Journal of Cleaner Production 96 (2015) 486–492

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Assessment of electrically-driven vehicles in terms of emission impacts and energy requirements: a case study for Istanbul, Turkey

Bunyamin Yagcitekin*, Mehmet Uzunoglu, Arif Karakas, Ozan Erdinc

Department of Electrical Engineering, Yildiz Technical University, Esenler 34220, Istanbul, Turkey

A R T I C L E I N F O

Article history:
Received 23 July 2013
Received in revised form
20 December 2013
Accepted 21 December 2013
Available online 28 December 2013

Keywords:
Electric vehicle
CO_2 emission
Carbon trade market
Energy requirement
Wind energy

A B S T R A C T

Emissions caused by the transportation sector account for a significant portion of the total emissions causing global warming. These emissions must be considered, especially for metropolitan cities with large numbers of vehicles on roads. Traffic congestion in such metropolitan areas is another reason for the evaluation of different technologies to be utilized in the transportation sector. Istanbul, with a population of approximately 13 million people using approximately 3 million road vehicles, is a suitable example of such metropolitan areas with many traffic problems. Thus, in this study, an assessment of electrically-driven vehicle (EDV) utilization instead of conventional vehicular systems for Istanbul is performed. The possible effects of urban road transportation electrification on carbon dioxide (CO_2) emission reduction and the economic benefit in the carbon trade market are investigated. In addition, the possibility of supplying the required vehicle charging energy from renewable sources is also evaluated. Thus, the main contributions of this study are the evaluation of the environmentally friendly operation of EDVs and the investigation of different penetration ratios of EDVs in energy and investment requirements as well as environmental factors. In addition, predictions are provided for the future market of EDVs, accounting for both the use of EDVs and electricity production to obtain highly accurate results. Consequently, a basis for the evaluation of the possible market penetration rate of EDVs is presented. Additionally, the use of sustainable transportation in such metropolitan areas is investigated in this study.

1. Introduction

Both the world energy demand and the emissions from conventional vehicles have been steadily growing for over two decades. The environmental concerns and limited resources of fossil fuels, especially oil, have led to the development of new, cleaner energy-based technologies in different areas, such as transport, power generation, etc. Among these application areas, a new generation of environmentally friendly vehicular systems has been given specific importance because of their potential to offer reduced emissions (mitigating greenhouse gas (GHG) emissions and other catastrophic effects) in the transportation sector as well as to reduce the dependence of many countries (including Turkey) on imported fuel (Offer et al., 2010; Guille and Gross, 2009; Thomas, 2009). In particular, the development of electrically-driven vehicles (EDVs) has come into prominence, and different EDV models have been developed by important vehicular system manufacturers all around the world (Kempton and Kubo, 2000).

EDVs have a significant potential for widespread use in the future. As some technologies of EDVs, such as battery-based electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), require electricity to charge the battery, additional electricity-generating capacity will most likely be required to supply the future recharging requirement of great numbers of EDVs connected to the grid (Duke et al., 2009). Hence, the analysis of EDVs is a challenging issue that requires detailed evaluation in terms of the future grid capacity, new energy generation sources, carbon dioxide (CO_2) emission impact and investment costs.

Many studies in the literature are dedicated to examining the economic and environmental impacts of different EDV technologies, based on case studies for different places. Brady and O'Mahony evaluated the possibility of vehicular systems-based emission reduction for the city of Dublin under different EDV market penetration scenarios (Brady and O'Mahony, 2011). The results proved that EDVs can be considered as long-term alternatives to conventional vehicles, with the potential for considerable emissions reduction. In another study, the benefits of the use of PHEVs related

* Corresponding author. Tel.: +90 212 383 5853; fax: +90 212 383 5858.
E-mail addresses: bunyamin@yildiz.edu.tr, byagcitekin@gmail.com (B. Yagcitekin).

0959-6526/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jclepro.2013.12.063

to the primary energy requirement and the reduction of CO_2 emissions were examined by Smith (Smith, 2010). The electrification of vehicular systems was found to have the potential to lower the primary energy requirement and CO_2 emissions by 50% per km. Browne et al. (2011) focused on the role that can be played by different fuel delivery structures for diesel vehicles and new EDVs in reducing freight traffic and its environmental impacts in towns and cities. The proposed structure reduced the total distance traveled and the CO_2 emissions by 20% and 54%, respectively. Perujo and Cuiffo (2010) found that the vehicle-to-grid (V2G) interaction of EDVs can contribute to the efficiency of the energy distribution system and lead to better environmental results. Zhang et al. (2008) proposed a method to establish travel distance-based dynamic emission factors for vehicles, including EDVs, and concluded that the EDVs can considerably contribute to the reduction of emissions. Görbe et al. (2012) described the idea of utilizing EDV batteries as storage devices in a low-voltage grid composed of distributed small-scale renewable power plants to contribute to both grid operation and environmental impact reduction. Moriarty and Honnery (2013) explored the efforts promoting the use of EDVs to replace transportation-based fossil fuel utilization and reduce GHG emissions, with a focus on reducing energy/emissions, and reported the mid-term and long-term positive impacts of EDV penetration.

In one of several studies demonstrating the reduction of GHG emissions in the transportation sector, a new model for the transportation sector in terms of energy utilization and emissions reduction was introduced (Brand et al., 2012). Ma et al. analyzed the contributions to GHG emissions of the implementation of electric vehicles in two different market places, considering factors such as the introduction of extra electricity demand for charging the batteries and the GHG emissions resulting from vehicle manufacturing and their disposal (Ma et al., 2012). The economic and environmental effects of different vehicle technologies were investigated in several studies, including the study of Nanaki and Koroneos (2013), which analyzed the economic and environmental aspects of conventional, hybrid and electric vehicles in the Greek market. In addition, Köhler et al. (2013) assessed the innovation structures for research & development (R&D) in low carbon vehicles in the European Union (EU) automobile industry, which is primarily based on conventional vehicle technologies. This study also compared battery electric vehicles (BEVs) to both hydrogen fuel cell electric vehicles (FCEVs) and hydrogen fuel cell plug-in hybrid vehicles (FCHEVs). Assessments of the impact on the power grid, energy market and other factors, such as environmental effects, were also evaluated in many studies (Silvester et al., 2013; Juul and Meibom, 2012; Fernandes et al., 2012; Mullan et al., 2011). The relevant literature studies are primarily focused on emission reductions and the impacts of the energy requirements of EDVs together with future estimations of EDV use for different locations. Some studies also considered renewable energy options for the supply of the EDV-based energy requirements with different ratios while neglecting the economic feasibility analysis of the renewable options.

In this study, a case study of EDV penetration for Istanbul, Turkey, is considered. As one of the most important renewable energy sources, the utilization of wind energy is evaluated, from both the investment cost and the emission reduction perspectives, for its ability to provide the necessary electrical energy requirement for the recharging of EDVs. Thus, this investigation will be useful for upcoming researchers specifically studying the utilization of EDVs in highly populated cities all around the world. The presentation of a scenario-based analysis of EDVs and the realization of a detailed Istanbul-based analysis for the first time in the literature are the main contributions of this study. Apart from the above given studies, complete assessments of the economic and environmental evaluations of EDVs are realized in this study. In addition, the economic evaluation of renewable energy options, including future estimations of different parameters for the Istanbul case, is considered. The economic value of the reduction of CO_2 emissions in the carbon trade market is also considered, which is neglected in the above-mentioned studies.

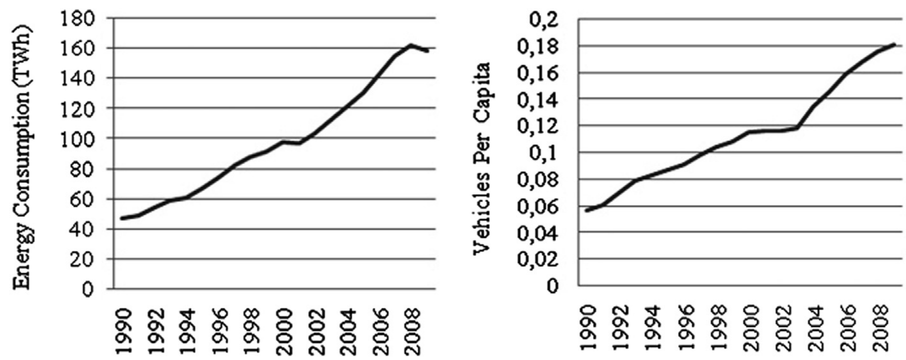
This paper is organized as follows: Section 2 describes the details of the study, Section 3 presents the obtained results with the necessary evaluations, and the concluding remarks are given in Section 4.

2. The current situation in Istanbul and Turkey

As a developing country, the total electrical energy consumption and the number of vehicles per capita in Turkey are continuously increasing. In parallel with a high level of population growth, with the population increasing from 56.5 million to 72.6 million people in the period of 1990–2009 (TURKSTAT, 2010a), the electricity consumption values for Turkey significantly increased in the same time period, from 47 to 158 TWh – an increase of 336%, as shown in Fig. 1(a) (TURKSTAT, 2010b). In addition, the increase in the number of vehicles per capita in the same period was 320%, which is shown in Fig. 1(b).

The electricity generation import-dependency ratio of Turkey was 59% in 2009 (EUAS, 2009). Thus, the electricity generation from local natural sources and the reduction of oil dependency, especially in the transportation sector, are significantly important issues for Turkey. Hence, the utilization of alternative vehicular systems is attractive for Turkey. In addition, due to the current environmental considerations and the regulations of the European Union candidature procedure and the Kyoto Agreement, the Turkish Government has set some future targets to generate a greater portion of its electricity from renewable sources. The CO_2 emissions have doubled during the past 15 years in Turkey, as shown in Fig. 2. Electricity consumption and road transportation account for a significant portion of the major sources of CO_2 emissions, as shown in Fig. 2 (TURKSTAT, 2010c). The emissions caused by road transportation have increased linearly. To develop a sustainable city life and to control emissions, the use of EDVs should be increased in urban life and renewable energy integration in such sectors should be promoted. Consequently, CO_2 emissions will be reduced and transportation can be transformed into a clean energy chain with the widespread use of EDVs.

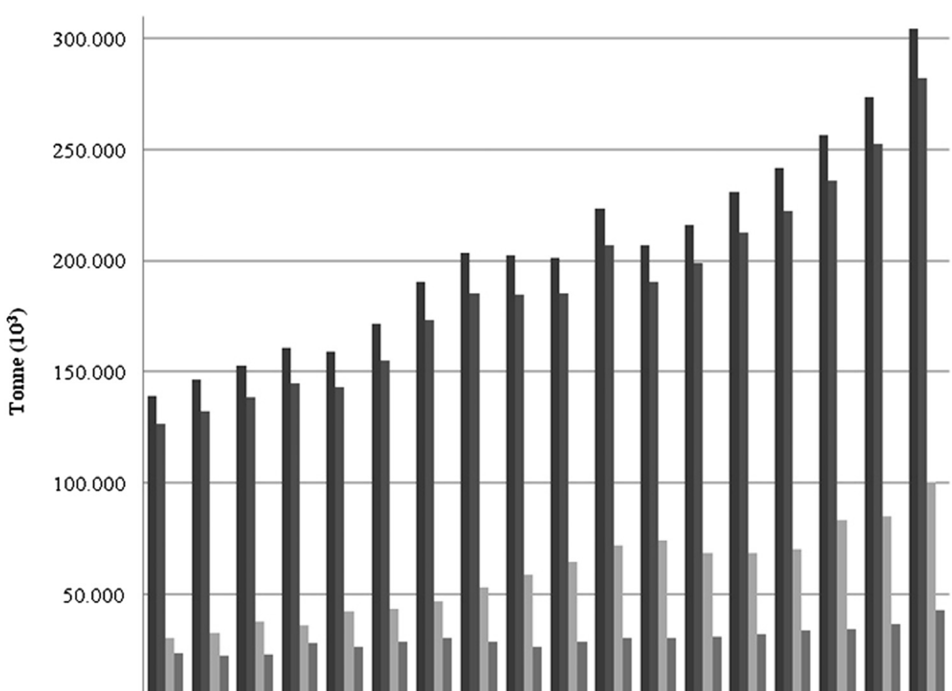
In Turkey, some legal regulations for supporting the use of environmentally friendly systems such as renewable energy have been recently realized. The electricity generated by renewable energy sources can be sold to the grid at a pre-defined price according to the Turkish Renewable Energy Law, Law No: 6094 (TOJ, 2010). Turkey has considerable wind energy potential, but the fraction of the wind energy capacity utilized has been very low (Akdag and Guler, 2010a). However, the total installed wind energy capacity of Turkey has significantly increased, which rose from 18 MW in 2004 to 2492 MW by the end of 2012 (EWEA, 2013). This recent significant growth in the wind energy sector is foreseen to increase. Turkey also provides support to EDVs in a manner similar to the support of renewable energy sources. In addition, to promote alternative vehicle technologies, significant tax incentives have been announced compared to conventional fuel-based vehicular systems: the private consumption tax ratio of electric vehicles will be 3% for a maximum 80-kW electric motor, while this value is 37% for conventional vehicles for a 1600cc conventional engine (TRA, 2013). In this regard, according to customer expectations in Turkey for EDVs, if the costs of EDVs are close to those of the conventional vehicles, Turkey can quickly transition to EDVs in the near future (Deloitte, 2011).



(a) The change of electric energy consumption (b) The change of vehicle numbers per capita

Fig. 1. The change in energy consumption and the number of vehicles per capita in Turkey between 1990 and 2009.

In this study, Istanbul, the largest city of Turkey, with a population of 13 million in the surrounding area and which is located in transit routes as a bridge connecting the continents of Asia and Europe, is investigated. Istanbul faces many of the same problems as other metropolitan cities, such as a rapid increase in population, air pollution and traffic congestion. All of these similar problems are affecting urban lifestyles and inflicting serious harm to the national economy. EDVs can be a good solution to address these problems. Over the last decade, the number of vehicles has grown from 1.281 million to approximately 3 million in Istanbul (TURKSTAT, 2010d). Today, nearly 24% of all of the light vehicles in Turkey are utilized in Istanbul. The road transportation efficiency is very low, due to the low traffic speeds and frequent blockages of the traffic flow that cause the decrease in the internal combustion engine (ICE) efficiency (Åhman, 2001). Thus, due to the many characteristic properties of daily life in Istanbul, there is a strong need to use EDVs. When the transition to EDVs is considered, the electricity infrastructure and electric energy consumption trends in Istanbul should be given specific importance. Note that nearly 20% of the total electrical energy of Turkey was consumed in Istanbul in 2009 (TEDAS, 2009). In addition, along with the continuous increase in the electricity demand, the introduction of EDVs to the vehicle market will further increase the energy demand in the near future (Nanaki and Koroneos, 2013). The utilization of some alternative energy technologies to meet the mentioned energy demand in an environmentally friendly manner should also be considered. These issues are addressed in the next section.



	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Total	139.59	146.54	152.93	160.90	159.10	171.85	190.66	203.72	202.71	201.71	223.80	207.37	216.43	230.98	241.88	256.43	273.70	304.47
Energy	126.70	132.47	138.63	145.24	143.20	155.34	173.36	185.59	185.00	185.20	207.05	190.87	198.95	212.96	222.28	236.05	252.79	282.47
Electricity Production	30.325	33.036	37.958	36.118	42.458	43.750	47.290	53.229	58.894	64.543	72.089	74.515	68.815	68.973	70.499	83.680	85.312	100.66
Road Transport	24.036	22.583	23.120	28.268	26.534	28.792	30.590	28.823	26.860	29.175	30.822	30.541	31.114	32.369	34.078	34.517	37.082	42.934

Fig. 2. CO_2 emission changes between 1990 and 2007.

3. Description of methods and evaluation of results

In this part of the study, a group of assessments is presented for the possible effects of EDV penetration in terms of energy requirements and CO_2 emissions for the case of Istanbul. Moreover, an evaluation of utilizing wind energy to supply the increasing EDV charge requirements is presented considering economic and environmental issues.

First, the prediction of the annual total electric energy consumption of Turkey is realized. A radial basis function network (RBFN) is chosen as the prediction approach implemented in the MATLAB environment. Similar to an artificial neural network (ANN), RBFN models generally have three layers, as observed in Fig. 3: an input layer, a hidden layer with a RBFN function and an output layer. However, in contrast to the classic ANN, the RBFN function and non-linear cluster analysis are used in hidden layers. The actual training, as well as the other types of ANN, is performed between the hidden layers and the output layer. The RBFN functions (gauss, exponential) at the hidden layers provide the transformation, and the output layer has an activation function (Ham and Kostanic, 2001). The RBFN model can be expressed by:

$$y_i = \sum_{k=1}^{N} w_{ik}\varphi_k(\| x - c_k \|), \quad i = 1, 2, \ldots, m \tag{1}$$

where y is defined as the output, $x \in R^{n\times1}$ is defined as an input vector, $c_j \in R^{n\times1}$ are defined as centroids, $\in_k(..) \in R^{+}$ is the radial basis activation function, w_{ik} are the weight vectors, N is the number of hidden layers, and $\|.\|$ represents the Euclidean distance. Many activation functions can be used within the RBFN model. A typical choice for the RBFN is a set of multi-dimensional Gaussian kernels:

$$\varphi_k(\|x - c_k\|) = \exp\left(-\frac{1}{2}\left(\frac{\|x - c_k\|}{\sigma_k}\right)^2\right) \tag{2}$$

where σ_k is the width factor of the k^{th} hidden unit in the hidden layer.

To obtain the predicted annual total electricity consumption of Turkey using the RBFN approach, first, all of the necessary inputs are determined. Then, the training set is prepared, the utilized network is trained, and the obtained results are analyzed. To provide the training set, the data obtained from TURKSTAT (2010b) for the period between 1998 and 2008 are utilized. The determined inputs for the RBFN structure are as follows:

- The electricity consumption in residential areas
- The electricity consumption in commercial areas
- The electricity consumption in public institutes
- The electricity consumption in industrial areas
- The electricity consumption for lighting
- The electricity consumption in other areas

As the output of the algorithm, the considered training set for the RBFN algorithm is described in Table 1. In addition, the test set for the algorithm is described in Table 2.

Using the input data given in Table 1, the value determined using the RBFN approach is 157,240 GWh for 2009. If we compare the real value with the data in the test set of 156,894 GWh, it can clearly be seen that the error is negligible and that the proposed structure can be further utilized for the forecasting of the following years.

The results obtained using the RBFN approach are presented in Table 3. It can clearly be seen that the electric energy consumption is rising and that the introduction of EDVs into the vehicle market will boost the energy consumption. Thus, the effects of possible EDV penetration rates should be evaluated.

In this study, the prediction of the number of light vehicles for 2020 was performed using a curve-fitting approach. The linear-polynomial method was chosen as the curve-fitting approach, which can be expressed by:

$$f(x) = P_1 x \cdot P_2 \tag{3}$$

The different penetration rates of EDVs, such as 2%, 5% and 10% of all light vehicles that will be replaced by EDVs by 2020, are evaluated, and the relevant light vehicle prediction for Istanbul is presented in Table 4.

To take into account the possible extra energy requirements due to EDV charging actions, we considered only one light vehicle in Istanbul. On average, most of the drivers use their vehicles to drive over 50 km per day in Istanbul (Çidimal, 2009). In addition, the assumed value for the average energy consumption of a midsize EDV is 0.20 kWh/km (Metz and Doetsch, 2012). Additionally, EDVs are assumed to be operated nearly 15,000 km for one year (Moura, 2006). Thus, the total yearly energy requirement per EDV can be calculated as:

$$A_{ER}(i) = D_W(i) \cdot D_E(i) \tag{4}$$

where $A_{ER}(i)$ is the annual energy requirements (kWh), D_W is the operated km for one year (km), and D_E is the energy consumption (kWh/km). i is an index of each of the EDVs.

Using Eq. (4), the total electrical energy demand for the cases of 2%, 5% and 10% of EDVs were calculated as 178, 447 and 894 GWh in 2020 for the predictions, respectively. Thus, the impact of EDVs on the total electric energy demand cannot be neglected. In addition, a comparative CO_2 reduction analysis considering the above given annual operation period of 15,000 km for EDVs was performed, and the results are described in Table 5. It is clear that the introduction of EDVs into the market and the use of EDVs instead of conventional vehicles considerably decreases the CO_2 emissions.

The use of EDVs in the transportation sector is likely to decrease the GHG and CO_2 emissions in metropolitan areas, as stated before. However, electrical energy is generally produced through the burning of fossil fuels in Turkey. Table 6 (IEA, 2009) shows the comparative CO_2 emissions from different energy sources used for EDVs. Note that the emissions generated during the construction actions for renewable sources are neglected in this study.

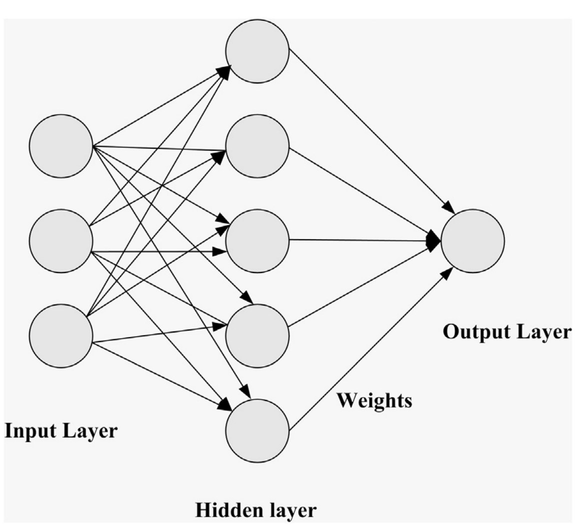


Fig. 3. General structure of a RBFN.

Table 1
Training set for the RBFN: annual net electricity consumption by sector during 1998–2008.

Year	Residential (GWh)	Commercial (GWh)	Public institute (GWh)	Industrial (GWh)	Lightening (GWh)	Other (GWh)	Total consumption (GWh)
1998	20,034.1	7733.8	4271.6	46,139.0	3691.2	5835.0	87,704.6
1999	22,584.3	8208.0	3775.1	46,480.3	4185.3	5968.9	91,201.9
2000	23,887.6	9339.4	4107.9	48,841.7	4557.7	7561.4	98,295.7
2001	23,557.3	9907.8	4370.0	46,989.0	4888.2	7357.7	97,070.0
2002	23,559.4	10,867.3	4580.5	50,489.4	5103.9	8347.3	102,947.9
2003	25,194.9	12,871.9	4554.0	55,099.2	4974.8	9071.2	111,766.1
2004	27,619.0	15,656.2	4530.7	59,565.9	4432.5	9337.5	121,141.9
2005	30,935.0	18,543.8	4662.7	62,294.2	4143.0	9684.1	130,262.8
2006	34,466.0	20,256.4	6044.8	68,026.7	3950.4	10326.2	143,070.5
2007	36,475.8	23,141.2	6933.2	73,794.5	4052.6	10737.9	155,135.3
2008	39,583.6	23,903.3	7344.3	74,850.3	3970.2	12295.9	161,947.5

Table 2
Test set for the RBFN: annual net electricity consumption by sector for 2009.

Year	Residential (GWh)	Commercial (GWh)	Public institute (GWh)	Industrial (GWh)	Lightening (GWh)	Other (GWh)	Total consumption (GWh)
2009	39,147.5	25,018.9	698.6	7470.1	3844.8	11,423.2	156,894.1

Table 3
Estimation of the yearly electricity demand of Turkey.

	2010[a]	2011[a]	2012	2013	2014	2015	2016	2017	2018	2019	2020
Net electricity consumption (TWh)	169 (172)[b]	176 (186)[b]	184	190	198	206	213	220	228	235	242

[a] Accuracy rate of prediction is over the 90%.
[b] Real value.

Table 4
Prediction of the number of light vehicles of Istanbul.

		2011[a]	2012[a]	2013	2014	2015	2016	2017	2018	2019	2020
Total light vehicles		1,911,340 (1,907,782)[b]	2,011,411 (2,009,777)[b]	2,121,906	2,242,825	2,374,168	2,515,935	2,668,126	2,830,741	3,003,780	3,187,243
Number of EDVs for different penetration rate											
EDVs penetration rate	2%	38,227	40,228	42,438	44,857	47,483	50319	53,363	56,615	60,076	63,745
	5%	95,567	100,571	106,095	112,141	118,708	125797	133,406	141,537	150,189	159,362
	10%	191,134	201,141	212,191	224,283	237,417	251594	266,813	283,074	300,378	318,724

[a] Accuracy rate of prediction is over the 90%.
[b] Real value.

If the above-mentioned energy requirements of EDVs are totally provided by renewable energy, these cars can be called “green” or “zero emission” vehicles because any type of tank-to-wheel pollution is removed. In the concept of renewable energy, Turkey has many potential sources, and among them, wind energy-based electricity production seems to be the most promising, as wind energy is a rapidly growing energy source in Turkey (Çelik, 2011).

To analyze the wind energy potential, the Catalca region in Istanbul was selected in this study. Catalca has significant wind energy potential. Small- and large-scale wind farms have already been constructed in that region. The characteristics and technical information of a wind farm located in this area are taken into account for the assessment of the possible supply of the EDV energy requirements in Istanbul using an environmentally friendly basis instead of the utilization of fossil fuels for electricity production. In the mentioned wind farm, 3-MW wind turbines are installed and the annual energy production is predicted to be 10.37 GWh for each turbine. The wind energy potential is also supported by Akdag and Guler (2010b) in that area. Thus, 18, 44 and 87 wind turbines are predicted to be required for the supply of the annual extra energy demand of EDVs under the penetration rate cases of 2%, 5% and 10%, respectively.

The total cost of such an extra investment should be evaluated for the entire project period. Thus, the capital cost, maintenance and operating costs as well as some other related costs should be taken into account together with the impacts of the inflation rate. The investment cost, which includes the capital cost for the land and similar construction, grid connection, etc., of the utilized wind turbine is approximately 2.78 million € per 3 MW turbine. Due to the equations described in Appendix A (Yang et al., 2007), the total lifetime cost of the investments for different EDV penetration rates for the 2%, 5% and 10% cases were calculated as 86, 210 and 416 million €, respectively.

The Turkish government provides the incentive price of 5.5 c€ per kWh of wind energy (MENR, 2010). For the different EDV penetration rate cases of 2%, 5% and 10%, the predicted additional income from wind is 9.357, 22.874 and 45.229 million €/year due to the energy requirements. Consequently, the repayment period is nearly 4.4 years for the 2% case, 5.2 years for the 5% case and 5.4 years for the 10% case.

Finally, another economic and environmentally positive impact on CO_2 reduction is to define the value of this carbon reduction in the free carbon market. If we take the data given in Tables 3 and 4 while considering Fig. 2, it can be seen that the CO_2 emission reduction is highly significant in the case of using EDVs instead of the conventional vehicles combined with the supplying of the required energy of EDVs from wind energy. The reduction of emissions for the different penetration cases of EDVs of 2%, 5% and

Table 5
Annual CO_2 emissions reduction from EDVs.

Different scenarios	Estimated number of EDVs for 2020	CO_2 g/km for conventional light vehicle[a]	Annual CO_2 reduction (ton)
2%	63,745	164.7	157,482
5%	159,362		393,705
10%	318,724		787,410

[a] Source: Istanbul Driving Cycle (IDC) – Euro 4 (a little higher than NEDC because of the land structure of Istanbul).

10% in Istanbul contribute to CO_2 reduction in Turkey at rates of 0.086%, 0.22% and 0.44%, respectively. If the ton/CO_2 mean price is assumed to be 16 € in the free carbon market (Abadie and Chamorro, 2008), the economic values of these reduction rates of 0.086%, 0.22% and 0.44% in the carbon trading market will be 4, 9 and 18 million €, respectively.

Consequently, it can briefly be concluded that the introduction of EDVs with the utilization of renewable energy sources provides many significant advantages for the sustainable growth of the alternative transportation sector in terms of both economic and environmental issues.

4. Conclusion

The conventional transportation technology is widely discussed in the literature due to its negative impacts on the environment and reliance on depleting conventional energy sources. Transportation-specific policies and R&D studies are strongly dedicated to finding competitive alternative vehicular options to meet the GHG reduction targets in the long term and to enable the political effects of energy independence. Among the possible alternatives, EDVs are given specific importance because they provide an environmentally friendly operation with higher efficiencies. In addition, EDVs have the potential to overcome the lower operating efficiencies of conventional vehicular systems in crowded cities with traffic congestion. In this regard, the specific analysis on Istanbul, the most crowded city of Turkey, was provided in terms of both the energy requirements and the related CO_2 emissions.

The analysis results indicated that the ratio of the energy consumption of future EDVs among the entire energy consumption in the country will be non-negligible. Accordingly, if the required energy can be supplied from wind energy, the wind settlement cost payback time is predicted to be approximately 5 years, and for different scenarios of the adoption rates of EDVs of 2%, 5% and 10% by 2020, the reductions in CO_2 emissions in the urban area of Istanbul are 157, 393 and 787 thousand tons, respectively. Additionally, the different EDV penetration rate cases of 2%, 5% and 10% in Istanbul are predicted to contribute to CO_2 reduction in Turkey at rates of 0.086%, 0.22% and 0.44%, respectively. In addition, the economic value of the total emissions reduction rates of 0.086%, 0.22% and 0.44% in the carbon trade market are 4, 9 and 18 million €, respectively. It can be concluded that the investigation of next-generation vehicular technologies together with renewable energy systems is quite necessary for enhancing the future sustainability of metropolitan cities such as Istanbul in terms of environmental and economic factors. With the obtained results, it is recommended that extra EDV charging requirements should be analyzed in detail by the appropriate production, transmission and distribution authorities of governments along with the consideration of alternative energy production options. "Green" charging stations can also contribute to this issue because locally produced energy can be utilized locally without posing an additional power load on existing production facilities. The possibility of using EDVs as mobile storage devices with additional incentives to reduce peak load periods should also be considered together with the analysis of the impacts of such an operating strategy on the battery lifetime, which is one of the most expensive and critical parts of an EDV. An analysis of the power production/consumption match considering real-time measured driving cycle patterns of vehicular systems in Istanbul in the concept of smart grid technologies will be presented as a future study by the authors.

Table 6
Energy sources and CO_2 emissions for electric power plants in Turkey.

	Percentage (2009)	kg CO_2/MWh (2007)	CO_2 emissions from annual energy requirements of EDVs for 2020 (ton)		
			2%	5%	10%
Coal	29%	1037	53,530	134,430	268,850
Oil	3%	675	3604	9052	18,103
Natural gas	49%	347	30,265	76,003	152,007
Renewable (hydro, wind etc.)	19%	0	0	0	0
Total			87,399	219,480	438,960

Appendix A

The annualized cost of the system (ACS) is calculated by:

$$\mathrm{ACS} = C_{\mathrm{acap}} + C_{\mathrm{amain}} + C_{\mathrm{arep}} + C_{\mathrm{aother}} \tag{A.1}$$

where C_{acap} is the annualized capital cost, C_{arep} is the annualized replacement cost, and C_{amain} is the annualized maintenance cost. The other costs (C_{aother}) are the construction cost, grid connection costs, etc.

The capital cost variation is given as:

$$C_{acap} = C_{cap} \cdot CRF(i,\ Y_{proj}) \tag{A.2}$$

where C_{cap} is the initial capital cost of each unit, CRF is the capital recovery factor, which represents a ratio to calculate the present value of an income, and Y_{proj} is the component life span in terms of years. In addition, the capital recovery factor is calculated by:

$$CRF(i,\ Y_{proj}) = \frac{i \cdot (1+i)^{Y_{proj}}}{(1+i)^{Y_{proj}} - 1} \tag{A.3}$$

where the annual real interest rate i is related to the nominal interest rate i' and the annual inflation rate f by the equation given below:

$$i = \frac{i' - f}{1 + f} \tag{A.4}$$

Here, an interest rate i' of 3.5% and an inflation rate of 6% are considered (CBRT, 2011). Additionally, the total replacement cost is assumed to be zero for a wind turbine because its economic lifetime is equal to the project lifetime, and accordingly, any replacement is performed during the project replacement. The system maintenance cost takes the inflation rate into account by the following equation:

$$C_{\mathrm{amain}}(n) = C_{\mathrm{amain}}(1) \cdot (1+f)^n \tag{A.5}$$

where $C_{\mathrm{amain}}(n)$ is the maintenance cost of the nth year.

References

Abadie, L.M., Chamorro, J.M., 2008. European CO_2 prices and carbon capture investments. Energy Econ. 30 (6), 2992–3015.

Åhman, M., 2001. Primary energy efficiency of alternative power trains in vehicles. Energy 26 (11), 973–989.

Akdag, S.A., Guler, O., 2010a. Wind characteristics analyses and determination of appropriate wind turbine for Amasra – Black sea region, Turkey. Int. J. Green. Energy 7 (4), 422–433.

Akdag, S.A., Guler, O., 2010b. Evaluation of wind energy investment interest and electricity generation cost analysis for Turkey. Appl. Energy 87 (8), 2574–2580.

Brady, J., O'Mahony, M., 2011. Travel to work in Dublin. The potential impacts of electric vehicles on climate change and urban air quality. Transp. Res. Part D 16 (2), 188–193.

Brand, C., Tran, M., Anable, J., 2012. The UK transport carbon model: an integrated life cycle approach to explore low carbon futures. Energy Policy 41, 107–124.

Browne, M., Allen, J., Leonardi, J., 2011. Evaluating the use of an urban consolidation centre and electric vehicles in central London. IATSS Res. 35 (1), 1–6.

CBRT, 2011. Central Bank of the Republic of Turkey. <http://www.tcmb.gov.tr/> (accessed January 2012).

Çelik, A.N., 2011. Review of Turkey's current energy status: a case study for wind energy potential of Çanakkale province. Renew. Sustain. Energy Rev. 15 (6), 2743–2749.

Çidimal, B., 2009. Analyzing Car Use in Istanbul. Graduate School of Science Engineering and Technology, (MSc Thesis). Istanbul Technical University, Istanbul.

Deloitte, 2011. The Deloitte Times. September–October 2011, ISSN: 1309-0054. <http://www.deloitte.com/assets/Dcom-Turkey/Local%20Content/Articles/The%20Deloitte%20Times/turkey_tr_deloittetimes_eylulekim2011_301111.pdf> (accessed September 2013).

Duke, M., Andrews, D., Anderson, T., 2009. The feasibility of long range battery electric cars in New Zealand. Energy Policy 37 (9), 3455–3462.

EUAS, 2009. Electricity Generation Company of Turkey, 2009 Annual report. <http://www.euas.gov.tr/apk%20daire%20baskanligi%20kitapligi/YILLIK_RAPOR_2009.pdf> (accessed September 2013).

EWEA, 2013. The European Wind Energy Association. Wind in Power: 2012 European Statistics. <http://www.ewea.org/fileadmin/files/library/publications/statistics/Wind_in_power_annual_statistics_2012.pdf> (accessed September 2013).

Fernandes, C., Frias, P., Lattore, J.M., 2012. Impact of vehicle-to-grid on power system operation costs: the Spanish case study. Appl. Energy 96, 194–202.

Görbe, P., Magyar, A., Hangos, K.M., 2012. Reduction of power losses with smart grids fueled with renewable sources and applying EV batteries. J. Clean. Prod. 34, 125–137.

Guille, C., Gross, G., 2009. A conceptual framework for the vehicle-to-grid (V2G) implementation. Energy Policy 37 (11), 4379–4390.

Ham, F., Kostanic, I., 2001. Principles of Neuro Computing for Science and Engineering. Macgraw-Hill, USA.

IEA, 2009. International Energy Agency. CO_2 Emissions from Fuel Combustion, 2009 ed. International Energy Agency, Paris.

Juul, N., Meibom, P., 2012. Road transport and power system scenarios for Northern Europe in 2030. Appl. Energy 92, 573–582.

Kempton, W., Kubo, T., 2000. Electric-drive vehicles for peak power in Japan. Energy Policy 28 (1), 9–18.

Köhler, J., Schade, W., Leduc, G., Wiesenthal, T., Schade, B., Espinoza, L.T., 2013. Leaving fossil fuels behind? An innovation system analysis of low carbon cars. J. Clean. Prod. 48, 176–186.

Ma, H., Balthasar, F., Tait, N., Riera-Palou, X., Harrison, A., 2012. A new comparison between the life cycle greenhouse gas emissions of battery electric vehicles and internal combustion vehicles. Energy Policy 44, 160–173.

MENR, 2010. Ministry of Energy and Natural Resources of Turkey. Renewable Energy Law of Turkey. No: 6094, Ankara.

Metz, M., Doetsch, C., 2012. Electric vehicles as flexible loads – a simulation approach using empirical mobility data. Energy 48 (1), 369–374.

Moriarty, P., Honnery, D., 2013. Greening passenger transport: a review. J. Clean. Prod. 54, 14–22.

Moura, F., 2006. Driving Energy System Transformation with "Vehicle-to-grid" Power. Interim Report IR-06-025. International Institute for Applied Systems Analysis.

Mullan, J., Harries, D., Braunl, T., Whitely, S., 2011. Modelling the impacts of electric vehicle recharging on the Western Australian electricity supply system. Energy Policy 39 (7), 4349–4359.

Nanaki, E.A., Koroneos, C.J., 2013. Comparative economic and environmental analysis of conventional, hybrid and electric vehicles e the case study of Greece. J. Clean. Prod. 53, 261–266.

Offer, G.J., Howey, D., Contestabile, M., Clague, R., Brandon, N.P., 2010. Comparative analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system. Energy Policy 38, 24–29.

Perujo, A., Cuiffo, B., 2010. The introduction of electric vehicles in the private fleet: potential impact on the electric supply system and on the environment. A case study for the Province of Milan, Italy. Energy Policy 38 (8), 4549–4561.

Silvester, S., Beella, S.K., Timmeren, A., Bauer, P., Quist, J., Dijk, S., 2013. Exploring design scenarios for large-scale implementation of electric vehicles; the Amsterdam Airport Schiphol case. J. Clean. Prod. 48, 211–219.

Smith, W.J., 2010. Can EV (electric vehicles) address Ireland's CO_2 emissions from transport? Energy 35 (2010), 4514–4521.

Thomas, C.E., 2009. Fuel cell and battery electric vehicles compared. Int. J. Hydrogen Energy 34 (15), 6005–6020.

TEDAS, 2009. Turkey Electricity Distribution Company. Net Electricity Consumption Statistics of Turkey. <http://www.tedas.gov.tr/29, Istatistiki_Bilgiler.html> (accessed August 2011).

TOJ, 2010. Turkish Official J. No: 6094. Republic of Turkey, Ankara.

TRA, 2013. Turkish Revenue Administration. Private Consumption Tax Rate. http://www.gib.gov.tr/fileadmin/mevzuatek/otv_oranlari_tum/22_09_2012_II_sayili_liste.htm (accessed September 2013).

TURKSTAT, 2010a. Turkish Statistical Institute, Population Statistics of Turkey 2010. <http://www.turkstat.gov.tr/UstMenu.do?metod=temelist> (accessed September 2013).

TURKSTAT, 2010b. Turkish Statistical Institute, Energy Statistics, Net Consumption of Electricity. <http://www.turkstat.gov.tr/PreTablo.do?alt_id=1029> (accessed September 2013).

TURKSTAT, 2010c. Turkish Statistical Institute, Turkey Greenhouse Gas Inventory, 1990 to 2008. National Inventory Report of Turkish Statistical Institute.

TURKSTAT, 2010d. Turkish Statistical Institute, Road Motor Vehicle Statistics. <http://www.turkstat.gov.tr/PreTablo.do?alt_id=1051> (accessed September 2013).

Yang, H., Lu, L., Zhou, W., 2007. A novel optimization sizing model for hybrid solar-wind power generation system. Sol. Energy 81 (1), 76–84.

Zhang, Q., XU, J., Wang, G., Tian, W., Jiang, H., 2008. Vehicle emission inventories projection based on dynamic emission factors: a case study of Hangzhou, Chine. Atmos. Environ. 42 (20), 4989–5002.