THE AVAILABLE SOLAR ENERGY FOR THE PROPULSION OF ELECTRIC CARS. CASE STUDY FOR THE MUNICIPALITY OF CONSTANȚA

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The purpose of this paper is to highlight the solar energy potential of the city of Constanța for the propulsion of electric cars. The solar energy available to the city of Constanța was obtained with the help of the PVGIS application and then, the energy was used for the propulsion of 6 models of electric cars. The cars were tested on 2 standard driving cycles, in order to obtain the distance traveled with the help of solar energy.

Keywords: autonomy, electric cars, solar energy, energy consumption, resistive forces

1. Introduction

Romania is in an area with a good solar potential of 210 sunny days per year and with an annual solar energy flux between 1000 kWh/m^2/year and 1300 kWh/m^2/year [1]. From this total amount around 600 to 800 kWh/m^2/year is technically feasible. The most important solar regions of Romania are the Black Sea coast, Northern Dobrogea and Oltenia with an average of 1600 kWh/ m^2/year [1]. Considering an average area of the roof of electric cars of 1.5 m^2, a value of approximately 1200 Wh/day of energy stored in the batteries of electric cars can be estimated, by placing PV panels on the roof [2].

In the paper called "Experimental Determination of the Energy Provided by the Photovoltaic Panels Placed on the Roof of a Vehicle with an Imposed Route", it has been obtained during an experiment with a Breckner 100 Wp solar panel placed on a roof of a car at a tilt angle of 45^0, a total amount of 977.60 Wh, of energy obtained during parking time interval 09:00-17:00, with a PV panel with the surface of 0.486 m^2. The parking lot was in Constanța, at coordinates 44.204, 28.619 (44°12'14.4"N 28°37'08.4"E).

According to another paper, entitled "Increasing the autonomy of electric cars using the energy provided by own photovoltaic panels" [4], a study was made in order to determine the autonomy of electric car using solar energy. In the paper, an experiment was held using a solar panel in a parking lot from Constanța, on 21st of October 2021, and the energy obtained was extrapolated in order to determine

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for each car the total amount of energy available. The results revealed that on a sunny day is enough available sun energy on the roof of EV, in order to extend the autonomy of electric cars with appreciable distances, between 13-19 km for an extra-urban cycle and ranges between 20-31 km for urban cycles.

These considerations are the basis of this work, which aims to carry out a study on the solar energy potential of the city of Constanța in order to use this solar energy for the propulsion of electric cars. The study is made to perform a more realistic determination of solar energy available, including cloudy days and shading. In the first part of the study, the paper aims to obtain, with the help of the PVGIS application, the available monthly solar energy and solar radiation, in a location in the city of Constanța. In the second part of the study, the paper aims to estimate the distance that electric cars can travel with the help of solar energy. This study will be carried out by choosing 6 electric cars, which will be subjected to 2 energy performance tests. The obtained energy consumption will be used to compare with the available energy to determine the distance that can be traveled by electric cars using solar energy.

2. Solar energy potential for Constanța

In this section it is proposed to determine the electric energy available from the sun to be used for the purpose of propulsion of electric cars. In order to determine the solar energy potential for the Constanta municipality, the PVGIS application was used.

PVGIS is a web application that allows the user to get data on solar radiation and photovoltaic (PV) system energy production, at any place in most parts of the world. PVGIS provides information for any location in Europe and Africa, as well as a large part of Asia and America [3].

The PVGIS application was used in this study to estimate the solar energy potential of a parking lot located in the city of Constanța, at the coordinates 44.205, 28.619, according to table 1 and Fig. 1. The simulation was performed for one year, monthly. The chosen place represents the location where the experiment from paper "Experimental Determination of the Energy Provided by the Photovoltaic Panels Placed on the Roof of a Vehicle with an Imposed Route" was carried out prior to this study, with a solar panel oriented at a tilt angle of 45^0, to estimate the potential solar energy to charge the batteries of electric cars stationary in the parking lot of the place of work or the parking lot of the residence.

One of the PVGIS facilities is that PV modules can be placed on mountings that move the PV modules to allow them to follow (track) the movement of the sun in the sky. This movement can be made in several different ways. Here are given three options: Vertical axis, Inclined axis and Two-axis tracker.

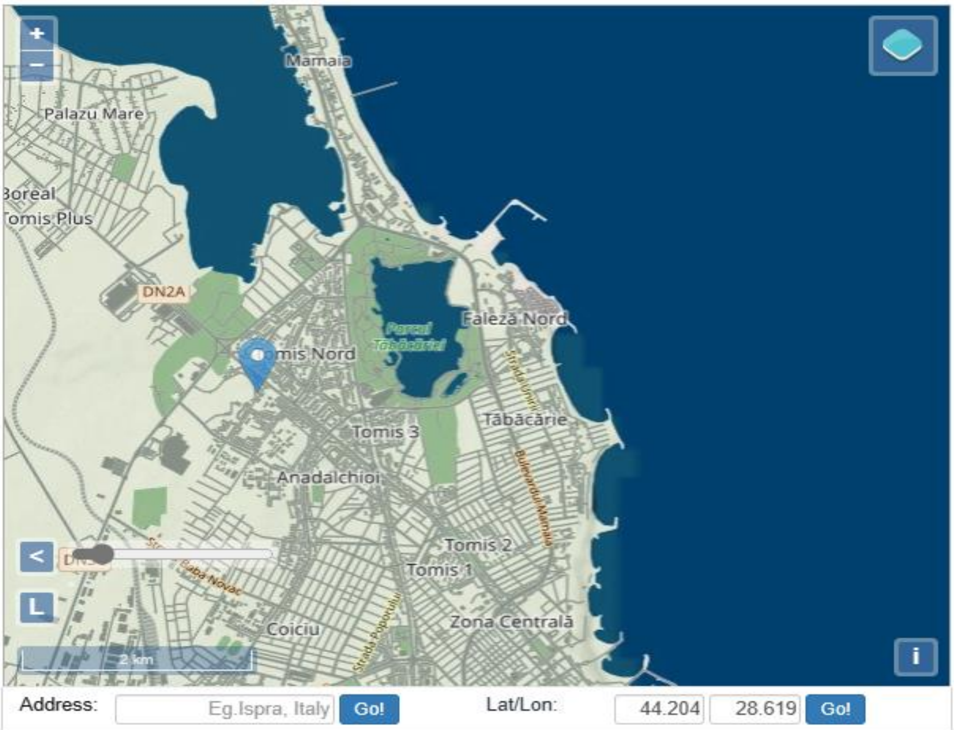

Fig. 1. The location used in PVGIS for experiment [3]

For this experiment the inclined axis option was chosen, in order to simulate the solar panel oriented at 45^0, on the car's roof.

Using PVGIS, in Fig. 2 it is expressed the monthly energy output for a 0.1 kWp solar panel, at a slope inclination of 45^0. It can be observed that the highest energy is reached during august, 19.4 kWh, and the lowest level of energy is attended due to December, less than half of the energy reached on July, 6.5 kWh.

Table 1

Data summary used in PVGIS for report [3]

Latitude/Longitude: 44.204,28.619	Yearly in-plane irradiation [kWh/m²]: 2110.21
Horizon: Calculated	Year-to-year variability [kWh]: 7.4
Database used: PVGIS-SARAH2	Changes in output due to:
PV technology: Crystalline silicon	Angle of incidence [%]: -1.53
PV installed: 0.1 kWp	Spectral effects [%]: 1.07
System loss: 22 %	Temp. and low irradiance [%]: -5.76
Slope angle [°]: 45	Total loss [%]: -26.84
Yearly PV energy production [kWh]: 154.38	

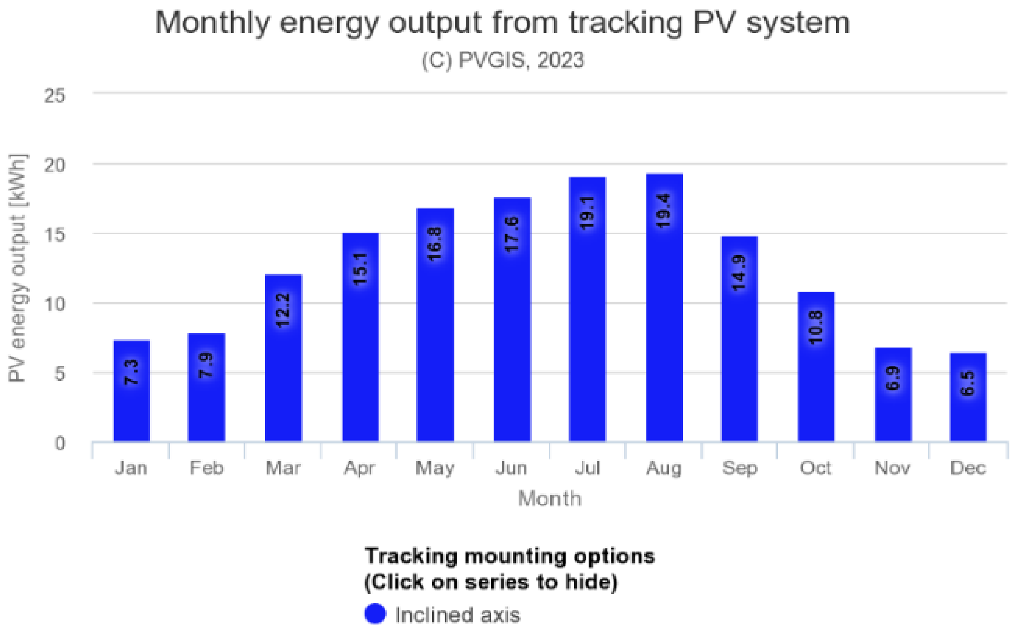

Fig. 2. Monthly energy output. Case study for Constanța [3]

The highest level of irradiation was reached in august, with a total of 276.4 kWh/m^2, and the lowest level on December with just 81.2 kWh/m^2.

Using the data obtained by PVGIS, representing the available energy, we can estimate the distance that can the electric car can go using just solar energy.

The experiment starts from the premise that the surface of the solar panel is equal to the surface of the roof of the electric car [5]. Thus, in the PVGIS application, the installed power values were inserted one by one according to the roof surface of each car model. The value of the installed electrical power is determined using the Breckner solar panel, 100 Wp, with an area of 0.49 m^2 as a reference. By extrapolation, the installed power values were determined for each electric car's roof model, using the equation:

$$P_{installed} = \frac{A_{roof} \times P_{pk}}{0.49} \quad (1)$$

Where $P_{installed}$ is the electrical power installed for each model of electric car for study, A_{roof} is the surface of each electric car's roof, P_{pk} =100 is the power peak value of the Breckner solar panel used as reference and 0.49 is the area of solar panel used for reference. Power installed for each type of electric car was displayed in table 2.

3. Determination of available solar energy for 6 types of electric car

In order to highlight the solar energy potential of using solar panels on the roof of electric cars, 6 types of electric cars were chosen for the study, with the main of the important technical characteristics for this study, highlighted in table 3. The rule for choosing these electric cars was the top electric car sales in Romania in 2022.

Table 2

Power installed for each type of electric vehicle [5]

EV's model	Dimensions (L·B·H) (mm)	Car's roof surface (m^2)	Power installed $\boldsymbol{P_{installed}}$(W)
Hyundai Ioniq 5.58 kWh	4636x1890x1605	1.692	345.31
Renault Meganne E-Tech	4199x 1768x1505	2.135	435.71
Volkswagen E-Up	3600x1645x1492	1.688	344.49
Opel Corsa E	4060x1765x1435	1.76	359.18
Hyundai Kona Electric 2021	4205x1800x1565	1.738	354.69
Mazda MX-30	4395x1848x1555	1.873	382.24

To determine the available electrical energy obtained with the help of solar panels, for each electric car model, the PVGIS software was used. Using the "Tracking PV" extension, "Installed peak-power", the installed power, $P_{installed}$ for each model of electric car was entered into the PVGIS application and the monthly values of electricity during one year were obtained and displayed in table 4.

Table 3

EV's specification [4]

EV Model	**Vehicle mass**	**Drag coefficient Cd**	**Frontal area A (m^2)**	**Wheel radius Rw (m)**	**Rolling resistance coefficient f**	**Roof area (m^2)**
Hyundai Ioniq	1830 kg	0.288	2.64	0.49	0.0125	1.692
Renault Meganne E-Tech	1708 kg	0.29	2.67	0.55	0.0125	2.135
Volkswagen E-Up	1160 kg	0.31	2.47	0.41	0.0125	1.688
Opel Corsa E	1455 kg	0.29	2.13	0.56	0.0125	1.76
Hyundai Kona Electric 2021	1685 kg	0.29	2.8	0.61	0.0125	1.738
Mazda MX-30	1660 kg	0.33	2.81	0.62	0.0125	1.873

Table 4

Monthly solar energy produced by solar panel on the car's roof E_{roof} (kWh)

Nr. crt.	**Month**	Hyundai Ioniq 5	Renault Meganne E-Tech	Volkswagen E-Up	Opel Corsa E	Hyundai Kona Electric 2021	Mazda MX-30
1.	January	17.3	31.9	17.2	18	17.8	19.1
2.	February	21.1	34.4	21	21.9	21.7	23.3
3.	March	36.4	53	36.2	37.8	37.4	40.3
4.	April	49.5	65.8	49.3	51.5	50.9	54.8
5.	May	58.7	73.4	58.5	61.1	60.4	65
6.	June	62.9	76.6	62.7	65.5	64.7	69.7
7.	July	67.2	83.2	67	69.9	69.2	74.4
8.	August	64.3	84.4	64.1	66.9	66.2	71.2
9.	September	45.6	64.8	45.4	47.4	46.9	50.5
10.	October	29.9	47.2	29.9	31.1	30.8	33.1
11.	November	17	30.2	17	17.7	17.5	18.8
12.	December	14.4	28.3	14.4	15	14.9	16

In order to determine the values of daily energy obtained for each type of electric vehicle, the monthly solar energy produced by solar panel on the car's roof was divided by the number of days of each month, 28, 30 or 31, and the daily average of electricity or each type of electric car has been obtained and displayed in table 5.

Table 5

Daily solar energy produced by solar panel on the car's roof E_{roofd} (Wh)

Nr. crt.	**Month**	Hyundai Ioniq 5	Renault Meganne E-Tech	Volkswagen E-Up	Opel Corsa E	Hyundai Kona Electric 2021	Mazda MX-30
1.	January	558.06	1029.03	554.84	580.65	574.19	616.13
2.	February	753.57	1228.57	750.00	782.14	775.00	832.14
3.	March	1174.2	1709.7	1167.7	1219.4	1206.5	1300.0
4.	April	1650.0	2193.3	1643.3	1716.7	1696.7	1826.7
5.	May	1893.5	2367.7	1887.1	1971.0	1948.4	2096.8
6.	June	2096.7	2553.3	2090.0	2183.3	2156.7	2323.3
7.	July	2167.7	2683.9	2161.3	2254.8	2232.3	2400.0
8.	August	2074.2	2722.6	2067.7	2158.1	2135.5	2296.8
9.	September	1520.0	2160.0	1513.3	1580.0	1563.3	1683.3
10.	October	964.5	1522.6	964.5	1003.2	993.5	1067.7
11.	November	566.7	1006.7	566.7	590.0	583.3	626.7
12.	December	464.5	912.9	464.5	483.9	480.6	516.1

4. Energy consumption of electric cars on ECE and EUDC test cycles

Identifying the energy consumption of electric cars on the ECE and EUDC test cycles is important for determining the distance traveled by each electric car model depending on the available energy and energy consumption. To determine the energy consumption of electric cars, it is necessary to determine the values of the resistive forces when moving and then they will be entered into the simulation scheme to determine the energy consumed [6]. Resistive forces differ from one car to another depending on the constructive parameters of each model.

A. The resistive forces

Traction force, $F_{t,}$ is the sum of all resistive forces and can be written as:

$$F_t = F_r + F_{aero} + F_p + F_i \tag{2}$$

or

$$F_t = f \cdot m \cdot g + \frac{\rho}{2} \cdot C_d \cdot A \cdot (v + v_0)^2 + m \cdot g \cdot sin\,\theta + m \cdot a \tag{3}$$

where: Fr- rolling resistance force, $Faero$- aerodynamic drag force, Fp- uphill drag force, Fi- inertial force, f=*0.0125,* is the rolling resistance coefficient, *m* is the mass vehicle for each of 6 car from the study, $g=9.8\ m/s^2$, the gravitational constant, ρ = 1.22 kg/m^3 - air density, *v* the instantaneous speed of the vehicle, Cd = 0.35*,* the air resistance coefficient, and v_0 =0 is the front wind speed [7].

$$a = \dot{v} \tag{4}$$

where: *a* is the acceleration of the EVs written as speed derivative,

Power to the wheels P_w:

$$Pw = Ft \cdot v \tag{5}$$

where F_t is the traction force.

Energy consumption $E_{c\,(t)}$:

$$Ec(t) = \int_0^t P_w \cdot dt \tag{6}$$

Distance *D(t)*:

$$D(t) = \int_0^t v \cdot dt \tag{7}$$

B. The EUDC and ECE cycles

The determination of the energy consumption of electric cars is determined according to European regulations that contain different sequences, in which the car moves at certain speeds, then stops for certain time intervals and then moves again, simulating the movement of the car on public roads.

The summary of EUDC and ECE urban cycle is displayed in table 6.

Table 6

ECE-15 and EUDC test cycles characteristics [8]

Characteristics	Unit	ECE 15	EUDC	NEDC
Distance	km	4×1.013=4.052	6.995	11.007
Duration	s	4×195=780	400	1180
Average Speed	km/h	18.7 (with idling)	62.6	33.6
Maximum Speed	km/h	50	120	120

The ECE+EUDC cycle (also known as the MVEG-A cycle) was used for emission certification of light duty vehicles in Europe (EEC Directive 90/C81/01) [8].

C. Determination of energy consumption using MATLAB-Simulink block diagram simulation

In the next part of the study, in order to determine the energy consumption of electric cars subjected to ECE and EUDC tests, a MATLAB-Simulink diagram was created, displayed in Fig. 3.

The simulation diagram is formed by functional blocks, mathematical operational blocks, and display blocks. Every functional block represents an equation of a movement resistance forces, or a constant parameter.

The main important functional blocks from the diagram represents:

-the inertial force, $F_{i,}$ block "Inertial force"

$$F_i = m \cdot a \tag{8}$$

where "a" is the acceleration of the vehicle, and "m" is the kerb weight specific for each car model;

-the rolling resistance force, F_r, block "Rolling resistance force";

$$F_r = f \cdot m \cdot g \tag{9}$$

where f=0.0055, the rolling resistance coefficient, and g=9.85m/s^2, the gravitational constant;

-the aerodynamic drag force, F_{aero}, block "aerodynamic drag force";

$$F_{aero} = \frac{\rho}{2} \cdot C_d \cdot A \cdot (v + v_0)^2 \tag{10}$$

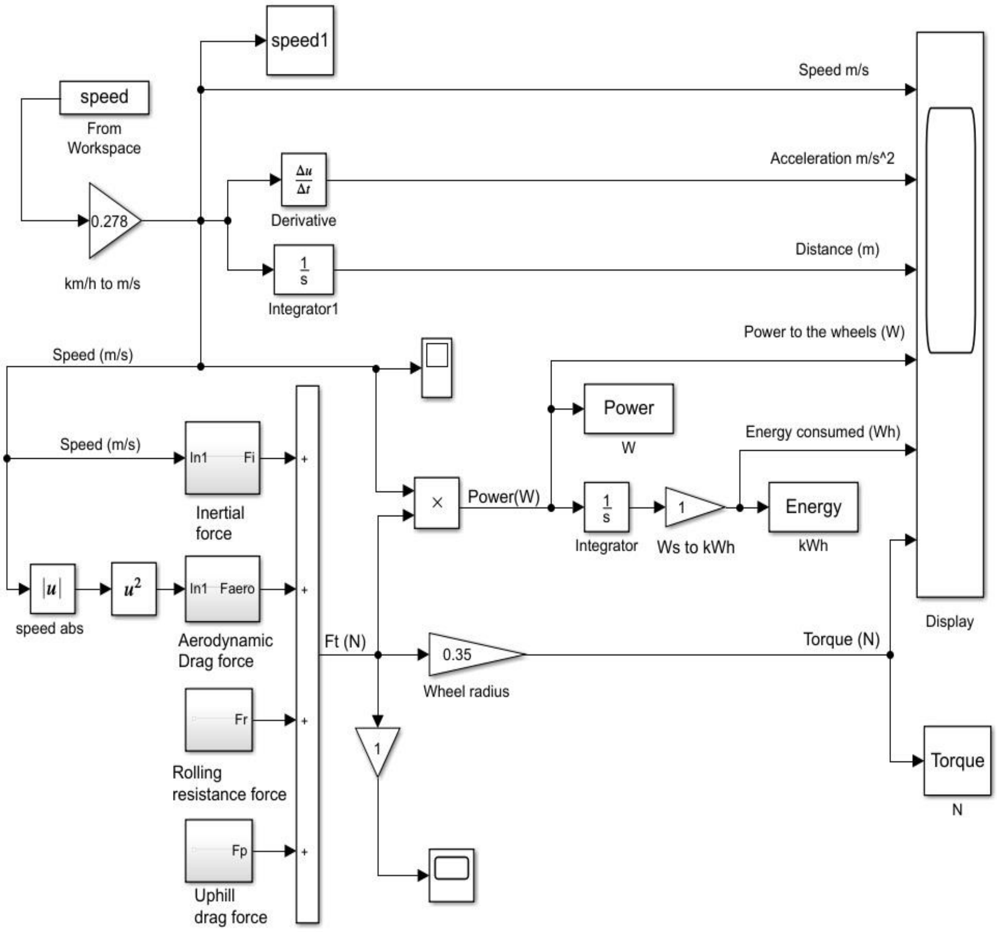

Fig. 3. Simulation block diagram on ECE+EUDC test cycles [4].

where ρ = 1.22 kg/m^3 - air density, v the instantaneous speed of the vehicle, Cd = 0.35, the air resistance coefficient, and v_0 =0 is the front wind speed;

-the uphill drag force, F_p, block "Uphill drag force",

$$F_p = m \cdot g \cdot \sin\theta \quad (11)$$

where θ is the angle of inclination of the road.

The instantaneous speed of the vehicle, v, was imported from an excel file containing the specific speeds for ECE and EUDC cycle, using the block "From Workspace ".

To obtain the energy consumption, the power to the wheels was necessary to integrate with time and block "integrate" was used. The values for energy were exported to to an excel file from workspace using block "Energy kWh". In the same way, for distance, block "integrate" was used to integrate the speed with time resulting distance.

The energy consumed by each car resulted by simulation using Matlab-Simulink is displayed in table 7.

Table 7

Energy consumed (Wh) for different types of electric cars"

	Hyundai Ioniq 5	Renault Meganne E-Tech	Volkswagen E-Up	Opel Corsa E	Hyundai Kona Electric 2021	Mazda MX-30
EUDC cycle	1802.8	1654.1	1269.1	1439.3	1710.1	1741.8
ECE-15 cycle	241.2	216.6	155.8	191.9	223.3	221.3

5. Distance traveled by electric cars using solar energy

By comparing the energy consumption of each car, with the monthly and daily solar energy produced by solar panel on the car's roof, E_{roof}, solar energy obtained with PVGIS, it is possible to estimate the distance that each model of electric car should travel using the electricity obtained with the help of solar panels.

To determine the value of the distance traveled by electric cars using solar energy, the equations 12 and 13 were used:

$$D_{EUDC} = \frac{E_{roofd} \times 6995}{E_c} \quad (12)$$

$$D_{ECE} = \frac{E_{roofd} \times 1013}{E_c} \quad (13)$$

where D_{EUDC} is the distance traveled by solar energy according on EUDC test cycle, D_{ECE} is the distance traveled by solar energy according on ECE-15 test cycle, E_{roofd} is the daily solar energy produced by solar panel on the car's roof (Wh), E_{roofm} is the monthly solar energy produced by solar panel on the car's roof , 6995 m is the total distance travelled according with EUDC extra-urban test cycle regulation and 1013m is the total distance travelled according with ECE urban test cycle regulation . In this study the urban test cycle ECE-15 was used in order to indicate the distance travelled by each car in Constanta.

Using equation 12, table 8 was created. According to the results for the distance travelled using solar energy, by each model of electric car on ECE15 urban test cycle, we can resume a daily total distance traveled using just solar energy between 1950.9 – 4269.5 m during December, the month with the lowest solar irradiation per month, and a total distance between 9104.2-14052.5 m during July, the month with the highest level of solar irradiation for the case study from Constanta.

Table 8

Distance traveled using solar energy on ECE15 test cycle D_{ECE} (m)

		Hyundai Ioniq 5	Renault Meganne E-Tech	Volkswagen E-Up	Opel Corsa E	Hyundai Kona Electric 2021	Mazda MX-30
Nr. crt.	**Month**	D_{pv}	D_{pv}	D_{pv}	D_{pv}	D_{pv}	D_{pv}
1.	January	2343.8	4812.6	3607.5	3065.1	2604.8	2820.3
2.	February	3164.9	5745.8	4876.4	4128.8	3515.8	3809.1
3.	March	4931.4	7995.9	7592.6	6436.7	5473.1	5950.7
4.	April	6929.7	10257.8	10684.8	9061.9	7696.9	8361.6
5.	May	7952.6	11073.5	12269.8	10404.3	8838.9	9598.0
6.	June	8805.7	11941.5	13589.0	11525.4	9783.7	10635.1
7.	July	9104.2	12552.0	14052.5	11902.8	10126.6	10986.0
8.	August	8711.3	12733.0	13444.3	11392.0	9687.6	10513.5
9.	September	6383.7	10101.9	9839.6	8340.5	7092.1	7705.5
10.	October	4050.8	7120.8	6271.2	5295.8	4507.2	4887.6
11.	November	2379.9	4708.0	3684.4	3114.5	2646.3	2868.6
12.	December	1950.9	4269.5	3020.2	2554.3	2180.4	2362.6

6. Conclusions

In this paper, a study was carried out on the solar energy potential of the city of Constanta, during a calendar year, in order to identify the energy available from the sun. The study was carried out using the PVGIS application, to estimate the solar energy potential in the city of Constanta. In order to perform the study, the PV panel power installed values for each type of 6 electric car were entered in the PVGIS application. According to the study, the surface of the solar panels is equal to the area of the roof of each electric car model, which determines the installed power that is input into PVGIS for simulation.

Using the PVGIS application, in Constanta, the available electrical energy obtained was between **464.5 Wh - 912.9 Wh/day** in December, and between

2161.3-2683.9 Wh/day in July. The energy values obtained differ depending on the roof surface of each car model, the variable that determines the installed electric power of the solar panels.

In the next part of the study, the 6 electric cars were subjected to ECE and EUDC tests to determine energy consumption in different operating modes. Using the solar energy obtained with the help of the PVGIS application as available energy, and as consumed energy the energy obtained after the ECE and EUDC tests, the distance traveled with the help of solar energy on the ECE and EUDC cycles was determined. The total distance resulted that can be travelled with the help of solar panels, on ECE15 urban test cycle, in Constanta, was between **1950.9 – 4269.5 m** in December, which is the month with the lowest level of solar radiation, and a distance between **9104.2-14052.5 m** in July, the month with the highest level of solar radiation. It should be mentioned that these values represent the daily average of the distance traveled with solar energy, for every month.

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