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Research Paper

Reducing air pollution with hybrid-powered robotic tractors for precision agriculture

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A hybrid energy system used in robotic tractors for precision weed and pest control in agriculture is evaluated and its exhaust emissions compared with the use of an internal combustion engine as a single power source. The agricultural implements require power for hydraulic pumps and fans which, initially, was provided by a power take-off system (PTO), wasting a lot of energy. The objectives of this work were to design and assess a hybrid energy system including the removal of the alternators from the tractor and the modification of the agricultural implements to replace the PTO power with electric power, using small pumps and small fans. These changes improved energy use and reduced the atmospheric pollution emission from the internal combustion engine. The hybrid energy system used the original combustion engine of the tractor in combination with a new electrical energy system, which consisted of a hydrogen fuel cell. An analysis of the exhaust gases using the internal combustion engine as the single power source and using the hybrid energy system was carried out to compare the results obtained. The results showed a reduction in emissions of almost 50% for the best case.

1. Introduction

Non-road vehicles, such as agricultural machines, use large amounts of energy, usually fossil fuels and emit large amounts of pollution to atmosphere. Off-road internal combustion engines (ICEs) emit carbon dioxide (CO_2), nitrogen oxides (NO_X), carbon monoxide (CO), particulate matters (PM) and hydrocarbon (HC). CO_2 and NO_X are greenhouse gases, and they contribute to global warming. Furthermore, they can

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List of symbols and acronyms

CO	Carbon monoxide
CO_2	Carbon dioxide
D	Implement draft force (kN)
E_{EES}	Energy demand supplied by the electrical energy system (kW h)
EES	Electrical energy system
E_{ICE}	Energy demand supplied by the internal combustion engine (kW h)
EMS	Energy management system
GPS	Global positioning system
HC	Hydrocarbon
HES	Hybrid energy system
HFC	Hydrogen fuel cell
ICE	Internal combustion engine
MR	Motion resistance (kN)
n	Number of tools
NO_X	Nitrogen oxides
P_{EES}	Power demand supplied by the electrical energy system (kW)
PEM	Proton exchange membrane
P_{ICE}	Power demand supplied by the internal combustion engine (kW)
$P_{IMP\ control}$	Electrical power of the implement control system (kW)
PM	Particulate matter
P_{Task}	Electrical power demand of the task (kW)
PTO	Power take-off
P_{Tool}	Electrical power of each implement tool (kW)
$P_{UGV\ control}$	Electrical power of the UGV control system (kW)
PV	Photovoltaic
PVGIS	Photovoltaic geographical information system
RDS	Row detection system
RTK	Real time kinematic
SFC_V	Specific fuel consumption volume (l kW h^{-1})
SHC	Specific hydrogen consumption (kg kW h^{-1})
TE	Total energy (kW h)
TPH	Three-point hitch
UGV	Unmanned ground vehicle
WDS	Weed detection system

cause health problems: NO_X may cause or worsen respiratory diseases, such as bronchitis or emphysema, and may also aggravate existing heart disease; CO binds to haemoglobin in the blood and can cause harmful health effects by reducing oxygen delivery to the body's tissues and organs (such as the brain and heart), reducing work capacity and mental skills; decreasing learning ability; causing headaches, nausea, and dizziness; and, at extremely high levels, can cause death. HCs are volatile organic compounds, such as xylenes, toluene, benzene and ethyl-benzene. These compounds can cause headaches, dizziness, loss of consciousness, etc. Furthermore, benzene is carcinogenic and increases the likelihood of leukaemia. Particle matter (PM) emitted from combustion engines is a complex mixture of liquid droplets and fine particles have a number of components, including sulphates and nitrates, metals, organic chemicals, and dust or soil particles. These particles can also affect the lungs or heart function causing serious health problems according to the US Environmental Protection Agency (EPA, 2015).

Some research analysing energy use and the pollution emitted by agricultural tractors has been carried out. Clements et al. (1995) analysed the energy used in weed control using herbicides and tillage and found that alternative weed control strategies can provide interesting energy savings. Hansson, Lindgren, and Norén (2001) compared different methods and calculated the average absolute and specific emission values from agricultural tractors. Considering the consequences of these emissions, we need to progressively reduce the use of hydrocarbon fuels. To achieve this, fossil fuels can be replaced by cleaner fuels or electrical systems. Dalgaard, Halberg, and Porter (2001) presented a model of fossil fuel use for Denmark and proposed the use of their model to simulate possible agricultural production scenarios in an effort to improve future techniques. Guzman and Alonso (2008) analysed energy use in Mediterranean agriculture and evaluated the contribution of the organic olive oil production towards improving energy efficiency and compared the results with respect to the conventional production. Soni, Taewichit, and Salokhe (2013) presented an analysis of the CO_2 emissions and energy consumption in agricultural task performed over rain fed crops. Peltre, Nyord, Bruun, Jensen, and Magid (2015) analysed how increasing soil organic carbon content decreased the draft force in ploughing and the consequent reductions in fuel consumption and emissions.

To date much research has studied alternative energy sources to the use of fossil fuels and ICEs. Biofuel is one of these alternatives. Gasparatos, Stromberg, and Takeuchi (2011), analysed the impact of biofuels on society and environment demonstrating that biofuels generate many impacts that must be considered. However, many works on alternative power sources propose the use of batteries; for example, Delucchi and Lipman (2001) analysed the lifecycle costs of battery-powered electric vehicles (that is, initial vehicle cost as well as operating and maintenance costs) to develop a detailed model of the lifecycle costs of electric vehicles. This model was compared to a gasoline ICE vehicle model and determined the battery properties needed to reduce the costs of electric vehicles to be economically competitive with ICE vehicles. Mousazadeh et al. (2010) looked at the various battery technologies available for use in solar-assisted plug-in hybrid electric tractors to be used in light-duty agricultural operations. This was extended by Mousazadeh et al. (2011) who carried out a life cycle analysis of a solar-assisted plug-in hybrid electric tractor and compared the results with that of a similar power output ICE tractor considering economic costs and environmental emissions. They determined that the life cycle costs of solar-assisted plug-in hybrid electric tractors are lower than those of ICEs.

Other important alternatives to batteries as the energy source in electric vehicles are fuel cells; usually, the same fuel can also be used by an ICE. For example, Mulloney (1993) proposed the use of environmentally benign fuel cells for power production, avoiding the use of fossil fuels for field crop production and distribution. They also presented an