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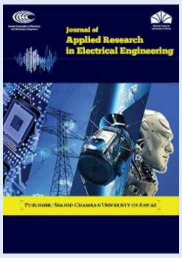

Research Article

Economic Analysis of Photovoltaic Systems During Peak Load of the Electric Power Distribution System in the Presence of Electric Vehicles

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Abstract: Considering the challenges of using fossil fuels, including price, pollution, and the increasing development of electric vehicles, the energy supply from other sources should be considered. One of the main challenges of electric vehicles is their impact on the distribution network, especially the time of charging and its coincidence with the peak load of the network, which causes an increase in power consumption, double pressure on the network, and more and faster depreciation of distribution network equipment. Also, producing more energy during peak times leads to increased costs and air pollution. In this paper, the use of renewable energy to charge electric vehicles is investigated in such a way that the consumers of electric vehicles use solar panels and batteries to store solar energy so that it can be used for charging during peak times. The costs of installing solar panels, the consumption of electric vehicles, the amount of energy generation, as well as the emission of fossil fuel pollutants that fossil power plants produce at peak times have been investigated. Furthermore, a comparison has been made between the use of renewable and non-renewable energy. Consequently, the proposed method is about 112494 dollars more economical than the system without renewable energy. It is also suggested to consider incentives from the government for the consumer to reduce the capital and operating cost of the photovoltaic system to diminish the investment return time.

Keywords: Electric vehicle, peak load, solar energy, economic analysis.

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1. Introduction

The increase in fuel prices and environmental concerns cause changes in the structure of power systems and energy management [1] becomes more crucial than before. One of these changes is the increasing use of renewable energies and electric vehicles which advents microgrids [2]. With the significant increase in the number of electric vehicles that can solve the challenge of environmental pollution, it has created new challenges such as creating overload on the network and simultaneity of charging this type of vehicle with peak load for the power system. By developing the utilization of renewable energy, electric vehicles can be adopted optimally and cleanly at a low cost, which improves energy efficiency. The research concerning this field is on the problem of electric vehicle charging timing and the use and optimization of the vehicle battery to reduce peak load and the use of algorithms for vehicle charging and discharging time, which will be investigated in the following. Concerning the connection of the electric vehicle to the grid, the opportunities, challenges, and executive structure, reference [3] after introducing electric vehicles as the future of the transportation industry, describes their challenges for the electricity industry and the vehicle to grid (V2G) connection and explains their requirements. In [4], the presence of electric vehicles with V2G system and different charging strategies in the distribution network has been considered and it has been shown that the use of electric vehicles without planning and control can cause tension and overload. Ref. [5] addresses the generation, distribution, and transmission costs of a unit of electrical energy imposed on the electricity industry of a country and compares it with the income of that industry, which can play an effective role in the macro-planning and development of the electricity industry excluding government subsidies which can be a respectable criterion for power system with renewable energies. A two-stage charging strategy for solving electric vehicle charging control problems based on fuzzy control is proposed in [6], in which the optimal charging of each vehicle is calculated in the first stage, and in the second stage, the accumulated power of the first stage is distributed between vehicles using fuzzy control. The probabilistic planning of the power system in the presence of an electric vehicle, considering the uncertainty of renewable sources, has been investigated in [7] which using a mixed-integer linear model. In [8], the power quality problems of the distribution system caused by the charging of electric vehicles are first mentioned, and then solutions to solve these problems are presented. In [9], with the aim of energy management and minimizing the negative effects of the electric vehicle load pattern, a new method for installing solar parking lot for electric vehicles in a network with uncontrollable distributed resources is presented. Modelling and optimization of energy consumption in a smart home with the presence of an electric vehicle, energy storage, solar cell, and load response has been investigated in [10]. In this study, according to the importance of the energy management process, the performance of a smart home in the presence of an electric vehicle capable of bidirectional exchange of power with the power grid, energy storage system and solar panels has been modelled and evaluated in the framework of a linear programming. In [11], the economic evaluation and feasibility of using a photovoltaic system to supply the electrical load required for household use has been investigated using statistics and real information. The results show that the use of this photovoltaic system is justified. In [12] the optimal placement of electric vehicle charging stations in a distribution network considering rooftop photovoltaic systems has been discussed, but the cost issues related to this consideration have not been conducted. The authors in [13] present the photovoltaic rooftop and electric vehicle parking lot models to provide the benefit in peak load as well as the spinning and regulation reserves. Power distribution impacts considering photovoltaic and electric vehicles have been assessed in [14, 15]. These two studies show that the load supplying, and the voltage profile are improved, which can serve more the EV charging demand. In [16] a bi-directional charger for electric vehicles is considered which causes operational profit for distribution power system integrated with photovoltaic and electric vehicles. In previous studies, the economic evaluation and the costs of using the photovoltaic system in the presence of the electric vehicle have not been addressed, and the effect of renewable energy and the electric vehicle on the actual reduction of the cost of electric energy supply has not been investigated. The present paper addresses this gap by adopting real data.

In this paper, with the aim of supplying the required energy for charging the electric vehicle, the solutions to reduce the costs considering the importance of environmental pollution have been investigated. These costs include the cost of electricity for charging and household consumption, fuel cost, emission cost, and maintenance cost. Furthermore, economic issues have been investigated in two cases of using and not using renewable solar energy to supply electric vehicle. Also, when renewable energy is used, it will be seen that by using a home solar power plant, the pollution and fuel cost for energy production can be reduced compared to the production of electricity by traditional power plants, and the challenges of charging an electric vehicle at peak times can be resolved.

The rest of the paper is organized as follows. In the next section, the description of the problem and the modelling of different parts are mentioned. The costs include consumer cost, power system cost and solar panel energy production, power plant fuel cost, pollution cost, and transformer cost, and the results are interpreted in the next section, and the conclusion is presented at the end.

2. Problem Description

In this study, the challenge of simultaneity of electric vehicle charging with the peak time of electricity consumption and the use of renewable energy in homes and the costs of consumers and the electricity distribution network in terms of emissions, fuel costs, and transformer depreciation costs have been modeled and investigated. The understudy system is a power distribution system and consists of 1000 EVs and household solar systems with 25 kilowatts output.

2.1. Photovoltaic System

In this section, the costs related to the production of solar energy in a small domestic power plant and the power generation relationships of this power plant have been examined. The construction of a solar power plant has different costs according to the type of equipment and installation conditions. Usually, for the construction of a solar power plant, two types of general costs can be imagined, which are mentioned below. These expenses are related to January 2022.

1. Cost of solar power plant equipment: Table 1 details the cost of each of the different parts of a small-scale solar power plant.
2. Ancillary costs: This type of cost includes the variable costs of panel washing and maintenance during operation.

One of the important parameters in photovoltaic power plant design calculations is the output power of the solar system, which is obtained from (1).

$$P_{PV} = E_{PV} E_{in} A_{PV} G \tag{1}$$

where P_{pv} is the output power of the solar system, E_{pv} is the efficiency of the panel, E_{in} is the efficiency of the electric power converter, A_{pv} is the area of the panel (m^2), and G is the irradiance (W/m^2) on the panel surface [17].

Table 1: The costs of a 5-kW solar power plant at home.

	Type of panel	No.	Price ($)
1	290 W crystalline solar panel	17	166.6
2	5200 W, 48 V tp-series inverter	1	572.6
3	Steel structure	3	89
4	Electrical panel and the related equipment	1	166.6
5	Installation cost		10% of the cost
6	Controller charger	1	463
7	100 Ah, 48 V battery	1	187
8	Total cost		3666-4266 $

According to the relationship between the output power of the panel, the output power depends on the parameters of the panel's efficiency in the ambient temperature and the inverter's efficiency, as well as the area of the panel and the intensity of sunlight [18]. There are 17 units of 290 W mono crystal type panels, considering 78% efficiency fore the whole solar system, and peak sun hour (PHS) equal to 6.5 for Shiraz, it is possible to produce 25kWh (17*290*0.78* 6.5) of energy for each day. If 5 kW of this power are used for electric vehicle charging, 20 kW can be injected into the main grid, which according to the tariff rate for purchasing electricity by the grid from domestic producers of electricity, below 20 kW was 0.073$/kW in the year 2022 which earns monthly income of about 53$ [17].

2.2. Electric vehicles

The electrical energy required by electric vehicles is different from the gasoline fuel consumption of internal combustion cars. The fuel consumption of internal combustion vehicles with the consumption of each liter of fuel per 100 km is analyzed, but electric vehicles are measured in terms of electricity consumption per kWh, which some examples are presented below.

1. Nissan Leaf consumes 10 kWh per 100 km with a battery capacity of 40-62 kWh.

2. Jaguar E-Pace consumes 19 kW of energy per 100 km with a 90-kW battery.

3. Carmania EK1 with a 44.5-kW battery and a distance of 3054 km with each charge, i.e., 4.5 kW for every 100 km.

4. Renault Zoe model 2020 with a 52-kW battery and a distance of 245 miles with each charge, i.e., 13.19 kW for every 100 kilometers

5- Kia e-niro 2019 electric vehicle with a 64-kW battery and a distance of 480 km with each charge, i.e., 13.3 kW for every 100 km.

In this paper, on average, for every 100 kilometers of distance, about 14 kW consumption is considered, which considering a 60-kW battery and considering that the minimum and maximum charge is 5 and 85%, the vehicle with each charge can travel 342 km.

Each type of battery has limitations based on its physical structure and manufacturing technology, one of which is the charge and discharge limit per hour, which is in the form of (2):

$$p_{batt}^{min} \leq p_{batt} \leq p_{batt}^{max} \qquad (2)$$

And another variable of the battery is the state of charge, which is 1 in the fully charged state, and 0 in the fully discharged state, which is according to Eq. (3).

$$soc_h = soc_{h-1} - \left(\frac{p_{batt}}{E_{batt}}\right) \qquad h=1,2,3,\ldots,24 \qquad (3)$$

where Soc_h is the state of charge of the battery at hour h, E_{batt} is the rated power of the battery.

Since p_{batt} is for 24 hours, we have

$$\sum_{1}^{j} p_{batt} \leq \left(soc_0 - (1-d)\right) * E_{batt} \quad j=1,2,3,\ldots,24 \quad (4)$$

D represents the maximum discharge deep of the battery. For instance, if $D = 0.8$, the battery charging should not be below 20% [19].

2.3. Distribution Transformer

Power transformers are one of the most important and expensive equipment of the power system, which can be used for more than 40 years if properly operated [20]. The way of loading is the most determining factor in the lifetime of the transformer and the aging of its insulation, so that by increasing the temperature of the hot spot of the winding by 6 points compared to its nominal value, the insulation life of the transformer is reduced by half. In addition, loading more than the nominal value of the transformer, especially in power transformers, can cause many risks, such as increasing the amount of moisture and gas production in the paper and oil insulation, increasing the leakage flux density outside the core and increasing the stress on the bushings, tap changer, end turns, and current transformers [21]. According to the standard IEEE Std.C57.91, the insulation life of the transformer is considered to be 180000 hours, the increase in the temperature of the transformer causes a certain amount of the life of the transformer to decrease. Equations (4)-(6) express the modeling of the decrease in life due to the increase in the temperature of the transformer for the reference temperature of 110°C [22-23].

$$FAA = e^{\left[\frac{15000}{\theta_h - 273} - \frac{15000}{383}\right]} \qquad (5)$$

FAA is the life reduction factor and θ_h is the temperature of the coils in K.

In order to calculate the amount of reduction in the life of the transformer, it is possible to obtain the value of the temperature changes of the windings due to the variations in the transformer loading by using the relation of power losses in the resistance [24]. In this paper, taking into account solar generation and electric vehicle charging, less power is absorbed from the network and the load of the 2 MWA transformer is reduced to about 12%. According to Fig. 1, a 10% decrease in loading reduces the temperature by 20%. Assuming the normal working temperature of the transformer, which is 110°C, the new temperature of the transformer is reduced and reaches 88°C. On average, reducing the temperature to 88°C, according to the diagram in Fig. 2, increases the life of the transformer by 0.1 per year, which adds 2 years to the total life of the transformer for a transformer with a life of 180,000 hours or 20 years.

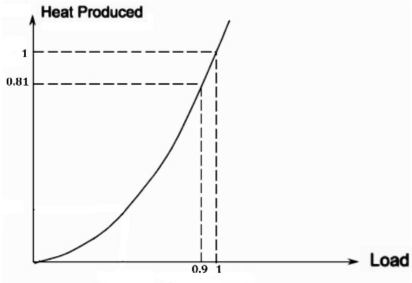

Fig. 1: The relation between loading in p.u. and temperature of transformer in p.u.

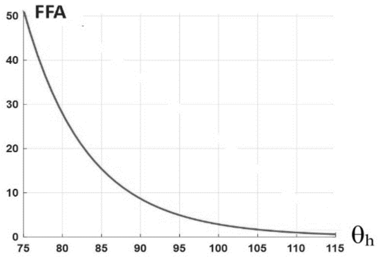

Fig. 2: The relation between temperature in °C and lifespan of transformer in p.u.

3. Costs

3.1. Consumer's Costs

Consumer costs include the fixed cost, which is the cost of construction of a solar power plant, and the variable costs include the maintenance of the solar power plant, as well as the costs of purchasing electricity from the grid for home consumption. The amount of electricity obtained from solar panels is deducted from the total cost and the excess energy obtained is sold. The cost relationship is in the form of (6):

$$C_{L_{Total}} = C_{Load} + C_{Ch} - C_{PV}$$
$$C_{PV} = C_A + C_B \tag{6}$$

In the mentioned equation, C_{L_TOTAL} is the total cost of the consumer, C_{LOAD} is the cost of buying electricity for household consumption, C_{Ch} is the cost of charging an electric vehicle, and C_{PV} is the cost of producing electricity by solar panels.

3.2. Power system's Cost

The costs are related to the production of electric energy and delivering it to the consumer, which include the cost of fuel, pollution, and distribution transformers.

$$C_{Total} = C_{Tr} + C_P + C_F \tag{7}$$

where C_{Tr} is the cost of transformer, C_P is the cost of pollution, and C_F is the cost of fuel. The cost related to the transformer is checked in terms of the transformer's lifespan according to the amount of peak loads that are applied to it. To elucidate, the increase in loading causes a decrease in lifespan and, as a result, its replacement cost, which was explained in the previous section. On average, the amount of electricity consumed by each household is 186 kWh/hour, which is equivalent to 6.5 kWh/day. According to the tariff announced in January 2021, it was on average 0.0003**$** to 0.002 **$** for consumption of higher than 100 to 300 kWh, and this cost is for households without electric vehicles.

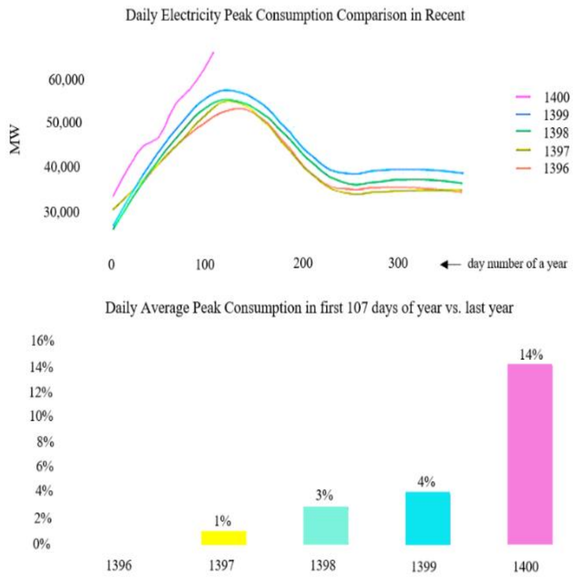

Fig. 3: Electricity consumption peaks within the last five years.

For an electric vehicle, taking into account 14 kW to travel every 100 km with a 60-kW battery and traveling a distance of 342 km with each charge, and taking into account the fact that the charging of the electric vehicle is according to the domestic tariff, an electric vehicle requires 1800 kW/day for charging if is charged every day. According to the tariff of 150 Tomans, the vehicle requires an average of 10**$** /month for charging above 30 kW. Fig. 3 shows the consumption of electricity in the last five years. According to the graph, electricity consumption is at its highest in the hot three months of the year, which was about 58,000 MW. But, in the year 2021, the peak of electricity consumption reached 62,000 MW [25]. In this paper, an average peak consumption of 52,000 MW is considered.

3.3. Power Plant's Fuel Cost

The electricity produced in winter in the country is significantly more polluted than the electricity produced in the first nine months of the year, which is due to the multiple growth of liquid fuels with higher polluting capability and reduced gas consumption. When gas is used for heating homes, power plants have a shortage of gas, so they have to use liquid fuel. Table 2 lists the consumption of different types of fuel to produce one kWh of electricity in the average form of their consumption in the first nine months of the year and three months of winter, the information obtained for the year 2018 per kWh of electricity production [26]. For a 12 MW power plant, it is as shown in Table 3.

Table 2: Amount of fuel consumption in the power plant for 1 kW of energy.

First nine months			Winter		
Gas (m^3)	**Mazut (L)**	**Gasoline (L)**	**Gas (m^3)**	**Mazut (L)**	**Gasoline (L)**
0.252	0.009	0.01	0.153	0.030	0.071

Table 3: Fuel consumption for 12 MW power plant.

First nine months			Winter		
Gas (m^3)	**Mazut (L)**	**Gasoline (L)**	**Gas (m^3)**	**Mazut (L)**	**Gasoline (L)**
3024	108	120	1836	360	852

Table 4: Cost of fuel consumption for one kW.

Gas (10^3m^3)	Mazut (10^3L)	Gasoline (10^3L)
Fuel cost in the first nine months		
75	42	681
Fuel cost in winter		
Gas (10^3m^3)	**Mazut (10^3L)**	**Gasoline (10^3L)**
213	90	459
Fuel cost of 12 MW for 12 months		
Gas (10^3m^3)	**Mazut (10^3L)**	**Gasoline (10^3L)**
30	27	756

3.4. Pollution Cost

Power plants need fossil fuel for power generation, leading to the emission of pollution. The pollutants produced are impose external costs to the power plant, which cannot be examined directly. So, the costs including the treatment of diseases and the costs caused by pollutants by destroying the environment should be investigated. Table 5 shows the cost of pollutants in general, which includes the external costs of polluting gases based on studies by the World Bank and Environmental Protection Organization in 2013 based on $/kWh [27].

SO_2, NO_X, and CO_2 are the most important air pollutants that every year, especially in winter, cause air pollution and the occurrence of various diseases. Table 6 provides the amount of pollution each of the pollutants cause by burning fossil fuel for electricity generation per unit of fuel consumed [27]. The flowchart of proposed model is shown in Fig.4.

4. Results and Analysis

At first, the costs related to the combined cycle power plant, the household solar power plant, and the consumer's cost are discussed. Therefore, in the first stage, charging of electric vehicles without solar panels is considered.

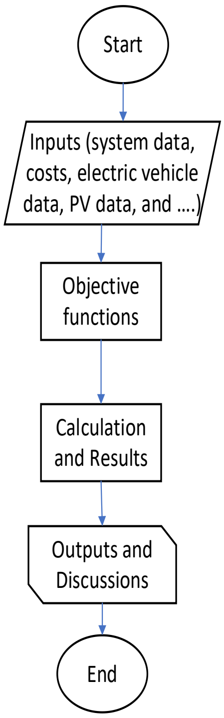

Fig. 4: Illustrative process flowchart.

As mentioned in the electric vehicle section, to charge an electric vehicle on average if it covers a distance of 20,000 km per year, about 2800 kW of electric energy is needed. Considering that the vehicle is charged at home from 6 pm to 6 am, which coincides with the peak hours, the challenges of the network increase during peak hours. Thus, according to the graph below, the peak load reached more than 65,000 MW in 2021, and its minimum value is 40,000 MW. Now, the electricity used to charge the electric vehicle should be added to it, and it should be emphasized that this amount is for one car, and if the result is checked for 1000 vehicle, it is expressed in the form of Table 7. (The amount of peak consumption is considered to be 52500 MW per year on average.)

As it is clear from Table 7, with the presence of 1000 electric vehicles, gas fuel consumption increased by 635,600 m^3, and fuel consumption increased by 39,200 liters and diesel by 70,000 liters, and the pollutants are also according to Table 8.

Now, considering the solar system for charging the vehicle in such a way that the battery is used to store energy for charging the vehicle, and even if more energy can be used for the peak hour of consumption with more batteries, solar power plant supplies about 7.3 MW to the power system on average. And, if it is considered for 1000 houses, it will be about 7300 MW. The description of costs is according to Table 9. The cost of pollutants with the presence of solar cells is shown in Table 10.

Generally, the total cost of fuel and emissions without using the solar power plant system and with the presence of an electric vehicle is $212,737.72 per year, and when a 5-kW home power plant is used, the costs reach $102,381.55 per year, which saves 110,356.17 $ for the network. By reducing the load on the transformer by about 12%, the temperature of the transformer winding decreases by about 20%, after which 0.1% is added to the insulation life of the transformer. In other words, the insulation life of the transformer is added 2 years on top of its lifespan of 20 years. According to the price of 2000 KVA transformer which is 21387 $ in 2023, with the increase of 2 years insulation lifespan of the transformer, 2138.7 $ will be saved economically for each stage of transformer replacement. The power system owner can support domestic electricity producers by using incentive schemes such as loans with low interest, support schemes, buying electricity with a more expensive tariff, can make it attractive more for small scale producers to solve the overload challenge created by electric vehicles.

Table 5: The cost of pollutants based on $/kWh.

	NO_X	SO_2	CO_2
Combined cycle power plant	0.0004	0.00045	0.0011

Table 6: Emissions production rate for each type of fuel and for each unit of fuel.

	NO_X (g per unit of fuel)	SO_2 (g per unit of fuel)	CO_2 (g per unit of fuel)
Gasoline	19	8.7	2900
Natural gas	7	0	210
Mazut	9	5.4	3900

Table 7: The amount of fuel consumption in peak load with and without an electric vehicle.

	Fuel consumption during peak load and charging of 1000 vehicles			Fuel consumption during peak load		
	Gas	Mazut	Gasoline	Gas	Mazut	Gasoline
1000 Liter	11917.5	735	1313.5	12553.1	7742	1382.5
$	11.47	0.51	0.89	8.57	0.51	0.94

Table 8: Pollutants for charging the vehicles.

Pollution produced in the presence of 1000 electric vehicles			
	NO_X	CO_2	SO_2
Gas	83422500	2507675000	0
Mazut	107257500	46478250000	64354500
Gasoline	226432500	34560750000	103683250
Cost ($)	21000	57750	23625

Table 9: Costs considering household solar power plant.

	Gas	Mazut	Gasoline
Fuel consumption (L)	10260400	632800	1120000
Cost ($)	701.12	432.4	765.3

Table 10: The cost of pollution with the presence of a solar power plant.

Amount of pollution produced in the presence of the solar cell			
	NO_X	CO_2	SO2
Gas	71822800	2154684000	0
Mazut	5695300	2467920000	3417120
Gasoline	21280000	3248000000	9764000
Cost ($)	18080	49720	30340

5. Conclusion

In this paper, economic studies related to the use of household power plants and its effect overall network costs with the presence of electric vehicles were investigated. As the results show, when the solar power plant is used, not only the cost of fuel, pollution and maintenance of the power plant is reduced, but also two years are added to the lifespan of the transformer compared to the state without the solar system. On the other hand, consumer expenses are also reduced and can have income. Finally, as it can be seen in the results, from the economic point of view, the use of household solar power plant is appropriate choice, and it is about 112,494.87 dollars more economical than the system without solar system.

Credit Authorship Contribution Statement

Musa Khosravi: Data curation, Formal analysis, Investigation, Resources, Software, Visualization, Writing - original draft. **Saeed Hasanvand**: Conceptualization, Formal analysis, Methodology, Project administration. **Mahyar Abasi**: Supervision, Validation, Writing - original draft, Writing - review & editing. **Mohammad Esmaeil Hassanzadeh:** Project administration, Writing - review & editing.

Declaration Of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The ethical issues; including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy has been completely observed by the authors.

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