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ORIGINAL PAPER

Environmental sustainability policy on plug-in hybrid electric vehicle penetration utilizing fuzzy TOPSIS and game theory

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Abstract
In this paper, environmental policymaking based on sustainable development was evaluated in Tehran to increase the penetration of plug-in hybrid electric vehicles. First, different aspects of sustainable development, including the environmental, economic, social, and technical aspects of Tehran's vehicles from 2002 to 2018, were examined through the extended sustainable development model. The model documented the unsustainability of the development of vehicles in Tehran, the main reason for which could be the current air pollution in this city. Following this, based on the principle of sustainable development, some policy indices for the development of plug-in hybrid electric vehicle penetration were introduced and ranked using the fuzzy TOPSIS method, which ranked in the point of view of two players, namely buyers of vehicles and the state. Finally, to find the appropriate policy index, using the game theory method and taking the vehicle buyer and the state as the players, the Nash equilibrium point was defined as an appropriate policy for the development of plug-in hybrid electric vehicles. Thus, using the data obtained, the number of these vehicles for the year 2032 was estimated.

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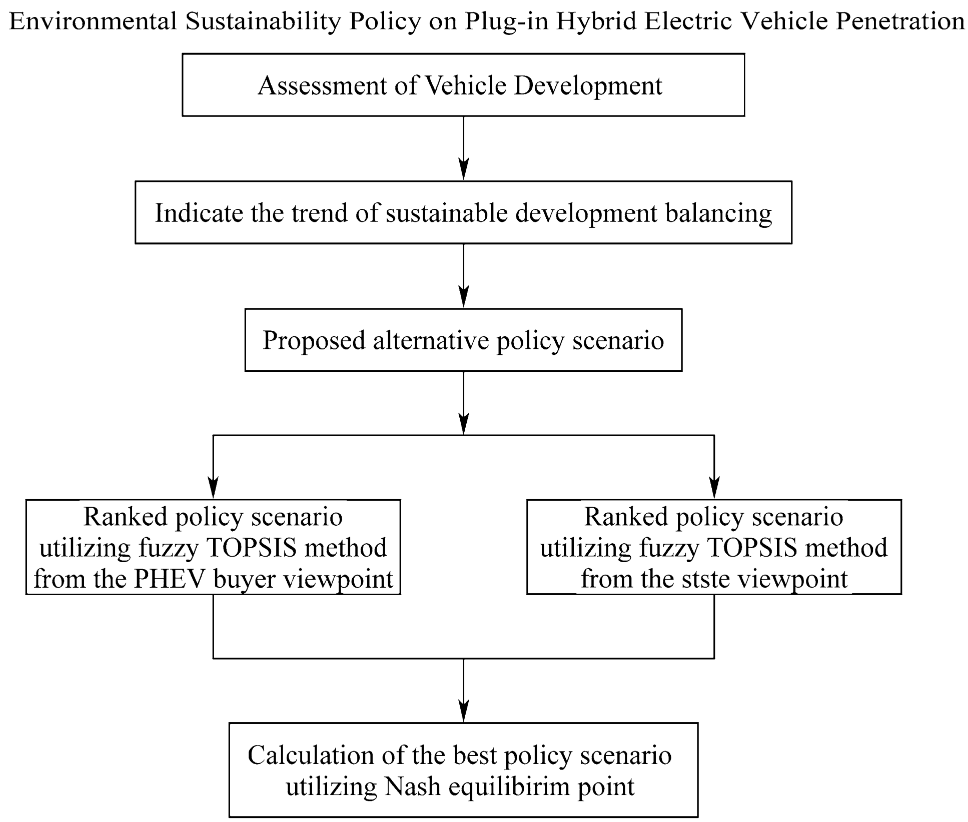
Graphic abstract



Keywords Environmental sustainability policy · Plug-in hybrid electric vehicle · Fuzzy TOPSIS

Abbreviations

PHEV	Plug-in hybrid electric vehicles
EV	Electric vehicle
CV	Conventional vehicle
BEV	Battery electric vehicles
HEV	Hybrid electric vehicles
SD	Sustainable development
NHS	Nature, human, and system
ANP	Analytical network process
WHO	World Health Organization
V2G	Vehicle-to-grid
G2V	Grid-to-vehicle
TLS	Time–location shifting

Introduction

Sustainable development (SD) is a concept that has emerged due to the negative environmental and social consequences of unilateral economic development. SD attempts to provide for comprehensive and balanced development. In the past few years, studies have mainly focused on different aspects of such development and have analyzed different variables that could play significant roles in SD in different countries. For example, the analysis of the strategic sustainability of electric vehicles in the European Union today and by 2050 is examined in Boren and Ny (2016). The EU aims to achieve sustainable transport, including a major reduction in greenhouse gas emissions from fossil fuel vehicles, particularly buses, trucks, and cars by 2050. Ahn et al. (2015) evaluate the optimization of energy resources for sustainable development in Korea. Policymaking based on sustainable transport development has been explored to increase the penetration of electric vehicles and thus reduce greenhouse gases in California (Javid and Nejat 2017). Jafari et al. (2017) consider the economic and environmental aspects of sustainability in the waste recycling process.

Compared to conventional vehicles (CVs), electric vehicles (EVs) make less noise and pollution using rechargeable batteries as their energy source and electric motors as their driving force. These vehicles are of three main types: battery electric vehicle (BEV), hybrid electric vehicle (HEV), and plug-in hybrid electric vehicle (PHEV). BEVs have an electric motor with batteries for electric power. Batteries can be charged through both the network connection and the car's brake energy. The main disadvantage of these vehicles is their full dependence on the battery. Therefore, the driving range of BEVs is relatively lower than that of the conventional ones. HEVs have both fuel and electric motors with enough battery power to store fuel from the engine and the car's brakes. The main disadvantage of these vehicles is the inability to recharge batteries from the network, thus depending on the fossil fuel engine. PHEVs are designed to eliminate the disadvantages of HEVs. PHEVs are rechargeable from the network, and the batteries should be capable of rapid discharge and fast charging. They can work alone with fuel and electric motor.

The use of electric vehicles has many benefits in reducing CO_2 emissions and reducing dependence on fossil fuels in the transport sector. Therefore, many countries have determined targets for developing EVs in recent years and have implemented policies to achieve environmental goals and reduce energy consumption. Sustainable options for electric vehicle technologies have been investigated in different studies (Poullikkas 2015). The introduction of incentive policies for the approval of electric vehicles across countries was investigated in Zhang et al. (2014). The charging of electric vehicles in China's power system was evaluated by Li et al. (2016). In their study, energy, economic, and environmental issues of EV development were studied, and its policy elements were analyzed. Various policy scenarios for the development of electric vehicles were presented in Zhou et al. (2015), Statharas et al. (2019), and Wang et al. (2018).

Various studies (see for example, Axsen and Kurani 2009) have shown that distribution networks are severely affected by the high penetration of electric vehicles that are charged uncoordinatedly. These effects can include increasing the maximum load and power losses and decreasing the system voltage. It has been suggested that the main solution to these inappropriately uncoordinated vehicle charging effects is to create a coherent process for charging. An effective way to manage the charging of electric vehicles is to use domestic consumption tariffs. Several power companies in different countries have offered hourly tariffs for their customers. The demand response is another effective method that can be used to manage the charge of vehicles (Green et al. 2010). In this method, the operator will allow the customer to cut off at peak time. According to Davidov and Panto (2017), the planning of electric vehicle infrastructures has been assessed based on the reliability of the charge and the quality of the services. Pye et al. (2015) suggested an uncertainty analysis for long-term energy planning in the UK. Based on their study, about 55% of air pollution caused by transportation was caused by cars. Thus, as they proposed, a pressing need is felt for sustainable development-based policymaking to reduce air pollution caused by cars.

There are several methods to evaluate policymaking. Using the data from cities around the world, Haghshenas et al. (2015) tried to assess the sustainable policy in the urban transport system by the use of dynamics systems. According to Lee et al. (2016), the hybrid electric vehicle market penetration model is capable of determining the best policy mix based on the consumer ownership cycle approach.

In the same line, the models of prediction of hybrid electric vehicle market have been investigated through Vensim software by the causal loop diagram. In Prebeg et al. (2016), long-term energy planning for the Croatian power system is presented using a multi-objective optimization approach focusing on renewable energies and the integration of electric vehicles. Sellitto et al. (2014) propose a regular environmental approach using the multi-criteria analysis to evaluate bus transit performance.

There are various methods to evaluate the performance of policies most important among which are fuzzy TOPSIS (Chen and Hwang 1992) and VIKOR (El-Santawy 2012). Kougias et al. (2016) also proposed a tool for the sustainability policymaking of renewable energy systems by MATLAB software. Moreover, Lechman et al. (2019) proposed a life cycle cost analysis method to produce two-layer laminates. The disadvantages of these methods are that they only consider one group of decision-makers. The game theory is another way to evaluate policy performance. The game theory approach considers models of interaction between different decision-makers (Attia et al. 2016). A dynamic game theory approach is proposed to develop a robust and secure distribution policy to optimize non-random Markov policy (Yang 2018). Madani and Hooshyar (2014) propose a learning theory-based game theory to determine the optimal performance of policies in multi-operator multi-repository systems. Multi-objective game theory and fuzzy programming approaches have been proposed to equilibrium economic development and environmental impacts (Moradi and Limaei 2018). The dual goals of multi-objective game theory and fuzzy programming approaches to minimize the detrimental environmental impacts and to maximize the economic revenues derived from various land uses have been outlined in Proskuryakova (2018). A three-level Stackelberg game has been proposed for modeling the interaction between the supplier, the charging infrastructure operator, and investors by Zhu et al. (2017). In Guo and Zhao (2015), the multi-criteria decision-making method for choosing the location of EVs' charging station is provided based on the TOPSIS fuzzy method.

In this paper, sustainable development policymaking for the acceptance and penetration of PHEVs in Tehran has been analyzed using fuzzy TOPSIS and game theory. The purpose of the study is to evaluate policy scenarios for PHEV development in Tehran from both the vehicle buyers and the state's point of view. The first section of the paper involves the introduction, which is followed in section two, by describing and analyzing fuzzy TOPSIS and game theory methods. Then, we discuss the extended model of sustainable development and examine the sustainability of existing vehicles in Tehran. Also, in this section, the parameters affecting the evaluation of vehicle sustainability in Tehran are determined over a 16-year period from 2002 to 2018. In the third section, sustainable development policymaking is evaluated by introducing some policy indicators to expand the number of PHEVs in Tehran using fuzzy TOPSIS and game theory. In the fourth section, the selected policy indicators are discussed, and finally, the number of PHEVs is predicted in 2032.

Background and problem statement

In this study, both the fuzzy TOPSIS and game theory method are used to increase the consistency of the obtained policymaking results. The advantage of this approach is that it considers both fuzzy TOPSIS and game theory for the development of PHEV from the vehicle buyers and the state's point of view.

Fuzzy TOPSIS method

People's thoughts are always associated with uncertainty, and this uncertainty affects decisions. Fuzzy logic is a type of reasoning method that is similar to how one would reason. The fuzzy logic approach follows human decision-making. One of the fuzzy decision-making methods is fuzzy TOPSIS for ranking options. In this method, the elements of the decision matrix, or the weight of the indices, or both are expressed as fuzzy numbers. The steps of the fuzzy TOPSIS method are as follows:

- Make a fuzzy decision matrix with dimensions $m \times n$ for individuals' views.

$$\tilde{D} = \begin{bmatrix} \tilde{d}_{11} & \tilde{d}_{12} & \dots & \tilde{d}_{1n} \\ . & . & . & . \\ . & . & . & . \\ \tilde{d}_{m1} & \tilde{d}_{m2} & \dots & \tilde{d}_{mn} \end{bmatrix} \tag{1}$$

where d_{ij} represents the ith option in the jth sub-criterion and is a fuzzy number represented by a triangular number as $\tilde{d}_{ij} = (a_{ij}, b_{ij}, c_{ij})$. The matrix of fuzzy weights is $\tilde{W} = [\tilde{w}_1, \tilde{w}_2, \dots, \tilde{w}_n]$, and the fuzzy weights are $\tilde{w}_j = (w_{j1}, w_{j2}, w_{j3})$.

- Normalize the decision matrix.

In this stage, we need to transform the fuzzy decision matrix into a normalized fuzzy matrix. To achieve a normalized matrix, if a criterion is positive, equitation (2) is used, and if they are negative, equation three is used:

$$\tilde{n}_{ij} = \left(\frac{l_{ij}}{u_j^*}, \frac{m_{ij}}{u_j^*}, \frac{u_{ij}}{u_j^*} \right), \quad u_j^* = \max u_{ij} \tag{2}$$

$$\tilde{n}_{ij} = \left(\frac{l_j^-}{u_{ij}}, \frac{l_j^-}{m_{ij}}, \frac{l_j^-}{l_{ij}} \right), \quad l_j^- = \min l_{ij} \tag{3}$$

where the decision matrix is as follows:

$$\tilde{N} = \begin{bmatrix} \tilde{n}_{11} & \tilde{n}_{12} & \dots & \tilde{n}_{1n} \\ . & . & . & . \\ . & . & . & . \\ \tilde{n}_{m1} & \tilde{n}_{m2} & \dots & \tilde{n}_{mn} \end{bmatrix} \tag{4}$$

- Make a weighted normalized Fuzzy Matrix V.

To make a weighted matrix, we need to multiply the normalized matrix by the weight of the criteria $v_{ij} = n_{ij} \times w_j$. The matrix is as follows:

$$\tilde{V} = \begin{bmatrix} \tilde{v}_{11} & \tilde{v}_{12} & \dots & \tilde{v}_{1n} \\ . & . & . & . \\ . & . & . & . \\ \tilde{v}_{m1} & \tilde{v}_{m2} & \dots & \tilde{v}_{mn} \end{bmatrix} \tag{5}$$

- Determine the positive ideal solution (A^*) and the negative ideal solution (A^-).

$$\tilde{A}^* = (\tilde{v}_1^*, \tilde{v}_2^*, \dots, \tilde{v}_n^*), \quad \text{Where} \quad \tilde{v}_j^* = \text{Max}(V_j) \tag{6}$$

$$\tilde{A}^- = (\tilde{v}_1^-, \tilde{v}_2^-, \dots, \tilde{v}_n^-), \text{ Where } \tilde{v}_j^- = \text{Min}(V_j) \tag{7}$$

- Determine the sum of components distance from the positive ideal and negative ideal values.

$$d_i^+ = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^*), \ i = 1, 2, \dots, m \tag{8}$$

$$d_i^- = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^-), \ i = 1, 2, \dots, m \tag{9}$$

- Determine the similarity to the ideal option.

The closeness coefficient (CC_i) is calculated by Eq. 10. The option with a higher ranking CC_i is better than the others.

$$CC_i = \frac{d_i^-}{d_i^- + d_i^+}, \; i = 1, 2, \ldots, m \tag{10}$$

Game theory for sustainable development-based policymaking

In the game theory, a game is an interaction or competition between several players where one player's decision or state affects the others.

A game consists of some players, a set of strategies, and winning. Winning every game does not only depend on luck, but has its own rules and principles, and each player tries to increase its chances for winning by applying those principles (Neck 2010). To define each game, it is necessary to specify the following elements:

- *Players* the parties to the game with at least two strategies.
- *Strategies of each player* actions that each player can take in different stages of the game.
- *Information structure* how much each player can know about their opponent's moves and preferences at any given moment of the game.
- *Equilibrium* the strategy that contains the best choice for all players is the equilibrium point of the game (or Nash equilibrium). Every game always reaches an equilibrium, which means players always come up with a solution based on their criteria. In the Nash point, the equilibrium is the condition obtained by a set of strategies and players' decisions the deviation from which will reduce the profit.

Problem statement

Sustainable transport has many socioeconomic and environmental benefits that can accelerate local, sustainable development (Meyar-Naimi and Vaez-Zadeh 2012). In the present study, the nested sustainable development framework is considered. In this sustainable development model, priority is given to nature, human, and system, respectively (Fig. 1).

The human depends on nature; however, nature will continue without humans. Also, the system depends on both the human and the nature. The human and system are limited by nature. In the proposed nested sustainable development model, nature, human (social and economic indicators), and system are prioritized, respectively. The equilibrium point (B) of this model is calculated as follows:

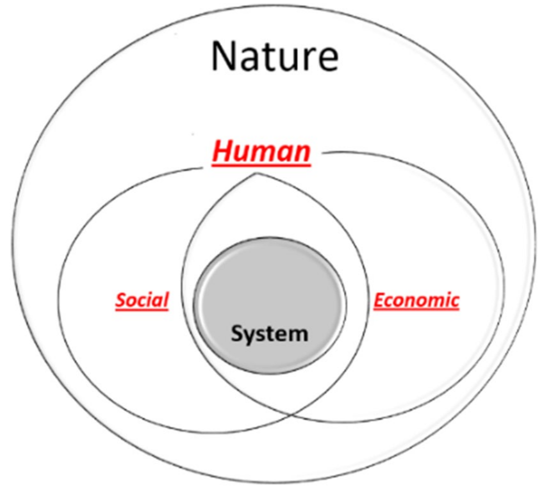


Fig. 1 Nested sustainable development framework

$$B = \mathrm{Max}\left(\frac{M_{\text{average}}}{3} \times \left(\frac{|A_N - A_H|}{(A_N - A_H)} + \frac{|A_H - A_S|}{(A_H - A_S)} + \frac{|A_N - A_S|}{(A_N - A_S)}\right), 0\right) \tag{11}$$

where A_N, A_H, and A_S are the values of nature, human, and system aspects, respectively. M_{average} indicates the average of the aspects.

Research methodology

In the present study, a methodology based on the SD model is applied including determination of time, human and nature reference perspective, determination of indicators, normalization of indicators, weighting and aggregating the indicators firstly to build up environmental, social, economic, and technical sub-dimensions and then to prioritize the main aspects, i.e., nature, human, and system. There are three types of electric vehicles on the market, including battery electric vehicle (BEV), hybrid electric vehicle (HEV), and plug-in hybrid electric vehicle (PHEV). In this paper, PHEV is selected for the study. The most important reason to consider PHEVs in this study is the lack of adequate charging stations for them in Tehran.

Determination of indicators

This section represents the effective nature (environmental), human (economic and social), and system (technical) indicators in the development of vehicles in Tehran from 2002 to 2018, which are illustrated in Table 1.

To that end, the weight of the normalized indicators was calculated using the analytical network process (ANP) to sort and aggregate them. In this part, the weights of the aspects, sub-aspects, and indicators of each sub-aspect

Table 1 Sustainable development indicators on the adoption of vehicles

Indicator	Description of indicators	Unit	Vehicles				Bandwidth		References
			Gasoline	CNG	Diesel	PHEV	LTI	HTI	
Nature									
N_1	CO emissions	g/km	1.81	0.96	0.63	0.01	1.81	0.01	Statharas et al. (2019), Wang et al. (2018), Boren and Ny (2016)
N_2	NO_x emissions	g/km	0.1	0.2	0.33	0.001	0.33	0.001	Statharas et al. (2019), Wang et al. (2018), Boren and Ny (2016)
N_3	CO_2 emissions	g/km	242	212	185	2	242	2	Wang et al. (2018), Silvia and Krause (2016), Zhang et al. (2014)
N_4	Wornout vehicle recycling system	year	10	9	10	4	4	10	Wang et al. (2018), Sellitto et al. (2014), Silvia and Krause (2016)
N_5	Noise level at 1 m distance	dB	70	75	80	65	85	65	Sellitto et al. (2014)
N_6	Life cycle assessment of vehicles	%	40	45	47	65	65	40	Sellitto et al. (2014), Javid and Nejat (2017), Silvia and Krause (2016)
Human									
Economic									
H_1	Vehicle cost	$	4000	10,000	20,000	40,000	40,000	4000	Zhou et al. (2015), Statharas et al. (2019), Wang et al. (2018)
H_2	Maintenance cost	$/year	250	500	600	2000	2000	250	Zhou et al. (2015), Wang et al. (2018), Lee et al. (2016)
H_3	Fuel price	cents/l	40	20	25	15	40	15	Wang et al. (2018), Wesseling (2016), Lee et al. (2016)
H_4	Number of vehicle manufacturers in Tehran	Number	5	4	3	1	1	5	Meyar-Naimi and Vaez-Zadeh (2012), Sadeghi-Barzani et al. (2014)
H_5	Cost of the battery	$/year	100	100	100	1000	1000	100	Statharas et al. (2019), Zhou et al. (2015)
H_6	Technology life cycle	year	10	8	7	4	4	10	Javid and Nejat (2017), Silvia and Krause (2016), Zhang et al. (2014)
Social									
H_7	Age structure	years	35	40	75	18	18	75	Javid and Nejat (2017), Silvia and Krause (2016)
H_8	Mortality rate in transportation system	Person/year	0.1	0.2	0.3	0.9	0.1	0.9	Javid and Nejat (2017), Silvia and Krause (2016)
H_9	Vehicle size	kg	900	1200	1100	1600	900	1600	Javid and Nejat (2017), Lee et al. (2016), Langbroek et al. (2016)
System									
S_1	Technical knowledge at national level (non-dependence on sanctions)	%	1	0.9	0.7	0.1	0.1	1	Shareef et al. (2016), Zhang et al. (2014)
S_2	Charging or refueling time	min	5	10	5	60	60	5	Javid and Nejat (2017), Shareef et al. (2016), Zhang et al. (2014)
S_3	Voltage imbalance index due to EV charging	%	0	0	0	1	0	1	Shareef et al. (2016), Poullikkas (2015)
S_4	Power loss index due to EV charging	%	35	40	40	30	30	40	Shareef et al. (2016), Poullikkas (2015)
S_5	Overall efficiency of vehicles	%	80	100	90	150	150	80	Statharas et al. (2019), Wang et al. (2018), Langbroek et al. (2016)

Table 1 (continued)

Indicator	Description of indicators	Unit	Vehicles				Bandwidth		References
			Gasoline	CNG	Diesel	PHEV	LTI	HTI	
S_6	Weight-to-power ratio	kW/kg	136	19	14	2	2	136	Statharas et al. (2019), Zhang et al. (2014), Langbroek et al. (2016)
S_7	The number of fueling/charging stations	Number	250	300	350	4000	4000	250	Sadeghi-Barzani et al. (2014), Lee et al. (2016), Statharas et al. (2019)

were calculated using ANP. In the ANP method, the system depends on nature and human. For example, the technical development of new vehicles is dependent on environmental, economic, and social aspects, and human depends on nature.

Sustainability evaluation of vehicles development in Tehran from 2002 to 2018

In this section, the historical development of conventional vehicles (gasoline, CNG, diesel engine) and PHEVs are evaluated from the sustainability point of view. Figures 2, 3, and 4 represent the temporal trend of environmental, economic, social, and technical indicators and their aggregated values from 2002 to 2018 in Tehran.

The temporal trend of aggregated nature indicators from 2002 to 2018 is shown in Fig. 2. As shown, most of the nature indicators had little growth between 2006 and 2014, while since 2014, most of them have been increasing.

Human indicators are shown in Fig. 3. As it is seen, H_1, H_2, H_3, H_4, and H_8 have had an increasing trend, whereas H_5, H_6, H_7, and H_9 indicators have had a decreasing trend.

System indicators are shown in Fig. 4. As indicated, S_1, S_2, S_5, and S_6 at first have been incremental, then decreasing, and then incremental again. S_3 and S_4 are related to V2G service at the charging station, which has been implemented since 2014. The rest of the technical indicators have been increasing from 2002 to 2018.

The temporal trend of aggregated nature, human, and system aspects is shown in Fig. 5. As reflected in the figure, the human and system aspects remained unchanged in 2002, and the nature aspect fell to its lowest value. In the years 2010–2016, nature ranked higher than the others, and then fell human and system aspects. From 2016, the growth of the system aspect has been more than the others. In this figure, B is the equilibrium point of the nested model. As seen in the figure, from 2006 to 2016, development was sustainable, but it was unstable from 2002 to 2006 and 2016 to 2018.

In Fig. 6, the percentage of gasoline, CNG, diesel, and plug-in hybrid electric vehicles in Tehran from 2002 to 2018 is shown. Based on the figure, since 2008, the CNG vehicles have outnumbered the diesel vehicles. Plug-in hybrid electric vehicles have been used since 2014.

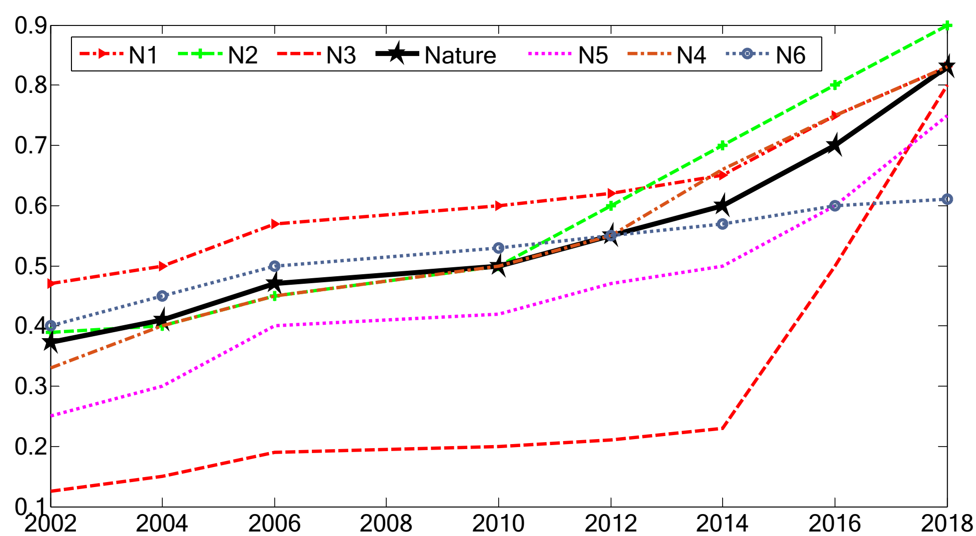


Fig. 2 Temporal trend of aggregated nature indicators

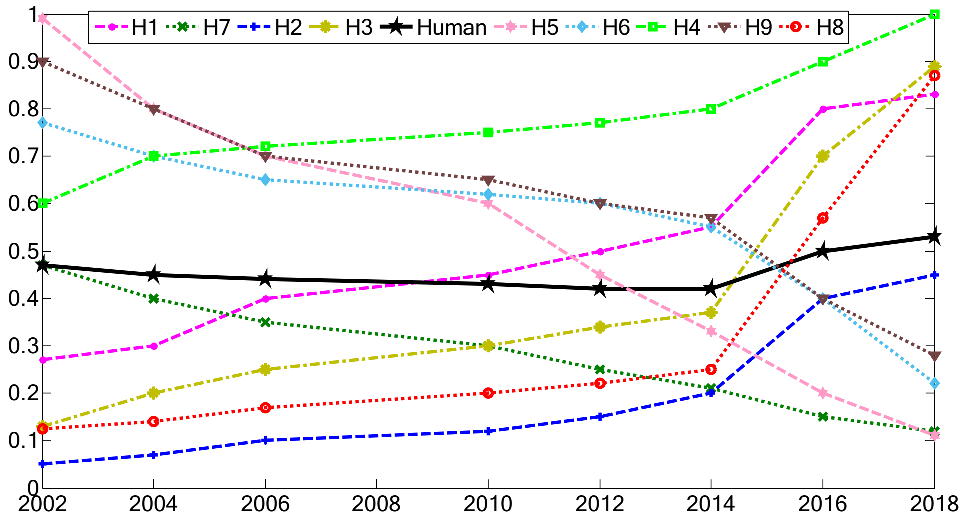


Fig. 3 Temporal trend of aggregated human indicators

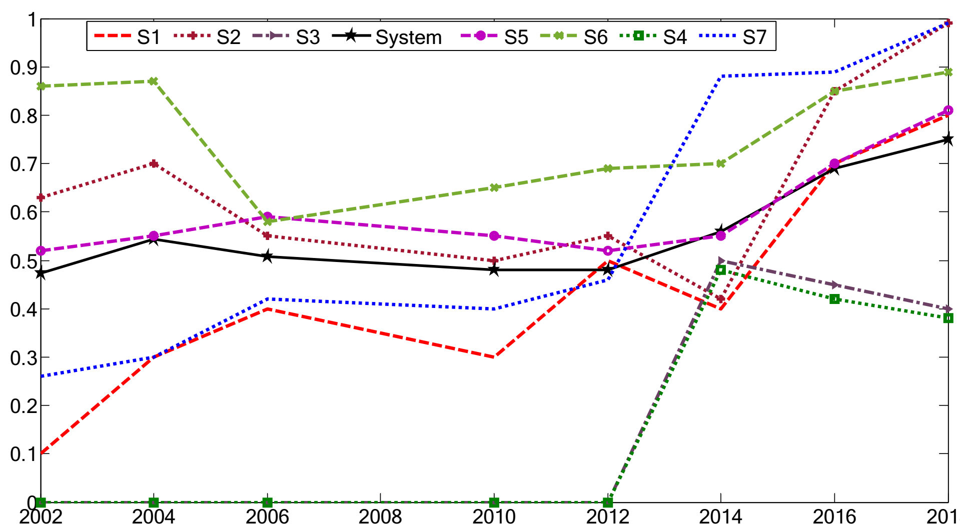


Fig. 4 Temporal trend of aggregated system indicators

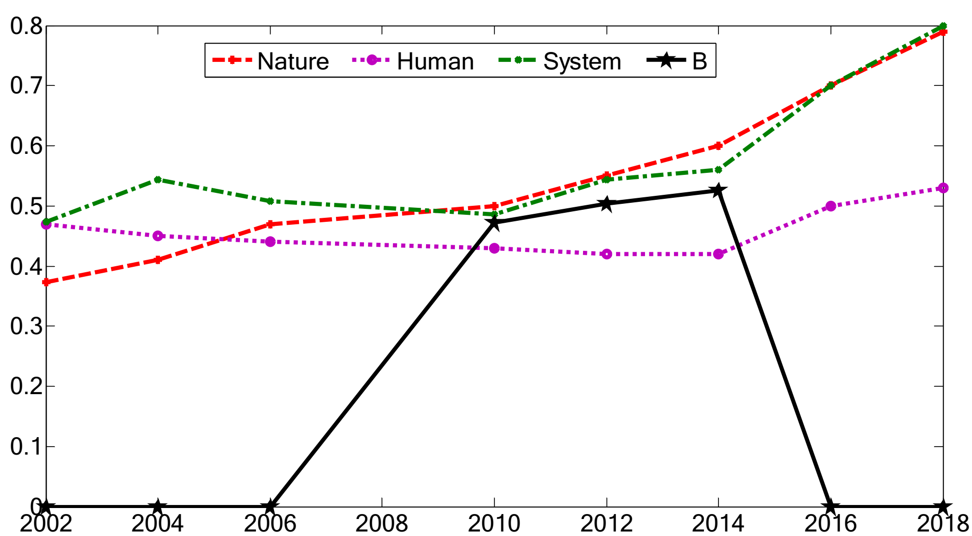


Fig. 5 Temporal trend of aggregated aspects and equilibrium point (B)

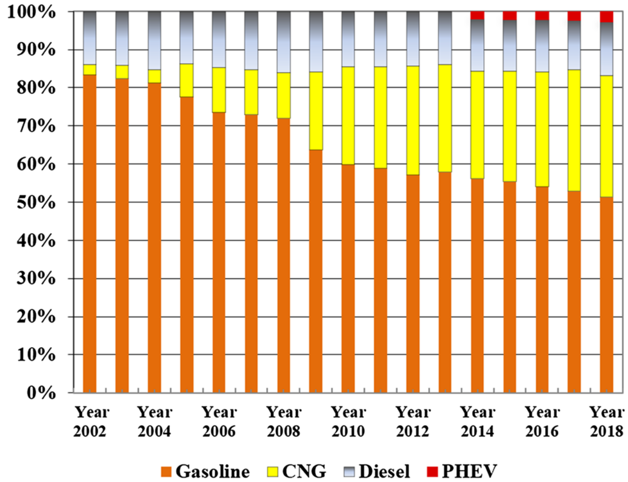


Fig. 6 Adoption of gasoline, CNG, diesel, and PHEV in Tehran from 2002 to 2018

Sustainable development-based environmental policymaking

In this section, a new approach to PHEV policymaking from the perspective of sustainable development in Tehran is presented. The fuzzy TOPSIS method is used to investigate various factors affecting the development of PHEVs in Tehran. Based on Fig. 5, at the equilibrium point of the nested SD model (B), it can be seen that the development of vehicles in Tehran has been unsustainable since 2016, which confirms the current Tehran air pollution. According to the World Health Organization (WHO), Tehran is one of the most polluted cities in the world in terms of particulate matter (Fig. 7).

Alternative policy scenarios

In this section, some policy scenarios for the development of PHEV in Tehran are proposed based on the sustainable development indicators (Table 2).

Policymaking using fuzzy TOPSIS method

In line with the fuzzy TOPSIS steps, four different criteria, including environmental, social, economic, and technical, are considered in this research. There are also eight alternative policy scenarios P_i, $i = \{1, 2, \ldots, 8\}$ concerning Tehran's transportation decisions, regulations, and directives. The criteria weights were assigned to the alternatives for the assessment of different policy scenarios (Fig. 8). The fuzzy variables for the criteria and their weights are shown in Fig. 9. The ratings of alternative policy strategies by decision-makers and the weight of criteria using fuzzy variables are illustrated in Table 3. The distance from the positive and negative ideal values (d_i^+, d_i^-) and the similarity to the ideal option (CC_i) from the state and vehicle buyer viewpoints are shown in Tables 4, 5, 6, 7, 8, and 9.

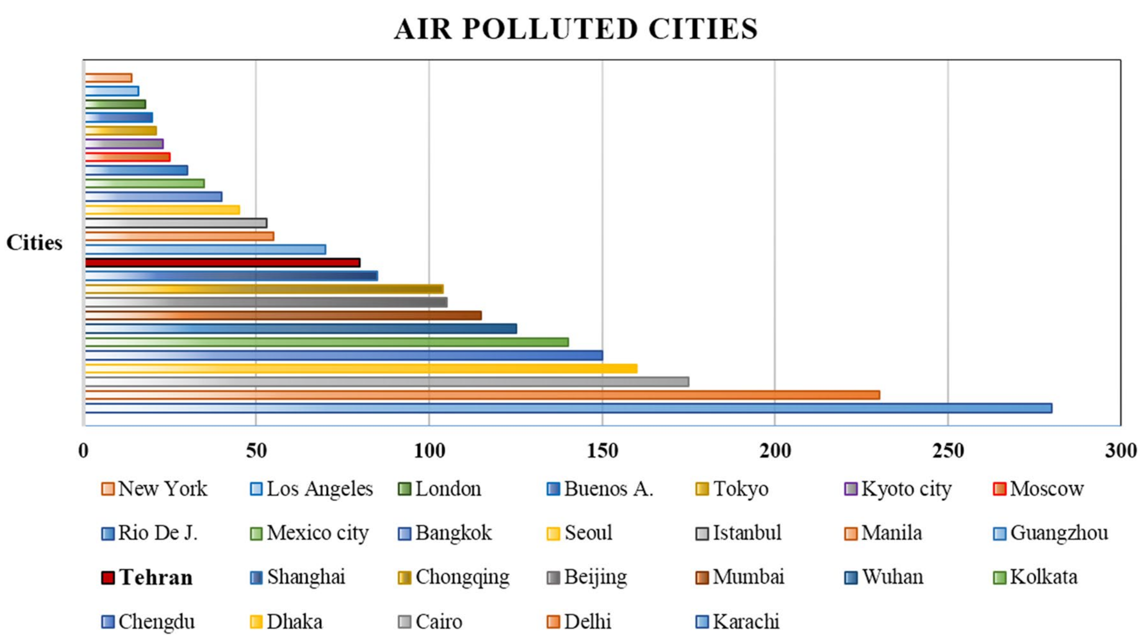


Fig. 7 Annual ambient level of PM_{10} ($\mu g/m^3$)

Table 2 Policy description for PHEV development in Tehran

SD aspects	Policy	Policy description	References
Environment	P_1	The policy of enforcing the use of PHEV for the reduction in NO_x and particle emissions in downtown	Statharas et al. (2019), Silvia and Krause (2016), Boren and Ny (2016)
	P_2	The policy of enforcing the use of PHEV charging and transfer CO_2 emissions from urban vehicle to power plants outside the city	Statharas et al. (2019), Wang et al. (2018), Silvia and Krause (2016)
Social	P_3	Affordability with designing smaller and chipper vehicle	Wang et al. (2018), Javid and Nejat (2017), Zhang et al. (2014)
	P_4	Attractive vehicle design for younger age	Javid and Nejat (2017), Silvia and Krause (2016)
Economic	P_5	Financial incentives (loans and tax incentives)	Zhou et al. (2015), Wesseling (2016), Zhang et al. (2014)
	P_6	Non-financial incentives (eliminating traffic constraints)	Zhou et al. (2015), Wang et al. (2018), Wesseling (2016)
Technical	P_7	Peak load shaving with load shifting	Shareef et al. (2016), Poullikkas (2015), Langbroek et al. (2016)
	P_8	Increasing the number of parking and charging stations	Shareef et al. (2016), Zhang et al. (2014), Sadeghi-Barzani et al. (2014)

The state viewpoint

The fuzzy TOPSIS step from the state viewpoint is shown in Tables 4, 5, and 6. After applying the fuzzy TOPSIS method, the resulted ranking of alternative policy scenarios from the state viewpoint using the closeness coefficient is: $P_1 > P_8 > P_6 > P_2 > P_7 > P_5 > P_3 > P_4$.

Vehicle buyer viewpoint

The fuzzy TOPSIS step from the vehicle buyer viewpoint is illustrated in Tables 7 8, and 9. Based on the fuzzy TOPSIS method (Table 9), the resulted ranking of alternative policy scenarios from vehicle buyer viewpoint is: $P_6 > P_3 > P_4 > P_7 > P_8 > P_5 > P_1 > P_2$.

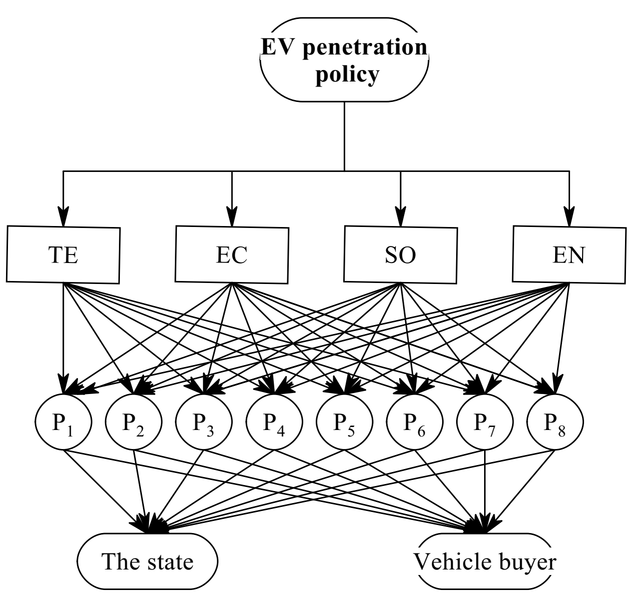


Fig. 8 Hierarchical structure for assessing the policy strategies in Tehran

Sensitivity analysis and game equilibrium point for PHEV policymaking

Sensitivity analysis is a tool for analyzing uncertainty in problems with different decision-makers. Sensitivity analysis helps understand how outputs change with input. Table 10 shows the different weights of the input criteria in the sensitivity analysis. Figure 10 shows the results of the sensitivity analysis in buyers and the state points of view (players in the game theory method). In game theory, each player's profit in different strategies is first calculated. Then, the Nash equilibrium point is calculated. This point represents the highest profit each player has for themselves in facing other players, so ignoring that the point can reduce their profits as well as others. Table 11 shows the closeness coefficients of the policy scenarios obtained using the Nash equilibrium point.

Results and discussion

There are several reasons why PHEV is not popular in Tehran. One is that the price of PHEVs is relatively higher than that of CVs because of their inadequate technology. The second reason is that the required charging infrastructure does not yet exist. Therefore, incentives should be given to developing charging stations. It seems that the suggestions proposed in this paper can help increase the number of PHEVs in Tehran.

One of the selected policy indicators for PHEV adoption is providing non-financial incentives such as eliminating traffic constraints in Tehran downtown (P_6). To increase

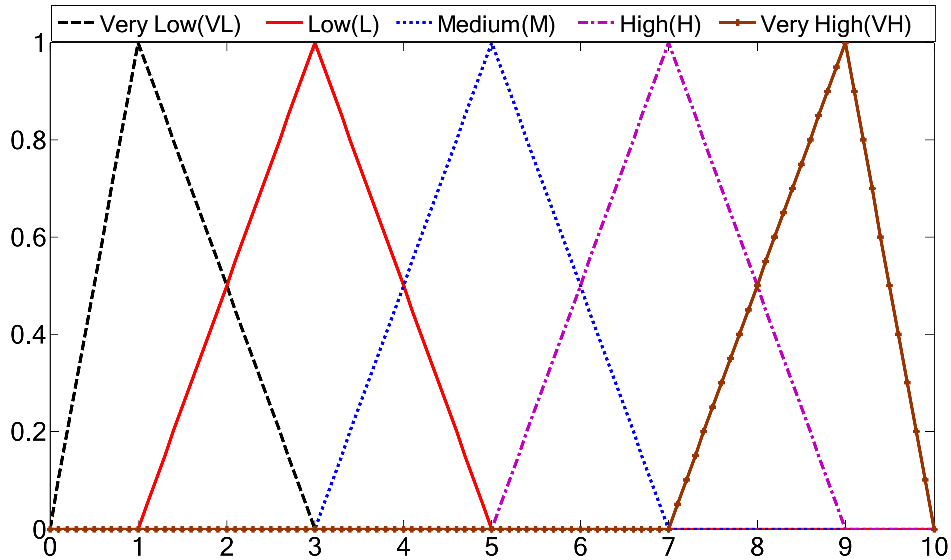


Fig. 9 Fuzzy variables

Table 3 Rating of alternative policy strategies by decision-makers

Decision-makers	Criteria	EN	EC	SO	TE
	Weight of criteria	VH	M	M	VL
Player 1: The state	P_1	VH	H	L	L
	P_2	VH	M	L	L
	P_3	L	H	H	M
	P_4	L	L	M	M
	P_5	L	VH	H	L
	P_6	VH	L	M	L
	P_7	L	VH	H	VH
	P_8	M	M	H	H
Player 2: Vehicle buyer	P_1	L	VL	VL	VL
	P_2	L	VL	VL	VL
	P_3	M	VH	VH	VH
	P_4	M	H	VH	VH
	P_5	L	VH	VH	M
	P_6	VH	VH	H	M
	P_7	H	H	M	VH
	P_8	M	M	VH	VH

Table 4 Distance from the positive ideal value from the state viewpoint

Policy scenarios	EN	SO	EC	TE	d_i^+
P1	4.323	5.9931	3.9986	2.6886	17.0034
P2	4.323	5.9931	4.7273	2.6886	17.7321
P3	9.5756	3.5648	3.9986	2.2441	19.3831
P4	9.5756	4.33	6.1649	2.2441	22.3145
P5	9.5756	3.5648	3.3853	2.6886	19.2143
P6	4.323	4.33	6.1649	2.6886	17.5065
P7	9.5756	3.5648	3.3853	1.8572	18.3828
P8	6.9852	3.5648	4.7273	2.0301	17.3074

Table 5 Distance from the negative ideal value from the state viewpoint

Policy scenarios	EN	SO	EC	TE	d_i^-
P1	7.4664	1.1618	3.6242	0.4199	12.6723
P2	7.4664	1.1618	2.6948	0.4199	11.7428
P3	1.3687	4.4296	3.6242	1.0757	10.4982
P4	1.3687	3.2936	0.9506	1.0757	6.6885
P5	1.3687	4.4296	4.5648	0.4199	10.783
P6	7.4664	3.2936	0.9506	0.4199	12.1304
P7	1.3687	4.4296	4.5648	1.7597	12.1228
P8	4.2446	4.4296	2.6948	1.4162	12.7851

the use of PHEVs in Tehran, there must be conditions that encourage citizens to use these vehicles. Such incentives can be both financial and non-financial. Financial incentives that can persuade consumers to buy PHEVs include direct loans, removing taxes and annual charges, discounts on commercial profits and PHEV tariffs, and domestic electrical systems in times other than the on-peak hours. Non-financial incentives can also affect PHEV buyers' interests. Non-financial incentives can include eliminating traffic constraints and allocating dedicated parking spaces to PHEVs.

Another policy indicator is the peak load shaving with load shifting (P_7). To describe this policy, we propose a new concept called time–location shifting (TLS) implemented by PHEV. TLS means power consumption by charging PHEV batteries during off-peak hours (during business hours and in the downtown) and by generating

Table 6 Similarity to the ideal option (CC_i)

Policy scenarios	CC_i	Ranking
P1	0.427	1
P2	0.3984	4
P3	0.3513	7
P4	0.2306	8
P5	0.3595	6
P6	0.4093	3
P7	0.3974	5
P8	0.4249	2

Table 7 Distance from the positive ideal value from the vehicle buyer viewpoint

Policy scenarios	EN	SO	EC	TE	d_i^-
P1	8.4937	6.1649	6.1649	2.6886	23.5121
P2	8.4937	6.1649	6.1649	2.6886	23.5121
P3	6.9852	3.3853	3.3853	1.8572	15.6129
P4	6.9852	3.3853	3.9986	1.8572	16.2263
P5	9.5756	3.3853	3.3853	2.2441	18.5902
P6	4.323	3.9986	3.3853	2.2441	13.951
P7	5.5655	4.7273	3.9986	1.8572	16.1486
P8	6.9852	3.3853	4.7273	1.8572	16.9549

Table 8 Distance from the negative ideal value from the vehicle buyer viewpoint

Policy scenarios	EN	SO	EC	TE	d_i^-
P1	2.7293	0.9506	0.9506	0.4199	5.0503
P2	2.7293	0.9506	0.9506	0.4199	5.0503
P3	4.2446	4.5648	4.5648	1.7597	15.1339
P4	4.2446	4.5648	3.6242	1.7597	14.1933
P5	1.3687	4.5648	4.5648	1.0757	11.5739
P6	7.4664	3.6242	4.5648	1.0757	16.731
P7	5.8409	2.6948	3.6242	1.7597	13.9195
P8	4.2446	4.5648	2.6948	1.7597	13.2638

power during on-peak hours by battery discharge (during the evening and night and in the suburbs). The average urban journey duration in Tehran is about 55 min (Samaie et al. 2020). Most people in Tehran are in downtown from 8 am to 5 pm, where there are many commercial and administrative buildings. In the afternoon, they return home from 5 pm. Applying the concept of TLS, power losses are effectively reduced, and as a result, emissions from the power plants supplying these losses are lessened.

Table 9 Similarity to the ideal option (CC_i)

Policy scenarios	CC_i	Ranking
P1	0.1768	7
P2	0.1768	8
P3	0.4922	2
P4	0.4666	3
P5	0.3837	6
P6	0.5453	1
P7	0.4629	4
P8	0.4389	5

Table 10 Weights of the criteria in a sensitivity analysis

Player strategies	EN	EC	SO	TE
Strategy 1	VH	M	M	VL
Strategy 2	H	M	M	L
Strategy 3	H	M	M	VL
Strategy 4	VH	H	H	L
Strategy 5	VH	H	H	VL
Strategy 6	VH	H	H	M
Strategy 7	VH	L	L	VL

Using the TLS scenario will expand the use of PHEV due to being profitable for the vehicle owner as well as the distribution network. To use PHEVs in the network, the time tariff policy can be suggested as given in Table 12. Using the TLS method, PHEVs can be recharged at off-peak hours in the downtown and inject battery power into the grid in on-peak hours in the suburbs, thereby reducing the peak.

Predicted number of PHEVs based on policy scenario from game equilibrium

The growth rate of PHEV in Tehran can be calculated as follows:

$$\mathrm{PHEV}_{\mathrm{Number}}(t) = \mathrm{PHEV}_{\mathrm{Number@2018}} \times (1 + \mathrm{CC}_{\mathrm{equilibrium}})^{(t-2018)} \tag{12}$$

where $\mathrm{CC}_{\mathrm{equilibrium}}$ is the amount of average closeness coefficient in the game equilibrium point, $\mathrm{PHEV}_{\mathrm{Number}}(t)$ is the PHEV number at year t, and $\mathrm{PHEN}_{\mathrm{Number@2018}}$ is the PHEV number in the year 2018.

In 2018, there were approximately 11,000 PHEVs in Tehran. As the closeness coefficient of the game equilibrium point is 0.4582 for the state player and 0.5591 for the buyer of PHEV player, the average of which is 0.50865. It can be predicted that there will be 3,211,221 PHEVs in 2032.

As shown in Fig. 11a, the transportation sector accounts for about 25% of the total energy consumption in Tehran. Gasoline and natural gas vehicles use 86.44% and 13.5% of

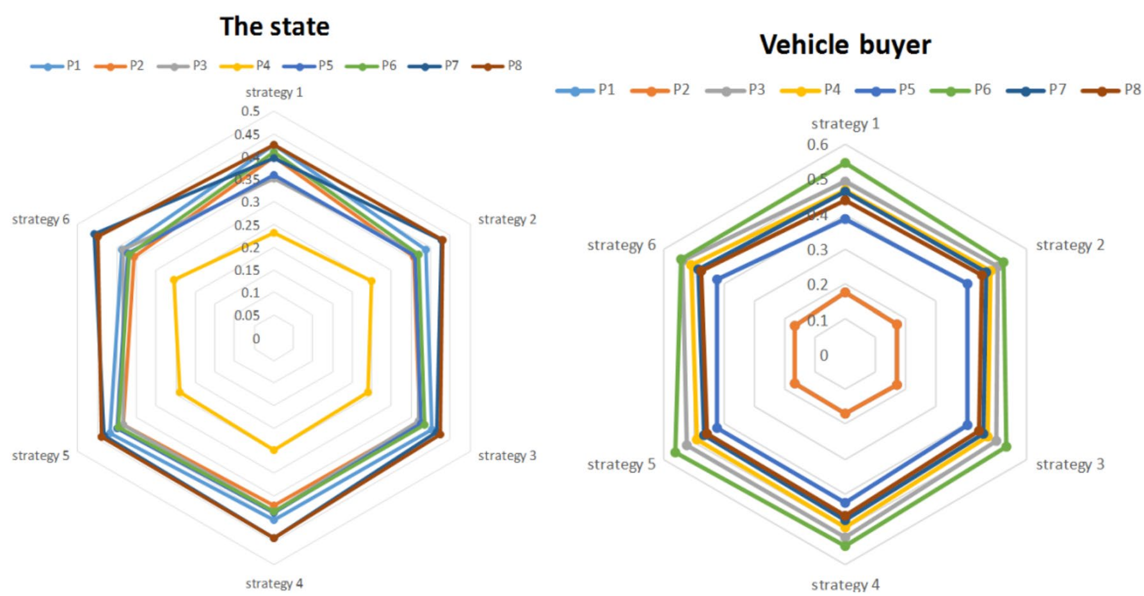


Fig. 10 Sensitivity analysis of PHEV buyers and the state point of views

Table 11 Closeness coefficient of the obtained policy scenario by Nash equilibrium point

	Strategy	Policy scenario
The state	10	$P_7 = 0.4582$
PHEV buyer	5	$P_6 = 0.5591$

energy in the transportation system, respectively. However, the contribution of PHEVs is very small.

As predicted above, PHEVs will account for about 20% of vehicles by 2032. Therefore, they can reduce gasoline consumption and increase electricity consumption, where the electricity consumption of the transportation sector will be about 20%. Based on this scenario, the energy consumption chart for 2032 is shown in Fig. 11b.

Conclusion

Systems' thinking is based on a worldview in which each large system consists of smaller sub-systems. The transportation system is a set of components that pursue specific goals. So, there is a need for a model that can tell whether the transportation sector development is doing well and what technology can improve the technical, environmental, economic, and social aspects of development. Sustainable development, which includes all aspects of development, can be chosen as a framework for this purpose.

In this study, a new approach to environmental policymaking was presented for sustainable development in Tehran. In this approach, a combination of the ANP, fuzzy TOPSIS, and game theory analysis is used to increase the penetration of PHEVs in Tehran. In so doing, first, the ANP approach was applied to the sustainability assessment of

Table 12 Time tariff policy based on Tehran load profile

	Time period of a day		Explanations
	8 am to 5 pm	5 pm to 10 pm	
Suburb			
V2G	Normal tariff	Incentive tariff	Incentive tariff to injecting PHEV battery power into the grid during on-peak hours at the suburbs
G2V	Normal tariff	Punitive tariff	Punitive tariff to prevent PHEV charging during on-peak hours at the suburbs
Downtown			
V2G	Punitive tariff	Normal tariff	Punitive tariff to prevent injecting PHEV battery power into the grid during off-peak hours in the downtown
G2V	Incentive tariff	Normal tariff	Incentive tariff to PHEV charging during off-peak hours in the downtown

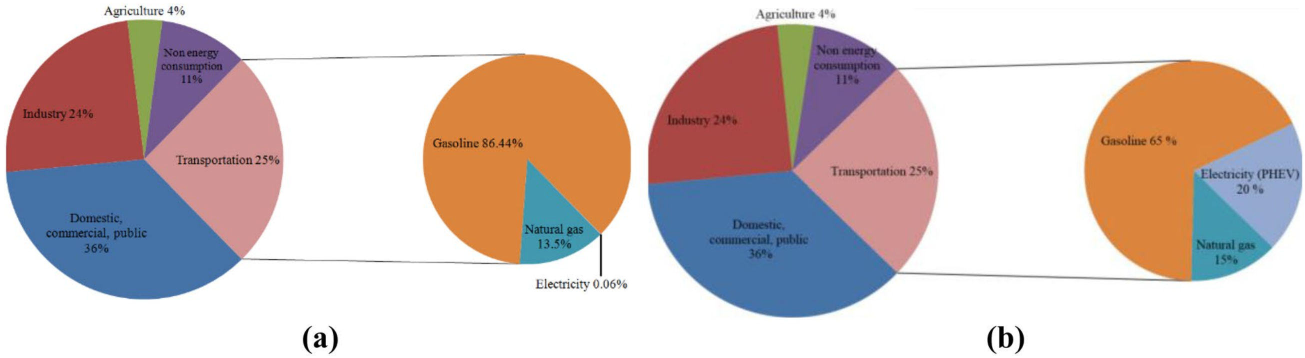


Fig. 11 **a** Current energy consumption chart of Tehran in 2018. **b** Energy consumption forecast of Tehran in 2032

different vehicles in Tehran from 2002 to 2018. And then, some policy scenarios for the development of PHEV in Tehran were proposed, and the fuzzy TOPSIS method was used to rank them. The policies were examined from the point of view of the vehicle buyers and the state, and then using game theory, taking into account the vehicle buyer and the state as the players, the Nash equilibrium point was determined, which yielded the best policy in the point of view of both players. This could help to gain greater knowledge and more understanding of the PHEV development problem, which is the ideal basis for well-founded decision-making. This method can provide for the evaluation of the alternatives, giving important insights into the most suitable policy scenarios for achieving Tehran's PHEV target by 2032.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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