster degrade of the battery. Another possibility is to swap the battery pack. Solectrac claims to have a technology that allows the farmer to swap the depleted batteries with charged ones more easily than changing implements. If this strategy was practiced, farmers would require exchange battery packs, and would have to drive back to the farm to swap unless being able to carry the extra battery pack out in the field.

The alternative of implementing a whole fleet of small electric battery tractors was explored for one of the large sized grain farms. Such a fleet has the potential to accomplish all included on-farm field operations, but would demand large investments in new tractors with especially designed machinery and equipment with adapted working width and capacity in order to fit smaller tractors. For the investigated grain farm type, six tractors were required to accomplich the work within the same time using diesel tractors. This corresponds to 0.08 tractor units per ha of farmed land.

4.3 Hydrogen tractors - potential with present and near-future technology

Hydrogen tractors will most likely be driven by fuel cells and electric engines. The technology of fuel cells is established and available for smaller vehicles, but still not commercially available on the market for tractors. The only prototype we are aware of is ten years old and produced by the company New Holland.

Due to this unavailability, hydrogen tractors do not represent an alternative to diesel tractors at time being and in the near future, unless manufacturers start to expand their production. Nevertheless, we think that our calculations are important to illustrate the potential energy inputs that were needed if the technology was available and affordable for farmers.

In contrast to battery tractors, hydrogen fuel cell tractors could replace diesel tractors in all field operations, when it comes to work load, driving distances and time efficiency in refuelling. Fuel cell technology could also be an alternative for combine harvesters that presently depend on fossil energy inputs.

The drawback of hydrogen compared to battery electric tractors is that the hydrogen production is highly energy demanding. Further, if the energy for hydrogen production was to be captured in on-farm PV-systems, an electrolyzer as well as storage tanks would be required. This would introduce some additional limitations and risks, given the high pressure required for hydrogen storage.

4.4 Local PV-systems as suppliers of energy to field operations

The electric energy required to replace fossil energy in all tractor operations on the 445 000 ha covered by our model varied between 445 and 465 GWh per year.

Foss et al. (2016) outlined a national yearly potential of 1 TWh for PV-systems mounted on the roofs of farm buildings. Following this estimation, it should, even if not all farm land, farm types and operations were covered in our present investigastion, theoretically, be possible to provide all energy demand from PV-modules mounted on farm buildings.

Regarding our model farms individually, large farms required between 370 and 710 m^2 of PV-modules. Based on Foss et al. (2016), who collected data on available roof space from four different farms in Østlandet with a variation between 791 m^2 and 2 590 m^2, it is reasonable to assume that the required area of roof space is available on today's farm buildings.

In this regard it is important to take into consideration that we have dimensioned PV-systems in order to deliver the total yearly requirements to produce hydrogen and/or charge batteries for tractor operations. It has not been taken into account whether energy expenditure coinsides with the time of capture and production. Surplus energy produced by the PV-systems off season is assumed to be stored in battery banks, converted to and stored as hydrogen, or exchanged with the power grid.

4.5 Future prospects

Worldwide, numbers of battery vehicles has increased exponentally in recent years (https://www.statista.com/statistics/270603/worldwide-number-of-hybrid-and-electric-vehicles-since-2009/) and is expected to increase further. As electric motors are more efficient than combustion motors, electric tractors should be a feasible alternative to ordinary combustion tractors in order to generate huge torque. Still, only few battery electric tractors are commercially available, while several options exist as prototypes. Presently, the available battery technology represents a severe limitation for battery tractors taking a larger share of the tractor market. As underlined by Du et al. (2018) and Sitompul et al. (2019) tractors powered with heavy Li-batteries may contribute to severe soil compaction and be inefficient with regard to energy consumption.

It is beyond the scope of our study to evaluate and foresee possible break throughs in ongoing research with the aim to develop more energy dense alternatives to the present lithium-ion batteries. Acoording to Zhu et al. (2019), progress has been made in the work with the aim to replace graphite anodes with silicon anodes, but we are far from having commercially available products.

DNV GL (2020) assumed a rapid development in battery technology, and that a 400 kWh battery with an energy density of 300 Wh per kg would be available within ten years. In line with this, they suggested that battery tractors could conduct all farm operations in 2030.

In 2016, John Deere overcame the battery technology problem by introducing GridCon, a fully electric autonomus machinery connected to a 1000 m cable. As this machinery is cable powered, its driving range will be limited by the length of the cable.

Hydrogen fuel cell vehicles are also electric options, but still more immature on the market. Ten years ago, Tollefson et al. (2010) stated that the development of fuel cell technology for transportation was given a low priority because battery-powered electric vehicles seemed to offer a much quicker and cheaper route to low carbon transportation. They seemed to be correct in their expectations, and hydrogen powered transport seems still to be several years behind (Staffel et al. 2019).

Because battery electric tractors are limited by battery technology and require long recharging periods, hydrogen fuel cell tractors are still regarded as up and coming, with water as the only direct emission. They have a large potential with the advantage of longer driving distance and higher workloads compared to battery electric vehicles. Fuel cell vehicles are currently more complicated with higher initial costs, fuel costs and lack of refuelling infrastructure. No hydrogen fuel cell tractor is commercially available, but one prototype exist. Hydrogen can be produced on the farm from on-farm generated electricity. It is energy demanding to produce, but can be stored and used when needed.

The scenario of using hydrogen directly as fuel in hydrogen internal combustion engines was not evaluated in this study, as there are two major problems associated with this. First, hydrogen is less energy-dense compared to diesel, and an internal combustion engine is less efficient than an electric motor powered by fuel cells. Secondly, when hydrogen is combusted, other emissions, as NO_X is produced in addition to water vapor.

5 Conclusions

With the presently available battery technology and tractors, it will not be possible to replace more than 10% of the diesel input in field work by electrical energy. The most important limitations are the capacity of the battery packs and long recharging time that can not sustain the high peaks in energy and effect demand during the growing season.

Hydrogen fuel cell tractors presently existing only as protoypes, can perform much heavier work than battery electrical vehicles and may conduct all outlined field operations. In total, 465 GWh electric energy per year would be required as input to hydrogen production that covers the field and transport work conducted on the 440 000 ha represented by our model farms.

It would be possible to produce the required electric energy to accomplish on-farm tractor work by battery and hydrogen fuel cell tractors by on-farm roof mounted PV-systems, also when the high energy input required for hydrogen production is taken into consideration. It is then assumed that the solar energy can be exchanged with the grid or stored over several months in battery packs or as hydrogen.

References

Alve, H.U. 2015. A feasibility study of the electrification of the tractor combined with solar energy production on the barn roof. Master thesis. Norwegian University of Life Sciences.

Bakken, A.K., Daugstad, K., Johansen, A., Hjelkrem, A.G.R., Fystro, G., Strømman, A.H., Korsaeth, A. 2017. Environmental impacts along intensity gradients in Norwegian dairy production as evaluated by life cycle assessments. Agricultural Systems. 158: 50-60.

Berg, H.Ø., Bekkelund, P.H., Sedal, H. 2016. Mulighetsrommet for alternativ teknologi på traktorer. MIL-ALT Rapport 003.

Bøe, J.K. 2000. Traktorer og basismaskiner, kurskompendium. 1. Utg. Ås: Norges landbrukshøgskole.

DNV GL. 2020. Elektrifisering av landbruket. Rapport 2020-0265.

Du, J., Noguchi, R., Ahamed, T. 2018. Feasibility Study of Motor Powered Agricultural Tractors Base don Physical and Mechanical Properties of Energy Sources. Agricultural Information Research. 27(2): 14-27.

Foss, S.E., Byrkjedal, Ø., Willing, T.M. 2016. Sluttrapport: Utnyttelse av fornybare energiressurser i det norske jordbruket – et utredningsprosjekt.

Henriksen, T.M., Korsaeth, A. 2013. Inventory of Norwegian grain production. Data from three average- and three high yielding cereal farms located in the major grain producing areas of Norway. Bioforsk report. 8(69).

Ivy, J. 2004. Summary of Electrolytic Hyrdogen Production: Milestone Completion Report. National Renewable Laboratory (NREL): Golden, CO.

Johansen, A., Daugstad, K., Bakken, A.K., Fystro, G. 2013. Inventories as basis for life cycle assessments of milk and meat produced at Norwegian dairy farms. Design and data for three modelled farms with medium productin intensity. Bioforsk report. 8(73).

Johansen, A., Hjelkrem, A.G.R. 2018. Livsløpsanalyser av norsk svinekjøttproduksjon med og utan heimeprodusert grassaft som fôr. NIBIO rapport. 4(103).

Korsaeth, A., Henriksen, T.M., Roer, A.G., Strømman, A.H. 2014. Effects of regional variation in climate and SOC decay on global warming potential and eutrophication attributable to cereal production in Norway. Agricultural Systems. 127: 9-18.

Kvalevåg, M., Hoem, B., Magnussin, A. S., Haugen, J. M., Huso, B., Søgaard, G., Høie, H. 2019. Jordbruksrelaterte klimagassutslipp. Gjennomgang av klimagassregnskapet og vurdering av forbedringer. https://www.regjeringen.no/contentassets/0f1af0ca7efe493e8e48b46b6fba5ffd/rapport-tbu-jordbruk_siste.pdf.

Pengwei, D., Lu, N. 2015. Energy storage for smart grids. Elseiver.

Roer, A.G., Johansen, A., Bakken, A.K., Daugstad, K., Fystro, G., Strømman, A.H. 2013. Environmental impacts of combined milk and meat production in Norway according to a life cycle assessment with expanded system boundaries. Livestock Science. 155: 384-396.

Samsonstuen, S., Åby, B.A., Crosson, P., Beauchemin, K.A., Wetlesen, M.S., Bonesmo, H., Aass, L. 2020. Variability in greenhouse gas emission intensity of semi-intensive sucler cow beef production systems. Livestock Science. 239, 1-12.

Sitompul, J., Zhang., Noguchi, R., Ahamed, T. 2019. Optimization study on the design of utility tractor powered by electric battery. IOP Conference Series: Earth and Environmental Science. 355.

Skiaker, O.G. 2019. Techno economic analysis of renewable energy production – A case tudy for emission free use of tractor in 2030. Master thesis. Norwegian University of Life Sciences.

SSB. 2020. https://www.ssb.no/stjord

Staffel, I., Scamman, D., Valazquez Abad. A., Balcombe, P., Dodds, P.E., Ekins, P., Shah, N., Ward, K.R. 2019. The role of hydrogen and fuel cells in the global energy system. Energy and Environmental Science. 12(2): 463-491.

Taner, T. 2018. Energy and exergy analyse of PEM fuel cell: A case study of modelling and simulations. Energy. 143: 284-294.

Tollefson, J. 2010. Hydrogen vehicles: fuel of the future? Nature. 464: 1262-1264.

Trentadue, G., Lucas, A., Otura, M., Pliakostathis, K., Zanni, M., Scholz, H. 2018. Evaluation of Fast Charging Efficiency under Extreme Temperatures. Energies. 11(8): 1937-1950.

Zhu, B., Wang, X., Yao, P., Li, J., Zhu, J. 2019. Towards high energy density lithium battery anodes: silicon and lithium. Chem. Sci. 10, 7131-7148.

Zinola, C.F. 2010. Electrolysis computiational, experimental, and industrial aspects. CRC Press: Boca Raton, FL, USA, ISBN 978142004544

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