01.020 DTP III
Modelling Uncertainty and Designing Energy Systems Report

SC03 Group 5
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Name	Peer Contribution
Caleb Ong	Mainly helped in building, fabricating for the product, as well as doing data analysis and editing the report.
Sylvia Goh	Assisted in the building of the product and testing of product
Titus Tsang	Helped in doing the CAD (computer aided design) for our products, 3D printing and fabricating of the device.
Utkarsh Raj	Helped in coming up with ideas for the product and doing cost analysis / editing report
Kenneth Koh	Mainly helped in data analysis, writing up the report, doing the hypothesis test and prototyping

1. Introduction

1.1 Problem Statement

In the food supply chain, waste is estimated to be about 30-40% of the total food production (USDA, n.d.). In 2020, Singapore wasted 665,000 tons of food (CNA, 2021). This is equivalent to about 1.5 bowls of rice wasted per person each day (or about 46,000 double decker buses for the Americans). To mitigate this, we will explore and evaluate building a solar-powered food dehydrator suitable for use in Singapore.

1.2 Definition of Product Specifications

The required specifications for our solar-powered food dehydrator are as follows:

1. The dehydrator has to work for at least 90% of all sunlit hours.
2. The dehydrator should be as small as possible yet be at least (3L) in size.
3. The dehydrator has to work as a standalone PV system with no battery or charge controller (only PV-cell and load).
4. The dehydrator utilises the pre-existing SM 10W Solar Panel provided as shown in **Figure 19**.

2. Design Process and Data Collection

2.1 Data Manipulation and Cleaning

- We will use historical sunlight data to predict **solar insolation (energy)** and hence specify solar panels we need for our requirements.
- We obtained the data from the National Solar Radiation Database (NSRDB), a service provided by the National Renewable Energy Laboratory (NREL), part of the U.S. Department of Energy. The dataset provides the hourly Global Horizontal Irradiance (GHI), a measure of the **solar irradiance (power)** at the designated location, from 1 Jan 2016 to 31 Dec 2020.
- The dataset provides GHI values with their respective hours. At hour 0 and from hours 11 to 23, the GHI was > 0, the GHI values were 0. This suggests that the timings are at UTC time. We thus converted the hours to UTC+8, Singapore's time zone.

2.2 Assumptions

1. We assume that the GHI values obtained from NREL, which represent the solar irradiance at SUTD (1.340299, 103.962987), can be approximately used to model the solar irradiance across all of Singapore, where we are designing the dehydrator to be used.
2. We assume that the GHI provided for each hour is representative of the solar power for the whole hour (i.e. solar irradiance GHI of $100\ W/m^2$ at hour 10 $\equiv$ $100\ Wh/m^2$ of insolation at hour 10).

2.3 General Trends & Observations from GHI Data (Refer to appendix for figures)

We aggregated the data by hour and month to understand and obtain general trends regarding our data.

2.3.1 Observations based on Aggregated Hourly GHI Data

We plotted a comparative box plot (**Figure 4**) of the aggregated hourly GHI data (GHI for each hour for all 5 years).

- We observed that there is generally significant incident irradiation in the 11 hours from 0800h – 1900h. **We thus restrict our dehydrator's operation hours and subsequent data analyses to this period**.
- We observed that the mean GHI in the 1st half of the day (0800h – 1300h) is lower than that of the 2nd half (1300h – 1900h).
- **We also observed that there is significant variance in the hourly GHI, as shown by the long whiskers in the plots.**

With the same data, we computed the 5-number summary, interquartile range (IQR) and mean (**Figure 5**) for 0800h – 1900h.

- We observed that the 2nd half of the day has **a consistently larger IQR** than the 1st. This greater variance in GHI in the 2nd half of the day can perhaps be attributed to the greater chance of adverse weather events in the afternoon, due to the monsoon seasons or development of cumulus clouds. (National Environmental Agency, 2009).
- **We see the merits in adding batteries and charge controllers to our dehydrator, which can help mitigate the large GHI variances.**

2.3.2 Observations based on Aggregated Monthly GHI Data

We plotted a comparative box plot (**Figure 7**) of the aggregated monthly GHI data (mean GHI for each month for each year).

- We observed that the GHI is higher on average in the periods of February to May and August to October, peaking in March and August.
- We observe that for the 5 years, GHI is most consistent (least variance) for the months of June, November and December.
- We observe that over the years, the GHI range ($GHI_{max\_month} - GHI_{min\_month}$) GHI has an upward trend, with the years 2019 and 2020 having comparatively greater ranges. **This corroborates with our understanding that climate change has brought about more erratic weather patterns, leading to a greater range of GHI.**

2.4 Further Mathematical Interpretation of GHI Data for Solar Insolation

To predict solar insolation (energy), we will sum up our GHI (power) data and further aggregate it for further manipulation and analysis.

2.4.1 Defining Variables and Terms

$\boldsymbol{A_{h,d,m,y}\ (W/m^2)}$: GHI during hour h of day d of month m of year y. It refers to the raw data from the NSRDB dataset.
$\boldsymbol{B_{h,d,m,y}\ (Wh/m^2)}$: incident solar energy during hour h of day d of month m of year y
$\boldsymbol{C_{d,w,y}\ (Wh/m^2)}$: the incident solar energy during day d of month m of year y.
$\boldsymbol{D_{w,y}\ (Wh/m^2)}$: incident solar energy during week w of year y.
$\boldsymbol{E_{m,y}\ (Wh/m^2)}$: incident solar energy during month m of year y.

$$B = A \times 1h\,, \qquad C_{d,m,y} = \sum_{h=1}^{h=24} B_{h,d,m,y}\,, \qquad D_{w,y} = \sum_{all\ days\ of\ week\ w} C_{d,m,y}\,, \qquad E_{m,y} = \sum_{all\ days\ of\ month\ m} C_{d,m,y}$$

2.4.1 Calculating Confidence Intervals for Mean Solar Insolation

To determine the technical requirements for our device, we need to analyze the average daily solar energy generated by our solar panels. This involves estimating the range which our true mean insolation (energy) is likely to fall in. However, simply applying confidence intervals to approximate this range is not feasible as the **underlying weather data is unlikely to be independent**. The *weather conditions* for each day are likely to affect the next day, thus $C_{d,m,y}$ are less likely to be independently and identically distributed (i.i.d.). Thus, we can instead obtain the sample daily mean of our data on a weekly $\overline{D_{w,y}}$ and monthly basis $\overline{E_{m,y}}$, This is shown below:

$$\overline{D_{w,y}} = \frac{D_{w,y}}{number\ of\ days\ in\ week,\ n_1}, \qquad \overline{E_{m,y}} = \frac{E_{m,y}}{number\ of\ days\ in\ month, n_2}$$

The sample daily mean insolation on a weekly/monthly basis are more likely independently and identically distributed (i.i.d) as:

1. Independence as weather patterns and solar irradiance in a week/month are unlikely to affect another week/month
2. GHI mean weekly/monthly values are drawn from the same underlying distribution of the same historical weather data.

We thus plot the QQ-plots corresponding to the variables shown above.

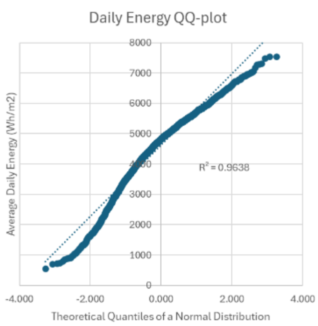


Figure 1: QQ-plot for $\boldsymbol{C_{d,m,y}}$

No. of data points = 1827

R^2 = 0.9638

$\bar{c} \approx 4618,\ s_x \approx 1195.64$

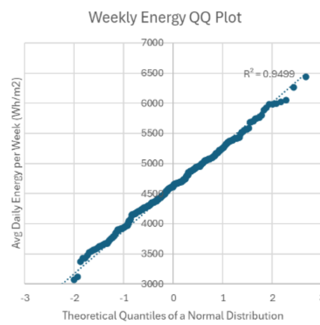


Figure 2: QQ-plot for $\overline{\boldsymbol{D_{w,y}}}$

No. of data points = 265

R^2=0.9499

$\bar{d} \approx 4596, s_x \approx 717.19$

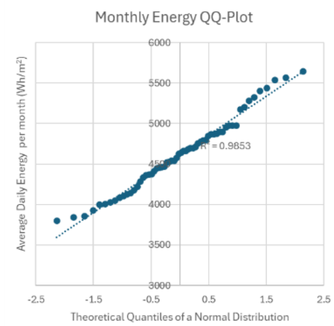
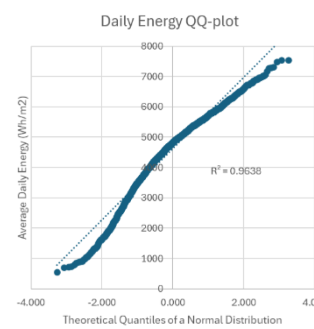


Figure 3: QQ-plot for $\overline{\boldsymbol{E_{m,y}}}$

No. of data points = 60

R^2 = 0.9853

$\bar{e} \approx 4620,\ s_x \approx 458.51$



After plotting all 3 QQ-plots, we observe that $\boldsymbol{C_{d,m,y}}$ is not normally distributed as seen in its QQ-plot in

Figure 1. The QQ-plot in Figure 3 does not show a reliable normal distribution. By observation, the QQ-plot in Figure 2 shows us $\overline{D_{w,y}}$ is fairly normally distributed.

We can now determine the range of values which our device's solar panels can gather. Although the QQ-plots for both monthly and weekly samples have similar R^2, we will use the weekly sample $\overline{D_{w,y}}$, as it has a larger number of data points. To recap, $\overline{D_{w,y}}$ gives us the average total energy for a given day in the week w. From our sample data, the sample mean $\bar{d} = 4596\frac{Wh}{m^2}$. We can also construct a one-sided lower confidence interval (CI) of 95% $\left[\bar{d} - t_{0.05,265}\frac{s_x}{\sqrt{n}}, \infty\right) = \left[4596 - 1.6506 \cdot \frac{717.19}{\sqrt{265}}, \infty\right) \approx [4523, \infty)$.

Hence, we are 95% confident that our actual daily mean insolation is likely contained within the range where daily solar insolation ≥ 4523 Wh/m².

2.4 Determining the amount of energy generated for a single solar panel using $\overline{\boldsymbol{D_{w,y}}}$

We would like $\bar{x}\ Wh$ to represent the ***daily*** output energy for a single solar panel with an area of 0.0696m², and a solar panel efficiency of 0.14. We thus apply the correction factor of $0.0696 \times 0.14 = 0.009744$ to $\overline{\boldsymbol{D_{w,y}}}$.

$$E(\bar{x}) = 0.009744\,\bar{d} = 44.78, \qquad Var(\bar{x}) = Var\left(0.009744\,\overline{\boldsymbol{D_{w,y}}}\right) = 0.009744^2(717.19^2) = 48.84$$

2.5 Will our device work? Deciding on our Device's Power and Energy Requirements

Based on the previous energy requirement, we formulate a hypothesis that our prototype should be able to support 2 fans – 1.8W and 2.4W. This translates to a power requirement of 4.2 Watts, an hourly energy requirement of 4.2 Watt-hours and a daily energy requirement of 46.2 Watt-hours (for 11 working hours per day).

2.5.2 Hypothesis Testing via energy requirements

We thus set up the null and alternative hypothesis as follows, where μ_0 represents the daily energy output.

$$\boldsymbol{H_0}: Our\ prototype\ does\ not\ work, i.e\ \mu_0 < 46.2, \qquad \boldsymbol{H_1}: Our\ prototype\ works, i.e\ \mu_0 \geq 46.2$$

Using the data gathered earlier, which represents a sample of daily mean solar energy $\bar{x}$ for a single solar panel, we can conduct a hypothesis testing at 1% significance level (i.e. $\alpha = 0.01$) to determine the threshold which indicates that our device will not work. We have used the student's T-Distribution here since we have a lack of data about population variance.

$$\bar{x} > \mu_0 + t_{0.01,239}\frac{s_x}{\sqrt{n}} \Rightarrow \bar{x} > 46.2 + 2.340\frac{\sqrt{48.84}}{\sqrt{265}} \Rightarrow \bar{x} > 47.2$$

Since our sample mean $E(\bar{x})$ for a single solar panel is 44.78 < 47.2, we do not reject the null hypothesis that our device fails to work at 1% significance level. **We can conclude from here that we will need to install 2 solar panels of this size for our device to work!**

2.6 Determining the days for which our device is likely to underperform

Since we would like our device to work > 90% of all the days (from 8am to 7pm), hence $p_0 = 0.1$ and null and alternative hypothesis are as follows:

$$\boldsymbol{H_0}: The\ device\ fails\ at\ least\ 10\%\ of\ the\ time\ p \geq 0.1, \qquad \boldsymbol{H_1}: The\ device\ fails\ less\ than\ 10\%\ of\ the\ time, p < 0.1$$

Since $np_0 = 265(0.1) \geq 10$, and $nq_0 = 265(0.9) \geq 10$, the large sample z-test can be used (chapter 9.3 of Textbook). Our aim is to determine the sample proportion of days $\hat{p} = \frac{\#\ of\ days\ with\ insufficient\ sunlight}{Total\ \#\ of\ days\ in\ sample,\ n}$ with insufficient sunlight to power the food dehydrator. This estimator $\hat{p}$ is approximately normally distributed, since n in our sample is large. Hence, the test statistic is:

$$Z = \frac{\hat{p} - p_0}{\sqrt{p_0(1-p_0)/n.}} = \frac{\hat{p} - 0.1}{\sqrt{\frac{0.1(1-0.1)}{265}}} \leq -z_{0.01}, where - z_{0.01} \approx 2.33$$

- where p_0 is the threshold proportion of days with insufficient sunlight, and n is the sample size.

Solving for $\hat{p}$ we get $\hat{p} \leq 0.143$. This works out to approximately 52 days in a year, if our sample size is 365, which is more than our 10% requirement.

We can also verify this by comparing with our 5 years historical data with respect to our estimator of proportion, $\hat{p}$.

- Our energy requirement is 46.2 Wh. Using Excel's COUNTIF function of our 5 years historical data, we obtain 866 days where average energy output for 11hours is less than 46.2 Wh, $p_1 = \frac{866}{365\times5} \approx 0.47$. Since $p_1 > \hat{p}$, our device will likely fail > 10% of the time, with only 1 solar panel.
- Instead, if we were to have 2 solar panels, each panel only needs to provide $\frac{46.2}{2} = 23.1\ Wh$. Using similar steps described earlier, $p_2 = \frac{107}{365\times5} \approx 0.058\ or\ 5.8\%$. Hence with two solar panels, as $p < \hat{p}$, our device will fail to work < 10% of the time.

This supports our conclusion to use *at least 2 solar panels* to power our desired load.

2.7 Finalizing the Specifications of our Food Dryer

With two solar panels, the effective area of our solar panels is $0.0696m^2 \times 2 = 0.1392m^2$. Hence the power requirements in GHI are thus $\frac{4.2W}{0.1392m^2\times0.14} \approx 215\frac{W}{m^2}$. Our **specifications** for the device based on our analysis and DES requirements can thus be summarized in the table below:

Dimensions	< 75 cm by 75cm
Solar Panels	2x 10-Watt Panels with a total effective area of $0.1392m^2$
Minimum Power Requirements	~ 4.2 Watts
Drying Area	200 mm (length) * 130 mm (width)* 90mm (height)
Expected GHI (Power)	215 W/m^2
Expected Working Duration	> 90% of all days from 8am to 7pm.

3. Results and Discussion

3.1 Cost Analysis

Referring to Table 2 in the appendix, we have broken down all the relevant costs which would go into making a single food dryer, assuming all items are bought. Maintenance costs for the food dryer is likely to minimal, as End-of-Life (EOL) lifespan of a solar panel is > 25 years (Sunollo, 2024), while a fan has an EOL lifespan of approximately > 3.5 years (NMB, 2011).

Therefore, the total cost of production of one such food dryer is S$118 which is constant due to no running charges. This initial cost can be contrasted with the losses incurred by food waste for a single household. Currently, the average Singaporean household throws away S$258 worth of food yearly (Jin, 2019).

Hence, this works out to a daily average of $= \frac{S\$258}{365\ days} \approx S\$0.71/day$

The breakeven point for our product will occur for the household after 167 days of use (**Figure 16**), which can be within ~1 year of purchase. However, an important point to note is that this calculation assumes that our product will be able to fully mitigate all losses from food waste.

3.2 Design Considerations

We made our design after several fluid and thermodynamic design considerations. As can be seen from the schematic diagram, the glass panel is tilted at 12° to maximize the area for collection of direct sunlight for heating. This is because the power transferred follows the formula:

$$Power\ (W) = Area \cdot I_{sun}\ = Area\ I_{sun} cos\theta$$

Tilting the solar PV at 12° makes it perpendicular to the sunlight in Singapore (area vector becomes 0° and hence cos (0°) = 1, leading to maximum power). This design consideration is reflected in our design for both the food dryer as well as the solar PV stand, as shown in **Figure 10** and **Figure 11**.

Moreover, the interior of the chamber is covered in metal sheets to accelerate the heating process. The black color of the box will absorb more heat, the glass will keep it trapped leading to high temperature inside and reduce heat loss to the surroundings. This affects the rate of evaporation as described by the relationship below:

$$E = k \cdot A \cdot (e_s - e_a) \cdot f(u)$$

where:

- k : Empirical Coefficient ($0.001 ms^{-1} at\ sea\ level$),
- A : Surface Area,
- e_s: Saturation vapor pressure at the water surface temperature (Pa) $= 6.11 \cdot e^{\frac{17.27T}{T+237.3}}$
- e_a: Actual vapor pressure of the surrounding air (Pa) $= RHe_s$, where RH is the relative humidity
- $f(u)$: $Wind\ Function\ (1 + 0.5u), where\ u\ is\ the\ wind\ speed$

Higher temperature, T, surface area, A and wind speed, u lead to faster evaporation, *which increases the mass of moist air carried out of the open system*. This is illustrated in **Figure 18: Open Energy System (assume minimal heat loss to surroundings)** at the end of the report. Additionally, the lower fan sucks in colder air at higher pressure. As the air heats up in the chamber and takes away the moisture from the food, it rises due to lower pressure and is ejected by the higher fan creating an efficient forced convection.

Lastly, we optimized our prototype to fit the physical dimensions of the specifications using computer aided modelling software SolidWorks. The final dimensions are shown in **Figure 10**.

3.3 Effectiveness of our Prototype

In our test runs, we used 50 grams of water for our sponges, measuring with a digital mass balance. One sponge is placed inside the enclosure, while the other sponge is used as a control for our experimental runs, located outdoors, next to our setup as shown in **Figure 17**. After a specified period, we will then revisit the setup and measure the mass of the sponges.

The DHT11 Sensors were left running inside the chamber to record the ambient humidity and temperature. The data gathered was then calibrated to the time when our experiment was started. Based on Error! Reference source not found., Error! Reference source not found. and **Figure 14** we can conclude that our device is generally able to remove moisture, as well as trap heat in the device, which occurred in sunny conditions. We can see that the chamber can heat up to as high as 38°C under direct sunlight and the relative humidity can be decreased to as low as around 50%. However, this effectiveness varies on the climatic conditions, as can be seen from **Figure 15**, where strong cloud cover combined with our experiment occurring during the sunset hours of the day led to inconsistent trends.

A summary of the completed experimental runs is detailed in **Table 1** of the Annex,

- To approximate the GHI during our time of testing, we decided to average the solar intensity based on the corresponding duration of time when our experiment occurred. This solar intensity data was taken from the sensor provided at Fab Lab
- To approximate total solar energy used for our device, we summed the incident solar energy on the sponge and the solar energy used to power the fan from the solar panels.

$$Fan\ Energy(J) = \ GHI\left(\frac{W}{m^2}\right) \times solar\ PV\ Area(m^2) \times PV\ Efficiency \times (End - Start\ Time(s))$$

$$Solar\ Energy(J) = GHI\left(\frac{W}{m^2}\right) \times sponge\ area\ (m^2)$$

Hence, the effectiveness is calculated as such. The values are calculated in the Excel Sheet('Effectiveness'):

$$Effectiveness\ (Outdoors) = \frac{Water\ removed\ (mg)}{Solar\ Energy(J)}, \quad Effectiveness\ (Inside\ Chamber)\ = \frac{Water\ removed\ (mg)}{Solar\ Energy(J) + Fan\ Energy(J)}$$

Based on Table 1, we can conclude that our device generally performs well in removing moisture as compared to a control when our device is in the presence of direct sun. In addition to that, it also protects the food from the environment, dust, microbes and the glass panel protects nutrients from being destroyed by harmful UV rays.

4. Conclusion – summarizes all key findings and results.

1. We are 95% confident that our actual daily mean insolation is likely contained within the range where daily solar insolation $\geq$ 4523 Wh/m^2.
2. Our sample mean $E(\bar{x})$ for a single solar panel is 44.78 < 47.2, hence, we can conclude that we will need to install 2 solar panels of this size for our device to work
3. Our device will likely fail > 10% of the time, with only 1 solar panel which supports our conclusion to use at least 2 solar panels to power our desired load
4. Our device performs well in removing moisture as compared to a control kept in the direct sun. In addition to that, it also protects the food from the environment, dust, microbes and the glass protects the nutrients being destroyed by harmful UV rays.
5. Our product will have recouped its costs to the end-user within 167 days of use.

5. References

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6. Appendix

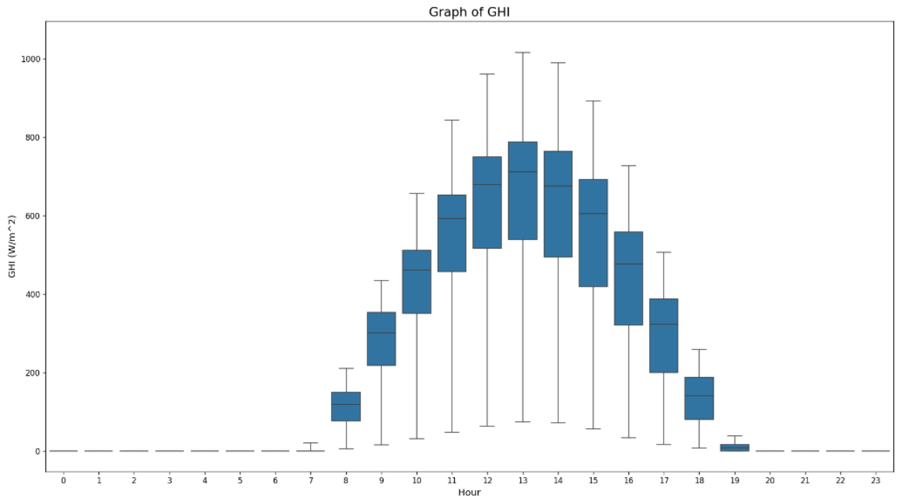


Figure 4: Box Plot of GHI by a given hour, across 5 years

Five Number Summary, IQR, Mean for each Hour							
Hour	Xmin	Q1	Median	Q3	Xmax	IQR	Mean
8	6.00	77.00	119.00	150.00	244.00	73.00	111.50
9	16.00	218.00	301.00	353.00	478.00	135.00	273.63
10	31.00	351.25	461.00	512.00	689.00	160.75	416.27
11	48.00	458.25	593.00	653.00	875.00	194.75	534.08
12	63.00	516.00	679.00	750.00	986.00	234.00	616.54
13	74.00	539.00	712.00	788.00	1044.00	249.00	644.76
14	72.00	495.25	676.00	764.75	1024.00	269.50	613.37
15	56.00	419.25	605.00	692.75	923.00	273.50	541.57
16	34.00	321.00	477.50	558.75	752.00	237.75	430.66
17	17.00	200.25	324.00	388.00	529.00	187.75	290.69
18	7.00	80.00	141.00	188.00	276.00	108.00	133.53
19	1.00	9.00	14.00	20.00	43.00	11.00	15.45

Figure 5: Five Number Summary, IQR, Mean for hourly GHI

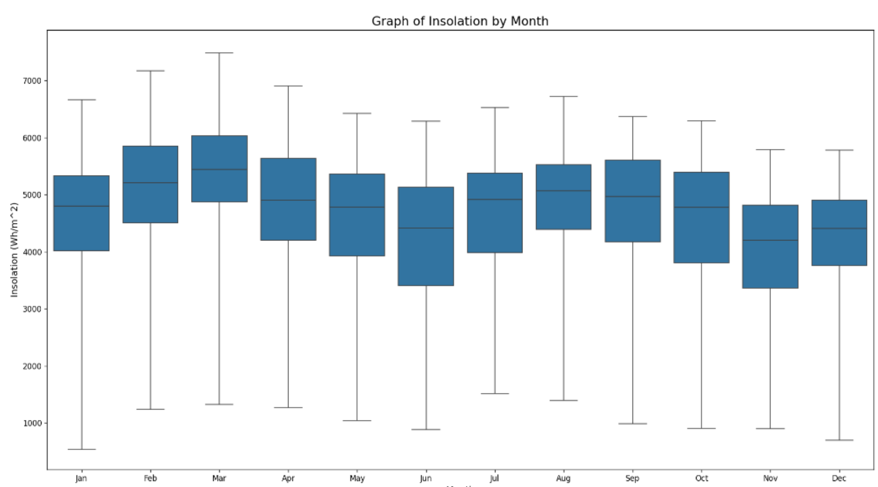


Figure 6: Comparison across months for given day

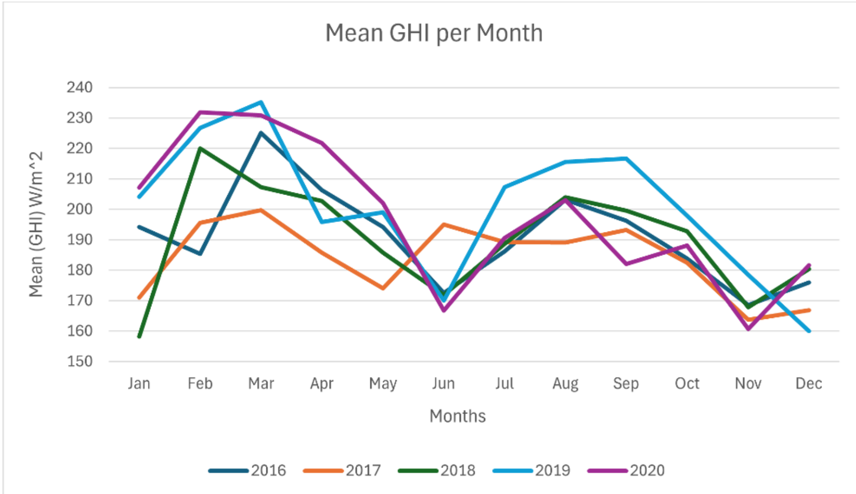


Figure 7: Climate Patterns from 2016 onwards

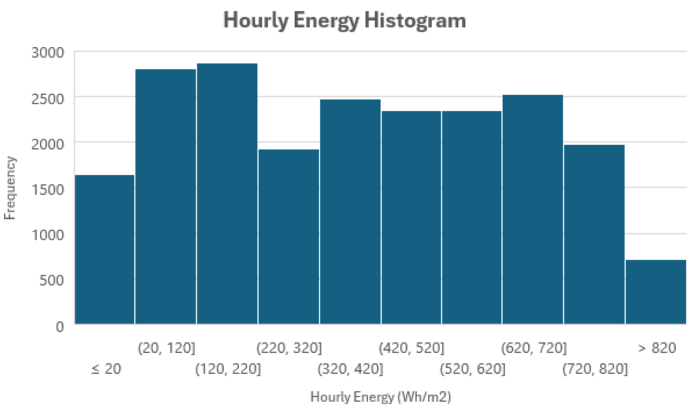


Figure 8: Hourly Energy Histogram

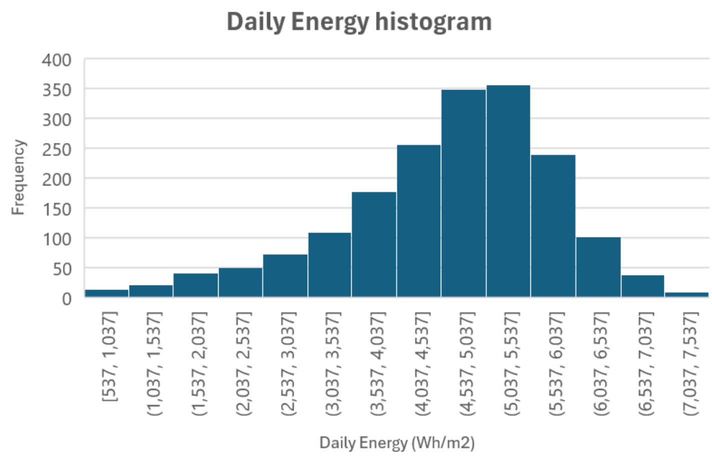


Figure 9: Daily Energy Histogram

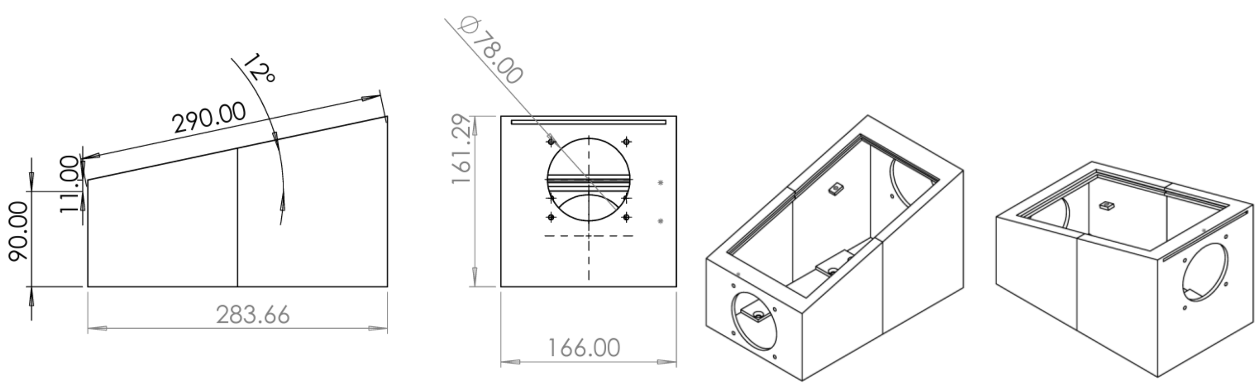


Figure 10: Schematics of the Prototype (Dimensions are in mm)

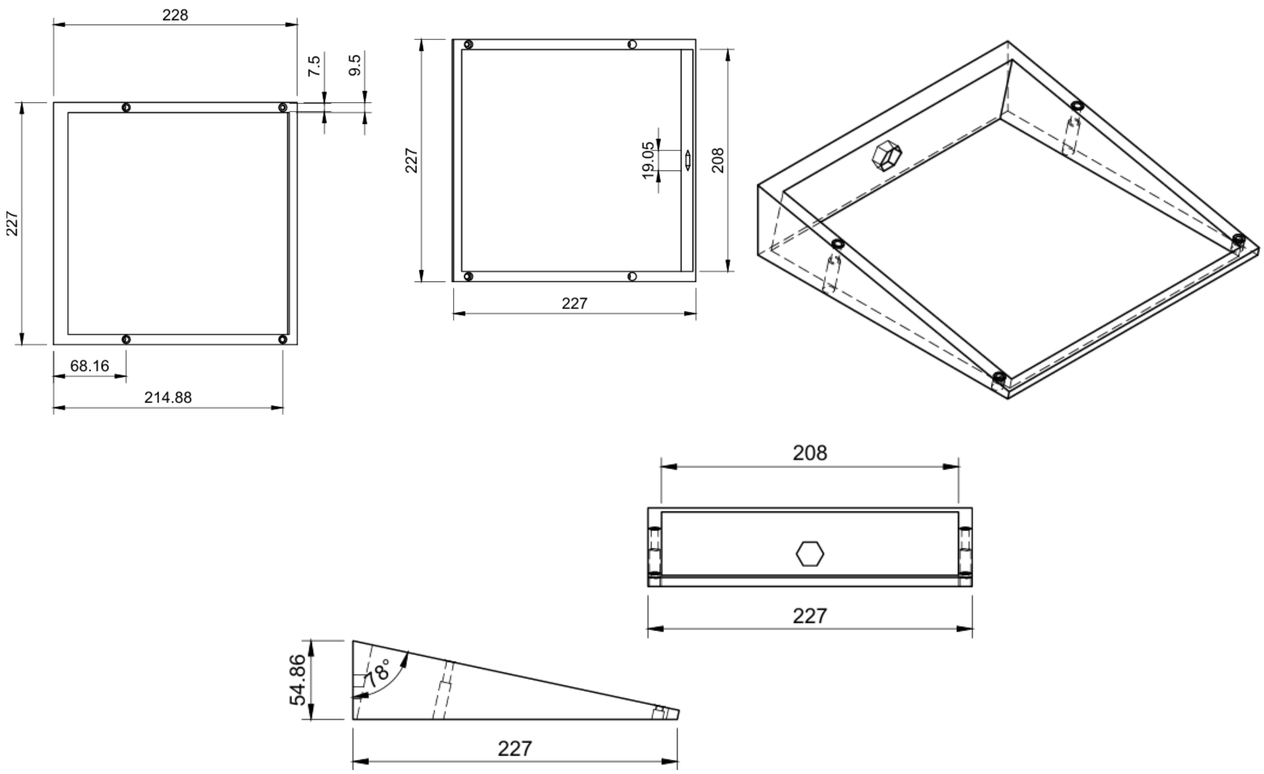


Figure 11: Schematics for the Solar Panel Stand

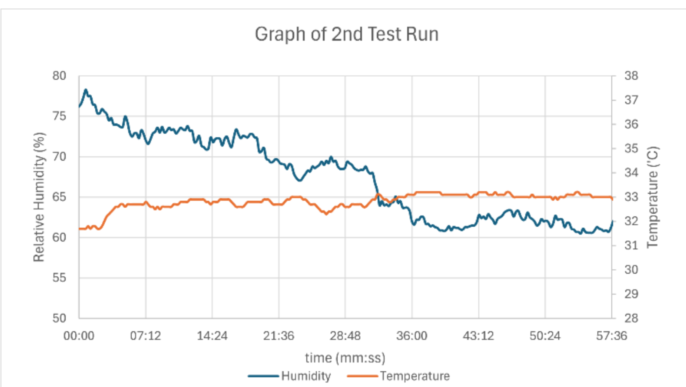


Figure 12: Graph of 2nd Test Run

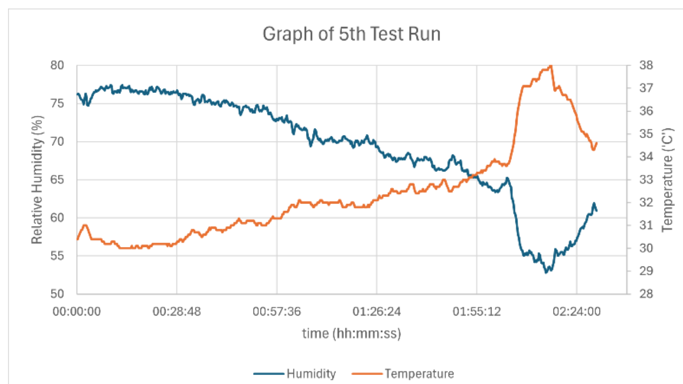


Figure 13: Graph of 5th Test Run

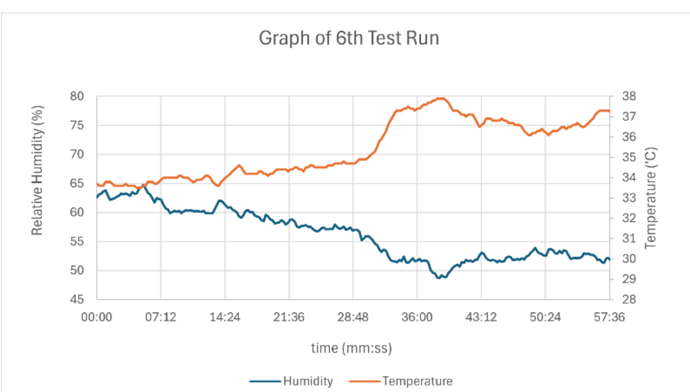


Figure 14: Graph of 6th Test Run

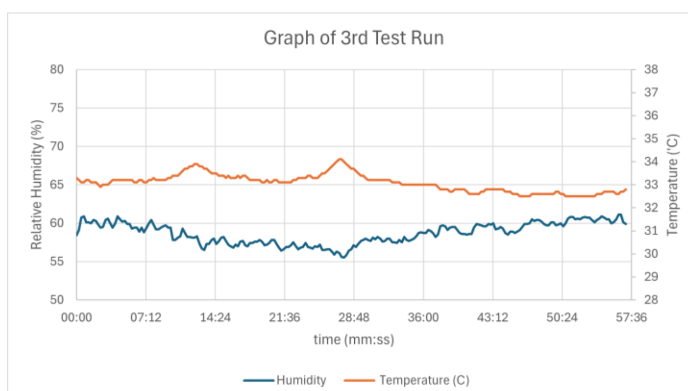
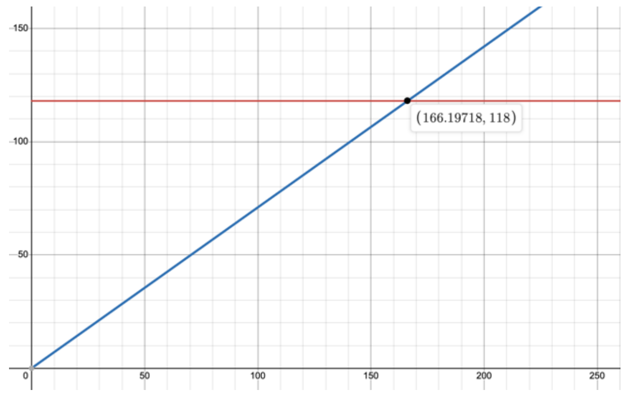


Figure 15: Graph of 3rd Test Run



Graph in Blue
(Cost incurred by Food Wastage):
$y = 0.71x$

Graph in Red (Cost of product): $y = 118$

Figure 16: Graph of Breakeven point

Figure 17: Experimental Setup with our Prototype

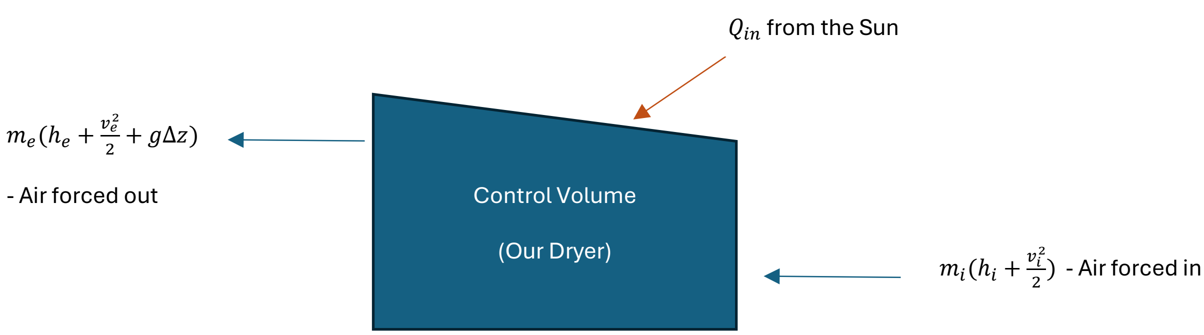


Figure 18: Open Energy System (assume minimal heat loss to surroundings)

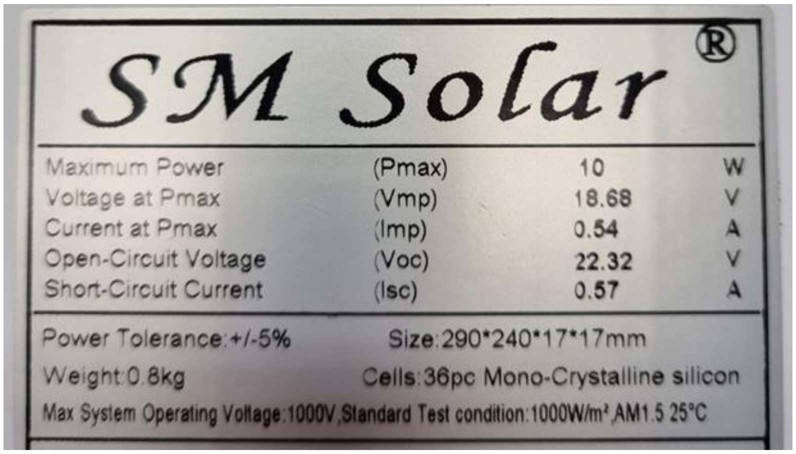


Figure 19: 10W SM Solar Panel Specifications

Table 1: Experimental Runs (see Excel 'Effectiveness' Sheet for Full Calculations)

Test Runs		**Sponge 1 (g) Inside the chamber**	**Sponge 2 (g) Control – Outdoors**	**Net Water Removed – Sponge 1 (g)**	**Net Water Removed – Sponge 2 (g)**	**Effectiveness – Inside Chamber**	**Effectiveness – Outside (Control)**	**Average Solar Irradiance W/m²**
Test Run 1: 4 Dec (1:22 pm - 2:15 pm)	Initial	20	20	11	11	0.709	7.62	226
	Final	9	9					
Test Run 2: 4 Dec (2:28pm - 3:31pm)	Initial	50	50	27	15	1.608	9.60	210
	Final	23	35					
Test Run 3: 4 Dec (3:38pm – 4:39pm)	Initial	50	50	17	17	1.533	16.47	141
	Final	33	33					
Test Run 4: 4 Dec (5:24pm – 6:12pm)	Initial	46	46	7	23	12.554	443.18	9.01
	Final	39	23					
Test Run 5: 5 Dec (9:12am – 11:49am)	Initial	54.7	50	42.9	33	0.937	7.74	226
	Final	11.8	17					
Test Run 6: 5 Dec (12:05pm – 1:05pm)	Initial	37.5	-	32.5	-	1.048	-	401
	Final	5						

Table 2: Full Inventory List for the dryer (assuming all parts are bought online)

Item	**Quantity**	**Estimated Total Cost (SGD)**
3D Printer Filament	1	$5
Fans (80mm)	2	$10
Glass (26 cm×15cm)	1	$3
Wires	As needed	$3
Solar Panel (10W)	2	$80
Buck converter	1	$10
Plywood (35cm × 25cm × 3cm)	1	$5
Screws	1	$2
	Total Price	$ 118