Solar Panel Size for a Single-Family House

Nuzhat Ahsan
Crescent Academy International
Canton, MI 48188, USA

Abstract

Emission of the greenhouse gases from fossil fuel is the main catalyst for global warming. Nations agreed to limit the amount of warming to 1.5º C above pre-industrial levels in the next twelve years. Motivation for this project is to study if solar energy can be used for household electricity consumption with a reasonable photovoltaic panel size which will reduce the use of fossil fuels and hence, the emission of greenhouse gases.
The project studied both, with a fixed photovoltaic (PV) panel, facing towards south and at a tilt angle of 66.55º with horizontal and with a TTDAT (Tip-Tilt Dual Axis Tracker) system to track the sun, is used to generate electricity. Generated electrical energy is calculated in watts per unit area of the PV panel. Average energy consumption per household in the USA obtained from the U.S. Energy Information Administration. Electricity use accounted for 44% of household energy consumption in 2017. Based on these data required PV system panel surface size is calculated for a single-family house.
Data from fixed PV panel and TTDAT system were used to calculate the PV-panel size. It is found that using tracking system the PV panel size can be reduced by 25% and hence the cost. This is due to the fact that tracking the sun minimizes the angle of incidence between the sun's ray and the line perpendicular to the PV panel surface and captures more solar energy.

Keywords
Solar Energy, PV Panel Size, TTDAT, Photovoltaic

1. Introduction
Recent brushfire in Australia which burned more than 72,000 square miles, wildfire and drought in California, melting of glacier and devastating flood in different parts of the world are awake up call for the scientific community of the impact of climate change. This project is to use solar energy for household electricity consumption, one way to reduce the use of fossil fuels which is largely responsible for greenhouse effects. Reduction of greenhouse gas emission will reduce the global warming and hence, the impact of greenhouse effects on the climate changes.

1.1 Objectives
Objective of this project is to calculate required size of PV-panel for a single-family house based on a south facing fixed tilt angle panel and a panel with tracking device. Also, investigate if tracking the sun, the PV system energy output increases or decreases compared to a south facing fixed tilt angle PV system.

2. Literature Review
Climate change and its effects are now pronouncing in every country on every continent. People all over the world are experiencing impact of climate change, which include changing weather pattern, rising sea level and extreme weather events. To address climate change, nations agreed (Paris Agreement) to limit the amount of warming to 1.5º C above pre-industrial levels in the next twelve years.
To achieve the goal of limiting global warming to 1.5º C requires far-reaching and unprecedented measures in a wide range of areas including energy, industry, buildings, transportation, and cities. These changes must reduce carbon dioxide emission to about 45 percent of 2010 levels by 2030 and to a neutral level of no carbon dioxide emissions by 2050.
Our project is an effort to reduce carbon-dioxide emission by using renewable energy in household energy consumptions. According to the U.S. Energy Information Administration the average energy consumption per

household is 100 Million Btu/year in the U. S. Midwest region. Electricity accounted for 44% of household energy consumption. Utilizing solar energy for household energy need would benefit like greenhouse gas emissions reduction and can in long run help mitigate the adverse effects of the climate change problem plaguing the entire earth.

3. Methods

A photovoltaic (PV) panel with a size of 6.5 cm x 6.5 cm is used to convert solar energy in to electrical energy. The PV panel was connected to a light bulb (resistor) and a multi-meter as shown in the test set up Figure 1. The multi-meter is used to read voltage and current output from the PV panel. The output data of voltage and current were collected every fifteen minutes. For the tracking PV system, a TTDAT (Tip-Tilt Dual Axis Tracking) type tracking system was used. The TTDAT system was manually adjusted towards the sun every fifteen minutes.

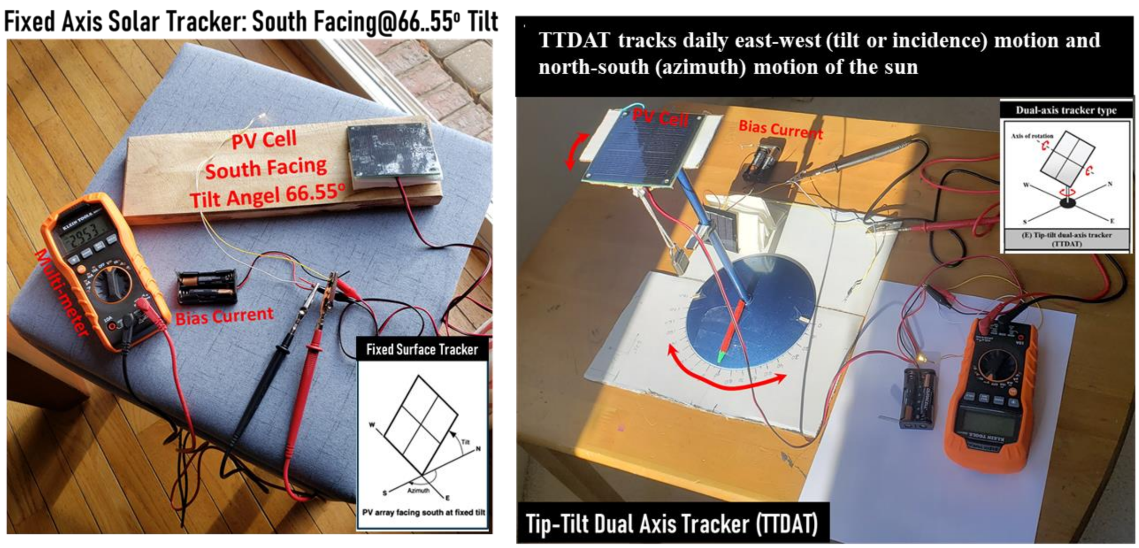

Figure 1: Test Setup for Fixed South Facing and TTDAT System Solar Panel

The altitude angle and azimuth angles were changed every fifteen minutes according to calculated values, as shown in Table-1. The sun's position at different clock time is calculated using following formulas, the angle of incidence, $\boldsymbol{\theta}$, is the angle between a beam incident on a surface and the line perpendicular to the surface at the point of incidence called the normal, *n*. The surface is inclined at β and the facing at an azimuth angle Υ, as shown in Figure 2.

Greek symbol	Definition
α_s	Solar altitude
β	Slope angle (of device)
γ	Surface azimuth angle
γ_s	Solar azimuth angle
θ_z	Zenith angle
L	Latitude Angle
δ	Declination Angle at Equatorial Plane
ω	Hour angle

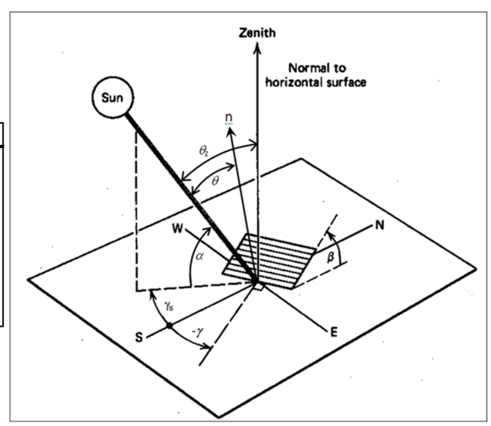

Figure 2: Solar Incident Angle and Azimuth Angle

An expression for cos θ is given by:

$\cos\theta = (\cos L \cos\beta + \sin L \sin\beta \cos\gamma)\cos\delta\cos\omega + \cos\delta\sin\omega\sin\beta\sin\gamma + (\sin L\cos\beta - \cos L\sin\beta\cos\gamma)\sin\delta$ and the solar azimuth angle Υ_s was calculated using $\sin\Upsilon_s = \cos\delta\sin\omega / \cos\alpha_s$.

Declination Angle $\delta = 23.45\sin\left(360\dfrac{284+n}{365}\right)$, where n is the day of the year

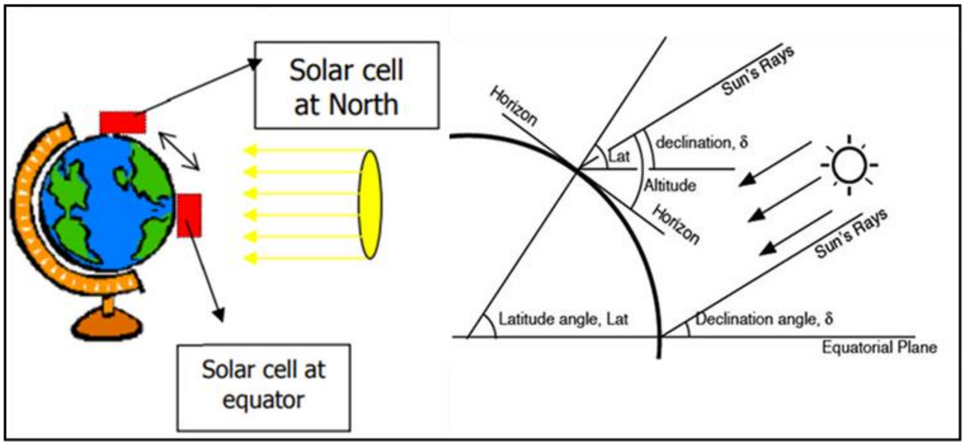

Figure 3: Solar Altitude Angle at Equator and at North of Equator

Local solar time $\quad LST = \text{Standard time} + 4(Long_{std} - Long_{loc}) + ET$

(For each degree of difference in longitude between the actual and reference, there is a 4-minute time difference)

ET is the "equation of time," which is: $ET = 9.87\sin 2B - 7.53\cos B - 1.5\sin B$ (in minutes)

$B = \dfrac{360(n-81)}{365}$ degrees, where n is the day of the year

Hour angle (degrees) $\quad \omega = \dfrac{180(LST-12)}{12}$

L = Latitude (for Detroit L = **42.3314°**)

$Long_{std}$ = The standard meridian for the local time zone (degrees): **75°** for Eastern Time Zone

$Long_{loc}$ = Local longitude (Detroit is **83.0458°** degrees west)

Table 1: Incidence and Azimuth Angle

n	20	day of the year
Latitude (φ)	42.3314	Detroit City
Clock Time	Sun's Angle of Incidence θ_z (deg)	Solar Azimuth Angle γ_s (deg)
10:00:00	72.567	-38.520
10:15:00	70.891	-35.301
10:30:00	69.344	-31.989
10:45:00	67.937	-28.580
11:00:00	66.679	-25.071
11:15:00	65.578	-21.464
11:30:00	64.644	-17.764
11:45:00	63.884	-13.980
12:00:00	63.304	-10.125
12:15:00	62.910	-6.215
12:30:00	62.705	-2.271
12:45:00	62.691	1.686
13:00:00	62.868	5.633
13:15:00	63.234	9.549
13:30:00	63.787	13.413
13:45:00	64.521	17.209
14:00:00	65.430	20.922
14:15:00	66.506	24.543
14:30:00	67.741	28.067
14:45:00	69.127	31.491
15:00:00	70.653	34.817
15:15:00	72.311	38.049
15:30:00	74.091	41.194
15:45:00	75.984	44.258
16:00:00	77.981	47.248
16:15:00	80.074	50.171
16:30:00	82.254	53.029
16:45:00	84.513	55.821
17:00:00	86.845	58.538
17:15:00	89.243	61.160
17:30:00	91.700	63.656

Using voltage and current data at different time of the electrical energy (Voltage multiplied by Current) in terms of Watts per unit area of the panel is calculated.

4. Data Collection

Tracking speed (frequency of angle change and data collection), tracking angles (altitude and azimuth angle), voltage and current were recorded. Table 2 shows collected data for a PV panel facing south zero azimuth angle) at a fixed altitude angle of 23.45 deg.

PV Cell Facing South: Azimuth Angle is Zero
PV Cell Set at Fixed Altitude Angle 23.45 deg

Panel Surface: 6.5 cm X 6.5 cm
Table 2: Collected Data and Calculations

South Facing 23.45 deg Inclination: No Sun Tracing Data Taken on January 20, 2020					
Time	Volt [V]	Current [mA]	Current [A]	Power [Watts]	Power [W/m^2]
12:15	2.703	90	0.09	0.24327	57.579
12:30	2.7	100	0.1	0.27	63.905
12:45	2.6838	80	0.08	0.214704	50.818
13:00	2.594	80	0.08	0.20752	49.117
13:15	2.588	80	0.08	0.20704	49.004
13:30	2.714	90	0.09	0.24426	57.813
13:45	2.539	90	0.09	0.22851	54.085
14:00	2.222	99	0.099	0.219978	52.066
14:15	2.289	86	0.086	0.196854	46.593
14:30	2.2	82.6	0.0826	0.18172	43.011
14:45	2.288	94	0.094	0.215072	50.905
15:00	2.133	97.4	0.0974	0.2077542	49.173
15:15	2.118	99.6	0.0996	0.2109528	49.930
15:30	2.126	99.41	0.09941	0.21134566	50.023
15:45	2.156	88	0.088	0.189728	44.906
16:00	2.145	60	0.06	0.1287	30.462
16:15	2.16	59	0.059	0.12744	30.163
			Time Average (W/m^2)		49.105

5. Results and Discussion

5.1 Numerical Results

Results are shown in Table-3, for south facing fixed PV panel and, in Table-4 for TTDAT system. Data of solar energy available per unit area of the PV panel is plotted with clock time and shown in Figure 4.

Table-3

Data Taken on January 20, 2020	
South Facing with Tilt 23.45 degrees	
Time	Power [W/m2]
12:15	57.579
12:30	63.905
12:45	50.818
13:00	49.117
13:15	49.004
13:30	57.813
13:45	54.085
14:00	52.066
14:15	46.593
14:30	43.011
14:45	50.905
15:00	49.173
15:15	49.930
15:30	50.023
15:45	44.906
16:00	30.462
16:15	30.163
Average	49.105

Table-4

Data Taken on January 20, 2020	
TTDAT Tracking	
Time	Power [W/m2]
12:15	67.968
12:30	67.749
12:45	67.470
13:00	66.758
13:15	65.130
13:30	62.646
13:45	58.280
14:00	61.527
14:15	61.577
14:30	64.620
14:45	64.589
15:00	61.635
15:15	60.005
15:30	57.643
15:45	54.972
16:00	48.834
16:15	44.515
Average	61.230

5.2 Graphical Results

Data collected with fixed angled south facing panel and with tracking system show similar trends. Data with tracking system shows a better efficiency in converting solar energy to electrical energy.

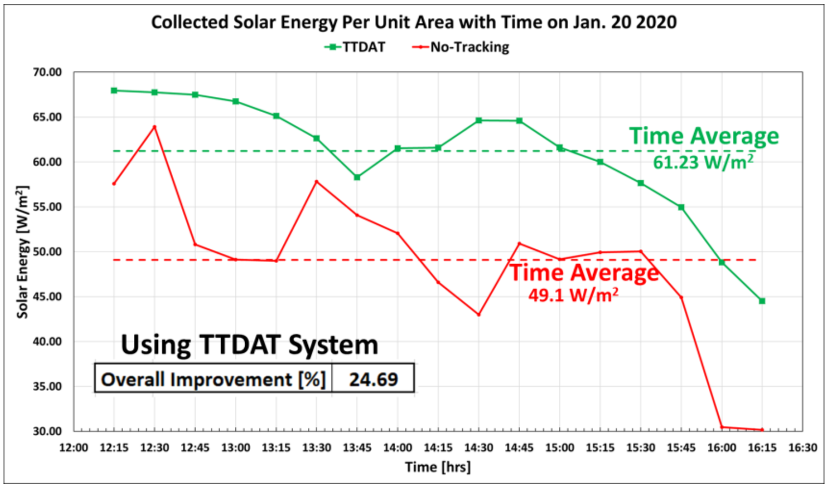

Figure 4: Comparison of Energy Collected by TTDAT and a Fixed Axis South Facing PV System with an Altitude Angle of 23.45º

Both data set show a decreasing available energy as the day passes from mid-day to sun set. The peak available energy is in the hours near the mid-day when the sun is close to the south. It is interesting that with tracking system energy output from the same size solar panel is higher than that of a fixed angled south facing panel at all times. Time averaged electrical energy is calculated over the period of time data is collected. Time averaged value of electrical energy show that tracking system converts 25% better than that of the non-tracking south facing panel.
Using this data and the data from the U. S. Energy Information Administration (USEIA) a solar panel size is calculated. The USEIA data is shown in Figure 5.

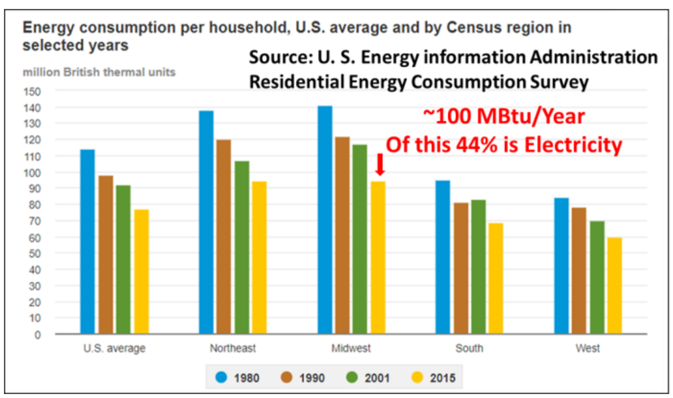

Figure 5: Energy Consumption per Household (Data source USEIA)

The USEIA data show that in 2017 the average use of household energy is 100 MBtu (MBtu is abirritation for million British thermal unit) per year in the Midwest of the U. S. A. Of that 44% is accounted for electrical energy. Based of this data household electrical energy consumption is calculated as 44,000,000 Btu per year which is equal to 120,548 Btu per day. Converting 120,548 Btu per day into kilowatts is 1.5 KW. For the fixed axis south facing PV panel time averaged available energy is 49.1 W/m^2 (Figure 4). Hence, the required panel size for a single-family house in the Midwest of region is 30 m^2 (5.5 m x 5.5 m). Similarly, using TTDAT system data (time averaged available energy 61.23 W/m^2 in Figure 4) panel size can be calculated for a single-family house. The require panel size with a tracking device is 24 m^2 (4.9 m x 4.9 m).

5.3 Proposed Improvements

The tracking device used in this study is home made and angles were adjusted manually. An improved and automatic tracking device will give more accurate results. Also, data collection was done manually. A computerized data collection system will improve data quality.

6. Conclusion

The U. S. Energy Information Administration (USEIA) data show that in the year of 2017 in the Midwest, average use of household energy is 100 MBtu per family per year. Of that, 44% is accounted for electric energy. The current study focused on the solar panel size for a single-family house to generate required electricity need. Use of solar energy for household electricity consumption, can reduce the usage of fossil fuels. Using USEIA data of average electric consumption (in average 44 MBtu per family per year) and the available energy from collected data, solar panel size was calculated. Calculations show that for a fixed angled south facing 30.0 m^2 panel (5.5 m x 5.5 m) surface area exposed to the sun will be enough for producing needed electric energy for a single-family house.

Collected data, with the TTDAT system, show that an average solar energy conversion can be improved by 25% for same size panel compared to a fixed angled south facing solar panel. Calculations show that with a TTDAT system, a panel size of 24 m^2 (4.9 m x 4.9 m) surface area exposed to the sun will be enough to produce needed electric energy for a single-family house.

The TTDAT system generates more energy, even when the sun is setting, compared to the fixed angled south facing panel. Another observation is that solar panel generates less and less energy as the sun was setting. Peak hour, near the mid-day hours, excess energy from the solar panel could be stored and stored energy can be used during night hours. In conclusion, in order to reduce fossil fuel use and greenhouse emissions requires far-reaching, unprecedented measures and lifestyle change.

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Biography

Nuzhat Ahsan was a student of Crescent Academy International in Canton, Michigan, where she did this study. This study was a part of 8th grade STEM (Science, Technology, Engineering and Mathematics) project. She is currently a high-school student. In Crescent Academy International, she was a member of Crescent honors society. In 2019, she was the winner of Middle School IEOM STEM competition in Detroit, Michigan.