UNIVERSITÉ DU QUÉBEC À TROIS-RIVIÈRES

CONCEPTION ET DÉVELOPPEMENT D'UN VÉHICULE HYBRIDE TOUT-TERRAIN ET FABRICATION D'UN SYSTÈME DE GESTION DE L'ÉNERGIE POUR L'ÉVALUATION DU CYCLE DE TRAVAIL

THÈSE PRÉSENTÉE
COMME EXIGENCE PARTIELLE DU
DOCTORAT EN GÉNIE ÉLECTRIQUE

PAR
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UNIVERSITY OF QUEBEC AT TROIS-RIVIÈRES

DESIGN AND DEVELOPMENT OF AN OFF-ROAD HYBRID VEHICLE AND FABRICATION OF A POWER MANAGEMENT SYSTEM FOR EVALUATION OF WORKING CYCLE

A THESIS PRESENTED
IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE
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Résumé

L'électrification du groupe motopropulseur et l'utilisation d'énergies renouvelables sont suggérées comme des solutions alternatives pour surmonter les problèmes causés par les combustibles fossiles. Cependant, les véhicules électriques hors route, comme les véhicules agricoles et miniers, sont encore aux premiers stades de développement. Il existe des inconvénients associés à l'autonomie limitée et à la lenteur de recharge des véhicules électriques purs actuels. Ces limitations seront plus problématiques dans les véhicules hors route sans accès à une infrastructure de recharge. Afin d'atténuer ces lacunes, l'objectif de cette thèse est défini comme une étude de faisabilité de l'hybridation du groupe motopropulseur de véhicules hors route par l'utilisation de sources d'énergie renouvelable. Nous étudions particulièrement les cas des tracteurs agricoles et robots mobiles.

Sur la base de la littérature, il n'y a pas de méthode standard pour concevoir et développer ce type de véhicules. Bien qu'il existe des cycles de conduite standard et des méthodes de conception et d'évaluation des performances basées sur des modèles pour les véhicules électriques urbains. Ceux-ci ne sont plus applicables dans les véhicules électriques hors route en raison de différences de spécifications comme la vitesse, l'application et la structure. De plus, ces véhicules sont généralement utilisés pour effectuer certaines tâches telles que le transport des matériaux, la traction des remorques, le levage, l'ensemencement et la pulvérisation. Ces particularités demandent un processus de conception différent de celui employé pour les voitures urbaines. Par conséquent, une méthode de conception conceptuelle a été proposée dans cette thèse pour de telles applications. À cet égard, certains cycles de travail typiques ont été conçus et mesurés sur la base de véritables cycles de travail agricoles afin d'estimer l'énergie requise en utilisant un modèle plus adapté à cette réalité. Afin de remédier aux limites des batteries, nous proposons une technologie d'extension d'autonomie avec une densité d'énergie élevée, des émissions faibles et des sources d'énergie vertes avec un potentiel d'application en zones rurales. Par exemple, les véhicules agricoles opèrent généralement loin des réseaux électriques et des stations d'essence. Par conséquent, fournir de l'énergie à ces zones augmente le coût de l'agriculture. Dans ce cas, un système d'alimentation renouvelable autonome, sur place, avec des sources d'énergie verte comme les biocarburants, l'hydrogène vert et l'énergie solaire semblent être une solution appropriée. Par conséquent, en tant qu'étude de cas, un tracteur électrique hybride électrique (ERSAPHT) rechargeable à autonomie étendue via une combinaison d'un système photovoltaïque (PV) et d'un ensemble de générateurs de moteur à biogaz (Bio-Gen) est proposé. De plus, pour mettre en évidence la validité de la méthode proposée, un robot mobile agricole (AMR) a été considéré comme deuxième cas d'étude. Étant donné que l'utilisation de moteurs à combustion interne dans les AMR est limitée en raison des contraintes d'espace et de poids ainsi que des risques pour la santé humaine pour les applications intérieures telles que les serres, une solution est proposée en incorporant les piles à combustible (FC) que, contrairement aux batteries, peuvent être rechargées en peu de temps dans de telles applications. Par conséquent, la faisabilité de la conception et du développement d'un robot mobile agricole photovoltaïque / pile à combustible (PV/FCAMR) a été analysée dans ce travail. Sur la base des architectures multisources des groupes motopropulseurs hybrides proposées, cette étude comprend aussi la conception d'un système de gestion d'énergie pour repartir efficacement la puissance des sources d'énergie.

En tant que résultat pratique, un prototype de ERSAPHT a été conçu, développé, puis testé avec succès dans certains cycles de travail typiques tels qu'une remorque, un pulvérisateur et une pompe à eau dans une véritable situation d'agriculture. Les résultats ont montré que le temps de fonctionnement des ERSAPHT augmentait respectivement de 230, 337 et 483% pour la remorque, le pulvérisateur et la pompe à eau par rapport au système tout électrique. De plus, les résultats d'évaluation des performances pour l'architecture PV/FCAMR montrent une augmentation de l'autonomie de 350%. En fait, le PV/FCAMR en utilisant un ensemble de 300 W PEMFC, un système photovoltaïque de 80 Wh, et une batterie au Plomb-Acide de 25Ah, permet de fournir l'énergie requise pour effectuer des tâches agricoles légères sans avoir besoin de charger le véhicule pendant une journée de travail.

Les résultats de l'expérimentation et de la simulation ont montré que le prolongateur d'autonomie proposé à base d'énergie renouvelable ainsi que le système de gestion de l'énergie heuristique (EMS) permettent d'opérer les systèmes électriques purs sans anxiété de recharge pendant la journée de travail. De plus, l'ERSAPHT et le PV/FCAMR pourront fonctionner comme des véhicules hybrides à énergies propres et de forme indépendante des réseaux électriques en cas d'accès à des infrastructures de carburants verts à la ferme. Ces systèmes constituent des éléments importants pour de futures recherches sur les véhicules hors route basés sur énergie renouvelable en zones isolées.

Bien que les résultats de l'étude de faisabilité aient montré qu'il n'y a pas d'obstacles technologiques majeurs pour répondre aux exigences de performance pour les groupes motopropulseurs électriques hybrides dans les véhicules agricoles hors route, les résultats d'évaluation économique révèlent qu'il existe encore des enjeux tels que le prix élevé, la durabilité, et le manque d'infrastructures pour ce type de véhicule. Par conséquent, il est prévu qu'en réduisant le prix des batteries, des piles à combustible et des technologies de production d'hydrogène vert, il sera possible à l'avenir d'utiliser ces types de véhicules pour relever les défis auxquels le secteur agricole est confronté actuellement.

Mots-clés: Véhicules Électriques Hors Route, Tracteurs Hybrides Électriques, Robots Mobiles Agricoles, Étendard de Gamme D'énergie Renouvelable, Générateur de Moteur de Biogaz, Piles À Combustible, Systèmes de Gestion de L'énergie, Cycles de Travail Agricoles.

Abstract

Powertrain electrification and the use of renewable energies are suggested as alternative solutions to overcome the problems caused by burning fossil fuels. However, electric off-road vehicles, such as agricultural and mining, are still in the early stages of development. Moreover, there are some drawbacks, such as poor durability and long recharging time of the current pure electric vehicles, which will be more drastic in the off-road vehicles with no access to charging infrastructure. In order to mitigate these shortcomings, the objective of this thesis is defined as a feasibility study of off-road vehicles' powertrain hybridization by the use of renewable energy power sources in the cases of agricultural tractors and mobile robots.

Based on the literature, no standard method exists for designing and developing these kinds of vehicles. However, there are some standard driving cycles and model-based design and performance assessment methods for urban EVs. Nevertheless, those are not applicable anymore in off-road EVs due to differences in specifications such as speed, application, and structure. Additionally, these applications are usually used for as material handling, trailer pulling, lifting, seeding, and spraying, which distinguish the design process from the one of urban cars. Therefore, a conceptual design method has been proposed in this study for such applications. In this regard, some typical work cycles were designed and measured based on real farm working cycles to estimate the required energy using a realistic model.

On the other hand, to solve the limitations of batteries, the idea was growing to choose an available range extender technology with high energy density, low life cycle emissions, and green energy sources with the potential for energy-independent application. For instance, agricultural vehicles usually operate far from the electrical networks and fuel stations. Therefore, providing energy to these areas increases the cost of farming. In this case, an independent on-site renewable power supply system with green energy sources like biofuels, green hydrogen, and solar energy seems to be an appropriate solution. Therefore, as a case study, an Extended Range Solar Assist Plug-In Hybrid Electric Tractor (ERSAPHT) via a combination of a photovoltaic (PV) system and biogas-fueled engine generator set (Bio-Gen) with the aim of a battery pack is designed, developed, and evaluated. In addition, to highlight the strength of the proposed method, an Agricultural Mobile Robot (AMR) has been considered a second case study. However, the use of internal combustion engines in AMRs is limited due to space and weight limitations as well as human health risks for indoor applications such as greenhouses. Therefore, the feasibility of designing and developing a Photovoltaic/ Fuel Cell Agricultural Mobile Robot (PV/FCAMR) is studied in this work. Instead, the proposed hybrid powertrains' multi-power sources make designing an energy

management system necessary to effectively split the generated powers between the energy sources.

As a practical outcome, the ERSAPHT has been successfully designed, developed, and then tested under typical working cycles, such as a trailer, sprayer, and water pump in a real farm situation. The results showed that the operating time range of ERSAPHT increased by 230, 337, and 483% for the trailer, sprayer, and water pump compared to the all-electric system, respectively. Moreover, the performance evaluation results for the PV/FCAMR architecture extend the autonomy of the basic pure electric system by 350%. In fact, the PV/FCAMR using a 300W PEMFC set and an 80 Wh photovoltaic system incorporating a 25Ah lead acid battery pack can provide the required energy to perform light-duty agricultural tasks without needing to charge the vehicle during the working day.

The results from experimental and simulation showed that the proposed renewable energy-based range extenders and a heuristic Energy Management System (EMS), could extend the limited autonomy of the basic pure electric systems without charge anxiety during the working day. In addition, the ERSAPHT and PV/FCAMR will operate as energy-independent renewable energy-based hybrid electric vehicles without the need for any fossil fuel and grid power in case of access to green fuel infrastructure on the farm. In fact, these systems are primary test beds for future research on autonomous renewable energy-based off-road hybrid electric vehicles.

The results of the feasibility study indicate that meeting performance requirements for hybrid electric powertrains in autonomous off-road agricultural vehicles is technically feasible without significant obstacles. However, the economic assessment indicates that there are still obstacles to be overcome, such as high costs, limited durability, and the absence of infrastructure. Therefore, it is expected that by reducing the cost of the battery, fuel cell, and green hydrogen production technologies in the future, it will be possible to use these types of vehicles to tackle the challenges facing the agriculture sector.

Keywords: Off-Road Electric Vehicles, Electric Hybrid Tractor, Renewable Energy Range Extender, Biogas Engine Generator, Fuel Cell, Energy Management System, Agricultural Working Cycles.

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A	Front Area	$I_{Batt.}$	Battery current
a_{lacc}	linear acceleration	P_{PV}	Photovoltaic system power
C_d	drag coefficient	r	Tire radius
C_{roll}	Rolling resistance coefficient	RE	Range extender
F_{acc}	Force required for acceleration	$\eta_{Batt.}$	Battery efficiency
F_{air}	Aerodynamic force	η_g	Transmission system efficiency
$F_{drawbar}$	Drawbar force	η_m	Motor efficiency
F_{hill}	Hill force	η_{PV}	Photovoltaic system efficiency
F_t	Traction force	η_{SAPHT}	Overall efficiency of SAPHT
g	Gravity acceleration	ρ	Air density
G	Gear ratio		

List of Abbreviations

ADC	Analogue to Digital Convertor
ASABE	American Society of Agricultural and Biological Engineers
Bio-Gen	Biogas Engine-generator
BPEV	Battery Powered Electric Vehicle
CB	Charge Blended
CD	Charge Depletion
CS	Charge Sustaining
DOD	Depth Of Discharge
EMS	Energy Management System
EPA	Environmental Protection Agency
EREV	Extended Range Electric Vehicle
ERSAPHT	Extended Range Solar Assist Plug-in Hybrid Electric Tractor
ESS	Energy Storage System
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
GHG	Green-House Gas
GPS	Global Positioning System
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engines
ICET	Internal Combustion Engine Tractor

ICEV	Internal Combustion Engine Vehicle
LCA	Life-Cycle Assessment
LCC	Life Cycle Cost
LCE	Levelized Cost of Energy
Li-ion	Lithium-ion
NASA	National Aeronautics and Space Administration
Ni-Ca	Nickel-Cadmium
Ni-MH	Nickel-Metal Hydride
PHEV	Plug-in Hybrid Electric Vehicle
PID	Proportional-Integral-Differential
PTO	Power Take Off
PV	Photovoltaic
PV/FCAMR	Photovoltaic Fuel Cell Agricultural Mobile Robot
PWM	Pulse Width Modulation
rpm	Round per minute
SAPHT	Solar Assist Plug-in Hybrid electric Tractor
SOC	State of Charge
STC	Standard Test Conditions
VRLA	Valve Regulated Lead Acid

Chapter 1 - Introduction

1.1 Motivation for Off-Road Vehicle Powertrain Electrification

The world's population is increasing, becoming around 8 billion [1]. Meanwhile, the demand for food and agricultural products continues to rise as living standards improve. The increase in the urban population and the decrease in the farming population have also promoted the development and application of new agricultural machinery due to labor shortage issues. On the other hand, the agriculture section faces several challenges, such as increasing energy demand, greenhouse gas emissions, and the effects of global warming [2]. Therefore, the farm machinery of the future must be completely redesigned compared to today's technology. It should be modular with exchangeable equipment integrated into the machine itself or autonomous and lightweight, so several small vehicles can work in the field, working continuously 24 hours a day, automatically changing equipment and batteries/refueling when needed [3].

Since the main environmental problems are associated with the burning of fossil fuels, the vehicle industry has been in a period of energy transformation from fossil fuels to clean energy. In this light, the transportation sector is widely blamed for fueling petroleum-derived commodities, like gasoline, in Internal Combustion Engines (ICEs). Moreover, the harmful emissions from conventional vehicles play a significant part in the growth of global warming [4]. In this connection, renewable energy and drivetrain electrification seem to be alternative ways to lessen these negative impacts of fossil fuels [5] and [6]. However, some downsides of the electrified powertrain in vehicular applications are limited infrastructure, poor durability, and the long recharging time of the current battery technologies. Nowadays, different vehicle architectures have been developed in the automotive industry to alleviate these challenges. They include the Hybrid Electric Vehicle (HEV), Plug-in Hybrid Electric Vehicle (PHEV), and Extended Range Electric Vehicle (EREV) to extend the vehicle range. The PHEV and EREV have the facility to plug into an electric outlet, and the vehicle no longer depends on a single energy source. This type of architecture can be found in the Chevrolet Volt and BMW i3. The range extender can also utilize an ICE, Fuel Cell (FC) stack or other energy sources. From this perspective, Toyota Mirai can also be treated as an FC extended-range electric vehicle.

On the other hand, while vehicle electrification yields lower emissions and increased energy efficiency, it brings additional concerns such as higher cost, enhanced weight, and volume requirements of the powertrain [7]. Although the battery vehicles have zero local emissions, the battery production is not zero emission. In fact, battery production is a much more environmental pollutant than the production of gasoline engines [7]. Therefore, the design of the energy storage system is a balance between these concerns for vehicle architecture, consumer requirements, etc.

Literature consideration indicates that the poor durability, long recharging time, and environmental emissions related to battery production has limited vehicle powertrain electrification. These limitations would be more drastic in off-road vehicles, which typically require more energy quickly [8]. Even in some cases, such as farm vehicles, the availability of a charging station is a big issue. Thus, hybrid electric vehicles (HEVs) have been proposed to interact with this technological and sustainable development as an interim solution. Moreover, there are several sources, including internal combustion engines (ICE), supercapacitors (SC), and fuel cells (FC), to hybridize the energy sources in HEVs.

Furthermore, stricter environmental protection policies, such as European Stage V non-road emission standards [9], tighten the emission level in off-road vehicles such as agricultural and construction vehicles. Instead of off-road vehicles, powertrain electrification is still at the initial stage. It seems to be an important step in the future. In this regard, even though some progress has been made in industrial and construction vehicles [10], hybrid electric agricultural tractors and mobile robots have not received adequate attention. Nevertheless, there is no in-depth analysis concerning the designing and developing approaches for off-road applications.

1.2 Problematic

Despite the advantages mentioned above, pure electric vehicles still face customer pushback due to concerns about higher prices, restricted range, and fewer incentives to access charging stations due to a lack of infrastructure. Regarding battery limitations, the trivial method to extend the autonomy is to choose a bigger battery in terms of storage capacity that would increase the cost, the recharging time, and the vehicle weight. Hence, hybrid powertrains have been developed by integrating the ICEs with batteries as well as other innovative power sources such as the FC, SC, and solar panels to propose the EREV. To address the problem of limited range, a range extender (RE) with a higher energy capacity (more than battery energy density) is often used to achieve a hybrid energy system. Nevertheless, these hybrid energy sources complicate the HEV's powertrain design and components packaging, making an EMS design necessary.

Moreover, based on this knowledge and the multi-power sources of HEVs, another problem is how to manage the power splitting between those hybrid energy sources and propulsion systems. Indeed, the power distribution flexibility of HEVs with a much more intricate Energy Management System (EMS) has been utilized for splitting the power. More studies have been focused on it in the literature [11], [12]. The EMS is needed to guarantee the entire system's efficiency without sacrificing the various components' performance and useful lifetime. Therefore, the component size, EMS, etc. could affect a hybrid vehicle's fuel economy and performance [13]. The design process and implementation of the road vehicle are mature. However, in off-road vehicles, including agricultural tractors and Agricultural Mobile Robots (AMRs), powertrain hybridization is still at the initial stage. Therefore, more effort must be devoted to getting the same level of technological maturity for off-road vehicles. For instance, the "working cycle" is poorly defined in such applications, and the system design is not straightforward. In fact, the major technical hindrance in deploying such vehicles is calculating energy requirements to size the energy storage systems.

Moreover, energy consumption greatly depends on the vehicle's working cycle condition. Nevertheless, based on the author's knowledge, there is no standard energy analysis and component sizing method for such applications regarding off-road HEV working cycle deviation and powertrain design. Therefore, the fundamental problem is understanding the work cycle that combines the power requirement for traveling and working.

In this regard, although there are some standard driving cycles and performance assessment methods for urban EVs. Nevertheless, those are no longer applicable in off-road EVs due to differences in speed, application, structure, etc. For instance, in off-road vehicle applications, using only velocity profiles is not enough due to fluctuations in working conditions in terms of task variation, transient work environment, soil deflection, etc.. Additionally, these applications are used to implement specific farming tasks such as material handling, trailer pulling, and lifting, which separate these applications from automobiles.

Furthermore, literature consideration shows that the model-based design is used as a powerful engineering aid tool to simulate vehicles in a computer before construction. However, there is some model-based software in the urban vehicle design process. Nevertheless, those are not applied directly to the off-road EVs due to differences in speed, application, structure, etc. Therefore, developing an appropriate energy model should be worthwhile and fundamental for a hybrid electric off-road vehicle design process. In fact, vehicle modeling and working cycle derivation are vital for components sizing and energy management strategy (EMS) tuning of a HEV designing process.

Consequently, these issues make the design process of an HEV for off-road applications (like agricultural tractors and Agricultural Mobile Robots (AMRs)) more challenging due to their different specifications, working environments, and expected duties. Typically, these vehicles are used for particular tasks or transporting materials that need extra energy. These specific characteristics have made designing an off-road model more complicated. Therefore, based on the previous researches’ outcome, the following objectives and contributions are considered to investigate the hybrid electric powertrain feasibility for the studied off-road vehicle applications.

1.3 Objectives and Contributions of the Project

This dissertation's main goal is to design and develop an off-road hybrid-electric platform with a heuristic energy management system by extracting some typical working cycles to extend the vehicle's working range. The practical purpose of this work is to design and develop a renewable energy-based hybrid vehicle to work independently from the fossil fuel station and power grid for agricultural light tasks. Based on these goals by pursuing the challenges mentioned above and potential, the following minor goals were established:

1. To propose a design approach to select an appropriate renewable energy-based range extender using Biogen, PV, and FC systems for off-road agricultural vehicle applications.
2. To propose and define working cycles for designing and validating off-road hybrid electric vehicles (agricultural tractors and AMR applications) based on experimental tests.
3. To propose and validate a heuristic energy management system, including a power splitting tailored for an off-road agricultural vehicle.
4. To evaluate the feasibility of developing a renewable energy-based extended-range electric powertrain for agricultural applications based on working range performance and life cycle cost analysis.

One significant point which needs to be clarified herein is the key differences between this and previous works. In this regard, it should be noted that a unified approach is proposed in this research to develop a RE by defining working cycles for the understudy agricultural hybrid electric powertrain applications as different from the previous works. In addition, a Biogens and FC system in cooperating with a Photovoltaic (PV) system is proposed in this research to run as a RE based on biogas, hydrogen, and solar panel for energy-independent farm applications compared to previous works, that run more by fossil fuel internal combustion engines (ICEs).

Moreover, the proposed multi-mode energy management strategy allows the range extender to operate in a near-optimal condition in almost constant power output, which allows employing the strategy in EMS module hardware in real-time application. Furthermore, an economic evaluation of powertrain hybridization for off-road agricultural vehicle applications is conducted in this work which could help to understand the project's feasibility in competition with the current fossil-fueled agricultural vehicles.

1.4 Methodology

The following methodology was considered to achieve the objectives:

The first stage of this work is reviewing the literature to determine state-of-the-art information about the proposed topic. The next stage of this work is to define some realistic "working cycles" based on typical tasks for the agricultural tractor and the AMR to employ them in the off-road hybrid electric vehicles design and evaluation process. In this regard, several experimental tests should be conducted in work environments such as fields and laboratories.

The third stage of the work deals with measuring and estimating the vehicle parameters to develop a model for off-road vehicle applications. A mathematical vehicle model must be established to conduct simulations to evaluate power and energy requirements for off-road vehicles in different working cycles. Such a model is vital before construction for RE sizing and energy management system evaluation.

The fourth stage of this work is to mitigate the autonomy problem of an EV in the off-road application by incorporating an appropriate range extender that consider the working environment and fuel accessibility. Therefore, an idea was growing to use an up-to-date renewable energy technology with high energy density, low life cycle emissions, and green energy sources. In this regard, vehicles such as agricultural tractors usually operate far from electrical networks and fuel stations. Hence, providing energy to these areas increases the cost of farming. Therefore, in such cases, an independent on-site renewable power supply system with green energy sources like biofuels and solar energy seems to be an appropriate potential solution. Hence, an Extended Range Solar Assist Plug-In Hybrid Electric Tractor (ERSAPHT) is suggested in this work. That system combines photovoltaic (PV) and biogas-fueled engine generator set (Biogen) with a battery pack as renewable energy sources. Furthermore, fossil fuel usage is limited in indoor greenhouse off-road vehicles such as agricultural mobile robots because human health can be in danger. Therefore, one solution is to incorporate a range extender like a fuel cell (FC), which, unlike batteries, can be charged in a few minutes without harmful emissions like the ICEs. Therefore, a Photovoltaic Fuel

Cell Agricultural Mobile Robot (PV/FCAMR) is suggested as a second case study to highlight the strength of the proposed method.

Due to the multi-power sources of the suggested hybrid powertrains, an energy management strategy is required to split the generated powers for each system. In this regard, the fifth stage of this work is designing an EMS to power splitting between energy sources. This work's control system suggests three modes: Economic, Normal, and High-power. It is worth reminding that the designed energy management has been validated on the prototype vehicle.

The last stage would validate the suggested RE vehicles to assess their performance under different situations by employing the multi-mode EMS based on real-world experiments. Furthermore, an economic assessment is performed to understand the feasibility of the understudy off-road agricultural hybrid electric vehicles.

1.5 Introduction Summary and Thesis Organization

In this chapter, the motivation for off-road vehicle powertrain electrification, along with some challenges, are mentioned. In this regard, some goals are defined, and then related methodology to address the obstacles and reach the goals are explained in short. The remainder of this document is organized as follows. Chapter 2 reviews the fundamentals of designing an off-road hybrid electric vehicle, including driving cycle derivation, vehicle modeling, components sizing, and energy management strategy approaches, along with the achieved results of the performed research and specific features of the case study off-road vehicles. Next, the off-road HEV powertrain design fundamentals, project background, developing methods, along with EMS experimental setup construction are described in Chapter 3. After that, the real-world test definition methods to derive working cycles and achieved results for the model validation, vehicle performance evaluation, and economic assessments are presented in Chapter 4. Finally, the conclusion is drawn with a detailed description of the future steps concerning this work in Chapter 5. Furthermore, additional information about powertrain modeling, and related parameters, are presented in the appendices. Finally, the resulting papers from this research work are given at the end.

Chapter 2 - Literature review

2.1 Introduction

This chapter presents a literature survey on off-road vehicle powertrain hybridization research. First, the survey emphasizes the working cycle's influence on off-road vehicle design, component size, energy management, etc., as a research gap. After that review highlights the off-road vehicle's powertrain electrification advantages and disadvantages, modeling, designing components, and energy management strategies. Finally, this study investigates the specifications, potentials, and challenges related to the two particular off-road vehicles comprising agricultural tractors and AMRs powertrain hybridization.

2.2 Off-Road Hybrid Electric Vehicles

An off-road vehicle is any ground vehicle that typically does not use regular roads for its operation. Examples of such vehicles include predominantly construction vehicles, industrial vehicles, agricultural vehicles like tractors, and so on. These vehicles operate at stationary or relatively low speeds [14]. Recently, fuel economy and pollution control issues have been focused on leading to a greener environment and, of course, economic operation. Hence the possibilities of using hybrid technology for off-road vehicles are being considered.

As different vehicle architectures can be designed with various components, it is impossible to compare relevant data between off-road vehicles without a predefined standard. In terms of performance assessment, light-duty vehicles are usually tested in specific conditions using different types of power-absorbing chassis dynamometers. At the same time, heavy-duty engines are experimented on a specific test bed [15]. Indeed, the time and cost involved in setting up an engine on a test bed can be far greater than the time and cost required for the actual test itself, and full-vehicle tests are often therefore more practical [16]. Therefore, analyzing vehicle performance is then performed as the vehicle progresses through a predefined driving cycle designed to represent a particular type of real-world operation.

Drive cycles are developed, created, and referred to for analyzing the designed vehicle performance, fuel economy, etc. The drive cycle is basically representative of the road. Drive cycles are usually used to diminish the expense of on-road tests, the test's time, and the test engineer's fatigue in the prototyping stage of the design process. The main idea is to bring the road condition to the computer simulation or the test lab (a chassis dynamometer) [17]. However, off-road vehicles often operate over rough terrain or specific pathways to do some work like material handling, loading, some specific tasks, etc. The working cycles are different in terms of torque need, auxiliary equipment, etc. Thus, the off-road vehicles discussed in this thesis have quite different drive cycles compared to regular automobiles. The following section will detail off-road vehicles working cycle differences versus road vehicle driving cycles.

2.3 Driving Cycle in Road Vehicle Versus Working Cycle in Off-Road Vehicles

Since a vehicle will be driven through all kinds of road profiles and environmental conditions, it is difficult to know precisely in advance which loads the vehicle may encounter in all situations. Therefore, for technical studies, a number of specific situations have been identified, covering more or less common road profiles and expected terrain. Some of these profiles can be used to generate or aggregate an arbitrary variety of road load profiles. Such profiles might include driving on streets under specific terrain conditions [14]. The introduction of drive cycles is to build a standard for manufacturers and customers to compare different types of vehicles [18]. The form of drive cycles is a series of curves with vehicle speed versus time, which represents expected user behavior in different road conditions. The driving cycle indicates how the vehicle is driven. It is usually represented by a set of vehicle speed data points against time to calculate power demand based on vehicle-specific parameters [19]. Different countries or regions may adopt different drive cycle standards based on their specified road condition and domestic industry standard. For example, two typical driving cycles for urban vehicles are shown in Figure 2-1.

(a)

(b)

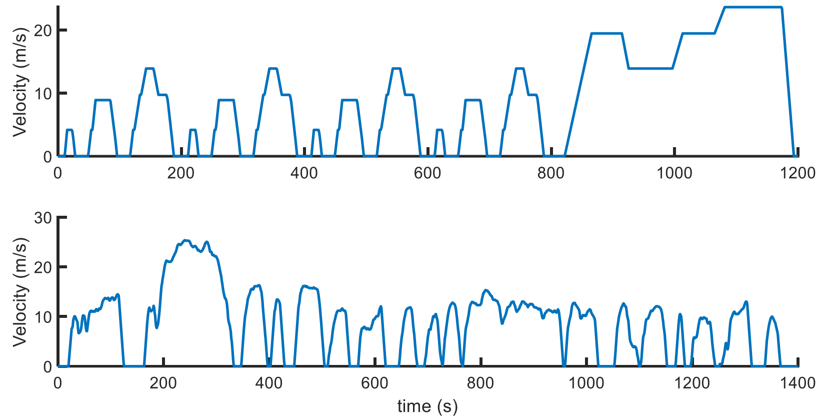


Figure 2-1. Two standard driving cycles are defined for urban vehicles, a) the New European Driving Cycle (NEDC) and b) Urban Dynamometer Driving Schedule (UDDS) [20, 21].

Some driving cycles are made theoretically, as is preferred in the European Driving Cycle (NEDC). These modal driving cycles involve protracted periods at constant speeds. In contrast to direct measurements of a typical road representative driving pattern, which involve many changes and are known as transient driving cycles, there are driving cycles like the UDDS that simulate the constant speed changes that occur during on-road driving [16].

The measured data from road tests (e.g., city or highway) are the inputs to the driving cycle preparation action. The data collection procedure involves the specific equipment of the test vehicle to collect information while driving on the defined test road. From this test, the vehicle versus road measured data is used to derive the road drive cycle, and the driver behavior data could be used to prepare the driver model. These data are used to estimate the vehicle's fuel consumption in a computer simulation tool or chassis dynamometer test bed [17]. Based on the literature, two types of drive cycles can be made. One is time-dependent (speed versus time) and the other one is distance-dependent (speed versus distance) [22]. Examples of time-dependent drive cycles are NEDC and UDDS which, some characteristics of them are summarized in Table 2-1. Time-dependent drive cycles are specifically used for chassis dynamometer test bed because the results can be obtained quickly and repeatable tests can be easily performed [16]. However, it should be noted due to differences in speed range and diverse applications of agricultural vehicles such as tractors and AMRs, most commonly, driving cycles used in road vehicles are not applicable directly.

Table 2-1. Characteristics of commonly used drive cycles for urban vehicles [16, 21].

Drive cycle	**NEDC**	**UDDS**	**HWEFT**
Description	Typical usage of a car in Europe	City driving conditions	Highway driving conditions
Duration (s)	1180	1369	765
Distance (km)	10,931	11,978	16.45
Average Speed (km/h)	33.35	31.5	77.7

In off-road applications, the speed profiles could not be adequately used due to fluctuations in environmental conditions in terms of surface topography, soil deflection, and other obstacles. In fact, due to the combination of traveling and specific duties such as material handling and pulling functionality, the working cycle definition is more applicable in such vehicles. Actually, the “working cycle” expression comes from considering energy consumption rather than the speed profile in such applications with lower speed and higher torque, which is needed for traveling and doing some tasks simultaneously. In addition, it should be considered that these vehicles perform some tasks such as material handling, trailer pulling, lifting, and traveling, which distinguishes design and energy consumption patterns from urban cars. In this regard, some modern agricultural tractor manufacturers have evaluated their vehicles on a chassis dynamometer using the New European Driving Cycle (NEDC) [23] and scaled-down (reduced in velocity) Urban Dynamometer Driving Schedule (UDDS) [24]. Also, a typical working cycle is defined in mining vehicles such as bulldozers [25]. Furthermore, several publications have been reported in the literature describing some standard driving cycles for road vehicles. However, there has been no specific standard working cycle for evaluating electric off-road vehicles until now. Therefore, one of the purposes of this work is to derive some realistic typical “working cycles” to employ in the off-road agricultural hybrid electric design and evaluation process.

2.4 Powertrain Electrification

Over the past few decades, there has been an increased desire to pursue environmental protection. In response, the whole automotive industry has been devoting its efforts on exploring sustainable transportation to cleaner resources. Vehicle electrification incorporates electric-powered architectures to reduce emissions and improve vehicle performance [26]. Among the existing rechargeable batteries, lithium-ion batteries are considered as a potential secondary source in EVs since it has the merits of high capacity, several charge-discharge cycles, and acceptable cost [27]. However, there are still some drawbacks like as low specific energy density, long recharging time, etc.

Power density and specific energy are commonly used parameters to describe various Energy storage systems (ESS). Figure 2-2 compares the power density versus the specific energy of different types of ESS. Referring to this plot, it can be identified that battery technologies have less energy density than fuels. For instance, FC has a much lower peak power density than other energy storage devices like fossil fuels. However, supercapacitors and advanced flywheels have low energy density compared to other technology [28]. The EVs and HEVs powertrains could be appropriate substitutes for conventional vehicles. However, the latter still relies on fossil fuels, and the former suffers from the restricted driving range and long-charging time. These downsides laid the foundations for developing alternative power sources like FCs and Biofuel ICEs in vehicular applications. Therefore, hybrid powertrains combing alternative fuel ICEs with batteries and other innovative Extended Range such as FCEVs have been developed.

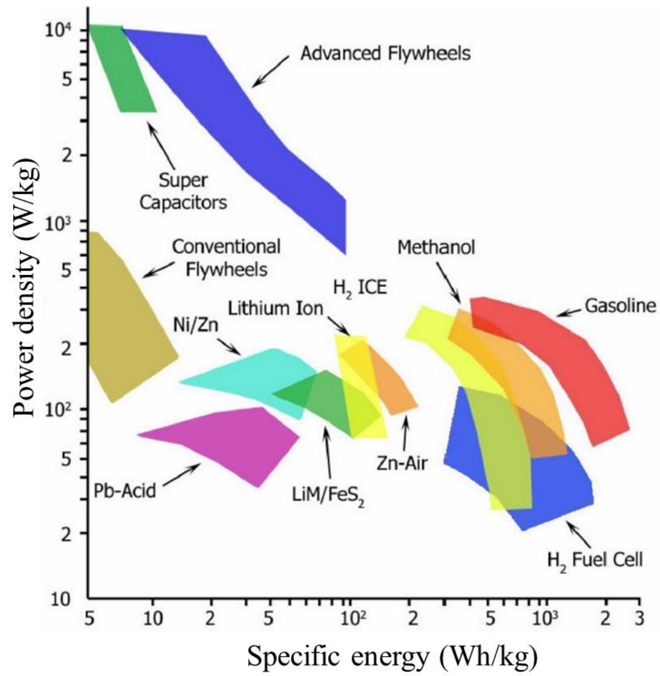


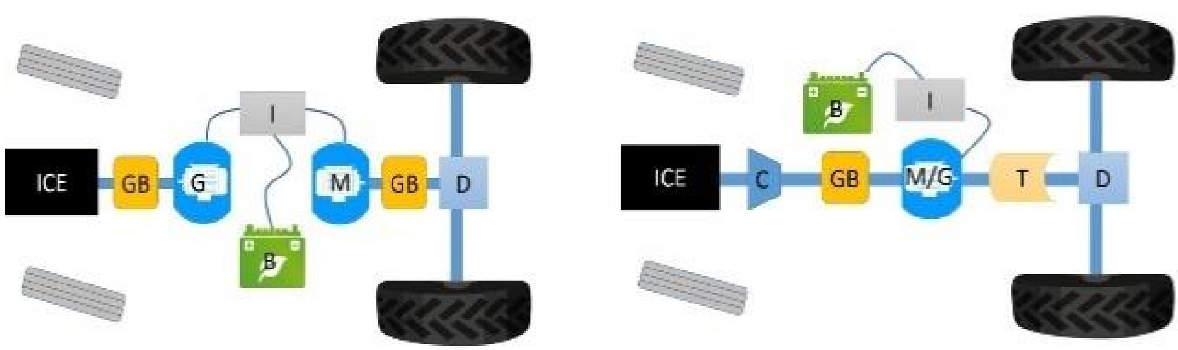
Figure 2-2. Ragone plot to compare power density versus specific energy characteristics in the various energy storage technologies [28].

2.4.1 Hybrid Electric Vehicles Powertrain

Generally, hybrid electric vehicles are assembled with an ICE with at least one traction electric motor for propulsion [29]. However, the notion of hybrid vehicles can also be extended to other configurations, such as an electric propulsion system combined with another energy source, such as FC, SC, and solar panel. This may lead to a reduction in the vehicle's environmental impact and fuel consumption [4]. Some of the advantages offered by HEVs are summarized as follows:

- Electric motors are more energy-efficient than ICEs. Also, the high torque specification of electric motors allows the vehicle to accelerate immediately from a stop position.
- Electrified propulsion systems can support technologies such as Idle-Off, and Regenerative Breaking.
- With support from an electric motor, engineers can reduce the range extender size so as to reduce costs and emissions.
- Easy drivability and improved control ability in autonomous and complex mechanisms such as agricultural tractors and AMRs [6].

Hybrid electric vehicles are classified based on the powertrain layout configuration, including series hybrid and parallel hybrid, as shown in Figure 2–3. In a series hybrid (Figure 2–3 [a]), the RE and a generator are coupled to convert the chemical energy of the fuel to electrical energy. Actually, a series EREV is usually an ICE-assisted electric vehicle. Series hybrid drivetrains offer several benefits, including: a) mechanical separation between the engine generator and the wheels, allowing for a downsized ICE to operate independently at its optimal level to achieve specific performance, efficiency, or emission targets, irrespective of the driver's demands; and b) due to the electric motor's almost ideal torque-speed characteristics, a multi-gear transmission is unnecessary [14]. Moreover, considering a bulky engine generator in a series hybrid, it is more suitable in traction and off-road applications like tractors. That is because there is usually enough space thus mass reduction is not an important objective for a tractor and could even seem like an advantage regarding the stability of the vehicle. However, it might result in a higher initial overall cost for prototyping. Also, in a parallel hybrid powertrain configuration (Figure 2.3 [b]), the electric motor and ICE are coupled with specific transmissions through the same drive shaft to drive the vehicle. This configuration is more applicable in urban vehicles with easy adaptation to the basic ICE-powered powertrain. However, the parallel configuration for agricultural tractors might result in less fuel efficiency due to a speed connection between load and ICE. Moreover, this configuration seems to be unsuitable for PTO and attached agricultural implements electrification due to its coupling mechanism and smaller battery capacity.



(a) (b)

B: Battery; C: Clutch; D: Differential; G: Generator; GB: Gear Box; I: Inverter; ICE: Internal Combustion Engine; M/ G: Motor-Generator; T: Transmission.

Figure 2-3. Basic architectures of a rear axle hybrid drive tractor: a) series hybrid; b) parallel hybrid; adapted from [4].

There are other hybrid configurations in literature for vehicular applications, such as series-parallel hybrid drivetrain and complex hybrid. The distinguishing feature of this configuration is the employment of two power couplers-mechanical and electrical components, which usually have more mechanical and electrical complexity, which might result in higher initial costs and design complexity. These configurations are reviewed in [4].

Table 2-2 compares vehicle types, including ICE vehicles, EVs, HEVs, and Plug-In HEVs (PHEVs). A PHEV or Extended Range Electric Vehicle (EREV) is an HEV with the possibility to recharge the battery from the grid. This adds the potential of using the vehicle as an electric vehicle without the range limitations in a pure electric vehicle. A PHEV may be a more suitable hybrid electric configuration to reduce fuel consumption because it could be charged by external electric power sources like a renewable stationary power plant. However, the PHEV configuration needs an appropriate EMS due to multi-power sources for efficient power splitting [4]. The EREV is a special type of PHEV with a fully functional EV mode combined with a RE to meet the speed and power requirements of the driving load.

Table 2-2. Comparison of ICE vehicles, electric vehicles, hybrid electric vehicles powertrains, adapted from [4, 14, 30] [6].

Type of Vehicle	ICE Vehicle	EV	HEV	PHEV
Propulsion	-ICE	-Electric motor drives	-Electric motor drives -Down sized ICE	-Electric motor drives -Down sized ICE
Energy System	-ICE	-Battery/SC (large battery based on range)	-ICE -Battery/SC (Small battery)	-ICE -Battery/SC (moderate battery based on AER)
Energy source and infrastructure	-Petroleum fuel and fuel stations	-Electric grid charging facility -Regenerative braking energy	-Petroleum fuel and fuel stations -Regenerative braking energy.	-Electric grid charging facility -Petroleum fuel and fuel stations -Regenerative braking energy.
Advantages	+Conventionally available with good infrastructure +Lower initial cost + More reliable in high-power tractors	+Zero tail pipe emissions +Independence on fossil fuel	+Low emissions +Higher efficiency + Reliable as ICEs	+Zero tailpipe emission capability +Less dependence on fossil fuel +Efficient than HEV + Applicable in low charging infrastructure
Disadvantages	-Higher tailpipe emissions -Low efficiency - Higher maintenance and fuel cost	-Limitations of battery Short range for high-power farm tasks -Charging infrastructure facilities in agriculture	-Dependent on fossil fuels -Complex architecture spatially for off-road vehicles applications - Higher initial cost	-Complex architecture spatially for off-road vehicles applications - Higher initial cost

2.4.2 Extended Range Electric Vehicle (EREVs)

A range extender can utilize an alternative-fueled ICE, FC system or other energy sources as secondary energy sources as described more in the following sections.

2.4.2.1 Internal combustion engine (ICE) and alternative renewable fuels

The most common RE uses the engine generator to charge the battery and/or provide actual power output during high-power loads. This type of architecture can be found in the Chevrolet Volt and BMW i3. The ICE converts fuel to mechanical energy and the generator is an electric motor mechanically coupled with the ICE to generate electric power to charge the batteries. It can also be employed to restart the ICE when it is necessary. The non-renewable energy resources utilized by ICE are extinguishing day by day and may not last long for our future generation.

On the other hand, alternative fuels such as ethanol, compressed natural gas (CNG), and biodiesel are considered to be the most promising at present for fueling ICEs. In some remote areas such as the farms and mines, the sun and biomass are the most available energy sources. These types of energies might be converted to electricity or heat. Furthermore, the biomass could be used to produce other types of fuels such as biogas, bioethanol, and biodiesel [31]. The biogas produces via the anaerobic digestion of crops and wastes. Raw biogas consists of about 60% bio-methane and 35% CO_2 with trace elements of H_2S. It is not high quality enough to be used as fuel gas for vehicles. The solution is the use of biogas upgrading or purification processes. The bio-methane content of standard upgraded biogas (type A) is more than 97% [32] that could be used as green fuel in gas-fueled engines.

2.4.2.2 Fuel Cell Extended Range Electric Vehicle

A FC stack converts chemical energy directly to electricity from the reaction of hydrogen with oxygen. Due to their high fuel efficiency and near-zero exhaust emissions, fuel cell vehicles (FCVs) have attracted considerable attention and are often considered the ultimate goal of vehicle powertrain electrification. Unlike a chemical battery, a FC generates electricity immediately rather than storing it and continues to produce electricity as long as sufficient fuel is supplied [4]. Therefore, the FCVs have the advantages of a longer range and faster refilling time when compared with PHEVs and battery EVs. Compared with ICE vehicles, it has the benefits of no emission because of the direct energy conversion without undergoing combustion in addition to high energy efficiency. The most popular FCV in the market is the Toyota Mirai (see Figure 2–4).

Figure 2-4. Toyota Mirai as a commercialized FC range extender (Hydrogen Research Institute, Université du Québec à Trois-Rivières)

Among various types of FC technologies, Proton Exchange Membrane Fuel Cell (PEMFC) has a great potential to be employed in a vehicular application, mainly due to high power density, low-temperature operation, and solid electrolytes [33]. FCV does not have the limitations of competitors and benefits from some certain advantages, such as higher efficiency, pollution-free fuel, and convenient maintenance requirements [34]. However, challenges keep arising in the evolution of the FCVs and have stopped them from full penetration into the automotive markets [35]. Some of the key challenges facing the FCVs are hydrogen production, refueling infrastructures, storage, cost, reliability, and performance. In this regard, ongoing research is being conducted with the aim of delivering renewable energy sources produced hydrogen to fuel stations cheaper than the cost of gasoline fueling for conventional vehicles, providing thousands of hydrogen stations, and shifting the hydrogen storage technology from high-pressure tanks to material-based storage [36]. Still, the hybridization of an FCV along with battery technology enables more benefits:

- Hybridization ensures that the FC can work at its high-efficiency area with the additional power supply from the battery system.

- The involvement of a battery system downsizes FC size and thus lowers the cost of the whole vehicle. Furthermore, vehicle fast start-up and regenerative braking are also applicable because of the existence of a battery system.

Therefore, utilizing a FC system as a single power source cannot meet all the requirements of a FCV due to its intrinsic characteristics. Therefore, a secondary power source, such as the battery, super capacitor (SC) is employed to satisfy the fast dynamic load in vehicles drivetrain, reduce the degradation rate of the PEMFC by absorbing the power peaks, decrease the hydrogen consumption, load power supply during the cold start, and energy recovery while braking. Common structures for hybridization of FCVs is FC-battery, however other configurations such as FC-SC, and FC-battery-SC are available in literature. All of these structures have their own advantages and disadvantages [37]. However, among them, FC-battery structure has been widely employed in practical FCVs [38, 39].

Considering the literature, this work will outline the development process of vehicle models and expand vehicle architecture to extended range electric vehicles with biogas fueled engine generator (Biogen) and PEMFC, as the up-to-date range extenders for agricultural off-road vehicle applications. However, given the multiple power sources of the suggested hybrid powertrains, an appropriate energy management strategy is required to split the generated powers among each system.

2.5 Hybrid Electric Vehicle Energy Management Strategy

The energy management strategy of electric and hybrid electric vehicles is the process that collects drive command information and then decides how to deliver the power and torque commands to the vehicle powertrain. Therefore, the main goal of an energy management strategy is to satisfy the drive command. The secondary objective is to optimize the efficiency of powertrain [4]. In battery EV, the strategy is quite straightforward and simple as there is only one power transmission path. However, the power distribution flexibility of PHEVs is associated with a much more complex EMS. Many studies have been concentrated on this area in the literature [11] and [12]. Generally, as shown in Figure 2-5, energy management strategies are broadly classified into rule-based and optimization-based strategies where each strategy family has advantages and disadvantages. For instance, rule-based methods due to easy implementation and reliability are widely used in a real-time vehicular control system; also, they do not need driving cycle information for running. Rule-based control strategies contain deterministic and fuzzy logic rule-based methods. At the same time, optimization-based approaches determine the control strategy, typically utilizing global optimization and suboptimal approaches [4]. Optimization-based strategies are often used offline because they usually might need high computational time and prior knowledge about driving information. However, they might be useful for refining rule-based methods. The following sections will provide an overview of some existing energy management control strategies in detail.

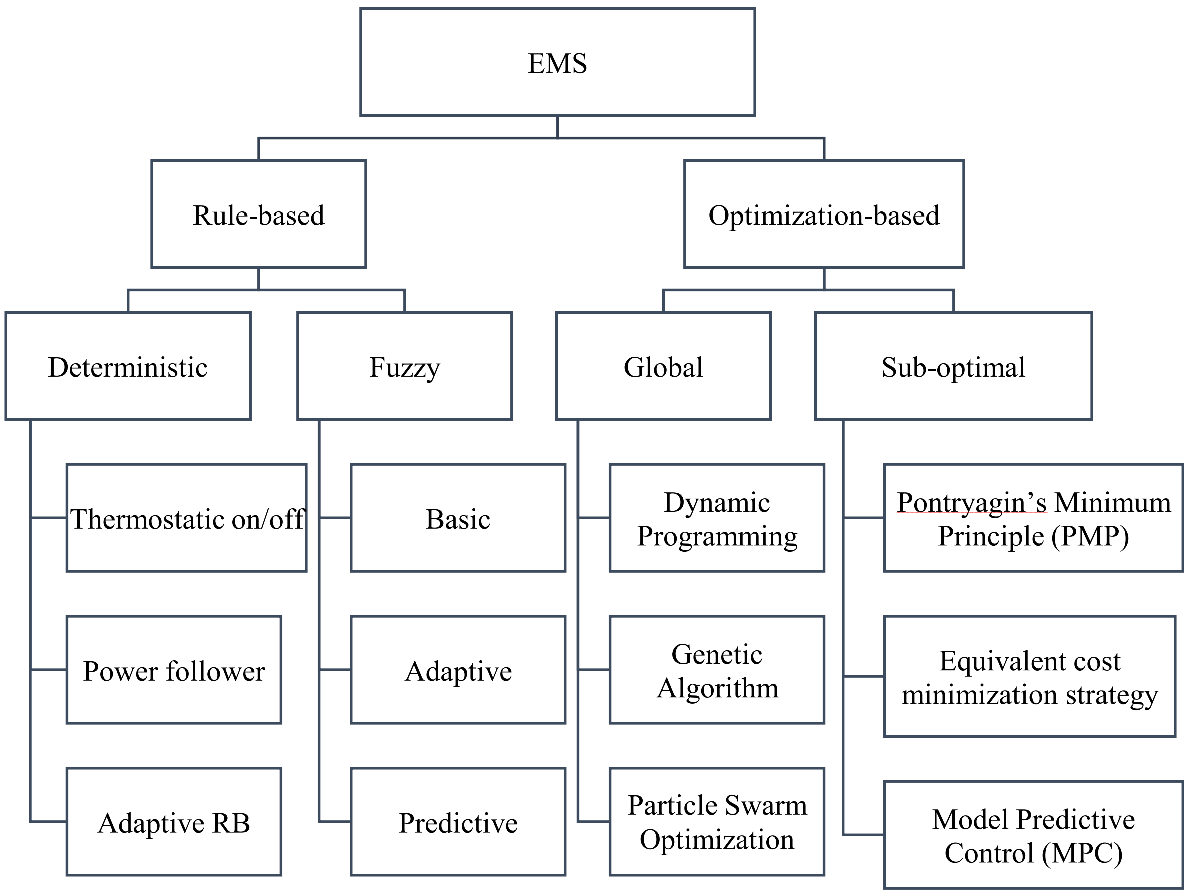


Figure 2-5. Energy management strategies classification adopted from [11] and [12].

2.5.1 Rule-Based Control Strategies

Rule-based methods are usually based on analysis of power flow in a hybrid drivetrain, efficiency/fuel maps of ICE, and human experiences, generally implemented in the form of lookup tables and by splitting powers between power sources [4]. Rule-based methods, due to easier implementation and reliability, are widely used in real-time vehicular control systems [11]. The rules are designed using fuel consumption rate or pollution information, engine maps, and driving experience. The implementation of the rules is done through the respective lookup tables to share the power demand between the ICE and the electric traction motor. The following sections will provide an overview of the existing power management strategies in detail.

2.5.1.1 Deterministic Rule-Based Control Strategies

The simplest Rule-Based control strategy is the thermostat control strategy which uses the generator or fuel converter to generate electrical energy used by the vehicle. In this strategy, the battery state of charge (SOC) as the main parameter is always maintained between predefined low and high levels by simply turning on or off the ICE [3]. However, this method could be used in higher complexity by some heuristic strategies. HEVs and PHEVs have a typical operation mode called “charge sustaining (CS) mode”. In this mode, the vehicle supervisory controller orders the other energy source (e.g., ICE) to charge the battery pack to maintain its State of Charge (SOC) at the desired level (e.g., 50%). It can extend the vehicle’s range and expand the battery life. While the SOC management of PHEVs is different from HEVs because of the involvement of charge depleting mode (CD) (see Figure 2–6). The vehicle operates only depending on the energy from the battery pack before switching into charge-sustaining mode. PHEVs have a predefined SOC operating range (e.g., 90% to 20%) [40]. This helps to maximize battery life and use stored electricity from the grid network instead of the tank’s fuel.

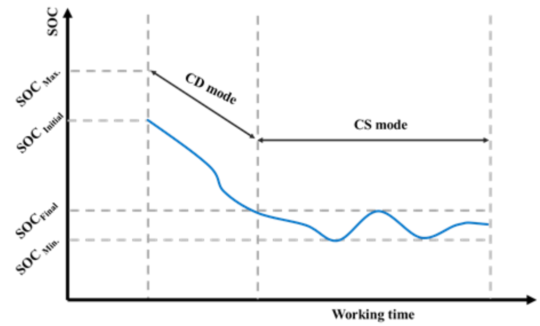


Figure 2-6. Plot of battery SOC management over CD and CS modes in PHEV adapted from [40].

2.5.1.2 Fuzzy Rule-Based Control Strategies

Due to the multi-domain, time-varying nature, and nonlinear of the hybrid electric vehicle powertrains, many researchers have studied the employment of Fuzzy logic as a control strategy solution. Fuzzy logic on hybrid electric vehicle powertrain EMS can be classified under the conventional fuzzy strategy and fuzzy predictive strategy categories [4]. In the conventional fuzzy strategy, efficiency is determined based on the selection of inputs, rules, and outputs base of this control strategy. The fuzzy-logic controller accepts the desired ICE torque and battery's SOC as inputs. The ICE operating point is set based on these inputs and the selected mode [41]. The advantage of this approach is that the operating points for the electric motor, ICE, and battery can be controlled within their optimal efficiency boundaries. However, the main disadvantage of this method is that emissions from the vehicle are not considered. A predictive fuzzy logic control strategy is proposed in [42] to achieve a higher degree of control over the fuel economy and emissions. The common inputs to the predictive controller are the vehicle speeds change relative to recent speeds, the vehicle speed state in the look-ahead window, and the elevation of the sampled points along a defined path. Based on the available motion history of the vehicle and possible changes to the vehicle's movement in the near future, the fuzzy-logic controller starts to estimate the optimal engine torque contribution to the vehicle's current speed.

2.5.2 Optimization-Based Control Strategies

In optimization-based control strategies, a benchmark for optimal power demand can be found by the cost function minimization, such as fuel consumption and harmful emissions. Globally optimal solutions can be found by performing optimization over a typical driving cycle. Nevertheless, with these techniques, it is not possible to directly manage power follow in real-time. However, the results from these optimal strategies could be useful to compare the characteristics among other control strategies [26], and also serve as the basis for determining the online performance of defined rules. Dynamic Programming (DP) [28], Particle Swarm Optimization (PSO), and Genetic Algorithm (GA) [29], etc. are frequently used in the literature to explore offline the fuel economy potential.

2.5.2.1 Dynamic Programming

The dynamic programming (DP) approach was initially developed by Richard Bellman, to find optimal control strategies for multi-stage decision processes [43]. Unlike rule-based algorithms, the dynamic optimization technique often depends on a model to compute the best control policy. The optimal solution can be found by minimizing the optimization parameters by evaluating the objective function at each time step of the drive cycle. References [44] and [45] utilize the DP technique to solve an HEV's optimal power management problem by minimizing a cost function over specific driving cycles. However, the computational complexity of the optimization method is the major constraint.

2.5.2.2 Particle Swarm Optimization

Particle swarm optimization (PSO) algorithm was developed by Kennedy and colleagues to find a solution for a problem by evolutionary stochastic global optimization techniques [46]. The idea of PSO algorithm originated from the swarm intelligence behavior that could be found in many natural systems in the group. Such systems usually consist of a population of single actors or elements interacting locally with their neighbors and group organization. Bird flocks, Ant colonies, and other animal herds are some examples of such natural organizations. In these systems, the agents interact locally, and this can lead to a global behavior. For instance, individuals can change velocity or position locally and a global behavior pattern can be attained [47]. This principle could be used to develop the global maximum or minimum technique in optimization problems.

Based on literature, optimize control strategy using the particle swarm optimization method to optimize design parameters for various hybrid electric vehicle configurations are proposed [48]. For instance, a control strategy parameter optimization using the PSO algorithm for a series plug-in electric hybrid vehicle studied in [49]. The control algorithm's goal is to manage the energy consumption of the ICE and the electric motor so that while the battery state of charge (SOC) is high, the energy consumption will be primarily from the battery. When the battery SOC falls below a lower limit level, the ICE will be employed as the main energy source. The flow chart for the PSO is given in Figure 2–7.

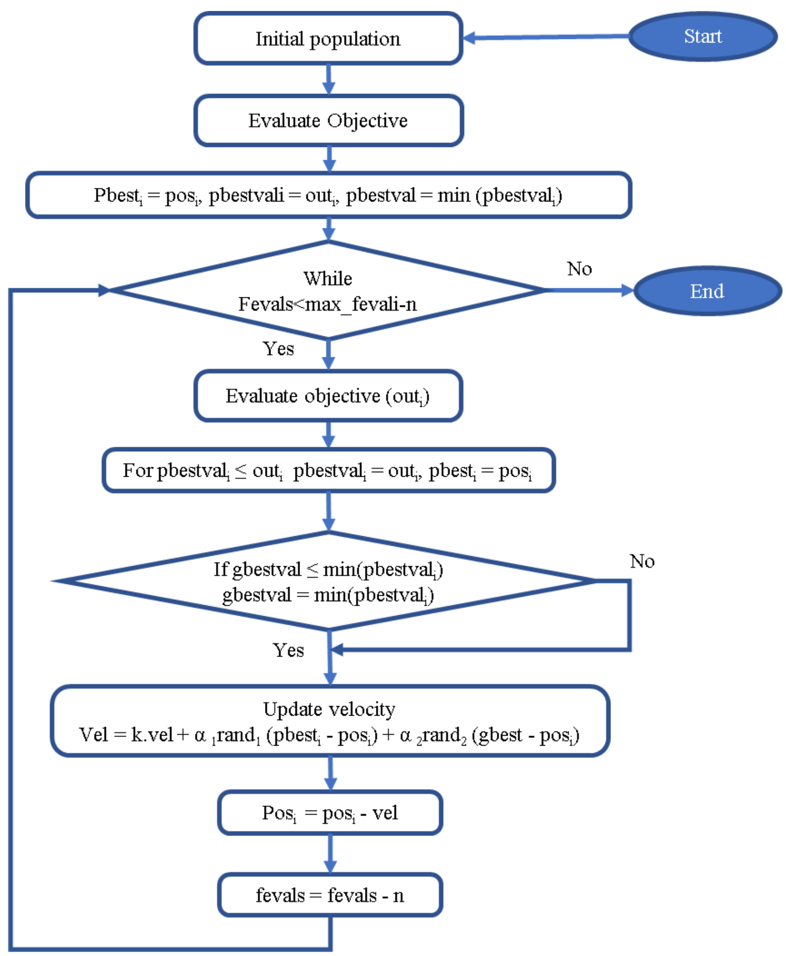


Figure 2-7. Flow chart of particle swarm optimization adopted from [50].

2.5.2.3 Genetic Algorithm

Genetic Algorithm (GA) is a stochastic global search approach that mimics the process of natural biological evolution. This technique has proven effective in solving complex engineering optimization problems featuring non-convex, multimodal, and nonlinear objective functions. The GA efficiently finds global optimum without getting stuck in local optimum [51]. The flow chart for the GA is given in Figure 2–8. The process begins with a randomly generated or selected set of potential solutions or chromosomes. The entire set of chromosomes forms a population. Chromosomes develop over several generations or iterations. Three commonly used operations are employed: reproduction, crossovers, and mutation. These operators are applied to the current generation solution during the search process. The chromosomes are then assessed based on certain fitness criteria, and the best ones are picked, while the others are rejected. This process is repeated until a chromosome with the best fitness value is selected as the best solution to the problem [52]. Unlike the conventional gradient-based tourniquets, the GA strategy does not require additional information or strong assumptions of objective parameters. The GA can also discover the solution space efficiently. However, this optimization method is very time-consuming and does not provide a wider designer's view.

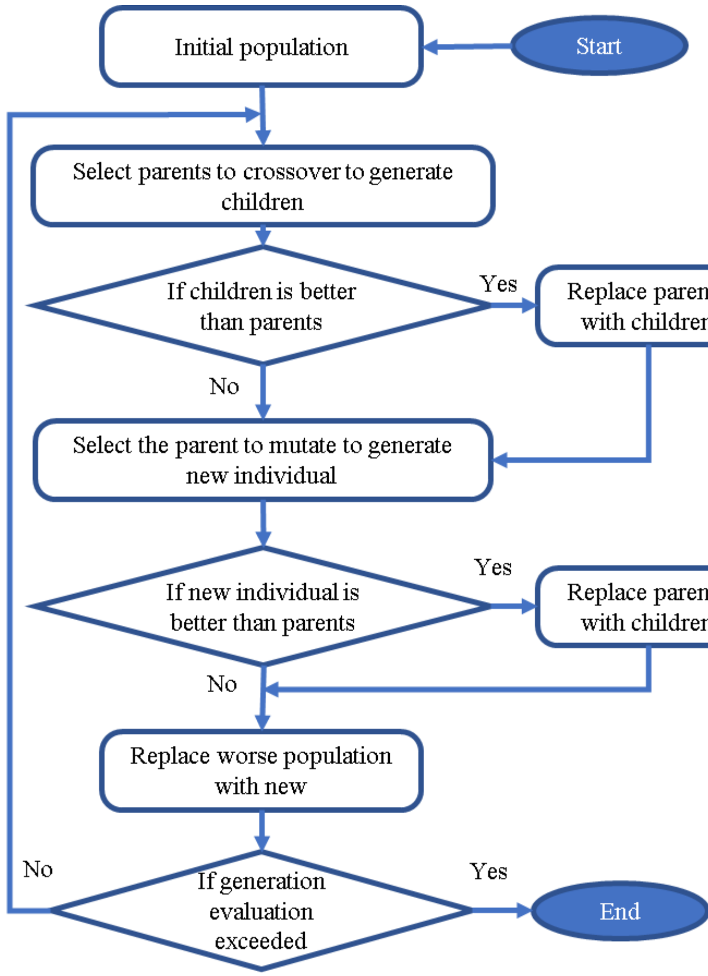


Figure 2-8. Flow chart showing the genetic algorithm adopted from [50].

2.6 Hybrid Electric Vehicle Optimization Design

Same as the control strategy issue, hybrid electric component sizing and system prototyping for an agricultural hybrid electric vehicle are problematic due to the variety of design options and constraints. As the literature review indicated, little effort has been expended to perform component sizing for off-road hybrid electric agricultural vehicles. However, optimal component sizing must meet vehicle performance requirements and constraints. In addition to optimizing the energy management control strategy, further research work is required to be focused on optimizing the drivetrain components. Literature shows that classic, gradient-based, and derivative-free optimization approaches have been proposed to handle HEV component sizing optimization design problems [50]. A detailed review of the HEVs' component sizing techniques can be found in [53]. The component sizing for HEVs can be categorized in terms of components considered, drive cycles, objective functions, optimization approaches, and powertrain architectures. One of the main candidates for solving the component sizing problem of HEVs is the application of natural optimization methods, such as evolutionary and swarm algorithms [54]. It has been demonstrated that natural optimization engines can find global optimum even when the solution space is large, highly nonlinear, constrained, and complex [55]. Based on the literature, population-based optimization approaches such as GA and PSO showed great potential for HEV design problems; they involve numerous local minima, discontinuity in the objective function, and nonlinear constraints. Furthermore, multiple trade-off solutions can be found in a single simulation run without the need for user-dependent artificial corrections and knowledge of objective derivation. These algorithms usually consider fuel economy and emissions as design objectives, drivetrain component parameters as design variables, and vehicle acceleration and gradeability performance criteria as constraints [4].

For instance, the GA is applied to the optimum component sizing of a fuel-cell-powered PHEV in [56]. In addition, an integrated PSO algorithm was used for the optimal powertrain component sizing and design of an FC locomotive application in [57]. They mentioned that the PSO is relevant with a few considering optimization parameters, good accuracy, and short computation time compared to other optimization approaches. However, the disadvantage lies in the selection of the constants in updating the velocity. If inappropriate constants are chosen, then the problem may not converge to the optimum [53]. However, there are another meta-heuristic-based optimization methods like Grey Wolf Optimization (GWO) [58] that could be applied to the optimization process, which is rare in the literature.

2.7 Model-In-The-Loop Design Optimization Process

The approach for HEV design optimization is typically a model-in-the-loop design optimization process, as shown in Figure 2–9. To design a hybrid powertrain, the performance and design objectives, such as overall powertrain cost and fuel economy can be evaluated with the aid of the vehicle model and computer simulation tools. Accordingly, the vehicle model is simulated using the design variables' initial values to obtain the objective function's numerical values in the first step. At the same time, the constraint functions should be evaluated. These simulated results are then fed back into the optimization algorithm to produce a new set of values for the design variables. Then the vehicle model is simulated again to achieve the values of the objective and constraint functions. The simulation results are fed back into the optimization algorithm to generate another new set of design variables. This iterative process repeats until the optimization process achieve the defined objective. Note that the design variables remain within their limitation boundaries during this process.

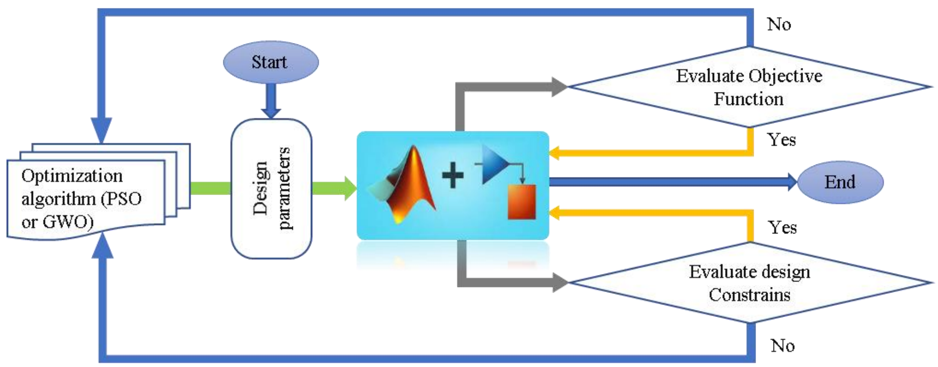


Figure 2-9. Model-in-the-loop design optimization process.

2.8 Vehicle Powertrain Modeling Fundamentals

Since product development is constrained by time and budget, a systematic approach establishes a working flow among engineers in different stages, ensuring the final product meets the initial requirements and shortens the product development process. Modeling plays an important role in the technical development of the actual system prior to construction. The model-based design technique has been introduced into the automotive industry as an effective approach to design HEVs [59]. Moreover, vehicle model-based design and simulation can address difficulties, especially when handling increased complexity of sizing and developing HEVs.

The complexity of the vehicle model depends on the user's need, while the accuracy depends on component parameters and the model-based design method. Two main approaches are widely used in vehicle modeling: Forward-Facing (Dynamic) and

Backward-Facing (quasi-static) (See Figure 2–10) [4]. In a forward-facing model, the input from the driver imposes to the vehicle performance. To follow the desired speed trace requirement from the driver model, the driver block will send out a command from the accelerator or brake pedal to the controller units. The driver model then adjusts commands based on how accurately it is following the trace. The benefits of this type of modeling method are that transient effects (e.g., engine turns on/off, FC starting, etc.) can be considered, and also the design of energy management strategy can be later tested on a test bench or in a prototype vehicle. In short, this type of model can almost simulate the real situation [60]. In contrast, the Backward-Facing model begins with the desired vehicle speed. Then the system determines how the engine and drivetrain should operate and displace to meet the desired speed. Backward models have fast running speeds and are usually used to define trends; however, transient effects and control systems cannot be implemented with this type of model [61]. Nevertheless, models always have some limitations due to assumptions and simplifications (order reduction).

Since there is no standard method for sizing and evaluating components for off-road hybrid electric vehicles on specific platforms such as tractors and AMRs, an appropriate energy model should be worthwhile for coordinating EMS and component sizing problem. In fact, it is a fundamental step for the EMS tuning and components sizing designing by employing the working cycle before the implementation in a real platform.

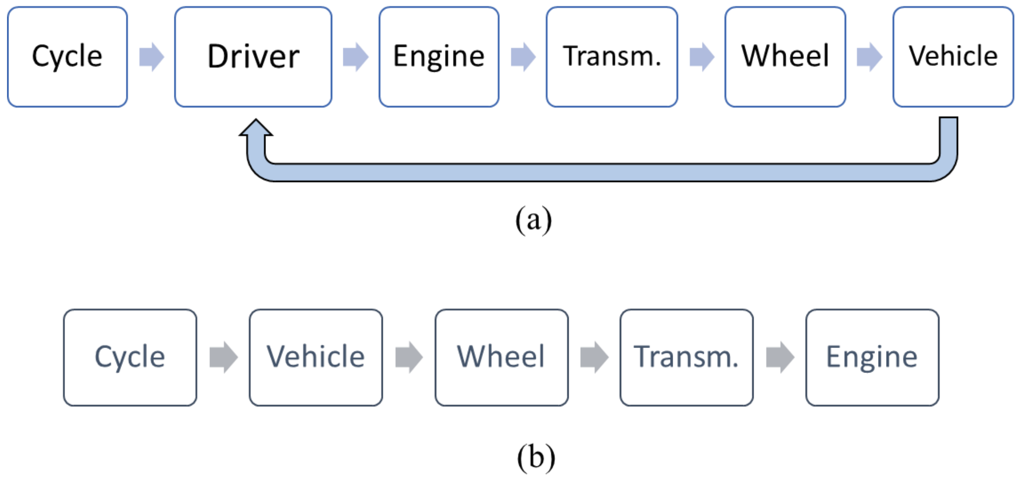


Figure 2-10. Vehicle modeling approaches, (a) forward-facing (dynamic), (b) backward-facing (quasi-static) adopted from [61].

The whole process of vehicle design is an incredibly complex problem, involving numerous variables, restraints, and considerations [14]. Although a comprehensive analysis of electric vehicle powertrain components modeling is beyond the scope of this work, based on vehicle dynamics, fundamental calculations involved in modeling of a Range Extender (RE) are addressed in this work. The dynamic movement of a typical vehicle is generally modeled as a dynamic point mass (M) (mass of the vehicle and the equivalent mass of the rotating parts) that can be moved forward by applying a driving force [62]. Considering a vehicle moving acceleration ($\ddot{x}$), on a slope of angle θ as shown in the Figure 2–11. The external longitudinal forces acting on the vehicle include aerodynamic longitudinal tire forces, drag forces, gravitational forces, and rolling resistance forces. Considering these parameters, the road load force is given by [63]:

$$M\ddot{x} = F_{xf} + F_{xr} - F_{aero} - R_{xf} - R_{xr} - Mg\sin\theta \quad (1)$$

Where F_{xf}, F_{xr}, R_{xf}, and R_{xr} are the longitudinal tire and rolling resistance forces at the front and rear tires, respectively. F_{aero} is the equivalent longitudinal aerodynamic drag force, and g is the acceleration due to gravity.

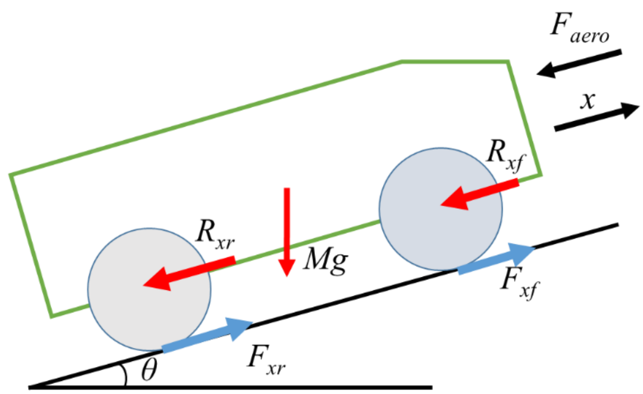


Figure 2-11. Longitudinal forces act on a vehicle moving on a ramp.

It should be noted that the calculations presented here could be used as a basic formulation in the modeling and simulation. To design a highly accurate model, additional considerations and parameters need to be added to the subsystems.

For any type of vehicle, the performance constraints must be defined first to be satisfied. These constraints are different depending on the vehicle type and architecture. From the powertrain and energy performance part of view, typical performance specifications could be considered including initial acceleration, cruise speed, gradeability, driving range, and many more for vehicles [14]. Although the requirements for designing a hybrid electric powertrain for an off-road vehicle vary from the automobiles, it still appears that the ongoing challenges for different off-road hybrid vehicle powertrains are essentially the same, except some specific terms. The following chapters describe two case studies including a hybrid electric tractor and Fuel cell autonomous mobile robot in agricultural application for energy management control strategy and the powertrain sizing optimization. Therefore, specific features of two cases studied in this work are discussed in the following sections.

2.9 Specific Features of Agricultural Hybrid Electric Tractors

A tractor is an off-road vehicle specially designed to provide high traction power at low speeds for different purposes, such as driving certain machines used in agriculture, construction. Traditionally, tractors are described as agricultural vehicles that provide traction and rotation power for various farm tasks [64]. Table 2-3 classified the main applications of conventional farm tractors. Agricultural equipment may be mounted or hauled by a tractor, and also, the tractor may provide rotational and electrical power for machines while working. The criteria for designing a drivetrain for such farm vehicles differ from that of an automobile. As an illustration, tractors are usually designed for attaching different implements for transportation and farm field operating. They are conceived essentially with more weight to operate at lower speed and range of acceleration [6]. Moreover, some field tasks require extra power that could be provided by the Power Take-Off (PTO), hydraulic systems, and electric outlet of the tractor. Therefore, these special features make the tractor working cycle very different from other vehicles.

Table 2-3. Typical farm working cycles classification adopted from [64].

Farming tractor applications			**Transportation**	**Fieldwork**		
Working type			Material handling	Farm operation		Stationary working
Implement example			Trailer	Sprayer	Plow	Water pump
Traction system usage			☑	☑	☑	☒
PTO system usage			☒	☑	☒	☑
Lifting system usage			☒	☑	☑	☒
	Heavy	❸				
Duty type	Medium	❷	❶❷❸	❶❷	❷❸	❶
	Light	❶				
	Low	①				
Speed	High	②	①②	①②	①	⓪
	Stationary	⓪				
Torque	Low	1	1 & 2	1 & 2	2	1
	High	2				

On the other hand, stricter environmental protection policies, such as European Stage V non-road emission standards [9], tightens the air pollution level in off-road vehicles such as agricultural tractors. In this regard, powertrain electrification and renewable energy usage seem to be alternative sustainable solutions in the context of agriculture 4.0 revolution, smart farming, and farm energy independence [5, 6]. As mentioned before, limited infrastructure, poor durability, and a long recharging time of the current batteries are some obstacles for the agriculture powertrain electrification progress. These limitations would be more intensive in off-road vehicles such as tractors, which require high amount of power in a short time for some tasks like plowing [8]. Also, failing a vehicle on the farm while doing a task is a catastrophe and it might cause many problems for farmers. Furthermore, using an electric vehicle at a low level of battery State of Charge (SOC) might reduce the battery lifetime [65, 66]. As mentioned above, hybrid powertrains have been suggested as an interim solution for vehicular applications specifically for areas such as agriculture and mining where electricity infrastructures are poor [6]. It should be noted that although there are several commercial models for on-road hybrid vehicles, the agricultural robots and Non-road vehicles' powertrain hybridization is still in the initial stages. Therefore, powertrain hybridization of off-road vehicles such as agricultural tractors seems to be a key step in the future.

To alleviate the challenges of agricultural HEV powertrains, some researchers in agricultural technologies tend to use low emission energy systems and alternative fuels such as biofuels and hybrid electric powertrains. Tritschler et *al.* (2010) investigated the potential of a FC hybrid configuration for an agricultural tractor. Their research outcome was shown that FC systems still have some drawbacks, including a high cost, limited lifetime, and problems related to hydrogen storage and distribution infrastructure [67]. However, some of these problems have become somewhat less important in developed countries or are expected to be resolved in the near future. Xie et *al.* (2013) studied the design process of a medium-sized hybrid electric tractor. Their results showed that a hybrid electric powertrain for agriculture tractors can reduce about 19% of fuel consumption compared to traditional ICE alone powered tractors [68]. Gonzalez et *al.* (2016) established an unmanned ground vehicle hybrid-powered robotic tractor. They mentioned that the new technologies built on clean energy sources could significantly reduce emissions of air pollutants and greenhouse gases. This occurred with the offloading of ICE and the addition of this load to an Electrical Storage System (ESS). This technique allows small farm tractors to move bigger implements, which have their own motors by the assistance of an ESS [69]. However, more developing in agricultural vehicles powertrain electrification seems necessary as a prerequisite for the smart farm.

Different types of hybrid architecture can be used in tractors. Since there is usually enough space, thus mass reduction is not an important objective for a tractor and could even seem like an advantage regarding the stability of the vehicle [70]. May also, considering a bulky engine generator in a series hybrid architecture, it seems to be more suitable in traction and heavy applications like tractors.

On the other hand, conventional tractors are usually tested by manufactures and researchers under specific conditions by various types of dynamometers in terms of performance evaluation. Nevertheless, evaluation of the realistic working cycle of farm tasks by tractors is usually time-consuming and expensive [71]. As mentioned before, the vehicle developers usually use several standard driving cycles for emissions testing and component sizing, and different technologies are typically evaluated using computer simulators [4, 72]. Nevertheless, due to differences in speed and applications, most commonly used driving cycles for urban cars are not applicable directly to off-road vehicles such as agricultural tractors. It should be noted that usually in tractor applications, due to the rough surface of terrain and soil deflection, the working cycle could be more adequate rather than driving cycle. Therefore, one of the purposes of this work is to derive some realistic typical "working cycles" in agricultural tractor applications to employ it in the hybrid electric tractor design process. In fact, the "working cycle" expression comes from the importance of considering the energy consumption rather than the speed profile in such applications like agricultural tractors with lower speed and higher torque requirements.

Usually, agricultural vehicles operate far from the electrical network and fuel stations. Therefore, providing energy to these areas increases the overall cost of farming. In this case, an independent on-site renewable power supply system can provide a meaningful alternative while helping to meet the farm energy demand or sell electricity to the local network [6, 73]. In addition, this could help to improve efficiency and reduce dependency on fossil fuels, as well as providing distributed electricity generation [74]. Therefore, a biogas-fueled engine/generator is considered along with a photovoltaic (PV) system as range extenders for a multipurpose agriculture tractor as a part of this project.

2.10 Specific Features of Agricultural Mobile Robots

The development of agricultural robot technology is an inevitable requirement for agriculture to find solutions to challenges related to labor shortage, precision control, farm work convenience, and green operation, which are difficult to achieve with conventional agricultural machinery [75]. As a result of the research efforts, several robotic solutions such as monitoring [76], mapping [77], crops and pests managing [78], environmental control [79], and planting [80], have emerged in recent years. For example, BoniRob [81] was originally developed for the plant phenotyping and mapping in the field. The Hortibot [82] is a robotic tool carrier for high-tech plant care. In addition, Vibro Crop Robotti [83] can also perform field work such as precision seeding and mechanical weeding. There are many more agricultural mobile platform projects than mentioned here, and there are several companies and robotic manufactures are working to specialize their mobile robots for agricultural tasks. However, most of them are not succeed in their mission due to some specific problems such as battery limitations and energy shortages.

On the other hand, robotics in agriculture contributes to some issues. For instance, in closed or semi-closed environments such as greenhouse and warehouse applications, there are two most important issues for a robot powertrain design. First, fossil fuel combustion in engines releases air pollution and harmful emissions for workers, and second, the working environment could be affected by high levels of engine noise. That's why most agricultural robots are powered by an electric propulsion system which is bringing many advantages such as improved efficiency, controllability, and powertrain design flexibility [84]. One of the most limiting technologies for many electric mobile platforms such as robots is still an energy storage system [85]. Some Non-Road vehicles such as forklifts and warehouse robots already have a long history of using electric propulsion systems [86]. However, the poor durability and long recharging time of the current batteries have created limitations in electric vehicles' autonomy and performance like AMRs in farm applications. These downsides would be more drastic when the vehicles are working in harsh environments such as large farms and greenhouses, which can result in an increase in the user cost under a multi-shift working conditions in the working season. Moreover, the electric AMRs must be charged after a certain operating period. However, in a real situation, a vehicle with nearly empty batteries is unavailable in the working process.

To that end, purely electric propulsion such as FCHEV seems more attractive, which basically leads to a plug-in electric FC range extender. Although there are some commercial light road FC vehicles and Non-Road vehicle that were developed recently, the applicability of specialized vehicles such as FC agricultural mobile robots are rarely taken into account. Regarding hybrid electric powertrain for indoor industry applications, some progress has been done in forklifts [87], however, other types of self-propelled machines such as agricultural mobile robots have not been taken into account.

Usually, such specialized autonomous robots are characterized by their movableness and compactness because of the importance of transferability in small spaces to move between rows and turn easily. Thus, this can lead to a challenge in the hybridization due to limited available space for the vehicle components. However, when vehicle energy sources are becoming hybridized by using batteries and FC system, the components size like the FC stack nominal power can be decreased and power transients become slower; meanwhile, peak power is attracted by the battery system [88]. This enables both capital and volume savings especially in a small vehicle design process like AMRs. Moreover, less cyclic operation of the RE especially in FC system increases its lifetime and reduces system control challenges which are more critical in FC systems. Since one purpose of this work is to design an extended range for agricultural mobile robot applications with a reasonable range and efficiency, the FC along with a photovoltaic (PV) system is chosen as the range extender for the agricultural mobile robot to avoid harmful emissions for indoor applications such as green houses and warehouses in agricultural section. It should be noted the working cycle, energy model, and EMS is still a challenge like the agricultural tractor.

2.11 Literature Conclusion

Literature indicates that there is a variety of HEVs powertrains to mitigate barriers and drawbacks in urban automobiles. However, it should be noted that there is no standard method to size and design the off-road vehicle in specific applications such as tractors and AMRs. Moreover, due to the difference in applications and structures of off-road vehicles existing standard driving cycles and energy models are not applicable directly in such vehicle powertrain design process. In this regard, this work aims to define typical working cycles, based on experimental tests, to develop a hybrid electric off-road vehicle, which has been suggested to deal with the problems caused by operating conditions variations due to the combination of traveling and tasks. Therefore, a series of predefined experimental working cycles are needed to estimate energy requirements to size RE and to investigate vehicle performance. Consequently, an appropriate energy model should be worthwhile and fundamental for tuning the EMS and components sizing by employing the working cycle before construction. In fact, such simulation tools provide a basis for estimating energy requirements, component size, and power demand and implementing various energy management strategies before practical experiments.

Apart from this point, this work intends to develop two innovative hybrid electric off-road vehicles. The first application was to develop a renewable energy-based hybrid electric off-road vehicle as a multipurpose farm tractor. Besides, on-farm renewable energy sources including photovoltaic (PV) and biogas are used as recharging source options. The second application is to design an FC range extender system for an autonomous agricultural vehicle as an AMR with a reasonable range and efficiency.

One significant point which needs to be clarified herein is the main distinctions between this work and the previous works in literature, which has been done before. In this respect, it should be reminded that the defined working cycles in off-road applications for designing a RE have been proposed in this thesis. Furthermore, a renewable energy-based range extender could help to energy independence of off-road vehicles especially in remote areas such as farms and mines.

Chapter 3 - Materials and Methods

3.1 Introduction

Literature considerations indicate that some aspects such as the propulsion systems, traction electric motor, and energy storage characteristics need to be specified based on the desired   of an off-road HEV in the designing process. The HEV design usually involves a modeling and simulation program that can take several iterations before the final design and development. Thus, this chapter will shortly present the off-road HEV powertrain designing process to calculate the required energy by considering some major working cycles in order to size an appropriate RE for an off-road vehicle. In fact, the design and development of off-road agricultural hybrid electric vehicles is a complex process; nevertheless, there is no standard methodology. This process is including several challenges such as component sizing, energy management system (EMS) designing, and performance analysis. Therefore, a general design process of the off-road agricultural hybrid electric vehicles powertrain is proposed for this kind of vehicle as shown in Figure 3-1. In this regard, the following steps are considered. First, define serval typical farm working cycles based on customer need. Next, modeling an agricultural vehicle for component sizing and EMS evolution before construction. Then, designing and developing a heuristic EMS. After that, designing and developing an appropriate range extender system. Finally, components integration and evaluation of the hybrid electric off-road agricultural vehicle.

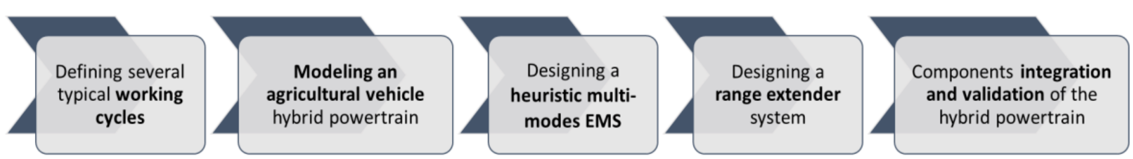


Figure 3-1. General overview of the proposed design process for the off-road agricultural hybrid electric vehicles powertrain.

Additionally, an economic evaluation of powertrain hybridization for off-road agricultural vehicle applications is performed in this work. This will help us understand the feasibility of projects. Further details about the project's background and design process are discussed in the two agricultural vehicle case study applications in the following sections.

3.2 Summary of Projects Background and Developing Methods

In this work, two existing pure electric low-speed off-road agricultural vehicles including a Solar Assist Plug-in Hybrid Electric Tractor (SAPHT) and an Agricultural Mobile Robot (AMR) are considered to develop extended range vehicles for agricultural applications, respectively. These case studies are agricultural vehicle platforms used as basic prototypes in this research, which are demonstrated in Figure 3-2. Despite some differences in functionality of basic vehicles, both had similar powertrain architectures. Specifications of the base systems are presented in Table 3-1. Both of these vehicles are used to extract the working cycle derivation, required parameters for components modeling, and performance evaluation. More details are described in the following sections.

(a) (b)

Figure 3-2. Basic pure electric low-speed off-road agricultural vehicles; (a) Solar Assist Plug-in Hybrid Electric Tractor (SAPHT) and (b) Agricultural Mobile Robot (AMR).

Table 3-1. Specifications of the base systems

Characteristic	AMR	SAPHT
Application	Agricultural mobile robot	Multi-propose tractor
Energy storage system (ESS)	Lithium-ion battery pack (570 Wh)	Lead-acid battery pack (16 kWh)
Propulsion system	Differential Drive (Two DC electric motors each of the 450 W)	Differential Drive (Two DC electric motors each of the 10.5 kW) PTO system (DC electric motor 16.8 kW)
Transmission	Single-speed gearbox (16)	Single-speed gearbox (18.66)
Speed range	0 – 1.8 m/s	0 - 25 km/h.
Energy sources	Grid connection + Photovoltaic system	Grid connection + Photovoltaic system
Expected range extender	Proton-exchange membrane fuel cell (PEMFC)	Biogas internal combustion engine/generator (Biogen)

The SAPHT was a pure electric, low-speed Off-Road vehicle designed for agricultural light applications. Speed range was limited up to 25 km/h and the power range was 0 to 35 kW. The powertrain system consists of three electric motors (two for driving wheels and one for the Power Take-Off (PTO) and lifting systems) with single-speed gearboxes. Two different sources of electrical energy were supplied to the SAPHT: onboard PV arrays and grid electricity. A 16.8 kWh lead-acid battery pack was utilized as ESS to supply energy. Although the regenerative braking system's functionality existed in the basic SAPHT, it was ignored due to design constraints and low speed. Despite acceptable energy efficiency in SAPHT, because of the limitations of the EVs, it was faced with a lack of energy in various operations [89] that occurred due to the fast degradation of the battery.

As a part of this research work, an existing Solar Assist Plug-in Hybrid Electric Tractor (SAPHT) is developed to be renewable energy-based Extended-Range Solar Assist Plug-In Hybrid Electric Tractor (ERSAPHT). As aforementioned, series hybrid architecture is more suitable for traction and heavy applications such as tractors. Therefore, the SAPHT developed to become the series ERSAPHT as shown in Figure 3-3. The new power sources include the onboard PV system, biogas fueled engine generator (Biogen), and ESS. Furthermore, the range extender system is developed by integrating components such as Biogen, fuel tank, regulator, AC/DC inverter, power management system, sensors, etc. with the base system.

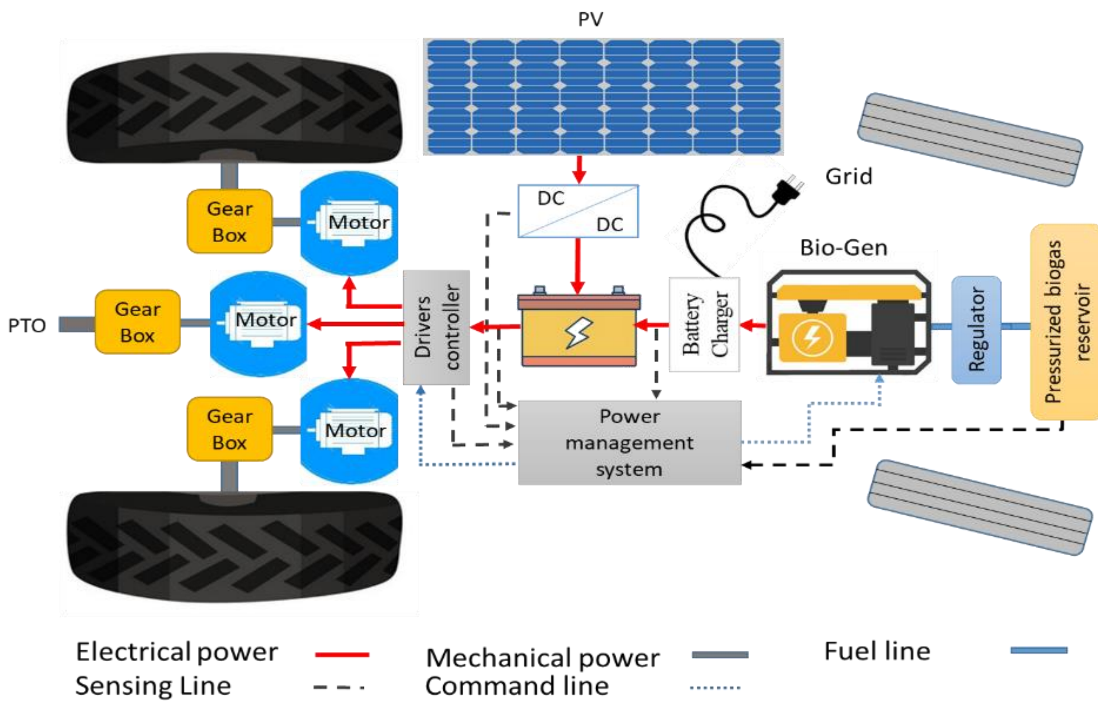


Figure 3-3. Simplified ERSAPHT schematic diagram.

Furthermore, a battery-powered agricultural mobile robot which was designed by our research team at Université du Québec à Trois-Rivières was considered as a second case study for developing a PV/FC/battery hybrid electric mobile robot for agricultural applications. This robot contains two main criteria, including software structure and hardware structure. The software structure contains control strategies, designing and developing path plan algorithms, energy management system, etc. On the other, the hardware structure contains aspects such as component sizes, and electronic and electrical circuits, which are described in the following sections.

The hardware structure of the case study AMR was made by considering the design requirements. Therefore, the deferential drive–steering method was used to navigate the robot. The robot powertrain consists of two electric motors with single-speed gearboxes (16:1 aspect ratio) for each driven wheel on the left and right sides of the chassis. The nominal power range of each motor was between zero and 450 W with a motor driver. In this context, the regenerative braking system is neglected due to the low-speed application and drive control limitation. The AMR is equipped with a LiDAR sensor, two encoders, and an inertial measurement unit (IMU) for autonomous navigation. Also, an onboarded computer (Raspberry Pi) was utilized to compute localization, navigation algorithms, and data acquisition. A remote-control system is configured to manually control the robot at a visual distance or to permit automated drive following a predefined trajectory. The data acquisition system monitors the wheels' speed and the battery status by measuring the battery voltage and current drawn from the battery pack.

3.3 Working Cycle Designing and Extracting Method

For off-road vehicles, if standardized tests exist at all, they are still unrepresentative of all real-world applications, since every application is inherently different. Based on the author's knowledge, there is no standard working cycle for agricultural electric vehicles. Therefore, one of the main challenges of the off-road agricultural electric vehicle simulation is the lack of standardized drive cycles, which makes comparing results from different studies difficult. As highlighted above, the lack of standardized working cycles often leads to researchers developing their own cycles to suit their needs. In this regard, some typical working cycles need to be designed and conducted to powertrain designing and evaluation of the hybrid electric AMR.

As aforementioned in the literature review, a typical driving profile for road vehicles consists of a complicated series of accelerations, decelerations, cruise, and frequent stops. The information is acquired by averaging the extensive data when the vehicle is driven under actual service conditions on designated routes where the driving pattern is representative of the prevailing working day pattern [90]. Therefore, the first step in extracting of a working cycle is to measure and record real vehicle working behaviors that are real-time behavior corresponding to the vehicle being designed. The obtained data has to be analyzed in forming a representative cycle from real working conditions. In any duty, the working conditions will vary accordingly to road conditions, requested tasks, and other factors. Average speed, required power, percentage of idle time, etc. could use as parameters for classifying the working conditions on a specific task. Subsequently, load measurement besides speed measurement proposed as a solution for off-road vehicles applications, in this work. Consequently, typical working cycles are designed for both off-road vehicles (the agricultural tractor and the AMR) in several working conditions, which are described in the following sections.

3.3.1 Working Cycle Designing and Experimental Tests to Derive Working Cycles for the Agricultural Tractor

As mentioned before the working cycle would be more reasonable in terms of the off-road vehicles which have been studied in this thesis. For example, an agricultural tractor is usually working in the farm to do some tasks such as product handling, spraying, seed spreading, either some stationary tasks like water-pumping. Therefore, a tractor requires additional power to propel the attached machine to do the desired work which directly affects its energy consumption. Literature consideration indicates that there is no specific available standard working cycle for the evaluation of electric farm tractors until now. Therefore, some experimental tests are conducted to derive Working Cycles for agricultural applications in this work.

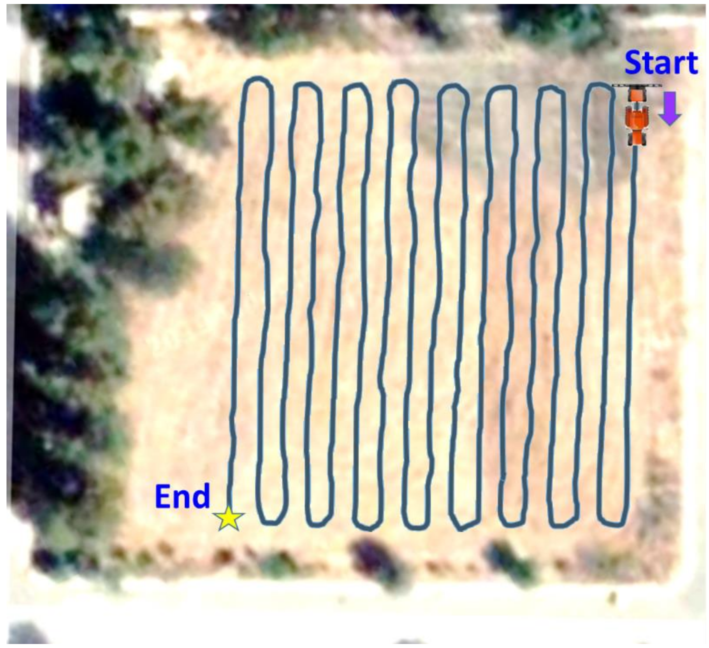
Generally, an agricultural tractor usually works during the day with repetitive operations on the farm. These tasks could be categorized in transportation and field works. In transportation applications, the tractor is usually used to haul the trailer on rural roads or fields. On the other hand, in fieldwork such as spraying, the traction system and PTO system might be used simultaneously to drive the machine by tractor. In addition, in stationary operations cases like as pumping and threshing, only the rotation force of the PTO system might be used. Therefore, in this research, the authors defined several real-world working cycles to assess the ERSAPHT performance under different loads with diverse average velocity and required power. To simplify the process, three typical predefined common farm operations are designed at constant parameters in flat ground as seen in Table 3-2.

Table 3-2. Predefined farm operation characteristics for experimental tests.

Farm duty	Typical implement	Speed range (km/h)	Machine weight (kg)	PTO speed (rpm)	Average rolling resistance
Driving at road	Trailer	0 - 25	2000	0	Asphalt (0.029)
Working at repetitive continuously move and stops in the field	Boom-type sprayer	0 - 10	400	540	No-tilled field (0.052)
Stationary operations with PTO	Water-pump	0	0	1000	0

The field experiments were conducted with three implements comprising: the trailer (traction load), boom-type sprayer (mixed traction and PTO load), and water-pump (PTO load) at a special testing farm. In fact, these real-world working cycles contain different contributions of light, medium, and high-power demand working conditions based on measured data from previous work [89]. Consequently, the SAPHT is employed only in electric mode to conduct these typical work cycles. Figure 3–4 shows a typical predefined route and speed profile by the boom-type sprayer in a 1800s testing field (Figure 3-4 (a)), which is repeated three times to derive related working cycle. This cycle is containing several stops and go transition along with PTO working conditions in typical farm operation (Figure 3–4 (b)). It should be noted in this work conditions; the PTO system is activated just during the field cruising period (this method is commonly used by the tractor operator to spray evenly over the entire farm surface.). Finally, the measured data from the real-time experiments were used to analyze the developed system under different farm operations conditions.

(a)



(b)

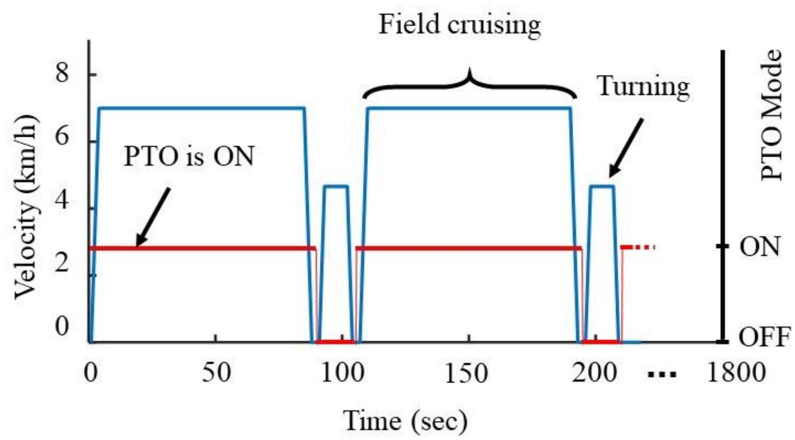
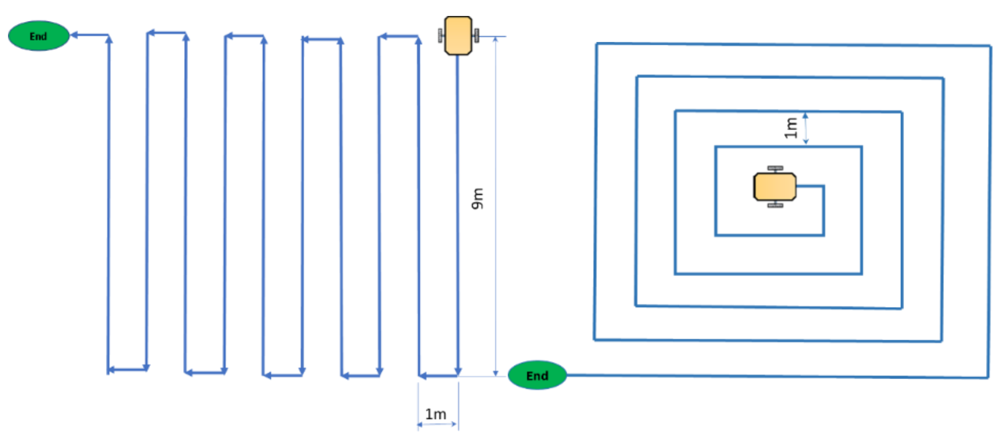


Figure 3-4. Typical predefined working cycle in the 1800s (repeated three times): (a) testing route for sprayer working cycle, and (b) driving velocity and PTO working cycle.

3.3.2 Working Cycle Designing and Experimental Tests for the Agricultural Mobile Robot

Based on the typical characteristics of off-road vehicles like AMRs, the driving cycle measurement has been considered as the starting point. Subsequently, for measuring the actual power requirement and energy consumption, the basic AMR is moved using different velocities similar to typical real working cycles. In the real farm environment, an AMR is usually employed in stop-and-go loop working conditions in different moving pattern. For example, tasks such as crop planting and spraying are usually done by moving between the rows, and other tasks such as data collection and crop harvesting can also be done in a circular movement. Therefore, two typical pathways were designed by considering the mixture of transitional and rotational movement's pattern including row linear movement pattern and perimeter circular movement pattern as shown in Figure 3–5. Each motion test was conducted for a 100 m distance, and it was repeated three times in the same condition on a flat asphalt surface to minimize unexpected situations. Besides, each experiment includes four sections, acceleration from stationary, constant velocities, and deceleration to stationary then turning 90 degrees left or right. In this respect, the battery voltage and current, motor power, and velocity of the wheels are recorded by the developed data logger with a 0.1 s sample rate. From these tests, by use of the speed profile, as well as the traction power required for completing the working cycles, could be employed by a dynamic model in the designing process such as estimation of energy requirements, tuning energy management strategies, and component sizing.



(a) (b)

Figure 3-5. Typical predefined testing routes (100 m) for the AMR; (a) Row linear movement pattern (b) Perimeter circular movement pattern.

3.4 Off-road EREV Powertrain Design and Modeling Fundamentals

Generally, the power generated from the propulsion system of a vehicle is ultimately used to drive a load. As mentioned before, in an automobile this load includes road resistance due to friction, uphill or downhill drive related to the road profile, and the environmental effect such as the wind and so on. In addition, some of the stored energy in the vehicle is wasted by the accessories. Furthermore, in off-road vehicles such as agricultural tractors and AMRs, extra energy is needed to drive attached machines that could be in the form of drawbar pulling, PTO, electric outlet, and so on. The whole process of off-road vehicle design is incredibly complex involving numerous variables, restraints, and considerations, as it could be released in several books. Therefore, an exhaustive analysis of electric vehicle powertrain components design is beyond the scope of this work. The overall procedure of the modeling and simulation of the road vehicle subsystems are explained in detail in [4]; therefore, it would not be repeated. However, some fundamental aspects that are necessary to develop an off-road hybrid electric powertrain modeling involved in designing a RE, electric motor, and energy storage system are addressed in this section.

3.4.1 Off-Road Electric Vehicle Road Load Modeling

A typical off-road vehicle dynamic movement is generally could be modeled as a dynamic point mass (mass of the vehicle and the equivalent mass of the rotating parts) that can move forward by exerting propulsion power. To overcome the resistive force (F_{res}) of the vehicle and its attached implements the following equations are determined [89]:

$$M_{tot.} \frac{d}{dt} v_{ev} = F_{tr} - F_{res} \quad (1)$$

$$F_{res} = F_{roll} + F_{air} + F_{acc} + F_{hill} + F_{work} \quad (2)$$

$$F_{res} = C_{roll} \cdot M_{tot} \cdot g \cdot \cos\alpha + \frac{1}{2} \rho A C_d \, (V + V_w)^2 + M_{tot} \cdot a_{lacc} + I \cdot \frac{G^2}{r^2} \cdot a_{lacc} + M_{tot} \cdot g \cdot \sin\alpha + F_{Work} \quad (3)$$

Where F_{roll}, F_{air}, F_{acc}, F_{hill}, and F_{work} denote the rolling resistance, aerodynamic drag, acceleration, hill climbing, and required forces to doing work, respectively. C_{roll} is the wheel rolling resistance coefficient; g is gravity acceleration; ρ, C_d, A, and V_w are air density, drag coefficient, frontal area, and wind velocity, respectively. M_{tot} is vehicle total mass; a_{lacc} is the wheel linear acceleration; I is the moment of inertia of the wheel and electric motor; G is the gear ratio from the electric motor to the wheel drive shaft; r is the drive tire radius; α is the road or field slope.

For any vehicle design, the performance constraints that should meet, must be defined first. These constraints are different depending on the vehicle type and size. From the powertrain point of view, typical performance specifications include initial acceleration, maximum speed, gradeability, working range, and so on [14]. In the case of series hybrid vehicles architecture like EREVs, the tractive force comes from the traction motor shaft.

Therefore, considering the speed (V) and the required traction force (F_{res}), the vehicle requested power (P_m) from the electric motor side could be then expressed as:

$$P_m = F_{res} V/\eta_m \eta_t \quad (4)$$

Where η_{m} and η_t denote the motor and transmission average efficiency, respectively. It should be noted, an off-road vehicle has other components such as onboard electronics, sensors, microcontrollers. etc. which is accessory's part of HEV powertrain. These components are extremely efficient nowadays due to the advancement in technology, but they still consume a portion of the battery's power. Therefore, the power loss due to the electronics is presented as P_a. It is the amount of battery power withdrawn by the other electronic components when the vehicle is running. To handle the desired loads, it is essential that the total power of the battery pack ($P_{Batt.}$) and the RE system power (P_{RE}) would be greater than the maximum rated power of the electric motors and accessories at any accepted time within the range of operation.

$$P_{Batt.} + P_{RE} \geq P_m + P_{work} + P_a \quad (5)$$

Where P_{work} and P_a are required power for doing work and other accessories, respectively. Finally required energy ($E_{req.}$) to fallowing the speed profile and doing specific work that commanded by the user could be calculated by taking the time integral of the power request. The total energy of the battery ($E_{Batt.}$) can be evaluated in terms of a time integral function of powers:

$$E_{req,} = \int_0^{t1} \eta_{Batt.} P_{Batt.} dt + \int_0^{t2} \eta_{RE} P_{RE} dt - \int_0^{t3} \eta_m P_m dt - \int_0^{t4} \eta_{PTO} P_{\text{PTO}} dt - \int_0^{t5} \eta_a P_a dt \quad (6)$$

Where $\eta_{Batt..}$, η_{RE}, η_{PTO}, and η_a donate the battery, range extender, PTO, and accessories efficiency; t_1, t_2, t_3, t_4, and t_5 are charging-discharging time intervals for the battery pack, the RE system, the propulsion motors, and accessory systems, respectively. Next, the vehicle working range could calculate from the required energy. Here working range refers to the working hours (e.g., 8 hours working shifts), that an off-road vehicle can work with a full tank and/or fully charged batteries before refueling or recharging. Satisfactory working range of an off-road hybrid electric vehicle is crucial for market acceptance. However, it is necessary to assure that the battery energy quantity lies between its maximum and minimum limits of total capacity [89]. Likewise, the average daily energy requirement allows the sizing of the battery as well as the RE.

3.4.2 Energy Storage System (Battery) Modeling

The State of Charge (SOC) is one of the most important parameters of the battery. Because not only does it inform to the user about the amount of remaining charge and mileage, but also it is a parameter that needs to be carefully monitored to avoid damage that can be caused by overcharging/discharging the battery. However, many research has been done to estimate the amount of battery SOC ($SOC_{Batt.}$) that is beyond the scope of this research [91]. Regarding the literature, the coulomb counting based on current integration remains one of the most commonly used methods due to its reasonable accuracy and implementation simplicity that is represented by the following equation [92]:

$$SOC_{Batt} = SOC_{Init.} - \frac{100}{3600\, Q_{Batt.}} \int_0^t I_{Batt.}\, dt \quad (7)$$

Where $SOC_{Init.}$ is initial SOC of the battery, $Q_{Batt.}$ and $I_{Batt.}$ are battery capacity and current, respectively. Since the purpose of this thesis is not the battery surveying, the battery model presented by [93] is considered using the parameters found in [94]. In addition, relationship in [95] used to determine total battery power ($P_{Batt.}$) from the battery characteristics manufactory SOC lookup table as:

$$P_{Batt.} = V_{OC}.I_{Bat.} - I_{Bat.}^2.R_{Batt.} \quad (8)$$

Where $R_{Batt.}$ and V_{OC} are resistance from experimental tests and open-circuit voltage of the battery. The Kirchhoff's current law is used to model the parallel connection between the battery pack, traction subsystem, accessory systems, and RE system:

$$I_{Batt.} = I_{TS} + I_a - I_{RE} \quad (9)$$

Where I_{TS} and I_a donate the requested currents from the traction and accessory systems, I_{RE} is supplied currents by the RE system. Output power and input power from the battery considered with positive and negative signs, respectively. Therefore, the power delivered by the range extender is regarded as a negative sign.

Consequently, by using the energy model along with a realistic working cycle can estimate how much energy is needed for a specific period (i.e., during a working day). Finally, considering the available energy of the battery pack, the RE characteristics (e.g., required power and fuel tank capacity) can be sized. However, due to the complexity of the components of an off-road HEV, performing the required calculations is not an easy task. Therefore, as mentioned in the previous chapter, usually engineer aid tools are employed to design and simulate vehicles in a computer before construction.

3.4.3 Select Renewable Energy Based Range Extenders

As mentioned previously, one of the most important steps in developing an EREV is choosing the appropriate secondary power source for the base electrical system. However, the RE of an off-road vehicle should design to provide average power during the extended working range [4]. Therefore, the range extender nominal power depends on the vehicle specifications and vehicle application. Nevertheless, an analytical RE model is difficult to obtain. It is, therefore, common to use the map to describe the fuel consumption of a specific range extender as a fuel converter. This map can be determined by empirical procedures on a RE test or can be computed by some software packages [96]. Therefore, the parameters suggested by the manufacturers are applied to the range extender's models. The fuel consumption of the engine ($\dot{m}_{fuel}$) is given by a steady-state map as a function of the RE output power.

$$\dot{m}_{fuel} = f\ (P_{RE}) \tag{10}$$

The power consumed of the RE can be computed from the fuel Lower Heating Value (LHV_{fuel}) as follows expressions.

$$P_{RE} = LHV_{fuel}\ .\ \dot{m}_{fuel}\ .\ \eta_{RE} \tag{11}$$

In order to take into account, the added onboard energy source, the State-of-Charge of the fuel tank (SOC_{fuel}) is estimated from the initial mass of fuel ($m_{fuel-init}$) by the following relationship.

$$SOC_{\ fuel} = \frac{m_{\text{fuel-init}} - \int_0^t \dot{m}_{fuel}\, dt}{m_{\text{fuel-init}}} \tag{12}$$

The electric machines and power electronics components, such as converters and motors drive, etc. are modeled based on the experimental lookup table data provided by the manufacturers; that determines the electric motors torque, speed, and related efficiency maps [97]. For example, the onboard PV system with approximately 6m^2 polycrystalline panels and 660 W peak power (W_p) were provided [89]. The generated energy by the PV system was combined with the battery energy to supply power in parallel.

Based on the data from National Renewable Energy Laboratory (NREL) website (2019, [98]), the average amount of hourly available PV power in Karaj, Iran (latitude 35° 48′ N, longitude 50° 58′ E, where the project was performed), applied as the PV system model. In Iran, agricultural operations are usually performed from April to September. The experimental field tests were conducted in June 2018 with zero-degree slope of the PV panel. Therefore, the average hourly solar power on 15 June 2018, applied to the model as a lookup table i.e., seen in Figure 3–6.

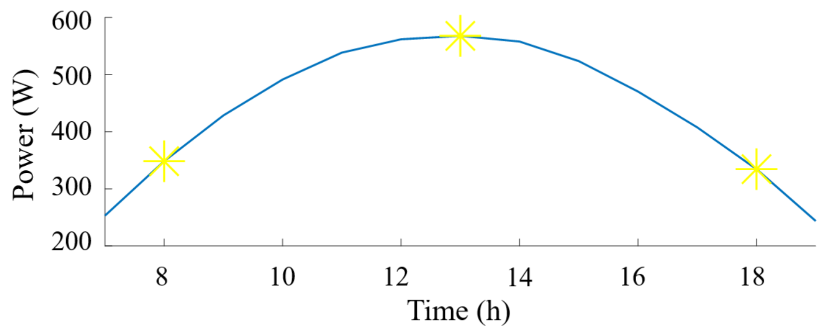


Figure 3-6. Calculated average hourly solar energy on 15th June applied to model [98].

Consequently, after the mathematical model formulated, the respective simulations using MATLAB Simulink could be made to create a final dynamic model for each off-road vehicle.

3.4.4 Develop a Simulink Model for Off-Road Electric Vehicle

Regarding to literature, although there is a few available software to designed road HEVs like ADVISOR and Autonomie, which are established based on MATLAB-Simulink. However, that software can be used for analyzing certain predefined models of the ICE vehicles, EVs, and HEV for fuel efficiency, predefined driving cycles, and emissions for different types of driving modes for urban vehicles [99]. Nonetheless, this kind of software could not be used in specific applications such as off-road vehicles due to limitations in the powertrain configuration and predefined driving cycles. Therefore, a specific model is necessary to develop based on the physical properties of the off-road vehicle components.

Consequently, a specific realistic MATLAB-Simulink model is established to simulate the off-road vehicles. It should be noted that to increase the simulation speed time, for specific components such as the battery pack, RE and electric machines considered in different levels of modeling such as physical models, lookup table data and efficiency map that was provided by the manufacturers and experimental test results. The main components specifications used in the established a simulation model for both vehicles are shown in Appendix A and Appendix C.

To validate the developed model, the real vehicles are moved with several velocities in specific paths to the measured parameters such as wheels rotational velocity, current, and voltage. Then, these experimental data are compared with the model results. These simulation tools provide a basis for individual components analysis, such as estimating energy requirements, component size, power demand, and implementing various energy management strategies prior to practical experiments.

In fact, this model makes it possible to simulate similar off-road vehicles by changes in parameters such as weight and components specifications. Moreover, it is necessary to determine the parameters of the vehicle which is under study. Consequently, a Solar Assist Plug-in Hybrid Electric Tractor (SAPHT) and an Agricultural Mobile Robot (AMR) are considered as the base off-road electric vehicles in this study. However, another challenge to mitigate the autonomy problem of both EV in the off-road application is incorporating an energy management system and appropriate range extenders. The main details of designing of EMS and range extender for each case study for both understudy agricultural hybrid electric off-road vehicles are given in the following sections.

3.5 The EMS Design Considerations and Flow chart of the Proposed Heuristic Controller Strategy

Literature consideration indicates that an EREV's power distribution flexibility carries with a more complicated EMS. Generally, four working modes are supposed for the EREVs namely electric vehicle (EV), charge-sustaining (CS), charge-depleting (CD) modes, and charge-blending (CB). According to the comparison of fuel consumption among these rule-based energy management strategies in [100], the charge-blending control mode with proper control parameters produces the lowest fuel consumption. Therefore, the EMS introduced based on power splitting between RE and batteries. As mentioned previously, the series architecture of an EREV allows the range extender operates in an ideal condition (constant power) that is suggested by the manufacturer. This hybrid energy source is not being necessary to comply with the dynamic load profile requirement by the electric motors due to batteries supply the power peaks. Usually, the ESS of an EV has a predefined SOC operating range to maximize battery life. On the other hand, the lifetime of REs might decrease in the case of cyclic operation; design constraints need to be taken into EMS considerations with the intention to minimize battery degradation and fuel consumption. Consequently, three power management strategies were defined in this study at the first step. The baseline energy management strategy was charge-sustaining (CS) mode to maintain the battery SOC at the desired level such that the RE starts to supply power when the battery SOC drops to the minimum threshold of 40% (to avoid fast degradation of the battery). The second strategy was charge-depleting (CD) mode that the battery is the main power source until the RE starts to supply power on the minimum threshold of battery SOC (20%). These energy management strategies emphasize a more utilization of the battery rather than the RE system, and also, they demand maximum power from the RE due to the risk of energy lack. However, the third energy management strategy is called charge-blending (CB) mode that emphasizes the efficiency of the RE by turning on when SOC reaches the threshold value of 60% and supplies a constant power corresponding to its maximum efficiency. For all the strategies, the RE then switches off when SOC reaches upper-level thresholds so that the battery may take advantage of the regenerative braking system. The following design considerations are established for these strategies:

a) According to [101] the minimum degradation can be achieved if the SOC is maintained between 40% to 85%. Therefore, the assumption is that the battery is fully charged at the beginning of work, and at the end of the working shift the battery charge is the minimum level (SOC = 40%).

b) Considering when the RE is ON, the output power and fuel consumption are constantly.

c) Considering when the SOC_{Tank} is 10% and the tank does not have enough pressure to supply pressurized fuel.

The flow chart of the proposed controller is presented in Figure 3–7. At first, three working modes (Economic, Normal, and High-power) are suggested by the EMS that represents somehow the CD, CS, and CB strategies respectively. To obtain diverse operational modes, the controller checks the battery SOC when the vehicle is started:

1) If the battery SOC is equal or greater than SOC_Min (depend on the mentioned modes), the battery pack energy is used to propel the vehicle;

2) If the battery SOC is below SOC_min, check the SOC of fuel tank (SOC_{Tank}). If SOC_{Tank} is larger than 10%, the RE activates to give out constant output power to charge the battery or provide power to propel the off-road EREV (simultaneously); when the battery SOC reaches SOC_Max, the RE turns OFF;

3) Fuel tank charging is terminated if the (SOC_{Tank}) is lower than 10%; and, the off-road EREV will stop if the SOC of the battery is subordinate to 20% to avoid battery damage.

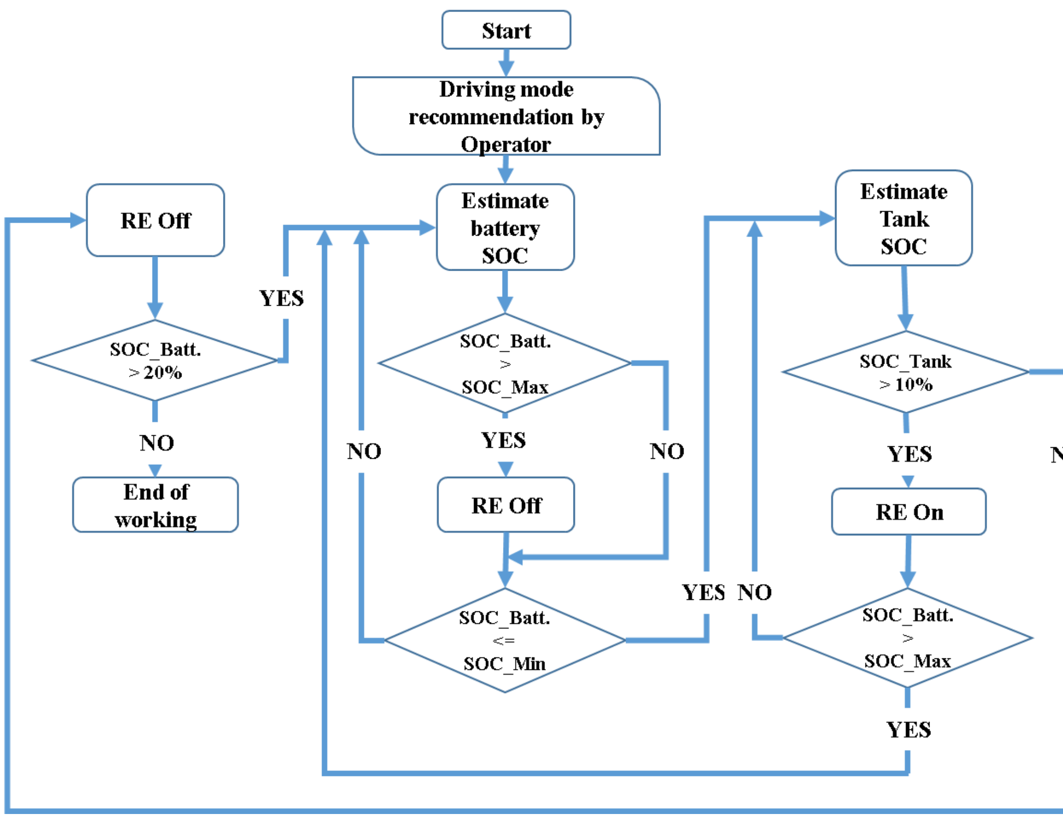


Figure 3-7. Energy management strategy (EMS) of the both off-road EREVs.

Table 3-3 demonstrates the considered battery SOC thresholds and average energy requirement for different working modes for the under study agricultural tractor application as a case study. These thresholds are defined based on energy requirements by the aim of the average energy requirement of each farm operation. After that, vehicle operator can determine the working mode according to the average required energy ($E_{Ave.}$) and the working time from the measured data for each operation that should be done. In this case, for a new condition of working cycles, the vehicle operator just needs to choose the working mode according to the average required power range for better efficiency.

Table 3-3. The Battery SOC thresholds for different working modes of ERSAPHT [70].

Working mode	Average energy requirement (Wh)	SOC_Min	SOC_Max
Economic	$E_{Ave.} < 5000$	55%	75%
Normal	$5000 =< E_{Ave.} < 8000$	65%	85%
High-power	$E_{Ave.} >= 8000$	75%	95%

It should be noted that, due to the similar hybrid architecture of both off-road vehicles in terms of powertrain hybridization, the suggested heuristic energy management strategy would be acting same in the EMS electronic modules. The EMS switching ON or OFF the range extenders in its near-optimal performance region (recommended by the manufacturer) to split the generated powers while considering the daily operation hours. The suggested EMS is acting the same role in both applications.

3.6 Select Renewable Energy Based Range Extenders

As literature review indicates that additional factors such as working environment and fuel accessibility must be considered in choosing an appropriate RE for an off-road electric vehicle. Therefore, an idea was growing to use up-to-date range extender's technology with high energy density, low life cycle emissions or green energy sources. Since providing electrical energy and fossil fuel for agricultural vehicles might increase the cost of farming, a PV system is considered a voltage source for both agricultural vehicles as energy assistance. Moreover, the solar panel could act as shade, and protector for the vehicles because most of the farm tasks are outside under the possibility of harsh environments such as rain, sun, and dust.

In the agricultural tractor case, an independent on-site renewable power supply system by green energy sources like biofuels and solar energy seems to be an appropriate potential solution. Furthermore, for the AMR with the possibility of working in closed environments such as greenhouse and warehouses, fossil fuel-based vehicle usage is limited because human health can be put in danger by harmful emissions. One solution might be to incorporate a range extender like FCs, which unlike the batteries, could be recharged in a few minutes without harmful emissions unlike the ICEs. Therefore, a biogas-fueled engine generator (for the agriculture tractor) and the Fuel Cell (for AMR) are selected as range extenders, which is playing exactly the same role in both vehicles. Moreover, the series hybrid configuration of both powertrains allows the range extenders operate in the most efficient region.

Furthermore, the multiple power source of the EREVs architecture allows the range extenders to operate in its high-efficiency region (recommended by the manufacturer instruction) with a near-optimal fuel consumption rate. Therefore, it could be considered that the electrical output power of the range extenders is constant. Additionally, it is obvious that the battery pack charging from the grid is more efficient than charging it via an onboard range extender. Consequently, it seems to be acceptable to hybridize the off-road vehicles with downsized range extenders.

3.6.1 Range Extender Selection and Developing Method for the ERSAPHT

Using the established energy model, the amount of energy required to work in a given working conditions can be calculated. Consequently, by using simulation can estimate how much energy is needed for a specific period (e.g., during a working day). Finally, considering the available energy of the onboard PV system and battery pack, the range-extender capacity (required power and fuel tank capacity) can be sized. In order to the RE sizing simplicity, a set of constraints should be considered in the model. All-Electric Range (AER), gradeability, and acceleration time have been considered as the most important constraints in the literature [4]. It is assumed that the ERSAPHT reaches its operational velocity with constant acceleration and the power rate during the operation. Then, the acceleration and corresponding requested torque becomes almost zero. The drive system of the SAPHT was designed to prevent sudden acceleration by the use of a high pedal disable (HPD) function, which controls the SAPHT to start from a stop and reach the final velocity in 10s approximately [89]. Therefore, the constant acceleration of 0.75 m/s^2 was obtained.

As mentioned in previous sections, multiple power sources of the series architecture of the ERSAPHT allows the Biogen to operate in its high-efficiency region (recommended by the manufacturer instruction) with a near-optimal fuel consumption rate. Therefore, it could be considered that the electrical output power of the Biogen is constant. Furthermore, charging a battery from the grid during the night is more efficient than charging it via onboard Biogen; consequently, it seems to be acceptable to hybridize the tractor with downsized Biogen. Hence, with respect to the design objective for agricultural light applications, a Biogen with 389 cc displacement developed and converted to use biogas due to its power-to-weight ratio and size. According to manufacturer data sheet, the maximum power that the engine can handle is around 13 Hp at the nominal speed of around 3600 rpm and this lightweight engine is designed originally for fueling by the natural gas and purified biogas. In addition, the generator was coupled on the same shaft without the reduction gear and its rated power of 4.4 kW. The technical specifications of the engine and the main components of the Biogen range extender systems are given in Table 3–4. The upgraded biogas selected as a renewable fuel allows fuel flexibility as well as potentially zero emissions when compared to the fossil fuels. An onboard battery charger used to convert the 220-VAC electricity from the grid and Biogen output power to an appropriate DC voltage to charge the 80 V battery pack. By considering 0.9 average efficiencies in the converter [89], the average amount of the supplied current and voltage are measured under 50 A and over 80 V from charger output, respectively.

Table 3-4. Developed Biogen range extender specifications.

Specification	Unit	Value
Engine-generator Model	-	NGCC5000
Starting Mode	-	Electric starter
Rated Power	kW	4.4
Rated Rotating Speed	RPM	3600
Displacement	CC	389
Engine Rated Power	Hp	13
Fuel Consumption at Rated Power (NG)	m^3/kWh	0.35
Weight	kg	93
Biogas Storage Capacity	kg	14

On the other hand, regarding the multi-power source of the ERSAPHT an appropriate energy management system is required to satisfy the vehicle performance in the accepted working range by splitting the generated powers between the energy sources subsystems. Therefore, the designed algorithm applied in a developed EMS electronic module to control the operation of the RE on the safe operating condition. The electronic components used in the development of the prototype EMS that includes the Arduino MEGA 2560 development board, power supply for the Arduino, 400 A-5V hall effect DC Current Sensor, DC voltage sensor module, four-channel relay, selector, 20 × 4 LCD display, LED, breadboard, socket-outlet for connections, etc. Figure 3-8 shows a simplified architecture block diagram of the manufactured EMS board.

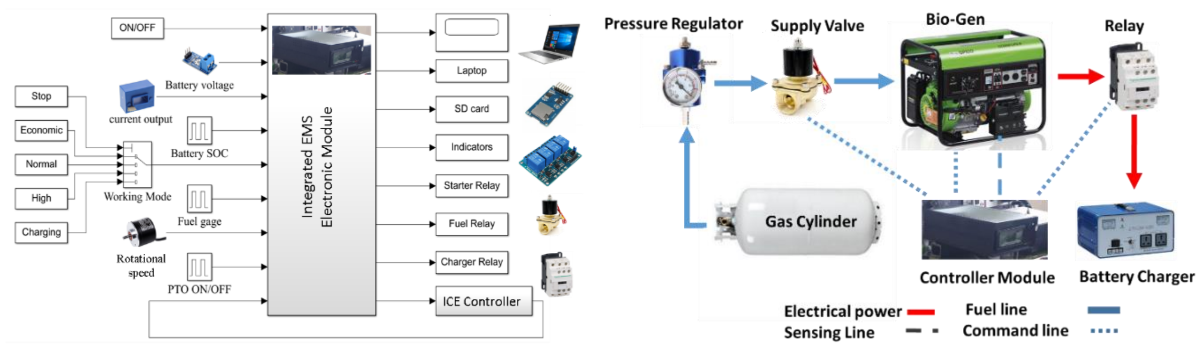


Figure 3-8. A simplified architecture block diagram of the integrated EMS electronic module for ERSAPHT prototype.

The inputs of the controller board are from the units like current sensors, voltage-measuring modules, working mode switch, etc. These inputs are processing in the EMS, and the output commands are commanding to the engine control module to drive the Biogen. The measured current is processed by the EMS to estimate the SOC of the batteries. From the operator module, it is just necessary to determine the working mode (Economic, Normal or High power) for more efficient performance. The vehicle status such as the operation mode, SOC, and voltage of the battery pack are visible in the display unit. In addition, the ERSAPHT velocity and global position are measured by using a GPS module. Furthermore, an additional module developed to control the Biogen starter, fuel flow and charging system. A module designed for collecting the user commands and measuring the parameters into a portable computer and SD card.

3.6.2 Range Extender Selection and Designing Method for the PV/FCAMR

Furthermore, based on the previous work experiences a battery-powered autonomous agricultural mobile robot which was designed by our research team at Université du Québec à Trois-Rivières is considered as second case study for developing a hybrid electric PV/FCAMR which is demonstrated in Figure 3–9. The primary energy system was designed according to the requirements of the drive system including a 24 Ah lithium-ion battery pack. The analysis is specially set during summer season, where the working cycle can begin at 8 a.m. and end at 6 p.m., which would require making at least 8 hours of work. Based on the experimental tests carried out on June 2022, the vehicle could not make more than 3 hours at an average speed of 1.2 under typical working conditions. In fact, it works would end up with an energy management system at the battery State of Charge (SOC) of 20% and this is not considered allowed to continue to work because it may degrade the battery and the system will be faced a failure in the farm. On the other hand, choosing a bigger battery would not be reasonable due to the cost, weight, and environmental concerns. Therefore, it is decided to hybridize the powertrain system by using more environmentally friendly power sources.

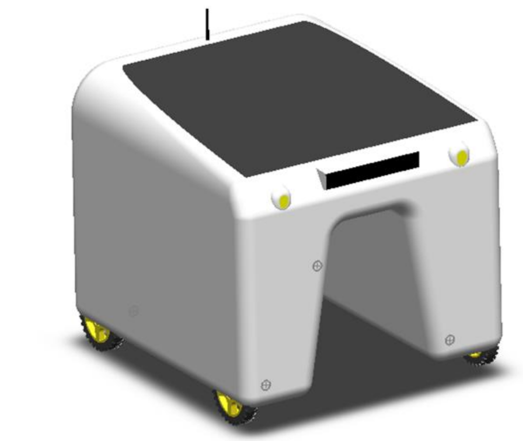


Figure 3-9. 3D model of the proposed PV/FCAMR platform.

Considering the goal of using renewable energy sources to provide the required energy for the AMR, one of the opportunities for solving the problem of autonomy is to incorporate a PV system to collect free energy from the sun while doing farm tasks outside during the day. Besides, the use of PV panels could act as a protector for the AMR because most of the farm tasks are outside under the possibility of harsh environments such as rain, sun, and dust. Moreover, these could increase the energy independence of the robot on faraway farms.

Another option is to integrate a modular PEMFC system with a hydrogen tank as an energy source that can be refueled in just a few minutes (less than five minutes) [102] as opposed to a battery with several hours of recharging time. Regarding the architecture of the designed AMR, the Fuel Cell Range Extender (FCREx) powertrain configuration seems to be more applicable in an FCAMR application because of its flexibility and simplicity. Similar to the series hybrid electric architecture the FCREx is a battery dominant system that uses a FC instead of an internal combustion engine. Indeed, this architecture allows a secondary power source (FC) to operate at its optimal region belong its more flexible location option for the designer [4]. For previous reasons, a plug-in PV/FC hybrid-electric configuration is considered a suitable powertrain for the AMR application because it has the option of connecting to the electric grid and might be charged from external electric power sources like stationary solar power plants as well. This system has three energy sources: the first is a battery pack, the second one could be an onboard PV system, and the third one used a hydrogen tank. The goal of this configuration is that the vehicle could operate all day long without having to connect to the charging station and work independently on the farm by use of renewable energy-based sources. In order to develop the range extender system, components including an integrated PV system, FC stack, DC/DC converter, power management system, sensors, hydrogen tank, etc. need to be integrated into the base system. A simplified powertrain for the proposed plug-in hybrid PV/FCAMR is presented in Figure 3–10. The detailed specifications of the FCAMR components are given in the Appendix C.

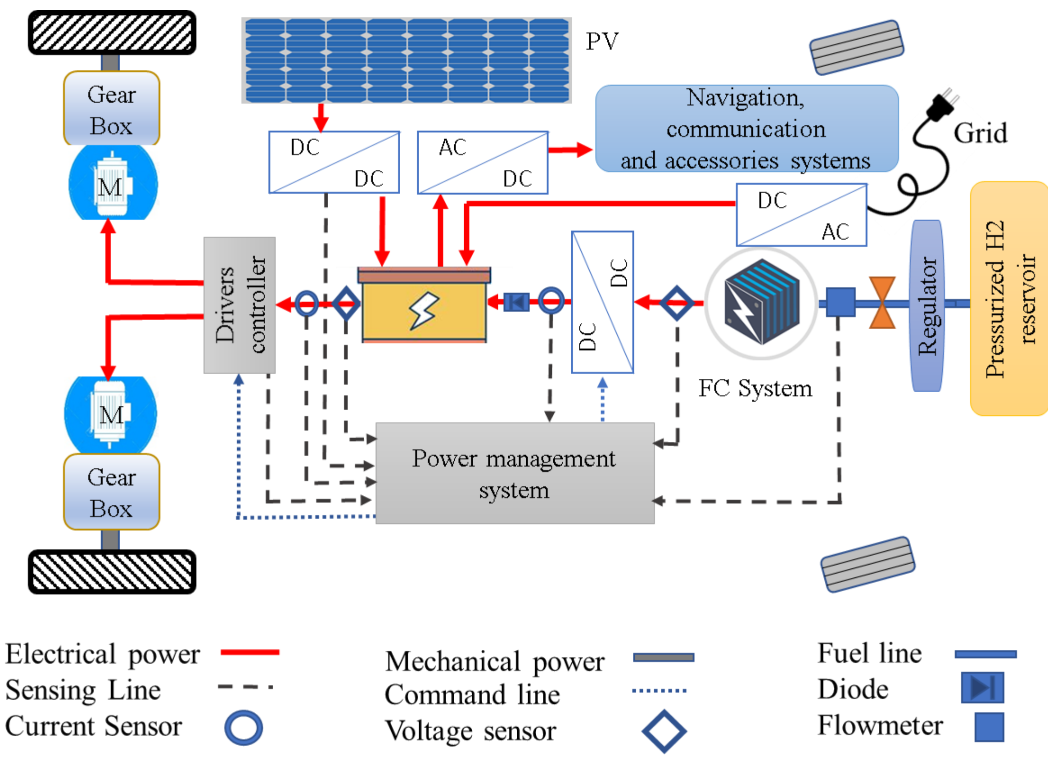


Figure 3-10. Simplified schematic diagram for the proposed PV/FCAMR.

Based on previous work experiences the established model modified and validated through the measured data. Furthermore, the measured working cycles from experimental hired in the developed simulation model to estimate required energy in an 8h working shift to size the proposed range extender components (PEMFC systems). Consequently, the size of the electric motor, batteries, and FC system could be established based on the energy requirements of the vehicle. Moreover, the range-extender capacity (required power and fuel tank capacity) can be sized by considering the available energy of the onboard battery.

As mentioned above the component sizing and system prototyping of a hybrid powertrain for an AMR is problematic because there are various design choices and constraints. As the literature review indicated, little effort has been devoted to performing the component sizing of off-road hybrid electric agricultural vehicles. In this regard, several assumptions have to be made in order to size these components. Generally, a Fuel cell range extender (FCREx) is a battery-powered electric vehicle with an FC range extender. In the FCRExs architecture, the electric machine is usually sized to comply with vehicle performance requirements, and the FC system power determines to meet the requested continuous loads. For instance, the battery pack should be able to support a road load with a 15% grade for a specific speed and is sized to drive 50% of the daily driving range in electric vehicle (EV) mode, using only electric power. Moreover, the acceleration time calculates the time taken for the vehicle to achieve its allowed maximum speed (1.8 m/s) from a stop. Both the battery pack and fuel cell can provide the power during this test. Also, sustainable maximum speed over at 15% grade is another assumption for designing. The battery pack will run out of energy in this case so the fuel cell will have to provide the continuous power required simultaneously [103]. These sizing logics are used to estimate the power required for each component over the predefined working cycles. In this case, the maximum continuous power requirement at the motor for 15% gradeability is calculated to be a 261 W. While accounting for the losses at various components, we see that the total electrical load on the fuel cell is around 300 W. Also, the FC system is composed of the DC-DC converter, a boost chopper, and a smoothing inductor for its current control [104], and their energetic performances are included in the FC static characteristics. Due to the series drivetrain architecture of this FCAMR, an appropriate PEMFC stack close to the calculated amount from the market can be chosen.

Furthermore, the onboard hydrogen storage requirement estimates vary with the range. It is important to check how much storage is possible within the specific vehicle. Moreover, assuming the required working range, tank dimensions, and storage pressure, the hydrogen storage system could be sized to meet FCAMR's overall working range requirements. Based on the results from the optimal components sizing for the FCAMR, the new powertrain should be including a 300 W PEMFC system (FCS-C300 from Horizon Fuel Cell Technologies (Table 3-5)) as a range extender belong with a PV system containing 0.5 m^2 monocrystal solar panel, 24 Ah 24 Volt lithium-ion battery pack including charger), a metallic hydride tank with 0.15 kg H_2, storage capacity at 300 Bars pressure, etc. More details on the FCAMR components integration are described in the next chapter. In the next step, the life cycle cost of the off-road agricultural vehicle has been considered in this study to examine the economic feasibility of these types of vehicles.

Table 3-5. Technical Specification of the H-300 Fuel Cell Stack [105].

Type of fuel cell	PEM
Number of cells	60
Rated Power	300 W
Performance	36 V @ 8.3 A
Reactants	Hydrogen and Air
External temperature	5 to 30ºC
Max. stack temperature	65ºC
H2 Pressure	0.45-0.55 bar
Hydrogen purity	≧99,995% dry H2
Humidification	self-humidified
Cooling	Air (integrated cooling fan)
Stack weight (with fan & casing)	2790 grams (±50 grams)
Controller weight	400 grams (±30 grams)
Dimension	11.8 cm x 26.2 cm × 9.4 cm
Efficiency of stack	40% @ 36 V

3.7 Life Cycle Cost Assessment

Life Cycle Cost (LCC) is the total present value of all the costs that arise in the path of the life cycle of a product. In different words, a vehicle LCC evaluation is an approach for assessing the entire value of project ownership in its entire life and in present value with the aid of using considering all costs of acquiring, owning, and disposing of a vehicle [106]. Providing a complete value evaluation of an off-road hybrid electric vehicle might be an exhaustive process because there is no available data in this area and even the components' price and specifications are changing unexpectedly. However, the purpose of this section is to provide a method to evaluate the economic feasibility of farming extended range off-road vehicles powertrain hybridization through a simplified LCC analysis in the case of ERSAPHT and PV/FCAMR configurations. The prototyping cost (C_P) or components purchase cost of the system is an important factor to investors, especially when there is a limited financial resource. Accordingly, for a prototype off-road hybrid electric vehicle project this cost could be calculated by the following simplified equations:

$$C_P = C_{\text{ini}} - S_{\text{V}} + C_{Bat} + C_{FC} + C_{PV} + C_{R\&D} \quad (13)$$

Where C_{ini} represents the initial cost of a basic system without the battery pack, fuel converter system, and PV array. S_V is the salvage value of the extended range vehicle at the end of its life. C_{PV} is the purchase cost of the PV system, C_{Bat} is the cost of the battery pack, C_{FC} is the cost of the fuel converter system, and $C_{R\&D}$ is the cost of the design and devopment process. Based on literature the research, design, development, and evaluation costs are almost 25% of the retail value for a hybrid vehicle on average [107]. Since the studied off-road vehicles in this study are prototype versions, this cost must be added to initial costs. The replacement cost (C_{Rep}) could be calculated for the components that need to be replaced after some years which are considered to be including the battery pack, and fuel converter system. In this study, the total lifetime of the whole system is considered to be 12 years. It is considered that there is no need to replace basic systems' main components in this study. However, some components such as the battery pack and FC stack might have a shorter lifetime than other components. Therefore, the replacement costs are given by [108]:

$$C_{Rep} = (C_{Bat} - S_{Bat}) \cdot \left[\sum_{j=1}^{NR_{Bat}} \left(\frac{1+i}{1+d}\right)^{\frac{N.j}{NR_{Bat}+1}}\right] + (C_{FC} - S_{FC}) \cdot \left[\sum_{j=1}^{NR_{FC}} \left(\frac{1+i}{1+d}\right)^{\frac{N.j}{NR_{FC}+1}}\right] \quad (14)$$

In this equation, NR_{Bat} , and NR_{FC} are the number of battery replacements for the battery pack, and fuel converter system, respectively. The discount rate (d) is the aspect that explains the value changing of a currency over time. It is equivalent to the amount of money that could be earned with the capital if it was invested in a banking account. Cost escalation, also referred to as inflation (i), is used to account for the truth that components and services typically get more expensive over time. In the present study, these factors have been applied to fuel, energy, maintenance costs, and replacement parts. These parameters are all subjected to high uncertainties; accordingly a constant inflation rate is assumed for all items. To reduce complexity, the discount rate (d) and the inflation rate (i) are considered the same amount to eliminate uncertainty. In addition, operation and maintenance costs ($C_{O\&M}$) include tax, insurance, maintenance, and repair which is considered here. In this regard, $C_{O\&M}$ derived for the first year ($C_{O\&M0}$) is then used to transform this estimation into the annual $C_{O\&M}$. Therefore, the $C_{O\&M}$ in the lifetime could be described with the aid of subsequent equation [109];

$$C_{O\&M} = C_{O\&M0}.\left(\frac{1+i}{d-i}\right)\left[1-\left(\frac{1+i}{1+d}\right)^{N}\right]+ C_{O\&M\_FC} \tag{15}$$

Where N is the life cycle period in years. $C_{O\&M\_FC}$ is operation and maintenance cost of the Fuel converter system which it could be accessible from the manufacturer data sheet. Same as daily refueling of ICE vehicles, extended range vehicles need daily charging of the battery pack and refueling of the gas tank from the grid and fuel station. On the other hand, the cost of drawn electric energy (C_{Elec}) in the lifetime is a variable cost and strongly dependent on inflation of electricity cost and discount rate. The cost of consumed electrical energy during the lifetime could be calculated using the next equation:

$$C_{Elec} = C_{yElec}.\left\{\left(\frac{1+i}{d-i}\right)\left[1-\left(\frac{1+i}{1+d}\right)^{N}\right]\right\} \tag{16}$$

Where C_{yElec} is the total cost of drawn electrical energy for the primary year. Similarly, considering the annual working hours of the fuel converter system and its fuel economy factor, the total fuel consumption cost (C_{Feul}) could be calculated. Consequently, by adding this amount to the electricity cost, the total cost of consumed energy could be obtained. After that, the LCC assessment of the extended range electric vehicles (LCC_{EREV}) in present financial value can be exposed as follows:

$$LCC_{\mathrm{EREV}} = C_{\mathrm{P}} + C_{Rep} + C_{O\&M} + C_{Elec} + C_{Fuel} \tag{17}$$

For comparing the LCC of two similar vehicles, an indicator is required. The Levelized Cost of Energy (LCE) is one of the commonly used indicators in LCC assessment. It can be defined as the ratio of the total annual cost to the vehicle's annual energy consumption. This method aims to convert the net cash flow LCC into a series of equal annual payments. The LCE could be calculated by following equations [110]:

$$LCE = \frac{LCC \, . AF}{E_y} \tag{18}$$

where E_y is the net energy converted to work in a typical year and AF is the annuity factor given as coefficients by following equation [110]:

$$AF = \frac{d \, . \, (1+d)^N}{(1+d)^N - 1} \tag{19}$$

Where N and d are the life cycle time in years and discount rate, respectively. In order to carry out an LCE analysis for an off-road vehicle, purchase costs of the various factors, as well as energy costs (fuel and electricity), need to be determined. As price cannot be precisely determined and could be altered in the near future time, therefore an average price should be taken into account. As for capital expenses, the main component prices for each case study are considered based on some available references as shown in Table 3-6. For instance, according to [111], for a diesel engine tractor, the ICE represents 19% of the tractor cost which is mentioned about 300 \$/kW on average. However due to the extended range powertrain configuration of the ERSAPHT and FCAMR the Biogen and FC system could be downsized, then the price is less than this amount. Based on a battery cost review in [112], it is reported approximately 140 \$/kWh average battery pack production price for VRLA technology. In addition, the average manufacturing cost of a 10 kW peak power electric motor is 800 \$. Therefore, an 80 \$/kW was taken into account regarding electric motor price with a single gear ratio gearbox. Based on a [108] the overall cost for the 6m^2 onboard PV system for the SAPHT project is estimated 2400\$, which is considered the average of 400 \$/m^2. Other additional devices and systems needed for powertrain electrification, e.g., additional sensors or cooling systems were ignored to reduce complexity and ambiguous estimation. Anyway, all prices of the other elements shared by both ERSAPHT and ICE tractor had been meant as initial purchasing costs.

Regarding to energy pricing reported by US Department of Energy [113] the average diesel fuel prices of 1.8 \$/L in August 2022 is considered for ICET. In addition, the compressed natural gas (CNG) price is considered 1.5 \$/kg [113] which could be used as bases for the Biogen system in the ERSAPHT. Depending on the time band, electricity price, ranges from approximately 0.08 to 0.18 \$/kWh in Canada. Electrical energy price was based on data published by the Hydro-Québec [114] for low-voltage non-household consumers in August 2022. The average residential cost of electricity including fixed and variable costs in

Quebec is \$0.073 per kWh for off-peak hours. Therefore, an average price of 0.11 \$/kWh was considered, as it was assumed that charging would happen mainly at night.

Table 3-6. Some economical parameters considered for cost assessment.

Parameters	Symbol	Units	Similar References				Average	Total values considered in this study				
			[115]	[116]	[108]	[112]		SAPHT	ERSAPHT	ICET	PV/FCAMR	AMR
Purchase price (Without battery and FC)	C_P	$	30000	-	15000	-	-	16000	16000	35000	6000	6000
Battery pack	C_{Bat}	$/kWh	-	-	160	140	150	2350	2350	-	570	570
Electric motors	C_{EM}	$/kW	-	-	70	80	75	800×2	800×2	-	270×2	270×2
PV system	C_{PV}	$/ m2	-		400	-	450	2400	2400	-	500	-
Fuel Converter + requirements	C_{FC}	$/kW	250	210	-	300	250	-	3000	-	1500	-
Fuel	C_F	$/kg	-2	16	2-3	1-2.5	2	-	1.5	1.8	16	-
Electricity	C_E	$/kWh	0.2	-	0.15	0.18	1.8	0.1	0.1	-	0.1	0.1

3.8 Summary

This chapter discussed the proposed agricultural off-road hybrid electric vehicle design and development process in detail. The key contribution of the research is to perform typical working cycles on off-road hybrid electric vehicles based on customer needs and design a renewable energy-based powertrain by use of a heuristic power management system. The idea was to design and develop an energy-independent off-road hybrid electric vehicle to work in faraway areas without the need for fossil fuel. This work contains two case studies with two different renewable energy-based range extender systems. In the first case study, an ERSAPHT system with a biogas-fueled engine/generator is designed, developed, and evaluated. In the second case study, an agricultural mobile robot (AMR) powertrain is hybridized by the use of a fuel cell system and PV panel to highlight the strength of the proposed method. In both cases, some typical farm working cycles are extracted based on an experiment. After that, a hybrid electric vehicle powertrain model was created in MATLAB/Simulink. This model can be used to estimate energy requirements for a specific working cycle and provide assistance in the HEV component sizing and EMS tune before construction. The series hybrid electric powertrain configuration is used in both vehicles because it allows the system modularity and relatively reduces the EMS complex city. Also, in this configuration, the range extender (Bio_Gen or FC) could operate in the most efficient region to recharge the battery pack and supplement traction power. A biogas-fueled range extender system is developed along a heuristic EMS module which was implemented in the developed ERSAPHT powertrain. Finally, several field experiments were conducted to evaluate the system's safe functionality and robustness. Moreover, an economical assessment between the proposed renewable energy-based agricultural vehicles and a conventional tractor was performed. To sum up, the aforementioned design process could allow flexibility and modularity for other similar off-road vehicles which is discussed in the next chapter.

Chapter 4 - Results and discussion

4.1 Introduction

In this chapter, results from working cycle designing and derivation for the ERSAPHT and PV/FCAMR applications are discussed. Next, measured experimental data are employed to evaluate the established model and analyze the off-road vehicles' performance and working range. Relatively, the life cycle cost of the ERSAPHT was evaluated and compared with a conventional tractor. Respectively, the life cycle cost of the designed PV/FCAMR was evaluated and compared with the basic pure electric system based on equivalent daily net consumed energy. And finally, the Levelized Cost of Energy (LCE) for both of the vehicles is evaluated and discussed compared to the basic pure electric systems and a conventional diesel tractor.

4.2 ERSAPHT Design and Development Process Evaluation (Case Study 1)

In this section, first, working cycle designing and derivation for the ERSAPHT application are described. Next, measured experimental data are employed to evaluate the established model. After that, the results from the experiment and the simulation are used to analyze the ERSAPHT performance. Then, the results regarding the performance of the EMS, the impact of the RE on the working range, and fuel consumption are discussed. Subsequently, the components integration and final evaluations of the ERSAPHT platform are demonstrated.

4.2.1 Experimental Working Cycle Analysis for the ERSAPHT

In this section, the results of experimental tests for the developed ERSAPHT with different typical farm operations are presented. Figure 4-1 shows real-world measured data including the velocity, battery current, battery voltage, and demanded power in trailer pulling operation. These data illustrated that the velocity range was under 25 km/h depending upon the road conditions and farm operation situation. This Figure also presents the required instantaneous power, from the measured current and voltage, that is related to vehicle velocity and required torque during the operation. Also, the average required power of 8.63kW obtained from the trailer working cycles after several repeats, which matches the reported data in [89]. Consequently, the high-power mode would be selected for EMS in trailer working conditions.

Figure 4-1 (b) shows that the start-up currents of the electric motors were up to 400 Amps, which is subsided several times of the rated current for a few seconds. The reason could be found in the vehicle required power for acceleration and the characteristics of electric motors. This is obvious that the battery voltage fluctuations occurred depending on the consumption current while the voltage level decreased by the energy consumption during the test. From the graphs, we can see that again the battery suddenly supplied higher currents when the battery voltage was decreased immediately. Furthermore, this shows the battery voltage increased during the stop mode due to enough time for battery recovery.

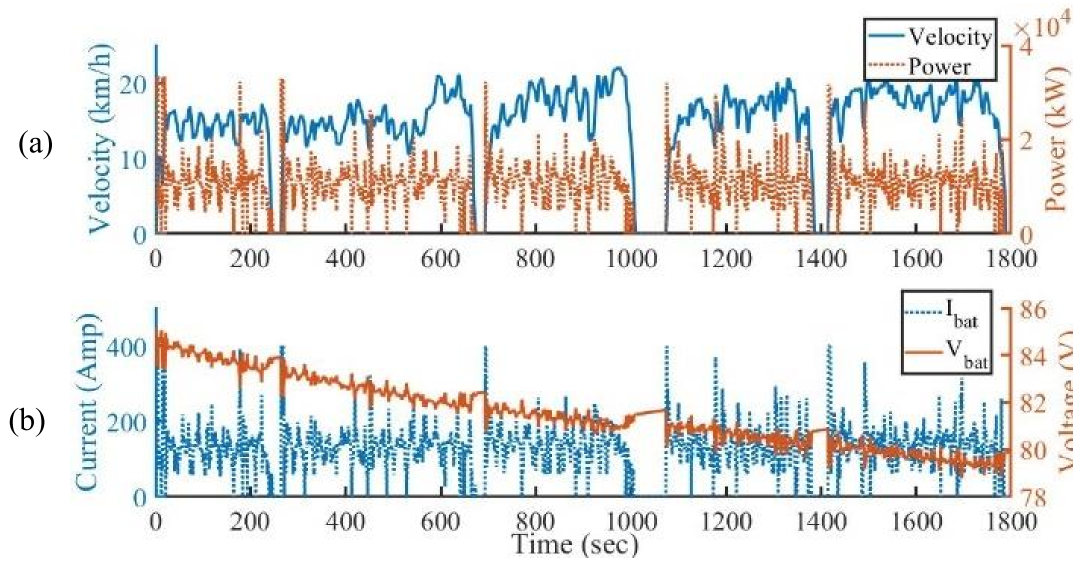


Figure 4-1. Measured experimental data during the Trailer working operation by the ERSAPHT (a) Velocity and required power, (b) battery output current and voltage.

Figure 4-2 shows the other experimental measured working cycle in boom-type sprayer operation conditions based on the predefined working cycle in Figure 4-2 (a). It can be seen that the velocity ranges in this cycle obtained up to 7.2 km/h depending on the farm conditions. Also, several repetitive stops and go occurred during the working cycle. Figure 4-2 (b) illustrates the mixed required power from the traction force, and electrical PTO power in boom-type sprayer operation. The results from several repeat of the field tests with the boom-type sprayer acquired 5.37 kW and 1.59 kW average power by traction system and PTO system respectively, which lead to 6.96 kW total average required power in this cycle. Consequently, the normal mode (see Table 3-3) seems to be an appropriate mode for this working cycle.

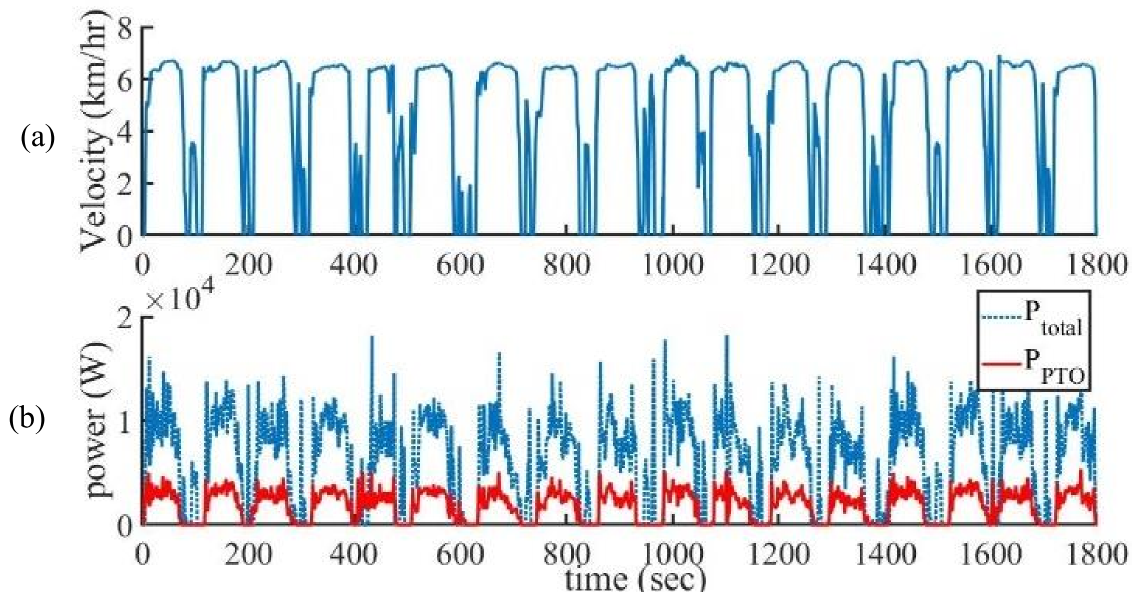


Figure 4-2. Measured experimental data during the boom-type sprayer working cycle by the ERSAPHT, (a) velocity, (b) overall required power and PTO system required power.

By comparing the working cycle between the Figure 4-1 and the Figure 4-2, it will appear that in the trailer cycle, the travel distance is usually longer than boom-type sprayer one and there were longer stops as well as much more transient trips, due to road and farm work conditions. In fact, when trying to maintain a certain velocity, a small amount of variation in the velocity occurs for a number of reasons, including slight variations in the throttle position, changes in train condition, and the consequences of the movements on the road path. While in the boom-type sprayer, it turns out that the operations are almost repetitive and the work cycles are almost similar including several stops and go phases by using the PTO system.

Nevertheless, it should be taken into account that the PTO does not work at the U-turns, and the speed of work is much reduced in the sprayer working cycle. However, in tasks like water-pump, the tractor is using in a stationary mode by employing the PTO system solely. As a result, an electrified powertrain is able to decrease the idle power losses and minimize fuel consumption in this kind of operation.

Table 4-1 compares the results of the three typical farm operations by the developed ERSAPHT. Experimental data analyses indicated that the average velocities obtained were 12.36 km/h and 6.24 km/h in the Trailer and Boom-type sprayer working cycles during the test, respectively. The trailer working cycle requires much more power due to more weight and velocity compared to the other ones. Furthermore, as aforementioned the required energy to doing specific work could be calculated by taking the time integral of the power request. The result illustrates that 4.31, 3.46, and 2.12 kWh electrical energy have been consumed during the 1800s testing with trailer, boom-type sprayer, and water-pump working cycles, respectively. These results are also consistent with the reported field experiment tests by the basic system [89].

Furthermore, the results of the experimental tests, it becomes clear that about one quarter (26%) of the total battery energy has been consumed during the 1800s test by the Trailer working cycle. Also, based on experimental tests the boom-type sprayer required 2.62 kWh and 0.84 kWh energy to drive the tractor by traction system and to work by PTO system, respectively. It is obvious that in the boom-type sprayer working cycle around 76% and 24% of total consumed energy is spent to drive the tractor by traction system and to work by PTO system, respectively. However, in the case of the Water-pump working cycle, all consumed energy was utilized by the PTO system to do stationary work.

Table 4-1. The experimental test results for the predefined farm operation.

Farm operation type	Unit	Trailer	Boom-type Sprayer	Water-pump
Test time	s	1800	1800	1800
Average velocity	km/h	12.36	6.24	0
Distance traveled	km	6.18	2.86	0
Average power requirement	kW	8.63	6.96	4.24
Total energy consumption	kWh	4.31	3.46	2.12
Required energy for driving the tractor	kWh (%)	2.29 (54)	2.62 (76)	0
Required energy for working	kWh (%)	2.02 (46)	0.84(24)	2.12 (100)

4.2.2 ERSAPHT Simulink Model Evaluation

To validate the established model and suggested energy management strategy algorithm, at the first step the simulation has been carried out based on the NEDC by considering a fully charged battery (initial SOC supposed 100%). Here the NEDC is used as the target condition in the simulation with the trailer working condition, which aims to simulate typical stop and go rural driving conditions. To comply with the 25 km/h speed limitations of the vehicle, the NEDC had to be scaled down, so that the top speed demanded by the cycle did not exceed due to the SAPHT's limits. Figure 4–3 (a) shows that the forward simulation model follows the scaled reference driving cycle in high precision. In addition, the average traction power of the cycle calculated 7.92 kW from the simulation results (Figure 4–3 [b]). Therefore, the established model can be used as the basis for the off-road vehicle component selection, EMS evaluation, and range analysis simulation before implementation.

(a)

(b)

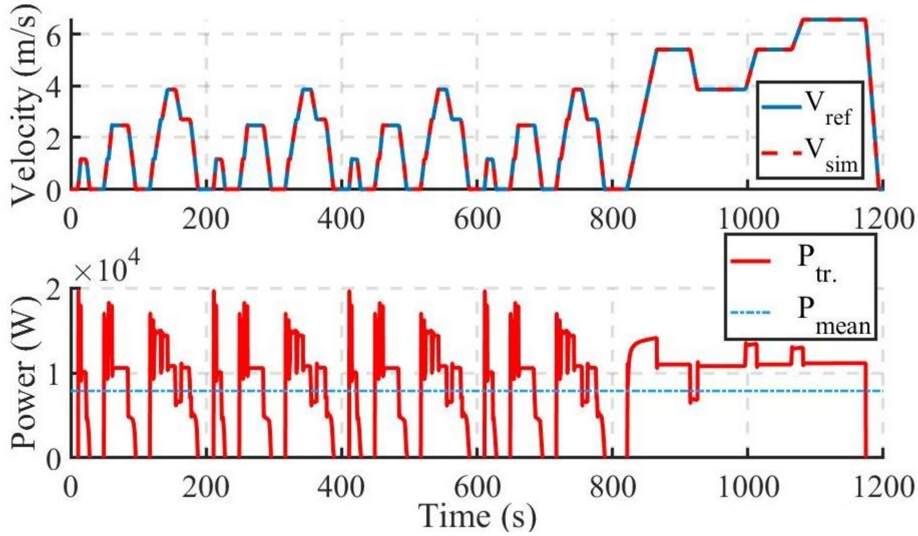


Figure 4-3. Simulation results for; (a) the reference scaled-down NEDC compared to Simulink results, (b) electric motor power demanded.

Since this work revolves around battery discharge for the EREV powertrain, the NEDC was simply to loop the cycle end-to-end to reach 20% of battery SOC. Because of the battery's discharge behavior, the total range of the vehicle could be extrapolated over time under these working conditions. The results of EV mode and charge blending (CB) mode simulation by the scaled-down NEDC is shown in Figure 4–3. It is obvious that with full charge existing battery pack the All Electric Range (AER) of the basic system in the EV mode (without allowing to turn on the RE) obtained up to 6000s (+1.67 h) to reach the final 20% SOC of the battery pack. However, when using the suggested heuristic EMS in a CB mode (allowing to turn on the downsized RE), the operating range increased to over 10,000s (+2.8 h). These simulation results also indicate that a RE with about 10 kW rated power is able to supply the existing system power for about 10 hours of continuous operation in the scaled-down NEDC.

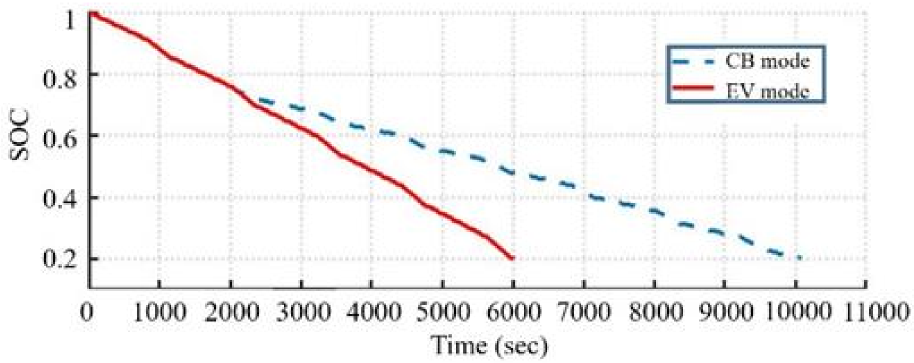


Figure 4-4. Simulation results of CD mode and CS mode in scaled-down NEDC to battery depletion with the trailer pulling operation mode.

Moreover, simulation results in Figure 4-5 (a) show that the motor required power for moving a trailer at a constant speed of 25 km/h with a two-ton load on an asphalt road with 10 km/h opposing wind velocity. It is obvious that in the beginning, the required power for acceleration (+45 kW) was more than four times compared to the constant speed. Regarding the results, it becomes evident that a +11.32 kW average traction power is required. This calculated quantity is close to the experimental result with the basic system. In addition, Figure 4-5 (b) shows the full charge battery SOC deviation against the required energy during the simulation. It can be found that with a full charge of the existing battery pack, the AER for the basic system in 4000s (under 27 km) would reach the final 20% SOC of the battery pack.

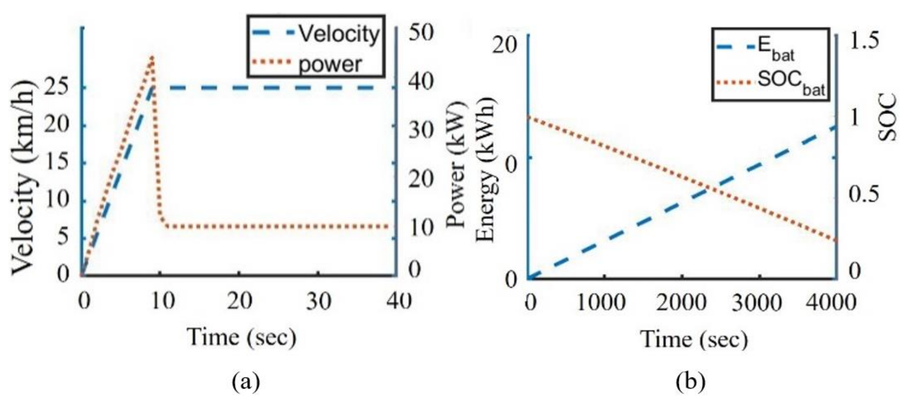


Figure 4-5. Simulation modeling results in EV mode when the vehicle is cruising to 25 km/h.

In addition, the comparison results between the SOC of the battery calculated from the measured data and the SOC estimated from the simulation model in Figure 4-6 show a less than 5% difference at the end of the cycle. Therefore, the developed Simulink model can be used to estimate the total working range and adjust various EMS parameters before building the desired off-road vehicle.

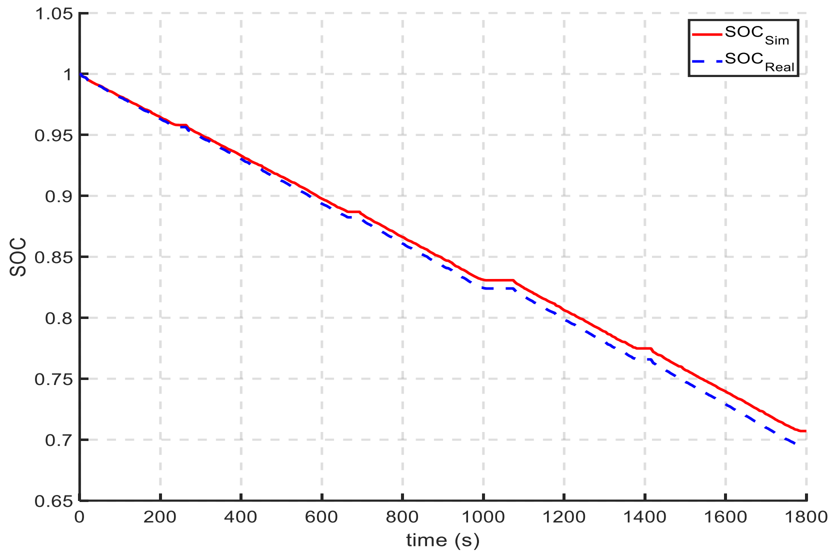


Figure 4-6. Comparison results between battery SOC calculated from measured data and SOC estimated by Simulink model.

4.2.3 Components Integration and Powertrain Validation of the ERSAPHT

The ERSAPHT project carried out at Mechanical Engineering of Biosystems' department, the University of Tehran as a case study (Karaj, Iran). As described in the previous chapter, after doing the literature review and completing the design process for various components in the simulation environment, the integration and development of new components such as Biogen system and EMS modules were carried out. A series of initial tests were also conducted during the development process to ensure the safe operation of the system. Preliminary results showed that, depending on the determined working mode by the operator, the EMS would provide enough power to propel the vehicle. For the energy management strategy, the battery pack is the major energy source to power the electric vehicle, while the RE gives out certain power output to propel the ERSAPHT and charge the battery. The RE will be turned ON when the SOC of the battery is less than the given minimum threshold and shuts down when the SOC is above a predefined threshold. When the Biogen is turned ON, an onboard single-phase charger inverts the power into an appropriate DC voltage to charge the battery pack. However, the vehicle runs with a battery pack and PV system when the Biogen is OFF.

In the following sections, the performance of the developed hybrid electric powertrain including EMS functionality and working range in real farm conditions is investigated. Figure 4-7 shows the developed ERSAPHT in real-world field experiments with typical road cruising, and trailer hulling.

(a) (b)

Figure 4-7. The ERSAPHT in real-world field experiments with typical implements: (a) Prototype tractor cruising, and (b) Trailer pulling.

4.2.4 EMS Performance Analysis

As mentioned previously, an EREV's working range is linked to various variables such as ESS capacity, RE running time, energy consumption under different working cycles, and driving behaviors. Figure 4-8 compares the ERSAPHT performance under the high-power mode (see Table 3-3) with an 80% initial battery SOC level. Figure 4-8(a) illustrates the comparative range between the CD mode and CB mode. The dashed line shows that the SOC changes when RE is activated while the dotty line displays the battery SOC deviation in pure electric mode. This result represents at least 10% SOC level difference between the two modes during the 1800s driving in the trailer working cycle. From Figure 4-8(b), when the battery SOC level is going under 75%, the Biogen will be triggered to help the battery pack in power supplying. Indeed, the EMS increased 10 percent of the battery SOC during around 1500 seconds for 750 grams of renewable fuel by activating the Biogen. Furthermore, these results show that the proposed algorithm was aimed at increasing the working hours range, as well as prolonging the battery lifetime to acceptable levels. As a result, due to the possibility of using a downsized Biogen in its near-optimal fuel consumption range in the ERSAPHT, less fuel would be used compared to conventional tractors in the same category.

(a)

(b)

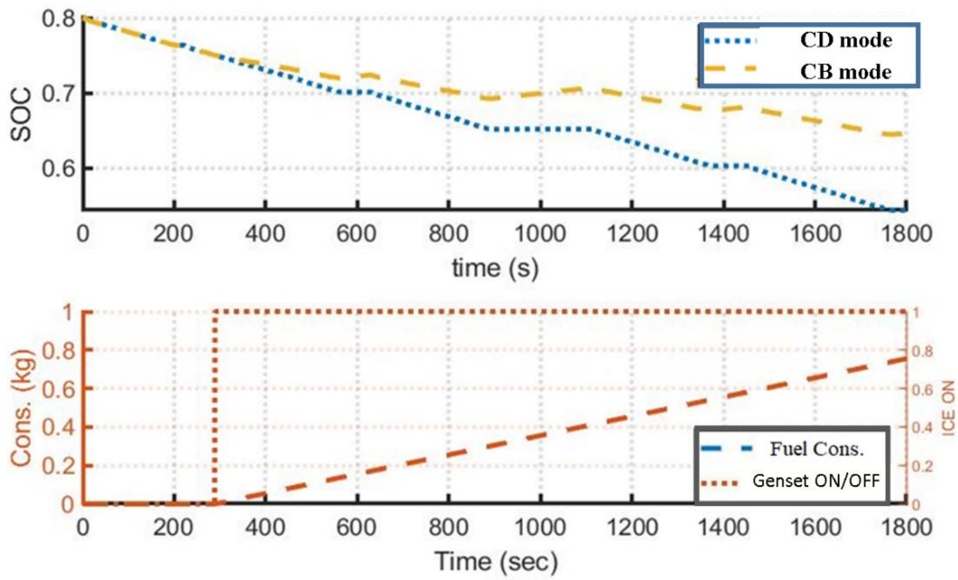


Figure 4-8. Experimental results in high-power mode during the trailer working condition by developed EMS (a) Battery SOC, (b) Biogen mode, and fuel consumption.

Table 4-2 compares the developed ERSAPHT performance results for the three typical farm working cycles by employing the suggested heuristic energy management strategies, which have been discussed in previous sections. From these results, it becomes clear that about one quarter (26%) of the total battery energy has been consumed during the 1800s test by the Trailer working cycle. Therefore, it is necessary to hire a RE to provide the extra power needed to ensure no energy shortage in the desired working range. The results from EV mode show that the energy consumption of the sprayer and water-pump work cycles are lower than the trailer working cycle. Therefore, the high, medium, and economic power modes respectively were considered in EMS for the trailer, sprayer, and water-pump work cycle during the experimental tests. By going in detail of the results from the CB mode, it is obvious that the final SOC amount for the boom-type sprayer was lower due to later start ON of the RE in medium mode and the simultaneous use of the PTO system. This is obvious that by utilizing the developed Biogen and EMS, the battery SOC depleting rate has decreased. However, in the Water-pumping working cycle due to the EMS strategies and low energy consumption, the Biogen was not turned ON during this same test time. The biogas consumption during the Trailer and Boom-type sprayer test was 750 and 160 grams, respectively. Comparing this amount of fuel consumption with the reported average fuel consumption over time in the Biogen manufacturer’s user manual is well matched. This reflects the good performance of the Biogen during use as a range extender in the ERSAPHT.

Table 4-2. The experimental test performance results for the predefined farm operation

Farm operation type	Unit	Trailer	Boom-type Sprayer	Water-pump
Test time	s	1800	1800	1800
Initial battery SOC	%	80	80	80
Final battery SOC in EV mode	%	54	61	67
Final battery SOC in CB mode	%	65	64	67
Delta SOC between CD and CB modes	%	11	3	0
Fuel consumption	kg	0.75	0.16	0

4.2.5 ERSAPHT working range comparison and analysis

Since experimental tests have many limitations and the 1800 second tests were found to be too brief to provide an appropriate measure of the total range. The solution proposed was simply to loop these cycles to reach 20% of battery SOC in different powertrain by importing the measured data to the established Simulink model. Considering the energy generated by the Biogen system, collected by the PV array, and provided by the battery pack, the total available energy calculated up to 63.12 kWh per day. Using this energy, the ERSAPHT could operate the Trailer, Boom-type sprayer, and water-pump by 3.41, 6.21, and 14.6 hrs at the specified conditions, respectively. In addition, results in Table 4-3 showed that by using the Biogen, operating time ranges were increased by 1.93, 4.37, and 11.58 hrs, respectively for the Trailer, Boom-type sprayer, and Water-pump operation compared to the basic pure electric system. Furthermore, this result shows that the Biogen will produce 15.09, 27.32, and 43.92 kWh during the typical working cycles that include almost 51.14%, 63.20%, and 71.20% of the total energy consumed. However, the fuel consumption in the trailer, boom-type sprayer, and Water-pumping operation working cycles were 5.13, 9.32, and 14.88 kg, respectively. Finally, from these results, it could be calculated that the onboard PV array provides almost 5.78%, 7.18%, and 8.09% of the total energy consumed during the Trailer, Boom-type Sprayer and Water-pump operation modes, respectively.

Table 4-3. Comparative working range in the different farm operation conditions.

	Unit	Trailer	Sprayer	Water-pump
Working range in EV mode (basic Sys.)	hr.	1.48	1.84	3.02
Working range in CB mode	hr.	3.41	6.21	14.60
Final battery SOC	%	20.00	20.00	20.00
Average power requirement	kW	8.63	6.96	4.24
Total available energy (consumed)	kWh	29.51	43.23	61.80
Battery provided energy	%	43.38	29.61	20.71
Total Produced energy by Biogen	kWh	15.09	27.32	43.92
Produced energy by Biogen	%	51.14	63.20	71.20
Total fuel consumption	kg	5.13	9.32	14.88
Total produced energy by PV	kWh	1.71	3.11	5.00
Produced energy by PV	%	5.78	7.18	8.09

4.3 PV/FCAMR Design Process Evaluation (Case Study 2)

The PV/FCAMR design process and powertrain evaluation are presented in the following sections. Consequently, experimental tests to derive working cycles for the AMR application are described and analyzed. Next, measured experimental data are employed to evaluate the modified model for the FCAMR application. Then, preliminary results from the PV/FCAMR powertrain designing tests are analyzed. Subsequently, the component selection and integration process are suggested at the end.

4.3.1 Experimental Working Cycle Analysis for the AMR

During the work of an AMR on a typical farm, there are several times of Stop and Go situations for avoiding obstacles, and following the path. In addition, there are several times of rotating situations for finding the route. In a large measure, the operating range of an electric AMR depends on the operating conditions such as accelerations, and decelerations at the beginning and end of the movement, correspondingly. Therefore, the obtained speed profile can be assumed as the typical behavior of a driver on a FCAMR working cycle. In this regard, several tests have been conducted on a test bench in different scenarios and cycles based on their speed profiles from the experiment.

In this work, an analysis of the AMR is performed on the two measured cycles as described in the previous section to evaluate the proposed methodology. Figure 4-9 shows the parameters of the rectangular working cycle pattern over time. Figure 4-9 (a) illustrates a part of the angular velocity profile of the left and right wheels as a control command from the AMR control unit during driving in the real condition. It is obvious that the wheels have the same rotational speed while the robot runs in a straight direction. However, the wheels have different rotational directions when turning in the corners because of the deferential drive architecture of the AMR powertrain. These data result in the linear velocity profile of the AMR moving in the working cycle in Figure 4-9 (b). Consequently, from measured data (battery output current and voltage) by the data acquisition unit, the instant total power consumption could be calculated as shown in Figure 4-9 (c). Finally, total energy consumption can be estimated from the accumulated instantaneous power. By estimating energy requirements in different scenarios, it is possible to estimate other aspects such as component sizes, EMS performance, and battery SOC.

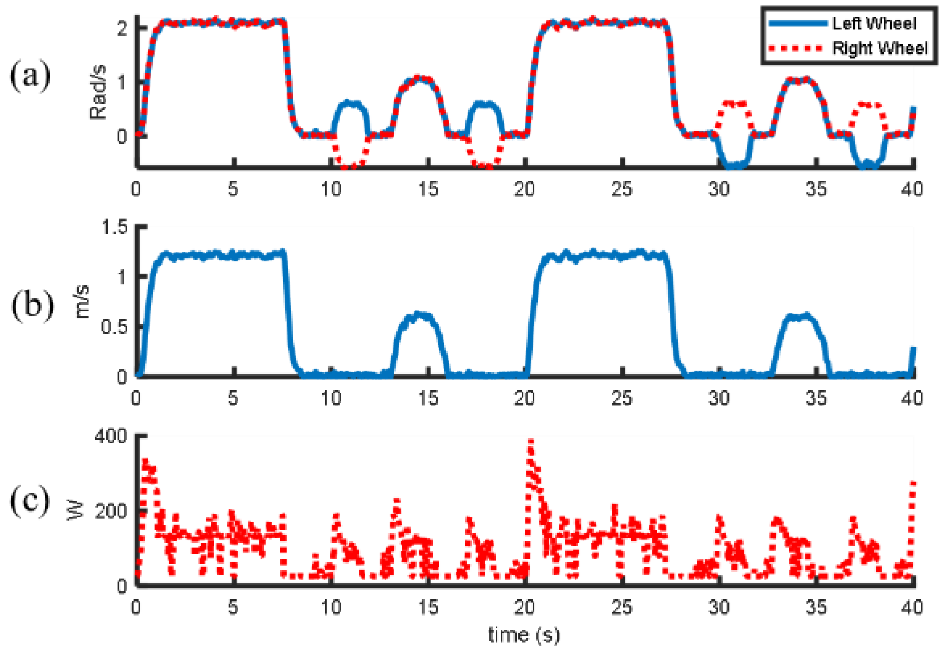


Figure 4-9. Obtained results for the measured speed profile during the rectangular movement pattern working cycle by the AMR in one round (20 meters), (a) Wheels angular velocity (control command), (b) AMR linear velocity, (c) Instant traction power.

Also, Figure 4-10 shows the circular working cycle pattern with a different speed profile in the whole cycle. In these scenarios the AMR move in a circular path (as presented in the section 3-3), therefore the diameter of the moving path increase during the test. Since the moving pattern is different than the rectangular one, its speed profile, power requirement, and energy consumption were obtained differently. It should be noted, based on data obtained at the two typical working cycles that the electric motors are rarely used on their maximum rated power. In fact, the drive system works most of the time in the partial load range. Note that electric motor operate in several ranges of angular velocities and under different conditions, so their efficiency deviates from its maximum level. Thus, the fluctuation in the power consumption could be occurred due to the various power requirements for acceleration, rolling resistance, and electric efficiency at different speeds.

(a)

(b)

(c)

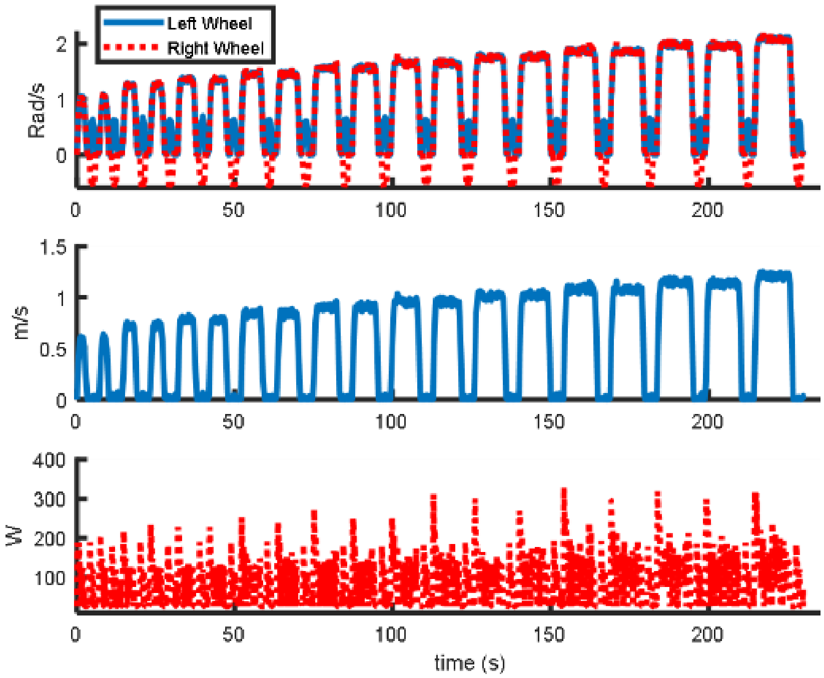


Figure 4-10. Obtained results for the measured speed profile during the circular movement pattern working cycle by the AMR in one cycle (100 meters), (a) Wheels angular velocity (control command), (b) AMR linear velocity, (c) Instant traction power.

Table 4-4 shows the results from the measured working cycles. It is considered the same travel distance of 100 m for both working cycles but in the case of the circular movement pattern, around 50 seconds more time is needed to reach the final destination due to lower speed at short movement distance at the beginning and extra required rotational movement. The average velocity is obtained at 0.56 m/s for rectangular movement pattern compared with 0.43 for circular one. However, the average power requirements for both of the working cycles are almost the same amount while in the circular movement pattern, the robot needs to have one more rotation movement to reach its destination. These results demonstrate a higher energy consumption of 8,855 kJ/h compared with 6,793 kJ/h on the rectangular movement pattern with almost 2 kJ/h more energy requirements.

Table 4-4. Measured parameters of the rectangular and circular movement pattern during the experiment with AMR.

Parameters	Units	Rectangular movement pattern	Circular movement pattern	Standard deviation
Travel distance	m	100	100	0
Time	s	180	230	50
Average velocity	m/s	0.56	0.43	0.13
Maximum velocity	m/s	1.29	1.2	0.09
Average power requirement	W	135.86	138.61	2.75
Maximum power requirement	W	460.95	371.03	61.92
Number of rotational movements	N	18	19	1
Total energy requirement	kJ/hr	6,793	8,855	2,062

Moreover, Figure 4-11 illustrates the comparison results between the longitudinal energy and rotational energy requirements of the each working cycle. It is found that a significant portion (more than five percent) of the vehicle stored energy is spent for rotational movement. For example, just for one round of traveling for rectangular movement pattern cycle (the 40s) in the investigated typical pathway, the AMR spends around 10 seconds on rotation compared to almost 35 seconds for translational movement. Consequently, the amount of 1.43 kJ (94.7%) and 0.081 kJ (5.3%) energies are consumed for the longitudinal and rotational movements, respectively (Figure 4-11 (a)). Accordingly, almost similar results obtained for rotational movements in the circular movement pattern working cycle (Figure 4-11 (b)). The importance of this phenomenon might be multiplied for crowded working environments where humans and AMRs work together, as the vehicle will need more alternate rotation and stop-and-go mode to avoid obstacles by finding an appropriate path to reach the desired position.

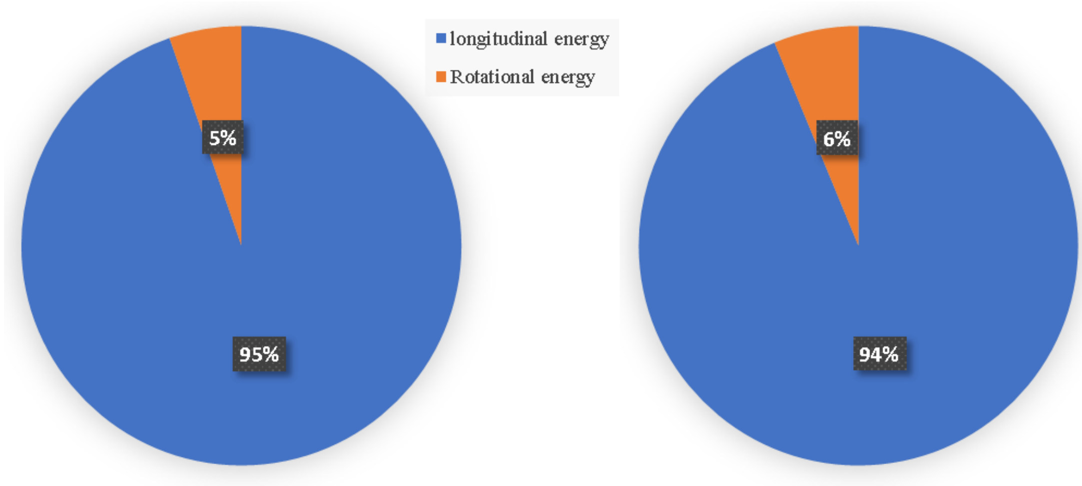


Figure 4-11. Comparison of the transitional energy and rotational energy requirements from experimental data; (a) Rectangular movement pattern, (b) Circular movement pattern

It should be noted, most agricultural work is performed repeatedly in certain rows with specific work patterns, but in free working conditions and trajectory planning situations, cyclical and random movements can occur. Therefore, the measured data from both cycles are integrated (called the mixed motion pattern) and used in the simulation process as a third working cycle.

4.3.2 PV/FCAMR Powertrain Model Evaluation

To evaluate the developed model, a comparative study in the first step is performed between the simulation results and the extracted experimental data by the basic battery-powered AMR. Therefore, the AMR is tested without a load while the wheels are off the ground to achieve full speed (1.8 m/s). This test has been conducted in order to eliminate surface effects on the performance of the AMR to assess model accuracy. Hence, the experimental data and simulation results for the vehicle when the environmental resistance and the vehicle weight are removed from the wheels are shown in Figure 4-12. Figure 4-12(a) compares the consumed current by the motors, and Figure 4-12(a) compares the DC-bus instantaneous voltage from the real-world test and the simulation. These results confirm an exact synergy (with an accuracy of 95%) between the energy model and the real battery-powered AMR performance.

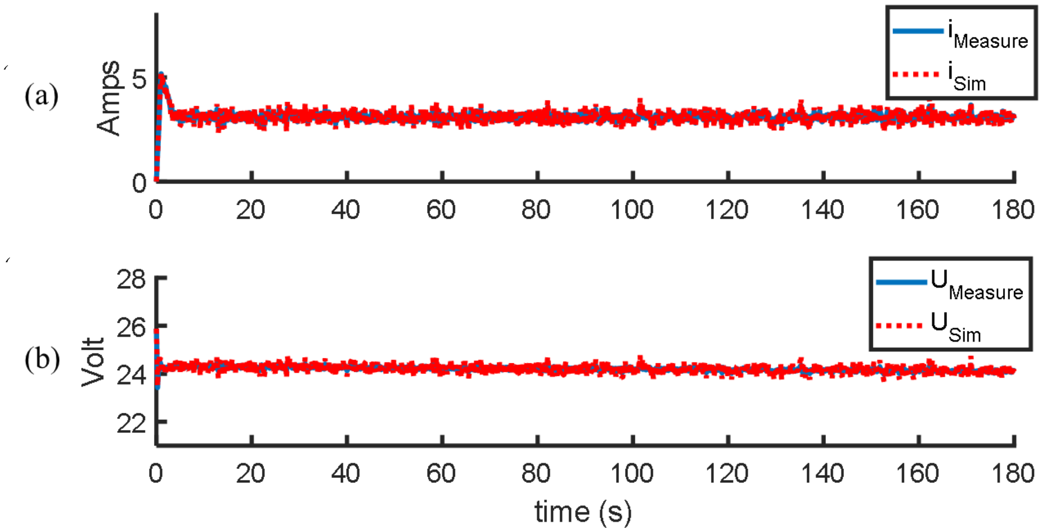


Figure 4-12. Comparison results between experimental data and simulations: (a) instantaneous voltage of the DC bus, (b) current by traction motors.

Moreover, in order to compare AMR movement results in real-world conditions and the Simulink model, several preliminary experiments conducted with the AMR in predefined paths using different velocity profiles including the pure transition in the X-direction, in forward and backward, trapezoid speed profile, circular movement, and rotation about the center of gravity. Each motion test was conducted for 11 s without extra load, and it was repeated three times in the same condition on a flat cement surface. In addition, each experiment includes three sections, acceleration from stationary, constant velocities, and deceleration to stationery. These measured speed profiles used as input for the model (same as ERSAPHT). Subsequently, the actual power requirement and energy consumption using different speed profiles are compared with the result from the AMR Simulink model. For example, in the trapezoid speed profile scenario (Figure 4-13 (a)), maximum linear velocity was considered as 1 m/s. Similarly, the acceleration time from rest to maximum speed and vice versa was adjusted to two seconds to prevent high mechanical and electrical stresses. Figure 4-14 (b) shows an adequate match between measured power requirements based on trapezoid speed profile as reference for the Simulink model and the obtained power requirement from the simulation. These results showed that the Simulink model has enough accuracy for energy estimation purpose for the rest steps of the hybrid AMR powertrain designing process.

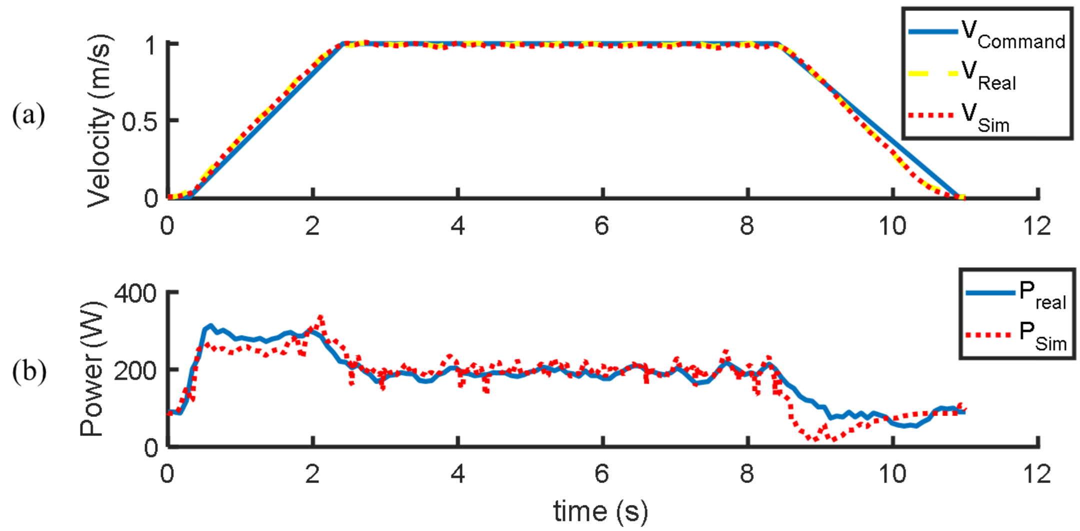


Figure 4-13. Comparison results of experimental data from real AMR versus the developed Simulink model by Trapezoid speed profile.

4.3.3 Evaluation of EMS and Battery Degradation Level Impact on the FCAMR Performance

By using the designed realistic energy model, it is possible to calculate how much energy is needed to work in a given path or for a specific period (e.g., during an 8h working shift). After that, the range-extender capacity (required power and fuel tank capacity) can be sized by considering the available energy of the onboard battery and the EMS. According to a recent research on battery degradation, reported in reference [117], the State of Health (SOH) level of a battery reaches a low of 75 percent after 1500 charging and discharging cycles at standard conditions. Therefore, a battery degradation lookup table is considered as a typical reference for the three battery SOH levels in this study. Subsequently, the impact of the FC sizing and battery degradation level on the AMR performance to operate for an entire 8h shift time is studied in this section.

An EMS with three modes of operation is proposed in this study. The first mode is known as charge-sustaining (CS) which maintains the battery SOC at the desired level such that the FC starts to supply power when the battery SOC drops to the minimum threshold of 40%.

For the second mode, called charge-depleting (CD), the battery is the main power source until the FC starts providing its maximum power as the battery SOC reaches its minimum threshold (20%). The third mode of the strategy is called charge-blending (CB) that emphasizes the FC efficiency by turning ON the FC when battery SOC reaches the threshold value of 60%. For CB mode, the FC supplies constant power corresponding to its maximum efficiency. For the three modes, the FC is turned OFF when battery SOC reaches 85%. Since each strategy employs the FC within a certain range, it is important to size energy resources appropriately to avoid energy shortages.

Since performing the real-world tests comes with limitations and the conducted experimental tests are short in duration, the mixed working cycle on the developed model has been repeated many times to investigate power sources performance for an 8h working shift. In this regard, the measured velocity profile for the mixed working cycle has been imposed to the simulated model as a reference. After that, the performance of the proposed FC/battery AMR powertrain is validated under the three EMS modes including the CD, CS, and CB. Then, each EMS mode is investigated by assuming a FC system with 300 W nominal power by considering three battery degradation levels (0, 750, and 1500 charge and discharge cycles) in 80% DoD.

4.3.1 PV/FCAMR Powertrain Performance Evaluation Considering battery degradation and EMS performance

In this section the performance of the designed PV/FCAMR powertrain performance is validated based on simulations. For instance, Figure 4-14 shows the impact of the EMS when the battery is new (zero charge/discharge cycle) on the CB Mode. Figure 4-14 (a) presents the power flow of the FCAMR system response including the FC system, battery pack, PV system, and storage systems' SOC compared to the total power load while the working cycle during 8 hours working daytime. It indicates that the FC turns ON after one hrs and 45 minutes to assist the battery pack during high-power demand or to charge the battery during low power demand periods on its higher efficiency rate. As can be seen, the hybrid drivetrain system is ensured by the hybrid power sources. The sum of the delivered powers (P_{FC} +P_{Bat} +P_{PV}) matches the total required power P_{Tot}. It can also be noticed from these figures that the load energy and power are effectively shared between the FC, the battery, and the PV system.

Dynamic and energetic constraints of the sources are respected under the working cycles. The battery supplies the fluctuated content of the demand of the power requirement and provides a high level of energy, and finally the FC provides the lower dynamic component (after several minutes of start-up) and ensures the highest part of the required energy. Obviously, the algorithm tries to use the FC in its most efficient range (nominal power), with less ON/Off switch. For instance, the FC starts and stops 5 times during the rectangular working cycle. Each time it was ON for approximately 1700 seconds. It is obvious when the FC system is ON the battery pack spends less power and becomes recharged when the driving demanded power is less than the generated power by the FC system and the PV system. The sources are, thus, well sized according to the load requirement.

In addition, Figure 4-14 (b) present the total supplied energy from each source for the entire working shift. From the total consumed energy (2725 Wh), the fully charged battery could supply only up to 254 Wh and the FC provides 1991 Wh of the required energy. Furthermore, the PV system could provide almost 1112 Wh renewable energy during the day. The SOC trajectory (Figure 4-14 (c)) tends to follow vehicle dynamic behavior and reaches the required final condition. The relevance of the sizing with respect to the energy storage systems' capacity constraints is also verified through the battery SOC. The recommended final limits ($SOC_{Bat} \approx 0.4$ and $SOC_{H2Tank} \approx 0.6$) are respected for the two storage systems capacity. This demonstrates the effectiveness of the CB control strategy for finding the proper SOC values for both the battery pack and the hydrogen tank. Since the proposed hybrid powertrain architecture for the FCAMR is a PHEV, the initial SOC of the battery pack and the hydrogen tank is assumed 100% at the start of the day. The final Depth of Discharge (DOD) reached to a reasonable level (0.6) for the battery. Therefore, the energy storage system sizing results are in respectable agreement with the energy demand. All in all, the proposed design process fulfills the power requirements under typical working cycles, achieve a reasonable power distribution between the FC, battery and PV, thus, prolong the continuous working time of the FCAMR.

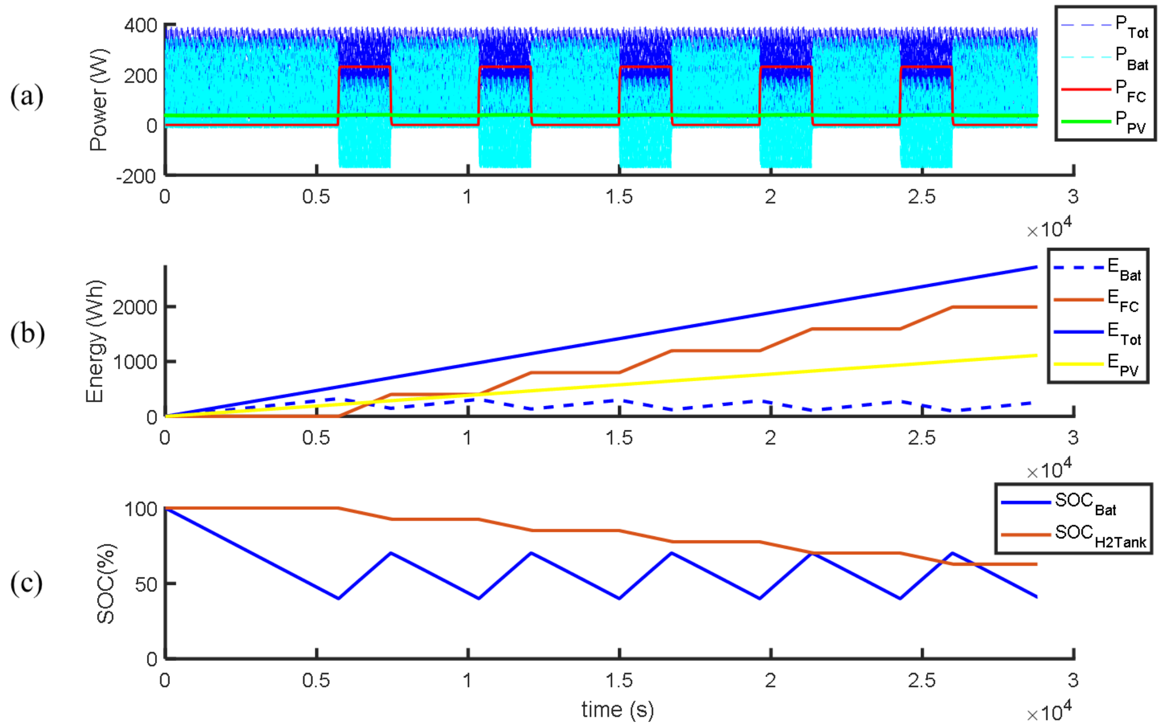


Figure 4-14. Simulation results for FCAMR in the CB mode during 8 hours working; (a) Instant power of the battery pack, FC system, and PV system compared to the total load requirement, (b) provided energy by each energy sources, and (c) Battery SOC and hydrogen tank SOC.

As a general outcome, Table 4-5 lists the comparison results for each EMS with three battery charge and discharge cycles (0, 750, and 1500) in terms of the working time, provided energy by sources, H_2 consumption, and final SOC of the battery. These results show that the system cannot meet an 8h working shift in CD mode with different FC power sizes due to the insufficient supplied power by energy sources for the power peak requirement (+460 W). These results showed that the suggested hybrid system would fail in the CD mode. As mentioned before, in the CD mode the battery pack supplies the required power without the assistance of the FC until the battery SOC reaches the low battery threshold level (20%). Therefore, the system failure occurs after almost two hours in the CD mode due to the insufficient available power of the battery and FC, which cannot support alone the power peak requirement of the AMR (+460 W) especially when the battery pack is almost degraded. It means that a FC system with a higher power (e.g., 500 W) is needed to satisfy the power peak of the AMR during the acceleration with the CD mode to accomplish the 8h working shift.

On the other hand, in the CS mode, the FC is turned ON at its maximum power when the battery SOC is around 50%, to ensure battery SOC sustenance until the end of work. Indeed, CS strategy acts similar to CD mode in the beginning if the battery is fully charged. Nevertheless, due to the higher battery SOC threshold level, the CS mode keeps the battery SOC higher than the minimum authorized SOC (20%) during the 8h working shift to supply the required peak power. Additionally, the simulation results showed that in the CD mode EMS scenario, the FC system must be turned on and off many times to keep the battery SOC level within the defined range. This phenomenon may cause more fuel consumption and lower efficiency as well as earlier degradation of the whole system. Moreover, since the FC operates at its maximum power rate during CD and CS modes which will lead to high fuel consumption, the objective of minimum fuel consumption and a long lifetime of the battery/FC sources may not be achieved in these modes.

However, in the CB mode, when the SOC reaches the threshold value of 70%, the FC supplies a constant power while the battery supplies the required peak power. Accordingly, the CB strategy allows turning ON the FC stack in its maximum fuel efficiency with a minimum ON/OFF cycles to minimize hydrogen consumption. Moreover, it prevents the battery SOC to reach the minimum threshold before the end of the working shift and avoids frequent power source fluctuations that could affect the FC life span. Therefore, it might increase the battery and FC lifetime by reducing their degradation.

Table 4-5. Comparison results of energy sources with different EMS and battery lifetime.

EMS mode	Battery charge and discharge cycle	Working range time (s)	Total energy consumption (Wh)	Provided energy by FC (Wh)	Provided energy by Battery (Wh)	Provided energy by PV (Wh)	H_2 Cons. (gr.)	Batt. SOH (%)	Batt. Final SOC (%)
Charge Depleting (CD)	0[a]	7615	715.6	15	429	286	+1	100	20
	750	6610	622	11	373	249	+1	90	20
	1500	5223	493	5	295	198	+1	75	20
Charge sustaining (CS)	0	28800	2735	2072	208	1112	+66	100	52
	750	28800	2737	2263	142	1114	+73	90	53
	1500	28800	2749	2527	92	1115	+80	75	51
Charge Blending (CB)	0	28800	2724	1991	254	1112	+55	100	40.96
	750	28800	2726	2198	198	1112	+61	90	40.83
	1500	28800	2728	2391	142	1114	+67	75	41.03

([a] 0 means new battery from reference [117])

As shown in Table 4-5, simulation result illustrates a difference of around 25% in hydrogen consumption for the same provided energy by the 300 W FC system during the typical 8hrs shift working cycles between the CS and CB modes. Therefore, in order to increase the system efficiency and to reduce hydrogen consumption, it is better to consider an EMS that uses the FC at its maximum efficiency similar to CB mode instead of using the FC at its maximum power as CS and CD modes. Moreover, results show that battery degradation has affected the capabilities of the EMS as well as vehicle performance by reducing the ESS capacity. By comparing the results, it can be seen that a 300 W FC system in the CB mode is able to maintain the battery SOC at the desired level (40%) even until the end of the useful life of the battery (up to 1500 battery charge and discharge cycles). Moreover, the results show that battery degradation impact on the vehicle performance is more drastic in the system with a smaller secondary power source because the final SOC is usually lower than the desired level. To summarize, the FC and hydrogen tank sizing of the hybrid AMR strongly depend on the EMS and the desired autonomy. It is also important to consider the degradation of power sources and the maximum load that can be transported by the AMR during the FC and hydrogen tank sizing.

4.3.2 Components Integration and Powertrain Evaluation Process for the FCAMR

The remaining steps regarding the development of the PV/FCAMR system process are developing a stationary test bench (Figure 4-15) by integration components such as a PEMFC stack, PV system, DC/DC converters, battery pack, energy management system, hydrogen supply system, measuring sensors, data acquisition systems, monitoring, and control interface, etc., which would be conducted by our research team at UQTR as prospective steps of this project. Given the proposed FCAMR configuration, the EMS is considered in the Economic, Normal, and High-power modes the same as the ERSAPHT. In this regard, the suggested energy management strategy in the EMS electronic module of the ERSAPHT is employed in FCAMR model with a similar functionality by switching ON or OFF the FC system in its near-optimal performance region (recommended by the manufacturer). The suggested algorithm is validated in the Simulink model to control the FCREx before applying on the real-time operating condition.

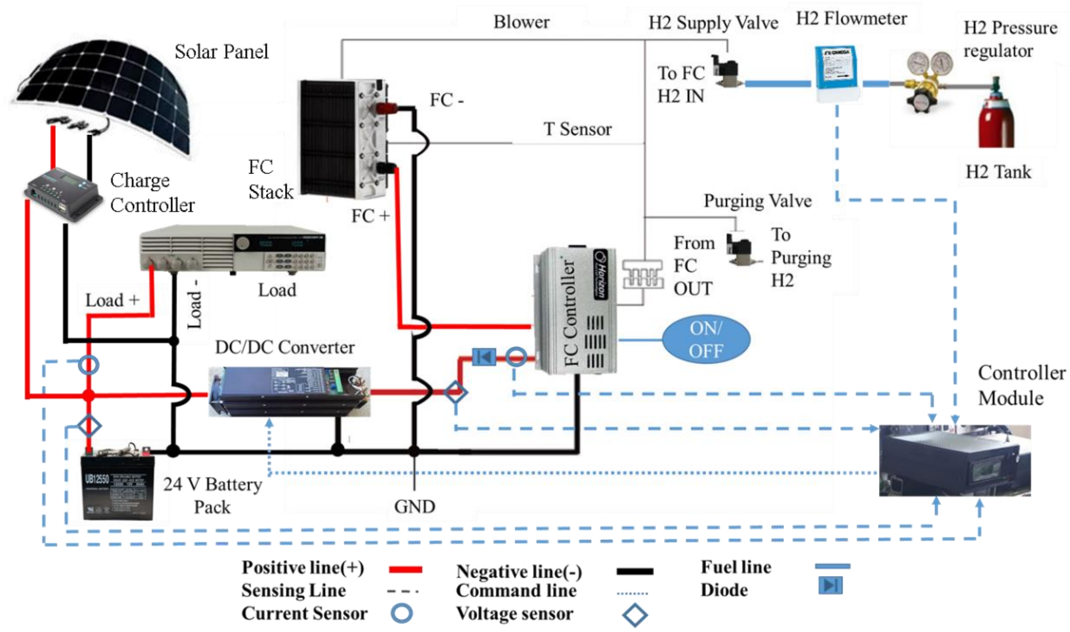


Figure 4-15. Simplified architecture block diagram for the integration of FC range extender for the PV/FCAMR application.

Figure 4-16 shows a simplified architecture block diagram of the suggested EMS electronic circuity. In this regard, the inputs of the controller module are from the units such as current sensors, voltage-measuring modules, hydrogen flowmeter, working mode switch. These inputs are processing in the EMS module, and the output commands are commanding to the DC/DC converter to adjust the PEMFC output. The measured current would be processed by the EMS to estimate the SOC of the battery pack based on the coulomb counting method.

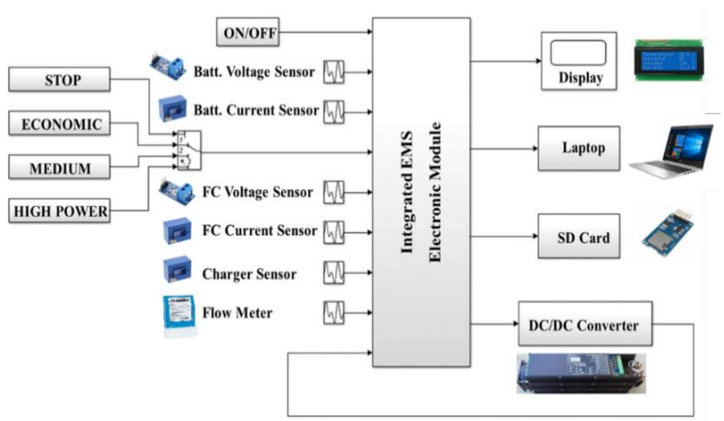


Figure 4-16. A simplified architecture block diagram of the integrated EMS electronic module for the FCAMR.

In this respect, from the controller module, the operator just needs to determine the working mode of the operation (Economic, Normal or High power) for more efficient performance. Depending on the determined working mode by the operator that depends on the working cycle features, the EMS would provide enough PEMFC output power to propel the vehicle beside of the battery pack. For the EMS, the battery pack is the major energy source to power the electric vehicle, while the PEMFC system gives the required power to propel the FCAMR and charge the battery. The RE system would be turned ON when the SOC of the battery is less than the given minimum threshold and shuts down when the SOC is above a predefined threshold. The vehicle status such as the operation mode, SOC, and voltage of the battery pack could be visible in the display unit. Finally, an electronic board could be designed for collecting the user commands and measuring the parameters into a portable computer or SD card by our research team at UQTR as prospective steps of this project. In this regard, a life cycle cost (LCC) analyzing results for the proposed PV/FCAMR platform is conducted in this study to find out whether a project is a wise investment which is discussed in the next section.

4.4 Life Cycle Cost (LCC) Assessment for the Off-Road Vehicles

It is possible to compare the LCC of understudy systems that can lead to a preferable design or powertrain configuration selection. The LCC assessment in this work contains three steps. First, a comparative LCC assessment between ERSAPHT and a similar (Class I) Internal Combustion Engine Tractor (ICET) was conducted. Then the result for comparing the PV/FCAMR project with the basic battery-powered AMR is discussed. Finally, a comparison result based on the Levelized Cost of Energy (LCE) assessments for the off-road agricultural vehicles is discussed to conclude the economical evaluations. It should be noted, there is much the uncertainty in projections about inflation and discount for upcoming years for each country. Therefore, in this study the inflation and discount rates considered the same amount as a constant value.

4.4.1 LCC Assessment of ERSAPHT vs. ICET

In this section, the life cycle cost of the ERSAPHT project is evaluated and the results are compared with an internal combustion engine tractor (ICET). Since EVs do not have many moving parts, their life span would be more than conventional off-road vehicles. Therefore, in this project, the ERSAPHT's life span is assumed to be 12 years. Consequently, the equivalent energy consumption method is used to compare the investigated case study systems. For instance, the PV system on the ERSAPHT consists of 6m^2 polycrystal solar panels with 14% cell efficiency and a 90% performance ratio [118]. Using the NREL website [98], the annual average solar energy data in Karaj (Iran), where the ERSAPHT project is performed, is estimated average as almost 6.32 kWh/m^2/day for April to September (the period that most agricultural operations are performed). The total lifetime collected energy (E_{PV}) by the PV array could be estimated by considering the available surface area (A) of the solar panels, module efficiency (η_{PV}), annual irradiance in the site (I), lifetime period (N) and performance ratio (PR), as indicated below:

$$E_{PV} = A \times \eta_{PV} \times I \times N \times PR = 16394\ kWh \tag{20}$$

Therefore, the total collected energy during the lifetime of the ERSAPHT was calculated as almost 16,394 kWh. The array's daily available energy is about 3.74 kWh which is delivered to an onboard 16.8 kWh Valve Regulated Lead Acid (VRLA) battery pack. Energy efficiency in this battery technology is approximately 86% [119]. The total energy from the grid to charge the battery pack for DoD = 80% of the battery pack is approximately 34,319 kWh during the ERSAPHT lifetime. Considering this energy efficiency, the daily energy of the PV system (3.74 kWh) and the battery energy (16.8 kWh), and the energy generated by the Biogen (4.4 kWh) the net daily available energy of ERSAPHT is up to 63.2 kWh for 10 hours working. In the case of Biogen for ERSAPHT, regarding the energy conversion aspect, a 0.33 kg/kWh fuel consumption is considered for the Biogen system based on the manufacturer data sheet (see Table 3-4). Therefore, the ERSAPHT consumes approximately 31.89 tons of purified biogas fuel over the comparison period of 12 years. Considering the total power of the ERSAPHT, it can be compared to many ''I-category'' ICE orchard tractors in the market. In this regard, the well-known John Deere 3320 [120] with a 32.8 HP diesel engine nominal power is chosen for comparison. Considering the

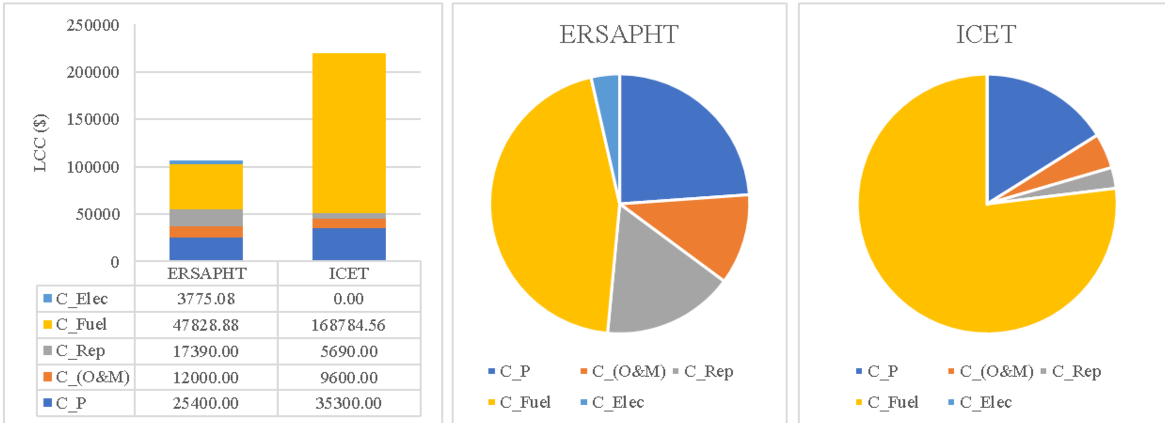
12,000 h wear-out life of a two-wheel drive tractor [121] this ICET would be replaced almost once in the comparison lifetime same as ERSAPHT.

Knowing that the ICET does not always run at full load, the 0.59 load factor is measured for diesel-powered farm tractors within the stated power range based on EPA reports [122]. Taking into account the ICET's full-load fuel consumption of 7.6 l/h and the load factor, the average fuel consumption is reduced to 4.48 l/h. Considering the diesel fuel density as 0.85 kg/L [123], fuel consumption rate becomes 3.8 kg/h. generally, diesel engines convert approximately 20.4% of fuel energy to useful flywheel work. If 2.2% of the total available power is consumed for running accessories, only 18.2% of fuel energy becomes accessible through the flywheel [123]. Regarding this ASABE [124] estimates an 82% transmission system efficiency for a typical agricultural tractor. Therefore, the ICET final fuel efficiency drops to 15%. Consequently, the ICET needs to consume 421.3 kW of fuel energy per day to produce 63.2 kW/day of net energy. With regards to the energy density of diesel fuel of 11.6 kWh/kg [123], the daily fuel consumption becomes at least 36.32 kg (42.7 L). By means of this amount of diesel fuel, the ICET can work up to 9.54 h every day and consume approximately 79.7 tons of diesel fuel over the comparison period of 12 years. Refueling also might cause some fuel wastes which might occur due to spillage and vaporization which is ignored here for the vehicles.

Regarding the maintenance cost for the ERSAPHT and ICET, the charge/discharge cycle of the battery pack at 85% DOD is about 700 times, based on the manufacturer data sheet [125]. Considering that the farm vehicles are operating for almost 6 months per year (April to September), continuously. Therefore, the battery pack needs to be replaced approximately every four years if daily charge/discharge cycles are applied during the working season. Considering a service life of 12-year lifetime, the battery packs should be replaced two times. Additionally, it is assumed that the tires and other degradable parts need to be replaced every four years one time [108], and each time it could be up to 10%. The ICE's regular services are considered to be almost 10% of the purchase cost of the vehicles [126] during the 12-year lifetime. Furthermore, the ICET and ERSAPHT salvage costs after 12 years can be estimated as 10% of their custom prices [108]. Accordingly, other detailed costs are ignored due to the lack of reliable data for specific agricultural off-road vehicles and to reduce redundant explanations.

On the other hand, diesel fuel price fluctuates daily these days, therefore the average price of diesel fuel for June of 2022 (almost 1.8 $/L in California) is considered a base for calculation [127]. Moreover, the LCC of compared systems was evaluated versus diesel fuel unit price. The values of inflation and discount rate for the systems are considered 10%. To calculate the energy cost, the hydrogen price assumed $16 per gasoline gallon equivalent (0.997 kg of H_2). Component costs are considered based on the 2020′ automotive FC system price defined by the US Department of Energy [128]. Battery cost is estimated using energy and power (e.g., $570 for a 24 Ah 24 Volt lead acid battery pack including charger). The FC system is calculated using cost calculations based on the peak power of the stack and capacity for the tank based on the assumptions used for the Fiscal Year 2018 fuel cell technology analysis [116].

Figure 4-17 shows the life cycle costs of the studied systems based on the contribution of the cost of each portion for the ERSAPHT and ICET. Results show that the fuel cost for the ICET is almost four times of the ERSAPHT which are equal to 168,785 and 47828 $, respectively. Since the battery pack needs to be replaced every four years, the replacement cost of ERSAPHT is three times that of ICET. Also, according to the graph, ICET maintenance costs are nearly 20% higher than ERSAPHT. Meanwhile, the electricity cost to charge the ERSAPHT's battery pack was about $3,775 over its 12-year lifetime. Overall, the total LCC of ICET is approximately two-times more than that of ERSAPHT for the lifetime comparison period. Details in Figure 4-17 (b) show that about 45%, 25%, and 10% of the LCC of ERSAPHT powertrains are related to biogas, initial, and component replacement costs. These results prove that by decreasing the price of renewable energy-based fuels in the future (possibly), there is an opportunity to reduce overall LCC for the ERSAPHT. On the other hand, for the ICET (Figure 4-17 (c)) the major portion (almost 75%) of LCC is related to the diesel fuel cost. However, if fuel prices are likely to increase in the future, the estimated fuel consumption cost may increase, probably.



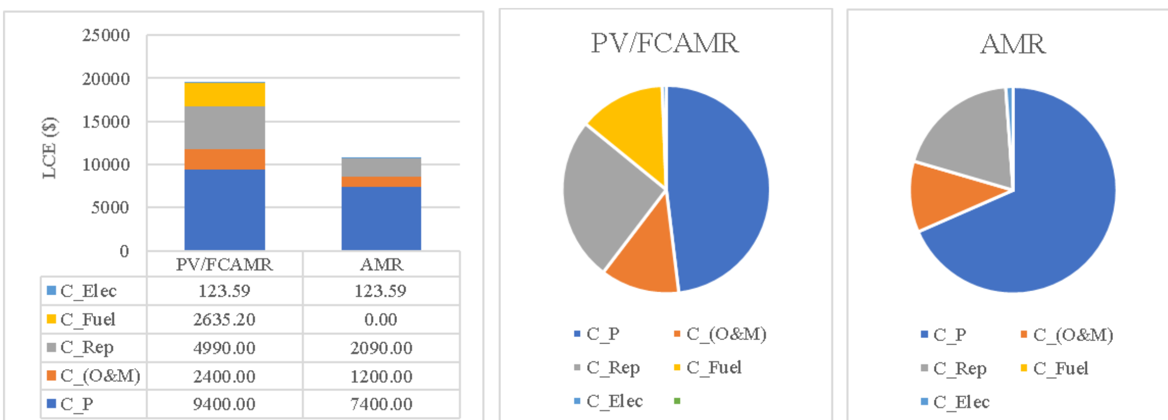
(a) (b) (c)

Figure 4-17. LCC of ERSAPHT compared to ICET; (a) total cost comparison of ERSAPHT vs. ICET, (b) ERSAPHT costs percentage for each portion, and (c) ICET costs percentage for each portion.

4.4.2 LCC Assessment of PV/FCAMR vs. Battery-Powered AMR

In the case of the PV/FCAMR, the 0.5 m^2 solar panel's daily energy production is about 80 Wh which is delivered to an onboard 570 Wh lead acid battery pack. Considering the battery energy efficiency (86%), the daily energy of the PV system, and the battery energy, the net daily electrical energy consumption of PV/FCAMR is about 0.692 kWh. The total electrical energy from the grid to charge the battery pack is approximately 1123.5 kWh during a 12-year lifetime of the PV/FCAMR. Considering the energy that could be generated by the FC system, battery pack, and PV system during a day, the total available energy for the PV/FCAMR is calculated up to 3.69 kWh/day which results in about 165 kg of H_2 consumption during the lifetime.

Figure 4-18 shows the LCC of PV/FCAMR compared to the AMR system based on the cost contribution of each portion. Neglecting the limited working range of the AMR results in Figure 4-18 (a) demonstrates that the PV/FCAMR powertrain costs around 8700$ more than the battery-powered AMR with almost 10800$ LCC during the almost 3 hours working range in 12 years of lifetime. In fact, this is because of the higher initial, replacement, maintenance, and, of course, hydrogen consumption costs in comparison. Interestingly, for both vehicles, the initial purchase cost was obtained as a major expense. However, the overall electrical energy consumption cost is estimated at approximately 124$ equally over a 12-year lifetime. Overall, the total LCC for AMR and PV/FCAMR systems are calculated at around 19549$ and -10814$, respectively. Detailed information in Figure 4-18 (b) show that approximately 48%, 26%, and 13% of LCC for PV/FCAMR powertrains are related to initial, component replacement, and fuel costs. Similarly, the pie chart in Figure 4-18 (c) indicates that around 70% and 20% of the overall LCC for the basic AMR system costs by the initial and component replacement expenses. These results indicate that there is an opportunity to reduce the total LCC of agricultural mobile robots by reducing the price of the battery packs and FC systems in the future. It should be noted, although from first glance it appears that the overall LCC for the battery-powered AMR is almost half of the PV/FCAMR. Multiple devices with the same functionality could result in different costs based on working hours and overall costs. Therefore, next section provides a comparison of studied agricultural vehicles based on LCE.



(a) (b) (c)

Figure 4-18. LCC of PV/FCAMR compared to AMR; (a) total cost comparison of PV/FCAMR vs. AMR, (b) PV/FCAMR costs based on the contribution of each portion, and (c) AMR costs based on the contribution of each portion.

4.4.3 LCE Assessment Between the Renewable Energy Based Powertrains and ICET

It is possible to make a comparison between the studied off-road vehicles based on equivalent energy consumption. Based on available daily onboard energy in the ERSAPHT it could provide about 3.29 times more working range and relatively energy compared to the basic pure electric system. It means without hiring the Biogen system we need to increase 3.29 times the battery capacity to have the same amount of working range. Another option is using three basic pure electric systems which will cause higher overall costs due to an increase in the other expenses such as battery replacement and components purchase costs as shown in Figure 4-19. However, the results show that by employing several pure electric tractors, the overall LCC still is less than using the diesel fuel ICET (almost 152300$ compared to 219370$, respectively).

In addition, bearing in mind the available energy for the PV/FCAMR is about 3.69 kWh/day from the battery pack, PV system, and FC system. This amount of energy is about 17.12 times less than the total onboard daily energy available for the ERSAPHT (63.2 kWh/day). Consequently, about 19,234.5 kWh of electrical energy, and 2819.7 kg of hydrogen fuel are required to provide the same amount of energy as ERSAPHT. Considering the energy density of hydrogen to 33.6 kWh of usable energy per kg the equivalent amount is almost 94742 kWh. As can be seen in Figure 4-19, for nowadays hydrogen, FC system, and battery prices, using several PV/FCAMR for doing the same amount of work compared to the ERSAPHT will cause a significant increase in the initial and replacement costs even higher than the ICET (almost 20% more). On the other hand, considering the 570 Wh lead acid battery of basic AMR with 86% energy efficiency, and minimum SOC of 20%, the total energy available for the pure electric powertrain is almost equal to 392 Wh. Therefore, the AMR needs to be about 161 times fully charged and discharged to provide 63.2 kWh. In other words, the capacity of the AMR's battery packs needs to be increased almost 161 times to provide the same amount of energy for doing the same work as the ERSAPHT which might cause more weight and need more space. In fact, another option would be using several AMRs with a bigger battery pack. It should be noted the battery packs need to be replaced almost every four years which will increase the overall price dramatically. Overall, it seems important to find a compromise between final system performance and overall cost using available technologies. In this respect, the use of green fuels such as biogas and biodiesel for powertrain hybridization in agricultural vehicles seems to be feasible.

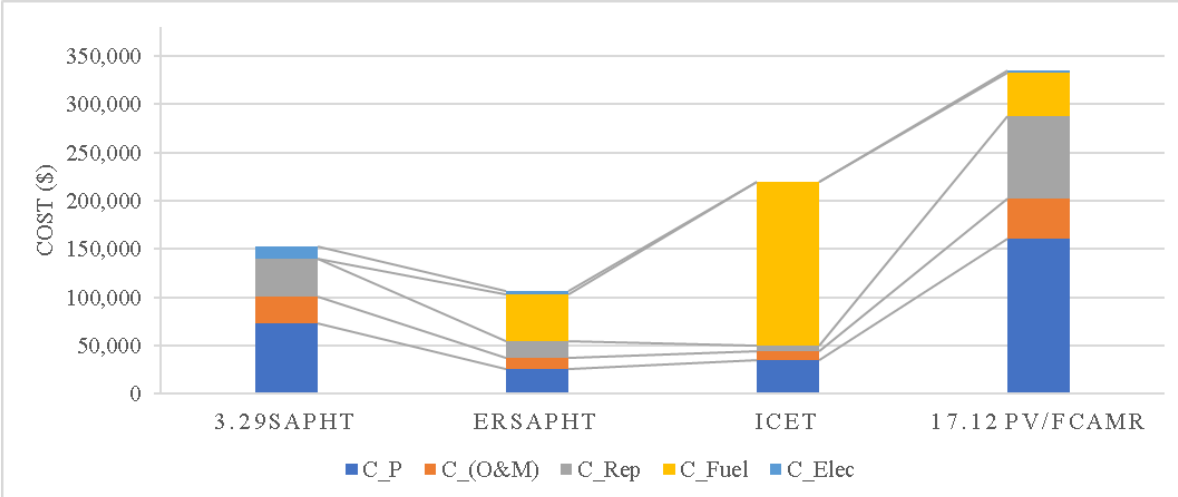


Figure 4-19. Levelized overall cost comparison of renewable energy-based powertrains versus ICET.

4.4.4 Levelized Cost of Energy (LCE) Assessment for the Off-Road Vehicles

As mentioned in section chapter 3, the Levelized Cost of Energy (LCE) is another parameter for comparison between systems with the same goal of powertrain electrification that is used in this study. To make comparison easier Figure 4-20 shows the LCE assessment results for the studied powertrain systems. This result illustrates that the LCE for the diesel ICET is almost 3.5 times the one of ERSAPHT at a discount rate of 10% which indicates the effectiveness of powertrain hybridization by using renewable energy-based downsized range extenders. In addition, the LCE results for the ERSAPHT powertrain represents almost 40% improvement compared to the basic pure electric system.

Surprisingly, the LCE comparisons result for the PV/FCAMR versus basic AMR shows a very significant improvement (almost sixfold) which might be due to many times charge/discharge energy losses of the only battery-powered system. However, the results for the PV/FCAMR powertrain shows a higher (2.77 times more LCE) in comparison with the ERSAPHT powertrain. Overall, the LCE results for the ERSAPHT powertrain show the highest level of energy economy among the vehicles studied.

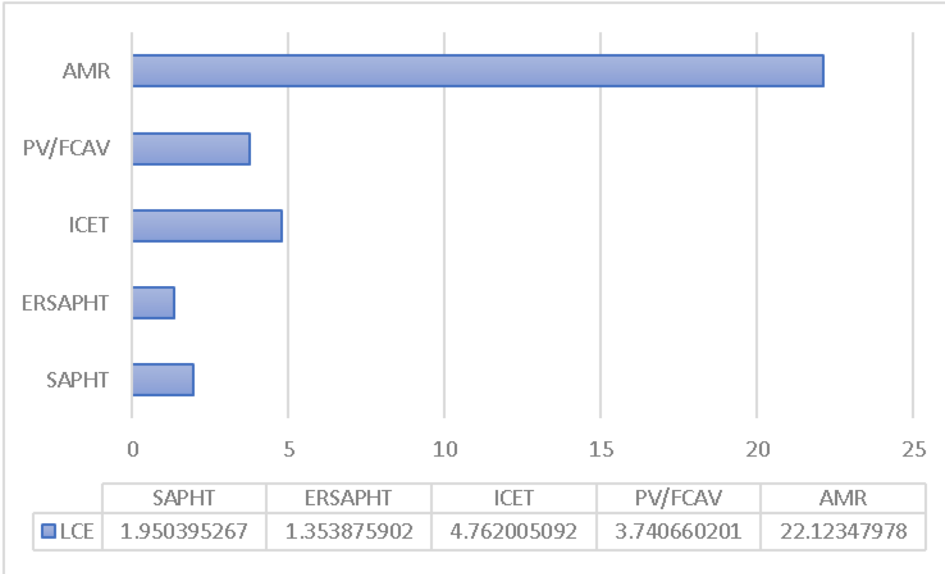


Figure 4-20. Levelized Cost of Energy (LCE) comparison of the agricultural off-road vehicles.

4.5 Summary

In this chapter, results related to the experimental tests, simulation and working range performance, and economic assessments of both studied off-road renewable energy-based hybrid electric vehicles for use in light agricultural operations were presented. As a necessary step in the design of such vehicles, several field tests were evaluated to hybridize the powertrain of these off-road vehicles, and therefore the following main results were obtained:

• Several typical duty cycles were considered as comparative scenarios to simulate and analyze vehicle performance. Average duty ranges for off-road vehicles were estimated based on typical duty cycles. Using the predetermined duty cycle, traction force, power, and energy requirements were estimated to size the appropriate range extenders and fuel tank capacity.

• The physical characteristics of the off-road vehicles were used to create a Simulink MATLAB model. This dynamic energy model was used to estimate the required energy and power. The results of the model evaluation showed that the developed Simulink model can estimate battery SOC and working range with acceptable accuracy (less than 5% error).

• Three energy management strategies namely charge sustaining (CS), charge depleting (CD), and charge blending (CB) modes designed to make an efficient power splitting between the onboard energy sources. In this regard, three working modes including economic, normal, and high-power mode was defined for EMS, to give the user options to choose a suitable working mode based on working conditions and battery charge levels. Then these modes are implemented in the EMS module of the ERSAPHT powertrain.

• A renewable energy-based range extender including a biogas engine generator (Biogen) was developed for agricultural tractor applications. In addition, a PEMFC system along with a photovoltaic system is designed for the agricultural mobile application. The results showed that the proposed downsized range extenders have acceptable performance in the vehicles.

• A method to evaluate the economic feasibility of studied agricultural off-road vehicles powertrain electrification using LCC analysis was developed. Feasible powertrain element prices were considered in the three different case studies including ERSAPHT, ICET, and PV/FCAMR. The LCC of the electric tractor and the diesel tractor is being assessed and the result shows that hybridized powertrains are less expensive in the long term. Moreover, the results related to the PV/FCAMR system revealed that by dropping the battery and FC technology prices, possibly in the future, the proposed powertrain could be a feasible architecture for agricultural mobile robots applications as an up-to-date alternative renewable hydrogen-powered off-road vehicles.

The results from the field tests evaluation of ERSAPHT showed that the developed off-road vehicle can perform light agricultural operations with minimal concerns about energy shortage. Also, due to providing the energy needed for this vehicle from available renewable resources on farms, it is possible to use this platform independently in remote areas far from the electricity network and fuel station. It is worth mentioning that this vehicle will be able to provide power for residential areas or agricultural buildings in emergency situations due to its independent operation. Therefore, in addition to providing electrical energy in emergency, it is possible to sell electricity to the grid when it is not used on the farm. As a result, this method could help to load distribution on the power grid and increase the farmer's income. It should be mentioned that since these projects were carried out as prototypes at the University of Tehran and the University of Quebec in Trois-Rivieres with minimal financial support, it was accompanied by many limitations. However, by introducing this platform based on renewable energy, we tried to present the best results to the scientific and agricultural community.

Chapter 5 - Conclusion and Future Works

Since the main environmental problems associated with the burning of fossil fuels, the vehicle industry has been in a period of the energy transition from fossil fuels to energy sources with low negative environmental impact. In all countries around the world like Canada and Iran, the usage of off-road vehicles for agricultural and industrial activities is high. In this way, using powertrain electrification and renewable energies in off-road vehicles such as agricultural applications seem to be potential solutions. However, pure electric vehicles are limited by current battery technology drawbacks such as long charging time and low energy density. To mitigate these challenges, different hybrid electric vehicle architectures have been suggested in the automobile industry to extend the vehicle range. Instead, powertrain electrification is still at an initial stage for off-road vehicle applications. However, variations in applications and powertrain structures of off-road agricultural vehicles such as tractors and AMRs have not received enough attention. Therefore, in the beginning, the idea was growing to study the feasibility of developing a renewable energy-based off-road HEV in agricultural applications.

In this research, a conceptual method is presented to design and develop of a renewable energy-based off-road hybrid electric vehicle-based to be used as an energy-independent agricultural vehicle. Accordingly, the first step is to conduct some experimental tests to extract vehicle parameters and typical working cycles based on customer needs. The next step was developing a Simulink model for the hybrid electric powertrain for components sizing and design of EMS. After that, it is possible to select and develop an appropriate renewable energy-based range extender system (RE) by considering the off-road vehicle's specific characteristics. Subsequently, the design and development of a heuristic EMS module need to be done. Finally, the integration and evaluation of the designed hybrid electric powertrain for the agricultural off-road vehicle could be done to ensure the proper performance and functionality of the system. It is noteworthy that all the steps mentioned are evaluated with the design, development, and evaluation of an off-road renewable energy-based hybrid electric tractor (ERSAPHT) with the support of field experiments and economical evaluation. In addition, to highlight the strength of the proposed method, a photovoltaic/fuel cell agricultural mobile robot (PV/FCAMR) is designed and evaluated as a second case study.

Due to the difference in some aspects such as working cycles and components of the studied off-road vehicles, a detailed conclusion for each application is summarized in the following sections. The results from different parts of this work can be categorized in three sections in accordance with the goals set that are including performance evaluation of the ERSAPHT, PV/FCAMR, and their economic assessment. More details about the results of extraction of the typical working cycles, the performance evaluation of the proposed range extenders, the EMS system, and the economic evaluation of each off-road agricultural vehicle are explained in the following sections, and some suggestions are made for future research.

5.1 Conclusion for the Extended Range Solar Assist Plug-In Hybrid Electric Tractor (ERSAPHT)

The first part of this work introduces the process of working cycle derivation, modeling, designing the Biogen system, implementation of EMS, and evaluation of the ERSAPHT, which is meant to be used in agricultural light applications as an independent renewable energy-based off-road vehicle. In this regard, several experiments on working cycles were defined and conducted in the field to derive typical farm working cycles. Moreover, the developed MATLAB Simulink model was involved to perform feasibility studies to develop the RE and EMS before construction. Furthermore, an EMS circuity was developed to implement the heuristic energy management strategy according to the required power and SOC. Finally, the experimental and simulation finding results showed that:

- The average power required in the trailer, sprayer, and water pump cycles were 8.63, 6.96, and 4.24 kW, respectively. These results showed that the trailer cycle needed the highest power among the measured cycles. The average speed in the trailer and spraying working cycles were obtained around 12.36 and 6.24 km/h, respectively. In fact, the higher speed range and weight in the trailer work cycle were the main reason to request more power.

- Based on the results obtained from the 1800 seconds of the test, the required energy in the trailer, sprayer, and water pump working cycles were approximately 4.11, 3.04, and 2.20 kWh, correspondingly. These results confirmed the direct relationship between the required energy and the requested power. More detailed results showed that about 74% of the energy consumption during the sprayer working cycle was spent on tractor movement on the field. In fact, about 26% of the energy was consumed by the PTO power transmission system. Hence, reducing tractor losses is of great importance. Therefore, in stationary operations such as water pumping which use the PTO system, an electric propeller can reduce energy losses.

- Since the EREV configuration was identified as suitable for agricultural off-road electric vehicles, it was possible to choose a downsized range extender. Therefore, based on the required energy and power during the measured working cycles, a 4.4 kW biogas engine/generator set was developed to charge the battery pack with the help of a photovoltaic system. Results of field experiments showed that consumption of biogas during trailers and sprayer working cycles is about 750 and 160 grams in 1500 and 320 seconds by the developed RE system, respectively. Consequently, the fuel consumption in the trailer, sprayer, and water pump work cycles were calculated at about 5.32, 9.32 and 14.88 kg/day, respectively. Therefore, a 15 kg fuel tank seems to be suitable for the RE system.

- The performance evaluation results based on the experiments showed that the ERSAPHT working range was increased up to 3.41, 6.11, and 14.6 hours for the trailer, sprayer and water pump, up to 230, 337, 483% compared to the base system, respectively. Also, the results of the energy evaluation showed that the photovoltaic system was able to supply approximately 5.87%, 7.8%, and 8.09% of the total energy consumed in the trailer, sprayer, and water pump working cycles, respectively.

In conclusion, these results showed that the developed hybrid electric powertrain has an acceptable performance in the tested working cycles. In fact, the ERSAPHT by use of a 4.4 kW biogas engine generator and a 600 W photovoltaic system can provide the required energy to perform light-duty agricultural works without charge anxiety about the lack of energy compared to conventional tractors using diesel-fueled ICE with tens of kWh power.

Also, in case of access to biogas fuel infrastructure on the farm, the ERSAPHT will be able to operate as an energy-independent renewable energy-based hybrid electric vehicle without the need for any fossil fuel and grid power. As an additional capability, this vehicle can supply electrical energy to residential units and agricultural buildings in emergencies or in remote areas where they are far from the electricity grid. The ERSAPHT can also help to increase farmers' income by the sale of electricity to the local network as an electrical energy supplier of a local network.

5.2 Conclusion for the Photovoltaic/ Fuel Cell Agricultural Mobile Robot (PV/FCAMR)

As a second case study, a feasibility study of a PV/FCAMR vehicle has been conducted to highlight the accuracy of the proposed off-road hybrid electric vehicle design and development process. This differential drive mobile robot is meant to be used in agricultural light applications such as plants phenotyping and field mapping as a renewable energy-based off-road vehicle by use of the photovoltaic system and green hydrogen. In this regard, several experiments including rectangular pattern and circular pattern working cycles have been conducted on a test bench. Moreover, the developed MATLAB Simulink model was modified to perform feasibility studies to develop the RE and EMS before construction. Experimental and simulation finding results showed that:

- The average speed in the rectangular movement pattern and circular movement pattern cycles were obtained around 0.56 and 0.43 m/s, respectively. Accordingly, the average power required in the rectangular movement pattern, and circular movement pattern cycles were obtained at 136 W and 139 W. These results demonstrate higher energy consumption of 8,855 kJ/h in the circular movement pattern compared with 6,793 kJ/h in the rectangular movement pattern. In fact, the more rotational movement and several accelerations and deceleration conditions in the circular movement pattern was the main reason to consume more energy. More detailed results showed that about 5% of the energy consumption during the cycles was spent on rotational movement on the field. Hence, reducing energy losses is of great importance for mobile robots' path planning, this issue should be considered with programming the autonomous movement of such kinds of vehicles.

- The results of the model evaluation showed that the developed Simulink model was capable of estimating the battery SOC and working range with acceptable accuracy (less than 5% error).

- Since the EREV configuration due to its modularity and other mentioned advantages was identified as suitable for agricultural hybrid electric mobile robots, it was possible to choose a downsized range extender such as PEMFC. Therefore, based on the required energy and power during the measured working cycles, a 300 W PEMFC set was selected to charge the battery pack with the help of an 80 W photovoltaic system. Simulation results based on experimental data showed that hydrogen consumption during the mixed movement pattern working cycle is about +55 g in 10 hours of the working day, respectively. Consequently, a metal hybrid hydrogen tank with a capacity of 150 g at 300 bar pressure seems to be suitable for the PV/FCAMR system which allows extending the autonomy up to 15 hours.

- In addition, the impact of the EMS strategy and battery degradation level on the FCAMR performance to operate for an entire 8h shift time is studied. Each EMS mode is investigated by considering three battery degradation levels (0, 750, and 1500 charge and discharge cycles) in 80% DoD. The simulation result illustrates a difference of around 25% in hydrogen consumption between the CS and CB modes. Therefore, to increase the system efficiency and to reduce hydrogen consumption, it is better to consider an EMS that uses the FC at its maximum efficiency similar to CB mode instead of using the FC at its maximum power as CS and CD modes. Moreover, results show that battery degradation has affected the capabilities of the EMS as well as vehicle performance by reducing the ESS capacity. To summarize, the FC and hydrogen tank sizing of the hybrid AMR strongly depend on the EMS and the desired autonomy. It is also important to consider the degradation of power sources and the maximum load that can be transported by the AMR during the FC and hydrogen tank sizing.

- The performance evaluation results for the suggested powertrain architecture extend the autonomy of the basic pure electric system by 350% as opposed to the pure electric system, which allows for making at least 7 hours more work with a hydrogen tank filled with

0.15 kg hydrogen. This allows the vehicle to run for more than 10 hours a day with the typical working cycle without charge anxiety. Besides, a PV system can extend the vehicle range by up to 5% and reduce fuel consumption costs by 7% compared to energy storage systems without PV.

These results are favorable and approve the aim of the arrangement to extend the autonomy of the vehicle with satisfactory performance under the tested situations so that it can work an entire day. In fact, the PV/FCAMR by use of a 300 W PEMFC set and an 80-Wh photovoltaic system incorporation of a 25 Ah lead acid battery pack, can provide the required energy to perform light-duty agricultural data acquisition without needing to charge the vehicle during the working day. In conclusion, these results showed that the developed hybrid electric powertrain could have acceptable performance in the tested working cycles. Also, in case of access to green hydrogen infrastructure on the farm, the PV/FCAMR will be able to operate as an energy-independent renewable energy-based hybrid electric vehicle without the need for any fossil fuel and grid power. In fact, this system is a primary test bed for future research of the hybrid FCAMR in various applications such as seeding, spraying, and plants phenotyping.

5.3 Economic Evaluation of the Agricultural Off-Road Electric Vehicles

The Life Cycle Cost (LCC) and Levelized Cost of Energy (LCE) assessments were conducted for the ERSAPHT and PV/FCAMR systems in comparison with other related agricultural vehicles in a 12-year lifetime. Comparison results of the LCC and LCE of the systems revealed that the ERSAPHT powertrain has the lowest cost than that of other configurations at the current level of technology and energy prices. Moreover, evaluation of LCC showed that the pure electric systems in degradable components replacement have more cost than others due to the battery pack and FC stack lifetime. Therefore, decreasing batteries and FC technology prices could lead to more differences between LCCs of electrified powertrain with the conventional diesel ICET. Furthermore, it is concluded that decreasing renewable energy-based fuel price could result in differences in the LCE for hybridized powertrains than that of the ERSAPHT and PV/FCAMR. Overall, fossil fuel availability itself becomes an important parameter for comparing renewable energy-based and fossil fuel-based systems. The depletion of fossil fuel resources is inevitable and rising prices will make projects such as ERSAPHT and PV/FCAMR more feasible. However, the non-renewable resource will not be recovered even if the price increases. Adding the PV system to the energy system increases the initial cost of the PV/FCAMR, but slightly decreases the FC and battery pack size parameters.

Although the feasibility study results showed that there are no major technological hurdles to meet performance requirements for hybrid electric powertrains in the autonomous off-road agricultural vehicles, economical assessment results reveal that there are still some challenges such as high price, durability, the lake of infrastructure is the main obstacle for this kind of vehicle. Therefore, it is expected that by reducing the price of batteries, fuel cells and green hydrogen production technologies in the future, it will be possible to use these types of vehicles to tackle the challenges facing the agriculture sector.

5.4 Suggestions for Future Research Work

Although the results of the experimental evaluation in this study confirmed the acceptable performance of the renewable energy-based off-road vehicles as the goal of this research work, some suggestions are mentioned for future research as follows:

1. Since these off-road agricultural hybrid electric vehicles are initial prototype systems, although the life cycle cost (LCC) assessment has been done in this work, it is suggested that the environmental life cycle assessment of the developed systems be considered compared to the conventional tractors for mass production.
2. Conducting an Exergetic study of the ERSAPHT and PV/FCAMR powertrains to analyze the performance of each section. It is noteworthy that excessive analysis requires precise measurement of energy consumption parameters in different parts of the device. Therefore, given the required assignment, it can be reviewed as independent research work.
3. Improves some of the mechanisms used in the base system to achieve a more efficient powertrain system. For example, the development of an energy recovery system for braking and PTO mechanisms. By applying this method, it is possible to increase the

energy efficiency of the devices. However, due to the low speed of motion and the complexity of the energy recovery systems, it was ignored in the base systems.

4. In addition, several off-road agricultural mobile robots and agricultural electric tractors could collaborate together to do the same task which might increase overall system efficiency. Moreover, it is suggested to study the possibility of use of other cutting-edge technologies such as advanced network communication (e.g., 5G and 6G), artificial intelligence techniques, vehicle-to-vehicle (V2V) connection, and internet of things (IoT) in conjunction with hybrid electric powertrain configuration to tackle with labor shortage issue to increase the overall efficiency of modern farms.

5. In the case of PV/FCAMR, the proposed system is still in the prototyping stage. Although the optimization method used for component sizing and hybrid system designing, an investigation of the main energy supply components degradation including battery and FC systems on the long-term performance of the developed system could be done in the future. This method requires long-term measurements of different parameters of the components such as battery and FC parameters which are not usually available in the literature.

6. In the case of the ERSAPHT powertrain, an intelligent energy management strategy for an off-road plug-in hybrid electric tractor based on farm operation recognition is suggested to achieve an automated control strategy. It is noteworthy that the basis of that EMS was raised as a part of this work, and only because the implementation of that kind of EMS was time and budget consuming. Therefore, it can be implemented and evaluated as a future works.

7. The suggested design process used in this work should be used to design and develop other types of off-road hybrid electric propulsion systems with special applications. It is suggested to use a modular design method for these types of vehicles to make the system more flexible for adapting to new applications, especially in small vehicles such as agricultural mobile robots. In addition, some parts could be produced by the use of 3D printing in order to decrease prices.

8. Studying the effects of ERSAPHT as a network-connected vehicle to rural areas and analyzing its benefits of power distribution for local power supply networks.

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Appendix A –The Main Components Parameters of the ERSAPHT

Table Appendix -1. The main components parameters of the SAPHT [89].

Parameter	Symbol	Value
Gear ratio efficiency	η_g	90%
Gear ratio	G	18.66
Battery cycle efficiency	$\eta_{Bat.}$	83%
Front area	A	1.8 m^2
Aerodynamic drag coefficient	C_d	0.2 to 0.4
Rolling resistance coefficient	C_{roll}	
Asphalt		0.029
Sand road		0.03 to 0.05
No-tilled field		0.04 to 0.065
Tilled field (harrow and cultivator)		0.09 to 0.16
Drive tire radius	r	0.55 m
Air density	ρ	1.25 kg m^{-3}
Gravity acceleration	g	9.80 m/s^2
SAPHT total mass	m	2100 kg
Moment of inertia for motor's rotor	I	0.3 kg m^2
PV system maximum power	P_{PV}	600 w
PV system efficiency	η_{PV}	90%
Motor efficiency	η_m	90%
SAPHT overall efficiency	η_{SAPHT}	62%

Appendix B –The PV/FCAMR's Main Components Parameters

Table Appendix.2. The main components specifications of the AMR.

Specification	Symbol	Value
Vehicle total mass	m	90 kg
Frontal area	A	0.7 m^2
Aerodynamic drag coefficient	C_{air}	0.45
Air density	ρ	1.225 kg/m^3
Wheel Radius (R)	R	0.096 m
Wheelbase	L	0.75 m
Rolling resistance coefficient	C_{roll}	0.1
Gearbox ratio	$\xi_j 0$	16
Moment of inertia for motor's rotor	I	0.3 kg m2
Gravity acceleration	g	9.81 m/s^2

Appendix C. Thesis achievements

https://scholar.google.com/citations?user=h-2rWy4AAAAJ&hl=en

Publications:

1. Ghobadpour, A., Cardenas, A., Monsalve, G., & Mousazadeh, H. (2023). **Optimal Design of Energy Sources for a Photovoltaic/Fuel Cell Extended Range Agricultural Mobile Robot**, Robotics 12 (1), 13.
2. Ghobadpour, A., Monsalve, G., Cardenas, A., & Mousazadeh, H. (2022). **Off-Road Electric Vehicles and Autonomous Robots in Agricultural Sector: Trends, Challenges, and Opportunities**. Vehicles, 4(3), 843–864.
3. Ghobadpour, A., Mousazadeh, H., Malvajerdi, A. S., & Rafiee, S. (2020). **Design, Development, and Evaluation of a PV_Biogen Range Extender for an Off-Road Electric Tractor**. International Journal of Renewable Energy Research (IJRER), 10(1), 388–399.
4. Ghobadpour, A., Boulon, L., Mousazadeh, H., Malvajerdi, A. S., & Rafiee, S. (2019). **State of the art of autonomous agricultural off-road vehicles driven by renewable energy systems**. Energy Procedia, 162, 4–13.
5. Ghobadpour, A., Mousazadeh, H., Kelouwani, S., Zioui, N., Kandidayeni, M., & Boulon, L. (2021). **An intelligent energy management strategy for an off-road plug-in hybrid electric tractor based on farm operation recognition**. *IET Electrical Systems in Transportation*, *11*(4), 333–347.
6. Ghobadpour, A., Amamou, A., Kelouwani, S., Zioui, N., & Zeghmi, L. (2020). **Impact of powertrain components size and degradation level on the energy management of a hybrid industrial self-guided vehicle**. Energies, 13(19), 5041.
7. Ghobadpour, A., Kelouwani, S., Amamou, A., Agbossou, K., & Zioui, N. (2019, October). **A Brief Review of Plug-In Hybrid Electric Vehicles Operation in Cold Climates**. In 2019 IEEE Vehicle Power and Propulsion Conference (VPPC) (pp. 1–5). IEEE.
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Appendix D – Off-Road Electric Vehicles and Autonomous Robots in Agricultural Sector: Trends, Challenges, and Opportunities

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Review

Off-Road Electric Vehicles and Autonomous Robots in Agricultural Sector: Trends, Challenges, and Opportunities

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Abstract: This paper describes the development trends and prospects of green-energy-based off-road electric vehicles and robots in the agricultural sector. Today, the agriculture sector faces several challenges, such as population growth, increasing energy demands, labor shortages, and global warming. Increases in energy demand cause many challenges worldwide; therefore, many methods are suggested to achieve energy independence from fossil fuels and reduce emissions. From a long-term point of view, the electrification of agricultural vehicles and renewable energy sources appear to be an essential step for robotic and smart farming in Agriculture 5.0. The trend of technological growth using fully autonomous robots in the agricultural sector seems to be one of the emerging technologies to tackle the increased demand for food and address environmental issues. The development of electric vehicles, alternative green fuels, and more energy-efficient technologies such as hybrid electric, robotic, and autonomous vehicles is increasing and improving work quality and operator comfort. Furthermore, related digital technologies such as advanced network communication, artificial intelligence techniques, and blockchain are discussed to understand the challenges and opportunities in industry and research.

Keywords: agricultural autonomous vehicles; digital agriculture; electric tractors; sustainability; hybrid electric powertrain; smart farming; robotics

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1. Introduction

Today, the agricultural industry faces serious challenges such as population growth, the energy crisis, climate change, a shortage of labor, and the risk of pandemic diseases. The population is projected to increase from 7.9 billion in 2022 to 10 billion in 2050, and agricultural production is expected to continue to rise [1]. Meanwhile, agricultural workers are being drawn to other industries, and the average age of farmers is increasing [2], which

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Appendix E – An intelligent energy management strategy for an off-road plug-in hybrid electric tractor based on farm operation recognition

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ORIGINAL RESEARCH PAPER

An intelligent energy management strategy for an off-road plug-in hybrid electric tractor based on farm operation recognition

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Abstract

Due to the growing emergence of vehicle electrification, agricultural tractor developers are launching hybrid powertrains in which energy management strategy (EMS) assumes a prominent role. This work mainly aims at developing an EMS for a plug-in hybrid electric tractor (PHET) to minimise fuel consumption and increase the operating range. The developed off-road PHET power sources are composed of a biogas-fuelled Internal Combustion Engine Generator (Bio-Gen), a photovoltaic system, and a battery pack. To control the power flow among different sources, a two-layer EMS is formulated. In this regard, initially, the farm operating mode is recognised by means of classification of a working cycle's features. Then, a control strategy based on a multi-mode fuzzy logic controller (MFLC) is employed to manage the power flow. At each sequence, the classifier identifies the farm operation condition and accordingly activates the relative mode of the MFLC to meet the requested power from the Bio-Gen. The performance of the proposed EMS has been evaluated based on three real-world typical agricultural working cycles. The results demonstrate the successful performance of the proposed intelligent EMS under farm conditions by maintaining the energy sources' operation in a high-efficiency zone which can lead to the extension of the working range and decrease fuel consumption.

1 | INTRODUCTION

Reducing environmental impacts and dependency on fossil fuels are considered important issues by energy policies around the world [1, 2]. Stricter environmental protection regulations, such as the European Stage V non-road emission standards [3], tighten the emission level in off-road vehicles, such as agricultural tractors and mining vehicles, which use internal combustion engines (ICEs) and have a significant share in the pollution [4]. Regarding the literature, powertrain electrification helps to increase overall vehicle efficiency and reduce exhausting emissions. Moreover, it can increase the controllability, reliability, and comfort in agricultural tractors [5]. In this regard, powertrain electrification seems to be a potential solution for the progress of the agriculture fourth revolution [5, 6]. One of the common technological solutions is to use pure electric vehicles. However, they suffer from long recharging time and low driving range limits. These limitations would be more drastic in off-road vehicles, which require more energy for travelling and doing some tasks in a short time [7]. In order to mitigate these shortcomings, several hybrid powertrains have been developed in the automotive industry [8]. Moreover, some research studies have been conducted in construction equipment and mining trucks' powertrain hybridisation. However, other kinds of off-road vehicles have not received enough attention [9, 10]. Among various hybrid electric configurations, a plug-in hybrid electric vehicle (PHEV) can be a suitable configuration for reducing fuel consumption because it can be charged by external electric power sources like renewable power plants [11]. Also, for a working range longer than the pure-electric working range, it is more economical to use a blended mode (ICE and battery together) than operating the vehicle as a battery electric vehicle [12, 13].

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Appendix F – Optimal Design of Energy Sources for a Photovoltaic/Fuel Cell Extended Range Agricultural Mobile Robot.

Optimal Design of Energy Sources for a Photovoltaic/Fuel Cell Extended Range Agricultural Mobile Robot

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ABSTRACT

This article analyzes the energy behaviour of a Fuel Cell Agricultural Mobile Robot (FCAMR) as the preliminary step or the development of a photovoltaic/fuel cell hybrid electric vehicle in the agriculture 5.0 concept. The proposed concept includes three energy storage sources to drive the powertrain; a battery pack, a hydrogen Polymer Electrolyte Membrane Fuel Cell (PEMFC) system, and a Photovoltaic (PV) system. This paper proposes an approach based on Grey Wolf optimisation (GWO) and Particle Swarm Optimisation (PSO) algorithms to determine the optimal sizes of the FC and battery of an FCAMR. A differential drive mobile robot is used as a case study to extract typical working cycles of farming applications. The FCAMR vehicle model was developed in MATLAB/Simulink to evaluate vehicle energy consumption and performance. For the energy analysis and evaluation, the FCAMR is tested based on two realistic working cycles comprising circular and rectangular moving patterns. Results show that the proposed arrangement could extend the FCAMR autonomy by 350% as opposed to the pure electric system. This allows for at least 8 hours of work with a tank filled with 150 g hydrogen and a PV system with a $0.5m^2$ monocrystalline solar panel. Simulation results have demonstrated the relevance and robustness of this approach in relation to various working cycles. Cost comparison between the theoretical and optimisation sizing methods showed at least an 8% decrease about FCAMR. Also, adding the PV system extend the vehicle range by up to 5%.

1. Introduction

Today, the world's population is growing increasingly, and it is becoming around 8 billion (Despoudi et al., 2021). At the same time, the demand for food and agricultural products continues to increase as living standards improve. Meanwhile, the increase in urban population and the decrease in the agricultural population have also promoted the development and application of new agricultural machinery due to labour shortage issues. On the other hand, the agriculture section faces several challenges, such as increasing energy demand, greenhouse gas emissions, and the effects of global warming (Rahman et al., 2022). Therefore, farm machinery of the future must be completely redesigned compared to today's technology. It should be modular with exchangeable equipment integrated into the machine, autonomous and lightweight. Thus, several small vehicles can operate in the field simultaneously, working continuously 24 hours a day, automatically changing equipment and batteries/refuelling when needed (Ghobadpour et al., 2022).

The development of agricultural robot technology is an inevitable requirement for agriculture to find solutions to challenges related to labour shortage, precision control, farm work convenience, and green operation. Such challenges are difficult to solve with conventional agricultural machinery, which has an important carbon footprint (Ghalazman E. et al., 2022). As a result of the research efforts, several robotic solutions such as monitoring (Kim et al., 2022), mapping (Gai et al., 2021), crop and pest managing (Vibhute et al., 2021), environmental control (Huang et al., 2021), and planting (Raj et al.). For example, BoniRob (Ruckelshausen et al., 2009) was originally developed for plant phenotyping and mapping in the field. The Hortibot (Jorgensen et al., 2007) is a robotic tool carrier for high-tech plant care. In addition, Vibro Crop Robotti (Green et al., 2014) can also perform field work such as mechanical weeding and precision seeding. We mentioned only some examples, but many more projects of mobile agriculture platforms have been started worldwide. However, most of them are unsuccessful in their mission due to battery limitations and energy shortages.

The main drawback of conventional agricultural machines