Connected and autonomous electric and fuel-cell powered agricultural power units: A feasibility study

Daniel Iftime[1] and Claude Laguë[2]

[1]*Tesla Canada, Toronto, ON*
[2]*Faculty of Engineering, University of Ottawa, Ottawa, ON Canada.*

Corresponding Author: Claude.Lague@uOttawa.ca

ABSTRACT

Agricultural labour shortages coupled with a required increase in global food production and increasingly stringent sustainable farming legislation are creating a 'perfect storm' opportunity for a much greater reliance on electric and autonomous technologies in agriculture. Fuel cell (FC), electric vehicle (EV), and connected and autonomous vehicle (CAV) technologies are being successfully adapted to meet the needs of several on-road and off-road vehicular applications. In this article, we focus on the feasibility of integrating FC, EV, and CAV technologies to power units adapted to the autonomous completion of agricultural field operations. Such small-scale autonomous agricultural power units (AAPU) would be intended for cluster/fleet operations and feature communication capabilities facilitated through a next-generation network infrastructure. These AAPUs would be compatible with a variety of agricultural implements to provide operational versatility and value to a wide range of farming operations. Such FC & EV powered AAPUs could reduce lifecycle greenhouse gas (GHG) emissions from agricultural operations by an average of 70% relative to emissions from diesel power units. This article further demonstrates that these autonomous technologies could be leveraged at a cost comparable to current diesel operations in agriculture.

RÉSUMÉ

Plusieurs facteurs contribuent à accroître l'intérêt pour une utilisation accrue de la motricité électrique et des technologies des véhicules autonomes en agriculture : rareté croissance de la main-d'œuvre agricole, augmentation de la production alimentaire à l'échelle mondiale, législations et réglementations visant la durabilité de la production agricole. Les technologies relatives aux piles à combustible (FC), aux véhicules électriques (EV) et aux véhicules autonomes et connectés (CAV) sont adaptées avec succès pour rencontrer les exigences liées aux déplacements routiers et aux applications hors-route. Cet article se veut une analyse de faisabilité portant sur l'intégration des technologies FC, EV et CAV sur des unités motrices pour la réalisation d'opérations agricoles autonomes. De telles unités motrices agricoles autonomes de taille réduite (AAPU) œuvrant de façon concertée pourraient communiquer entre elles par le biais de réseaux de communication de prochaine génération. Ces AAPU pourraient opérer des machines et équipements agricoles variés en fonction des différentes productions et types de pratiques culturales. En raison de l'utilisation des technologies FC et EV, ces AAPU permettraient de réduire les émissions de gaz à effet de serre (GES) associées aux opérations agricoles par un facteur de 70% comparativement à celles résultant de l'utilisation d'unités motrices alimentées en carburants fossiles tout en présentant des coûts d'utilisation comparables.

KEYWORDS

Cluster/fleet operation, Connected & autonomous vehicles, Electric vehicles, Fuel cell, Power units

MOTS CLÉS

Flottes de véhicules, véhicules connectés et autonomes, véhicules électriques, piles à combustible, unités motrices.

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INTRODUCTION

Agriculture must confront a key challenge at the global level: Increasing the quantity and quality of agricultural and food products to meet the needs of a growing population and of increased standards of living worldwide while relying on an ever-decreasing number of farmers and agricultural workers. In addition, agriculture must reduce its reliance on and use of fossil fuels. Therefore, automating agricultural field operations and using more sustainable energy sources for agricultural machines and equipment must become a priority.

Both electric (EV) and fuel cell (FC) vehicles are now commercially available for consumer and commercial applications. However, due to the high prices of hydrogen gas for newer FC technology and the energy density limitations of current li-ion batteries in EVs, the direct transfer of these technologies to agriculture are not possible currently due to the power intensity and extended operating hours that characterize most agricultural field operations. Likewise, the labour gap in the industry highlights the need for state-of-the-art connected and autonomous vehicles (CAV) in agriculture to increase operational efficiencies and subsequently decrease farmer costs of production and the need for human labour. The CAVs typically bring along high capital costs coupled with technical complexities, proving problematic for the limited capital often available to many agricultural producers.

EV technologies & agricultural applications

EVs have gained popularity due to proven advantages in urban transportation compared to fossil fuel alternatives (Schwartz et al., 2009). Practicality benefits and a search for less polluting systems motivated by intensifying global warming have fueled the EV industry (Pukalskas, et al., 2018). Except for short-distance consumer travel, the development and adoption of EVs for other vehicular applications continue to be limited due to technological shortcomings. One example: Li-ion batteries currently have energy densities that are five times lower than fossil fuels (Engineering ToolBox, 2001). The lower energy densities lead to added mass for energy storage (batteries) and lengthy charge times (Pod Point, 2020), which become major disadvantages for several power-intensive on- and off-road applications.

The uniquely large power requirement of agricultural machinery highlights these disadvantages. Innovative approaches to de-carbonizing agricultural equipment have been proposed previously, including: 1. Hybrid drivetrains involving the complementary use of Li-ion batteries and solar panels (PV) (Mousazadeh et al., 2010); 2. Continuous supply of electric power through lengthy extension cords (John Deere, 2020), and 3. Control algorithms capable of increasing the electric power produced by solar panels cells by nearly 60% (Schuss et al., 2012). The micro-tractor concept, a recent area of research in reducing the environmental impacts of agricultural field operations, has gained popularity over the past decade due to the reduced power needs and the possibility of autonomous drive systems (Mousazadeh et al., 2009). Nonetheless, the fundamental shortcomings of the Li-ion battery power source remain prevalent.

FC technologies and agricultural applications

FCs have long been used in transportation, power applications, stationary and portable machinery (Office of Energy Efficiency & Renewable Energy, n.d.) and are now delving into the consumer market. FCs operate at higher efficiencies (near 60%) than internal combustion engines (ICE) and emit no CO_2 or smog-creating air pollutants. FCs feature lower greenhouse gas (GHG) emissions ratings (expressed in mass of CO_2-eq emitted per distance travelled) stemming from manufacturing and transportation than battery-powered electric vehicles (Sternberg et al., 2019), and they are quieter in operation than ICEs.

For these reasons, numerous ambitious and established FC projects range from the Siemens Mireo Hydrogen-Powered Train to off-road applications such as Hyundai Construction Equipment's FC-powered excavating machines (FuelCellsWorks, 2020). The National Institute of Agro-Machinery Innovation and Creation (China) designed an FC-powered electric tractor in June, 2020 (CHIAIC, 2020). Denoted as the ET504-H, it uses 5G functionality and uses an autonomous drive mode or can be user-controlled remotely (FuelCellsWorks, 2020).

There has been little and insufficient research to date into FC technology applied to agricultural machinery. Exploring FC-powered farming systems is necessary to reduce the carbon footprint of the industry. Significant challenges are associated with the technology barriers listed above, and new ways to deliver highly variable power (electric, hydraulic, mechanical, tractive) to agricultural machines and implements must be developed.

CAV technologies & agricultural applications

Major areas of interest for automation and Internet of Things (IoT) capabilities have included personal vehicles but also off-road applications such as mining, construction, and agriculture. Due to legal and regulatory barriers, introducing these automated technologies to open-world consumer markets have proved tedious and challenging. Off-road applications provide opportunities for which many regulatory limitations are not hindering automated development due to the closed operational environments and specific functional requirements. The mining, construction, and transport industries have developed the technologies required to successfully automate many of their operations (Rio Tinto, 2018; Fennelly, 2018).

In agriculture, different automation levels have been achieved, beginning as far back as the 1990s through controlled traffic and precision seeding methods (Isbister et al., 2013). Since then, automatic/guided implement control and steering control have been the primary developmental focuses due to the increased "efficiency, reliability, precision, and reduced need for human mediation" (Burks et al., 2005; Schueller, 2014; Hameed et al., 2016; Antille et al. 2015, 2016). Systems present in most consumer vehicle automation systems similarly facilitate the autonomous operation of agricultural machinery (Thomasson et al., 2019). Machine operation involves operating tractors autonomously and accurately positioning implements. The operations require models that enable mechanical and machine coordination and electromechanical systems that analyze and respond to real-time situations (Thomasson et al., 2019). Existing barriers to adopting CAVs in agriculture stem from the current automation model's high capital costs (associated both with the infrastructure and the autonomous machines themselves), resulting in a low probability that small-scale farmers could adopt, use, and benefit from the technology in the near future (Case IH, 2018).

Robotic Fleet/Cluster Technologies and Agricultural Applications

Completing operations by means of clusters (i.e., teams) of automated machines has been shown to increase efficiency and, subsequently, output through high-level resource allocation of uniquely designed capabilities of individual power units (Michael, 2019). Examples of this are demonstrated in the automotive sector, where much of the car manufacturing assembly line consists of robotic arms which are timesaving, space-saving, re-deployable, and can be operated in homogenous or heterogenous operations with neighbouring arms (Universal Robots, n.d.). Similarly, security robots such as Knightscope's fully autonomous data security machines work in fleets and collaborate with human security officers to patrol public areas such as malls and tourist attractions, performing real-time data analytics (Markman, 2018).

Autonomous Agricultural Power Units (AAPU) used in greenhouses and state-of-the-art farm applications are typically fully autonomous, and communications are facilitated through 5G and autonomous cloud computing algorithms. Ecorobotix has developed a solar-powered robot that operates in fleets to spray crops (both autonomous and traditional field crops) with a demonstrated 90% reduction in herbicide use that reduces operational costs by 30% (Alexander, 2018). Many of this state-of-the-art AAPUs and their implements, such as autonomous harvesters and cultivators, are very large and expensive, preventing the average farmers from deploying these autonomous technologies. Micro-robot fleet technology can thus be leveraged to overcome traditional barriers of autonomous implementation by operating multiple AAPUs in fleets on both large and small-scale farms.

The general objective of this work is to complete a preliminary feasibility study on the use of small-scale AAPUs operating on a plug-in hybrid FC powertrain. Specific objectives include: To compare the performance and environmental impact of the proposed AAPU to that of existing ones, and to evaluate the power consumption, operational costs, and logistics associated with the conceptual operational requirements of an AAPU.

METHODOLOGY

This section outlines the general variables, parameters, and mathematical models pursuant to standards published by the American Society of Agricultural and Biological Engineers (ASABE): EP496.3 FEB2006 (R2020) Cor. 1 Agricultural Machinery Management; ASAE D497.7 MAR2011 (R2020) Agricultural Machinery Management Data; ASAE S495.1 NOV2005 (R2020) Uniform Terminology for Agricultural Machinery Management. The mathematical models were used to calculate GHG emissions, power requirements, fuel requirements, and operational costs for the proposed agricultural power unit for five (5) differing field operations: primary tillage, planting, spreading, spraying, and field cultivation.

Fuel cell power

To overcome the barriers of EVs, we recommend using the plug-in hybrid FC technology as the energy source for the proposed power unit. The plug-in hybrid format of the FC was selected for two reasons:

1. Tractive power provided by the AAPU can be delivered by the progressive power generated by the FC stack. Concurrently, PTO, hydraulic and any other auxiliary power can be supplied by Li-ion batteries power due to the torque-rich and instant power delivery that they can achieve. It is also expected that any implement relying on hydraulic power sources could eventually be replaced with direct electrical drive power due to reliability. The plug-in method of charging is chosen because using traditional hybrid methods such as regenerative braking is impossible during farming operations.

2. Much of the EU and Asia offer hydrogen fuel at around CAD$5.00/kg. In North America, the fuel is priced at CAD$12.50/kg (Royal Dutch Shell, 2020). The greater cost of hydrogen fuel contributes to the capital cost barriers referred to in the literature review. Using only hydrogen power at this stage in development, the cost of operations for a fuel cell needing sufficient power would be substantially higher than that of current fossil fuel operations. By adopting a plug-in hybrid model, the cost of the hydrogen fuel is decreased while the battery size can be reduced to make it more practical for agricultural use.

Two type IV hydrogen fuel tanks are proposed for use on the AAPU. Each tank has a capacity of approximately 5 kg of hydrogen fuel (Toyota, 2017) and a mass of 87.5 kg. The AAPU can carry 10 kg of hydrogen fuel at maximum capacity. The type IV tank is made of carbon fibre-reinforced polymers (CFRP) and stores the hydrogen fuel at 70 MPa (Toyota, 2017) with a maximum fill pressure of 87.5 MPa. Refuelling time is around 5 minutes.

Parameters and specifications

Tables 1 and 2 present the parameters and specifications of the proposed AAPU and the field equipment that it could operate. Factors such as field capacity and field efficiencies have been determined from ASAE EP496.3 and ASAE D497.7 Table 3, respectively.

Energy and power requirements

The total power requirements for operating implements attached to the AAPU for each field operation were calculated according to ASAE EP496.3. The mechanical efficiency was taken as 0.98 due to the one-gear design of

Table 1 Parameters of the proposed AAPU.

Component	Mass (kg)	Applicable Operation
Hydrogen Storage Tank	87.5	All
Frame & Driveline Components [a]	800	All
Li-ion Battery[b]	18.0	All
Hydrogen Fuel	10.0	All
Chemicals[c]	757	Spraying
Dry Fertilizer[d]	220	Spreading
Planting Seeds & Fertilizer[e]	74.2	Planting
Spraying Implement[f]	130	Spraying
Spreading Implement[g]	83.0	Spreading

[a] Average 18HP garden tractor driveline component mass = 225 kg (Jones, 2021); the AAPU adds an estimated 575 kg for all autonomous, FC, EV, Motor, and hitch compatibility components.
[b] Average EV battery = 18 kg (Smart Motorist, 2020).
[c] Land Champ Three-Point Hitch Sprayer 200 Gallon Capacity chemical mass capacity = 757 kg (Enduraplas, n.d.).
[d] Kubota VS220 Dry Fertilizer Spreader fertilizer mass capacity = 220 kg (Kubota, n.d.).
[e] John Deere 1745 Compact Planter seed & fertilizer capacity = 74.2 kg (John Deere, n.d.).
[f] Land Champ Three-Point Hitch Sprayer 200 Gallon Capacity mass = 130 kg (Enduraplas, n.d.).
[g] Kubota VS220 Dry Fertilizer Spreader mass = 83 kg (Kubota, n.d.).

EV and FC powertrains. The tractive efficiency (E_t) was calculated using net traction and gross traction models substituted into ASAE D497.7 as shown in Eq. 1:

$$E_t = (1 - s_p)\frac{0.88(1 - e^{-0.1B_n})(1 - e^{-7.5s_p}) - \frac{1}{B_n} - \frac{0.5s_p}{\sqrt{B_n}}}{0.88(1 - e^{-0.1B_n})(1 - e^{-7.5s_p}) + 0.04} \quad (1)$$

where:

s_p = slip (decimal),

B_n = dimensionless ratio for agricultural drive tires on the soil surface (ASAE D497.7).

Slippage of the wheels in the drive setting is a power loss. The slip was set at 8% (0.08) for a firm, untilled soil (ASAE EP496.3). The soil is assumed to be tilled for spraying, spreading, and planting, and the slip ratio was set at 12% (0.12) for those operations. The dimensionless ratio, B_n was set at 55 for firm soil conditions, 40 for freshly tilled soil, and 80 for hard soil conditions (ASAE D497.7).

Table 2. Implements analyzed for the proposed AAPU.

Operation	Operating Speed (km/h)	Operating width (m)	Field Efficiency	Field Capacity (ha/h)
Primary Tillage	10.00	2.29	0.80	1.83
Planting	9.00	3.70	0.65	2.16
Spreading	18.00	15.00	0.70	18.90
Spraying	20.00	10.67	0.65	13.87
Field Cultivation	15.00	1.83	0.85	2.33

Drawbar power for the drawn implement was computed per ASAE EP496.3 The *draft force* (*D)* of the implement was calculated per standard ASAE D497.7 and subsequently scaled to kN. Tillage depth for minor tillage tools and seeding implements, as well as soil adjustment parameters F_i are available in ASAE D497.7 Table 1 (no-till planting was assumed). The soil was of loamy medium texture (Agriculture & Agri-Food Canada, 2020). For spreading and spraying operations, the motion resistance of the transport wheels must be added. Since the implements are mounted and have no transport wheels of their own, this is neglected, and the wet mass of the tractor with spreading/spraying materials is added to the mass calculations in Eq. 5.

The PTO requirement of the implement was calculated using rotary power parameters from ASAE D497.7 Table 2 and calculated as modelled in ASAE EP496.3. The fluid power required by the respective implement's hydraulic power systems was calculated according to ASAE EP496.3. Power to lift and lower implements hydraulically were neglected. The electrical power required to operate the electrical drives of certain implements was computed as shown in EP496.3. The total power that the AAPU must provide is then depicted in Eq. 2. A safety factor of 20% was applied for various power requirements (i.e. changes in topography, cooling systems, data systems, etc.). This is shown below:

$$P_T = 1.2(P_{T,I} + P_{T,T}) \quad (2)$$

where:

P_T = total power required for operation (kW),

$P_{T,T}$ = total power required to move the power unit (kW),

$P_{T,I}$ = total power required to operate the implement (kW).

The total power required to move the power unit was calculated using Eq. 3 and substituted into Eq. 2:

$$P_{T,T} = \frac{D_T \times s}{3.6} \quad (3)$$

where:

D_T = power unit draft (kN).

Table 3. Lifecycle emissions of respective power sources.

	FC (Mixed Power Grid)	FC (Renewable Power Grid)	EV – 90 kWh (Mixed Power Grid)	EV – 90 kWh (Renewable Power Grid)	Diesel
Lifecycle Emissions (g CO_2/eq km)	105	55	175	90	215

$$D_T = \frac{(M_{Robot} + M_{Battery} + (M_{H\,Tank} \times N) + M_{H\,Fill} + M_{I,w.m.} + M_i) \times r_{c,T} \times a_g}{1000}$$

where:

M_{Robot} = mass of frame, driveline, components, etc. (kg),
$M_{Battery}$ = mass of the Li-ion battery required (kg),
M_H = mass of a 5 kg capacity hydrogen fuel tank (kg),
$M_{I,\,w.m.}$ =wet mass of loaded implement material [i.e. mass of seeds/fertilizer/chemicals] (kg),
M_i = mass of implement mounted directly on AAPU [spreading & spraying only] (kg),
N = number of hydrogen tanks required (dimensionless),
$M_{H\,Fill}$ = mass of hydrogen used in operation (kg),
$r_{c,T}$ = rolling resistance coefficient for the power unit (dimensionless).

The mass values of the various components, such as tanks, driveline components, etc. are presented in Tables 1 and 2 above. The rolling resistance coefficient was selected as 0.07 (Engineering ToolBox, 2001).

Specific energy requirements

The total specific energy requirement was modelled as follows:

$$E_T = \frac{P_T}{C} \tag{5}$$

where:

ET = total specific energy requirement (kWh/ha),
PT = total power requirement (kW),
C = field capacity (ha/h).

Field capacity was calculated according to ASAE EP496.3 Field efficiency is provided in ASAE D497.7 Table 3 for differing implements.

To find the specific fuel cell energy requirement, Eq. 6 was used:

$$E_H = \frac{1.2\left(\left(\frac{P_{db}}{E_m E_t}\right) + P_{T,T}\right)}{C} \tag{6}$$

where:

E_H = fuel cell specific energy requirement (kWh/ha),
P_{db} = drawbar power requirement (kW),
E_m = mechanical efficiency [decimal],
$P_{T,T}$ = total power required to move the power unit (kW).

A similar equation was used for determining battery power-specific energy requirement:

$$E_B = \frac{1.2(P_{pto} + P_{hyd} + P_{el})}{C} \tag{7}$$

where:

E_B = Li-ion battery specific energy requirement (kWh/ha),
P_{el} = electric power requirement (kW),
P_{pto} = PTO requirement (kW),
P_{hyd} = hydraulic power requirement (kW).

Hydrogen fuel consumption

Specific hydrogen fuel consumption was determined using the resulting specific energy requirement of the fuel cell calculated in Eq. 7. For each operation, hydrogen fuel consumption was calculated considering a hydrogen fuel energy density of 33.6 kWh/kg:

$$\psi_{H_2} = \frac{E_H}{\varrho_H} \tag{8}$$

where:

ψ_{H2} = specific hydrogen fuel consumption (kg/ha),
ϱ_H = energy density of hydrogen fuel (kWh/kg),

Li-ion battery sizing

The size of the required li-ion battery:

$$\chi_B = \frac{E_B}{\varrho_B} \tag{9}$$

where:

χ_B = required battery unit mass (kg/ha),
ϱ_B = battery energy density (kWh/kg).

Note that Li-ion battery sizing was performed for two types of Li-ion batteries. The Panasonic Model NCR18650PF. The second Sion Power's next-generation battery (NASA, 2018).

Diesel fuel consumption

Specific diesel fuel consumption was calculated using the total specific energy requirement of each operation:

$$\psi_d = \frac{E_T}{\varrho_d} \tag{10}$$

where:

ψ_d = specific diesel fuel consumption (L/ha),
ϱ_d = energy density of diesel fuel (9.7 kWh/L).

Energy costs

The operational cost of the hydrogen fuel operations was calculated as follows:

$$\vartheta_{H_2} = \psi_{H_2} \times \varpi_{H_2} \tag{11}$$

where:

ϑ_{H2} = specific cost of operation due to hydrogen ($/ha),
ϖ_{H2} = cost of hydrogen fuel ($/kg).

A similar model was derived for the cost of operations due to the charge from the electrical power grid.

$$\vartheta_{el} = E_B \times \varpi_{el} \tag{12}$$

where:

ϑ_{el} = specific cost of operation due to electricity ($/ha)
ϖ_{el} = cost of electricity ($/kWh)

The total cost of energy for the operation of the plug-in hybrid FC was then calculated as follows:

$$\vartheta_T = \vartheta_{el} + \vartheta_{H_2} \tag{13}$$

where:

ϑ_T = total plug-in hybrid operational cost ($/ha),

This value was then compared with those of diesel, pure electric, and pure hydrogen with current pricing. The total specific energy Eq. 5 was used for comparisons.

Finally, the diesel cost of operations was calculated to determine the feasibility of the fuel cell hybrid model using the following equation:

$$\vartheta_d = \psi_d \times \varpi_d \tag{14}$$

where:

ϑ_d = total diesel operational cost ($/ha)
ϖ_{el} = cost of diesel fuel ($/L)

Fuel cell EV hybrid greenhouse gas emissions

Using the specific power requirements calculated, the specific GHG emissions of the plug-in hybrid:

$$\epsilon = d_T(\alpha_{el}\gamma_{el} + \alpha_{H_2}\gamma_{H_2}) \tag{15}$$

where:

ϵ = GHG emissions of the hybrid operation (g CO_2/ha)
d_T = distance travelled in operation per hectare according to implement width (Table 2) (km/ha),
α_{el} = lifecycle GHG emissions of battery electric power (g $CO_{2\text{-}eq}$/km),
γ_{el} =percent power delivered from the battery (decimal),

α_{H2} = lifecycle GHG emissions of fuel cell hydrogen electric power (g $CO_{2\text{-eq}}$/km),
γ_{H2} = percent power delivered from fuel cell (decimal).
The percentages of power delivery (power delivery rates) were determined as follows:

$$\gamma_{el} = \frac{E_B}{E_T} \quad (16)$$

and similarly:

$$\gamma_{H_2} = \frac{E_H}{E_T} \quad (17)$$

Diesel greenhouse gas emissions

The specific GHG emissions of an equivalent operation with current diesel fuel can be found for comparison:

$$\epsilon_d = d_T \alpha_d \quad (18)$$

where:
ϵ_d = GHG emissions of the equivalent diesel operation (g CO_2/ha),
α_d = lifecycle GHG emissions of diesel (g $CO_{2\text{-eq}}$/km).

EV greenhouse gas emissions

Using the total specific power requirement calculated, the specific GHG emissions of an equivalent operation with current diesel fuel can be found for comparison:

$$\epsilon_b = d_T \alpha_{el} \quad (19)$$

where:
ϵ_b = GHG emissions of the equivalent diesel operation (gCO_2/ha).
The lifecycle emissions (gCO_2/km^2) for the battery FC and diesel drivetrains were obtained from EEA (2018), Sternberg et al. (2019), and USDE (2020) and are Tabulated in Table 3.

RESULTS AND DISCUSSION

Specific energy requirements

Calculated total specific energy, fuel cell-specific energy, and battery-specific energy requirements are presented in Fig. 1. With this current preliminary model, the power required for the field cultivation and primary tillage operations is entirely provided by the FC because of their higher power requirements. The spreading and spraying field operations require less energy.

Sizing of batteries and hydrogen fuel tanks

Using the specific energy requirements, the Li-ion battery was sized for the two battery models outlined in *Sizing the Required Li-ion Battery,* along with the charge time required per operation using level 3 charging infrastructure. Table 4 also presents the number of necessary refuels per operation for the two 5 kg capacity hydrogen fuel tanks in the AAPU. Both batteries were assumed to charge at the same rate, dependent on the infrastructure used.
Cluster operations allow for smaller-sized batteries with cheaper and quicker charging. Primary tillage and field cultivation requires no battery power. Planting requires the greatest energy from the Li-ion battery. The highest refuelling requirement is observed in primary tillage, where only drawbar power is needed and thus powered only by hydrogen. Refuelling would be required every 9.25 ha.

Energy costs

The subsequent specific costs of operations of the fuel cell and battery's consumptions were then calculated. Then, the total cost of operations of the hybrid drivetrain was calculated and presented in Table 5.

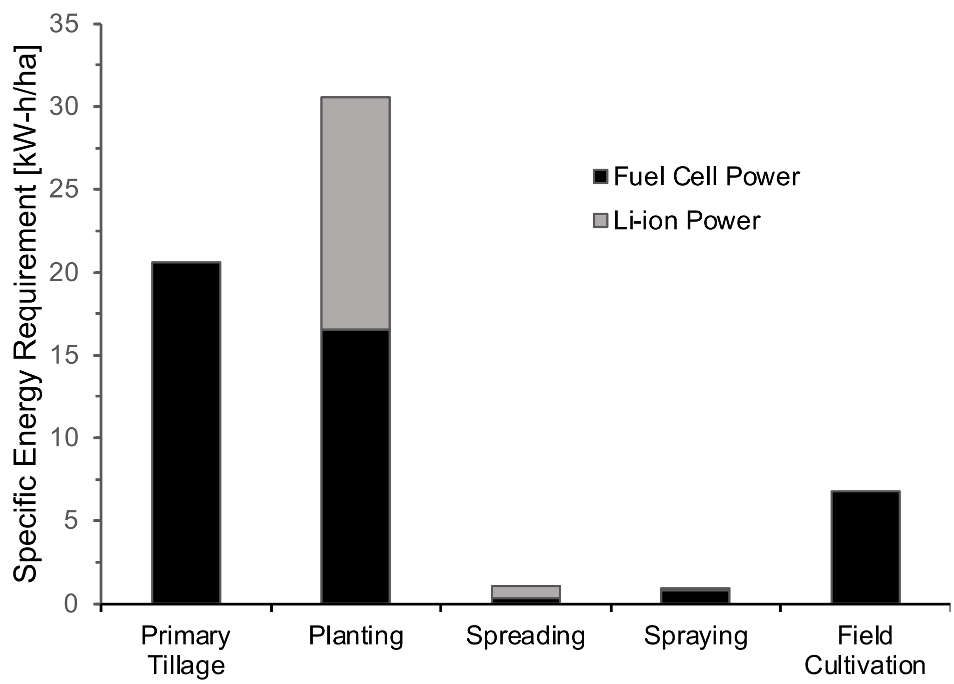

Fig. 1. Specific energy requirements and energy source for varying field operations. Total specific energy requirements for the FC and Li-ion battery (Eq. 6 & 7, respectively) are summed for the total energy requirement per field operation per hectare.

Table 4. Battery size and refuelling requirements.

Operation	Licerion Size[a] [kg/ha]	Panasonic Size[b] [kg/ha]	H_2 Refueling Needs [ha/unit refuel stop]
Primary Tillage	0	0	16.896
Planting	28.027	51.902	17.705
Spreading	1.445	2.676	1180.157
Spraying	0.221	0.408	538.615
Field Cultivation	0	0	55.723

[a] The Licerion battery is a state-of-the-art Sion Power & NASA collaborative battery design. Licerion Battery Energy Density = 0.5 kWh/kg

[b] Panasonic Battery NCR18650PF is the battery model most typically used in EVs. Panasonic Battery Energy Density = 0.27 kWh/kg

Planting requires the most energy and consequently has the greatest cost of operations. In 2020, this would mean a cost of $7.82/ha, while by 2030, at a lower hydrogen cost, the operational cost would be $4.18/ha. During this current period where hydrogen fuel is more expensive, farmers will still benefit from the autonomous model due to the government subsidies aiding in the transition to sustainable energies and from increased yield/ha associated with autonomous agricultural machinery (Burks et al., 2005; Schueller, 2014; Hameed et al., 2016; Antille et al. 2015, 2016). The province with the most notable subsidy for zero-emissions vehicles/machinery is British Columbia. The province offers $14,000 in incentives meaning nearly 6,000 cultivated hectares, 54,000 hectares of spraying, 75,000 hectares of spreading, and 1900 hectares of tilling and no consumption costs. Subsidies in other regions are $8,000 in Québec and $5,000 in all other provinces & territories (CanadaDrives, 2020).

With current hydrogen fuel pricing in Canada, the operational costs of a hybrid AAPU are nearly twice those of the equivalent diesel operation. However, by 2030, with the expected drop of hydrogen fuel cost in Canada to that of the current global market price, the operational costs of an FC EV hybrid AAPU have been modelled to be below that of current diesel operations by an average of nearly 5%. As such, the proposed hybrid FC EV AAPU model is demonstrated as feasible within less than ten years.

Greenhouse gas emissions

Using the lifecycle GHG emissions values (EEA, 2018; Sternberg et al., 2019; USDE, 2020), the environmental footprint of the proposed design for the varying operations and power grids was determined. The results are presented in Fig. 2 and compared with diesel, battery EV (mixed & renewable power grid) and the proposed hybrid FC (mixed & renewable power grid). The GHG emissions calculated for renewable energy hybrid FC powertrains were an average of 70% lower than those of diesel powertrains.

DISCUSSION

Agriculture emits nearly 7 billion tonnes of CO_2-equivalent into the atmosphere each year (Russel, 2014). The 70% reduced emissions from the hybrid drivetrain that were calculated and compared in Fig. 2 would have a sizeable impact in lowering the GHGs emitted in agriculture from agricultural machinery (with a more significant effect once an entire FC powertrain is economically viable). While it is not within the scope of this paper to present logistics, software, and general communications methodology, the proposed autonomous and cluster format is further supported by extensive literature in the fields of agricultural connected and autonomous machinery. Robotic cluster operations that present efficiency increase, with supply and operational costs decrease (see the Literature Review). Benefitting from current government incentives and high-speed communications initiatives, infrastructural costs are kept to a minimum allowing for a unique opportunity for both small and large-scale farms to benefit.

The EV technology alone cannot support the energy-intensive and constant operations unique to agriculture. A pure FC propulsion system is too costly for farmers to adopt in the near future. Ultimately, the preliminary feasibility study finds a proposed AAPU plug-in hybrid model would reduce GHG emissions by an average of 70% compared to

Table 5. Specific energy costs of the hybrid FCEV model.

Operation	Battery Portion[a] [$/ha]	Fuel Cell (2020)[b] [$/ha]	Fuel Cell (2030)[c] [$/ha]	Total Hybrid (2020) [$/ha]	Total Hybrid (2030) [$/ha]	Current Diesel [$/ha][d]
Primary tillage	0	7.40	2.96	7.40	2.96	3.05
Planting	1.74	7.06	2.82	8.80	4.56	4.56
Spreading	0.09	0.11	0.04	0.20	0.13	0.15
Spraying	0.01	0.23	0.09	0.25	0.11	0.11
Field Cultivation	0	2.24	0.90	2.24	0.90	0.96

[a] Cost of Hydro was taken as current Ontario, Canada rate = $0.124 $/kWh

[b] Cost of hydrogen fuel was taken as the current Canadian rate = $12.50/kg

[c] Cost of hydrogen fuel was taken as $5.00/kg in 2030 (Global Market Price)

[d] Cost of diesel fuel was taken as $1.462/L in Nov. 2020

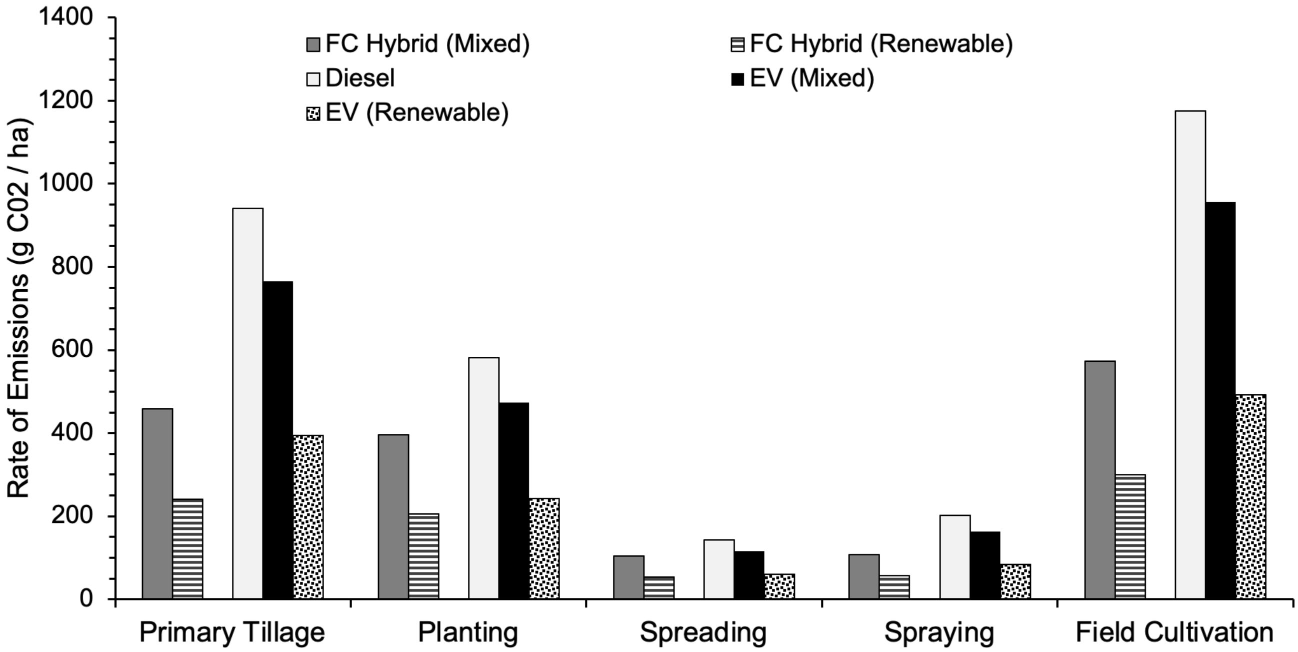

Fig. 2. GHG emissions per operation.

current diesel platforms, with projected operational costs by 2030 ranging from $0.10/ha to $4.18/ha. By 2030, operating costs of an FC EV hybrid were demonstrated to drop below the cost of current diesel operations, supporting that this hybrid model is feasible by 2030. Further research and experimental data collection leading to conclusions as to finite increases in efficiency, supply needs, and operational reliability are encouraged to build from this feasibility study.

SUMMARY and RECOMMENDATIONS

The results in this paper build from the existing research on the benefits of autonomy in agricultural power units and the facilitation of said autonomy through the next-generation network infrastructure. This paper proposes a sustainable approach to these next-generation adaptations, and its feasibility is investigated. While sustainable energy sources for agricultural power units are typically overlooked due to the high PTO power requirements and the comparatively low energy densities of Li-ion batteries, a novel fuel-cell & Li-ion hybrid powertrain is proposed. Preliminary feasibility calculations depict an average reduction in GHG lifecycle emissions of 70%, with current operational prices expected to range from $0.19/ha to $7.49/ha, with these expected to drop by 2030 to $0.11/ha to $4.56/ha. Though immediate prices are increased compared to the diesel operational costs of agricultural operations, significant government subsidies and benefits are readily available for green operational adjustments in Canada. Similar benefits are available worldwide. Further areas for improvement and suggested research to build on these preliminary results include:

High-Profit Crops: The size of the AAPUs may vary for greater initial capital in high-profit crops (allowing for larger-scale versions), leading to greater acquisition costs and benefits.

Economic Modeling: An economic analysis calculating capital recovery, profit, yield, nominal power ranges for the profitability of the AAPU, and experimental data leading to operational costs and general costs associated with this format compared to existing autonomous green and diesel power units are required.

High-Density Li-Ion Batteries & Variable Drivetrains: Existing and future research in increasing li-ion batteries' power-to-weight ratios (eventually 1:1). Investigate the most efficient way to ratio power from battery & FC to optimize SCO, minimal GHG emissions.

Cluster & Communications: Optimal size & formation of an AAPU cluster must be calculated using area capacity, and a model of the AAPUs communications (such as the possibility of leveraging 5G networks in rural areas and how this can be achieved), logistics and autonomous build (such as artificial intelligence, GPS and LIDAR mapping, etc.) are next steps

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