ENGINEERING PERSPECTIVE

CONTENTS

Review Articles **Page Number**

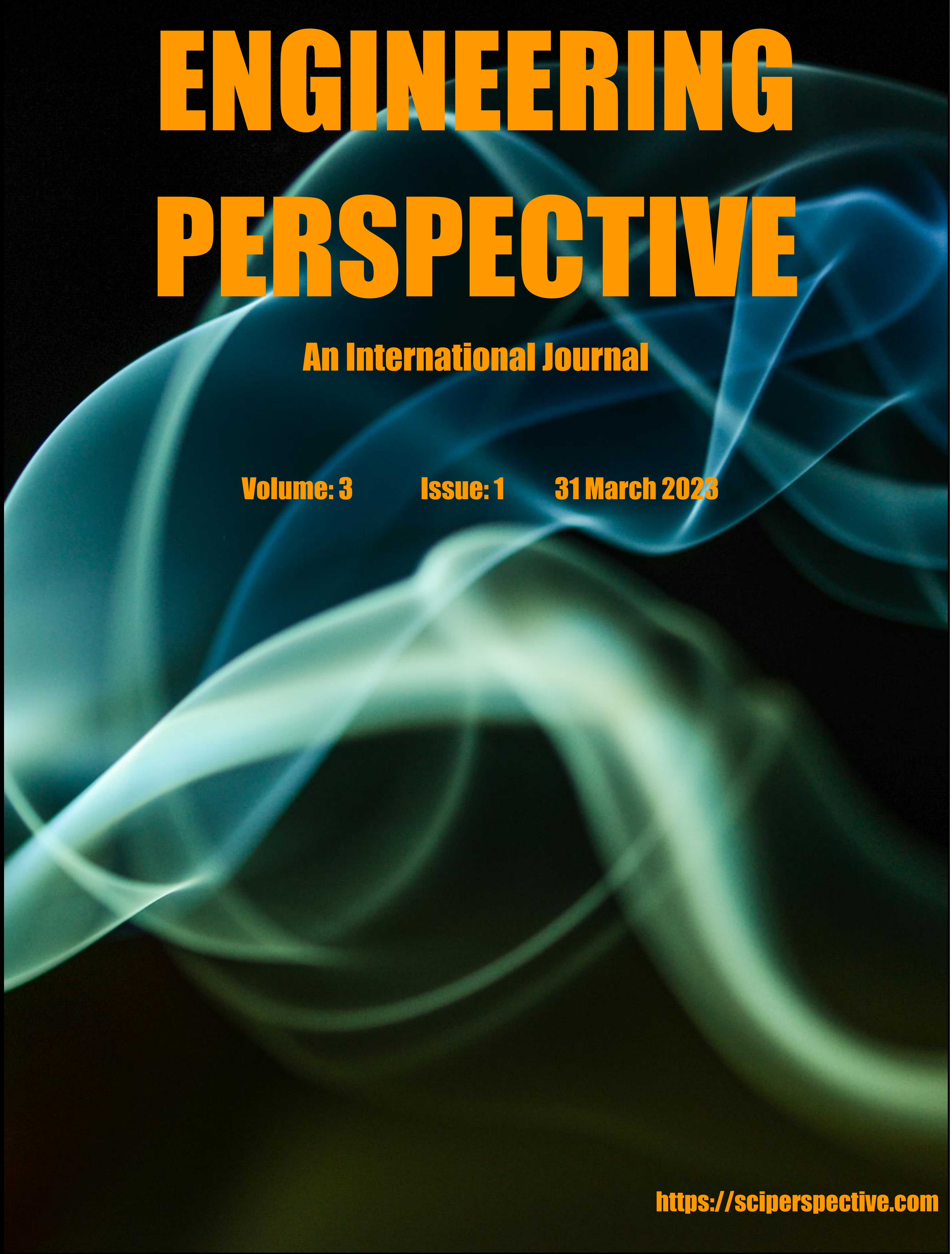
Tolga KOCAKULAK, Turan Alp ARSLAN
Investigation of the Use of Fuel Cell Hybrid Systems for Different Purposes 1-8

Research Articles

Sai Venkata Phanindra Chary ARENDRA, Vijay Sai Goud POLAGOWNİ
Evaluation of Electrification of 4W Light Commercial Vehicle 9-17

ENGINEERING PERSPECTIVE Volume: 3 Issue: 1 31 March 2023

e-ISSN: 2757-9077 Open Access



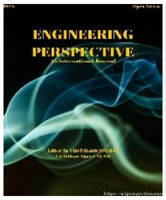
ENGINEERING PERSPECTIVE

An International Journal

Volume: 3 Issue: 1 31 March 2023

https://sciperspective.com

Engineering Perspective 3 (1): 1-8, 2023



e-ISSN:2757-9077

ENGINEERING PERSPECTIVE

https://sciperspective.com/

Review Paper

Investigation of the Use of Fuel Cell Hybrid Systems for Different Purposes

Tolga Kocakulak[1*], Turan Alp Arslan[2]

[1] *Vocational School of Technical Sciences, Burdur Mehmet Akif Ersoy University, Burdur, 15100, Turkey*
[2] *Automotive Engineering Department, Faculty of Technology, Afyon Kocatepe University, Afyonkarahisar, 03200, Turkey*

ABSTRACT

With the increase in global energy demand, air pollution becoming uncontrollable does not fall off the agenda. It is inevitable to use and spread of renewable energy sources to make energy production cleaner, more reliable and sustainable. In studies for this purpose, the use of fuel cell systems comes to the forefront thanks to its many advantages. The use of hybrid systems is becoming more common day by day in order to minimize the efficiency losses that may occur in the energy production, use and waste management process, to ensure energy reliability and to prevent systemic problems. In this study, hybrid systems created with fuel cells are discussed in detail, and examined under three main headings: hybrid systems created with renewable energy sources, created with storage devices, and created for energy recovery. It has been observed that the main purpose of hybrid systems created with renewable energy sources is to ensure energy reliability. In addition, the electrical energy required for the electrolysis of hydrogen used as fuel in fuel cells can be provided by photovoltaic panels or wind turbines, thus eliminating fuel storage and transportation problems. In hybrid systems created with storage devices, it is aimed to prevent instantaneous interruptions in the system by meeting the instantaneous power needed by the system and successful results have been achieved. In the hybrid systems created for energy recovery, it has been seen that it is possible to recover the heat and unburned fuel energy released from the fuel cell with thermophotovoltaic cells, gas turbines and heat exchangers.

Keywords: Efficincy, Fuel Cell, Hybrid System, Hydrogen, Renewable Energy

History
Received: 04.11.2022
Accepted: 17.02.2023

http://dx.doi.org/10.5281/zenodo.7820933

Author Contacts
**Corresponding Author*
e-mail addresses : tkocakulak@mehmetakif.edu.tr*, talparslan@aku.edu.tr
Orcid numbers : 0000-0002-1269-6370, 0000-0003-3259-4854

1. Introduction

It is observed that the energy crisis and greenhouse effects are increasing day by day. Therefore, the use and spread of renewable energy systems is inevitable for cleaner, more reliable and sustainable energy production [1]. Wind, solar, biomass and fuel cells are at the forefront of renewable energy sources and systems [2]. Renewable energy sources have advantages and disadvantages compared to each other. Solar panels and wind turbines are among the widely preferred renewable energy sources today thanks to their high energy efficiency, no fuel costs and low maintenance costs. However, the energy produced by these systems may vary depending on seasonal and climatic changes and interruptions may occur. In addition, it is difficult to use in mobile applications due to its low power density.

Fuel cell systems are of interest in studies on the use and spread of renewable energy sources. Fuel cells are systems that convert fuel directly into electrical energy using electrochemical methods. With the advancement of technology, the use of these systems, which have many advantages, is becoming more common day by day. Some advantages of fuel cell systems can be listed as high energy density, near-zero CO2 emissions, silence and uninterrupted operation [1,3]. It is possible to use fuel cells in military devices, portable electronic devices, uninterrupted power systems, hybrid electric vehicles, airplanes, submarines and space vehicles [4]. After electricity production in fuel cells, water and heat are released as waste. Fuel cells are divided into three main groups according to their operating temperatures: fuel cells operating at low, medium and high temperatures. Although the heat released from fuel cell systems operating at high temperatures causes a decrease in fuel cell efficiency, it is possible to recover this heat.

Integrated hybrid systems have been developed to take advantage of renewable energy systems and minimize their disadvantages. The most basic criteria in the development of hybrid systems are to increase energy reliability and reduce costs and emission values [5,6]. The use of hybrid energy systems in off-grid, on-grid and mobile applications offers many advantages. Devices, machines and systems with the potential to create hybrid systems are shown in Figure 1 [2]. Biomass, photovoltaic panels, wind turbine, micro hydroelectric power plants, fuel cells, super capacitors and batteries are used in the creation of hybrid systems with renewable energy systems [5,6].

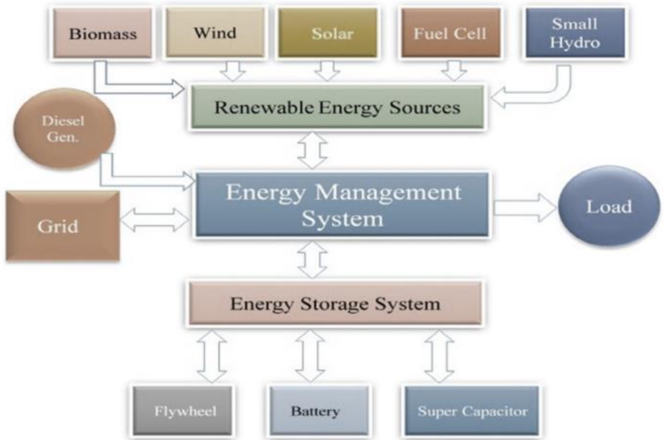


Figure 1. Hybrid renewable energy system [2]

There are many technologies and systems that can convert different primary energy sources into electrical energy and heat. A few-step processes are carried out until the desired energy form is achieved. In the production of electrical energy with fuel cells, heat release as waste is also inevitable. This heat energy can be recovered as electrical energy with various recycling systems [7].

In the literature research, hybrid systems to be created with the use of fuel cells are seen as the best solution in order to ensure energy reliability, which is the biggest problem of renewable energy sources. In this study, information about the types of hybrid systems created with fuel cell integration, their working principles and studies related to this subject are given. Renewable energy sources and storage devices used by hybrid systems created with fuel cell systems and energy recovery methods applied to these systems are mentioned in detail.

2. Fuel Cell Hybrid Energy Systems

In off-grid, on-grid and mobile systems, hybrid systems are used in order to increase the reliability of electrical energy, reduce the cost and improve the emission values [8]. Today, it is aimed to use renewable energy sources as much as possible to meet the load demand in energy production systems [9,10]. In hybrid systems created with renewable energy sources, integrating the fuel cell into the system is one of the most effective methods to ensure energy reliability [11,12].

There are three basic methods in the creation of fuel cell hybrid systems. In this study, hybrid systems created with fuel cells were examined under three headings: hybrid systems created with renewable energy sources, hybrid systems created with storage devices and hybrid systems created for energy recovery.

2.1 Hybrid systems created with renewable energy resources

The biggest disadvantage of renewable energy sources other than fuel cells is that they cannot provide energy reliability. Especially in wind and solar energy, generating electrical energy without using any fuel is an important advantage compared to the fuel cell. On the other hand, fuel cells stand out with their uninterrupted generation of electrical energy as long as fuel is supplied to the system. Energy can be produced from solar energy with photovoltaic panels and from wind energy with wind turbines. In order to ensure energy reliability in these systems, hybrid systems are created with fuel cells. The most common hybrid systems in which fuel cells are used with renewable energy sources are divided into two basic groups: FC (Fuel Cell)-PV (Photovoltaic) and FC (Fuel Cell)-PV (Photovoltaic)-WT (Wind Turbine). In addition to these, different combinations can also be applied.

Fuel cell-Photovoltaic hybrid systems

Hybrid systems created with photovoltaic and fuel cell systems are widely used in on-grid and off-grid systems, and they can also be used in mobile applications. These systems are more useful thanks to their simple structure and high efficiency [13]. Today, one of the most important limitations in the use of photovoltaic systems is the difficulties in storing the generated electrical energy. Due to this limitation, PV systems can only be used in summer and sunny hours in regions with low solar energy potential. In regions with high solar energy potential, it carries a high risk of interruption due to weather conditions [14].

The FC and PV hybrid system is shown in Figure 2. The basic elements of the system are the photovoltaic panel and the fuel cell. The battery or battery pack is used to prevent interruptions that may occur in the system during the transition phase and high power demand. Photovoltaic panels provide energy to the system under appropriate conditions, and the excess energy they produce is stored in the battery pack. The fuel cell, on the other hand, activates when an extra energy is required to feed the system. However, in mobile systems, this power control may be different. If the system shown in Figure 2 is used on a mobile system, FC becomes the primary power source [15]. PV feeds the system continuously. The battery pack stores the excess energy produced by the FC power supply and PV panels and feeds the system when the system needs instant power [15].

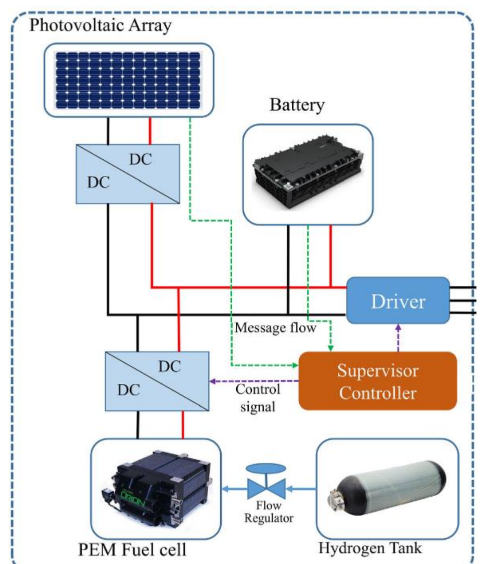


Figure 2. FC and PV hybrid system [15]

Yeşilata et al. analyzed the use of hybrid systems created with PV and FC in their studies. The hybrid system consists of PV panel, electrolysis unit, hydrogen tank and fuel cell. The electrical energy supplied from the PV panel is used for hydrogen production in the electrolysis unit. In cities with high solar energy potential, it has been seen that it is possible to produce hydrogen, needed by the fuel cell, with the electrical energy produced in the PV panel in 6 months. However, it has been concluded that extra electrical energy is required in the remaining months. It has been stated that the efficiency is very low since the electrical energy produced from solar energy goes through electrolysis and fuel cell processes. [14]. Ezzat et al. investigated the hydrogen consumption of the hybrid system consisting of FC and battery and the hybrid system consisting of PV, FC and battery under the same conditions. It has been obtained that the hybrid system consisting of PV, FC and battery consumes 561 g less hydrogen compared to the other system when it is operated for 3 hours at 98.32 kW power conditions. It has been concluded that the PV system reduces hydrogen consumption by 11.2% [16].

Fuel cell-Photovoltaic-Wind turbine hybrid systems

Supporting batteries and diesel generators with wind or solar energy reduces fossil fuel consumption. Replacing diesel generators and batteries with fuel cells offers a great opportunity to prevent environmental pollution and reduce operating and maintenance costs. As a promising alternative, the fuel cell can be used as an efficient energy conversion device for a hybrid generation system [17]. Alternative energy conversion systems such as photovoltaic panels and wind turbines can be operated in conjunction with fuel cells in a variety of on-grid systems [18]. FC, PV and WT hybrid systems are preferred to be used in regions with high solar and wind energy potential.

The hybrid system consisting of photovoltaic panels, wind turbines and fuel cell is shown in Figure 3 [8]. PV and WT systems on the hybrid system are used as primary sources in electricity generation. A battery pack is used to prevent instantaneous power interruptions in the system. When PV and WT systems cannot produce enough electrical energy, FC steps in and supports electricity generation [12,19].

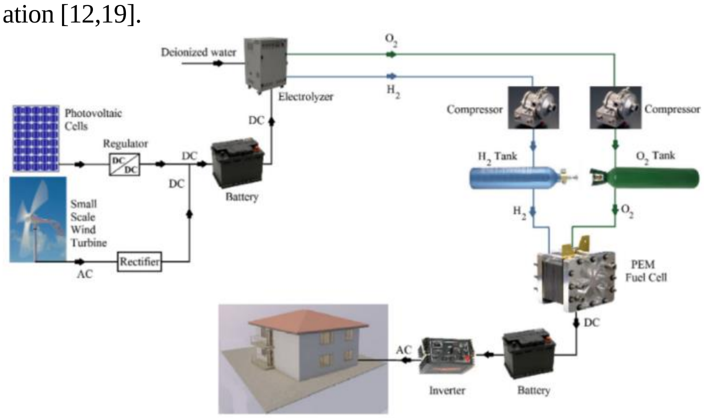


Figure 3. FC, PV and WT hybrid system [8]

Devrim et al. analyzed the use of a hybrid system consisting of FC, PV and WT devices for a 150 m2 house in Ankara. Since the use of PV and WT system for this house cannot provide uninterrupted electrical energy, FC has been integrated into the system. In the study, solar and wind energies were used as the primary energy source, and PEMFC (Proton Exchange Membrane Fuel Cell) was used as the supporting power source. In the hybrid system, there is a wind turbine with a power of 3 kW, photovoltaic panels with an area of 17.97 m2 and a fuel cell with a power of 1 kW. Considering the daily energy requirement of the examined house as 5 kWh, it is seen that the hybrid system meets the electricity need uninterruptedly throughout the year, except for November. In the other months, the energy requirement of the house is more than met and it can be used for cooling and heating of the house [8].

2.2 Hybrid systems created with storage devices

Fuel cells are constantly exposed to temporary power surges and dynamic loads according to their usage areas. Fuel cell systems have many effective advantages. Despite these advantages, it has longer start-up time and slow dynamic response compared to electronic systems due to the limitation of chemical reaction and fuel delivery system [20]. For this reason, hybrid systems are created by integrating electronic storage sources such as battery packs or capacitors into fuel cell systems [4]. The creation of hybrid systems with fuel cells and storage devices is generally carried out with three different combinations: FC-Battery, FC-Capacitor or FC-Battery-Capacitor.

Fuel cell-Battery hybrid systems

Batteries can effectively increase power performance by responding to rapid transient power pulses. FC stack characteristic is more suitable for working under constant loads. For this reason, hybrid systems consisting of fuel cell and battery have been created. The hybrid system created from the fuel cell-battery is shown in Figure 4 [20]. When the power demanded from the system is less than the fuel cell power, the excess energy produced is stored in the battery pack. When the power demanded from the system is more than the power of the fuel cell, the energy stored in the battery pack is supplied to the system and the need for power fluctuations is met uninterruptedly. In addition, fuel cell efficiency increases in this hybrid system. If the system where the electrical energy is transmitted needs constant power, such a hybrid system may not be necessary [4,20].

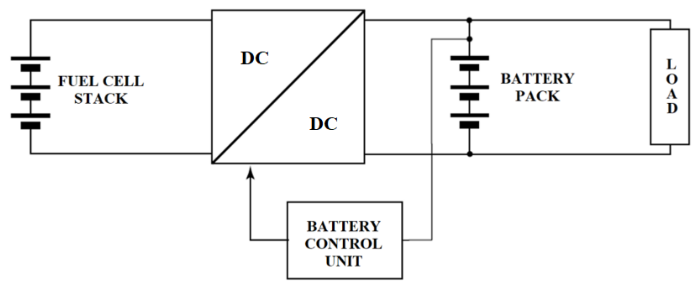


Figure 4. FC and battery hybrid system [20]

Gonzalez et al. experimentally investigated the fuel cell-battery hybrid system developed for use in an unmanned ground vehicle. The battery pack formed with lithium phosphate battery cells and the PEM fuel cell stack with 200 W power are connected in series. When the battery charge rate drops below a certain level, the fuel cell is activated. Approximately 49% of the energy produced by the fuel cell was transmitted to the power system for propulsion of the vehicle and 59% to the battery pack for storage. In the tests, it was determined that the average energy efficiency of the PEM fuel cell stack was 39%. As a result of the study, it was concluded that the energy required for the unmanned ground vehicle was successfully provided in the system created with the fuel cell and battery [21].

Fuel cell-Capacitor hybrid systems

Due to the slow dynamics of fuel cells, it is not suitable for use alone in systems with sudden fluctuations. The use of fuel cells alone in such systems shortens the life of the fuel cell and may cause instant interruptions in the system. Hybrid systems have been developed by combining fuel cells with capacitors to avoid this problem [22]. Hybrid systems created with FC-Capacitor devices are shown in Figure 5 [26]. There are some advantages and disadvantages of using a capacitor instead of a battery in the system. Although battery packs start to lose their efficiency after about 10 thousand charge-discharge cycles, capacitors can maintain performance for about one million cycles [23]. In addition, capacitors have a higher power density than batteries and can absorb higher power waves. Despite these advantages of capacitors, the biggest disadvantage is their low energy density [24]. However, this disadvantage does not prevent the use of capacitors with fuel cells. FC-Capacitor hybrid system is more suitable for mobile systems and is widely used [25].

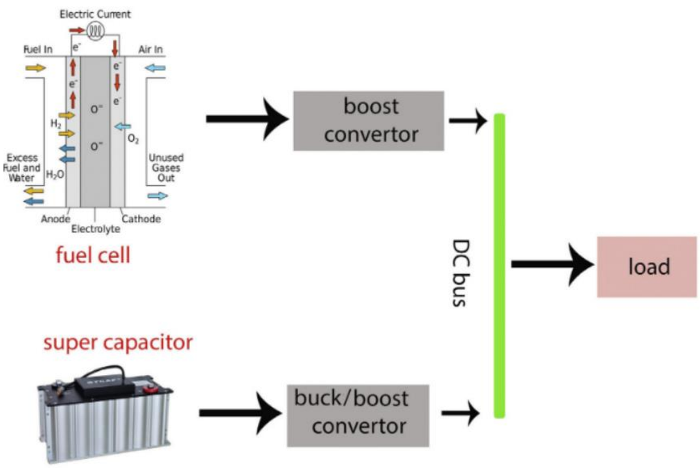


Figure 5. FC and capacitor hybrid system [26]

Allaoua et al. investigated the use of PEMFC as the main energy source and supercapacitor as auxiliary power source in an electric vehicle. MATLAB Simulink software was used in the simulation study. The slow dynamics of PEMFC has been tried to be eliminated with a super capacitor. Thus, it is aimed to improve fuel cell performance and life. In the study, it was concluded that PEMFC and super capacitor work in harmony and the stabilization of the system increased [27].

Fuel cell-Battery-Capacitor hybrid systems

In cases where the power requirement of the system to be energized is very fluctuating, a hybrid system can be created with FC, battery and capacitor. The hybrid system consisting of FC, battery and capacitor is shown in Figure 6 [28].

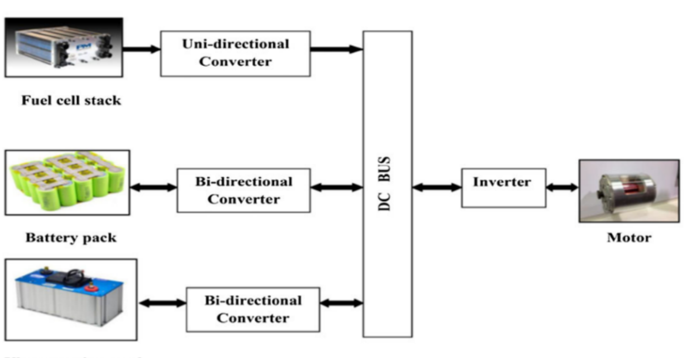


Figure 6. FC, battery and capacitor hybrid system [28]

The fuel cell produces the electrical energy required for the system, the battery and the capacitor store the surplus energy. When the energy need of the system increases, the system is fed by the battery and capacitor.

Chandan et al. simulated a hybrid system consisting of FC, supercapacitor and battery devices on an electric vehicle. A control strategy has been established in order to ensure that the hybrid system can meet the energy needs of the electric vehicle. The results have been obtained that the hybrid system created meets the electrical energy needed by the vehicle and the system works stably [29].

2.3 Hybrid systems created for energy recovery

It is aimed to increase the efficiency of the systems used in the energy production process and to reduce their emission values. As a result of the reactions taking place in fuel cells, high temperatures occur and heat is discharged to the outside. In addition, it is known that not all of the fuel supplied to the anode catalyst can be used. It is possible to recover energy from the heat released as a result of the reaction and from the unused fuel, by using systems outside the fuel cell [30]. Hybrid systems can be created by integrating systems such as gas turbine, thermophotovoltaic cell and heat exchanger into fuel cell systems. These systems, in which the heat and fuel discharged from the fuel cells are recovered with the integrated system, are examined under the title of hybrid systems created for energy recovery [31].

SOFC (Solid Oxide Fuel Cells) and MCFC (Molten Carbonate Fuel Cells) are called HTFC (High Temperature Fuel Cells) because they operate at high temperatures such as 800-1000 °C and 500-700 °C, respectively. The waste heat from these HTFC stacks is of high quality [32]. By integrating HTFC stacks with other thermal energy conversion devices, the overall energy efficiency of the system is increased, and the waste heat energy can be recovered with the hybrid systems created [33].

Thermophotovoltaic cell hybrid systems

TPVC (Thermophotovoltaic Cells) are devices that efficiently convert thermal radiation obtained by the sun, burning fuel or other methods into electricity [34]. The main advantages of TPVCs are their small size, no moving parts, low noise, easy maintenance, high power densities and high heat-electricity conversion [35,36]. Thanks to these advantages, TPVCs are among the common hybrid systems that provide energy recovery by integrating into fuel cells [31,36,37].

A hybrid system formed with HTFC and TPVC is shown in Figure 7 [36]. The HTFC-TPVC hybrid system consists of HTFC, regenerator, emitter, back surface reflector and TPVC. The regenerator heats the air and fuel that are about to enter the fuel cell with some of the heat released from the fuel cell. Thanks to the highly conductive material used between the HTFC and the emitter, heat flow to the emitter occurs. The emitter and the TPVC are separated by a vacuum cavity, and the heat transfer that takes place obeys Stefane Boltzmann's law. The emitter emits photons with thermal power density towards the TPVC. Moreover, a back surface reflector that can reflect photons back is used to increase the efficiency of the hybrid system [38].

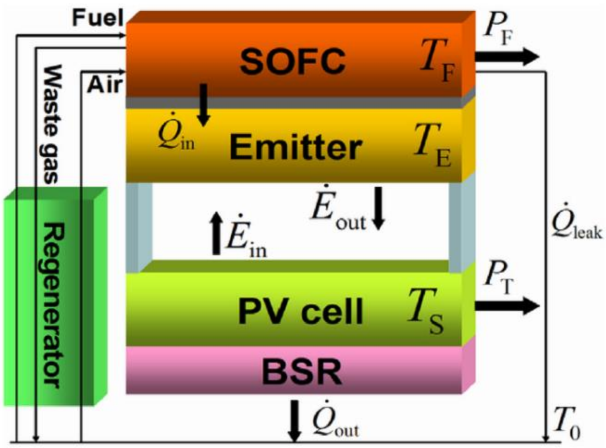


Figure 7. HTFC and TPVC hybrid system [36]

Zhimin Yang et al. numerically modeled and optimized the output power density in a hybrid system created with a DCFC (Direct Carbon Fuel Cell) and TPVC. More than twice the power that DCFC gives alone under the same operating conditions is obtained by this hybrid system. It has been determined that the output power density and efficiency increase as the operating temperature of the DCFC increases [31]. Dong et al. created a hybrid system with SOFC and TPVC. SOFC waste heat was transferred to thermophotovoltaic cells with water. As a result of the study, it was observed that the created hybrid system had higher efficiencies than the use of SOFC alone [39].

Gas turbine hybrid systems

By using HTFC and gas turbine systems together, a hybrid system aimed at energy recovery is obtained [40]. The main reason for using gas turbine hybrid systems is to provide energy production with high efficiency and low emission values. It is possible to achieve 70% efficiency in hybrid systems created by integrating gas turbines with SOFC, and it is almost impossible to achieve this efficiency with conventional fossil fuel systems [41]. With the use of gas turbine hybrid systems, even in power plants with low power outputs (200-400 kW), an efficiency of over 60% can be achieved [42]. The major disadvantages of these hybrid systems are the high initial setup cost and the difficulty of controlling between systems [41].

The heat energy required for the gas turbine is provided by the HTFC instead of the heat source used in the Brayton Cycle. In the system, the gas turbine has basic tasks such as generating electricity and giving pressure to the air that the fuel cell needs. In addition, the heat exchangers in the system heat the air and the fuel before entering the fuel cell. In order to obtain the high temperature and pressure gas required for the gas turbine, the heat released as a result of the chemical reaction in the fuel cell and the heat obtained by the re-oxidation of the fuel used in the fuel cell are utilized. One side of the turbine is connected to the compressor and the other side is mechanically connected to the generator. While a small part of the mechanical energy obtained in the turbine is consumed for the compressor, the majority of it drives the generator and produces electricity. Electricity generation with the electrochemical method in the fuel cell has high efficiency and low emission values. For this reason, it is aimed to produce as much of the electrical energy as possible in the fuel cell. The gas turbine hybrid system integrated with HTFC is shown in Figure 8 [40,43].

One type of gas turbine is micro gas turbines. Micro gas turbines are widely used for the conversion of heat energy from a system into electrical energy. Micro gas turbines, which have a lower weight and volume than normal gas turbines, bring gas turbine technology to smaller dimensions [40]. Their usage is quite advantageous for units in the range of 30-200 kW [44].

Mehrpooya et al. have created a hybrid system in which MCFC, gas turbine, steam engine and TPVC are integrated. The efficiency of MCFC was obtained as 44.58% under the conditions of 0.8 fuel consumption coefficient, 1 atm pressure and 650 ºC temperature and 2.5 vapor-carbon ratio. In the hybrid system, which was created by integrating only a gas turbine into the MCFC, the total efficiency was obtained as 54.83%. By adding gas turbine, steam engine and TPVC to MCFC, the total efficiency of the system was increased to 67.3%. It has been observed that a 22.72% increase in total energy efficiency has been achieved with the combined use of MCFC, gas turbine, steam engine and TPVCs [45]. Leal et al. examined a hybrid system with SOFC and gas turbine. The SOFC and gas turbine power ratio in the system is approximately 1.5. As a result of the study, SOFC efficiency was 40.8%, gas turbine efficiency was 27.1% and total efficiency was 62.1%. It has been determined that under the same conditions, the power of SOFC decreases with the increase of gas turbine power and the system efficiency decreases by 7% [46].

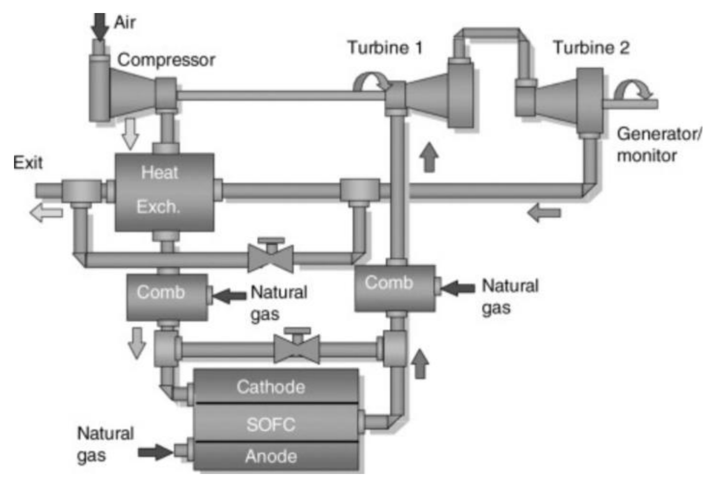


Figure 8. Pressure HTFC and gas turbine hybrid system [43]

Hybrid system with heat exchanger

SOFC and MCFC fuel cells operate at high temperatures and heat dissipation is inevitable. In addition, it is possible to recover some heat energy by reusing the fuel from the fuel cell. A combustor is used in the system to reburn the unused fuel. Although it is aimed to operate this combustor with fuel that has not been used by the fuel cells, some fuel can be added to the system from outside. It is important in terms of energy efficiency that the heat released by high-temperature fuel cells and the heat obtained from the re-burning of unused fuels are converted into useful work with heat exchangers. Hybrid systems with heat exchangers can consist of a single heat exchanger or more than one heat exchanger [30,47].

A hybrid system with heat exchanger is shown in Figure 9 [47]. This hybrid system consists of SOFC stack, combustor, air heater, fuel heater and HRS (Heat Recovery System). In the fuel cell, the unreacted anode and cathode exhaust gases are burned in a combustor to produce heat. The heat generated as a result of the reactions occurring in the fuel cells and the heat generated in consequence of the burning of the unused fuel are collected by the heat exchangers. The heat collected in the heat exchangers can be used to heat the fuel and air that are about to enter the fuel cell [48]. In addition, the collected heat can meet the hot water need of a house in hot seasons and can be used for heating the house in cold seasons [30,47].

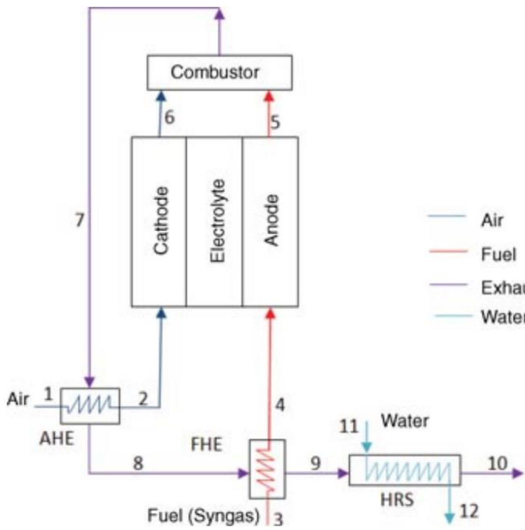


Figure 9. Hybrid system with heat exchanger [47]

Samavati et al. experimentally investigated the energy efficiency of a hybrid system with 5 kW SOFC and heat exchangers. In addition to heating the air and fuel entering the fuel cell with waste heat, the water in the external source is also heated. As a result of the study, the electrical energy efficiency, heat energy efficiency and total efficiency of the system were examined and these values were determined as approximately 20%, 50% and 75%, respectively [47]. Quoc et al. investigated hybrid systems that can be created to recover the heat produced by PEMFC and to use it in different heating/cooling and power cycles. It has been emphasized that with the use of hybrid systems to provide energy recovery in PEMFC, energy efficiency increases, operating costs and greenhouse gas emissions are significantly reduced [48].

3. Results and Discussion

In this study, the working principles, types and effects of hybrid systems created with fuel cells are examined in detail. FC hybrid systems are examined under three headings: hybrid systems created with renewable energy sources, created with storage devices, and created for energy recovery. It has been observed that the main purpose of hybrid systems created with renewable energy sources is to ensure energy reliability. Interruptions in the energy production of PV panels and WT due to seasonal and weather conditions are eliminated by the environmentally friendly structure of the FC. In addition, providing the electrical energy required for the electrolysis of hydrogen, which is used as fuel in FC, with PV panels or WT, eliminates fuel storage and transportation problems. In hybrid systems created with storage devices, it is aimed to meet the instant power needed by the energized system and to prevent instant interruptions in the system. In the studies examined, it has been observed that the interruptions and fluctuations that will occur in the system are absorbed by the use of a battery, capacitor or battery-capacitor together with the FC. Thus, the life of the FC is extended. In the hybrid systems created for energy recovery, it is aimed to recover the heat lost from the FC and the unused fuel energy. This energy recovery is carried out successfully with TPVC, gas turbines or heat exchangers and FC efficiency is increased.

Nomenclature

DCFC	Direct Carbon Fuel Cell
FC	Fuel Cell
HRS	Heat Recovery System
HTFC	High Temperature Fuel Cell
MCFC	Molten Carbonate Fuel Cell
PEMFC	Proton Exchange Membrane Fuel Cell
PV	Photovoltaic
SOFC	Solid Oxide Fuel Cell
TPVC	Thermophotovoltaic Cell
WT	Wind Turbine

Conflict of Interest Statement

The authors must declare that there is no conflict of interest in the study.

CRediT Author Statement

Tolga Kocakulak: Writing-original draft, Conceptualization, Investigation. **Turan Alp Arslan:** Writing-review & editing, Visualization.

References

1. Jang, M., Ciobotaru, M., and Agelidis, V. G. (2013). Design and implementation of digital control in a fuel cell system. IEEE Transactions on Industrial Informatics, 9(2), 1158–1166.
2. Singh, A., Baredar, P., and Gupta, B. (2017). Techno-economic feasibility analysis of hydrogen fuel cell and solar photovoltaic hybrid renewable energy system for academic research building. Energy Conversion and Management, 145, 398-414.
3. Chen, J., Xu, C., Wu, C., and Xu, W. (2016). Adaptive fuzzy logic control of fuel-cell-battery hybrid systems for electric vehicles. IEEE Transactions on Industrial Informatics, 14(1), 292-300.
4. Yuan, H. F., and Dung, L. R. (2014). A hybrid fuel cell-battery power system. IECON 2014-40th Annual Conference of the IEEE Industrial Electronics Society, 4096-4102.
5. Ashourian, M. H., Cherati, S. M., Zin, A. M., Niknam, N., Mokhtar, A. S., and Anwari, M. (2013). Optimal green energy management for island resorts in Malaysia. Renewable Energy, 51, 36-45.
6. Tzamalis, G., Zoulias, E. I., Stamatakis, E., Varkaraki, E., Lois, E., and Zannikos, F. (2011). Techno-economic analysis of an autonomous power system integrating hydrogen technology as energy storage medium. Renewable Energy, 36(1), 118-124.
7. Bohn, D. (2005). Micro gas turbine and fuel cell–a hybrid energy conversion system with high potential. Micro Gas Turbines, 13, 1-46.
8. Devrim, Y., and Bilir, L. (2016). Performance investigation of a wind turbine–solar photovoltaic panels–fuel cell hybrid system installed at İncek region–Ankara, Turkey. Energy Conversion and Management, 126, 759-766.
9. Al Busaidi, A. S., Kazem, H. A., Al-Badi, A. H., and Khan, M. F. (2016). A review of optimum sizing of hybrid PV–Wind renewable

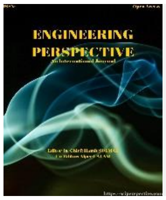
energy systems in oman. Renewable and Sustainable Energy Reviews, 53, 185-193.

10. Bensmail, S., Rekioua, D., and Azzi, H. (2015). Study of hybrid photovoltaic/fuel cell system for stand-alone applications. International Journal of Hydrogen Energy, 40(39), 13820-13826.
11. Samy, M. M., Barakat, S., and Ramadan, H. S. (2019). A flower pollination optimization algorithm for an off-grid PV-Fuel cell hybrid renewable system. International Journal of Hydrogen Energy, 44(4), 2141-2152.
12. Einan, M., Torkaman, H., and Pourgholi, M. (2017). Optimized fuzzy-cuckoo controller for active power control of battery energy storage system, photovoltaic, fuel cell and wind turbine in an isolated micro-grid. Batteries, 3(3), 23.
13. Aygen, M. S., and Mustafa, İ. (2019). Performance results of photovoltaic/fuel cell based hybrid energy system under variable conditions. ICPEA 4th International Conference on Power Electronics and their Applications, 1-6.
14. Yeşilata, B., ve Demir, F. (2006). Fotovoltaik ve yakıt pili birleşik sisteminin analizi. Isı Bilimi ve Tekniği Dergisi, 26(1), 37-44.
15. Huang, Z., Zhang, C., Zeng, T., Lv, C., and Chan, S. H. (2019). Modeling and energy management of a photovoltaic-fuel cell-battery hybrid electric vehicle. Energy Storage, 1(3), e61.
16. Ezzat, M. F., and Dincer, I. (2016). Development, analysis and assessment of a fuel cell and solar photovoltaic system powered vehicle. Energy Conversion and Management, 129, 284-292.
17. Chen, H. C., Chen, P. H., Chang, L. Y., and Bai, W. X. (2013). Stand-alone hybrid generation system based on renewable energy. International Journal of Environmental Science and Development, 4(5), 514.
18. Barbir, F., and Gomez, T. (1997). Efficiency and economics of proton exchange membrane (PEM) fuel cells. International Journal of Hydrogen Energy, 22(10-11), 1027-1037.
19. Khan, M. J., and Mathew, L. (2019). Fuzzy logic controller-based MPPT for hybrid photo-voltaic/wind/fuel cell power system. Neural Computing and Applications, 31(10), 6331-6344.
20. Larminie, J., and Dicks, A. (2003). Fuel cell systems explained. 2nd Edition, John Wiley & Sons Ltd, Chichester, UK, 207-225.
21. González, E. L., Cuesta, J. S., Fernandez, F. J. V., Llerena, F. I., Carlini, M. A. R., Bordons, C., and Elfes, A. (2019). Experimental evaluation of a passive fuel cell/battery hybrid power system for an unmanned ground vehicle. International Journal of Hydrogen Energy, 44(25), 12772-12782.
22. Siangsanoh, A., Bahrami, M., Kaewmanee, W., Gavagsaz-ghoachani, R., Phattanasak, M., Martin, J. P., and Didierjean, S. (2021). Series hybrid fuel cell/supercapacitor power source. Mathematics and Computers in Simulation, 184, 21-40.
23. Bubna, P., Advani, S. G., and Prasad, A. K. (2012). Integration of batteries with ultracapacitors for a fuel cell hybrid transit bus. Journal of Power Sources, 199, 360-366.
24. Boynuegri, A. R. (2017). A power management unit with a polarity changing inverter for fuel cell/ultra-capacitor hybrid power systems. International Journal of Hydrogen Energy, 42(43), 26924-26932.
25. Fathabadi, H. (2018). Fuel cell hybrid electric vehicle (FCHEV): Novel fuel cell/SC hybrid power generation system. Energy Conversion and Management, 156, 192-201.
26. Behdani, A., and Naseh, M. R. (2017). Power management and nonlinear control of a fuel cell–supercapacitor hybrid automotive vehicle with working condition algorithm. International Journal of Hydrogen Energy, 42(38), 24347-24357.
27. Allaoua, B., Asnoune, K., and Mebarki, B. (2017). Energy management of PEM fuel cell/supercapacitor hybrid power sources for an electric vehicle. International Journal of Hydrogen Energy, 42(33), 21158-21166.
28. Kasimalla, V. K., and Velisala, V. (2018). A review on energy allocation of fuel cell/battery/ultracapacitor for hybrid electric vehicles. International Journal of Energy Research, 42(14), 4263-4283.
29. Chandan, R. S., Kiran, T. S., Swapna, G., and Muni, T. V. (2020). Intelligent control strategy for energy management system with FC/Battery/SC. Journal of Critical Reviews, 7(2), 344-348.
30. Samavati, M. (2012). Polygeneration system based on low temperature solid oxide fuel cell/Micro gas turbine hybrid system. KTH School of Industrial Engineering and Management, Energy Technology, Master of Science Thesis.
31. Yang, Z., Liao, T., Zhou, Y., Lin, G., and Chen, J. (2016). Performance evaluation and parametric optimum design of a molten carbonate fuel cell-thermophotovoltaic cell hybrid system. Energy Conversion and Management, 128, 28-33.
32. Liao, T., He, Q., Xu, Q., Dai, Y., Cheng, C., and Ni, M. (2020). Harvesting waste heat produced in solid oxide fuel cell using near-field thermophotovoltaic cell. Journal of Power Sources, 452, 227831.
33. Zhao, Y., and Chen, J. (2009). Modeling and optimization of a typical fuel cell–heat engine hybrid system and its parametric design criteria. Journal of Power Sources, 186(1), 96-103.
34. Lenert, A., Bierman, D. M., Nam, Y., Chan, W. R., Celanović, I., Soljačić M., and Wang, E. N. (2014). A nanophotonic solar thermophotovoltaic device. Nature Nanotechnolgy, 9(2), 126–30.
35. Ferrari, C., Melino, F., Pinelli, M. and Spina, P. R. (2014). Thermophotovoltaic energy conversion: Analytical aspects, prototypes and experiences. Applied Energy, 113, 1717–1730.
36. Liao, T., Cai, L., Zhao, Y., and Chen, J. (2016). Efficiently exploiting the waste heat in solid oxide fuel cell by means of thermophotovoltaic cell. Journal of Power Sources, 306, 666-673.
37. Zhang, X., Liu, H., Ni, M., and Chen, J. (2015). Performance evaluation and parametric optimum design of a syngas molten carbonate fuel cell and gas turbine hybrid system. Renewable Energy, 80, 407–414.
38. Datas, A. (2015). Optimum semiconductor bandgaps in single junction and multijunction thermophotovoltaic converters. Solar Energy Materials and Solar Cells, 134, 275-290.
39. Dong, Q., Cai, L., Liao, T., Zhou, Y., and Chen, J. (2017). An efficient coupling system using a thermophotovoltaic cell to harvest the waste heat from a reforming solid oxide fuel cell. International Journal of Hydrogen Energy, 42(27), 17221-17228.
40. Roberts, R. A., Brouwer, J., Liese, E., and Gemmen, R. S. (2006). Dynamic simulation of carbonate fuel cell-gas turbine hybrid systems. Journal of Engineering for Gas Turbins and Power, 128, 294-301.
41. Oryshchyn, D., Harun, N. F., Tucker, D., Bryden, K. M., and Shadle, L. (2018). Fuel utilization effects on system efficiency in solid oxide fuel cell gas turbine hybrid systems. Applied Energy, 228, 1953-1965.
42. Li, Y., and Weng, Y. (2011). Performance study of a solid oxide

fuel cell and gas turbine hybrid system designed for methane operating with non-designed fuels. Journal of Power Sources, 196(8), 3824-3835.

43. Rao, A., D., (2012). Combined cycle systems for near-zero emission power generation. Elsevier.
44. Brown, J. E., Hendry, C. N., and Harborne, P. (2007). An emerging market in fuel cells? Residential combined heat and power in four countries. Energy Policy, 35, 2173–2186.
45. Mehrpooya, M., Khodayari, R., Moosavian, S. A., and Dadak, A. (2020). Optimal design of molten carbonate fuel cell combined cycle power plant and thermophotovoltaic system. Energy Conversion and Management, 221, 113177.
46. Leal, E. M., Bortolaia, L. A., and Junior, A. M. L. (2019). Technical analysis of a hybrid solid oxide fuel cell/gas turbine cycle. Energy Conversion and Management, 202, 112195.
47. Samavati, M., Raza, R., and Zhu, B. (2012). Design of a 5-kW advanced fuel cell polygeneration system. Wiley Interdisciplinary Reviews: Energy and Environment, 1(2), 173-180.
48. Nguyen, H. Q., and Shabani, B. (2020). Proton exchange membrane fuel cells heat recovery opportunities for combined heating/cooling and power applications. Energy Conversion and Management, 204, 112328.

Engineering Perspective 3 (1): 9-17, 2023



e-ISSN:2757-9077

ENGINEERING PERSPECTIVE

https://sciperspective.com/

Research Paper

Evaluation of Electrification of 4W Light Commercial Vehicle

P. Vijay Sai Goud[1*] and A. Sai Venkata Phanindra Chary[2]

[1]*School of Mechanical, Aerospace and Automotive Engineering, Coventry University, Coventry, CV1 5FB, United Kingdom*
[2]*Automobile Engineering Department, VNR Vignana Jyothi Institute of Engineering and Technology, Hyderabad, 500090, India*

ABSTRACT

Road transport is a prime contributor to CO_2 emissions in the Indian transportation sector. The motor vehicle fleet in India is responsible for 90% of the total energy consumption in the transport industry and of this, 45% is consumed for freight transport. Currently, petroleum is used primarily to generate energy for road transport and most of it is imported. With the increase in environmental issues and oil prices, it has become necessary to switch to alternative propulsion systems. Current ICE vehicles can be adopted for Electric vehicle retrofitting which aids in reducing the transport sector emissions. In this paper, the process of conversion of a 4W Light Commercial Vehicle into an Electric Vehicle adhering to the vehicle conversion norms in India is discussed. A numerical analysis of the vehicle was done to evaluate its performance. A cost comparison of the ICE vehicle, a Retrofitted Electric vehicle, and a New Electric vehicle was carried out. The results showed that the converted vehicle has better performance than that of an ICE vehicle and costs lower than the new electric vehicle.

Keywords: Conversion; Electric Vehicle; Internal Combustion Engine Vehicle; Light Commercial Vehicle; Regenerative Braking; Retrofit

History
Received: 12.01.2023
Accepted: 17.03.2023

http://dx.doi.org/10.5281/zenodo.782096

Author Contacts
*Corresponding Author
e-mail addresses : vijaysai00027@gmail.com, sai,arendra16298@gmail.com
Orcid numbers : 0000-0002-6516-3842, 0000-0002-9211-0084

1. Introduction

Globally, India is the third largest emitter of Greenhouse gases (GHG) [1]. After joining the Paris agreement, India aims to reduce the intensity of emissions by 33 – 35% when compared to the levels in 2005. For the transportation sector to align with the Paris agreement's and India's goals, the GHG emission levels should be substantially lower than the current emissions. On the other hand, the demand for transportation increased significantly due to population and economic growth. To reduce GHG emissions, the fuel efficiency of conventional vehicles has to be improved and Electric Vehicles (EV)/Alternative propulsions should be adopted. India has set the norms for fuel efficiency/emission standards by limiting CO_2 emissions. Approximately 12 Gt of CO_2 is emitted into the air per year worldwide due to the production and combustion of the fuels used for transportation [2].

The EVs have zero tailpipe emissions but are still associated with the emissions produced while manufacturing, charging, and recycling. The life-cycle GHG emission of a Passenger EV is approximately 19-49 % lower compared to that of gasoline cars in India, and in the future, EVs may emit around 30 - 63% lesser throughout their life cycle than their counterparts [2-3]. The adoption pace of EVs in India can be improved potentially by ICE to EV retrofitting. The Ministry of Road Transport and Highways of India, made amendments to the Central Motor Vehicle Rules 1989, legalising the retrofitting of ICE vehicles to EVs. Retrofitting will extend the useful life span of the existing vehicles based on their structural integrity by at least 5 - 7 years and will prevent the vehicle from falling into the new scrappage policy in India .

1.1 Urban Freight

Urban freight contributes a major share to the social and economic development of cities. Globally, it accounts for 10% to 15% of the vehicle equivalent miles travelled in the city and provides employment to 2% – 5% of the urban population. Two-wheelers, Light commercial vehicles (LCVs), and Heavy commercial vehicles (HCVs) are generally used for freight transportation in urban areas. The accelerated urbanisation in India in recent times has raised the demand for the movement of freight remarkably. As a result, the freight vehicle traffic is rising thereby increasing the total energy consumption for the movement of these goods and services by road [4] which contributes to GHG emissions, traffic congestion, and noise pollution. To curb these adverse impacts, decarbonization of urban freight is necessary, and based on the comparison of life-cycle GHG emissions of ICE vehicles and an EV, the EVs are substantial as they emit lower.

1.2 Light Commercial Vehicle

The Light commercial vehicles segment comprising trucks, vans, and three-wheelers are the most common modes of freight transportation in India. These vehicles are generally used for the carriage of goods and their GVW doesn't exceed 3.5 tons. According to the Road Transport yearbook 2018-19, out of the total newly registered transport vehicles, LCVs account for a share of 24.1 %, out of which 67.7.% are Four-wheeler LCVs [5]. The emissions due to vehicular movement for urban freight cause a severe impact on the environment. To decarbonize the environment, the conventional vehicles used for urban freight have to be switched to electric vehicles as their operation is clean compared to the ICE vehicles. Electric vehicles are more efficient than their counterparts in the cities because of regenerative braking which converts most of the kinetic energy lost while deceleration by using the electric motor as a generator and stores it in the battery which in turn improves the range. However, this efficiency depends on how the vehicle responds to the stop-go traffic in the cities. On the contrary, fuel-based cars convert the kinetic energy while braking into waste heat.

1.3 Vehicle Retrofitting

Electric retrofits involve converting an ICE vehicle to an electric drivetrain, aiding the transition to zero-emission vehicles while operating by adapting current vehicles and, thus, reducing the transport sector emissions. Electric vehicles offer lower operating costs but their high initial cost and range anxiety are influencing the shift toward widespread adoption of EVs in India. The high initial cost issue can be resolved by converting the existing ICE vehicles into electric vehicles. This process is both cost-effective and eco-friendly in operation [6].

The conversion process presented in this paper had the following objectives:

- Compliance with Indian Legislation: The retrofitted vehicle should comply with the Central Motor Vehicle Rules (CMVR), 1989 in India, and also should conform to the requirements mentioned in AIS 123 standard [7]. Based on the AIS 123, the vehicles selected for retrofitting into pure electric are manufactured on or after 01 January 1990, and should not be provided with permits to carry dangerous or hazardous goods as mentioned in the CMVR [8].
- The range of at least 100 km/day for urban freight transport.
- To integrate the technology with proper design and sizing.

2. Vehicle Conversion Process

2.1 Selecting the vehicle

Various parameters have to be inspected while selecting a vehicle for conversion into an electric vehicle. According to Indian Road transport office norms, a commercial vehicle aged more than 15 years should be scrapped if the vehicle doesn't pass the fitness and emission tests [9]. Almost all the vehicles in India come with a warranty of 1,00,000 km and the average life of a vehicle is 15 years or 3,00,000 kilometres [10]. Therefore, the life expectancy of the selected vehicle should be at least 5 more years or 1,00,000 kilometres and the chassis must be inspected for structural integrity else the conversion will not be beneficial. Above all, the Vehicle must comply with Indian Legislation. The complexity of the conversion process increases with the increase in the number of electrical and electronic components in the vehicle. The number of auxiliary electrical and electronic components also affects the range of the vehicle [11]. The following are the specifications of the conventional 4-wheeler LCV – N1 category chosen for retrofitting to an Electric vehicle.

Table 1. Specifications of Light Commercial Vehicle [12].

Parameter	Specification
Make and Model	TATA and ACE HT+
Engine	2-cylinder, 800 CC Common Rail Engine
Max. Power output	26 kW @3750 rpm
Max. Torque	85 Nm @ 1750 – 2750 rpm
Suspension	Leaf spring suspension with shock absorbers
Tires	155R13 LT 8PR
Wheelbase	2250 mm
Max Gradeability	36 %
Gross Vehicle Weight	1950 kg
Payload	900 kg
Gearbox type	GBS 65-5/5.07
Frontal Area	2.37 m^2

Figure 1. Selected ICE vehicle for conversion into Electric Vehicle

2.2 Removal of the Powertrain

The next step in the conversion process is the removal of the ICE powertrain and related components. The powertrain components that have to be removed depend on the method of conversion i.e., an ICE vehicle can be converted into an electric vehicle by either replacing the engine and clutch with the motor and operating the vehicle with the existing gearbox in a fixed reduction or by replacing the entire ICE powertrain unit with the Electric powertrain unit. The aforementioned process is more cost-effective than the latter. The stripped vehicle has to be observed or studied for possibilities of mounting the Electric powertrain unit, and electrical and electronic components of the vehicle.

2.3 Sizing of Motor, Controller, and Battery

This paper deals with the electric LCV in urban driving conditions. The speed of the vehicle is limited to 50 kmph. Numerical analysis was performed to calculate the power required by the vehicle to achieve the speed of 50 kmph with its GVW (1950 kg) at a ruling gradient of 3.3 % in a plain rolling area [13].

The total driving resistance (in N) of the vehicle is calculated as follows:

$$F_{resistance} = F_r + F_w + F_g \tag{1}$$

Where F_r = Rolling resistance force (in N).

$$F_r = mgC_{rr}(\cos\alpha) \tag{2}$$

Where m is the mass of the vehicle (in kg), g is the acceleration due to gravity (9.81 m/s^2), C_{rr} is the coefficient of rolling resistance, which is 0.01 in this case, and α is the slope of the road (in radians).

F_w = Aerodynamic drag force (in N)

$$F_w = \frac{1}{2}\rho A C_d V^2 \tag{3}$$

Where ρ is the density of air (1.2 kg/m^3), A is the frontal area of the vehicle, which is 2.37 m^2 in this case, C_d is the drag coefficient of the vehicle, and V is the velocity of the vehicle (in m/s).

F_g = Gradient climbing force (in N)

$$F_g = mg(\cos\alpha) \tag{4}$$

Let P (in Watts) be the power required to propel the vehicle. The power required by the vehicle can be calculated as follows:

$$P = VF_{resistance} \tag{5}$$

Let T_w be the torque (in Nm) at the wheels and r be the tire rolling radius (in m). Let $\eta_{powertrain}$ be the efficiency of the powertrain which is operating with the overall gear ratio of i_t. Therefore, for N_w wheel speed (in rpm) and T_w torque, N_m will be the required motor speed (in rpm) with T_m torque. The actual power required by the motor P_m (in kW) to propel the vehicle in the drive cycle can be calculated as follows:

$$T_w = F_{resistance}r \tag{6}$$

$$N_m = N_w i_t \tag{7}$$

$$T_m = \frac{T_w}{i_t \eta_{powertrain}} \tag{8}$$

$$P_m = \frac{2\pi N_m T_m}{60000} \tag{9}$$

The motor power required in the drive cycle can also be determined by interpolating the Speed, Torque, and Power values provided by the manufacturer of the motor.

By substituting the corresponding values in Eq. (1), Eq. (2), Eq. (3), and Eq. (4), $F_{resistance}$ is obtained as 1063.8 N, and from Eq. (5), the power required as 14.7 kW, which is 15 kW approximately.

There are several types of motors, at different operating voltages, available in the market. A 96 V PMSM motor with a rated power of 15 kW is considered in this study. The specifications of the motor and the controller are listed in the tables 2 and 3 respectively.

Table 2. Specifications of the Motor.

Parameter	Specification
Motor type	Permanent Magnet Synchronous motor
Rated power	15 kW
Rated Torque	47.7 Nm
Rated speed	3000 rpm
Peak power	30 kW
Peak torque	115 Nm
Peak speed	8000 rpm
Rated current	150 A
Peak current	380 A
Protection level	IP67
Weight	34 kg

Table 3. Specifications of the Controller.

Parameter	Specification
Control Method	PG Vector Control
Rated capacity	18.5 kVA
Peak capacity	40 kVA
Rated current	150 A
Peak current	400 A
Peak torque	115 Nm
Peak speed	8000 rpm
Operating voltage	12 V
Input voltage range	72 – 120 VDC
Protection level	IP67
Weight	6.8 kg

There are various types of cells with different cell chemistries and capacities available for electric vehicle propulsion. Each one has its advantages and disadvantages [14]. Lithium Ion and Lithium Polymer are the most commonly used batteries in electric vehicles due to their high energy density and life span [15]. The battery capacity depends on the range requirement and auxiliaries power consumption of the vehicle. The range of an electric vehicle depends on many factors such as vehicle design, the load of the auxiliaries, driving, environment, etc. [16].

Taking into consideration of the required vehicle power, average ancillary power, and the design limits of the motor and inverter, the battery pack with a configuration of 30 series and 1 parallel (30s1p) cells was designed which gave a nominal voltage of 96 Volt and a total energy capacity of 22.08 kWh (the total energy capacity of the battery can be obtained by the multiplying the cell's nominal voltage, nominal capacity, number of cells in series and number of cells in parallel). The specifications of the cell and the battery pack were listed in the tables 4 and 5 respectively.

Table 4. Specifications of the Cell.

Item	Parameter	Specification
Voltage	Charge voltage	3.65 V
	Nominal voltage	3.2 V
	Discharge voltage	2.5 V
Capacity	Nominal capacity	230 Ah
Current	Max Continuous charge/discharge current	0.5 C/1 C
Energy	Maximum energy	736 Wh
Size	Dimension (Width x Thickness x Height)	173.9 mm x 53.9 mm x 207.2 mm
	Weight	4.14 kg

Table 5. Specifications of the Battery Pack.

Parameter	Specification
Battery pack voltage	96 V
Pack Capacity	230 Ah
Battery energy capacity	22.08 kWh
Battery pack configuration	30 series x 1 parallel
Battery pack weight	124.2 kg
Total enveloping space	80 litres

The mass of the conventional IC engine vehicle is 1050 kg. The mass of the engine is approximately 90 kg and the mass of the fuel tank, radiator and other components collectively is 40 kg. Therefore, the mass of the vehicle without the engine and other components is 920 kg. On the other hand, the mass of the motor is 34 kg, the mass of the Inverter is 6.8 kg, the mass of the battery pack is 124.2 kg, and the mass of the battery envelope and other electric accessories collectively is 40 kg. Therefore, the mass of the retrofitted vehicle is 1125 kg.

2.1 Selecting the vehicle

There are 4 types of charging methods/modes established for electrical vehicles and 4 types of charging ports standardized [15]. The charging method of type 1 (240V 50Hz, Maximum output current of 32A) and charger port of type 1 (SAE-J1772-2009) was selected in this case. The charging time of the battery is 7.2 hours approximately. The charging time of the battery can be calculated in the following way:

$$T_{ch} = \frac{V_{cb} A_{nc}}{V_{ch} A_{maxch}} \tag{10}$$

Where T_{ch} is the Charging time (in hours), V_{cb} is the Charge voltage of the battery (in V), A_{nc} is the nominal capacity of the battery (in Ah), V_{ch} is the output voltage (in V) of the charger and A_{maxch} is the maximum output current (in A) of the charger.

3. Integration

The variation in the weight distribution before and after conversion into an electric vehicle has to be minimum so that there will be minimal changes in the vehicle dynamics. As the selected vehicle is a light commercial vehicle with the payload at the rear, the battery pack has to be placed forward biased on a rigid frame and fully constrained in all directions, by making necessary alterations to the vehicle's frame.

In this case, the wheels are to be driven by the motor through the existing gearbox, propeller shaft, and differential. Both the gearbox input shaft and the motor output shaft have external spline shafts. Therefore, a flange coupling, with a hub with the tooth profile of the gearbox input shaft at one end and the tooth profile of the motor output shaft at the other end should be designed and installed. To keep the performance better and driving convenient, the gearbox has to be locked in the 2nd gear, which offers suitable reduction as per the chosen motor, and eliminates the hassle of gear changing, making the transmission fixed reduction. Though the rest of the gears and components such as the gear shifter, synchronizers, dog clutch, etc. in the gearbox are now made idle, it is advised not to remove them as it could affect the balance of the shafts. The gear selector of an EV replaces the gear shifting lever in an ICE vehicle.

In this Electric vehicle, the clutch is eliminated and so is the clutch pedal. The conventional accelerator pedal of the ICE vehicle has to be replaced with an Electric vehicle accelerator pedal i.e., a pedal with a rotary potentiometer. Since the converted vehicle doesn't have an engine, a vacuum booster for the brakes can be driven by a compressor. The cluster should provide information such as Battery SoC, Range, Battery/Motor temperature, vehicle speed, etc. has to be displayed on the cluster. All the electrical systems and their connections should be adhering to the safety norms and regulations of electric vehicles in India.

4. Evaluation of Vehicle performance

The following are the key parameters of the retrofitted vehicle:

Table 6. Specifications of the vehicle after retrofitting.

Parameter	Specification
Gross Vehicle Weight	1950 kg
Payload	825 kg
Kerb Weight	1125 kg
Gear ratio	11.712:1
Frontal Area	2.37 m2
Tires	155R13 LT 8PR
Max Speed	50 kmph (Limited)
Motor Max power	30 kW
Motor Rated power	15 kW
Battery pack voltage	96 V
Battery pack capacity	230 Ah

4.1 Electrical energy consumption of the vehicle

Generally, Modified Indian Drive Cycle (MIDC) is used to assess the engine emission levels and passenger car fuel economy. The cycle consists of Urban and Extra Urban drive cycles each lasting for 780 and 400 seconds respectively. The Urban drive cycle represents city driving conditions, generally characterised by low vehicle speed. Assuming that the road is straight, flat, and dry, the Urban drive cycle was used to calculate the electrical energy consumption/km, State of Charge (SoC), and an electric range of the vehicle without and with regenerative braking. The distance travelled by the vehicle in the cycle is 3.98 km. Considering the intermittent, continuous, and prolonged loads, the average power required for the auxiliaries in the vehicle is 0.5 kW.

4.1 Energy Consumption of the vehicle with regenerative braking

Regenerative braking in electric vehicles converts most of the kinetic energy of the vehicle while deceleration into electrical energy and charges the battery.

The energy regenerated into the battery is calculated as follows:

The vehicle acceleration/deceleration power (in kW).

$$P_{dec} = \frac{maV}{1000} \tag{10}$$

Where a is the deceleration of the vehicle (in m/s^2).

Braking power (in kW) applied to generate the deceleration,

$$P_{braking} = P_{dec} - P_{roadload} \tag{11}$$

Where $P_{roadload}$ is the deceleration power (in kW) produced due to the road loads.

The energy dissipated (in kWh) due to the applied braking power $P_{braking}$ is:

$$E_{braking} = \frac{P_{braking}}{3600} \tag{12}$$

$P_{braking}$ is considered to be zero when P_{dec} is less than or equal to $P_{roadload}$.

The net regenerative braking energy returned to the battery in the city is 32% [18] and this estimation may vary depending on the different vehicles and different drive cycles [19].

The analysis is carried out initially with a payload of 70 kg only, i.e., the weight of the driver. The energy required to power the auxiliaries is consumed from the battery. So, during the driving conditions, the battery energy is utilised for vehicle propulsion and auxiliaries and during braking, the braking energy recaptured by the electric motor would charge the battery which can compensate for the energy required by the auxiliaries.

The propulsion energy consumed by the vehicle in the drive cycle, E_1, is 0.473 (kWh).

E_2 be the energy consumed by the auxiliaries in the drive cycle (in kWh).

$$E_2 = \frac{P_{aux}T_{dc}}{3600} \tag{14}$$

Where P_{aux} is the average power required by the auxiliaries (in kW), and T_{dc} is the Drive Cycle duration (in seconds).

Therefore, from Eq. (14), E_2 is 0.108 kWh.

The electrical energy recovered from regenerative braking in each cycle, E_3, is 0.129 kWh.

The total energy consumed from the battery per drive cycle with regeneration is:

$$E_b = E_1 + E_2 - E_3 \tag{16}$$

By substituting the corresponding values in Eq. (16), E_b is 0.453 kWh.

Let E be the total electrical energy consumed from the battery per km (in kWh/km) per drive cycle.

$$E = \frac{E_b}{T_{dc}} \tag{15}$$

From Eq. (15), the total electrical energy consumed from the battery in a drive cycle with regenerative braking is 0.113 kWh/km

4.2 Energy consumption of the vehicle without regenerative braking

The analysis is carried out initially with a payload of 70 kg only, i.e., the weight of the driver. The energy required to power the auxiliaries is consumed from the battery. So, during the driving conditions, the battery energy is utilised for vehicle propulsion and auxiliaries and during braking, energy is utilised for auxiliaries.

The propulsion energy consumed by the vehicle in the drive cycle E_1, is 0.473 (kWh).

From Eq. (14), E_2 is 0.108 kWh.

The total energy consumed from the battery per cycle without regeneration is, E_b is the sum of E_1 and E_2, i.e., 0.582 kWh.

Therefore, from Eq. (15), the total electrical energy consumed from the battery in a drive cycle without regenerative braking is 0.146 kWh/km.

Table 7. Electrical energy consumption at various payloads without regenerative braking.

Payload (kg)	Propulsion Energy Requirement/Cycle (kWh)	Battery Energy Consumed/Cycle (kWh)	Electrical Energy Consumption (kWh/km)
70	0.473	0.582	0.146
300	0.518	0.626	0.157
500	0.556	0.665	0.167
700	0.595	0.704	0.177
825	0.619	0.728	0.183

Table 8. Electrical energy consumption at various payloads with regenerative braking.

Payload (kg)	Propulsion Energy Requirement/Cycle (kWh)	Energy recovered/Cycle (kWh)	Battery Energy Consumed/Cycle (kWh)	Electrical Energy Consumption (kWh/km)
70	0.473	0.129	0.453	0.113
300	0.518	0.159	0.467	0.117
500	0.556	0.184	0.481	0.120
700	0.595	0.210	0.494	0.124
825	0.619	0.226	0.502	0.126

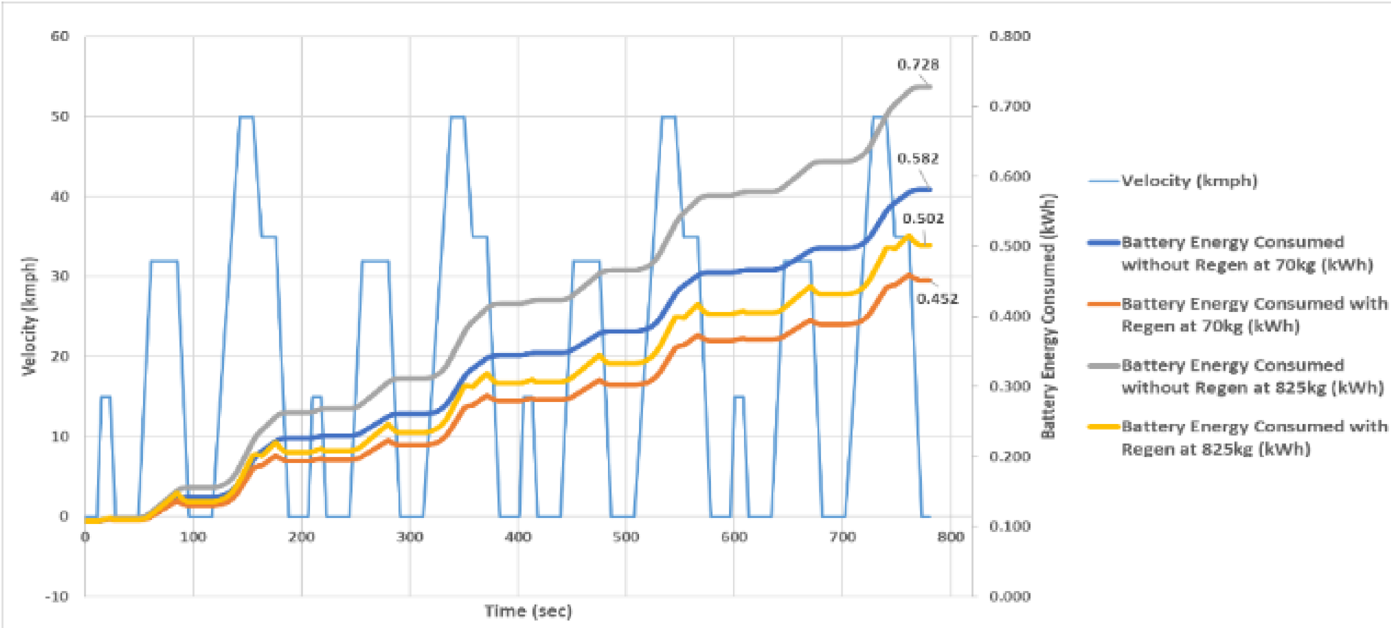


Figure 2. Battery energy consumption in the Drive Cycle

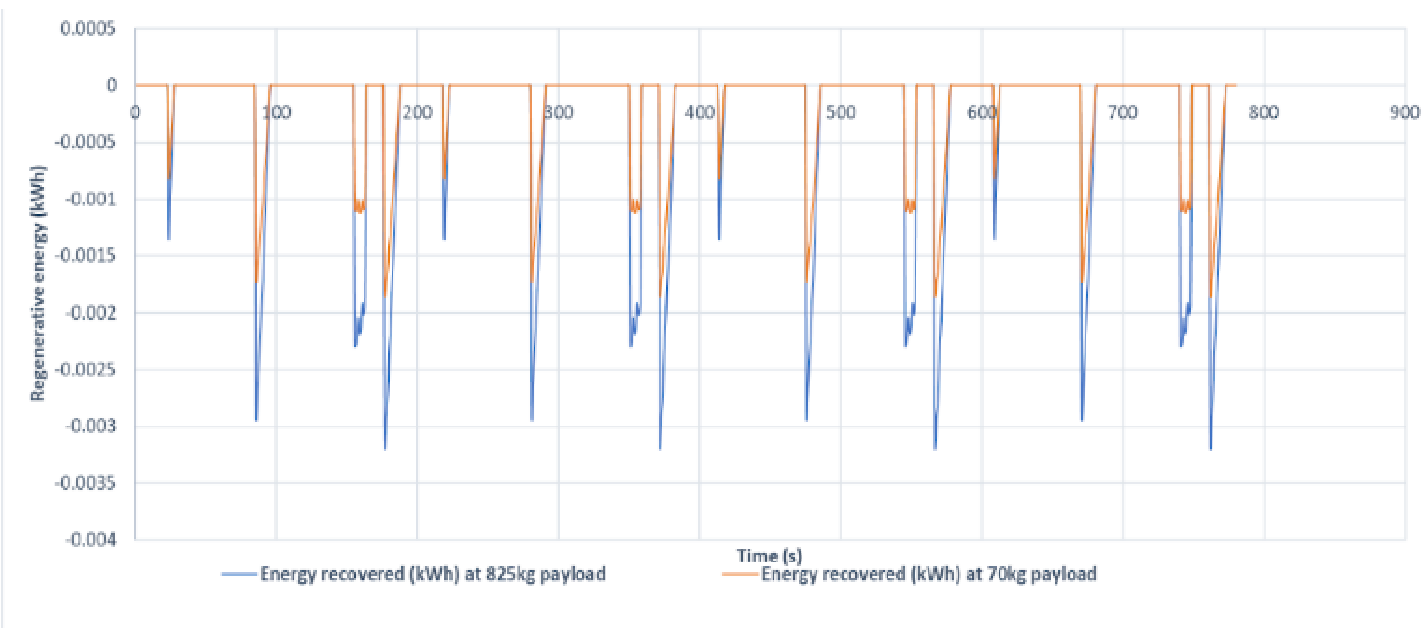


Figure 3. Comparison of Regeneration energy at 70 kg and 825 kg payload

4.3 Range of the vehicle

The range of an electric vehicle can be calculated by dividing the available electrical energy in the battery (in kWh) by the electrical energy consumption of the vehicle per km Eq. (15). Only 10 – 90 % of the battery capacity is used to maximise the battery life. The range of the vehicle without and with regenerative braking at various payloads was calculated and tabulated as follows:

Table 9. Range of the vehicle at various payloads without and with regenerative braking.

Payload (kg)	Theoretical Range without Regenerative braking (km)	Theoretical Range with Regenerative braking (km)
70	120.7	155.3
300	112.1	150.2
500	105.65	146.1
700	99.8	142.2
825	96.5	139.9

4.4 Maximum gradeability of the vehicle

The gradeability of the vehicle is determined using Eq. (17).

$$Gradeability\ \% = 100\left(\frac{F_t}{g \times GVW} - C_{rr}\right) \quad (17)$$

Where F_t is the Tractive force, which can be calculated in the following way:

$$F_t = \frac{T_m \eta_{powertrain} i_t}{r} \quad (18)$$

By substituting the corresponding values in Eq. (17), the gradeability of the vehicle is 22.1%.

4.5 Cost comparison of ICE and Retrofitted EV

The cost of owning and operating an ICE vehicle and an Electric vehicle can be compared directly. The owing cost of the selected ICE vehicle is approximately ₹6,50,000.

Approximately 10 kWh of energy is available in 1 litre of diesel. The mileage of the selected ICE vehicle is approximately 18 kmpl.

Assuming the usage of 100,000 km in 5 years, the fuel consumption can be calculated in the following way:

$$Fuel\ Consumed = \frac{Distance\ travelled}{Mileage} \quad (19)$$

By substituting the corresponding values in Eq. (19), the fuel consumption of the selected vehicle for 5 years is 5,555.5 litres.

The diesel price for one litre in India is ₹90, therefore the total fuel expenses for 5 years will be ₹5,00,000. And the total service and maintenance costs, and costs of spares for 5 years account for approximately ₹1,50,000, under normal operating conditions.

Therefore, the total owning and operating cost of an ICE vehicle for five years is the sum of owning cost, fuel expenses, and maintenance cost, i.e., ₹13,00,000.

The energy consumption of the ICE vehicle can be calculated by using Eq. (20).

$$Energy\ consumption = E_f F_c \eta_E \quad (20)$$

Where E_f is the energy available per litre of fuel (in kWh), F_c is the fuel consumption per kilometre (in litre/km) by the vehicle, and η_E (=30%) is the efficiency of the vehicle's engine. By substituting the corresponding values in Eq. (20), the energy consumption of the ICE vehicle is 0.167 kWh/km.

The resale value of the selected ICE vehicle after 10 years is ₹250,000 approximately.

The total cost incurred for converting, (i.e., the sum of costs of the old vehicle, battery pack, motor, controller, supporting electrical and electronic equipment, and miscellaneous), the selected vehicle into a pure Electric vehicle is approximately ₹8,50,000. And the maintenance cost, i.e., brakes, lubrication, cost of spares, etc. of the Electric vehicle for 5 years will be ₹80,000 approximately under normal operating conditions.

The cost of electrical energy is ₹8.24/kWh [20]. Then the total cost incurred in charging the vehicle over 5 years i.e., 1,00,000 km with a charging efficiency of 80% is:

$$Cost\ of\ Charging = \frac{E \times Cost\ electrical\ energy \times Distance\ travelled}{Charging\ efficiency} \quad (21)$$

By substituting the corresponding values in Eq. (21), the cost of charging the vehicle for 5 years is ₹1,17,000.

Therefore, the total cost of owning and operating a converted or retrofitted Electric vehicle for 5 years is the sum of conversion cost, cost of charging or operating cost, and maintenance cost, i.e., ₹10,47,000.

The cost of owning the new similar Electric Vehicle, as per the market at the time of writing this paper, is approximately ₹14,00,000.

Therefore, the total cost of owning and operating a new Electric vehicle for 5 years is the sum of owing cost, cost of charging or operating cost, and maintenance cost, i.e., ₹16,00,000.

From the above calculations, we can observe that the operating and maintenance cost of an Electric vehicle are less than that of an ICE vehicle, though the initial cost of an Electric vehicle is high. And the total cost of a converted Electric vehicle for five years is 20% less than the total cost of a new ICE vehicle and 35% less than a new Electric vehicle for 5 years.

5. Results and discussion

The Evaluation of the conversion of the ICE 4-Wheeler Light commercial vehicle was carried out. The electrical energy consumption/km, SoC, and range of the vehicle were determined using Modified Indian Drive Cycle- Part 1 at various payloads without and with regenerative braking.

At 70 kg payload, the electrical energy consumed was 0.113 kWh/km and at the payload of 825 kg, the energy consumed was 0.126 kWh/km with regenerative braking. The calculations showed that the range of the vehicle with Regenerative braking was 155.3 km and 139.9 km at 70 kg and 825 kg payload respectively. On the other hand, the energy consumed by the ICE vehicle was 0.167 kWh/km, and to achieve a similar range as the retrofitted vehicle at 70 kg payload, i.e. 155.3 km, the fuel required was 8.62 litres and the CO_2 emissions were 146.5 gm/km. Electric vehicles don't produce any CO_2 emissions while operating.

The maximum gradeability of the vehicle was 22.10%. A cost comparison study of both vehicles was carried out. The cost of operation of the retrofitted EV and ICE vehicle for 5 years is ₹1,97,000 and ₹6,50,000 respectively. The total cost incurred for conversion was ₹8,50,000 and the total cost for 5 years was approximately ₹10,47,000.

7. Conclusions

The conversion process of an ICE vehicle into a pure electric vehicle is presented in this paper. Though the conversion process discussed was for a Light Commercial Vehicle, the conversion procedure remains more or less the same for any vehicle. Sizing of the motor, controller, and battery pack was done. The mathematical model of the retrofitted EV in the Modified Indian Drive Cycle- Part 1 was developed and numerical analysis was carried out at various payloads with and without regenerative braking to evaluate the performance of the vehicle. The total cost i.e. sum of owing cost, operating cost, and maintenance cost of a converted Electric vehicle for 5 years is approximately 20% less than that of a new ICE vehicle and 35% less than that of a new Electric vehicle. The higher initial cost, charging infrastructure, and range anxiety are the major reasons for people stepping back to buy an Electric vehicle. This study shows that one of the ways to overcome the higher initial cost is by converting the existing ICE vehicles into Electric vehicles. The Government of India should also provide subsidies for EV retrofitting with which the cost parity with new ICE and electric vehicles can be achieved. Electric vehicles don't emit particulates while in operation. But, are still associated with the emissions produced while manufacturing, charging, and recycling. The charging infrastructures which use renewable resources of energy such as solar, wind, etc. have to be developed to reduce the emissions associated with EV charging and also to lower the costs incurred for charging the battery of the vehicle.

Acknowledgment

We are thankful to all our well-wishers for their inspiration and help. We take this opportunity to express our deepest gratitude and appreciation to those who have helped us directly or indirectly towards the successful completion of this.

Nomenclature

$F_{resistance}$	The total driving resistance of the vehicle (N)
F_r	Rolling resistance force (N)
F_g	Gradient climbing force (N)
F_w	Aerodynamic drag force (N)
m	Mass of the vehicle (kg)
g	Acceleration due to gravity (m/s^2)
C_{rr}	Coefficient of rolling resistance
α	Slope of the road (rad)
ρ	Density of air (kg/m^3)
A	Frontal area of the vehicle (m^2)
C_d	Drag coefficient of the vehicle
V	Velocity of the vehicle (m/s)
P	Power required to propel the vehicle (W)
T_w	Torque at the wheels (Nm)
r	Tire rolling radius (m)
$\eta_{powertrain}$	Efficiency of the powertrain
i_t	Overall gear ratio of the drivetrain
N_w	Speed of the wheel (rpm)
N_m	Speed of the motor (rpm)
T_m	Torque of the motor (Nm)
P_m	Power of the motor (kW)
P_{dec}	Power required to decelerate the vehicle (kW)
a	Deceleration of the vehicle (m/s^2)
$P_{roadload}$	Deceleration power due to road load (kW)
$P_{braking}$	Applied braking power (kW)
$E_{braking}$	Energy dissipated due to applied braking powe r (kWh)
T_{ch}	Charging time (h)
V_{ch}	Charge voltage of the battery (V)
A_{nc}	Nominal capacity of the battery (Ah)
V_{ch}	Output voltage of the charger (V)
A_{maxch}	Maximum output current of the charger (A)
E_1	Propulsion energy consumed by the vehicle in the drive cycle (kWh)
E_2	Energy consumed by the auxiliaries in the drive cycle (kWh)
P_{aux}	Average power required by the auxiliaries (kW)
T_{dc}	Drive cycle duration (s)
E_b	Total energy consumed from the battery per drive cycle (kWh)
E	Total electrical energy consumed from the battery per km (kWh/km)
E_3	Electrical energy recovered from regenerative b ra king in each cycle (kWh)
F_t	Tractive force (N)
E_f	Energy available per litre of fuel (kWh)
F_c	Fuel consumption per kilometer (litre/km)
η_E	Efficiency of the vehicle's engine

Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

CRediT Author Statement

P. Vijay Sai Goud: Conceptualization, Data curation, Writing-original draft, Investigation.

A. Sai Venkata Phanindra Chary: Conceptualization, Writing-review & editing, Investigation.

References

1. New Climate Institute, (2020). Decarbonising the Indian Transport sector pathways and policies, Available at: https://climateaction-tracker.org/documents/832/CAT_2020-12-09_Report_DecarbonisingIndianTransportSector_Dec2020.pdf
2. Bieker G., (2021). A Global comparison of the Life-cycle Greenhouse gas emissions of Combustion Engines and Electric passenger cars. The International Council of Clean Transportation.
3. Megha K, Zhenying S, Caleb B, and Anup B., (2022). Decarbonizing India's road transport: A meta-analysis of road transport emissions models. The International Council on Clean Transportation.
4. The Energy and Resources Institute, (2020). Road map for electrification of urban freight in India. Shakti Sustainable Energy Foundation.
5. Transport Research Wing. Road Transport Year book 2017-18 & 2018-19, (2019). Ministry of Road Transport & Highways, Government of India, Available at: athttps://morth.nic.in/print/road-transport-year-books
6. Silva J E, Urbanetz J., (2019). Converting a conventional vehicle into an electric vehicle (EV). Braz. Arch. Biol. and Technol., 62:1–12.
7. Ministry of Road Transport & Highways, (2022). The Central Motor Vehicle Rules, 1989. New Delhi: Commercial Law Publishers (India) Pvt. Ltd., Government of India.
8. Ministry of Road Transport & Highways, (2017), CMVR Type Approval of Electric Propulsion Kit Intended for Conversion of Vehicles for Pure Electric Operation. ARAI, India, Available at: https://www.araiindia.com/downloads
9. IBEF, (2022). Vehicle Scrappage Policy, Available at:

https://www.ibef.org/blogs/vehicle-scrappage-policy#:~:text=According%20to%20the%20new%20policy,the%20fitness%20and%20emission%20tests (Date of Access: 7.7.2022).

10. The Economic Times, (2020). The lifecycle of a car in India: From being sold again to finally being scrapped, Available at: https://economictimes.indiatimes.com/industry/auto/cars-uvs/the-lifecycle-of-a-car-in-india-from-being-sold-again-to-finally-being-scrapped/lifecycle-of-a-discarded-car/slideshow/78789283.cms (Date of access: 7.7.2022).
11. Vrazic M, Vuljaj D, Pavasovic A, and Paukovic H., (2014). Study of a vehicle conversion from internal combustion engine to electric drive. ENERGYCON 2014 - IEEE Int. Ener. Conf. 1544–1548.
12. Tata Motors Limited, (2022). Tata Ace HT+, Available at: https://ace.tatamotors.com/mini-truck/tata-ace-gold/tata-ace-gold-ht-plus.aspx (Date of Access: 4.8.2022).
13. Deloney M. L., (2014), Gradient of road, Available at: https://civiljungle.com/limiting-gradient/ (Date of Access: 17.7.2022).
14. Larminie J, Lowry J., (2012). Electric Vehicle Technology Explained. 2nd ed. John Wiley & Sons Ltd.
15. Sanguesa J. A., Torres-Sanz V., Garrido P., Martinez F. J., Marquez-Barja J. M., (2021). A review on electric vehicles: Technologies and challenges. Smart Cities, 4(1):372–404.
16. Varga B. O., Sagoian A., Mariasiu F., (2019). Prediction of electric vehicle range: A comprehensive review of current issues and challenges. Energies, 12(5).
17. EVE Energy North America, (2022). Prismatic LFP Specifications, Available at: https://www.evebatteryusa.com/copy-of-18650-and-21700-specifications (Date of Access: 7.7.2022).
18. Gyanesh V., (2022). Regenerative Braking System in Electric Vehicles and how it works?, Available at: https://e-vehicleinfo.com/regenerative-braking-system-in-electric-vehicles/ (Date of Access: 7.7.2022).
19. Office of Energy Efficiency & Renewable Energy, (2022), Where the Energy Goes: Electric Cars, Available at: https://www.fueleconomy.gov/feg/atv-ev.shtml (Date of Access: 8.7.2022).
20. Globalpetrolprices.com, (2022). Indian Electricity Prices, Available at: https://www.globalpetrolprices.com/India/electricity_prices/ (Date of Access: 8.7.2022).