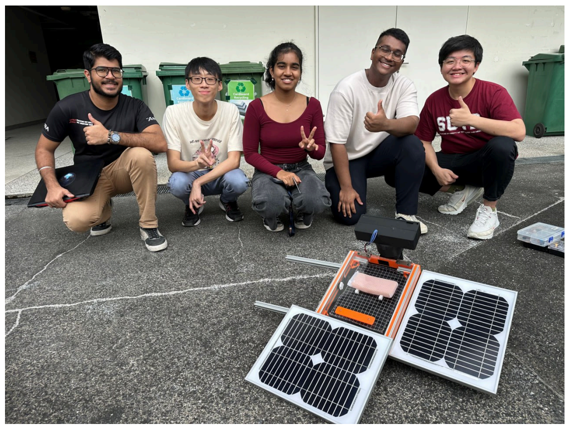
Singapore University Of Technology and Design

Design Thinking Project III



Group 7

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1. Introduction

Solar energy, a clean and sustainable resource, offers a promising solution for food preservation through dehydration. Unlike energy-intensive methods like refrigeration or heat-based dehydrators, solar-based systems leverage renewable energy but face challenges from environmental conditions, weather, design, and energy efficiency. Variations in solar irradiance further introduce uncertainties requiring careful modeling.

This report evaluates the effectiveness of a solar dehydrator by analyzing its water removal rate, offering insights into its potential for food-drying applications through data analysis, statistical modeling, and prototype testing.

2. Methods

- **Assumptions:** The GHI follows a normal distribution due to the sunrise-sunset patterns and the temperature peaks in the afternoon.
- **Data Collection**: Water removal was measured over 2 hours under controlled conditions, with solar energy inputs recorded using calibrated sensors.
    a. The mass of the sponges was weighed before and after
    b. 1 sponge was placed inside and the control is placed adjacent to the device on the floor.
    c. The device was faced south due to the sun's path travelling from Southeast-Southwest
    d. Arduino is turned on when the test is ready to begin and the SD card is taken out to analyse humidity and temperature at the end of the test.

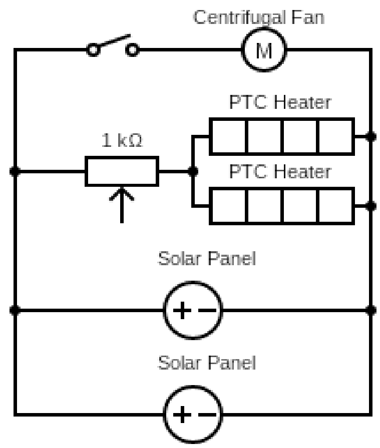


Fig.1. Electrical Schematic

- **Solar Panel Sizing:** Two 10W solar panel [*Refer to Appendix*]
- **Prototype Design Flow:**
    a. Sun→ Solar Panel → Centrifugal Fan & Heaters → Internal Drying Unit → Food(Sponge)

3. Results and Discussion

i. Effectiveness Analysis

The total solar energy value was taken over 2 separate days from Firebase with the values integrated over the intervals from 12:30 to 15:30 for the 1st test and 09:45 to 11:45 for the 2nd test. The formula for the calculation of total solar energy is as such:

$$\sum_{i=1}^{n} \frac{P_i + P_{i+1}}{2} (t_{i+1} - t_i)$$

where, *n = total data points , P_i =initial data point, P_{i+1} = following data point, t_i =initial time, and t_{i+1} = following time*

The effectiveness was assessed using the formula:

$$Effectiveness = \frac{Water\ Removed(mg)}{Total\ Solar\ Energy\ (J)}$$

Testing Parameters								Result		
Test	Weather Condition	Fan	Heater	Mass of Tested Sponge Before (mg)	Mass of Tested Sponge After (mg)	Mass of Controlled Sponge Before (mg)	Mass of Controlled Sponge After (mg)	Total Water Removed [Test](mg)	Total Solar Energy(J) [refer to Appendix]	Effectivenes s
1	Moderate Sun, Slightly Cloudy	1	1	19000	9000	18000	8000	10000	577907.4455	0.0173
2	Very Sunny, Cloudy	1	0	53000	26000	62000	45000	27000	452829.9475	0.0596

Table 1- Testing Parameters

During Test 2, the heaters were not activated due to technical issues. However, the fan alone, combined with sufficient light intensity, was able to remove water effectively, even over a shorter duration. The improved performance can be attributed to the higher initial voltage of **12.57V** compared to **4.33V** in Test 1, despite both tests experiencing relatively stable weather conditions. This higher voltage indicates increased power delivery to the fan, enhancing airflow and promoting evaporation.

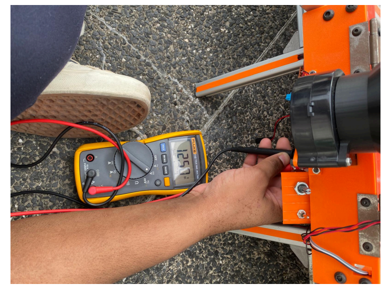


Figure 2 - Initial voltage for test 1

While effectiveness gives a preliminary understanding of performance, it does not fully capture the system's energy efficiency. To evaluate this, the efficiency of water removal was calculated as the ratio of energy used to evaporate water to the total solar energy absorbed.

Figure 3 - Initial voltage for test 2

Energy Required for Evaporation

The energy required to evaporate water (Q_{total}) is calculated using the formula:

$$Q_{total} = Q_{heating} + Q_{vaporisation}$$

$$Q_{heating} = mc\Delta T$$

$$Q_{vaporisation} = mL$$

where, m = mass of water removed(27g)

c = heat capacity of water(4.186 J/g°C)

T_f = 100°C [Evaporation Temperature]

T_i = 34.645°C [*refer to Table 6 in Appendix*]

$$Q_{heating} = 27 \times 4.186 \times (100 - 34.64509395) = 7386.542\,J$$

$$Q_{heating} = 27 \times 2260 = 61020\,J$$

$$Q_{total} = Q_{heating} + Q_{vaporisation} = 7386.542\,J + 61020\,J = 68406.542$$

$$Efficiency = \frac{Q_{total}}{Total\ Solar\ Energy}$$

$$Efficiency = \frac{68406.542}{452829.9475} = 0.151$$

Despite inactive heaters, the device achieved **15.1% efficiency**, showcasing the fan's contribution to effective water removal under strong solar irradiance. However, this shows that the device has room for improvement in regards to energy transfer, insulation and overall system design.

The foundational principle in processes like food dehydration, where increasing air temperature accelerates moisture evaporation from food. This phenomenon occurs because warm air can hold more moisture, reducing relative humidity as the temperature rises.

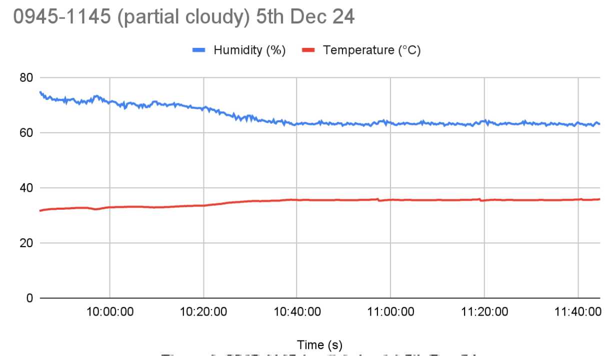


Figure 4- 0945-1145 (partial cloudy) 5th Dec 24

There was strong sunlight unblocked by clouds this particular morning. We started the measurement when we were still in the fab lab, thus the low starting temperature of 25.1°C. The first 15 minutes were sunny and hot, allowing our fan and heating element to work hard, increasing the temperature while decreasing the moisture.
However, the strong sunlight was short-lived. The clouds started building up and got darker and darker and we had to stop the experiment as it started to rain.
The cloud blocking the sun had very obvious impacts on the temperature and humidity on our setup, as the temperature went down towards ambient temperature and humidity skyrocketed with some fluctuations.

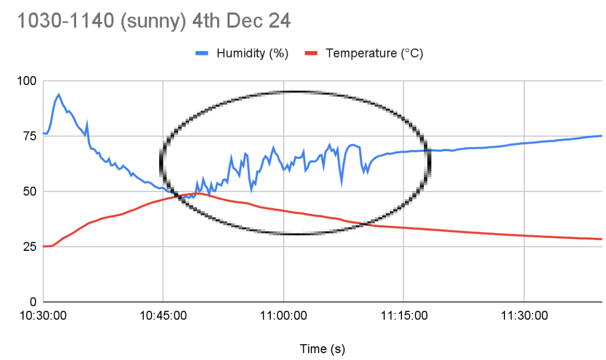


Figure 5 - 1030-1140 (sunny) 4th Dec 24

This could be explained as air from the atmosphere gets saturated with moisture as clouds form, which leads to humidity increasing which is often observed right before rainfall.
As the air vent was still open, this allowed high-humidity air to enter our setup, thus leading to an increase to humidity (as shown in the figure 5).

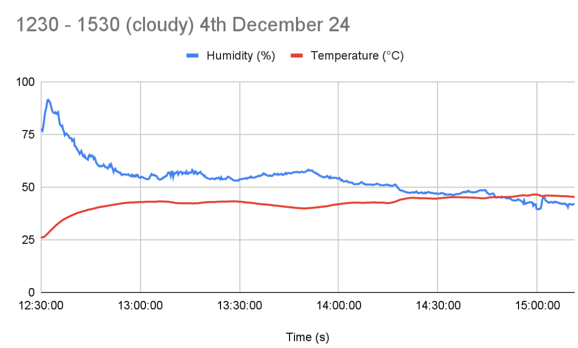


Figure 6 - 1230 - 1530 (cloudy) 4th December 24

As the temperature increases, we observe a significant drop in humidity levels (Figure 6), illustrating the inverse relationship between temperature and relative humidity. In controlled systems like a dehydrator, this relationship is essential for efficient drying. The higher the temperature retained within the system, the greater the air's capacity to absorb moisture, resulting in a steeper decline in humidity levels. Thus, the observed pattern between temperature and humidity levels aligns closely with scientific theories of evaporation and relative humidity dynamics

ii. Data Cleaning and Statistical Analysis

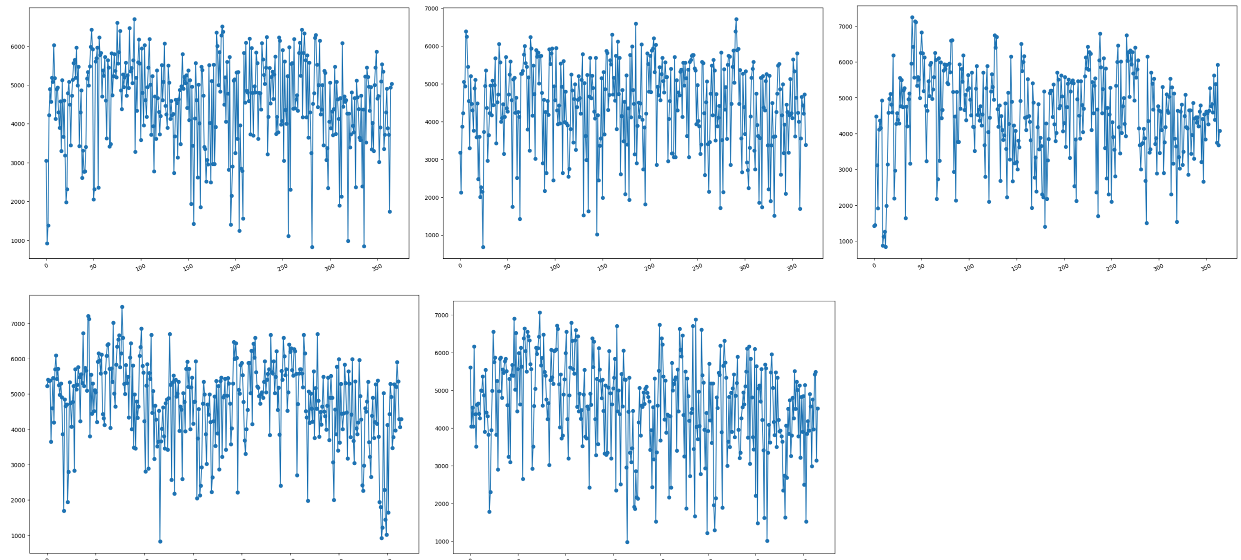


Figure 7- 2016 - 2020 Daily PSH

The above graphs show the daily PSH for the years 2016 to 2020. A general trend of a sinusoidal function can be observed within each year. However, generating a general function for each year is not sufficient as it only models for that specific year and is unable to account across the years.

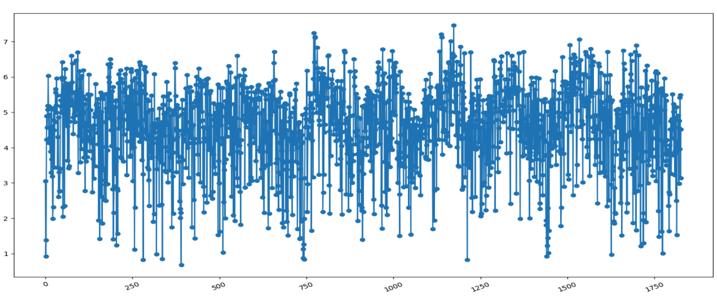


Fig. 8. Combined Daily PSH

Hence a combined graph of daily PSH from 01 January 2016 to 31 December 2020 is plotted to find a sinusoidal function that can model PSH behaviour across the years and will be able to predict beyond 2020.

A general function can be modelled in the form Y = A sin(B (x + C)) + D where A, B, C and D are various parameters that need to be found. Using extrapolation and curve fitting algorithms,
The parameters for the following sine function are Y = 0.55 sin(0.0347 x - 28.463) + 4.575.

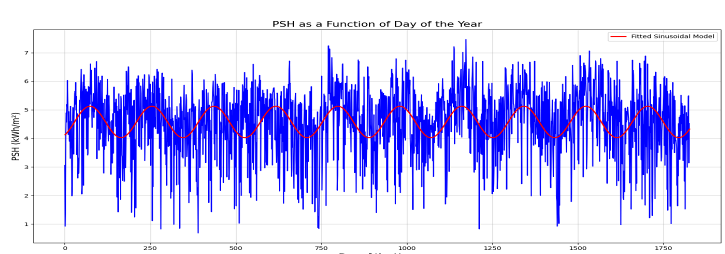


Figure 9 - Included sine function

From the historical data, the PSH distribution is skewed to the right, primarily due to weather conditions such as cloud cover and rain, which cause fluctuations in solar radiation. This is also evident in the clearsky GHI data, where the graph shows inconsistent trends throughout the year [refer to appendix]. The Q-Q plot for PSH (based on daily GHI) further confirms a non-linear relationship, indicating that GHI does not follow a normal distribution.

In contrast, the temperature data demonstrates a normal distribution, which provides valuable insight into designing our device. The predictable nature of temperature, with regular daily peaks in the afternoon due to sunrise-sunset cycles, supports our decision to implement additional heaters in the design. These heaters compensate for reduced solar power during times of inconsistent sunlight, ensuring the fan and other components function efficiently.

This approach also allows us to refine our initial assumption that 'GHI follows a normal distribution due to the sunrise-sunset patterns and the temperature peaks in the afternoon.' While the assumption holds true for temperature, the observed variability in GHI necessitates a more adaptive design. The inclusion of heaters enables the device to maintain consistent performance, even under less favorable solar conditions.

4. Material Sheet and Cost Analysis

The prototype was constructed at an estimated cost of **$327.79**, leveraging recycled materials and loaned solar panels to significantly reduce expenses to **$83.16**. The primary costs incurred were attributed to electronics, filaments, and aluminum extrusions.

Cost reduction opportunities include bulk purchasing of materials and adopting more efficient production methods, such as injection molding and manufacturing raw materials to precise specifications. This cost analysis underscores the potential scalability of the design and its feasibility for broader applications, paving the way for cost-efficient production at scale.

Figure 10- Original Design Dimension: 82 x 34 x 38.3 cm

Figure 11 -Adjusted Design Dimension (Test 2): 62 x 62 x 38.3 cm

5. Conclusion

The analysis highlights the potential of solar-powered dehydrators for efficient food drying, with effectiveness strongly influenced by solar intensity and environmental conditions. Test 2 achieved higher effectiveness (0.0596) than Test 1 (0.0173) due to stronger sunlight and higher voltage, despite the absence of additional heating. Trends in temperature and humidity align with evaporation principles, emphasizing the importance of consistent internal heating. While GHI data was skewed, the temperature followed a normal distribution, showcasing the prototype's reliability and scalability within cost constraints. Improved insulation, adaptive features, and cost reductions could further enhance practicality and scalability.

6. Appendix

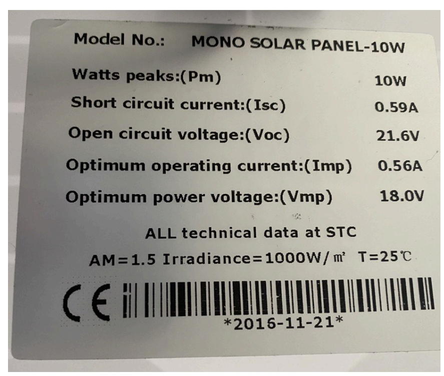
Table 1:Average Monthly Solar Irradiance Data from historical data(Data from 2016 - 2020)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
PSH	**4.236**	**5.068**	**5.204**	**5.737**	**4.506**	**4.168**	**4.621**	**4.915**	**4.721**	**4.485**	**3.031**	**4.194**
Lower Confidence Interval	**4.181**	**5.013**	**5.155**	**4.700**	**4.473**	**4.130**	**4.586**	**4.881**	**4.667**	**4.475**	**4.011**	**4.161**

**** Google sheet explaining the math and calculation done**
https://docs.google.com/spreadsheets/d/1w8zL5_j3NzJ993KDqp-7sLpfH_MqULZABs25jpO6nFg/edit?usp=sharing

Decide on an A:L: 1.1
A:L (array-to-load ratio): The average daily photovoltaic ampere-hours (Ah) available to charge the battery for standalone system divided by the average daily load in ampere hours.
Typical values used for A:L are as follows:

• For non-critical loads and areas with high and consistent solar radiation, an A:L of 1.1 to 1.2 is typical.
• For critical loads or areas with low solar irradiance, an A:L of 1.3 to 1.4 or higher is typical.



SM Solar, 10 Wp

- Current at maximum power (Imp):0.56 A
- Short circuit current (Isc):0.59 A
- Open circuit voltage (Voc): 21.6 V
- Voltage at maximum power (Vmp): 18.0 V
- Maximum power (Pmax): 10 W

Total Load

Centrifugal Fan: 0.36A x 2 hrs = 0.72 Ah

PTC Heaters: $\frac{3W}{12v}$ x 2 x 2 hrs = 1 Ah

Solar sizing

Daily photovoltaic ampere-hours needed: *(1+0.72) x 1.1* = ***1.892*** Ah/day.
(this converts the percentage to a decimal) and subtract from 1: 0.70
Shunt, series, and PWM controller calculations:
Daily photovoltaic ampere-hours per chosen solar panel *0.7 x 4.011 x 0.56* = ***1.572*** Ah/day
Number of panels required *1.892 / 1.572* = ***1.203***
Actual number of panels required: ***2***

Table 1: Material list with price points.

Part	Qty	Material	Function	Dimension(cm)	Price $GD
Solar Panel	2	-	To transform solar energy into electrical energy for fan and heater	34 x 28 x 1.7	$103.48
Centrifugal Fan	1	-	To push airflow into the device	7.5 x 7.5 x 3	$10
Heaters	2	-	To further heat the air trapped within the 'solar capsule'	5 × 1.5 × 0.35	$10.40
Heatsink	2	Metal	To dissipate the heat from the heaters	6 x 4.5 x 2.3	$5.6
-	-	PLA weight (gm)	3d-printed parts	-	**$15/kg**
Front Vent	1	PLA (173)	To allow hot air to be either trapped in the device or allow airflow to go through	25.4 x 6.4 x 2	$2.60*
Back Cover	1	PLA (51)	Placed at the back to secure the fan and prevent air from flowing back out	25.4 x 6.4 x 1	$0.77*
Fan Holder	1	PLA(228)	Attach onto the back cover and hold the fan in place	9.65 x 6 x 1.1	$3.42*
Solar Capsule	1	PLA(9.92)	Attached to the fan to trap hot air in - have vents integrated as well	20 x 9.4 x 15.5	$0.15*
Trunking	12	PLA (15*12)	Prevent air leaks through the aluminum profile	20 x 1	$2.70*
End Cap	2	PLA (1*2)	Prevent air leaks through the shorter aluminum cover	2 x 2 x 0.5	$0.03*
Handle	1	PLA (18)	To facilitate the easier opening of the lid	12.8 x 2 x 1	$0.27*
L-Bracket	4	PLA (4*4)	To connect the four corners of the bed	24 x 20 x 24	$0.24*
Solar Panel Holder	2	PLA (52*2)	To prop up the solar panel	19.5 x 11 x 0.5	$1.56*
Base	1	Wood	The foundation of the device	30 x 25 x 2	$17.52
Base Plate	1	Metal	Sprayed black to absorb more heat and release in the device	30 x 25 x 0.3	$20.75
Mesh	1	Metal	To suspend and hold the food(sponge)	16 x 23 x 0.3	$5
Lid	1	Acrylic	To cover the device	30 x 25 x 0.4	$68.88
Hinge	2	Metal	To allow the lid to open and close	5 x 5 x 0.45	$1
Screws	16 x M6 12 x M5 12 x M4 4 x M3	Metal	Tighten and connect parts	-	$20.60 (880 pieces)
T-Nut	8	Metal	To connect parts to the aluminium profile	-	$2.65
Aluminium Profile 2020	2	Aluminium	Provide structural support and pillars for connecting parts	15 x 2 x 2	$35.75
	4			25 x 2 x 2	
	6			30 x 2 x 2	
Aluminium Profile 2040	2	Aluminum	Provide structural support and pillars for connecting parts	35 x 2 x 4	$26.16

**PLA price: weight(g)* x 0.015

Table 2: Solar Irradiance, Total Solar Energy for Test 1 from 12.30 to 3.30

Timestamps(s)	Date & Time	Solar Power Intensity (W/m^2)	Solar Energy per Unit Area (Wh/m^2)
1733286581	2024-12-04 12:29:41+08:00	482.65	72.50624
1733287132	2024-12-04 12:38:52+08:00	464.8	66.05113
1733287683	2024-12-04 12:48:03+08:00	398.3	62.11377
1733288234	2024-12-04 12:57:14+08:00	413.35	66.64039
1733288785	2024-12-04 13:06:25+08:00	457.45	57.88178
1733289336	2024-12-04 13:15:36+08:00	298.9	59.75783
1733289888	2024-12-04 13:24:48+08:00	480.55	70.28311
1733290439	2024-12-04 13:33:59+08:00	437.85	52.49806
1733290990	2024-12-04 13:43:10+08:00	248.15	38.89142
1733291541	2024-12-04 13:52:21+08:00	260.05	47.94465
1733292092	2024-12-04 14:01:32+08:00	366.45	51.61416
1733292643	2024-12-04 14:10:43+08:00	308	63.62183
1733293195	2024-12-04 14:19:55+08:00	521.85	67.06894
1733293746	2024-12-04 14:29:06+08:00	354.55	56.51576
1733294297	2024-12-04 14:38:17+08:00	383.95	47.46253
1733294848	2024-12-04 14:47:28+08:00	236.25	52.92661
1733295399	2024-12-04 14:56:39+08:00	455.35	63.9887
1733295950	2024-12-04 15:05:50+08:00	380.8	52.71233
1733296501	2024-12-04 15:15:01+08:00	308	47.30717
1733297053	2024-12-04 15:24:13+08:00	309.05	48.85533
1733297604	2024-12-04 15:33:24+08:00	329.35	
Area(m^2)	0.14		
Total Solar Energy Accumulated(Wh/m^2)	1146.642		
Energy Density (J/m^2)	4127910		
Total Solar Energy (J)	577907.4		

Table 3: Solar Irradiance, Total Solar Energy for Test 2 from 9.45 to 11.45

Timestamps(s)	Date & Time	Solar Power Density (W/m^2)	Solar Energy per Unit Area (Wh/m^2)
1733362723	2024-12-05 09:38:43+08:00	207.2	34.79335
1733363274	2024-12-05 09:47:54+08:00	247.45	35.83796
1733363825	2024-12-05 09:57:05+08:00	220.85	35.48976
1733364376	2024-12-05 10:06:16+08:00	242.9	41.35561
1733364927	2024-12-05 10:15:27+08:00	297.5	52.0835
1733365479	2024-12-05 10:24:39+08:00	381.85	57.45323
1733366030	2024-12-05 10:33:50+08:00	368.9	56.67647
1733366581	2024-12-05 10:43:01+08:00	371.7	60.31919
1733367132	2024-12-05 10:52:12+08:00	416.5	63.10481
1733367683	2024-12-05 11:01:23+08:00	408.1	63.72085
1733368234	2024-12-05 11:10:34+08:00	424.55	68.24747
1733368785	2024-12-05 11:19:45+08:00	467.25	113.5318
1733369337	2024-12-05 11:28:57+08:00	1013.6	132.0487
1733369888	2024-12-05 11:38:08+08:00	711.9	83.8094
1733370439	2024-12-05 11:47:19+08:00	383.25	
Area(m^2)	0.14		
Total Solar Energy Accumulated(Wh/m^2)	898.4721181		
Energy Density (J/m^2)	3234499.625		

Total Solar Energy (J)	452829.9475		

Data for 'Results and Analysis':

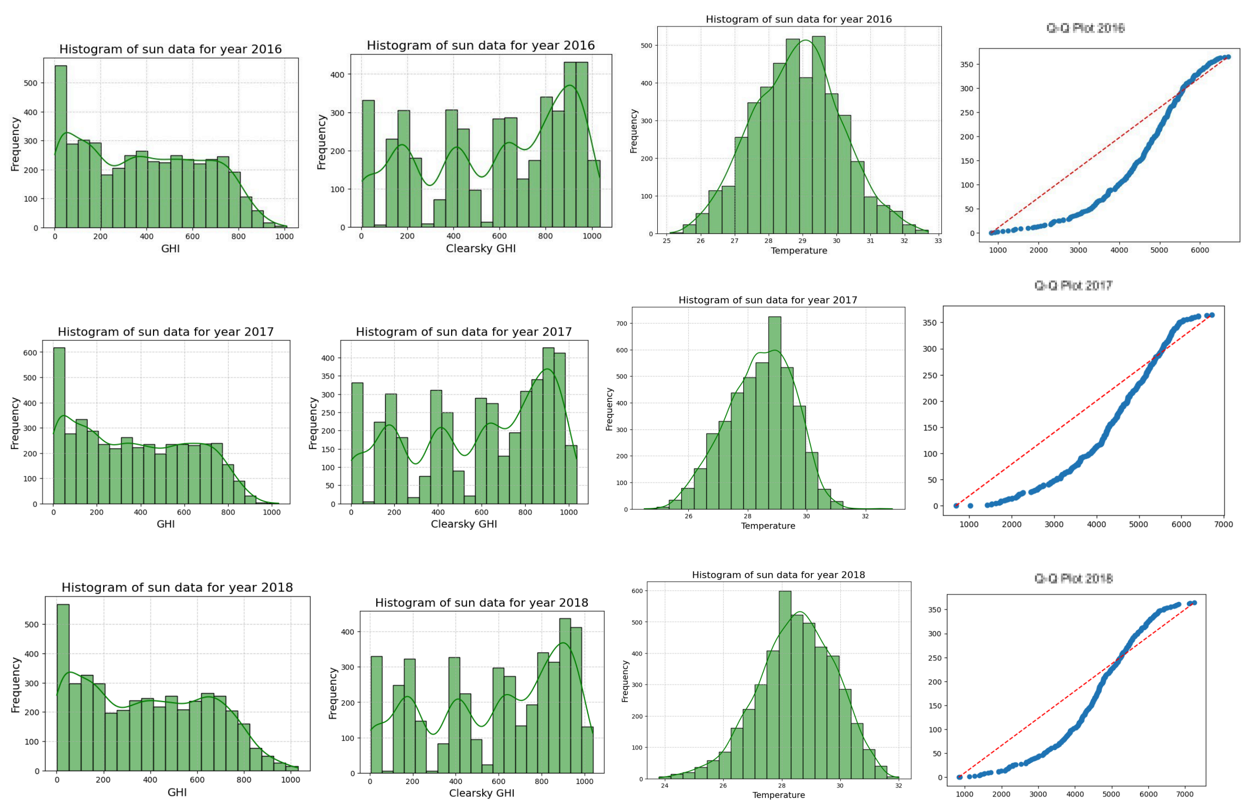
https://tinyurl.com/DTP3Solar

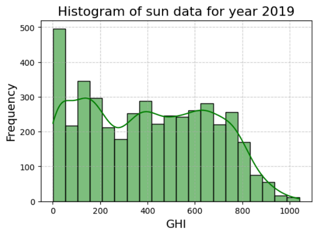
For reference:

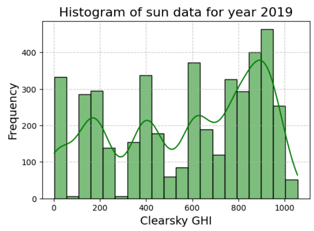
Table 4: Humidity and Temperature Measurement from Arduino for Blank Test 10:30 - 11:40

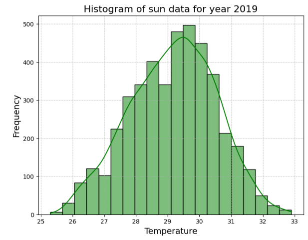
Table 5: Humidity and Temperature Measurement from Arduino for Test 1 12:30 - 15:30

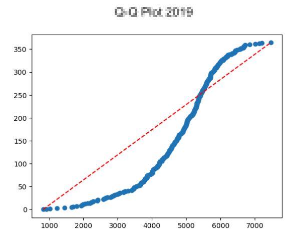
Table 6: Humidity and Temperature Measurement from Arduino for Test 2 9:45- 11:45

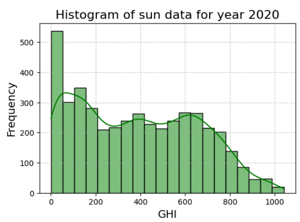


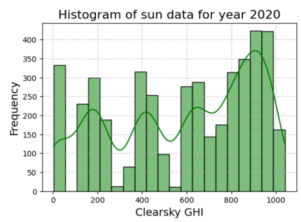

Histogram of sun data for year 2019
Frequency
GHI

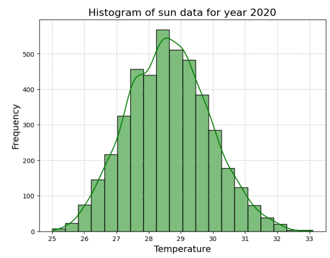

Histogram of sun data for year 2019
Frequency
Clearsky GHI

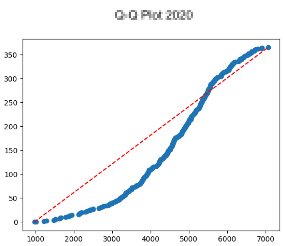

Histogram of sun data for year 2019
Frequency
Temperature


Q-Q Plot 2019


Histogram of sun data for year 2020
Frequency
GHI


Histogram of sun data for year 2020
Frequency
Clearsky GHI


Histogram of sun data for year 2020
Frequency
Temperature


Q-Q Plot 2020