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ORIGINAL RESEARCH

Optimal plug-in hybrid electric vehicle performance management using decentralized multichannel network design

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Abstract

In addition to providing mobility, plug-in hybrid electric vehicles (PHEVs) provide a two-sided energy exchange opportunity which makes them highly flexible distributed energy storage systems for the future of energy systems. This paper analyzes PHEVs' performance from the perspective of urban traffic and energy using a decentralized multichannel blockchain network based on the hyperledger model. This network using a layered design and local management of energy sources can significantly contribute to urban management and optimal use of its infrastructures. Then, dynamic modelling of PHEVs in this network is performed, and their data is added to the network to evaluate the network performance compared with the current centralized networks. The results indicated that the proposed blockchain network could simultaneously optimize PHEVs' performance, urban traffic management, and energy systems. Furthermore, by utilizing smart contracts, it can consider and optimize multiple challenges, such as congestion in the electricity network, urban traffic, and limited fuel, simultaneously. Therefore, it gives a strong tool to study the impact of mass deployment of PHEVs and their value and role in the sustainable cities and communities of the future while helping to support the global efforts toward affordable and clean energy for all.

1 | INTRODUCTION

Electric vehicles are one of the major challenges and future opportunities of the electrical industry [1]. If there is a notion that despite the pervasiveness of electric vehicles, centralized networks can handle system management, it is worth noting that Intel predicts that an electric vehicle will generate 4,000 GB of data per day by 2025 [2]. The data will be used for smart vehicle control, urban traffic, routing, and even parking space [3]. On the other hand, electric vehicles are highly dependent on ambient conditions and the uncertainties caused by time, location, and energy charge [4]. One who buys a smart electric vehicle might have different objectives at any time, and personal preferences and ambient conditions might lead to different decisions at different times [5]. Hence, decentralized blockchain networks can play an important role in the future of energy and managing urban traffic and infrastructure due to their high local energy management and flexibility, which is remarkably more important than vehicle charging. Hence, this paper presents a decentralized multichannel network seeking to simultaneously manage hybrid vehicles in three fields of electric energy, fossil fuels, and urban traffic to demonstrate the effectiveness of decentralized networks in optimal utilization of urban infrastructures and reducing energy costs, environmental pollution, and urban traffic. On the other hand, smart contracts provided by the network show how urban macro-policies can be established indirectly and democratically using financial incentives in different urban fields.

2 | LITERATURE REVIEW

Different studies and research works have been conducted on electric and hybrid cars so far, focusing on the performance and optimization of these cars in the manufacturing sector. However, the viewpoint that is important in this paper is how to model a hybrid car intelligently to be employed as a smart agent in the power network. One of the most conventional modelling methods for hybrid cars is based on torque–speed curve, which is mainly seen in papers published in the mechanical engineering field. In this modelling method, the torque–speed curve of the electric and thermal motors is used to determine the car's operating point. How these curves are plotted, and the car operates are detailed in ref. [6], as used in the present paper. Also, some other studies add more detailed calculations, consider different scenarios of hybrid cars in different operating conditions, and model the forces applied to the car's body based on the road slope and air friction [7]. More recent papers have a more accurate approach to car performance and try to consider the driving conditions in their modelling procedure. According to the direct effect of traffic on the car's performance and its operating point, it is tried to predict the car velocity in different phases in the road to predict its operating point subsequently [8]. This issue plays a critical role in estimating the electrical energy and fuel required in the path to optimize the electrical energy consumption in the path [9]. To this end, many papers have attempted to simplify the performance of hybrid and electric cars to simulate more cases [10]. However, the most important issue is how the car velocity is predicted. Some research works consider the operational information of the vehicle or GPS in real paths [11]. Considering different cases of urban traffic, other studies depict different scenarios and define new operating points for them [12]. However, the method applied in this study is to use decentralized information on cars with a blockchain basis. Already, the information about cars in the blockchain network has been used to evaluate the car velocity, traffic level, road slope, and wind speed in the field of urban traffic and the performance of traffic signals. However, this paper tries to use this information all together to determine the optimal performance of electric and hybrid cars to predict the energy required for the car. The only challenge in this process is that the performance curves of electric motors and internal combustion engines are nonlinear, which hardens solving these problems. To reduce the time of computations in these studies, the functions and curves are estimated and simplified. In this paper, as another recommended novelty, the nonlinear speed-torque curves convert to linear to determine the optimal operating point rapidly after many iterations.

Indeed, hybrid cars in this study are merely agent factors that are used for the goal of higher order, i.e. in multichannel decentralized networks. Research works on decentralized networks are shorter in life relative to those on electric and hybrid cars. Up to now, these networks have been further used in banking and insurance networks, and research works conducted in the energy field can be divided into some categories. The first category includes studies that evaluate blockchain communication infrastructures in power grids, and these papers mainly emphasize the decentralized management of wide area networks with a mass of data [13]. These papers use decentralized networks to present a strong, scalable, and economical mechanism to manage a significant number of transactions of small-energy elements in the power grid [14]. In some studies, a reliable decentralized network, such as Ethereum, forms the blockchain infrastructure of the network [15], and the infrastructure of all exchanges and transactions is based on this platform. Presenting a private blockchain network, some other studies use different consensus algorithms, such as proof-of-work or proof-of-stake, to confirm transactions and energy transfer [16]. Another viewpoint in these studies is to use systems relying on the management of the smallest members of the network via the Internet of Things (IoT). Smart contracts in different blockchain-based structures, such as solidity, can purchase the required energy from the decentralized network without the intervention of the third party [17] and address this issue that the development of decentralized networks and daily growth in using small-scale renewable energies cause the tendency to island operation of networks. This decentralized network can facilitate the interaction between these islands and increase the network's reliability along with its financial interests [18]. A new intelligent SVM-based framework for cyberattack detection in electric vehicles' CAN bus is proposed. The framework is evaluated on two public datasets and achieves high accuracy and low false positive rate [19] and the model uses a modified support vector machine (SVM) algorithm to detect anomalies in CAN bus traffic [20]. The other paper proposes a secure energy management architecture for smart hybrid microgrids considering PEM-fuel cells and electric vehicles. The architecture uses a blockchain-based framework to secure the communication between the microgrid's components. The framework is evaluated on a simulated microgrid and is shown to be effective in preventing cyberattacks [21]. A novel stochastic blockchain-based energy management framework for smart cities using vehicle-to-grid (V2G) and vehicle-to-station (V2S) is proposed. The framework uses a blockchain-based distributed ledger to coordinate the energy transactions between vehicles, charging stations, and the grid. The framework is evaluated on a simulated smart city and is shown to be effective in improving the efficiency and reliability of the energy system [22]. This paper uses a hyperledger-based structure for the decentralized power network, which has high responsibility and inflexibility due to its layered structure. Heretofore, this structure was used in the banking and insurance sectors and could also be used for the power network integrated with the urban traffic and fossil fuel network. The second category of conducted studies has focused on the role of decentralized networks in financial settlement. These studies have mainly investigated smart contracts, online and multistage settlement systems, and how these tasks are classified in the blockchain platform [23, 24]. However, a major portion of research work has been performed in the power field, focusing on the P2P local energy exchange, because local exchanges do not change the network's operating point, and there is no need to consider the technical constraints of the network [25]. Among the prominent points of these studies is a smart contract, which can play a critical role in directing and driving decentralized systems in addition to decreasing the system's operating cost. These highly versatile contracts with different structures can provide what is required for network members for risk management [26]. Albeit, there are some research works that investigate the efficiency of enterprises in the decentralized structure, discuss several algorithms to manage requests in the network and avoid extreme price fluctuations, and use different algorithms, such as the iceberg algorithm to handle the demand side [27]. This paper attempts to examine the role of smart contracts in directing electric vehicles and optimizing their energy

TABLE 1 Comparison of references in the literature and this paper.

Ref	Innovation	Subject	This Paper
[6]	Torque–speed curve of the electric and thermal motors	Hybrid	Linearization functions
[7]	Operating conditions and model the forces	Hybrid	
[8]	Predicting the direct effect of traffic on the car's performance	Hybrid	Intelligent model
[9]	optimize the electrical energy consumption in the path	Hybrid	
[10]	Simplify the performance of hybrid and electric cars to simulate	Hybrid	Traffic modelling
[11]	consider the operational information of GPS in real paths	Hybrid	
[12]	Considering different cases of urban traffic	Hybrid	Optimization performance
[13]	Manage the issues of extensive networks with massive data	Infrastructure	
[14]	Look for a robust, scalable mechanism in V2G network	Infrastructure	
[15]	A model based on existing blockchain structures	Infrastructure	Hyperledger blockchain
[16]	A model mainly depends on its consensus mechanism	Infrastructure	
[17]	The transaction structures are designed to be executable such as solidity	Infrastructure	
[18]	Decentralized networks to interact between such islands	Infrastructure	Multichannel
[19]	A new intelligent SVM-based framework for cyberattack detection	Infrastructure	
[20]	A support vector machine algorithm to detect anomalies in CAN bus traffic	Infrastructure	
[21]	A secure energy management architecture considering PEM-fuel cells and EV	Infrastructure	Network design
[22]	A novel stochastic blockchain-based energy management for smart cities	Infrastructure	
[23]	Blockchain multi settlement base Peer-to-peer trading framework	Financial	
[24]	Financial systems include contracts, online, and multi stage settlement	Financial	Smart contract
[25]	Contract model for electric vehicle base peer to peer	Financial	
[26]	Smart contracts manage decentralized microgrid	Financial	Multi objective
[27]	Managing request sending in various algorithms such as iceberg	Financial	
[28]	Control the voltage using blockchain infrastructure	Power system	
[29]	A reward-punishment system based on voltage changes	Power system	Multi-level optimization
[13]	Focus on mixing centralized and decentralized approaches	Power system	
[30]	An economic load dispatch mechanism in a decentralized network	Power system	Network constraints
[31]	Coordinate flexible demand response and renewable energy sources	Power system	

consumption and to model this role in a decentralized network, aiming at the proposal of a smart contract to prevent the disruption of transmission lines and increased network costs for electric cars. Finally, the third category of studies aims at power quality improvement. Among the most important indicators of these improvements in the distribution network is the voltage control realized in a blockchain platform [28]. The major portion of these studies is based on reward and punishment system and focus on the formation of a sensitivity matrix for voltage control buses in a decentralized network, which is of great importance at the end of radial grids [29]. Research works in this field have been conducted to improve the power grid performance for centralized planning and operating of the system, and the objective function is the enhancement of power quality besides decentralized management of the network, which is highly important for large-scale networks [13]. In some other papers, the goal is to use an economic load dispatch mechanism for enhancing outputs in a decentralized network [30]. In another paper, a novel model is proposed to coordinate flexible demand response and renewable energy sources for scheduling community integrated energy systems with electric vehicle charging stations. The model considers uncertainties in renewable energy generation and user preferences, and uses a dynamic pricing mechanism to incentivize demand response [31]. However, the present paper specifically considers the economic load dispatch as an indicator of confirming the registration of any block to ensure that this decentralized network provides responses that consider all principal technical constraints of the power grid even when the initial operating point is altered. A comparison of the references discussed in the literature review is shown in Table 1.

Beyond what was mentioned above, the novelty of the present study relative to previously conducted studies that have mainly focused on the technical aspect is that this study attempts to propose a multichannel network to jointly provide and optimize three fields of urban traffic, fossil fuel, and power grid. The main advantage of the proposed network over current centralized networks is its high flexibility and low response time. This network provides its members with a multiobjective environment where any member can select the optimal

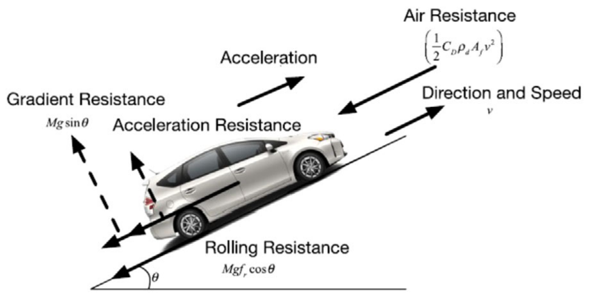

FIGURE 1 The driving model of the PHEVs [32].

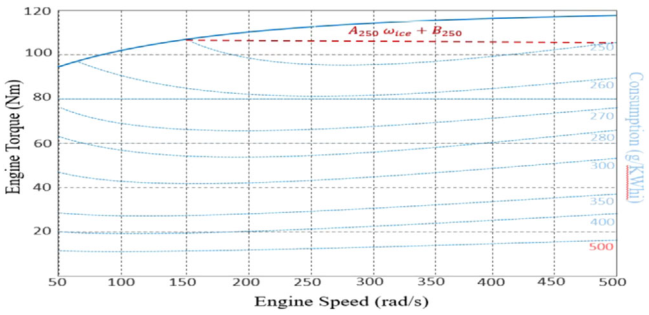

FIGURE 2 The torque–speed curve for combustion engines [33].

solution according to his/her objective. Hence, apart from technical subjects in the decentralized network structure and hybrid car modelling. The major innovations of the paper include the following:

- Structural design of a decentralized multichannel network to simultaneously manage the effects of urban traffic.
- Multiobjective optimization of hybrid cars in the decentralized network considering urban traffic.
- Employing smart contracts for systematic management of power grids jointly with other fields.

The paper is structured as follows. In Section 2, hybrid vehicles are modelled in a simulated environment, and the torque–speed curves are linearized for combustion and electric engines. The optimal operating point of the vehicle is determined by predicting the route information. In Section 3, a multichannel blockchain network is introduced, and network layers, definitions, tasks, how the components interact in each layer, and the proposed design for a hyperledger-based network are discussed. Section 4 describes how the proposed decentralized network optimizes the hybrid vehicle performance. In Section 5, the proposed decentralized network is simulated for a small system, and the effect of each field and smart contract on network performance is evaluated. In the last section, the performance results are evaluated and analyzed.

3 | HYBRID VEHICLES

In this study, hybrid vehicles are considered vehicles that use electric and fossil fuel energy as their driving force. Hybrid vehicles include a combustion engine, an electric engine, a battery, and usually an electric generator. The engines are designed in series, parallel, and combined arrangements based on the functions of these two energy sources. Similar to fossil fuel vehicles, hybrid vehicles should also overcome the total force exerted on them. The total force required to move a vehicle Figure 1 is calculated using q(1–4). as a function of gravity and friction forces. In our study, hybrid vehicles were regarded as smart network loads, challenging the operation of decentralized networks. Hence, for modelling these smart loads, it is necessary to model the different operation modes of these vehicles and their energy generation sources.

$$F_{TR} = F_g + F_{roll} + F_{ad} + m\alpha \tag{1}$$

$$F_g = \mathrm{mgsin}(\alpha) \tag{2}$$

$$F_{roll} = \mathrm{mg}\left(C_0 + C_1 \cdot V^2\right) \tag{3}$$

$$F_{ad} = \frac{1}{2}\rho C_D \cdot A_F (V + V_{wind})^2 \tag{4}$$

Where F_{TR} is the tractive force, F_g is the gravitational force, F_{roll} is the rolling resistance force, and F_{ad} is the aerodynamic drag force of the vehicle. α is the grade angle, m is the mass, and $g = 9.81\ \mathrm{m/s^2}$. C_0 and C_1 are the rolling resistance coefficients. V is the vehicle speed. ρ is the air density, C_D is the aerodynamic drag coefficient, A_F is the equivalent frontal area of the vehicle, and V_{wind} is the headwind velocity.

3.1 | Combustion engines

Combustion engines turn fossil fuels into kinetic energy. The efficiency of these engines is low, but they produce high power. In cases of slopes or at high speeds where the vehicle needs more power, these engines can have a significant effect on the ultimate power of the vehicle. The torque–speed curve for combustion engines is a visual representation depicting the correlation between the engine's torque output and its rotational speed. This curve delineates the operational range of the engine, specifying the minimum, and maximum speeds at which the engine can function effectively. The area beneath the torque–speed curve symbolizes the engine's capacity to perform work across a spectrum of speeds. The characteristics of this curve are influenced by factors such as transmission and gear ratios. Varied gears have the potential to modify the engine's operational position on the curve. Comprehending the torque–speed curve is imperative for optimizing engine performance. The combustion engine was modelled using the torque–speed–fuel curve presented in [33].

Figure 2 represents the torque as a function of the fuel consumption rate at different rotor speeds. The torque curve was assumed linear to increase the computational speed for consecutive iterations. The assumption is a reasonable approximation, according to the engine curve. This turns the assumption into a linear optimization problem, and if the vehicle speed and the moving force are known, the optimal operating point and the fuel consumption rate of the combustion engine can be calculated at any moment in Equation (5) and (7).

$$0 \leq T_{\text{ice}} \leq A_{\text{i}}\omega_{\text{ice}} + B_{\text{i}} \tag{5}$$

$$\omega_0 \leq \omega_{\text{ice}} \leq \omega_{\max} \tag{6}$$

$$P_{\text{out}} = T_{\text{Ice}} \times \omega_{\text{Ice}} = \eta_{\text{ICE}} \times H_{\text{v}} \times m_{\text{fuel}} \tag{7}$$

Where T_{ice} is the torque of the combustion engine, ω_{ice} is the rotational speed of the shaft, η_{ice} is the engine efficiency, m_{fuel} is the fuel consumption, and h_{v} is the fuel heating value [34].

3.2 | Electric engine

Electric engines in electric vehicles can be AC or DC. DC engines are cheaper, and simple electric vehicles usually employ such engines. However, AC engines have very advantages, including a wide range of torque–speed and highly efficient performance, and thus, advanced hybrid vehicle manufacturers adopt AC engines. The torque–speed curve in electric and hybrid vehicles illustrates the motor torque at various speeds of the vehicle. This curve displays different points of motor torque in relation to the speed function of the vehicle. The examination of this curve is crucial as it has a direct correlation with the performance and efficiency of the vehicle. The torque–speed curve usually has two distinct regions:

- High torque region: In this region, the motor torque is high, but the vehicle speed is low. This area is described as the starting or uphill movement zone at relatively low speeds. Here, the motor, due to its high torque, can overcome the weight of the vehicle and its peripheral components.
- Low torque region: In this region, the vehicle speed increases while the torque decreases. This area is typically used for maintaining a constant speed or ascending under mild conditions.

Torque–speed–efficiency curves Figure 3 were derived from [33] to model the electric engine. Figure 3 shows the torque as a function of engine efficiency at different rotor speeds. As reported by [33], most operating points are located in the center of the curve. Hence, torque–speed curve boundaries were assumed linear to increase the computational speed for consecutive iterations. As shown in Figure 3, the boundaries are composed of a straight and a diagonal line. This leads the problem to reach its optimal point faster, and as the figure suggests, the approximation did not have a significant effect on the final result. Since the vehicle speed and the force to move the vehicle are known, the electric engine's optimal operating point can be calculated at any moment in Equations (8)–(10).

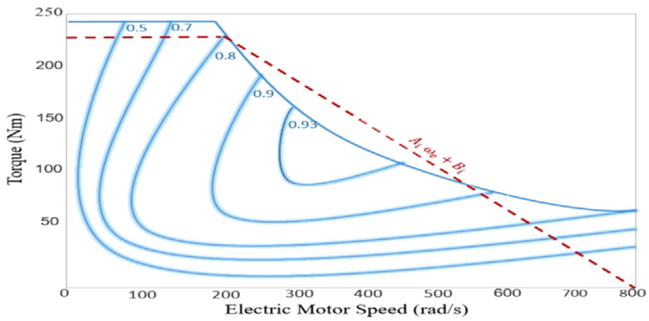

FIGURE 3 The torque–speed curve for electric engines [33].

$$0 \leq T_{\text{e}} \leq A_{\text{i}}\omega_{\text{e}} + B_{\text{i}} \tag{8}$$

$$0 \leq \omega_{\text{e}} \leq \omega_{\max} \tag{9}$$

$$\eta_{\omega,T} = \frac{T_{\text{e}} \cdot \omega}{K_w \cdot \omega^3 + K_{\text{i}} \cdot \omega + K_{\text{c}} \cdot T_{\text{e}}^2 + T_{\text{e}} \cdot \omega + \text{ConL}} \tag{10}$$

Where T_{e} is the torque of the electric engine, ω_{e} is the rotational speed of the shaft, $\eta_{(\omega,T)}$ is the engine efficiency, k_{ω} is the wind loss coefficient, K_{i} is the iron loss coefficient, K_c is the copper loss coefficient, and *ConL* is the constant loss at any speed [33].

3.3 | Electric battery

Electric batteries play an important role in vehicles chargeable from the grid, and the main advantage of these vehicles is their capability to store energy through their batteries. State of charge (SOC) is a critical metric in electric vehicles, representing the percentage of the battery's total capacity that is currently in use. It serves as a fundamental parameter for battery management and user awareness. SOC enables users to plan their trips effectively by providing insights into the remaining battery energy. As a key indicator, SOC plays a vital role in the efficient use of electric vehicle batteries. The charge rate of vehicle batteries and their charging and discharging schedule is handled based on their efficiency and the current energy level in Equations (11)–(14) [35].

$$P_{\text{loss}} = (1 - \eta_{\text{batt}}) \times P_{\text{batt}} \tag{11}$$

$$\text{SOC} = \frac{\int (P_{\text{batt}} \pm P_{\text{loss}})}{W_{\text{batt}}} \tag{12}$$

$$\text{DIF}_{(h)} = \eta_{\text{batt}} \times P_{\text{ch}(h)} - (1 - \eta_{\text{batt}}) \times P_{\text{disch}(h)} \tag{13}$$

$$\text{SOC}_h = \text{SOC}_{h-1} + \text{D}_h \tag{14}$$

Where P_{batt} is the battery power, n_{batt} is the battery efficiency, P_{loss} is the battery losses, W_{batt} is the maximum battery power, $\text{DIF}_{(h)}$ is the change of battery power, and $\text{SOC}_{(h)}$ is the state of charge [35].

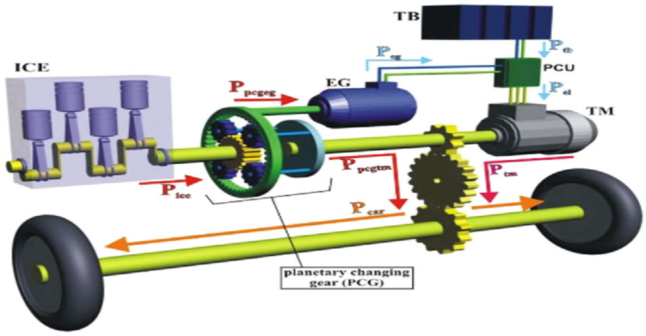

FIGURE 4 Configuration of Toyota's combined hybrid-electric drive [37].

3.4 | Hybrid vehicle performance

In this study, a combined hybrid vehicle model was used, composed of a series and a parallel design. These vehicles are more expensive than similar vehicles, but they offer better performance and lower operating costs, and they contribute to air pollution reduction due to the possibility of integrating different energy sources. As shown in Figure 4, combined hybrid vehicles are designed with an internal combustion engine (ICE), an electric induction engine (TM), and an electric generator (EG). These vehicles can provide the energy required by vehicle wheels by ICE at high speeds in series and use the electric engine for starting and at low speeds. However, the main feature of the combined hybrid vehicle is achieved in a parallel arrangement where the ICE can drive the wheels as well as the generator. The electric energy produced by the generator can be employed to charge the battery and/or drive the electric engine, achieving more torque. Furthermore, the generator can store the energy of wheels during braking or on slopes as electric energy and maintain the vehicle efficiency at the optimal point.

The main feature of the vehicle's performance is the automatic gearboxes of combustion and electric engines, adjusting the torque of each engine based on the vehicle speed, wheel diameter, and rotational speed of each engine. The relationship between gear, engine speed, and vehicle speed can be expressed using the following formulas As shown in Equations (15) and (16).

$$\mathrm{gr}_{\mathrm{i,min}} \leq \mathrm{gr}_{\mathrm{i}} = \frac{V_{\mathrm{vehicle}}}{r_{\mathrm{wheel}} \times \omega_{\mathrm{i}}} \leq \mathrm{gr}_{\mathrm{i,max}} \tag{15}$$

$$T^{*}_{\mathrm{TM}} = \frac{T^{*}_{\mathrm{wheel}} - T^{*}_{\mathrm{ice}} \times \mathrm{gr}_{\mathrm{ice}}}{\mathrm{gr}_{\mathrm{TM}}} \tag{16}$$

where gr_i is the gear ratio, V_{veh} is the vehicle speed, r_{wheel} is the radius of the wheels, ω_i is the rotational speed of the engine, T^{*}_{wheel} is the torque of the wheels, T^{*}_{ice} is the torque of the internal combustion engine, and T^{*}_{TM} is the torque of the electric engine [34]. Battery SOR can decrease or increase depending on the operating mode of the hybrid vehicle in Equations (17) and (18).

$$P^{*}_{\mathrm{ice}} - P^{*}_{\mathrm{wheel}} = K\left(\mathrm{SOC}^{*} - \mathrm{SOC}\right) \tag{17}$$

$$P^{*}_{\mathrm{ice}} = K\left(\mathrm{SOC}^{*} - \mathrm{SOC}\right) \tag{18}$$

where K is a constant depending on the average efficiencies of the battery, P_{ice} is the power of the internal combustion engine, and P_{wheel} is the power of the electric engine [34].

Hence, a smart hybrid vehicle management system requires information about vehicle speed along the route and in different time intervals, road, electric energy level and fuel at the destination, and economic analysis of fuel consumption. In previous studies, the data has been collected from the previous information and predicted information of the future. However, decentralized blockchain networks allowed for a new perspective on smart vehicle management. This paper used a decentralized multichannel network for data communication and energy exchange, improving vehicle efficiency and system indicators. Hybrid vehicles operate in different modes, and each mode determines how the car functions based on the required speed and power. If the vehicle is in braking or descending a slope, kinetic energy from the vehicle's motion is converted into electrical energy and stored in the battery. The ability to switch between these modes allows hybrid vehicles to optimize fuel efficiency and reduce emissions based on driving conditions. The integration of regenerative braking enhances overall energy efficiency by capturing and storing energy that would otherwise be lost during braking or descending slopes. Different cases of operation of hybrid cars is shown Figure 5.

4 | DECENTRALIZED BLOCKCHAIN-BASED NETWORKS

Decentralized blockchain networks lay the groundwork for storing and updating the information required by the network. This can contribute to providing a transparent view of the network and information exchange in networks with a lot of information. However, the information of a network can sometimes be of interest to other networks [36]. Hence, multichannel blockchain networks can enable information sharing between networks while protecting their privacy. Smart vehicles manage a huge amount of information at any moment, including vehicle speed, route specifications, energy source level, how the energy is consumed, and the vehicle's daily schedule. Decentralized networks enable the vehicle to not only collect better information regarding the route, urban traffic, energy price, and energy station limitations along the way but also determine the optimal operating point of the vehicle and accurately plan the energy exchange in a decentralized platform. Indeed, blockchain networks are distributed ledgers supported by a chain of verified blocks. In the network, each vehicle or vehicle energy supplier can observe the data of other members in the network and register its requests without knowing their identity [37]. Network members require initial approval to enter the network, but their identity is completely confidential in the network. Vehicles can use the route data shared by other vehicles on a certain route, determine and purchase their required energy at the destination while driving or sell their surplus energy using P2P trading, and determine their optimal operating point along the way based on the destination energy value. However, the most important feature of the decentralized network is smart contracts that can

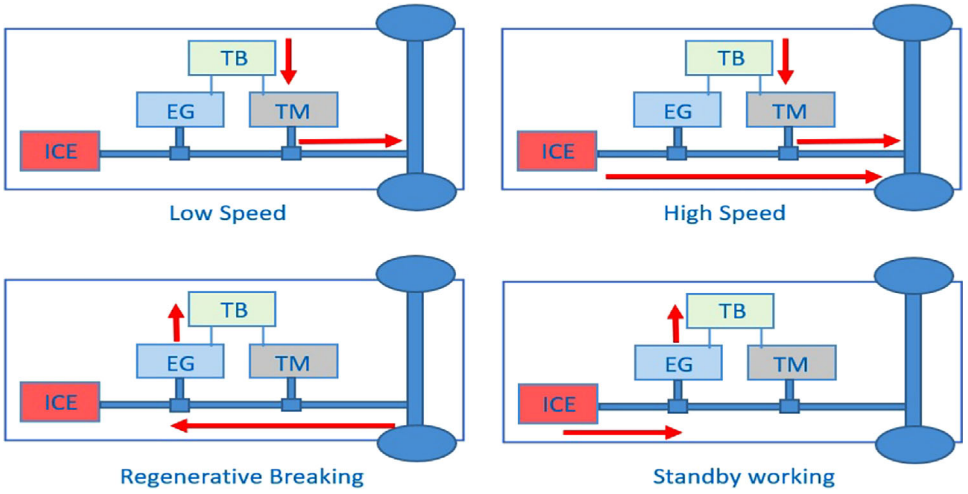

FIGURE 5 The state work of the PHEVs.

be defined in the network. Smart contracts not only enable the vehicles to purchase their required energy at a lower price but also offer a tool for local government organizations to better manage urban resources, traffic, and pollution by granting energy price incentives.

4.1 | How a decentralized multichannel network works

It is possible for multichannel networks to parallelly activate several decentralized networks and share their information. In this study, a decentralized three-channel network was proposed. The network is composed of a main and two related channels [38]. The first channel is a related channel corresponding to transportation and urban traffic information, in which all data collected from official organizations and the vehicles in the network is shared, and vehicle privacy is protected due to the confidentiality of vehicle identity. The data can be used to calculate urban traffic and other required parameters along the way. In the second channel, the information about fuel stations and fuel purchase and reserve requests are shared, and in the third channel (i.e. the main channel), the information on the power network, energy price of each bus, and inter-network exchange requests are shared. In a hyperledger fabric network, one cannot access the other channel's distributed ledger, but private data shared in all channels are available, based on which the distributed ledger of the main channel is updated.

4.2 | Urban traffic channel

Traffic channels are those which share the route information, speed, and urban barriers with other channels and thus form an information hub of urban routes. Using the data, a decentralized network shares the latest traffic situations on roads, minimum, maximum, and average vehicle speed under current traffic, and even information regarding road slope, inertia, and environmental friction. The channel can have different applications for urban traffic, transportation, and even parking spots. Based on the data, smart vehicles can select the optimal route and optimize the vehicle performance based on multiobjective functions, such as time, route, the energy available by the car, and the price of the required energy at the destination. This is not feasible in current centralized apps, such as Google Maps, merely aiming to minimize the time. The modelling of smart vehicle routes is based on defining different route scenarios and offering the vehicle a choice. The following formulas Equation (19-22) dictate that hybrid vehicles determine their route based on initial decision-making, ensuring route continuity and avoiding the repetition of a path during movement. Equation (19) is designed to guarantee that the vehicle follows the correct trajectory. Equation (20) is crucial for ensuring that the vehicle successfully traverses the entire designated path. The focus of Equation (21) is to guarantee the continuous movement of the vehicle along the path. Equation (22) plays a pivotal role in route planning by ensuring the optimal selection of a path. In summary, these formulas collectively contribute to a comprehensive modelling approach for the vehicle's movement path, encompassing correctness, completion, continuity, and intelligent route selection.

$$V_{\mathrm{drive}_{(M,Ro,S)}} \leq U_{\mathrm{road}_{(M.Ro.S)}} \tag{19}$$

$$\mathrm{SV}_{\mathrm{drive}_{(M.Ro.S)}} = \sum_{r}^{R} V_{\mathrm{drive}_{(M.Ro.S)}} \tag{20}$$

$$\mathrm{SV}_{\mathrm{drive}_{(M.Ro.S)}} = \sum_{\mathrm{r}}^{\mathrm{R}} U_{\mathrm{road}_{(M.Ro.S)}} \times \delta_{\mathrm{drive}_{(M.S)}} \tag{21}$$

$$1 = \sum_{\mathrm{S}}^{\mathrm{S}} \delta_{\mathrm{drive}_{(M.S)}} \tag{22}$$

For modelling each vehicle (M) on route (Ro) and using scenario (S), U_{road} is the default road from the starting point to the destination, V_{drive} is the roads chosen by the vehicle, SV_{drive} is the total route, δ_{drive} is the final road choice variable, and Equation (19) is the condition that ensures the selection of only one route.

4.3 | Fuel channel

In this channel, fossil fuel or hybrid vehicles can acquire their required energy decentrally and/or use other related services and share energy prices and available fuel options between network channels. Hybrid vehicles use the information to choose the strategy for changing energy sources. This channel can have other applications, including connecting fossil fuel consumers with supplier stations and fuel reservation and/or pollution mitigation and fuel consumption management

4.4 | Electric channel

The electric energy channel is the most important channel in managing hybrid vehicles. In this paper, one of the most valid concepts of the blockchain network called "IBM hyperledger fabric" was adopted to design the decentralized electric energy network [39]. The main advantage of the model is that the network is defined in several layers, each with particular roles and responsibilities [36]. This improves the efficiency and performance of the network and allows for handling large networks. Such a network has been used by banking, insurance, and social service industries, but here, its concepts are redefined because of the different natures of energy. Hence, the concepts of the blockchain network used in our study [40], based on hyperledger blockchain, are defined below and the network is shown in Figure 6.

– Endorser: Endorsers [41] are a company (or companies) granting identity licenses to market players and dealing with their violations and complaints. Endorsers are authorized by the network supervisory body. If these companies verify an actor, they give identity to a token by which the actor can directly or by proxy participate in the network.
– Committer: Like trading stocks on financial markets, each actor must use a brokerage firm to connect to the network and use its services [41]. However, since most network actors are ordinary citizens who are not interested in complicated energy purchase systems, committers provide a set of different smart contracts to their clients. Smart vehicles can perform more optimally based on these smart contracts. A new concept is added to the network called "GAS" as the request-to-request fee, determined by contract type or the direct offer by the requestor.
– Anchor: Anchors [41] are companies that especially manage P2P in the network, and the requests made by committers are referred to anchors before being presented to the main chain of the blockchain. Each anchor has its own unique area of activity in power systems and urban networks. So, all requests of a particular area, which can be exchanged as P2P, are received and settled before being presented to the main chain. Thus, the main chain workload is reduced, and the load can be responded to very fast.
– Ordering: In a hyperledger network, ordering [41] is the equivalent of miners in blockchain terminology, and it is the most important layer of the network. Ordering can provide or supply the required surplus energy. Ultimately, orderings can record all P2P and supplied surplus requests as shown in Figure 6.

4.5 | Consensus algorithm

Consensus algorithms in blockchain networks allow for decentralized management in the network. Based on their performance, the algorithms can have different types including [42]:

– Proof of work (POW): In this method, a problem is selected as the objective function of the system, and solving it becomes the criterion for mining information in the main chain. This approach is known for its complexity, high energy requirements, and time-consuming process. However, it exhibits high scalability and decentralization [43].
– Proof of stake (POS): This algorithm is designed based on the level of participation in the blockchain network rather than solving a computational problem. Despite requiring less energy and having a faster process, it maintains scalability and decentralization to a considerable extent [44].
– Proof of vote-based (POV): In this algorithm, voting and transparency of members are the basis for decision-making. This algorithm is very fast and energy-efficient, making it suitable for smaller and private networks [37].

The first two algorithms are usually suitable for distributed public networks, and they have a long delay in creating a block, which makes them unsuitable for energy industries. Therefore, this paper employed proof of vote, which has different types. For hyperledger-based networks and our study, practical byzantine fault tolerance (PBFT) algorithm is used [37].

The PBFT algorithm is one of the most practical consensus models in terms of performance. It provides low-latency consensus and can achieve high transaction throughput compared to some other consensus algorithms. PBFT is made of two members: distributer ledger keeper and verifier. The advantage of this consensus algorithm is its low power consumption, high response speed, and resilience to out-of-network sabotage attacks [45]. The consensus algorithm of each channel can be different from other channels and suitable to the function of the channel [36]. In the power network channel, the operator system is the consensus verifier, but internal exchanges do not require the approval of the operator system, and the block is verified if two third of the network vote yes. More details can be read in our other paper about this [46].

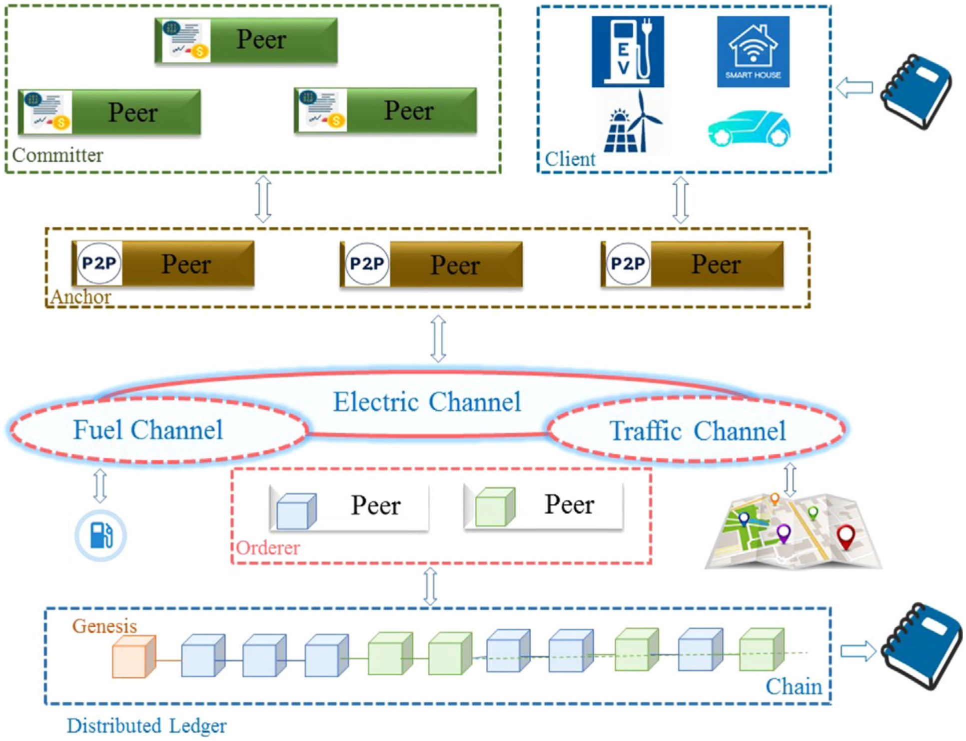

FIGURE 6 Schematic view of the proposed design for the decentralized multichannel network.

4.6 | Multi-level optimization

This paper actually proposes a multi-level optimization.

- First level: The network operator runs an optimization problem with the objective function of minimizing the system costs and considering network constraints and initial information of the network. The operator records this information in the genesis block, which is the starting point for a decentralized network.
- Second level: Every car optimizes its operating costs based on the information of the genesis block and objective functions about the path selection, charging time, and using smart contracts.
- Third level: At the time of the creation of every block, the market operator executes the DC load distributor for the network and updates the LMP level of each bus based on new information. The limitations of the line and production of units are checked, and if the block is confirmed, it is recorded in the primary chain; otherwise, it is converted to a secondary block and removed from the chain.

This paper preserves the role of the operator in confirming the block of a decentralized network because the emphasis of this paper is on the application of data interaction in multichannel networks and the optimization of the performance of hybrid cars. However, more efficient consensus algorithms, such as Ripple protocol or PoW, can be used in developing this paper. As such, the technical confirmation is handed over to another decentralized network, and this idea has been investigated in another paper [47].

4.7 | Decentralized network performance

Step 1: The hybrid vehicle operating process in the decentralized network is as follows:

Step 2: The proposed decentralized multichannel network is composed of urban traffic, fuel, and power network channels, each operating separately to achieve its objectives;

Step 3: These three channels can receive information on routes, traffic, fuel price, fuel stations, and power price in each bus, and instead, actors must share their related information without revealing their identity;

Step 4: Each vehicle can predict its optimal route and energy based on the information and its objective function using a genetic algorithm;

Step 5: Each vehicle can request the energy needed to continue its drive using online committers and/or smart contracts;

Step 6: Committers handle and refer the requests to anchors based on the request type;

Step 7: Anchors manage inter-network exchanges (P2P), evaluate all requests of a bus, and prioritize and handle them based on GAS, if possible;

Step 8: Requests not capable of inter-network exchanges are given to pool block to supply their orderings from the power system;

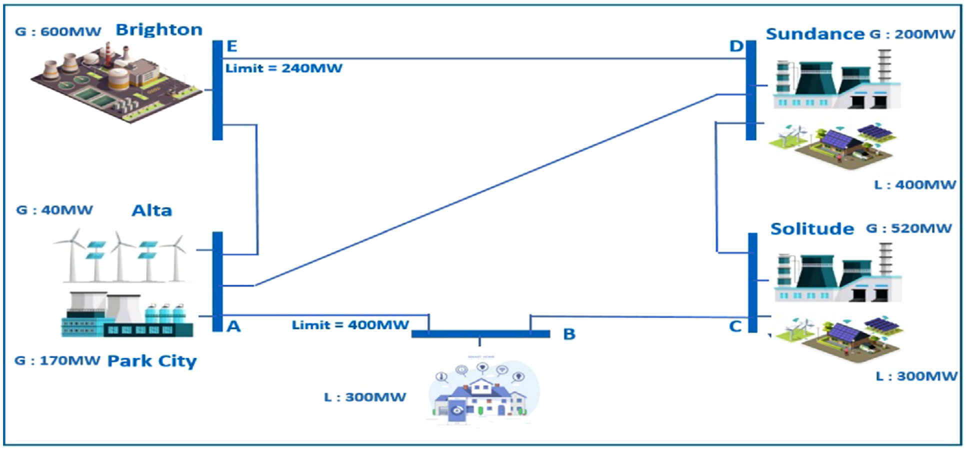

FIGURE 7 IEEE 5-bus power network.

Step 9: Orderings aggregate all requests in each time interval and send them to the network operator for approval to be accounted for in the new working point of the network;

Step 10: By carrying out the economic dispatch at the last operating point of the network, the network operator verifies requests that the network is capable of supplying regarding network constraints. As the verifying member of the consensus algorithm, the network operator gives them tokens to be recorded in the main chain, but the internal network exchange requests do not need approval tokens, and they can be recorded upon the consensus of two-thirds of the members. All requests approved by orderings are registered in the main chain network and updated in the distributed ledger.

5 | CASE STUDY

A combined hybrid vehicle was used to assess the performance of a smart hybrid vehicle in the proposed decentralized network. The vehicle parameters for the PHEV with the generic motor are as follows: total vehicle mass = 950 kg; wheel diameter = 0.5 m; aerodynamic drag coefficient = 0.22; frontal area = 2m^2, rolling resistance coefficient = 0.008; motor maximum torque = 240 Nm; motor maximum speed 800 rad/s; motor power = 40 kW; and final drive ratio = 3.5. In this study kc, k, kw and ConL, 0.2, 0.008, 0.00001, and 400 respectively [33]. Also, a simple PJM 5-bus network (1999) [26] was employed to model the energy network. The PJM network consists five energy generator, and the network specifications are shown in Figure 7.

A simple geographic map of a city was considered for the network as shown in Figure 8 Such a network was chosen to observe the effect of the decentralized network in a stepwise manner. It was assumed that 30,000 hybrid vehicles in five groups, as listed in Table 2, travel from a particular starting point to the destination and back.

TABLE 2 Number of vehicles and the starting and ending point of each group.

PHEV	EV-1	EV-2	EV-3	EV-4	EV-5
Start point	B	B	C	D	D
Number	6,000	6,000	6,000	6,000	6,000
Destination point	A	D	D	B	E

TABLE 3 The routes for each group and all possible choices of route.

Route	R1	R2	R3	R4	R5	R6
Rba - 1	BG	GF	FA			
Rba - 2	BG	GH	HI	IJ	JF	FA
Rbd - 1	BG	GF	FJ	JI	ID	
Rbd - 2	BG	GH	HI	ID		
Rcd – 1	CH	HI	ID			
Rcd – 2	CH	HG	GF	FJ	JI	ID
Rde – 1	DI	IJ	JE			
Rde – 2	DI	IH	HG	GF	FJ	JE

The information about routes, including average speed, length, and slope, was stored in each block and, ultimately, in the distributed ledger of the network. The vehicles could choose their routes among all possible cases in Table 3 based on a multiobjective function of travel time and energy cost.

The genetic algorithm was selected to determine the optimal operating point of the hybrid vehicle. The objective function was to maximize the driving force of the vehicle based on the combustion and electric engine operating curves. The torque was determined based on traffic speed and road slope, rotor speed of the combustion and electric engines, and their gear ratio, and the results are listed in Table 4.

The optimization results are shown in Figure 9. The internal combustion engine was only activated at speeds of 80 and 100

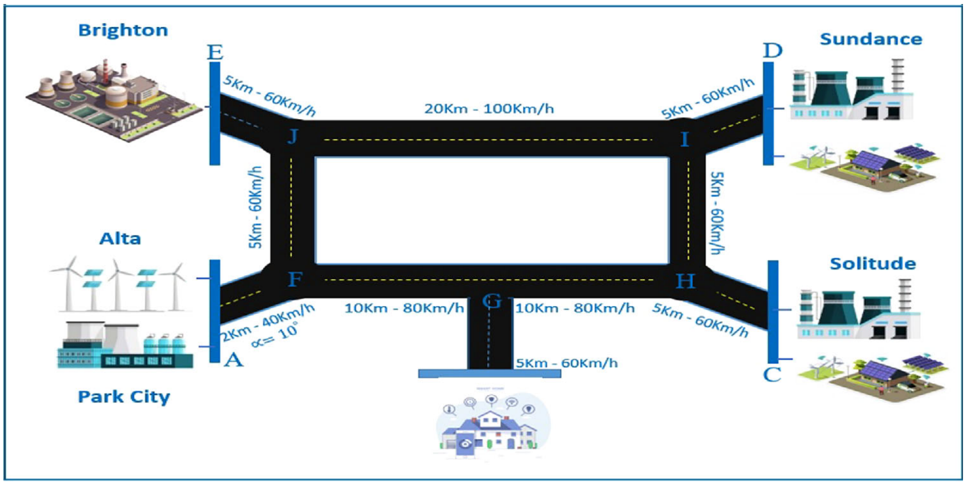

FIGURE 8 The geographic map for the IEEE 5-bus power network.

TABLE 4 The optimal operating points of the electric engine.

Speed	Degree	T_e	w_e	gr_e	T_{ice}	w_{ice}	gr_{ice}
40	10	114.64	348.9	0.8	50.89	465.2	0.6
20	0	12.20	232.6	0.6	–	–	–
40	0	18.02	389.9	0.71	–	–	–
60	0	27.13	523.3	0.8	–	–	–
80	0	22.1	516.8	1.08	28.34	498.9	1.11
100	0	33.89	697.8	1	37.93	500	1.39
40	−10	−218.8	464.9	0.6	–	–	–

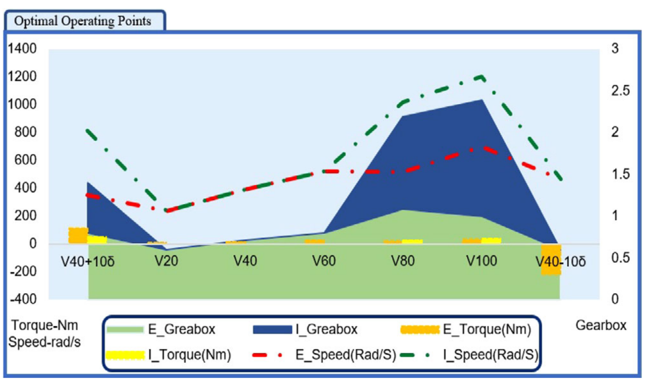

FIGURE 9 The rotor speed, electric engines, and their gear ratio of the hybrid [26].

km/h and on uphill roads. At other speeds, torque was provided only by the electric engine. For more clarity of modelling steps, it was assumed that the decentralized network is applied to the three intervals of the starting point, destination, and return, and there are four main blocks in the chain. However, the decentralized network can be made of a limitless number of partial blocks in each time interval, which is prioritized based on time sequence or transaction fee. Main block chain are shown in Figure 10.

TABLE 5 LMP of each bus in the genesis block.

Bus	A	B	C	D	E
LMP	16.98	26.38	30	39.94	10

- The genesis block is composed of the energy price for each bus announced by the operator and fixed information on routes. The genesis block also includes the latest LMP price for each bus in Table 5, and vehicles can use the price for managing energy exchange.
- The first block includes the first time interval in which each vehicle selects the route and requests its initial estimation of the required energy based on the genesis block information, objective functions, and smart contracts.
- The second block includes the time interval in which the vehicles reach their destination. In this block, vehicles optimally plan energy exchange and select their return route.
- The third or ending block includes the time interval in which the vehicles return to their starting points. In this block, vehicles can supply their surplus energy to the network and return to their initial SOC at the starting point.

In our study, the new operating point of the network for decentralized network requests was determined by the network operator using DC economic dispatch, and the supplying requests were assigned with an approval token. Based on LMP calculations, bus prices in the genesis block are listed in Table 5. The modelling was evaluated using three scenarios:

- First scenario: shortest urban route regardless of traffic;
- Second scenario: minimizing the cost of energy consumed by the vehicle considering the traffic;
- Third scenario: minimizing the travel time considering the traffic.

In this model, urban traffic was applied by reducing the speed in blocks, and it was assumed that the speed on routes HI and

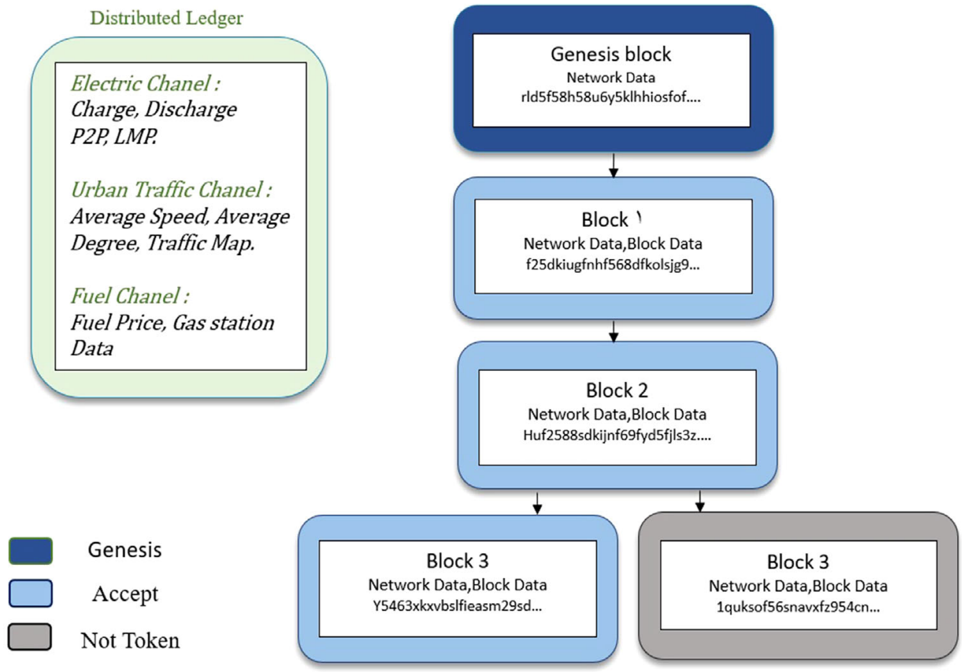

FIGURE 10 The main blockchain in hyperledger.

TABLE 6 The consumed energy (in kW) for 1,000 vehicles.

	Senario-1		Senario-2		Senario-3	
PHEV	**Block-1**	**Block-2**	**Block-1**	**Block-2**	**Block-1**	**Block-2**
EV1	4,118	1,479	4,152	1,513	5,694	3,055
EV2	5,022	0	6,477	0	8,484	0
EV3	848	848	1,576	1,576	1,576	1,576
EV4	2,511	2,511	3,238	3,238	4,242	4,242
EV5	2,228	2,228	5,218	5,218	2,262	2,262
Sum	14,727	7,066	20,662	11,545	22,258	11,135

TABLE 7 The consumed fuel (in litres) for 1,000 vehicles.

	Senario-1		Senario-2		Senario-3	
PHEV	**Block-1**	**Block-2**	**Block-1**	**Block-2**	**Block-1**	**Block-2**
EV1	0.67	0.49	0.18	0.18	0.67	0.49
EV2	0.49	0.49	0.49	0.49	0.49	0.49
EV3	0.00	0.00	0.00	0.00	0.00	0.00
EV4	0.49	0.49	0.49	0.49	0.49	0.49
EV5	0.49	0.49	0.49	0.49	0.49	0.49
Sum	2.15	1.98	1.66	1.66	2.15	1.98

GF were reduced to 40 and 20 km/h, respectively, due to traffic so that resilience and performance of hybrid vehicles under severe traffic can be assessed and compared to initial results. All vehicles calculated their required energy using the information provided by the decentralized network and handled their energy exchange through the same network. Tables 6 and 7 present the consumed energy and fuel for each scenario and results are shown in Figure 11.

- For the first scenario, vehicles chose the shortest route and did not manage their energy consumption.
- For the second scenario, the electric energy cost increased, and fuel cost decreased by accounting for traffic and optimizing energy consumption because the ICE was turned off in traffic as the vehicle speed was reduced.
- For the third scenario, the electric energy and fossil fuel consumption increased by 4% and 24%, respectively, by accounting for traffic and minimizing travel time.

However, the main advantage of decentralized networks over centralized networks is the application of P2P energy exchange and smart contracts. These two not only can reduce the final cost of energy for electric vehicles and the network, but also they are powerful tools for controlling the network, and they significantly contribute to guiding it toward the optimal point.

As the power network was assessed, line ED reached its maximum energy exchange (i.e. 240 MW), and it is not practically possible to reduce the LMP of bus D at the current operating point. Hence, two smart contracts were defined for the network so that energy can be transferred to bus D. These two contracts were proposed based on repeating values for calculating the minimum price bid to have a positive balance. The positive balance of the contracts indicates that applying the contracts would not incur any extra costs on the option provider, and the bus price difference would eventually lead to a positive balance for the option in the whole system.

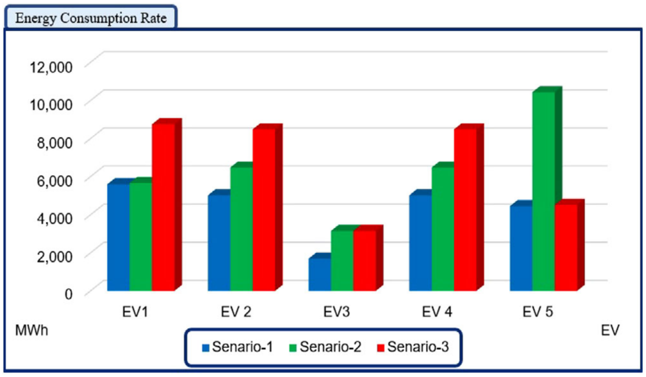

FIGURE 11 Electric energy consumption rate for each vehicle group in each scenario.

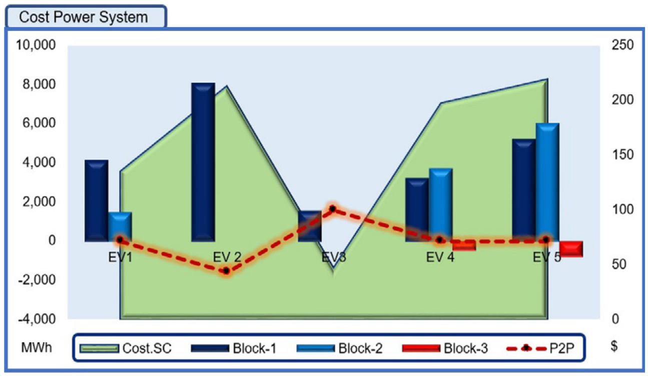

FIGURE 12 Electric energy consumption for each vehicle group per each chain block.

TABLE 8 System cost after applying smart contracts and P2P per 1,000 vehicles.

PHEV	Block-1	Block-2	Block-3	P2P	Cost	Final Cost
EV1	4,152	1,513	0	0	135	135
EV2	8,053	0	0	−1,576	212	212
EV3	1,576	0	0	1,576	47	47
EV4	3,238	3,724	−486	0	228	197
EV5	5,218	6,001	−783	0	268	219
Sum	22,238	11,238	−1,268	0	891	810

– **Smart contract with the fixed price option of 3.64 cents per watt, provided that 15% of the vehicle battery charge is available.**

This contract means that if a vehicle wants to use the smart option in a certain bus, it is only required to make 15% of the purchased energy in that day to the option provider in the form of battery charge and, instead, purchase the total required energy at the price of 3.64 cents per watt. The results of this smart contract are listed in Table 8. This option would lead to adding 1.268 MW of energy per 1,000 vehicles to bus D in the third block with a balance of zero.

– **Smart contract with the option of exploiting the free capacity of vehicles for P2P at 0.362 cents per kW.**

This contract indicates that a vehicle can rent its free capacity to another vehicle for energy exchange at 0.362 cents per kW. The results of this smart contract are listed in Table 8. This option would lead to adding 1.576 MW of energy per 1,000 vehicles to bus D in the second block with a balance of zero. This means that energy is transferred from bus B to C in a P2P manner.

Ultimately, applying the two smart contracts would reduce the system expenditures by 81 dollars per 1,000 hybrid vehicles in Table 8. The difference between vehicle performances under smart contracts is shown in Figure 12. The results indicated how the vehicles could lead to energy transfer to bus D using incentives in contracts despite network congestion. The results also demonstrated how much a decentralized multichannel system with information sharing between layers, local exchanges, and smart contract tools could reduce system expenditures, enhance response speed, and improve system flexibility, and they can even be employed in handling power network congestion, reducing pollution or managing urban traffic. The results of this table compare the system performance between centralized and decentralized states and indicate that the proposed network decreases costs by 10% relative to the initial centralized network, which is apart from the disruption management in bus D and urban traffic management.

6 | CONCLUSION

In this paper, a decentralized multichannel network based on Hyperledger is introduced to facilitate data management across multiple channels (here, energy, urban, and fuel distribution systems). To oversee urban traffic, fuel consumption, and electric energy within power networks simultaneously, the study leverages smart contracts as a mean to coordinately manage them together. This research examines the performance of the energy network in relation to urban traffic and fuel supply systems. Using information exchange between these domains, the results reveal how using such a holistic approach performance can be enhanced and costs mitigated. As a result of utilizing this capability, urban managers will be able to deal with electricity and fuel provision systems and urban traffic issues in a dynamic and autonomous manner. Also, the paper provides a dynamic environment for private businesses, allowing them to compete for the opportunity to offer innovative smart contracts on a decentralized platform in an increasingly competitive environment. By using information from the network, these contracts can offer a wide variety of services. In light of urban infrastructures and energy and transportation constraints, the network enables city authorities to address these three domains simultaneously. An analysis of network resilience and efficiency is conducted at mass deployments of PHEVs and simulating severe traffic conditions. The findings demonstrate the network's capacity to enhance PHEVs performance, reduce energy costs, minimize fossil fuel consumption, and consequently alleviate environmental pollution. Moreover, PHEVs are equipped with advanced control systems that utilize the speed torque curves of electric motors and combustion engines. This enables them to take into account real-time price fluctuations and urban traffic when making decisions. Furthermore, the dynamic impact of smart contracts is observable at every stage of the modelling process. Additionally, the study reveals the potential for PHEVs to serve as energy transfer mediums within power system across different geographic locations.

AUTHOR CONTRIBUTIONS

Seyed Peyman Mousavi Mobarakeh: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; resources; software; writing—original draft. **Mohammad Sadegh Ghazizadeh**: Conceptualization; investigation; methodology; project administration; validation. **Vahid Vahidinasab**: Conceptualization; investigation; methodology; project administration; supervision; validation; visualization; writing—review and editing.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the references of this article.

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