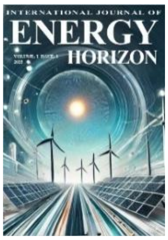
International Journal of Energy Horizon

International Journal of Energy Horizon

journal homepage: https://dergipark.org.tr/tr/pub/ijeh



Research Article

Dynamic Modeling and Performance Analysis of A Hydrogen Fuel Cell-Battery Hybrid Excavator Powertrain System

Ekin Can Kayar[1],*
[1]Hidromek A.Ş., Ankara, Türkiye
[1]ORCID No: 0009-0004-4191-587X

ARTICLE INFO

Article History:

Received: 12 January 2026
Revised: 17 April 2026
Accepted:18 April 2026
Available Online: 11 May 2026

Keywords:

Heavy-Duty Vehicles
Hydrogen Fuel Cell
Battery
Hybrid Excavator
Hydrogen Storage

ABSTRACT

This study presents a system-level modeling and numerical analysis of a hydrogen fuel cell–battery hybrid powertrain for heavy-duty construction machinery. The hydrogen storage and supply process, as well as the operating principles of the fuel cell–battery system, are described, and a DC bus-based power-sharing architecture is developed. In the proposed configuration, the fuel cell is responsible for supplying the average power demand, while the battery supports transient and peak load requirements. Numerical simulations are performed based on time-dependent power demands representative of excavator operation. The results demonstrate that the proposed hybrid system can effectively meet dynamic power requirements while maintaining stable operation. The fuel cell provides a continuous and stable power output, whereas the battery compensates for rapid load variations. The battery state of charge (SOC) remains within a controlled range, indicating the effectiveness and sustainability of the implemented rule-based power-sharing strategy. The developed model aligns with recent studies on fuel cell hybrid excavators; however, unlike optimization-based approaches, this work focuses on a simplified and practical system-level model combined with a rule-based energy management strategy suitable for real-time applications. The findings indicate that the proposed hybrid system offers a promising alternative to conventional diesel- powered excavators in terms of operational stability, efficiency, and emission reduction. The developed modeling framework provides a foundation for future studies on advanced energy management strategies and realistic duty cycle analyses.

1. INTRODUCTION

Heavy-duty construction machinery operates under demanding conditions requiring high power and robustness. Diesel engines have been widely used in such applications due to their durability and high performance. However, increasing environmental concerns, stringent emission regulations, and global sustainability targets have necessitated the development of alternative power systems for heavy-duty vehicles [1]. Among these alternatives, hydrogen-based energy systems have attracted significant attention due to their zero-emission operation and high energy density. Proton exchange membrane fuel cells (PEMFCs) convert chemical energy directly into electrical energy with high efficiency and stable output characteristics. However, fuel cells alone are not well suited to meet highly dynamic and transient power demands, such as those encountered in excavator operations [2]. Excavators operate under highly variable load conditions, resulting in fluctuating power demands over time. In such systems, fuel cells are typically used to supply the average power demand, while peak and transient loads are handled by auxiliary energy storage systems. Therefore, fuel cell–battery hybrid architectures have emerged as a promising solution for heavy-duty construction machinery applications [1]. To effectively manage power distribution in hybrid systems, various energy management strategies (EMS) have been developed. These strategies can be broadly classified into rule- based, optimization-based, and predictive approaches. Rule-based EMS are widely preferred due to their simplicity, robustness, and real-time applicability. In contrast, optimization-based methods such as Dynamic Programming (DP) and Pontryagin's Minimum Principle (PMP) aim to achieve global optimality but are computationally intensive. Predictive strategies, including Model Predictive Control (MPC), utilize future load estimations to improve performance but require accurate system models and high computational effort. Therefore, the selection of EMS plays a critical role in the performance and feasibility of hybrid systems [3]. In recent years, several studies have investigated hybrid hydrogen-powered excavator systems and advanced EMS approaches. For instance, Do et al. proposed a hybrid excavator system combining a fuel cell, battery, and supercapacitor, demonstrating improved energy efficiency and extended component lifespan through advanced control strategies [4]. Similarly, Li et al. analysed energy management and economic performance of hybrid excavators, highlighting the importance of optimal power distribution for reducing hydrogen consumption [5]. Zhao et al. provided a comprehensive classification of EMS approaches, emphasizing the significance of control strategy design in hybrid systems [6]. More advanced EMS approaches have also been explored in the literature. Truong et al. proposed a fuzzy logic-based EMS for a PEM fuel cell–battery–supercapacitor hybrid excavator, achieving improved efficiency and adaptive power sharing under dynamic conditions [7]. Trinh et al. developed an optimization-based EMS framework to minimize hydrogen consumption and enhance system efficiency [8], while Trinh et al. introduced a comprehensive control strategy integrating multiple control layers for improved system stability and performance [9]. In addition, Dao et al. proposed a hybrid optimization–fuzzy EMS, demonstrating enhanced system performance compared to conventional rule-based methods [10]. Similar hybrid architectures and advanced energy management strategies have been extensively investigated in the literature. However, most existing studies focus on complex optimization- based or intelligent control methods, often requiring high computational effort and detailed system modeling. In contrast, the present study focuses on the development of a simplified and practical system-level model of a hydrogen fuel cell–battery hybrid excavator, combined with a rule-based energy management strategy suitable for

---

*Corresponding author
E-mail address: ekincnkayr@gmail.com
journal homepage: https://dergipark.org.tr/tr/pub/ijeh
https://izlik.org/JA94KW99WB

real-time implementation in heavy-duty applications. The main contribution of this study lies in the system-level modeling of the hybrid architecture, the implementation of a robust rule-based power-sharing strategy, and the evaluation of dynamic system behaviour under transient operating conditions. Unlike previous studies that emphasize optimal control, this work prioritizes engineering applicability, simplicity, and real- time feasibility, providing valuable insights into the design and operation of hydrogen-based hybrid construction machinery. In this study, a hydrogen fuel cell–battery hybrid excavator system is modeled at the system level and analysed using numerical simulations. The power demand characteristics of the excavator are evaluated, and the impact of the proposed power-sharing strategy on system performance is investigated. The results demonstrate that the hybrid system can effectively meet dynamic power requirements while maintaining stable operation.

2. SYSTEM STRUCTURE AND SYSTEM MODELING

The system's main power source is a PEM fuel cell system. Its operating principle is the conversion of hydrogen, stored in high-pressure tanks, into electrical energy through electrochemical reactions. The fuel cell is positioned to generate electricity regularly to meet the excavator's average power needs [11]. The fuel cell system cannot respond to sudden load changes. Therefore, a battery energy storage unit is used in the system. The battery system is connected to the DC bus via a bidirectional DC/DC converter. This allows it to operate in both charging and discharging states. The battery system supports the fuel cell when the machine has high power requirements. When the machine has low power requirements, the excess electrical energy produced by the system can be stored in the battery. This structure increases the system's efficiency and stabilizes power sharing [12]. Electrical energy supplied by fuel cell and battery systems is transferred to the electric motor via an inverter through the DC bus. The mechanical power produced by the electric motor is converted into hydraulic energy by means of a hydraulic pump. The excavator's field operations are carried out through this hydraulic system [12]. Figure 1 summarizes the main components of a hydrogen fuel cell-battery hybrid excavator system and the energy flow between these components.

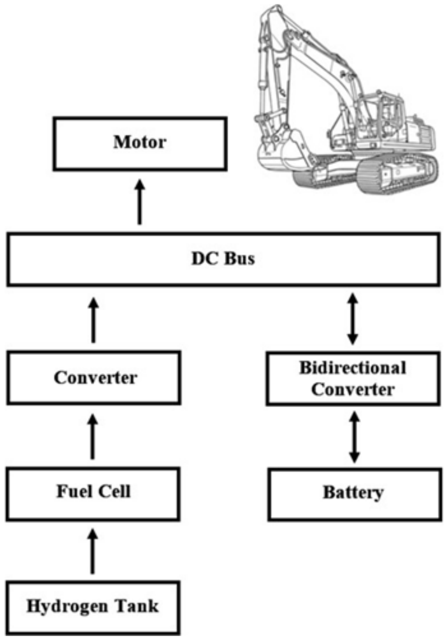


Figure 1. System Structure of a Hydrogen Fuel Cell-Battery Hybrid Excavator

2.1. Hydrogen Filling Process and Storage System

In the hydrogen fuel cell-battery hybrid excavator, the hydrogen storage system is refueled from an external hydrogen fuel station. During the refueling process, hydrogen is stored within safe operating limits. The hydrogen refueling infrastructure is resistant to 350 bar pressure. The time-dependent change in the mass of hydrogen in the tank during refueling is expressed by the mass balance

$$m_{H_2}(t) = m_{H_2,0} + \int_0^t \dot{m}_{H_2}(\tau)\,d\tau \tag{1}$$

Here, $m_{H2}\ (t)$ represents the mass of hydrogen in the tank at time t (kg), $m_{H2,0}$ represents the initial mass of hydrogen (kg), $\dot{m}_{H2}$ represents the mass flow rate of hydrogen entering the tanks (kg/s), and t represents time (s). Assuming a constant average filling rate, the filling time is defined as follows [13]:

$$t_{fill} \approx \frac{\Delta m_{H2}}{\dot{m}_{H2}} \tag{2}$$

Here, t_{fill} represents the hydrogen filling time (s), Δm_{H2} represents the total mass of hydrogen added to the tank (kg), and Δm_{H2} represents the average hydrogen filling rate (kg/s). During the filling process, the pressure-temperature-mass relationship inside the tank is expressed at the system level by the ideal gas equation [13]:

$$PV = mR_{H_2}T \tag{3}$$

Here, P represents the internal pressure of the tank (Pa), V the internal volume of the tank (m^3), m the mass of hydrogen in the tank (kg), T the internal temperature of the tank (K), and R_{H_2} the specific gas constant of hydrogen ($J\cdot kg^{-1}\cdot K^{-1}$). During filling, pressure and temperature tend to rise due to the increase in the mass of hydrogen in the tank. Therefore, the filling process is monitored to ensure it remains within safe operating limits.

2.2. Hydrogen Feeding to the Fuel Cell

In a hydrogen fuel cell-battery hybrid excavator, hydrogen is transferred from storage tanks to the fuel cell. The hydrogen is delivered to the anode side under controlled pressure and flow rate. Inside the fuel cell, it undergoes electrochemical reactions. The mass flow rate of hydrogen fed into the fuel cell is related to the electrical power produced by the fuel cell. This relationship, taking into account the energy conversion efficiency of the fuel cell, is expressed as follows [14]:

$$\dot{m}_{H2} = \frac{P_{FC}}{\eta_{FC} \times LHV_{H2}} \tag{4}$$

Here, $\dot{m}_{H2}$ represents the mass flow rate of hydrogen fed into the fuel cell (kg/s), P_{FC} represents the electrical power (W) produced by the fuel cell, η_{FC} represents the electrical efficiency of the fuel cell, and LHV_{H2} represents the lower calorific value of hydrogen (J/kg). The pressure of the hydrogen entering the fuel cell is reduced via regulators. It is maintained at a level suitable for the operating requirements of the fuel cell. The mass flow rate and pressure of hydrogen at the fuel cell anode inlet are adjusted according to the power demand. The portion of hydrogen participating in electrochemical reactions in the fuel cell is defined by the following relationship [14]:

$$\dot{m}_{H2,reacted} = \frac{IM_{H2}}{2F} \tag{5}$$

Here, $\dot{m}_{H2,reacted}$ represents the mass flow rate of reacting hydrogen (kg/s), I represents the total electric current drawn by the fuel cell (A), m_{H2} represents the molar mass of hydrogen (kg/mol), and F is the Faraday constant (C/mol). The total hydrogen flow rate fed into the fuel cell includes the amount of excess hydrogen used to manage in-cell gas and ensure operational stability. Therefore, the fuel cell supply is controlled in direct relation to power demand.

2.3. PEM Fuel Cell System

A proton exchange membrane (PEM) fuel cell is an energy converter that directly converts the chemical energy of hydrogen into electrical energy through electrochemical reactions. In a PEM fuel cell, hydrogen reacts at the anode and oxygen at the cathode. This process produces electrical energy, heat, and water. The basic electrochemical reactions that take place in a PEM fuel cell are as follows [15]:

Anode reaction [15]:

$$H_2 \rightarrow 2H^+ + 2e^- \tag{6}$$

Cathode reaction [15]:

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \tag{7}$$

Total cell reaction [15]:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \tag{8}$$

The electron flow resulting from these reactions creates the electrical output of the fuel cell. The instantaneous electrical power of the fuel cell is defined by the relationship between the cell voltage and current [15]:

$$P_{FC} = V_{FC} I_{FC} \tag{9}$$

Here, PFC represents the electrical power (W) produced by the fuel cell, VFC represents the output voltage (V) of the fuel cell, and IFC represents the electrical current (A) drawn from the fuel cell. The theoretical reversible stress of a PEM fuel cell is expressed by the Nernst equation [15]:

$$E = E^0 + \frac{RT}{2F} \ln\left(\frac{P_{H2} P_{O2}^{1/2}}{P_{H_2O}}\right) \tag{10}$$

Here, E represents the reversible voltage of the cell (V), E^0 the standard cell voltage (V), R the universal gas constant (J·mol⁻¹·K⁻¹), T the cell temperature (K), F the Faraday constant (C·mol^{-1}), and P_{H2} , $P_{O2}^{1/2}$, P_{H_2O} the partial pressures (Pa) of hydrogen, oxygen, and water, respectively. Under actual operating conditions, the cell voltage is lower than the theoretical reversible voltage due to activation, ohmic, and concentration losses. The electrical efficiency of a fuel cell is defined as the ratio of the electrical power produced to the chemical energy input of hydrogen [15]:

$$\eta_{FC} = \frac{P_{FC}}{\dot{m}_{H2} LHV_{H2}} \tag{11}$$

Here, η_{FC} represents the electrical efficiency of the fuel cell, $\dot{m}_{H2}$ represents the mass flow rate of hydrogen fed into the fuel cell (kg/s), and LHV_{H2} represents the lower calorific value of hydrogen (J/kg). PEM fuel cells are operated to meet average power needs. They do not meet sudden power demands. Therefore, the fuel cell is positioned as the primary power source in a hybrid powertrain system.

2.4. Battery System

The battery provides power to meet sudden power needs and stores energy in the hybrid excavator. It ensures the efficient operation of the system. The electrical energy stored by the battery is expressed in terms of battery voltage and capacity as follows [16]:

$$E_{BAT} = V_{BAT} Q_{BAT} \tag{12}$$

Here, E_{BAT} represents the electrical energy stored in the battery (J), V_{BAT} is the rated voltage of the battery system (V), and Q_{BAT} is the electrical capacity of the battery (C). The instantaneous electrical power of a battery is defined by the relationship between battery voltage and current [16]:

$$P_{BAT} = V_{BAT} I_{BAT} \tag{13}$$

Here, $PBAT$ represents the electrical power (W) of the battery, and $IBAT$ represents the battery current (A). Positive battery power indicates that the battery is discharged; negative battery power indicates that the battery is charged. The battery's state of charge (SOC) is defined as the ratio of the amount of available energy stored in the battery to its nominal capacity [16]:

$$SOC = \frac{Q_{BAT,(t)}}{Q_{BAT,nom}} \tag{14}$$

Here, SOC represents the battery's charge status, $Q_{BAT,(t)}$ represents the battery capacity as a function of time (C), and $Q_{BAT,nom}$ represents the battery's nominal capacity (C).

The change in battery charge status over time is expressed as follows [16]:

$$\frac{dSOC}{dt} = -\frac{I_{BAT}}{Q_{BAT,nom}} \tag{15}$$

Here, $dSOC/dt$ represents the rate of change of the battery charge status (s⁻¹). The battery's energy efficiency is defined as follows, representing the electrical losses that occur during the charging and discharging processes [16]:

$$\eta_{BAT} = \frac{E_{out}}{E_{in}} \tag{16}$$

Here, η_{BAT} represents the energy efficiency of the battery, E_{out} represents the electrical energy drawn from the battery (J), and E_{in} represents the electrical energy supplied to the battery (J). In hybrid powertrain systems, the battery system meets short-term high-power needs. It is used to store electrical energy produced during regenerative energy recovery. The battery is positioned as an energy storage element. The fuel cell is considered an energy source responsible for continuous power generation.

2.5. DC Bus Structure and Power Sharing

In a hydrogen fuel cell-battery hybrid excavator, the fuel cell and battery systems are connected to a common DC bus. The DC bus allows energy sources with different voltage levels to be combined at a common voltage level and transferred to the load side in a controlled manner. The fuel cell is connected to the DC bus via a one-way DC/DC converter, while the battery system is integrated into the DC bus via a bidirectional DC/DC converter. The electrical energy drawn from the DC bus is converted to alternating current via an inverter and transmitted to the electric motor. The power balance at the DC bus level is expressed [17]:

$$P_{DC}(t) = P_{FC}(t) + P_{BAT}(t) \tag{17}$$

Here, $P_{DC}(t)$ represents the total electrical power (W) transferred from the DC bus to the load, $P_{FC}(t)$ represents the electrical power supplied from the fuel cell to the DC bus (W), and $P_{BAT}(t)$ represents the electrical power supplied from or transferred to the battery from the battery to the DC bus (W). Additionally, $P_{BAT}(t)$ > 0 indicates battery discharge, and $P_{BAT}(t)$ < 0 indicates battery charge. The power transferred from the DC bus to the electric motor is defined as follows, considering the inverter efficiency [17]:

$$P_{AC} = \eta_{inv} P_{DC} \tag{18}$$

Here, P_{AC} represents the alternating current power (W) transmitted to the electric motor at the inverter output, η_{inv} represents the inverter efficiency, and P_{DC} represents the DC bus power (W). The power transferred from fuel cell and battery systems to the DC bus can be written as follows, considering the efficiencies of the relevant power electronics converters [17]:

$$P_{DC,FC} = \eta_{DC/DC,FC} P_{FC} \tag{19}$$

$$P_{DC,BAT} = \eta_{DC/DC,BAT} P_{BAT} \tag{20}$$

Here, $P_{DC,FC}$ represents the power transferred from the fuel cell to the DC bus (W), $P_{DC,FC}$ represents the power transferred from the battery to the DC bus (W), $\eta_{DC/DC,FC}$ represents the DC/DC converter efficiency on the fuel cell side, and $\eta_{DC/DC,BAT}$represents the DC/DC converter efficiency on the battery side. The DC bus architecture allows for flexible power sharing between the fuel cell and the battery. The fuel cell meets average power needs, while the battery meets instantaneous power needs. The power transferred to the electric motor is provided in a controlled manner through to this structure.

2.6. Electric Motor and Hydraulic Power Conversion

In a hydrogen fuel cell-battery hybrid excavator, the electric motor converts electrical energy into mechanical energy. The electric motor is powered by current, controlled by an inverter. This creates rotational motion in the motor shaft, generating mechanical energy. The output power of an electric motor is expressed by the relationship between the torque and angular velocity at the motor shaft [18]:

$$P_{mech} = T_m \omega_m \tag{21}$$

Here, P_{mech} represents the mechanical output power (W) at the motor shaft, T_m represents the torque (N·m) produced by the motor, and ω_m represents the angular velocity (rad/s) of the motor. The mechanical output power of an electric motor is defined as follows, considering the electrical input power of the motor and the motor efficiency [18]:

$$P_{mech} = \eta_m P_{AC} \tag{22}$$

Here, η_m represents the efficiency of the electric motor, and P_{AC} represents the electrical power (W) supplying the motor at the inverter output. The mechanical power obtained from the engine shaft is transmitted to the hydraulic pump to drive the excavator's hydraulic system. The hydraulic power produced by the hydraulic pump is expressed in terms of pressure and volumetric flow rate as follows [18]:

$$P_{hyd} = \Delta p Q \tag{23}$$

Here, P_{hyd} represents the hydraulic power output (W), Δp the pressure difference across the hydraulic pump (Pa), and Q the volumetric flow rate of the hydraulic fluid (m³/s). The power transmitted from the motor shaft to the hydraulic pump can be related to the pump efficiency as follows [18]:

$$P_{hyd} = \eta_p P_{mech} \tag{24}$$

Here, η_p represents the mechanical-hydraulic conversion efficiency of the hydraulic pump. With the combination of an electric motor and a hydraulic pump, electrical energy is converted into mechanical and hydraulic energy. This energy is used to power the excavator's field operations. This conversion ensures the electric motor operates with high efficiency.

2.7. Excavator Power Demand Characteristics

The power requirements of a hydrogen fuel cell-battery hybrid excavator vary depending on the field operations. The machine's instantaneous total power requirement is defined through the mechanical power transferred from the electric motor to the hydraulic system [19]:

$$P_{load}(t) = P_{hyd}(t) \tag{25}$$

Here, $P_{load}(t)$ represents the total power requirement of the machine as a function of time (W), and $P_{hyd}(t)$ represents the hydraulic power transferred to the hydraulic system (W). The machine's power requirement can be defined as the average power requirement, calculated by averaging the power requirements over time [19]:

$$P_{avg} = \frac{1}{T}\int_{0}^{T} P_{load}(t)dt \tag{26}$$

Here, P_{avg} represents the average power requirement (W), and T represents the duration (s) of the operating cycle under investigation. Average power is the fundamental quantity that determines the continuous operation of the fuel cell. The peak power is defined as the short-term highest power demand that occurs during the excavator's operating cycle [19]:

$$P_{peak} = \max\left[P_{load}(t)\right] \tag{27}$$

Here, P_{peak} represents the maximum power requirement (W) during the operating cycle. Peak power is a critical parameter that determines the power capacity of the battery system and the inverter-motor sizing. The total mechanical energy consumed by the machine during a work cycle is defined using the power-time relationship as follows [19]:

$$E_{load} = \frac{1}{T}\int_{0}^{T} P_{load}(t)dt \tag{28}$$

Here, E_{load} represents the total energy (J) required during the work cycle. This energy requirement is met by converting electrical energy, supplied by fuel cell and battery systems, into hydraulic work. The machine's power requirement is met in the hybrid powertrain system through the following fundamental relationship [19]:

$$P_{load}(t) = P_{FC}(t) + P_{BAT}(t) \tag{29}$$

Here, $P_{FC}(t)$ represents the electrical power (W) supplied by the fuel cell, and $P_{BAT}(t)$ represents the electrical power (W) supplied by or transferred to the battery. This statement forms the basic theoretical framework for power sharing in a hybrid system.

3. RESULTS

This section presents the numerical analysis of the proposed hydrogen fuel cell–battery hybrid excavator system. Considering the power requirements of the excavator, the effect of the hybrid power-sharing strategy on overall system performance is investigated. In this context, the total power demand of the machine is compared with the power supplied by the fuel cell and the battery. In addition, the battery state of charge (SOC) variation is analysed to evaluate the effectiveness of the energy management strategy. The results indicate that the proposed hybrid system is capable of meeting dynamic power demands in a stable, balanced, and reliable manner. The simulation results presented in this study are based on a simplified synthetic load profile with a duration of 60 seconds, which is designed to represent transient operating conditions and to evaluate the dynamic response of the proposed energy management system. It should be noted that this load profile does not correspond to a standardized excavator duty cycle, such as the dig–swing–dump–return sequence, which typically involves longer operating periods. Therefore, the presented results primarily focus on system dynamics and control performance rather than long-term operational behaviour. Furthermore, key performance indicators such as total hydrogen consumption (kg/h), overall system efficiency from hydrogen input to hydraulic output, and regenerative energy recovery are not explicitly quantified in the present study. These metrics require extended simulation durations and more comprehensive system-level modeling. In future work, more realistic duty cycles with longer simulation periods (10–30 minutes) will be implemented, and a detailed energy balance analysis including hydrogen consumption, system efficiency, and regenerative energy recovery will be conducted. Nevertheless, the proposed model provides valuable insights into the dynamic power distribution characteristics and control behaviour of hybrid fuel cell systems, particularly for heavy-duty construction machinery applications.

Table 1. Hydrogen Refueling, Storage, and Excavator Operating Parameters

Parameter	Value
Hydrogen Refueling Standard	SAE J2601
Hydrogen Storage Pressure	350 bar
Refueling Time	12 min
Tank Type	Type IV Composite
Tank Configuration	Five-Cylinder Tank Package
Usable Hydrogen Mass	22 kg
Excavator Operating Time	8 h (full shift)

Table 1 shows the hydrogen refueling conditions, storage system, and machine operating time for a hydrogen fuel cell-battery hybrid excavator. Hydrogen is supplied from an external refueling station at a pressure of 350 bar according to the SAE J2601 standard. It fills the tanks in approximately 12 minutes, storing a total of 22 kg of usable hydrogen. This storage capacity enables the excavator to operate for approximately 8 hours of a full shift.

Table 2. Fuel Cell System Parameters

Parameter	Value
Fuel Cell Type	PEM
Rated fuel cell power	90 kW
Operating Mode	Continuous (Base Load)
Operating Voltage	500-700 V
System Efficiency	50%

Table 2 presents the main characteristics of the PEM fuel cell used in the proposed hydrogen fuel cell–battery hybrid excavator system. The fuel cell has a rated power of 90 kW and operates as the primary energy source, supplying continuous base-load power within the hybrid architecture. It is connected to the common DC bus through a unidirectional DC/DC converter and is responsible for meeting the average power demand of the machine. In practical fuel cell systems, auxiliary components such as air compressors, humidifiers, and cooling fans introduce additional power consumption. These auxiliary loads are typically reported to be in the range of 10–15% of the fuel cell stack power, depending on operating conditions and system configuration. Such consumptions directly influence overall system efficiency and hydrogen consumption. In the present study, auxiliary power consumption and thermal management losses are not explicitly modeled, and the fuel cell output is considered as the gross stack power. Therefore, the obtained results represent an idealized system behaviour. It should be noted that the reported system efficiency of 50% corresponds to the gross efficiency of the fuel cell stack. When auxiliary consumption and thermal losses are taken into account, the net system efficiency would be lower. The inclusion of auxiliary loads and detailed thermal management effects will be addressed in future studies to enhance the accuracy and realism of the model.

Table 3. Battery System Parameters

Parameter	Value
Battery Type	Lithium-Ion
Energy Capacity	15 kWh
DC Voltage	600-700 V
Operating SOC Range	30%-90%

Table 3 presents the main parameters of the battery system used in the proposed hydrogen fuel cell–battery hybrid excavator. The battery functions as an energy storage component supporting the primary energy source within the hybrid power architecture. It is responsible for supplying transient power demands and maintaining stable operation of the fuel cell. The battery is connected to the common DC bus through a bidirectional DC/DC converter, enabling controlled charging and discharging and ensuring balanced power flow within the system. In the proposed hybrid system, the battery is subjected to relatively high C-rate values during transient operating conditions. It should be noted that these high C-rate levels occur only for short durations, particularly during peak power demands or sudden load changes. In hybrid energy systems, such transient high C-rate operation is common, as the battery is supported by the fuel cell, which supplies the average load demand over time. Moreover, modern lithium- ion batteries are capable of handling high pulse discharge rates within acceptable thermal and operational limits. Therefore, the observed C-rate values in this study are considered acceptable for short-term dynamic operation. However, for long-term durability and lifetime considerations, limiting the battery C-rate would be an important design aspect, and this will be addressed in future studies.

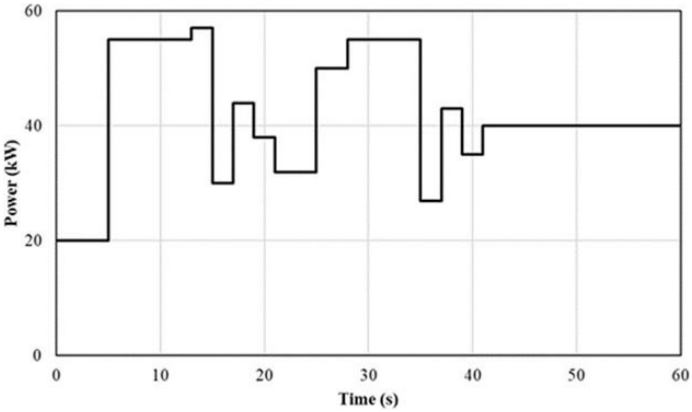


Figure 2. Required Power of the Excavator

Figure 2 shows the power required by the excavator during 60-second operating period. The graph reveals that the machine's power requirements are variable. It can be seen that the power demand varies between approximately 20 kW and 55 kW, and there are sudden power needs. This variable power requirement indicates that the machine performs different site operations.

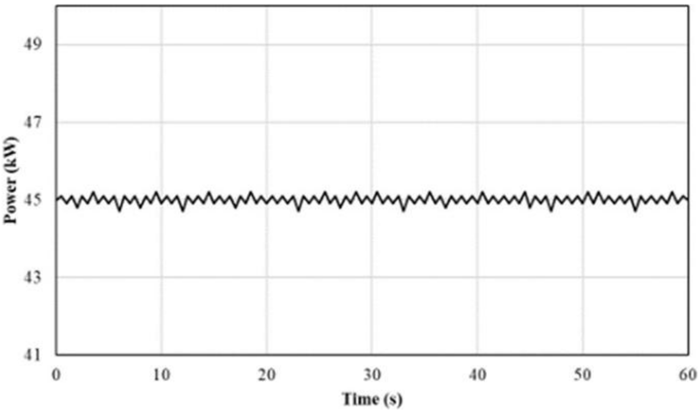


Figure 3. The Power Provided by the Fuel Cell

Figure 3 shows the power delivered by the fuel cell during 60-second operating period. The graph shows that the power generated by the fuel cell is maintained at approximately 45 kW throughout the operating period. This power profile indicates that the fuel cell is positioned as a stable power source. Figure 4 shows the power provided by the battery during 60-second operating period. Looking at the graph, it can be seen that the battery power takes both positive and negative values. Positive power values indicate the discharge state where the battery is supplying electrical energy to the system. Negative power values indicate that the battery is charging by drawing energy from the system. This time-dependent change in battery power indicates that the instantaneous load requirements are being met.

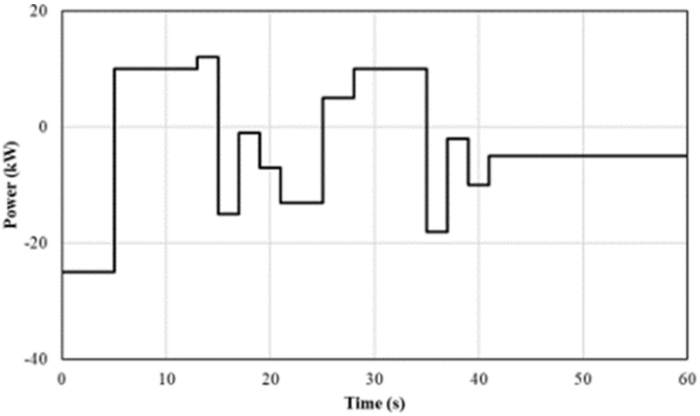


Figure 4. Power Provided by the Battery

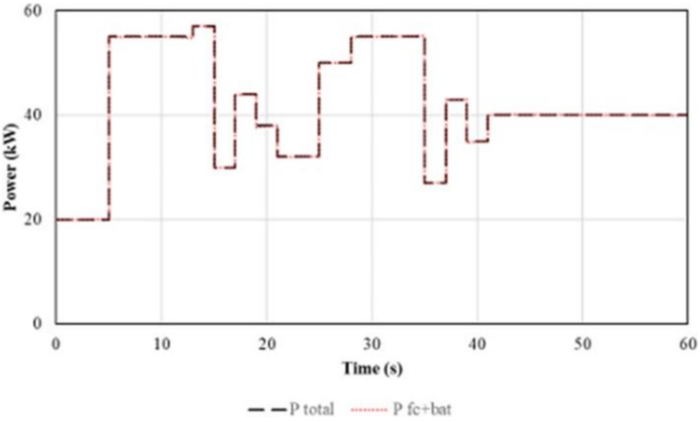


Figure 5. Comparison of Excavator Power Requirements with the Total Power Supplied by the Fuel Cell and Battery

Figure 5 shows a comparison of the total power required by the excavator during 60-second operating period with the total power supplied by the fuel cell and battery. The graph shows that the total power supplied by the fuel cell and battery meets the machine's power requirements. This result demonstrates that the hybrid power-sharing approach effectively maintains the power balance of the system.

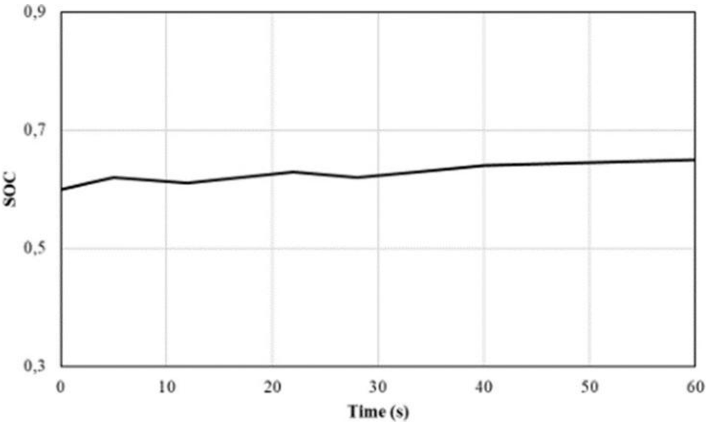


Figure 6. Battery State of Charge

Figure 6 shows the battery charge change during 60-second operating period. The SOC (State of Charge) remaining at approximately 60-65% indicates that the battery is operating as a system that meets the instantaneous power demand. The limited change in the SOC value shows that the power sharing between the fuel cell and the battery is balanced. This reveals that the battery's energy level is maintained throughout the operating period.

4. CONCLUSION AND DISCUSSION

This study investigates a hydrogen fuel cell–battery hybrid powertrain system for excavators through a system-level numerical modeling approach. The hydrogen storage and fuel supply process, as well as the operating principles of the fuel cell–battery hybrid system, are described in detail. A power-sharing architecture based on a common DC bus is developed, enabling the evaluation of system behaviour under varying power demands of the excavator. The numerical results demonstrate that the proposed hybrid system is capable of meeting the dynamic power requirements of the excavator. The fuel cell operates as the primary energy source, supplying the average power demand, while the battery compensates for transient and peak loads. The combined power output of the fuel cell and battery is shown to be consistent with the total power demand of the machine, indicating effective power distribution within the hybrid architecture. The battery state of charge (SOC) behaviour further confirms the effectiveness of the proposed energy management strategy. The SOC remains within a stable operating range, indicating that the battery successfully balances power fluctuations and maintains energy sustainability throughout the operating period. The developed model aligns with recent literature on fuel cell hybrid excavators, such as Truong et al. (2020), Trinh et al. (2022, 2023), and Dao et al. (2021), where hybrid architectures and advanced energy management strategies are employed to improve system efficiency and dynamic performance. While these studies primarily focus on optimization-based or intelligent control strategies, the present work demonstrates that a simplified rule-based energy management approach can achieve stable and reliable system performance under dynamic operating conditions. This highlights the practical applicability of the proposed method for real- time control in heavy-duty construction machinery. In addition, the hydrogen storage system considered in this study consists of a five-cylinder tank package with a total hydrogen capacity of 22 kg. From a practical engineering perspective, the integration of such a storage system within the excavator chassis presents important packaging challenges. The spatial constraints, weight distribution, and structural integration of high-pressure hydrogen tanks must be carefully evaluated to ensure safe and efficient operation. Although a detailed geometric packaging analysis is beyond the scope of this study, it is expected that the tanks can be integrated into available compartments such as the counterweight region or upper structure of the excavator, where sufficient volume and structural support are available. Future studies will focus on detailed tank placement, structural integration, and safety considerations to enhance the practical feasibility of the proposed system. In conclusion, the proposed hydrogen fuel cell–battery hybrid system provides a viable and promising solution for excavator applications. The developed numerical model offers a solid foundation for evaluating hybrid powertrain performance and energy management strategies. Future work will focus on extending the model to longer and more realistic duty cycles, incorporating detailed energy balance analysis, and investigating advanced energy management strategies for further performance optimization. The proposed Nuclear-Driven Seawater Desalination System (Figure 1.) integrates a nuclear reactor as the primary heat

REFERENCES

[1] R. K. Ahluwalia and X. Wang, "Fuel cell systems for transportation: Status and trends," *Journal of Power Sources*, vol. 177, no. 1, pp. 167-176, 2008.

[2] N. Mebarki *et al.*, "PEM fuel cell/battery storage system supplying electric vehicle," *International Journal of Hydrogen Energy*, vol. 41, no. 45, pp. 20993-21005, 2016.

[3] Q. Li *et al.*, "Energy management strategy for fuel cell/battery/ultracapacitor hybrid vehicle based on fuzzy logic," *International Journal of Electrical Power & Energy Systems*, vol. 43, no. 1, pp. 514-525, 2012.

[4] T. C. Do *et al.*, "Energy management strategy of a PEM fuel cell excavator with a supercapacitor/battery hybrid power source," *Energies*, vol. 12, no. 22, p. 4362, 2019.

[5] T. Li, L. Huang, and H. Liu, "Energy management and economic analysis for a fuel cell supercapacitor excavator," *Energy*, vol. 172, pp. 840-851, 2019.

[6] X. Zhao *et al.*, "Energy management strategies for fuel cell hybrid electric vehicles: Classification, comparison, and outlook," *Energy Conversion and Management*, vol. 270, p. 116179, 2022.

[7] H. V. A. Truong *et al.*, "Mapping fuzzy energy management strategy for PEM fuel cell–battery–supercapacitor hybrid excavator," *Energies*, vol. 13, no. 13, p. 3387, 2020.

[8] H.-A. Trinh *et al.*, "Optimization-based energy management strategies for hybrid construction machinery: A review," *Energy Reports*, vol. 8, pp. 6035-6057, 2022.

[9] H.-A. Trinh *et al.*, "Comprehensive control strategy and verification for PEM fuel cell/battery/supercapacitor hybrid power source," *Int. J. Precision Engineering and Manufacturing-Green Technology*, vol. 10, no. 2, pp. 421-436, 2023.

[10] H. V. Dao *et al.*, "Optimization-based fuzzy energy management strategy for PEM fuel cell/battery/supercapacitor hybrid construction excavator," *Int. J. Precision Engineering and Manufacturing-Green Technology*, vol. 8, no. 4, pp. 1267-1285, 2021.

[11] O. Tremblay and L.-A. Dessaint, "Experimental validation of a battery dynamic model for EV applications," *World Electric Vehicle Journal*, vol. 3, no. 2, pp. 289-298, 2009.

[12] S. J. Chapman, *Electric Machinery Fundamentals*, vol. 5. New York, NY, USA: McGraw-Hill Education, 2003.

[13] Y. A. Cengel and M. A. Boles, *Thermodynamics: An Engineering Approach*. Sea, vol. 1000, no. 8862, pp. 287-293, 2002.

[14] C. Borgnakke, *Fundamentals of Thermodynamics*. Hoboken, NJ, USA: John Wiley & Sons, 2025.

[15] A. Esposito, *Fluid Power with Applications*. Columbus, OH, USA: Pearson Prentice Hall, 2009.

[16] J. Larminie, A. Dicks, and M. S. McDonald, *Fuel Cell Systems Explained*, vol. 2. Chichester, UK: J. Wiley, 2003.

[17] M. Ehsani, Y. Gao, S. Longo, and K. Ebrahimi, *Modern Electric, Hybrid Electric, and Fuel Cell Vehicles*, 3rd ed. Boca Raton, FL, USA: CRC Press, 2018.

[18] F. Barbir, *PEM Fuel Cells: Theory and Practice*. Cambridge, MA, USA: Academic Press, 2012.

[19] R. O'hayre *et al.*, *Fuel Cell Fundamentals*. Hoboken, NJ, USA: John Wiley & Sons, 2016.