Driving cycle and temperature effects on the energy performance of a solar-powered electric vehicle in Istanbul

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Abstract

The global warming and climate change problem can be solved by emitting less greenhouse gases by transportation. Switching from fossil fuel burning cars to electric vehicle cars is one of the most promising solutions, however; they are as clean as their energy source. In this study, a generic model to estimate energy generation from PV-covered parking lot system and energy demand from electrical cars is established, and Istanbul is selected for a case study. Two main effects are investigated in the demand side: i) ambient temperature and; ii) driving style. In this study, it is considered that a 150 m2 parking lot for 10 cars is covered with 90 PV modules, size of 22.5 kW, to charge EVs in Istanbul, Turkey. The results show that the total annual energy consumption can be covered by a grid-connected PV system. Additionally, an off-grid PV system can cover about 198 and 268 days of energy demand in a year for the urban and highway driving conditions, respectively. Overall, ambient and driving conditions can affect the energy demand by 40%–60%.

Keywords: Driving cycles, electric vehicle, solar charging, temperature effect.

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1. Introduction

There is a direct relationship between increase in global temperature and increase in CO_2 emission levels. Currently, the total CO_2 emission in the atmosphere is about 405 ppm which is much more than any levels during the past 800,000 years of period (climate.gov, 2018). CO_2 level keeps rising due to energy need which is covered by burning fossil fuels. According to EIA (2009), transportation sector is accounted for 20% of the world energy use and 25% of the world energy- based CO_2 emissions. In addition, passenger vehicles accounted for 50% of this CO_2 emission. On the other hand, energy security is vital for growth of the society. Economy of 'energy secure' countries grows faster because energy is key for the growth of nations. On the other hand, countries like Turkey which can be called 'energy insecure' are vulnerable to fuel supply, fuel prices and especially currency fluctuations. Turkey has energy dependence of 73% on the foreign sources (TPAO, 2016). Therefore, mitigation for the global warming and assuring energy security for a country go hand in hand.

There are various clean energy technologies which promise sustainable transportation. Electric vehicles (EVs) are the most promising technology among those based on the burned fuel and emitted CO_2 per km. A typical EV in a moderately clean grid emits about 50 g of CO_2 per km while an efficient internal combustion engine (ICE) emits 100–150 g of CO_2 per km. The difference is quite noticeable. However, if an EV charged by the grid whose power is supplied from coal-burning power plant, the total CO_2 emission of the EV might be as high as ICE. Therefore, the EVs should be charged by the clean grid to be considered as a sustainable option. In other words, EVs are only as clean as their power source. A clean grid mix can be achieved by implementing renewable energy technologies. Today, two of the most popular renewable energy systems are solar and wind energy. Compared to wind, PV makes more sense for EV charging since wind has larger spatial and temporal variation and a grid infrastructure is required to bring electricity to the parking lot. On the other hand, solar energy is much easier to imply and estimate its energy production. PV plants can be installed in a decentralised way. Every parking lot can be covered with PV so that every parking lot can be decentralised PV plant. In Turkey, there are about 16.3 million registered cars (TUIK, 2018). Since all the cars are required somehow to be parked on parking lots, the total amount of required parking area for entire population of the cars in the Turkey is about 160 million m^2 (TUIK, 2018). Huge amount of this parking area can be directly covered with PV panels without requiring extra infrastructure. In other words, transformation of parking lots into decentralised PV power plants does not need too much infrastructure investment rather than PV and structure investments.

As above mentioned, the CO_2 emissions due to transportation should be decreased which can be achieved by increasing the number of EVs and enabling a clean grid mix. Additionally, the foreign energy dependency of Turkey must be decreased because the economic growth of Turkey is vulnerable to fuel prices and currency fluctuations. The proposed concept is covering the parking lots with PV panels. By doing so, EVs can be charged using the energy that comes from the sun, without buying fossil fuel from foreign countries and emitting CO_2. Therefore, the total GHG emission and foreign energy dependency might be decreased at the same time. Use of parking lots as a solar charge station for EVs was first attempted in California. In that pilot project, there is 2.1 kW capacity PV power plant which can charge up to seven EVs (Nunes, Figueiredo & Brito, 2016).

There are several case studies available in the literature and each study points out different problem and solution of the concept. There are two types of EV charging strategies, which are controlled and uncontrolled. Xydas, Marmaras and Cipcigan (2016) compared both charging strategies. This study concluded that the controlled charging strategy is more responsive to a sudden change in the renewable energy due to its source like sun or wind. In addition, Forrest, Tarroja, Zhang, Shaffer and Samuelsen (2016) compared the charging strategies based on their environmental benefits. The study concluded that to achieve the same environmental goal (reduction in CO_2 and

other greenhouse gas emissions), uncontrolled charging schemes require more storage and higher capacity of the PV plant compared to the controlled (smart) schemes.

In the previous studies in the literature, energy demand of an EV is estimated by assuming on the average power consumption. Using average power consumption values for EVs cause inaccurate results because the power consumption of an EV depends on several parameters which doubles the consumption in certain conditions. Therefore, assuming average power consumption values to determine the demand might underestimate real consumption. This study takes the effects of the ambient conditions and driving scheme into account while estimating demand.

2. Theory and methodology

In this paper, a general model for energy generation from PV covered parking lot system and energy demand for electrical cars is established. This general model can be applied to all locations. Model is composed of four different subsections, and Figure 1 shows these subsections as a flowchart.

Intensity of solar radiation depends on the longitude and latitude of the location. Therefore, the first step is deciding on the location where the system will be established, as well as the capacity of the parking lot. The capacity of the parking lot directly fixes the total available physical area that can be covered by the PV module (step 1). The Typical Methodological Year (TMY) is a collection of selected weather data for a specific location, listing hourly values of solar insolation and meteorological elements for a 1-year period. (Hall, Prairie, Anderson & Boes, 2018). Since solar insolation intensity changes location to location, the insolation data which are included in the TMY are required for the selected location. In addition, the model of the PV modules should be decided in order to estimate the rated power of the PV system (step 2). Consequently, the model is divided into two subsections which are PV output estimations and demand estimations. After the general model is generated, a case study for Istanbul is done.
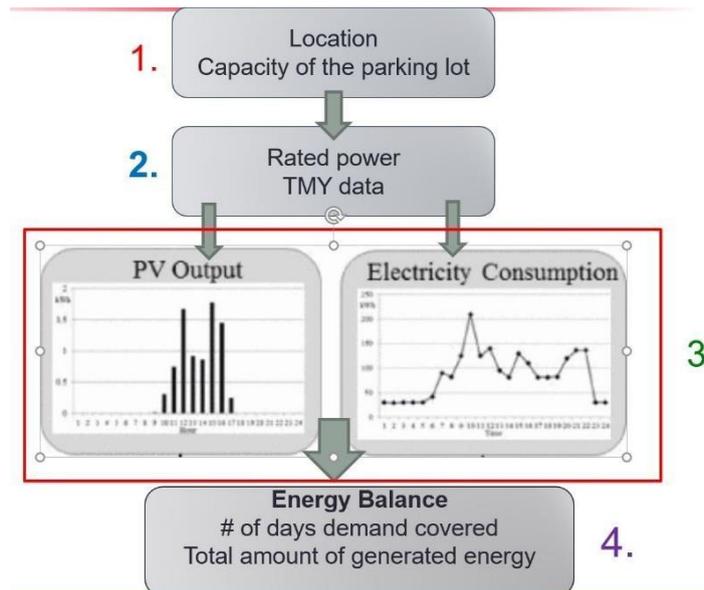

Figure 1. Methodology flow chart

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2.1. PV output estimation

The insolation incident on a PV module is estimated based on the methodology given in Duffie and Beckman (2013). There are several angles should be found in order to estimate incident insolation (I_{pv}), After finding the incident insolation of a PV module(I_{pv}), total energy production can be found by using Eq. 1. The number of panels is decided before based on the parking lot capacity. The meteorological data are obtained via Typical Meteorological Year (TMY) for Istanbul, which include hourly solar irradiation and ambient temperature data.

$$E = I_{pv} \times A_{pv} \times \# \, of \, modules \qquad (1)$$

Fixing the parameters such as location, total available area, the PV power output can be calculated. For the Istanbul case study, Table 1 summarises the PV side parameters which are used to estimate the energy generation from the system.

Table 1. PV system parameters for Istanbul case study

Selected City	Capacity of parking lot	Total area available	Used PV module	Single Module Area	# of modules	Rated Power	Grid configuration
Istanbul	10 cars	150 m²	AXITEC AC-250P/156–60S	1.63 m²	90 module	22.5 kW	Off-grid

The next step is estimating the demand side so that demand and production can be compared at the end.

2.2. Demand side estimation

There are three important parameters that affect the energy consumption of an EV so as demand. The first one is the travel distance because the energy consumption of an EV and travelled distance are directly proportional. The second one is the driving pattern. The final factor that affects the demand is the ambient temperature during driving.

The average daily distance driven by a typical car owner varies among countries and even among regions. Table 2 represents the daily average travelled distance by transportation type for 2009 and 2023 in Istanbul. In 2023, the average travelled distance with passenger cars will be 25 km per journey. This means a person will travel about 50 km to commute work and back. Therefore, it is assumed that average travelled distance as 50 km for demand estimation of EVs. In this study, it is assumed that EVs are charged during parking like usual, so it is important to estimate to average parking time for Istanbul.

Table 2. Daily average travelled distance (per journey) (Istanbul Metropolitan Municipality, 2011)

Situation	Year	Automobile	Shuttle	Public Trans.
		[km]		
Current	2010	14	15.91	15.32
Future	2023	25	24.11	26.52

It is also important because the charging process requires a certain time and whether energy to travel 25 km (one-way trip) can be provided to EV during the parking period become an important question. Figure 2 represents trip distribution by time of the day.

As can be seen from the figure, people do not travel during the hours between 9:00 and 17:00, which means that the cars are at the parked position during those times. Therefore, it can be assumed that EVs are connected to charge port at 9:00 and they can be charged until 17:00. This ensures that the EVs will be stay parked for about 8 hours in the weekdays.

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The impacts of the temperature of the maximum range of vehicle were explained in the introduction section. There are a few EV car models, which are officially imported to Turkey. BMW i3 is selected for this study among these because there is enough and necessary information to model its energy consumption. Table 3 presents the assumed energy consumption of BMW i3 under different driving conditions and ambient temperatures taken from Downloadable Dynamometer Database by Argonne Lab (Argonne National Labs, 2018). For this study, the power consumption is assumed to form of a step function.
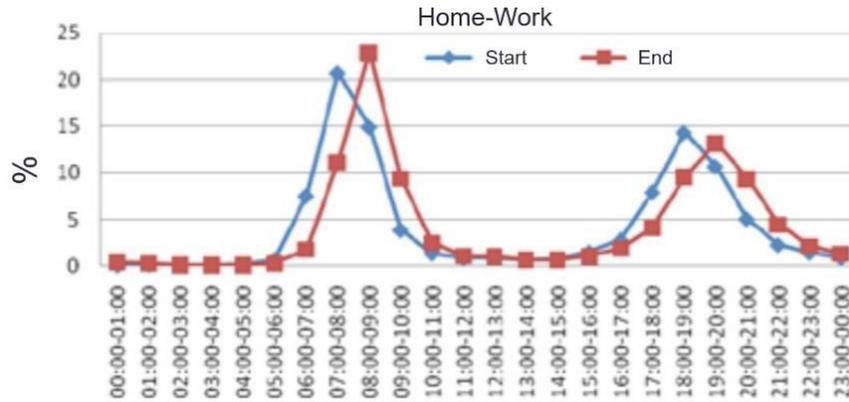

Figure 2. Trip distribution during a typical day in Istanbul (Istanbul Metropolitan Municipality, 2011)

In other words, between some pre-determined temperature values which represent different ambient conditions (cold, mild and hot), the power consumption is assumed to be constant. These temperature ranges developed from the Downloadable Dynamometer Database (Argonne National Labs, 2018).

**Table 3. Energy consumption of BMW i3 under different ambient conditions
and driving cycles (Argonne National Lab., 2018)**

		$-10°C<T_{amb}<-1°C$		$-1°C<T_{amb}<15°C$		$15°C<T_{amb}<30°C$		$30°C<T_{amb}<∞°C$	
Electrical Vehicle	Daily trip	UDDC	Highway	UDDC	Highway	UDDC	Highway	UDDC	Highway
		(km)				(Wh/mile)			
BMW i3	50	420.6	276.49	368.2	246.1	267.44	186.31	204.32	188.89

Figure 2 is also used for determining the time which EV is being driven. According to Figure 2, most of the cars are on the road between 7:00 to 9:00 in the mornings. The TMY data include the hourly temperature data for Istanbul. These temperature values are used to determine the exact hourly energy consumption of BMW i3 by combining the data from Table 3 and Figure 2.

3. Results and discussion

As previously presented in Figure 1, the study has four steps. In the theory and methodology part, how to estimate the PV output and load demand is discussed. After estimating the PV output and electricity consumption in step 4, the demand and generation of energy is compared. The main aim is to create this general model and applying the model into different cities, i.e., applying the model to different case studies. The parameters are selected for the case study.

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The data provided in Table 1 are used to calculate hourly energy generation for a year from the PV covered parking lot whose capacity is 10 cars. UDDS and highway driving cycles are extreme cases for energy consumption. Normally, the maximum power consumption case is simulated by the US06 driving cycle. However, the data include the power consumption for US06 only for a hot start which makes US06 has lower consumption value than the UDDS cycle with a cold start. Figure 3 represents the daily energy generation from the PV system. As it can be seen from Figure 3, the production is higher in the spring and summer compared to winter and autumn. Figure 3 also shows the daily demand for UDDS and highway driving cycles reflecting the effects of ambient temperature. Moreover, the average energy consumption for combined driving conditions, which is presented in the technical data sheet of the BMW i3, is presented in Figure 3 (bmw.co.uk, 2018). The technical specifications of BMW i3 state that mixed power consumption is 200 Wh/mile. However, assuming a constant demand, i.e., ignoring the effects of temperature and driving profile on energy consumption will not give accurate results as compared in Figure 3. Constant demand case underestimates the energy consumption about 30%–50% in winter compared to cases which temperature effects are included. Regardless of temperature change, the energy consumption for UDDS is always higher than the highway cycle as expected because UDDS represents the aggressive driving, while highway cycle represents the mild driving. For example, the daily peak energy consumption for UDDS is 160 kWh, while it is 100 kWh for the highway cycle, which means that energy consumption of BMW i3 under city drive conditions is about 50% higher than the highway conditions.
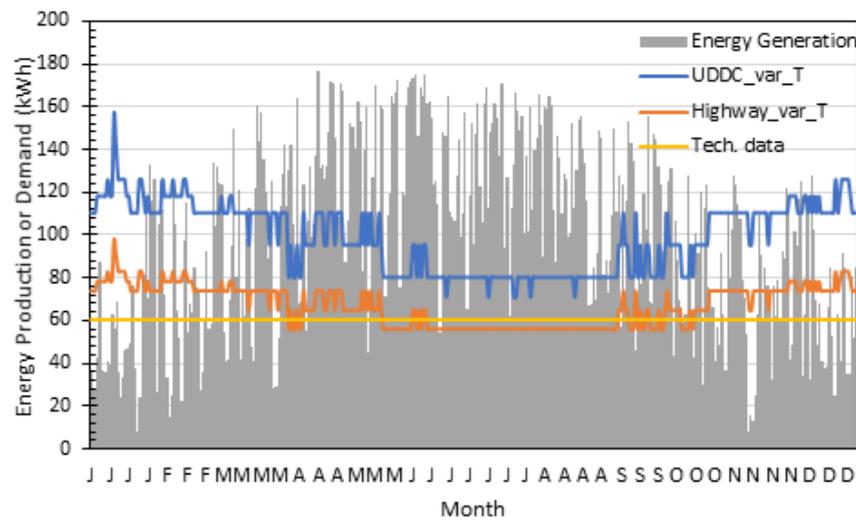

Figure 3. Energy generation from 22.5 kW PV system in Istanbul

In addition, as the weather gets warmer, energy consumption decreases for both driving cycles as expected. Figures 4 and 5 represent the amount of demand covered by solar energy for UDDS and highway cycles, respectively. For UDDS, solar energy that is generated from the PV system can cover full demand for about 198 days which is higher than the half of the year. On the other hand, the generated solar energy can cover full demand for about 268 days for the highway cycle. The difference between the number of days which demand is covered for two cycles cannot be neglected as previously stated. On the other hand, as presented in Figure 3, the energy generation increases as the weather gets warmer while energy consumption for both cycles decreases. This effect can be seen in Figures 4 and 5 clearly, as the weather gets warmer, the amount of demand covered by solar energy increases.
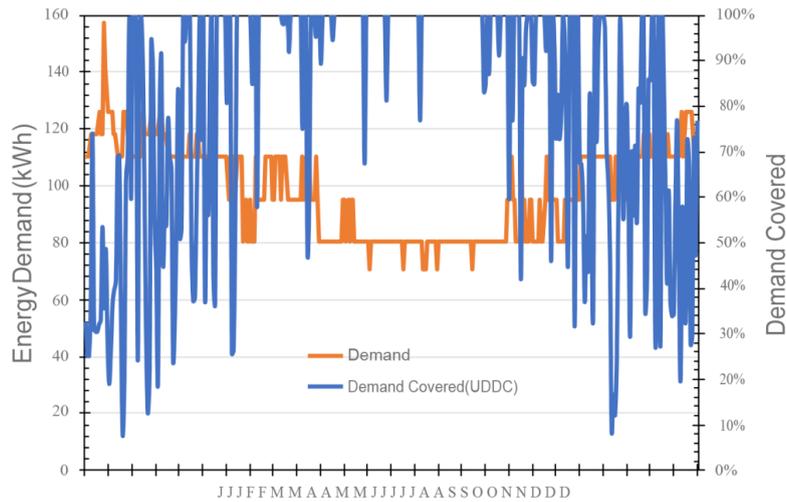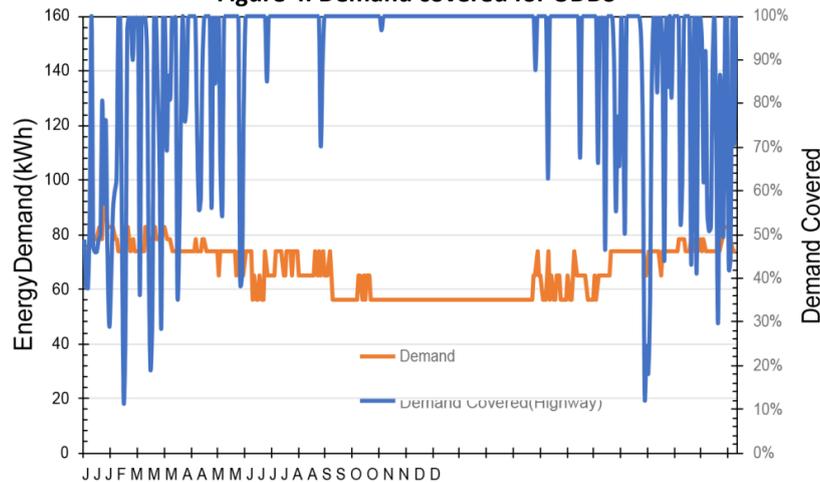
Figure 4. Demand covered for UDDS

Figure 5. Demand covered for highway drive cycle

Although the system is designed off-grid as previously stated in Table 1, the effects of the connecting system to the grid are also investigated. Figure 6 represents the monthly demand for UDDS and where the demand is covered. As can be seen from Figure 6, the grid can supply the energy deficit from the PV system and the whole demand can be covered. Additionally, the yearly total energy generation from the PV plant is about 36.7 MWh while the total yearly demand is about 36 MWh. Some of the days, the PV system generates energy higher than required, and on some of the days, generated energy is lower than required as presented in Figure 3. If excess energy is given to grid and re-taken from the grid when it is needed, the whole demand can be covered by solar energy which will lead to zero emission of the EVs. In addition, if constant demand was assumed as in the previous studies in literature, the total annual demand would be about 22 MWh. In that case, designed PV system can cover demand for 15 cars instead of 10, which emphasises that ignoring temperature and driving conditions effects and assuming constant demand underestimates the power consumption about 50%.
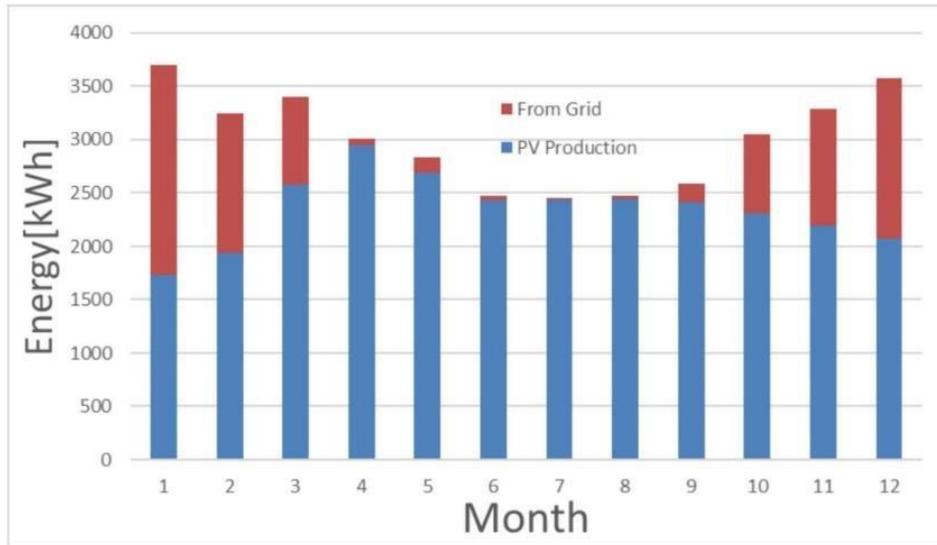
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Figure 6. Total demand for UDDS and coverage of demand by source

4. Conclusion

World CO_2 emissions are much above the tolerable limits, GHG emissions should be decreased to mitigate the effects of global warming. According to EPA, transportation is encountered for the 25% of the CO_2 emissions. Electrification of transportation is considered one of the most promising options. Electric vehicle, which is charged by the moderately clean grid, can significantly decrease GHG emissions. Therefore, renewable energy technologies should be implemented for charging of EV to decrease the emissions. On the other hand, 20% of global energy demand is for transportation. For the countries which are dependent on foreign countries for energy, dependency might be decreased if EVs are promoted and charged by renewable energy sources. Hence, integration of renewable energy technologies to charge EVs will both decrease the GHG emissions and foreign energy dependency of the country.

In this paper, a parking lot in Istanbul with a capacity of 10 cars is covered by PV panels to both charge the parked EV and provide the shade for the parked cars. The simulations are divided into two parts, which are PV output and demand side. The total area that is covered by PV modules is 150 m^2 and rated power of the PV system is 22.5 kW. Simulations show that the PV system can generate annual energy of about 36.7 MWh.

On the demand side, BMW i3 selected for the simulations. None of the previous studies in the literature takes the effects of temperature and driving conditions (city, highway, aggressive, mild). All the previous studies assumed a constant power consumption, which neglects the effects of temperature and driving style. The daily assumed travelled distance is 50 km. Simulations show that ambient temperature can decrease total range to 50%. In addition, for the same ambient conditions, the maximum range differs about 40%–60% for different driving patterns like city driving, highway driving, etc. In addition, the city driving is simulated by UDDS cycle and total annual energy demand for UDDS is about 36 MWh. This shows the PV system with a rated power of 22.5 kW in Istanbul can cover annual demand for 10 EVs. On the hand, if constant demand is assumed, annual energy demand will be about 24 MWh. Hence, the power consumption is underestimated about 50% compared to the real case.

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