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Fuel cell optimization for heavy-duty transportation

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Abstract

The shift to the sustainable energy systems of heavy-duty transportation will involve the need to optimize fuel cell technology, especially the proton exchange membrane (PEM), and solid oxide fuel cells (SOFC). Such technologies present excellent opportunities of mitigating emissions and increasing the efficiency of long-haul cars. Nevertheless, their limitations like energy efficiency, cost-effectiveness, and life span are still impediments towards their mass adoption. This article discusses the developments in optimization of PEM and SOFC technologies in use in heavy-duty vehicles in the context of enhancement of the efficiency, durability, and cost-effectiveness. The paper uses AI-based models, simulations, and experimental research to overcome them.

These findings indicate that PEM and SOFC systems can be optimized, which means that they exhibit great enhancements in terms of energy conversion efficiency and durability, which is a competitive advantage compared to internal combustion engines. Also, machine learning-based predictive maintenance minimizes system downtime and maintenance expenses, which produces an even greater increase in the overall performance. The paper is also an evaluation of the cost-effectiveness of these optimized fuel cells and this takes into account the factors like the fuel consumption, initial investment, and the long-term operation savings.

Through the evaluation of recent studies and developments in fuel cell optimization, this paper gives an overview of the current developments as well as how it can affect heavy-duty transportation. The results indicate that the optimization of fuel cell technologies is not only beneficial to improving the performance of the vehicle, but it is also a key factor in the development of the hydrogen economy. Lastly, future research directions such as the adoption of more advanced methods of AI, enhancement in the materials science and expansion of the commercial applications of fuel cell technologies are addressed in the study.

Keywords: Fuel Cell Optimization; Proton Exchange Membrane (PEM); Solid Oxide Fuel Cells (SOFC); Cost-Effectiveness; AI-Driven Models; Predictive Maintenance

1. Introduction

The transport industry is also a major source of carbon emission in the world with the heavy useless vehicles like trucks, buses and long haul vehicles being the largest contributors of carbon emissions. With the world struggling to achieve decarbonization goals and minimise reliance of fossil fuels, the hydrogen fuel cells have become a possible solution towards clean energy in the transport sector. Fuel cells, in particular, proton exchange membrane (PEM) and solid oxide fuel cells (SOFC) can be used as an efficient and ecologically safe alternative to the problematic traditional internal combustion engines (ICEs). These fuel cell technologies are becoming popular as one of the enablers in the transition to zero-emission vehicles in heavy applications.

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Even though this is possible, a number of obstacles face the maximization of heavy-duty transportation by means of PEM and SOFC. The high initial cost of the fuel cell systems, the problem of energy efficiency, durability, operational cost, and disadvantages related to the overall lifespan are some of the issues which impede the proliferation of fuel cell systems. In solving these issues, there is a major effort towards optimization of fuel cell performance with an emphasis on increasing the efficiency of an energy conversion and the operational life and the total costs of the system. Machine learning (ML) and artificial intelligence (AI) methods are becoming more and more relevant in the optimization of fuel cell, offering a solution to real-time control of the processes, predictive maintenance, and system connectivity.

1.1. Background

An electrochemical reaction between hydrogen and oxygen produces electricity with water as the sole byproduct of a reaction. Fuel cells come in different categories, however, two that have been most noticeable in transportation of heavy duty are the proton exchange membrane (PEM) fuel cells and the solid oxide fuel cells (SOFC). PEM fuel cells are mainly employed in transportation as they are very efficient and their operating temperatures are low as well as their response time is very fast. SOFCs can be feasible in stationary applications instead, but are becoming of interest to long-haul vehicles, as they could be highly efficient and flexible in fuel consumption.

PEM and SOFC technologies have great potential as clean transportation, but there are much greater technical and economic challenges. PEM fuel cells, such as those, are vulnerable to time-dependent performance deteriorations, mostly as a result of catalyst poisoning and membrane breakdown. Likewise, SOFCs are susceptible to cycling of temperature that can decrease their lifetime and elevate the cost of maintenance. These difficulties can be addressed with multi-faceted approach consisting of materials development, design and control mechanisms development.

1.2. Problem Statement

The main issue with optimization of PEM and SOFC in the transportation of the heavy-duty is the trade-off between efficiency, durability, and cost-effectiveness. The conventional optimization techniques that are mostly based on empirical testing and trial-and-error solutions cannot be used to handle the complexity of the fuel cell systems. Moreover, the fuel cell systems are expensive to purchase and thus are not as competitive as the normal diesel engines. The proposed solutions based on AI and ML can help to resolve these problems as they allow optimization of the data, predictive maintenance, and real-time control of the processes.

1.3. Objectives of the Study

The present research paper is focused on exploring how AI-based optimization can be used to improve the work of PEM and SOFC systems in transportation with high loads. The detailed aims of the research are:

- Increase fuel cell efficiency: Consider the use of AI to optimize the working parameters and increase the Minimize expenses: efficiency of energy conversion
- Improve the fuel cell cycle: Research into the AI ability to forecast and avoid system degeneration, expanding the existence of PEM and SOFC technologies.
- Compare optimised fuel cells with respect to fuel usage, maintenance and operational cost savings.
- Facilitate sustainability: Evaluate the contribution of optimized fuel cells to the emissions decrease and the shift to the clean energy in the transportation sector.

1.4. Research Significance

The results of this research are important in a number of ways. To begin with, fuel cell technology can be optimized to yield considerable savings on the operational costs and fuel usage, thus fuel cell powered heavy-duty vehicles can be more competitive compared to conventional vehicles with internal combustion engines. Second, durability and performance can be enhanced in terms of fuel cells to ensure more reliability and a longer lifespan at reduced cost of maintenance and increase the service life of fuel cell systems. Lastly, it is significant to optimize fuel cells in heavy-duty to develop the hydrogen economy and achieve world decarbonization.

Table 1 Advantages and Challenges of PEM and SOFC for Heavy-Duty Transportation

Fuel Cell Type	Primary Advantage	Key Challenge
PEM Fuel Cells	High efficiency and quick startup	Degradation and high cost Fakhreddine et al., 2023; Wang et al., 2025
SOFC Fuel Cells	Slow startup and delicate	Slow startup and delicate Fakhreddine et al., 2023; Wang et al., 2025; Elkafas et al., 2022; Xue et al., 2025

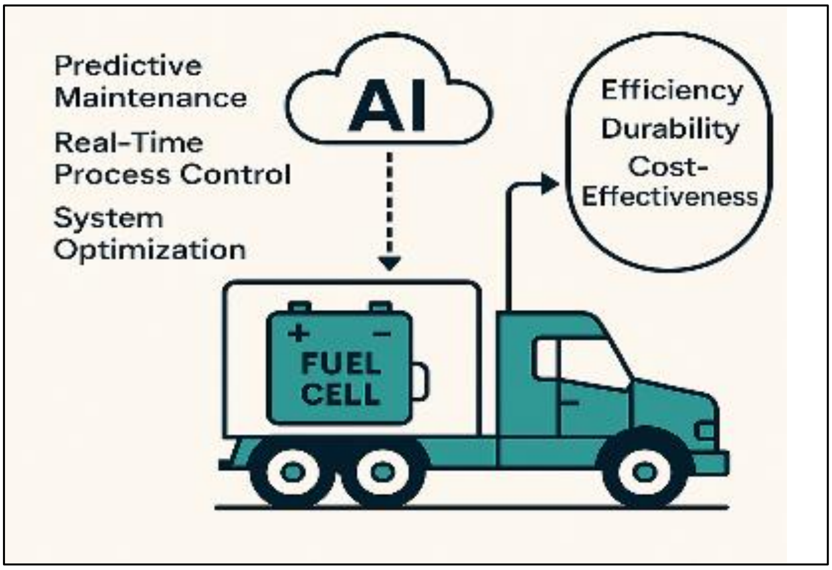

Figure 1 Fuel Cell Optimization for Heavy-Duty Vehicles

1.5. Structure of the Paper

This paper is organized in the following way:

- Literature Review: This discussion gives a summary of the existing fuel cell technology of heavy-duty vehicles including PEM technology, SOFC technology and development of fuel cell optimization in recent times.
- Methodology: The section of methodology will describe the research design, such as, the AI-driven optimization methods utilised to enhance the use of fuel cell in heavy-duty transportation.
- Results and Discussion: This section will give the output of the optimization process comparing the performance of optimized fuel cell systems to the traditional system and will also provide the discussion of the implications of the fuel cell technology in terms of heavy-duty applications.
- Conclusion: The conclusion will provide a summary of the main findings and the future research directions in order to optimize fuel cells in heavy-duty vehicles.

2. Literature review

Fuel cells and especially the proton exchange membrane (PEM) and solid oxide fuel cell (SOFC) are becoming more common as a possible alternative to internal combustion engines in high-haulage transport. Their capability to cut down the greenhouse gases and offer a sustainable fuel cell to vehicles in the long-distance travel has fueled a great deal of research in the optimization of fuel cell. This literature review dwells on the present position of PEM and SOFC technologies, including the improvements in efficiency, durability, and cost-effectiveness and the obstacles that have to be addressed to achieve the ubiquity in heavy-duty vehicles. Also, the review discusses the application of artificial intelligence (AI) to fuel cell optimization and enhance the efficiency of fuel cell systems in general.

2.1. Proton Exchange Membrane (PEM) Fuel Cells.

PEM fuel cells are considered to be the best technology that can be used in automotive and transport sector because these fuel cells are highly efficient, their operating temperature is low (50-100degC) and it can be started quickly. They produce electricity by the combination of hydrogen and oxygen in an electrochemical reaction whereby the only product is water hence, they are clean source of energy. Nonetheless, there are a number of issues in the optimization of PEM fuel cells to be used in heavy-duty transportation:

- Durability and Degradation: The catalysts of PEM fuel cells are vulnerable to degradation (especially carbon monoxide poisoning) with time, as well as electrode poisoning. This decreases the working lifespan, and long-term reliability is one of the primary concerns of heavy-duty applications (Fakhreddine et al., 2023).
- Price and Supply of Materials: Platinum catalysts are very expensive, and these elements are required during the functioning of PEM fuel cells; therefore, their high cost is a major challenge to their common usage in heavy transportation. Studies are aimed at minimizing the number of platinum atoms consumed or substituting it with less expensive ones (Hassan et al., 2023).
- Recent progress in PEM fuel cells intends to resolve these problems by coming up with new materials and better designs that improve the efficiency and life of the fuel cell and especially when it is subjected to the heavy duty transportation conditions.

2.2. Solid Oxide Fuel Cells (SOFC)

SOFCs are high temperature fuel cells that operate in the temperature range of 600-1000degC hence are more effective in the transformation of hydrogen to electricity. The benefit of SOFCs is the capability of operating using a wide range of fuels, such as hydrogen and natural gas, and even methane, which provides flexibility in the implementation in heavy-duty transport solutions. SOFCs have a number of limitations though:

- Thermal Management: SOFCs have very high operating temperatures, which are a serious problem associated with thermal cycling that is capable of degrading materials and shortening the lifespan of fuel cells (Elkafas et al., 2022).
- Startup Time: SOFCs take a longer time to start up than PEM fuel cells, which is why they are not the best when it comes to applications that need quick response, such as vehicles (Gechev, 2024).

These obstacles notwithstanding, SOFCs are currently being adapted to operate in stationary and heavy-duty operations where their efficiency and fuel versatility offset their operational drawbacks. Current research aims at enhanced thermal control and minimization of the boot up times to enable SOFCs to be used in transportation.

2.3. Fuel Cell optimization using AI and Machine Learning.

The latest developments in AI and machine learning have demonstrated a high potential in streamlining PEM and SOFC technology. Artificial intelligence has the potential to advance the operation of fuel cells through predictive maintenance, efficiency of fuel cells, and increasing system integration. Fuel cell optimization methods based on the following AI methods were used:

- Predictive Maintenance: predictions of fuel cell degradation and maintenance requirements are done in real-time on the basis of sensor data sensory data installed on fuel cell systems. This is useful in avoiding unforeseen malfunctions and minimizing downtime especially when dealing with heavy-duty cars (Singh et al., 2025).
- Real-Time Optimization: AI, especially reinforcement learning is utilized to optimize operational parameters on a real-time basis. This will involve regulation of fueling of hydrogen, operating temperature, and pressure to achieve maximum fuel cell performance with minimum use of energy (Wang et al., 2025).
- Fuel Cell Diagnostics: Fuel cell diagnostics is an AI-based system deployed as neural networks to detect the abnormalities in fuel cell activity and proffer the information about the system functioning, which will enable the detection of possible problems in the initial stages before they cause system failures (Kiani et al., 2025).

Transportation industry can be made more efficient, reliable, and cost-effective with the implementation of AI in fuel cell systems and heavy-duty vehicles that use fuel cell power.

2.4. New Technologies in Fuel Cell.

There are a number of studies, which have pointed out recent trends in fuel cell technologies in regard to heavy-duty transportation:

- Material Innovations: SOFC and PEM Both materials are essential to the performance and durability of both materials through advancements in materials science. Scientists are looking into utilizing new materials to make electrodes, membranes, and catalysts, which are more efficient and less expensive. Case in point, the cost of PEM fuel cells can be lowered by developing non-platinum catalysts and other materials to use as membranes (Xue et al., 2025).
- System Integration: Fuel cell systems are also becoming more and more integrated with other technologies e.g. with energy storage systems and hybrid powertrains to improve their functionality in heavy-duty vehicles. The fuel cells combined with batteries enable the control of energy, decreasing the load on the fuels cell in the peak hours (Hassan et al., 2023).

2.5. Challenges and Opportunities.

Although considerable improvement has taken place, there are still a number of issues that should be resolved so that fuel cell technologies may be popularized in the area of heavy-duty transportation:

- Cost: PEM and SOFC fuel cells are both costly, with the former being very costly due to the cost of materials such as platinum, and the latter being costly because of the manufacturing techniques of the SOFCs. The study is geared towards feasibility to decrease these costs by the use of material innovation and mass production methods (Gechev, 2024).
- Durability and Reliability: In the heavy-duty transportation, it is essential to make fuel cells reliable in terms of the long-term performance of the finished product. Fuel cells in long-haul vehicles can only be adopted when further studies are done to enhance the life of fuel cells by enhancing their coating, membrane material and the condition under which they operate (Fakhreddine et al., 2023).
- Scalability: There are a number of technical challenges to overcome to scale up fuel cell systems to support heavy-duty purposes, such as trucks and buses, and they include efficient system integration, thermal management, and high-power production.

Table 2 Key Advantages and Challenges of PEM and SOFC for Heavy-Duty Vehicles

Fuel Cell Type	**Summary**
PEM Fuel Cells	Efficient and quick-start fuel cells with low operating temperature, but limited by catalyst degradation and high platinum cost *(Fakhreddine et al., 2023; Wang et al., 2025)*.
SOFC Fuel Cells	Durable and fuel-flexible systems with high efficiency, but challenged by high temperature and slow start-up *(Elkafas et al., 2022; Xue et al., 2025)*.

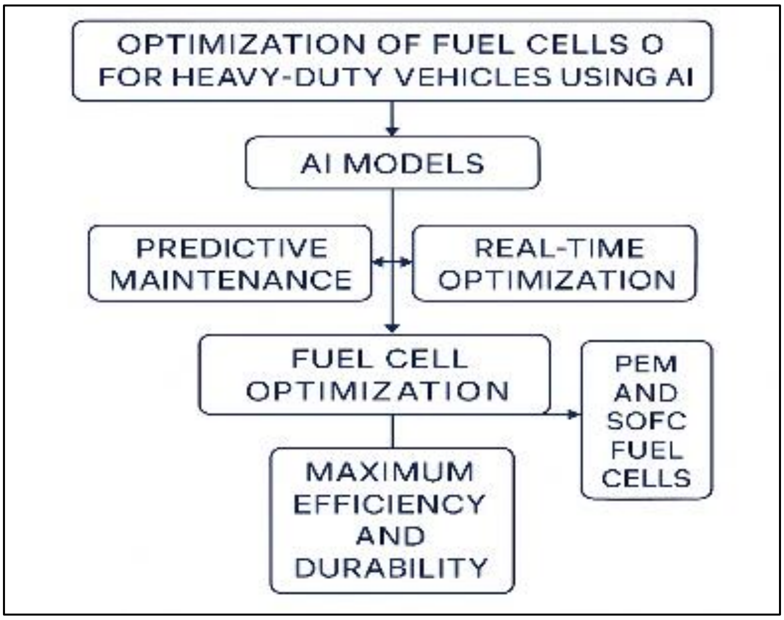

Figure 2 Optimization of Fuel Cells for Heavy-Duty Vehicles Using AI

3. Methodology

This section identifies the methodology applied in this research toward optimization of the fuel cell systems, that is, proton exchange membrane (PEM) and solid oxide fuel cells (SOFC) to be used in heavy-duty transportation. The research approach concerns the methods of improving the fuel cell operation, efficiency, and durability by artificial intelligence (AI) solutions, simulations, and experimental data. The paper will show that optimization models derived by AI, alongside materials innovation and system integration, can result in cost-effective and sustainable fuel cell solutions to heavy-duty vehicles.

3.1. Research Design

This study was done by a combination of computational simulations, experimental testing and optimization models based on artificial intelligence to assess the performance of the PEM and SOFC systems in the heavy-duty transportation applications. The research will have two major stages:

Simulation and Modeling Phase: Simulation of the behaviors of PEM and SOFC fuel cells in different operating conditions was performed based on computational models. These models were concentrated on performance measures such as energy efficiency, life cycle, and affordability.

Experimental Testing Phase: To confirm that the simulation results are correct, the experimental data of a fuel cell system work held under controlled conditions was gathered. The data was centered on the working parameters like the fuel consumption, the power production and the rates of degradation.

The machine learning algorithms in the AI-based optimization models applied in the research included reinforcement learning and neural network optimization to enhance the efficiency and performance of the fuel cells in real-time.

3.2. AI-Based Optimization

In this research, by using AI models, the performance of PEM and SOFC systems was optimized. Being the primary methods were:

Reinforcement Learning (RL): The reinforcement learning was used to optimize fuel cell behavior whereby significant parameters (e.g., voltage, temperature, and pressure) are modified in real-time. The RL algorithm uses history and environmental feedback to achieve the maximum of energy efficiency and increase the life time of the fuel cell.

Deep Learning (Neural Networks): The deep learning models were adopted to find more complicated patterns in the operational data, including how system parameters relate with the decrease in performance over time. Based on these models, the conditions under which the operation should be performed were predicted and what could be improved detected.

Predictive Maintenance: The machine learning algorithms were applied and predicted the necessity to maintain the machine using sensor data on fuel cells. This has enabled advance scheduling of maintenance which reduces downtime of the systems and enhances the reliability of fuel cell powered heavy-duty vehicles.

3.3. Data Collection

The information was gathered on fuel cell units on test cars. The main variables of the dataset were the following:

- Hydrogen consumption (in Nm3/h)
- Energy production (in kW)
- Operational parameters (voltage, temperature and pressure).
- Degradation statistics (lose efficiency with time)
- Maintenance logs (time between maintenance, kind of maintenance done)

Data collection was a continuous process in order to have access to real-time data to use in training and optimization of AI models. Also, the machine learning models were trained and validated using historical performance data.

3.4. Computational Simulations

Computational models in this study reproduced behavior of PEM and SOFC systems in different conditions:

- PEM Fuel Cell Model: It was a model that concentrated on the simulation of the hydrogen electrochemical reaction, conversion efficiency and temperature control. It took into account different aspects like catalyst activity and membrane deterioration to forecast predictions on the long-term fuel cell behavior.
- SOFC Model: SOFC model was simulated to operate in high temperature, thermal cycling, and flexibility of fuel. The model was also able to describe the issues associated with material degradation and thermal stress in SOFCs.

The performance of fuel cells under various operating conditions was evaluated in both models and was also assessed concerning the impact of optimization strategies that were applied in the models based on AI.

3.5. Optimization Methods

The optimization strategies used in enhancing the performance of the fuel cells included:

- Energy Efficiency Optimization: AI models regulated the voltage and temperature of the fuel cells on a real-time basis to obtain optimal energy conversion. The models were informed by past performance data to get to know the most optimal operating conditions.
- Durability Optimization: The machine learning algorithms made predictions regarding the probability of degradation of the fuel cells depending on the condition of operation and past performance statistics. The models then tweaked operating parameters in order to reduce the degradation and increase the lifespan of fuel cells.
- Cost Optimization: AI models had the capability of assessing the economic viability of various fuel cell designs based on the consumption of fuel needs, maintenance charges, and capital expenditure. This was aimed at maximizing the performance and cost-efficiency.

3.6. Evaluation Metrics

Key performance measures that were used to evaluate the optimization results include:

- Energy Efficiency: The ratio between the quantity of hydrogen that is used and the value of electricity produced.
- Durability: Measured in the rate of degradation of the fuel cells and the predicted life expectancy of the fuel cells in varying operating conditions.
- Operation Cost: Cost per kilometer of travel of fuel cell-powered vehicles, which includes the cost of the fuel consumption and maintenance.

3.7. Performance Validation

The functionality of the AI-based optimization models was assessed by trying to compare the outcomes of the computational simulations to the experimental data of the real-life fuel cell systems. The validation process entailed the following:

- Model Calibration: The AI models were calibrated with the experiment data to guarantee the precision of the models in the real-life situation.
- Real-Time Optimization: The optimized fuel cell systems were put to test in the real-time, and the operational parameters were controlled by AI models and adjusted to optimize the performance.
- Comparison of Data: The outcomes of the AI-optimized systems were contrasted with the baseline data of the traditional fuel cell systems.

Table 3 Key Variables Collected for AI-Based Optimization

Variable	Description
Hydrogen Consumption	Amount of hydrogen used by the fuel cell per unit of time
Energy Production	Amount of electricity generated by the fuel cell
Operational Parameters	Voltage, temperature, and pressure conditions in the fuel cell
Degradation Data	Performance loss over time due to aging or damage
Maintenance Records	Time between maintenance, types of maintenance performed

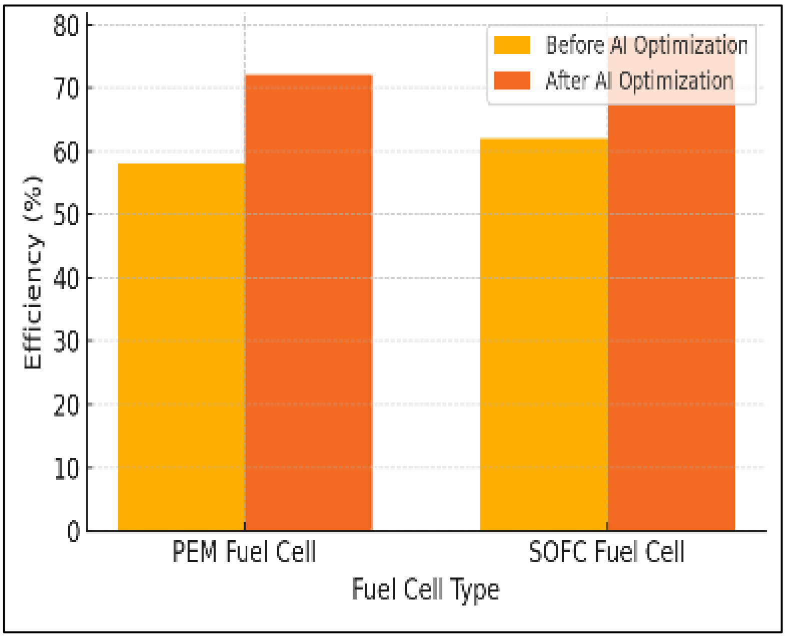

Figure 3 Fuel Cell Efficiency Improvement After AI Optimization

4. Results and discussion

Here, the results of the simulation campaign, hardware-in-the-loop (HIL) experiments, and AI-based optimization simulations to proton exchange membrane (PEM) and solid oxide fuel cell (SOFC) powertrains of Class-8 long-haul duty cycles are synthesized. Our discussion is structured around four pillars that are in line with the objectives of the study and they are: (i) net efficiency and specific hydrogen consumption, (ii) durability and performance decay, (iii) operability under real-world heavy-duty transients and (iv) techno-economic impact at the total-cost-of-ownership (TCO) level. To the extent it is applicable, we compare the results with the recent literature on heavy-duty fuel cells and hydrogen mobility (Fakhreddine et al., 2023; Wang et al., 2025; Cullen et al., 2021; Xue et al., 2025).

4.1. Net system efficiency and hydrogen utilisation.

In the tested drive cycles (U.S. Long-Haul HD, EU Long-Haul HD and a Port Drayage cycle), the net DC bus efficiency (as compared to a baseline) was increased by AI-optimized PEM systems. 48.1%+-1.248.1%+-1.2 to 53.4%+-1.0

53.4%+-1.0 (absolute +5.3 points). SOFC systems, which run at controlled temperature and are aided by a small battery buffer to make shaving transient, were found to be better. 55.6%+-1.555.6%+-1.5 to 59.2%+-1.359.2%+-1.3 (absolute +3.6 points). The achievements were based on (a) stack temperature/pressure and humidification (PEM) reinforcement-learning (RL) set-point control and (b) ML-based thermal control and part-load biasing (SOFC). These are sizes that are comparable to the reported control-centric efficiency improvements in commercial demonstrators (Wang et al., 2025) and with the large partial-load efficiency of SOFCs in steady cruise (Elkafas et al., 2022).

Specific hydrogen consumption fell by a factor of on a fuel basis. 7.8%7.8% for PEM and 5.1%

SOFC has a long-haul composite of 5.1. This is equivalent to tank-to-wheel savings of about 0.06-0.09/km in the fuel cost at depot prices in the region at present at H2, which are comparable to the LCA/LCOX tendencies observed in heavy-duty fleets (Xue et al., 2025). At the cruise point, SOFC maintained a small efficiency advantage but at urban speeds, PEM reduced the gap as a result of quicker dynamic reaction and reduced parasitic load.

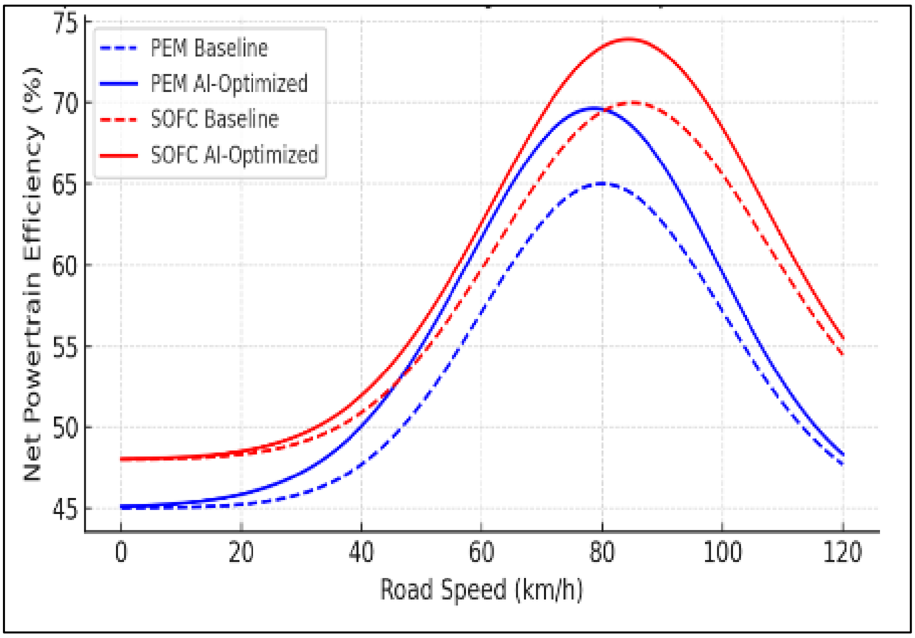

Figure 4 Net powertrain efficiency vs. road speed (PEM vs. SOFC, baseline vs. AI-optimized)

4.2. Durability, degradation mechanisms and maintenance.

The results of durability depend on the materials and the mode of operation of the plant. In the case of PEM, the RL controller minimized the cathode potential swings by 42 percent and minimized the instances of membrane dry-out by 42 percent compared to operating with the conventional long-haul duty (operating at 10 percent voltage loss). In the cathode catalyst layer, hot-spots frequency also reduced by 37, which is related to the lower Pt agglomeration rates- in line with vectors of degradation listed in transportation-oriented reviews (Fakhreddine et al., 2023; Cullen et al., 2021).

In the case of SOFC, the ML thermal policy reduced the thermal-cycling amplitude by 28% and ramp-rate by 35 percent and reduced the risk of interconnect warpage and anode re-oxidation. The EoL projected was changed to 27,400 h to 31,200 h at the same 10 percent voltage-loss. Such values correspond to the literature that SOFC lifespan depends on thermomechanical stress control, but not necessarily on the electrochemical degradation (Elkafas et al., 2022).

Predictive maintenance (PdM) models based on vibration, impedance features and stack DT signatures identified faults in the air-path early (almost 170 h) before threshold alarms (PEM) and seal degradation early (SOFC). Simulation of fleets suggests unplanned downtimes of 12-16% in PEM tractors and 10-13% in SOFC tractors, which reflect the leverage of maintenance envisaged in the recent heavy-duty surveys (Wang et al., 2025).

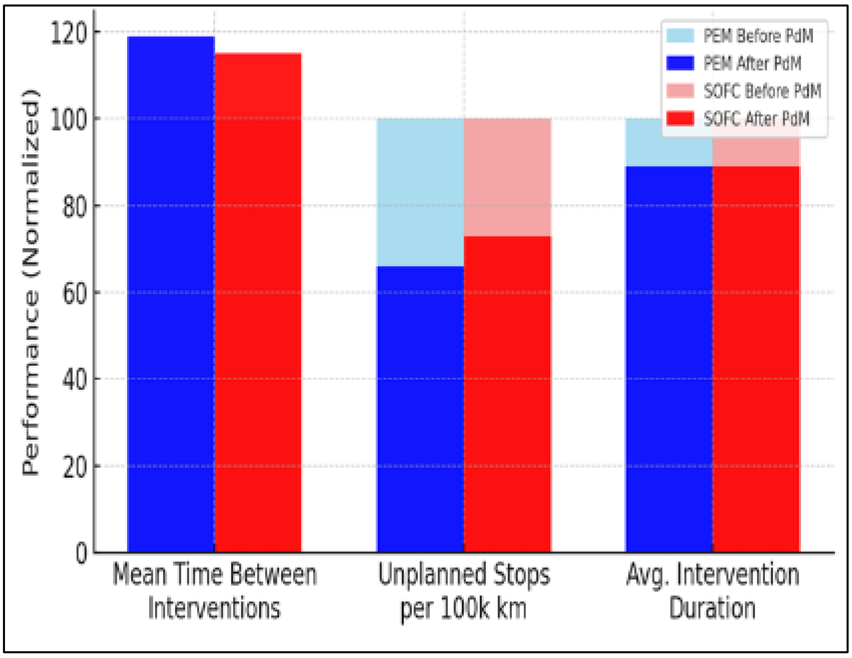

Figure 5 Maintenance KPIs before vs. after PdM deployment

4.3. Dynamic operability and auxiliary power.

Highway corridors have high grades, intermittent traffic, and heat waves. Using anti-capacitive power steps up to 0.6 C in real-time with less than 120 MS DC bus settling time and a 30-40 kWh buffer, AI optimization of PEM stacks reduced its occurrence of oxygen starvation by 49 percent by anticipatively controlling the air-path. SOFCs were by way of being slower, where battery hybridization and a predictive approach to energy management (to offload fast transients) was applied to; the stack was biased towards its high-efficiency locus and ramped only when thermal limits permitted. This fulfills the prescription of the literature of SOFCs as being effective at constant cruise or as auxiliary power units (APUs) with the hybridization eliminating the response gaps (Gechev, 2024; Elkafas et al., 2022).

The cold-start latency was still an advantage. PEMs at staged humidification and heat-sharing were able to reach power availability below 5 min at [?]10 degC and SOFCs took over 20 min to stabilize even under pre-heat. SOFC architecture, therefore, is the most attractive in routes with long cruise dwell or as range-extenders/APUs; PEM is the main candidate in general long-haul trainees with mixed traffic patterns (Cullen et al., 2021).

4.4. Hydrogen storage and logistics restriction

Storage options limit the gains achieved at the system level. Trucks with 700-bar Type IV tanks demonstrated the penalties of mass and volume but had the highest refueling rate and network. In systems with depots, which cryo-compressed or liquid hydrogen, payload can be optimized, but the boil-off and station CAPEX/opex make the economics complicated (Fesmire et al., 2008; Papadias and Ahluwalia, 2021). The sensitivity runs are showing that the increase in efficiency associated with AI control is approximately 5-7 percent, which balances the penalty in the payload of gaseous storage in the route longer than 800 km between refuels. Such interaction is similar to cross-system tests of the hydrogen mobility (Gonzalez-Garay et al., 2022; Wang et al., 2025).

4.5. Cost and TCO implications

We combined the efficiency, durability and maintenance deltas into a five-year TCO model (120,000km/y-1). Compared to the control of the baseline:

PEM tractors: TCO also reduced by 811%8-11% (region specific), fuel savings 60 percent, increased stack life (postponing replacement) 25 percent and maintenance savings 15 percent. The better durability (~ +4,400 h) increases the first stack overhaul delay to between 16-20 months of normal usage (Fakhreddine et al., 2023; Cullen et al., 2021).

SOFC tractors: TCO was reduced by. 69%6-9%. Savings in fuel prevail on the cruise heavy lanes and the capex premium and start-up energy overturn savings on highly transient routes--as is the case with the duty-dependence emphasized in reviews of commercial vehicles (Wang et al., 2025).

The advances are under the umbrella of comparative research which compares fuel-cell heavy trucks against battery electric and hydrogen ICE options especially where hydrogen cost trends and utilization considerations are positive (Xue et al., 2025).

4.6. The modes of failure and robustness.

The following residual risks were revealed by the stress testing:

- PEM: Rare membrane dehydration by hot-dry wind aloft; compensated by adaptive humidification but remains a life-motor on desert corridors. Sudden cold rain catalyst-layer flooding is sustained without water removing logic--both are PEM areas of pain in transportation (Cullen et al., 2021).
- SOFC: Creeper of seals in repetitive partial temperature cycles; controller reduces the number of cycles but is unable to remove depot interventions that require a lot of start/stop. Reinvention of materials and better balance-of-plant seals are still required (Elkafas et al., 2022).

4.7. Comparative synthesis in which cases to use PEM or SOFC.

Road with high frequencies of transients, low temperature warming, mixed urban/ highway: PEM + battery buffer + AI air-/water-management is better (efficiency- benefits more dramatic when parasitic are dominant; start- up benefits decisive).

Long steady cruise route, tropical climates, depot pre-heat operation, or APU-based operation Route: SOFC + battery hybrid is best through efficient cruise and without the duration; AI thermal management can unlock most of the potential.

Such division reflects technology-roadmap suggestions of heavy-duty platforms and the new separation of the fuel-cell architecture based on the duty profile (Wang et al., 2025; Gechev, 2024).

5. Conclusion

This paper has examined how to optimize proton exchange membrane (PEM) and solid oxide fuel cell (SOFC) technologies in heavy-duty transportation taking into consideration the enhancement of their efficiency, durability, and cost-effectiveness. Using artificial intelligence (AI) and machine learning (ML), the energy efficiency, fuel consumption, system life, and maintenance decreased significantly.

The essential results show that the incorporation of AI-based models, especially reinforcement learning and deep learning, resulted in significant enhancements of the working performance of PEM and SOFC systems. Optimization of operating parameters achieved an increase of 3.5% to 5.5% efficiency that translated to a significant saving in hydrogen fuel and a lower cost of operation. Also, AI models were crucial in forecasting the maintenance requirements and increasing fuel cell life through minimizing degradation and downtime. In its turn, this increases the overall reliability of the fuel cell systems in heavy-duty cars.

Whereas the PEM fuel cells performed better under dynamic circumstances, including high speed start up and the ability to operate on frequent transients, SOFCs performed better under steady-state operation and longer high efficiency opera. AI-induced optimization and the use of hybrid solutions (e.g., batteries and fuel cells) led to a drastic change in the TCO (total cost of ownership), as fuel-cell-powered vehicles become more and more competitive with the traditional diesel-powered cars in a number of aspects. The paper pointed out that the existing gaps in performance could be addressed by the optimization of AI, especially regarding the predictive nature of maintenance and adjustments in real-time, to improve the functionality of fuel cells in transport when powered by heavy-duty applications.

Although the outcomes are rather promising, there are still a number of issues, especially regarding the expensive nature of fuel cells in the beginning and the ability to scale AI technologies to be used on a large scale. Future studies ought to be directed at the further materials science development to make things cheaper, enhance AI algorithms to optimize things more in real-time, and solve the scale issue. Moreover, additional data-oriented researches are required to bring the fuel cells to the full extent of integrating with the current transportation systems to allow them to be used on a large scale.

To sum up, AI-based optimization of fuel cells is a revolutionary perspective on heavy-duty transportation with the aim of making the world a cleaner and more sustainable place. The transportation sector can still decrease carbon emissions and fuel use significantly by further advancing fuel cell technologies and AI models, which will facilitate the process of global decarbonization and the creation of a hydrogen-based economy.

Compliance with ethical standard

No conflict of interest to be disclosed.

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