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Comparison of sustainability models in development of electric vehicles in Tehran using fuzzy TOPSIS method

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ABSTRACT

In the present article, regarding the concept of sustainable development (SD), the sustainability of Electric Vehicles (EVs) development in Tehran is evaluated. This paper expends the conventional definition of sustainable development based on a broad philosophy of harmonizing and prioritizing key aspects of human, nature, and systems performances. In the new proposed philosophy of this paper, the emphasis is placed on the aspects of development (Nature, Human, System), their balance, and priority. Then, using a proposed model (NHS), the sustainability of vehicle development in Tehran from the past to the present is evaluated. The results show that this development based on the new proposed SD model has been sustainable from 2010 to 2012. But it has been unstable in 2002–2010 and 2012-2018. Then, according to the most critical aspects of SD, some policy scenarios for the development of EV penetration are introduced. In the proposed method, the closeness coefficient of each policy scenario calculated utilizing fuzzy TOPSIS and the various policies affecting the development of EVs in Tehran ranked. According to the selected policy, a new concept is proposed called Time-Space Load Shifting (TSLS) which is done by EVs. This concept will modify the instability from 2018.

1. Introduction

An EV is referred to as a vehicle that utilizes an electric motor to provide all or part of the mechanical power needed to drive it. In Chris and Krause (2016) three types of EVs have introduced: Battery Electric Vehicle (BEV), Fuel Cell Electric Vehicle (FCEV), and Hybrid Electric Vehicle (HEV). Battery EVs save energy electrochemically in batteries. Since these vehicles need to be connected to the grid, the additional costs for the Vehicle to Grid (V2G) implementation are insignificant (Kempton & Tomic, 2005). In Denholm and Sioshansi (2011), Plug-in Hybrid Electric Vehicle (PHEV) is described as the new generation of vehicles, which has the advantage of high-performance battery vehicles and the high advantage of conventional vehicles. In recent years, the development of EVs has taken new directions. Optimization of intelligent parking of hybrid EVs with renewable energy sources to enhance distribution network features has been explored (Farivar, Vafaeipour, Rahbari, & Rosen, 2014). In Sterman (2000), the growth rate of the number of battery EVs in a city has been forecasted. To increase the use of EVs, several multi-criteria decision-making methods have been used with different goal functions like cost or air pollution minimization.

The most important model or framework that should be considered when developing new technology is the SD framework. Such frameworks consider various aspects of development, such as social, economic, environmental and technical. In Meyar-Naimi and Vaez-Zadeh (2012b), an overview of the origination and formulation of the SD concept and the related policy-making frameworks presented. Moreover, using the Analytical Hierarchy Process (AHP) with a set of criteria, it was shown that The Pressure–State–Response (PSR) and the Driving-Force-Pressure-State-Impact-Response (DPSIR) have the highest and lowest priorities from the intensity of the application point of view. According to Meyar-Naimi and Vaez-Zadeh (2012a), some critical points regarding the SD concept were discussed. It was argued that the SD is concerned with selected sectors and regions rather than the whole society and all regions of the world. To tackle this shortcoming, the conventional definition of SD is extended in (Meyar-Naimi

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& Vaez-Zadeh, 2012a) based on a broad philosophy of harmonizing key aspects of human, nature and systems performances over generations. The Decision-Making Trial and Evaluation Laboratory and Analytic Network Process (ANP), known as the DEMATEL-ANP approach, have been applied to other research disciplines to address these shortcomings (Gholamreza et al., 2017).

There are three models for monitoring the SD. They are a 3-legged stool model of sustainable development, a three-ring sector view of sustainable development, and Nested sustainability model. According to three-legged stool model, if all three legs have equal length, the system is sustainable, and if any leg is bigger or smaller than the others, the system is not sustainable (Dawe & Ryan, 2003). The three-ring sector view of sustainable development (Meyar-Naimi & Vaez-Zadeh, 2012a) is the balancing of the three SD aspects, and increasing the overall aggregated indicator was also considered. There are major weaknesses and limitations in the three-ring model (Tom, Hugé, Verbruggen, & Wright, 2011). It assumes the separation and even autonomy of the sustainability aspects from each other. In the proposed model (Nested sustainable development), the priority is given to Nature, Human, and System, respectively. This model trying to maintain a balance between all the 3 'pillars'.

Because of uncertainty, there is usually a difference between what is forecasting and what is realized. Fuzzy logic can be applied to uncertainty problems (Donglin, Yu, Wang, & Tao, 2019). In order to use expert opinions to compare criteria, Linguistic values must be converted to fuzzy numbers. When the fuzzy operation is performed, fuzzy results are obtained. These fuzzy results cannot be easily interpreted so they have to be converted to precise quantity. The process of converting fuzzy numbers to precise quantity is called defuzzification. The defuzzification methods are include centroid method, weighted average method, mean max membership, center of sums, max membership principle, etc. In Yunna, Zhang, Xu, and Li (2018), the fuzzy ANP method was introduced to reflect the correlation among the criteria based on the sustainability perspective for large commercial rooftop photovoltaic system site selection. Human thinking is associated with uncertainty and this uncertainty has an impact on decision making. So, fuzzy decision making methods are used, one of which is fuzzy TOPSIS method for ranking options. In this method, the decision matrix elements, the weights of the indices, or both, are expressed as fuzzy numbers. The Fuzzy TOPSIS method is an effective method due to its simplicity and ability to consider a non limited number of alternatives and criteria in the decision making process. Sen and Zhao (2015) suggested a multi-criteria selection method based on the TOPSIS fuzzy method to select the location of the Electric Vehicle charging station. One of the methods for solving multi-criteria decision-making problems is Fuzzy TOPSIS, first developed by Chen and Hwang in 1992 (Chen & Hwang, 1992). In this model, weights and decision matrices are defined as fuzzy numbers and rank as the classic TOPSIS based on the distance from the positive and negative ideal.

In this paper, EV development in Tehran, the capital of Iran, is analyzed from the standpoint of SD using a proposed model in which the conventional definition of SD is extended to include such key dimensions as Human, Nature and System factors. In the decision-making problem, the inter-dependencies between criteria and aspects are considered using the ANP. By using the ANP, the dependencies and feedback between the decision-making elements are modeled, and the weights of criteria are precisely calculated. In so doing, firstly, the effective aspects of the model are identified, and secondly, they are organized by the use of ANP technique. Then, various policies affecting the development of EVs in Tehran were studied. For this reason, fuzzy decision-making methods were used, one of which is fuzzy TOPSIS for ranking options. Finally, a new concept called Time-Space Load Shifting (TSLS) was proposed. In the downtown, the distribution network is stronger and mostly consists of the administrative and commercial texture and is loaded in off-peak hours. On the contrary, in suburb the distribution network is weaker due to long feeders, and more often has a residential texture and is loaded in on-peak hours. So the proposed concept of TSLS leads to the sustainable development of EVs in Tehran.

2. Sustainable development (SD)

"Sustainable Development" is a global solution for human and economic development for present and future generations. It is a socio-economic and environmental process that is characterized by fulfilling human needs while preserving the quality of the environment indefinitely. Sustainable transport has many socio-economic and environmental benefits that can accelerate local SD. Sustainable transport can help job creation and improve transport safety and environmental benefits and can render access to social opportunities more cost-effective and efficient. Investment in sustainable transport provides practical opportunities for saving people's time and income, as well as government budgets.

2.1. Sustainability philosophies

There are three main philosophies for SD: 3-legged stool, three-ring sector view, and Nested sustainability model.

The three-legged stool is a simple philosophy, as illustrated in Fig. 1-a. If all three legs have equal length, the system will be sustainable, and if not, the system will not be sustainable (Dawe & Ryan, 2003).

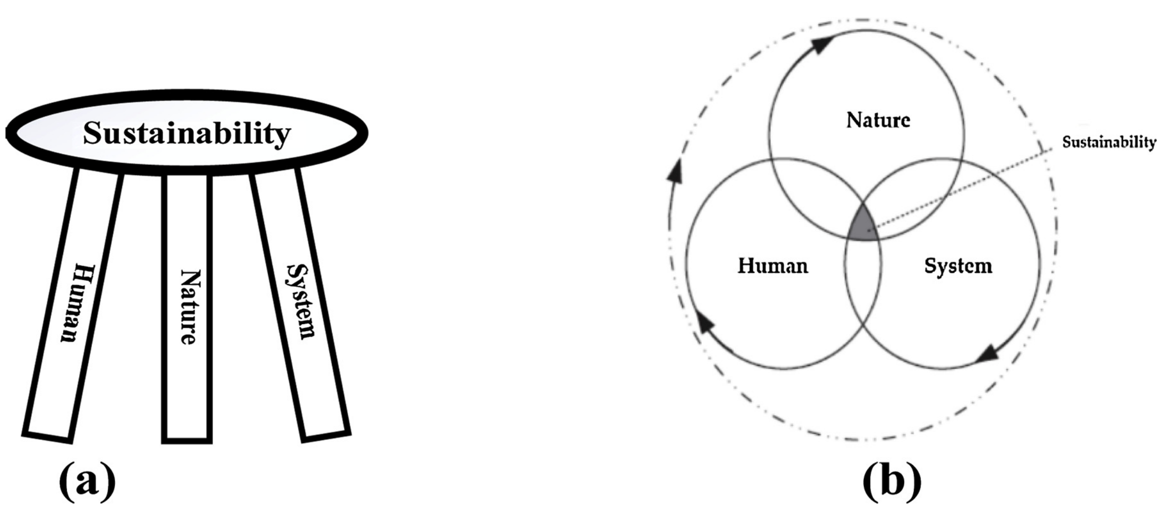

Fig. 1. (**a**)Three-legged stool philosophy of SD, (**b**) Common three-ring sector view of SD.

Also, the conventional definition of SD was extended based on a broad philosophy of harmonizing key aspects of human, nature, and systems (HNS) performances over generations (Meyar-Naimi & Vaez-Zadeh, 2012a). Based on this extended definition, an improved Driving Force–State–Response (DSR-HNS) policy-making framework was introduced, the main contribution of which was the modeling of the state block by Human, Nature, and Systems components to design overall and coherent policies. In this framework, the three sectors were presented as three interconnected rings (Fig. 1-b). The balancing of the three SD aspects and increasing the overall aggregated indicator was also considered in (Meyar-Naimi & Vaez-Zadeh, 2012a). There are major weaknesses and limitations in the three-ring model (Tom et al., 2011). It assumes the separation and even autonomy of the human, nature and system aspects from each other. This view of SD cannot consider priority between Nature, Human and System aspects.

In this article, an improved version of the HNS model is proposed. We consider the priority of aspects (H, N, S) in addition to their balance as a new criterion of sustainability. We convert the previous model to NHS, which shows the superiority of N to H and then H to S. In our model, the overall aggregated indicator is eliminated, and only the balance and priority of H, N, and S are taken into account.

A more accurate presentation of the relationship among Human, Nature, and System is one in which in a sustainable state, the system circle falls inside the Human circle, and both of them are embedded within the Nature circle (Fig. 2). As shown in Fig. 2, based on the previous model, all three aspects are equally balanced, but according to our proposed model (NHS), case (a) is more sustainable than (b) and (b) is more so than (c). In the proposed model, the priority is given to Nature, Human, and System, respectively (Fig. 2-a). Human depends on nature, while nature would continue without human while the system depends on human and nature at the same time. In essence, sustainability implies a responsible approach that minimizes the negative environmental impacts, while trying to maintain a balance between all the 3 'pillars'. The human and system aspects are to be constrained by the nature aspect.

The balance of aspects and increasing the overall aggregated indicator has been considered in the common three-ring sector view of SD (Meyar-Naimi & Vaez-Zadeh, 2012a). In this view, the equilibrium point (B_1) of the aspects is calculated as:

$$B_1 = \frac{|H - S| + |S - N| + |N - H|}{M} \tag{1}$$

Where H, S, and N are the values of associated aspects, and M denotes the average of the aspects. In the proposed nested SD model (NHS), priority is given to Nature, Human, and System, respectively. The equilibrium point (B_2) of the NHS model is calculated as:

$$B_2 = \max\left(\frac{M}{3} \times (\frac{|N - H|}{(N - H)} + \frac{|H - S|}{(H - S)} + \frac{|N - S|}{(N - S)}),\ \ 0\right) \tag{2}$$

2.2. Aspects of sustainable development

In this section, the aspects of sustainable development that have brought on the model are considered. These include human, system, and nature aspects.

2.2.1. Human aspect

The human aspect of sustainable development includes social and economic dimensions. Tehran is the most populous city in Iran (with a population of around 12,223,598 people). Karaj is a suburb of Tehran, which hosts a population of around 1.97 million. A large number of people in Karaj travel to Tehran every day for work, which increases the volume of traffic in Tehran.

2.2.2. System aspect

There are three types of electric vehicles: HEV, FCEV, and EV. According to (Hadley & Tsvetkova, 2009), all PHEVs in the Municipal fleet can be divided into six general classes as Electric motorcycles and scooters (class 1), Highway-capable EV (class 2), City speed EV (class 3), Low-speed EV (class 4), Supercar EV (class 5), and Electric truck & electric bus (class 6). This paper aims at highway-capable EV (class 2) vehicles. A highway-capable EV is a road car. These types of vehicles are plug-in electric cars that are propelled by one or more electric motors, using energy typically stored in rechargeable batteries.

2.2.3. Nature aspects (Environment)

Using fossil fuel in the transportation system causes air pollution through the production of particulates, and global warming through the emission of carbon dioxide. Conventional vehicles in the transportation system have the greatest impact on global warming. In Tehran, there is a large number of fossil-fueled vehicles that emit greenhouse gases. In the year 2016, about 4800 people died in Tehran because of air pollution.

3. Proposed method

In this study, a sustainable development based policy making method on the adoption of EVs in Tehran is applied. The block diagram of the proposed method illustrated in Fig. 3.

3.1. Sustainability evaluation methodology

In this paper, a methodology based on the proposed SD model is applied, which includes the determination of time, Human and Nature reference perspective, determination of indicators, normalization of indicators, and weighing and aggregating the indicators. Then, the environmental, social, economic and technical sub-dimensions are built. Also, the main aspects of SD, i.e. Nature, Human, and System are determined.

3.1.1. Reference perspective

In sustainability assessment, the first step that should be taken is

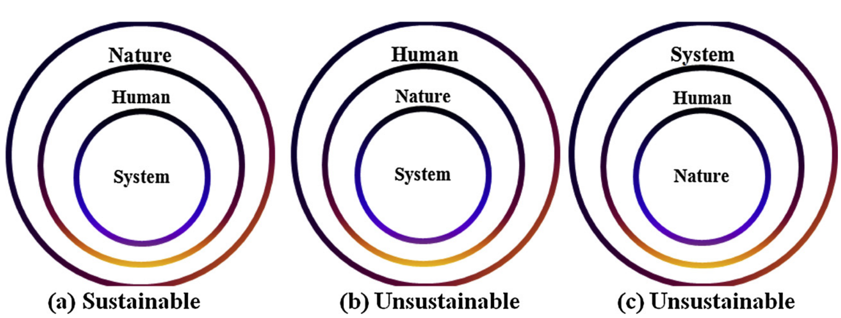

Fig. 2. Nested SD.

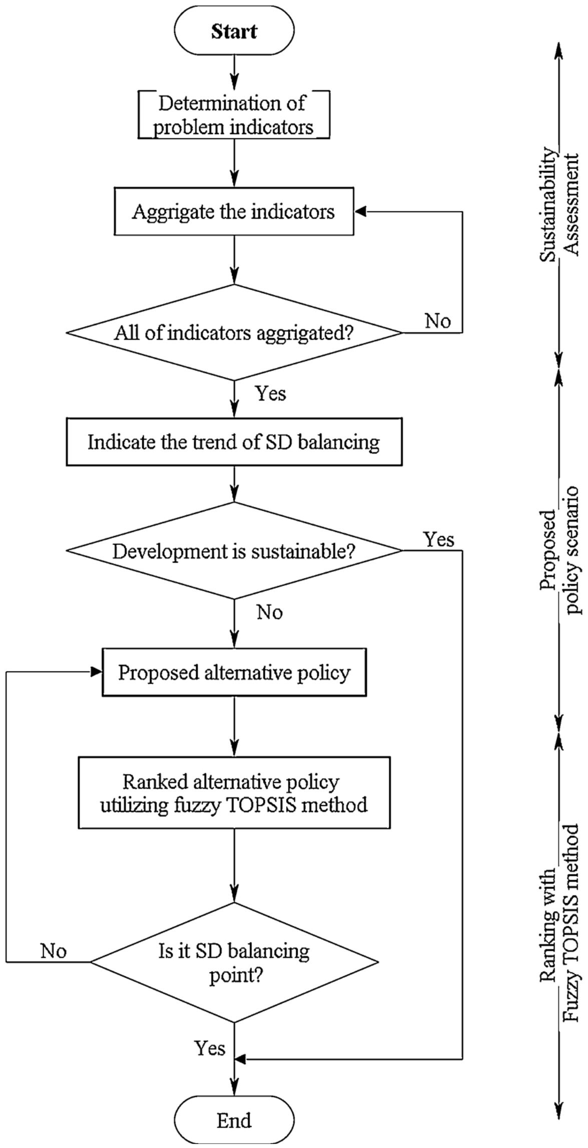

Fig. 3. Block diagram of SD-based policymaking.

that the reference perspective of Electric Vehicle Sustainable Development (EVSD), including the period and the horizon of human and environmental influences needs to be defined. The time span can be considered as short term (a few years ahead), medium-term (lifetime of the technology or the human kind) and long term (future generations). Likewise, the horizon of humans can be defined as a family, a society or all human beings (Meyar-Naimi & Vaez-Zadeh, 2012b). The horizon of nature can be specified as a city, province, country, region or the whole world. A 3-dimensional space is chosen to illustrate the perspectives as shown in Fig. 4. The reference time span begins in 2002 and extends to the next three generations of vehicle technology (2002–2018). The reference horizon of human and environment influences is defined as Tehran with a population of 13 million and a surface area of 730 km^2.

3.1.2. 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. The indicators are selected according to national documents and reports on energy and transportation systems, and weighted according to expert opinions.

3.1.2.1. Nature (Environmental) indicators. Environmental indicators are listed in Table 1. EN_1, EN_2, and EN_3 include the rates of CO, NO_x, and CO_2 emissions in gr/km, respectively. Life-cycle assessment is a technique to assess environmental impacts associated with all the stages of a product's life from raw material extraction through materials processing and manufacturing and also its distribution, use, repair, maintenance, disposal, or recycling. There are a total of 17 million vehicles and 11 million motorcycles in Tehran.

The share of transportation in greenhouse gas emissions in Tehran is 12%. Weighing the environmental indicators depends on the reference horizon perspective and the share of the transportation system in local greenhouse gas emissions. For example, if the reference horizon is considered as global, vehicle the gas emissions weight is low; however, as the reference horizon is taken into account as local (Tehran), air pollutants emission from vehicles will be highly weighted.

EN_4 is the consumed vehicle recycling system and is measured in years while it's minimum and maximum values are 4 and ten years, respectively. EN_5 is noise level at a 1-meter distance, measured in dB with minimum and maximum values of 65 and 85 dB, respectively. And finally, EN_6 is the life-cycle assessment of vehicles in percent with minimum and maximum values of 40 and 65 percent. These Environmental indicators are illustrated in Table 1.

3.1.2.2. Human indicators. Human indicators are categorized as Economic and Social ones. Economic indicators are illustrated in Table 2. EC_1 is the cost of the vehicle in dollars ($). EC_2 is maintenance cost (replacement of tires & batteries) in $/year. As the average annual income of the people in Tehran ranges from 6000 $ to 12,000 $, the expansion of EVs should aim at vehicles in this price range. EC_3 is fuel price in cent/liter. EC_4 is the number of vehicles manufactures in Tehran. 35% are made by foreign manufacturers: Renault, Hyundai, Toyota, Nissan, BMW, Kia, Sang Yang, Mitsubishi, and Lexus. EC_5 is the cost of the battery measured in terms of $/year. EC_6 is the technology life cycle measured in years.

The social indicators are listed in Table 3. SO_1 is the safety measured by dividing the number of people injured in accidents by one million. SO_2 is the justice measured in percent. SO_3 is the age measured in years. While SO_4 is the mortality rate in the transportation system, as measured by calculating the ratio of the people killed in an accident in a year. The minimum and maximum values of mortality are 0.1 and 0.9 person/year, respectively. SO_5 is vehicle weight measured in kg with the minimum and maximum values of 900 and 1600 kg, respectively.

3.1.2.3. System (Technical) indicators. The technical indicators are listed in Table 4. TE_1 is technical knowledge at the national level (non-dependence on sanctions) in percent. TE_2 is charging or refueling time, its unit is minute, and their minimum and maximum values are 5 min and 60 min, respectively.

The presence of EVs will increase voltage imbalance and power losses in the uncontrolled charging strategy (Hussain, MainulIslam, & Mohamed, 2016). TE_3 represents the voltage imbalance index due to EV charging. The voltage variation network happens when the loads are unequal in three phases. The voltage imbalance (VI) is calculated as follows:

$$\%VI = \left|\frac{V^-}{V^+}\right| \times 100 \tag{3}$$

Where V^- and V^+ showing the negative and positive sequence voltages, respectively.

TE_4 is the power loss index. Penetration of EVs increase power losses in the distribution network, and can be calculated as:

$$\%\Delta P_L^{EV} = \frac{P_{L,total}^{With.EVs} - P_{L,total}^{Without.EVs}}{P_{L,total}^{Without.EVs}} \tag{4}$$

In which $\%\Delta P_L^{EV}$ is the percentage of power loss due to EV charging and discharging process. $P_{L,total}^{With.EV}$ is total power loss of distribution

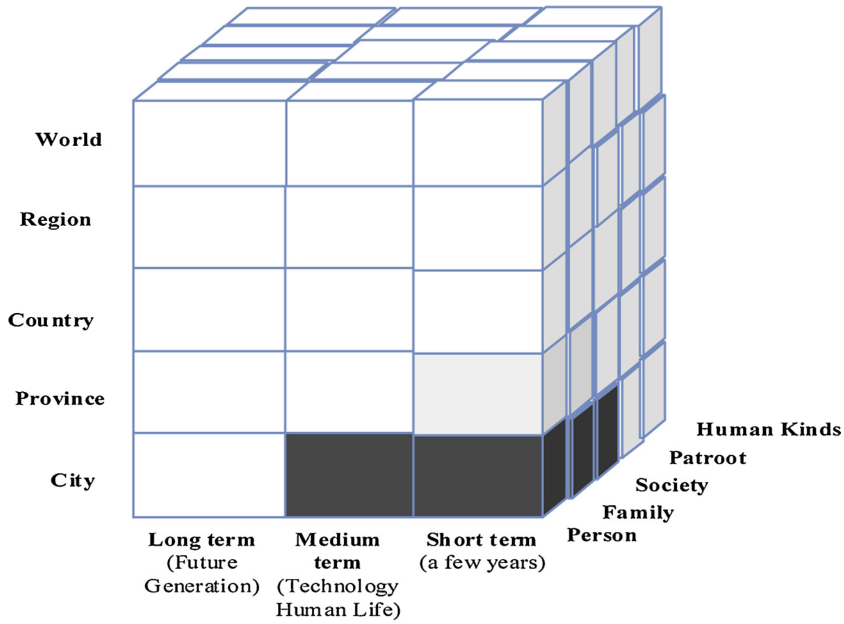

Fig. 4. Reference perspective of EVSD.

Table 1
Environmental Indicators on the Adoption of Vehicles.

Environment Indicators	Unit	Weight	Conventional vehicle (CV)			Electric vehicle			LTI	HTI
			Gasoline	CNG	Diesel	EV	FCEV	HEV		
EN_1	gr/km	0.169	1.81	0.96	0.63	0.01	0.1	0.3	1.81	0.01
EN_2	gr/km	0.171	0.1	0.2	0.33	0.001	0.003	0.01	0.33	0.001
EN_3	gr/km	0.162	242	212	185	2	12	50	242	2
EN_4	year	0.168	10	9	10	4	3	6	4	10
EN_5	dB	0.166	70	75	80	65	65	68	85	65
EN_6	%	0.164	40	45	47	65	55	60	65	40

network with EV, and $P_{L,total}^{Without.EV}$ is total power loss of the network without EV.

TE_5 is the overall efficiency of vehicles in percent. TE_6 is weight to power ratio (kW/kg) with the minimum and maximum values of 80 and 150 kW/kg, respectively. TE_7 is the number of fueling/charging stations with the minimum and maximum values of 1 and 136 in Tehran, respectively.

It is observed that many of the technologies that have reached their maturity have consistent indicators (such as gasoline prices); however, the prices of new technologies such as EV prices seem are being matured over time.

3.1.3. Normalization of the indicators

A comparison between the real quantity of an indicator and its target quantity is required to evaluate the sustainability of development (Shamsheer & Ismet, 2019). The target quantity of an indicator can be considered as bandwidth with a lower boundary (weak sustainability), and a higher boundary (strong sustainability). These boundary quantities can be calculated based on the empirical judgment, national standards, international standards, environmental values, and the average global quantities (Zhu, Liu, & Zhang, 2009). Once the bandwidth of target quantities is used, the indicators can be normalized by a linear function (Tom et al., 2011) as:

$$NI = \frac{AI - LTI}{HTI - LTI} \tag{5}$$

Where NI is the normalized indicator, AI is the actual indicator and, LTI and HTI are the lower and higher boundaries of target bandwidth, respectively. The upper and lower limits are calculated based on the latest universal technology. HTI and LTI quantities for indicators of different aspects of development are given in the last two columns of Tables 1–4.

Table 2
Economic Indicators on the Adoption of Vehicles.

Economic Indicators	Unit	Weight	Conventional vehicle (CV)			Electric vehicle			LTI	HTI
			Gasoline	CNG	Diesel	EV	FCEV	HEV		
EC_1	$	0.167	4000	10000	20000	25000	40000	35000	40000	4000
EC_2	$/year	0.164	250	500	600	1200	2000	1500	2000	250
EC_3	cents/ liter	0.171	35	20	25	3	40	7	40	3
EC_4	number	0.174	5	4	3	1	0	1	0	5
EC_5	$/year	0.161	100	100	100	900	1000	700	1000	100
EC_6	year	0.163	10	8	7	4	3	6	1	10

Table 3
Social Indicators on the Adoption of Vehicles.

Social Indicators	Unit	Weight	Conventional vehicle (CV)			Electric vehicle			LTI	HTI
			Gasoline	CNG	Diesel	EV	FCEV	HEV		
SO_1	number/ million people	0.211	0.4	0.4	0.4	0.9	0.7	0.9	0.9	0.4
SO_2	%	0.197	0.9	0.8	0.8	0.3	0.2	0.3	0.2	0.9
SO_3	years	0.194	35	40	45	25	30	33	18	75
SO_4	person/year	0.202	0.1	0.2	0.3	0.9	0.9	0.9	0.1	0.9
SO_5	kg	0.196	1000	1200	1100	1300	1500	1600	900	1600

3.1.4. Weighing and aggregating indicators

In the present work, the weights of the dimension, the sub-dimensions, and the indicators of each sub-dimensions are calculated using ANP, as shown in Fig. 5. In level 1, the goals of the hierarchy are described. In level 2, the philosophy of the SD and the overall objectives of the Tehran perspective are considered. The dimensions of Tehran's transportation, i.e., human, system, and nature, are shown in level 3 of Fig. 5. In levels 4 and 5, the sub-aspects and indicators are weighed to the related dimension and sub-dimensions, respectively. 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 sub-dimensions.

Similarly, Human depends on Nature. The criteria for weighing the dimension, sub-dimensions, and indicators are C_1, C_2, and C_3; C_1 is increasing the vehicle efficiency, C_2 is reduction of vehicle size, and C_3 is preservation of the environment. These criteria are selected due to the lack of sufficient parking lots, air pollution, and high energy consumptions in Tehran.

The number of households in Tehran from 2006 to 2018 is shown in Fig. 6-a. It can be seen that, in 2018, a larger number of families had 3 members. So, the use of smaller vehicles will increase. It is also to be considered that more than five million cars travel in Tehran every day. The vehicle per capita in Tehran from 1976 to 2018 is illustrated in Fig. 6-b. As indicated in the figure, the ratio for 2018 was 400, that is, 400 vehicles per 1000 people. The minimum area required for parking in Tehran buildings is 5*2.5 square meters. Therefore, smaller sized vehicles are preferred.

There are around 0.08 parking lots per household in Tehran, which is a very low rate. In comparison, there are around five parking lots per household in Seattle. Des Moines, a much smaller city, also has roughly 19.4 per household. The small town of Jackson, Wyoming, has 27.1 parking lots per household and Philadelphia has more than 3.7 per household.

4. 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 EVs are evaluated from the sustainability point of view. Figs. 8–10 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 Environmental indicators and their aggregated value from 2002 to 2018 is shown in Fig. 7. As shown, most of the environmental indicators show little growth between 2006 and 2014. Since 2014, most of the indicators have been increasing.

Also, economic and social indicators are shown in Fig. 8. As it is seen, economic indicators EC_1, EC_2, $EC_{3,}$ and EC_4 reflected an increasing trend, while indicators EC_5 and EC_6 had a decreasing trend. As shown in this figure, between 2002 and 2018, social indicators SO_3 and SO_5 declined, and indicators SO_1, SO_2 and SO_4 increased. Between 2010 and 2014, SO_2 indicator witnessed a dramatic increase.

Further, the technical indicators are shown in Fig. 9. As it is seen, TE_1, TE_2, $TE_{5,}$ and TE_6 were at first, incremental, then decreasing and finally incremental again. TE_3 and TE_4 is voltage imbalance and power losses on Tehran's distribution network due to EV charging, which has been created since 2014. TE_7 is increasing from 2002 to 2018.

The Temporal trend of aggregated NHS aspects is shown in Fig. 10. In this figure, Human and System aspects were almost the same in 2002, while the Nature aspect stood at its least. In the years 2010–2012, Nature was given more consideration that followed by Human and System. From 2014, the growth in the System aspect was more profound than the others.

As shown in Fig. 11, B_1 is the equilibrium point in the three-ring sector view of SD, and B_2 is the equilibrium point of the NHS model. As seen in the figure, based on the three-ring model, there has been a balance every year. But based on the NHS model, from 2010 to 2012, development was sustainable, but it was unstable from 2002 to 2010 and 2012 to 2018.

In Fig. 12, the percentages of gasoline, CNG, diesel, and EVs in Tehran from 2002 to 2018 are shown. As the figure shows, since 2008, there have been more CNG vehicles in the streets than the diesel ones. EVs have been used since 2014.

5. Fuzzy TOPSIS technique

As the fuzzy method training, human thoughts are associated with uncertainty, and this uncertainty impacts decision making. For this reason, fuzzy decision-making methods are used, one of which is fuzzy TOPSIS for ranking options. In this case, the elements of the decision matrix, or the weights of the indices, or both, are expressed fuzzy and with fuzzy numbers. The main features of the TOPSIS method are as

Table 4
Technical Indicators on the Adoption of Vehicles.

Technology Indicators	Unit	Weight	Conventional vehicle (CV)			Electric vehicle			LTI	HTI
			Gasoline	CNG	Diesel	EV	FCEV	HEV		
TE_1	%	0.141	1	0.9	0.7	0.1	0	0.1	0	1
TE_2	min	0.146	5	10	5	30	60	25	60	5
TE_3	%	0.140	-	-	-	0.4	0.5	0.55	0.4	0.55
TE_4	%	0.138	-	-	-	0.38	0.5	0.6	0.38	0.6
TE_5	%	0.143	35	40	40	30	60	35	30	60
TE_6	KW/KG	0.145	80	100	90	130	140	150	150	80
TE_7	Number	0.147	136	19	14	2	1	2	1	136

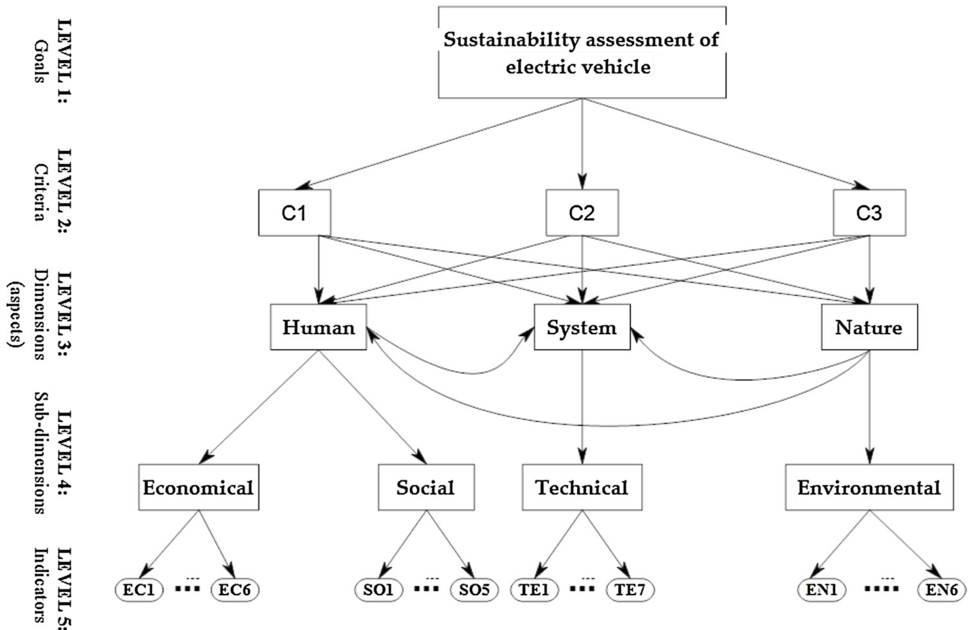

Fig. 5. The proposed hierarchical structure for weighting the dimensions, sub-dimensions, and indicators using ANP.

follows: it can be performed with any number of criteria, it can be done with positive and negative criteria, and it can be done with qualitative and quantitative criteria. The next section of the article describes the steps of the Fuzzy TOPSIS method.

5.1. Fuzzy TOPSIS steps

The fuzzy TOPSIS technique steps are as follows:

Step 1: Create a fuzzy decision matrix with dimensions $m \times n$ for individuals' views.

$$\tilde{D} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \dots & \tilde{x}_{1n} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \dots & \tilde{x}_{mn} \end{bmatrix} \tag{6}$$

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

Step 2: Normalization of the decision matrix.

In this step, we need to transform the fuzzy decision matrix into a normalized fuzzy matrix. To obtain a normalized matrix, if a criterion is positive, the equitation (2) is used, and if they are negative, Eq. (3) is used:

$$\tilde{r}_{ij} = \left(\frac{l_{ij}}{u_j^*}, \frac{m_{ij}}{u_j^*}, \frac{u_{ij}}{u_j^*}\right), \quad u_j^* = \max u_{ij} \tag{7}$$

$$\tilde{r}_{ij} = \left(\frac{l_j^-}{u_{ij}}, \frac{l_j^-}{m_{ij}}, \frac{l_j^-}{l_{ij}}\right), \quad l_j^- = \min l_{ij} \tag{8}$$

Where the decision matrix is as follows:

$$\tilde{R} = \begin{bmatrix} \tilde{r}_{11} & \tilde{r}_{12} & \dots & \tilde{r}_{1n} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{r}_{m1} & \tilde{r}_{m2} & \dots & \tilde{r}_{mn} \end{bmatrix} \tag{9}$$

Step 3: Create a weighted normalized Fuzzy Matrix V.

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

$$\tilde{V} = \begin{bmatrix} \tilde{v}_{11} & \tilde{v}_{12} & \dots & \tilde{v}_{1n} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{v}_{m1} & \tilde{v}_{m2} & \dots & \tilde{v}_{mn} \end{bmatrix} \tag{10}$$

Step 4: Calculate Positive Ideal solution A^* and Negative Ideal solution A^-.

$$\tilde{A}^* = (\tilde{v}_1^*, \tilde{v}_2^*, \dots, \tilde{v}_n^*), \quad Where \quad \tilde{v}_j^* = Max(V_j) \tag{11}$$

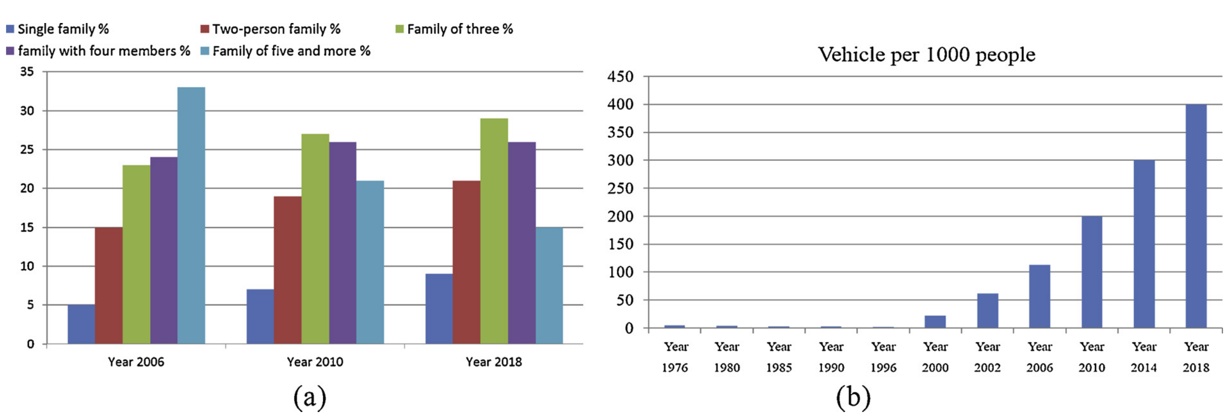

Fig. 6. (**a**) The number of households (%), (**b**) Vehicle per capita in Tehran from 1976 to 2018.

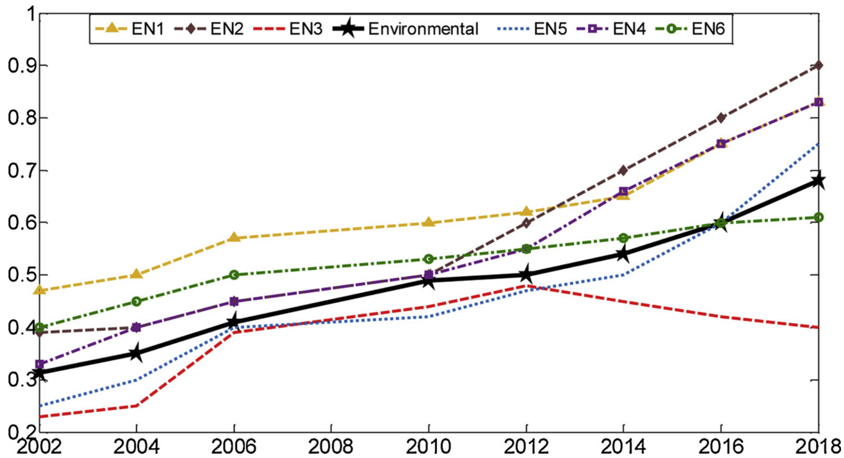

Fig. 7. Temporal trend of aggregated environmental indicators (Nature).

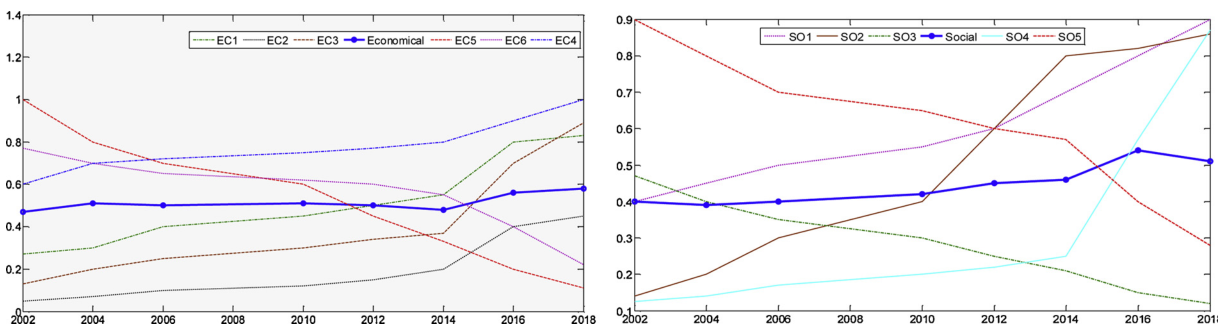

Fig. 8. Temporal trend of aggregated economic and social indicators (Human).

$$\tilde{A}^- = (\tilde{v}_1^-, \tilde{v}_2^-, \ldots, \tilde{v}_n^-), \quad Where \quad \tilde{v}_j^- = Min(V_j) \tag{12}$$

Step 5: Calculate the sum of components distance from the positive ideal and negative ideal values.

$$d_i^+ = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^*), \quad i = 1, 2, \ldots, m \tag{13}$$

$$d_i^- = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^-), \quad i = 1, 2, \ldots, m \tag{14}$$

Step 6: Calculate the similarity to the ideal option. For this purpose, the Closeness coefficient (CC_i) calculate in Eq. (15). The option with a higher ranking CC_i is better than the other.

$$CC_i = \frac{d_i^-}{d_i^- + d_i^+}, \quad i = 1, 2, \ldots, m \tag{15}$$

There is a need for a model that can tell whether the transportation development sector has gone the right way, and what technology can improve the technical, environmental, economic, and social aspects? SD is chosen as a framework for this purpose.

6. Sustainable development based policymaking using fuzzy TOPSIS method

In this section, a new approach to EV policy is presented in the point of view of sustainable development in Tehran. Fuzzy TOPSIS method is used to study the various factors affecting the development of EVs in

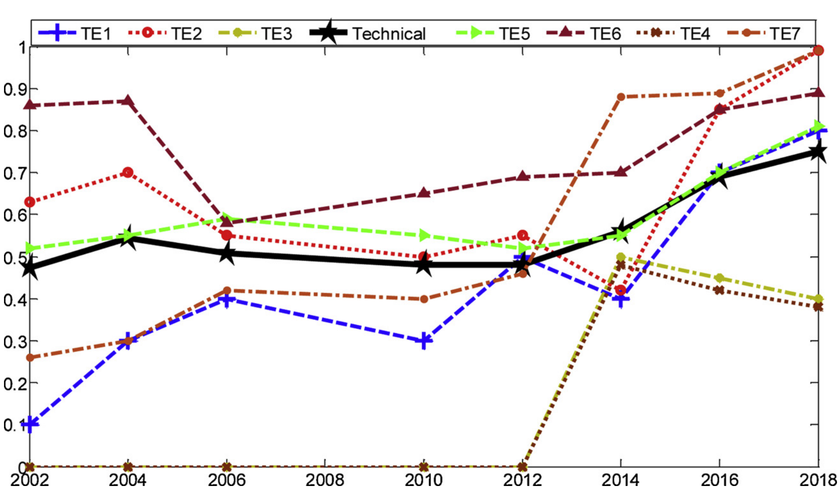

Fig. 9. Temporal trend of aggregated technical indicators (System).

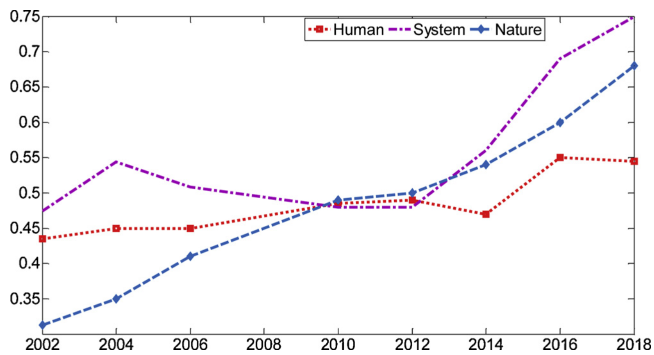

Fig. 10. Temporal trend of aggregated NHS aspects.

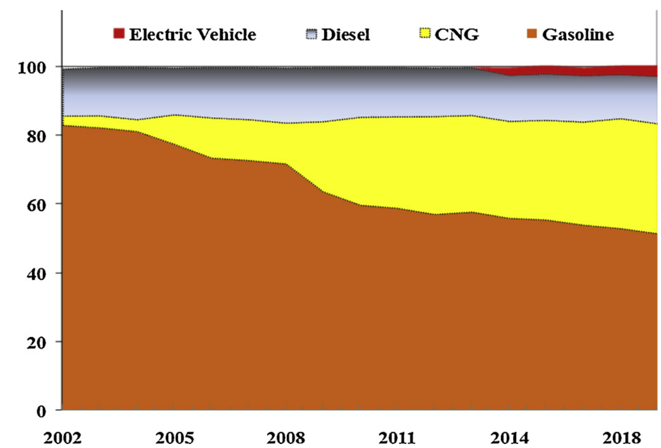

Fig. 12. Adoption of gasoline, CNG, diesel and electric vehicles in Tehran.

Tehran. Referring to Fig. 12 and according to the equilibrium point of the NHS model (B_2), it is observed that SO_5, EC_5, EN_3, and TE_4 are the most critical indicators.

According to Fig. 8, the most critical aspect of the temporal trend of aggregated social indicators is SO_3, which is vehicle size. Based on Iran's vehicle development policies (Special reports on Iran's energy smart grid, 2015), one of the policies for the development of electric vehicles is smaller EV designs. The most critical aspect in temporal trend of aggregated economic indicators (Fig. 8) is cost of the battery. According to literature research, using of new generation of batteries in EV is one of the policies for the development of EVs. The most critical aspect in temporal trend of aggregated environmental indicators (Fig. 7) is EN_3, which is CO_2 emission. Utilizing electric vehicles is one of the ways to reduce CO_2 emissions. According to Fig. 9, the most critical aspect in temporal trend of aggregated technical indicators is power losses. Based on literature research, one of the policies for the development of electric vehicles is the management of EV charging at different times and in different places. Table 5 shows the most critical indicators and proposed policies.

Based on the fuzzy TOPSIS steps, this research has four different criteria (TE, EC, SO, EN), and four alternative policy scenarios Pi, i = {1, 2, 3, 4} in respect to the Tehran's transportation decisions, regulations, and directives (Fig. 13). The criteria weights were assigned based on the Nested sustainable development model with priority between Nature, Human, and System aspects (NHS). Also, there is a committee of decision-makers, that utilizing the linguistic variables to evaluate the importance of the alternative policy scenarios weights.

In the fuzzification step, the input numbers are converted to fuzzy membership functions for criteria and their weights. So, the numbers and information that need to be processed will be converted to fuzzy sets and numbers. The five triangular membership functions used are Very High (VH), High (H), Medium (M), Low (L), and Very Low (VL)

Table 5
Critical indicators and appropriate policies.

Indicators	Description	Policy	Policy description
SO_5	Vehicle size	P_1	Smaller EV designs
EC_5	Cost of the battery	P_2	Use of a new generation of batteries in EV
EN_3	CO_2 emission	P_3	Increase EV number
TE_4	power losses	P_4	EV charging management

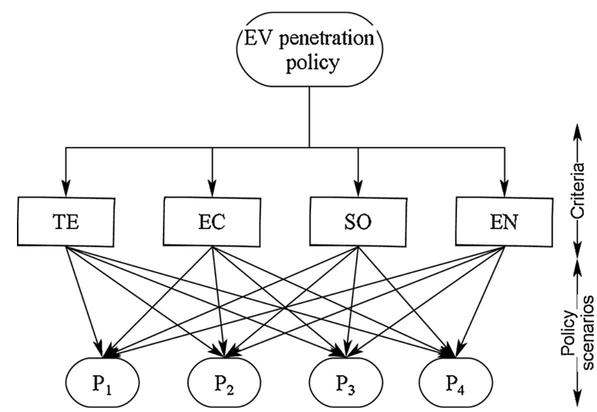

Fig. 13. The hierarchical structure for assessing the policy strategies in Tehran.

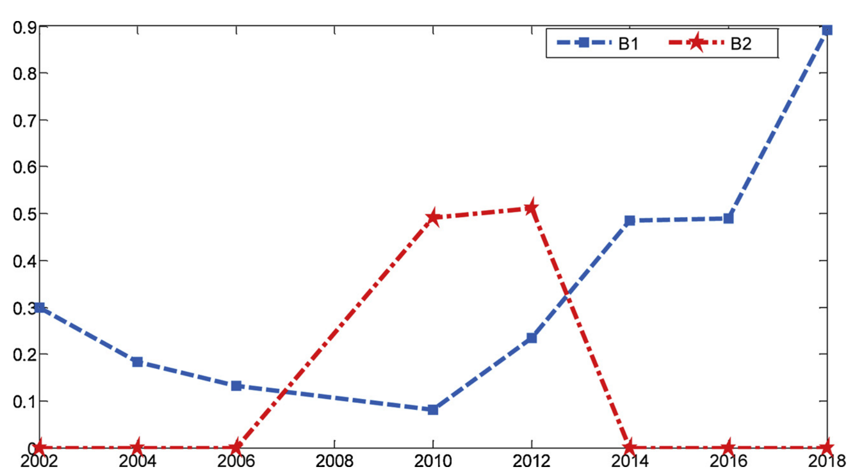

Fig. 11. The equilibrium point of the aspects (B_1: three-ring model & B_2: HNS model).

Table 6
Rating of alternative policy strategies by decision-makers.

Criteria	TE	EC	SO	EN
Weight of criteria	L	M	M	VH
P_1	L	M	M	VH
P_2	M	VH	VL	VL
P_3	L	L	M	VH
P_4	VH	H	VL	VL

Table 7
The distance from the positive ideal value.

Policy scenarios	EN	SO	EC	TE	d_i^+
P1	9.5756	3.8474	4.7273	2.4885	20.6388
P2	9.5756	5.7357	3.3853	2.2441	20.9406
P3	4.323	3.8474	5.5258	2.4885	16.1848
P4	9.5756	5.7357	3.9986	1.8572	21.167

(Amjed & Faza, 2019). Rating of alternative policy strategies by decision-makers using fuzzy variables illustrated in Table 6. These rating of policy strategies are assigned based on the Nested SD model with priority between Nature, Human and System aspects (NHS). For this purpose, national documents and reports on energy and transportation prepared by government officials and scholars have been used.

The distance from the positive and negative ideal value (d_i^+, d_i^-) and the similarity to the ideal option (CC_i) shown in Tables 7–9.

After applying the fuzzy TOPSIS method, the resulting Ranking of alternative policy scenarios using the closeness coefficient is: $P_3 > P_1 > P_2 > P_4$.

6.1. Model validation utilizing the VIKOR method

The VIKOR method used for comparative analysis to prove the reliability and applicability of the proposed model. The VIKOR method is a multi-criteria decision-making technique that aims to rank research options (Mohamed, 2012). Ranking of policy scenario utilizing VIKOR and fuzzy TOPSIS methods illustrated in Tables 9 and 10, respectively.

After applying the VIKOR method, the resulting Ranking of alternative policy scenarios is $P_3 > P_1 > P_2 > P_4$. As shown in Tables 9 and 10, the results obtained by VIKOR and fuzzy TOPSIS methods are consistent.

7. Penetration of EVs using load shifting policymaking

The high variations and non-uniformity of the load curve during different hours of the day has led the use of all power plant installed capacities in Tehran at on-peak hours. Since the cost of electricity generation and its selling price varies considerably over 24 h. The idea of electricity storage is offered during off-peak hours (cheap electricity) and supplying it at peak hours (expensive electricity), traditionally.

Energy storage by electric vehicle batteries is a solution for the above challenge by load curve leveling, frequency control, delaying the expansion of the power distribution network, reducing voltage fluctuations, increasing the power quality and reliability.

Energy demand can be shifted over time to match demand and supply and to help the integration of various supply sources. To study the time-shifting, we have to consider the concept of Demand-Side Integration (DSI). Services provided by DSI considering flexible loads, distributed generation, storage, and plug-in Electric Vehicles are load shifting, valley filling, peak clipping, and energy efficiency improvement (Janaka, Liyanage, Jianzhong, Yokoyama, & Jenkins, 2012).

Table 8
The distance from the negative ideal value.

Policy scenarios	EN	SO	EC	TE	d_i^-
P1	1.3687	4.2346	2.6948	0.7423	9.0403
P2	1.3687	1.4938	4.5648	1.0757	8.5029
P3	7.4664	4.2346	1.7938	0.7423	14.237
P4	1.3687	1.4938	3.6242	1.7597	8.2463

Table 9
The similarity to the ideal option (CC_i).

Policy scenarios	CC_i	Ranking
P2	0.2888	3
P3	0.468	1
P4	0.2804	4

Table 10
Ranking of policy scenario utilizing the VIKOR method.

Ranking	Policy scenarios	Si	Ri	Q
1	P3	5.000	5.000	0.0000
2	P1	6.667	5.000	0.0806
3	P2	15.000	9.000	0.9839
4	P4	15.333	9.000	1.0000

7.1. Time-Space load shifting (TSLS)

In this paper, along with the concept of time-shifting, we propose a new concept called Time-Space Load Shifting (TSLS), which is done by EV and will increase the number of EVs in Tehran (policy strategy P_3 in fuzzy TOPSIS method).

The TSLS means power consumption by charging EV batteries in off-peak hours (during working hours and in downtown) and power generation by discharging the batteries at peak hours (during the evening and at night and in the suburb).

There is an only time-shifting possibility with the installation of nonmoving power storage in the grid. However, with energy storage in the battery of moving storage like EV, the space shifting can also be implemented in addition to the time-shifting. Earning profit through the price difference in the two markets can be both in terms of time (the current and future markets) as well as in terms of two different locations.

In the downtown, the distribution network is stronger and mostly consists of the administrative and commercial texture and is loaded in off-peak hours. But, in the suburb, the network is weaker due to the length of feeders, and more often has a residential texture and is loaded in on-peak hours. So the concept of TSLS is proposed as a new idea.

In this article, the city of Tehran has been studied. The average time for an urban journey in Tehran is about 55 min (Power Balance Sheet in Iran, 2013).

At on-peak hours, people are more likely to be in the suburbs, which is weaker with more voltage drop and power loss, where EVs can help. The figure below shows the TSLS in the afternoon. Most people in Tehran are in downtown from 8 am to 5 pm, which has mostly commercial and administrative buildings and in the afternoon going back to home at 5 pm.

Fig. 14 shows the distribution network status in Tehran. According to Fig. 14, the distribution network with short feeders and multiple substations is stronger in downtown. In the suburb, the network is weaker because of the long feeders.

To reduce the cost of charging EVs in proposed TSLS concept, time tariffs for charging EVs in Grid to Vehicle (G2V) mode, and injecting power to the grid in Vehicle to Grid (V2G) mode, proposed in Table 11.

EV owner's profit is to minimize the cost of charging electricity and maximizing V2G service in Tehran's suburb. The objective function of EV owner profit is represented as:

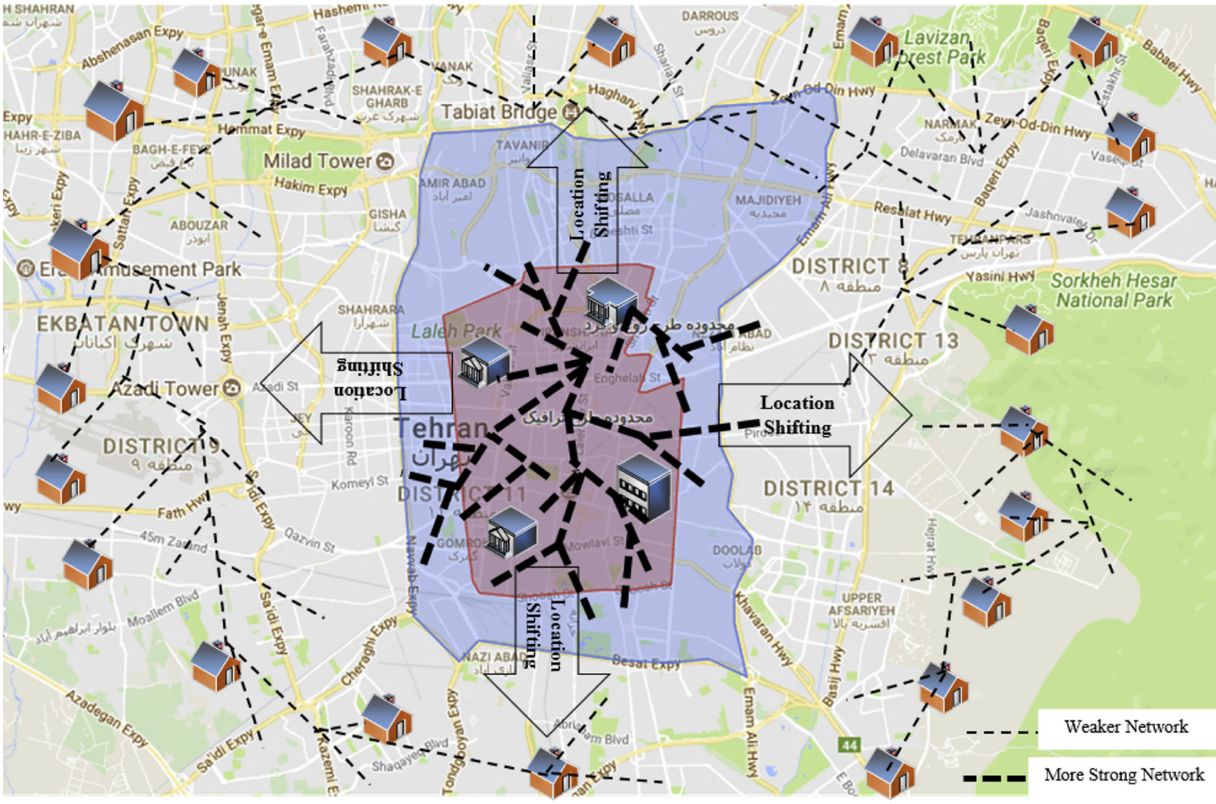

Fig. 14. Distribution network in Tehran.

$$EV\ \ owner\ \ profit = \min \sum_{i=1}^{N} L_m^{G2V}(i).\ C_i^{G2V}.\ T_i + \min \sum_{i=1}^{N} \frac{1}{L_m^{V2G}.\ C_i^{V2G}.\ T_i} \tag{16}$$

Where:

C_i^{G2V}: Price of EV charging electricity

C_i^{V2G}: Price of power injected by EV batteries to Tehran's suburb network in V2G mode.

T_i: Time periods.

$L_m(i)$: Capacity of EV batteries that can be altered in time and location.

Using the TSLS method, EVs can be charged at off-peak hours in the downtown, and injecting of battery power into the network at peak time hours in suburb, reduced some of the peak load.

With the TSLS, losses are reduced effectively, and the emissions from power plants are supposed to supply these losses is reduced, consequently.

Fig. 15 presents a comparative market price and battery capacity evaluation of different EVs, depending on battery capacity (Iclodean, Varga, Burnete, Cimerdean, & Jurchiș, 2017).

Based on policy scenarios in Table 5 and comparison of market price and battery capacity of different EVs, and the number of households (reducing the number of households and the need for small vehicles), the VW E-Golf car with Li-ion battery is suitable for Tehran's transportation. The battery stored energy in this vehicle is 24.2 kW h (Iclodean et al., 2017).

In the batteries, the State of Charge (SOC) is defined as the remaining capacity of a battery, and it is affected by its operating conditions such as load current and temperature (Kwo, Wang, Wang, & Strunz, 2013). The SOC is a critical condition parameter for battery management. The lithium-ion batteries must be at a SOC, not exceeding 30% of their rated design capacity. So, in the studied EV: $70\% \times 24.2^{kWh} = 16.94^{kWh}$.

Tehran's transportation with the car from downtown to suburb takes 55 min. After 55 min and consumption of 4.5^{kWh} of batteries energy, the remaining capacity of a battery is $16.94^{kWh} - 4.5^{kWh} = 12.44^{kWh}$. As a result, each EV can provide 12.44^{kWh} to the grid in V2G mode.

7.2. SD-based EV penetration

Referring to Fig. 11 and according to the equilibrium point of the NHS model (B_2), it is observed that nature is the most critical aspect, so development is unsustainable in recent years. The TSLS concept, due to the profitability of the vehicle owner and the distribution network, will extend the use of EVs. Based on the transportation system forecast (Special reports on Iran's energy smart grid, 2015), the number of EVs will be about 20% of Tehran's vehicles in the year 2030.

Fig. 16 shows how Nature, Human, and System contribute to the general sustainability of Tehran with EV penetration and TSLS concept. Therefore, reducing the CO_2 emission produced by conventional vehicles and peak load shaving in suburban areas has led to lower energy consumption and, consequently, the need for power plant production

Table 11
Time tariffs for EV owners based on proposed TSLS concept.

	8 a.m. to 5 p.m.	5 p.m. to 10 p.m.
G2V in downtown (charging EV)	Electricity tariff= $\alpha \times B$	Electricity tariff= $(1-\alpha) \times B$
V2G in the suburb (injecting power to the grid)	Electricity sales tariff= $\alpha \times B$	Electricity sales tariff= $(1-\alpha) \times B$
Commercial loads: $\alpha = 0.05$, Residential loads: $\alpha = 0.1$, Industrial loads: $\alpha = 0.2$, Average cost of electricity: B		

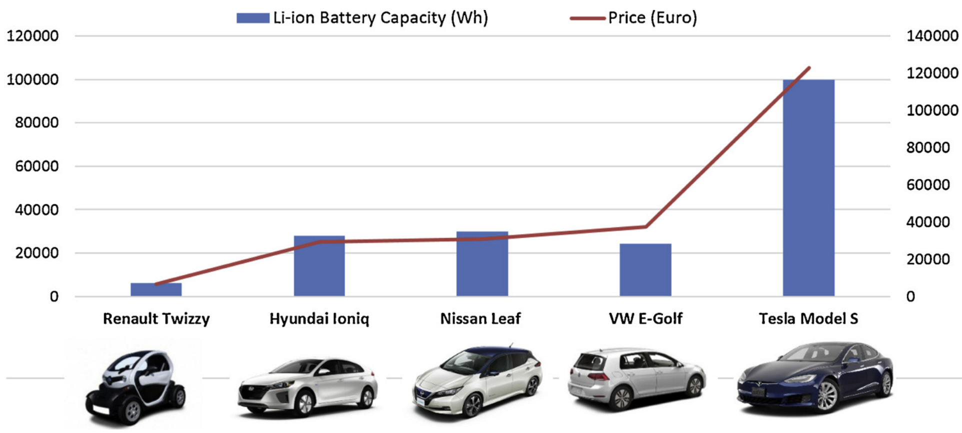

Fig. 15. Comparison of market price and battery capacity.

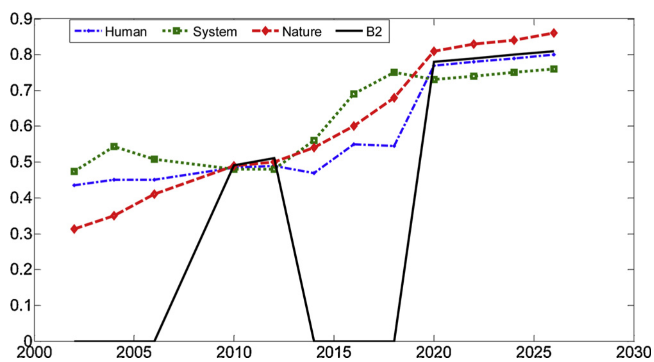

Fig. 16. Sustainability from 2020 with EV penetration.

and its emissions reduced. The TSLS method also improves the technical indicators of the power distribution network in the suburbs. So, the instability in 2018 due to individual look at the development of the system in which the aspect S is higher than N and H is modified by the above concept, and so the N aspect is higher than H and both above S.

8. Conclusion

With the growing consumption of fossil fuels and the end of its resources soon, they should be replaced by alternative energy sources. Another disadvantage of fossil fuels is environmental hazards such as pollution and global warming, which will destroy humanity. The existing solutions are moving towards renewable energies and electric vehicles (EVs). Sustainable development has tried to find possible solutions to the problems caused by industrialization and population growth. Investigating the various aspects of sustainable development that can affect the acceptance and penetration of electric vehicles and the behavior of vehicle owners in charge scheduling can be effective in determining government policies and solutions to promote the consumption culture and energy efficiency in this respect.

In this article, by defining a sustainable development model, a framework for evaluating vehicle development with the Analytic Network Process (ANP) is presented. In the new philosophy of sustainability of this paper, the emphasis is on the aspects of development, their balance, and priority of Nature to Human and Human to System.

In sustainable development frameworks, NHS and the three-ring sector view of sustainable development were compared with each other. Then, using a proposed NHS model, the sustainability of vehicle development in Tehran was evaluated from the past to the present. Based on this approach, the important parameters identified in the model were found to be: economical, technical, social, and environmental aspects. In this model, the reference period begins in 2002 and extends to the three next generations of vehicles technology (2002–2018).

The reference horizon of human and environment influences is defined in Tehran. Then, the temporal trend of aggregated NHS aspects is shown. As it is seen, the Human and System aspects were almost the same in 2002, while the Nature aspect stood at its least. In the years 2010–2012, Nature was given more consideration that followed by Human and System. From 2014, the growth in the System aspect was more profound than the others, which represents unsustainable development. Air pollution in Tehran was the result of unsustainability. So, it should provide sustainable development in Tehran with proper policies. For this purpose, the fuzzy TOPSIS method is used to study the critical aspects and policies affecting the development of EVs in Tehran. According to the aspects of sustainable development, some policy indices for the development of EV penetration are introduced. The most critical aspect of the temporal trend of aggregated social indicators is vehicle size. According to Iran's vehicle development policies, one of the policies for the development of electric vehicles is smaller EV designs. The most critical aspect in temporal trend of aggregated economic indicators is cost of the battery. According to literature research, one of the policies for the development of electric vehicles, using new generation batteries in EVs. The most critical aspect in temporal trend of aggregated environmental indicators is CO_2 emission. Utilizing electric vehicle is one of the ways to reduce CO_2 emission. In temporal trend of aggregated technical indicators, the most critical aspect is power losses. According to literature research, one of the policies for the development of electric vehicles is the management of EV charging at different times and in different places.

In the proposed method, the closeness coefficient of each policy indices calculated utilizing Fuzzy TOPSIS and the various policies affecting the development of EVs in Tehran ranked. Based on selected policy, to optimal EV penetration, a new concept called Time-Space Load Shifting (TSLS) was proposed, which was done by EVs. The TSLS concept, due to the profitability of the vehicle owner and the distribution network, will extend the use of EVs. So, the instability in 2018 due to individual look at the development of the system will modify. In this article, the reference horizon of human and environment influences is defined in the city of Tehran. It is suggested that in the future study, the country of Iran considered.

Declaration of Competing Interest

None.

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