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Introduction

Food Wastage in Singapore is a growing problem. In 2021, over 817000 tonnes of food were lost every day in Singapore (NEA, 2022). A shift in mindsets amongst households towards the preservation of excess food is needed.

The proposed solution is a Community Solar Dehydrator. It aims to allow households in the community to dehydrate their excess food. This reduces food wastage as it prolongs the lifespan of the food. Ideally, the dehydrator would be working continuously every day.

This paper aims to determine an appropriate specification for the Solar Dehydrator and the level of confidence that it will function continuously for a week by analysing daily solar irradiance.

Methods

To design our system, we chose 3 different mathematical concepts to help us better analyse the data:

Percentile: Describes how a data point lies in relation with other data points. By defining a k^{th} percentile, Q_k is obtained that is the least amount of Solar Irradiance required for our prototype to work $(1-k)^{th}$ times in a month.

Q-Q plots: Used to investigate the distribution (primarily to check if it is normal) of the data.

Confidence level: The probability that our dehydrator will be continuously working for a week. This is to supplement the limitations of the percentile.

Results and Discussion

Data Cleaning

For clarity, Solar GHI is interchangeable with solar irradiance in this paper. To standardize, the term solar irradiance will be used in this report.

The original data set includes copious amounts of data with unrelated categories such as the wind speed. To reduce the verbosity of the data set, unrelated data is hidden from view.

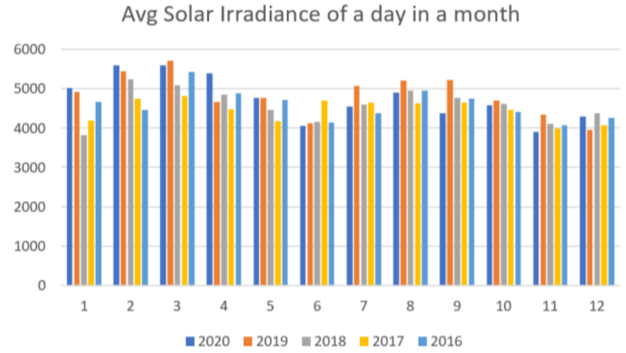
The data is also filtered to an hourly record of solar irradiance to make the data set more manageable and less verbose.

The 29th of February for leap years are also excluded to standardize the number of days for every year.

In the Confidence Interval segment, the last day of the month is removed so that the data can be formatted (by weeks or 7 days) and analysed as there are 52 weeks with an additional day for every year.

Statistical Analysis

General Trend

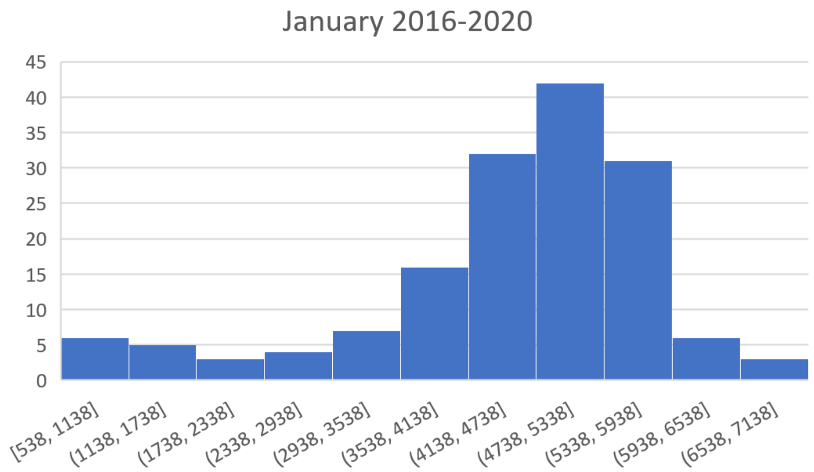


With reference to the graph the average solar irradiance of a day in a month (above graph), the maximum solar irradiance for each month differs across the years. Thus, there are no distinctive trends observed in the graph across the years. Therefore, we reason that there are no specific trends for solar irradiance over the years. This may imply that out dataset of 5 years may be too small for climate change to have a significant impact on our data.

Percentile

Since there are no distinctive trends to follow, we took the average of the solar irradiance per day in a month across the 5 years to plot a histogram. (See Appendix A)

For every month, a left skewed graph is observed. The left side of the graph shows the lowest range of solar irradiance in a month. Assuming that our solar dehydrator would not work with very low solar irradiance, the 25th percentile is used as our cut off point. For days below this cut off point, the dehydrator would not work.



The 25th percentile for every month from 2016 to 2020 are:

Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
4111	4452	4880.5	4092	4019.5	3549.5	3920	4300	4135.75	3821	3412.75	3829

To account for the worst-case scenario, the minimum solar irradiance that our dehydrator require is 3412.75W/m^2 ≈ 3400W/m^2. (Using November's data which is the lowest out of all the months)

Using 3400W/m^2, the percentage uptime of the dehydrator for the respective months (from 2016 to 2020) would be:

Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
89.8%	91.9%	92.4%	84.9%	76.4%	84.4%	91.5%	86.2%	86.2%	82.2%	75.5%	82.6%

However, this percentile is not representative of how often our dehydrator will work in a month. Concluding whether the dehydrator works or not for a whole day is too binary. In fact, our dehydrator will be equipped with batteries to store the excess solar energy (off grid system). Realistically, the battery will supply the energy needed by the dehydrator for it to function. Moreover, there will still be solar irradiance on any day of the year which would supply energy to the system (through the solar panels). Thus, an alternative method is required to supplement the percentile method. A confidence level method shall be used.

Confidence Level

To establish a confidence level, we investigated the type of distribution for the data set using a Q-Q plot. However, the Q-Q plot did not produce any identifiable distribution. (See Appendix B)

To determine the confidence level of the dehydrator functioning (continuously) for any week, we calculated the probability of the mean solar irradiance per day in that week being larger than 3400W/m^2. Some symbols are defined below.

> X_{ij} – A random variable representing the i^{th} lowest average solar irradiance per day in a week on the j^{th} year.
>
> S_x – The standard deviation of the sample data X_{ij}. As the population variance σ_X is unknown, S_x is approximated to be σ_X.

To determine the confidence level, 6 weeks (with the lowest solar irradiance per day in a week) out of 52 weeks of a year are chosen. These weeks will be used to represent the worst-case scenarios for the dehydrator. We also chose 6 weeks per year (instead of less weeks) to ensure that our number of data points (N) is sufficiently large enough to use Central Limit Theorem. More than 6 weeks would be less representative of the worst-case scenarios as it includes one more datum point that would be larger and better than the rest. This process is repeated for all five years from 2016 to 2020. Hence, we can obtain 30 data points and calculated the following values for the sample.

N (Number of Data Points)	30
S_x (Standard Deviation of the sample)	432.7249836
$\bar{X}_N$ (Mean of the sample)	3503.485714

We reason that the X_{ij} datapoints are relatively scattered randomly among the weeks of a year (see Appendix C). Hence, we assume that X_{ij} to be independent (or at least with negligible dependence). In addition, to simplify calculations, we have to assume that X_{ij} is identically distributed (or at least very similarly distributed).

With $N = 30$, N is sufficiently large to use the Central Limit Theorem. Hence, X_{ij} can be approximated as a normal distribution. To be conservative and account for errors, a t-distribution is used to measure the probabilities. Subsequently, we found the probability of the true mean of X_{ij} $(represented\ by\ \theta)$ being larger than 3400W/m^2. This probability represents our dehydrator working continuously over any week in a year.
Using a one-sided confidence interval with the confidence interval of [3400, ∞):

$$\mathbb{P}(\theta \geq 3400) = 1 - \alpha$$

$$\mathbb{P}\left(\bar{X}_N - t_{N-1,\alpha}\left(\frac{\sigma_X}{\sqrt{N}}\right) \geq 3400\right) = 1 - \alpha$$

$$\mathbb{P}\left(t_{N-1,\alpha} \geq \frac{\sqrt{N}}{\sigma_X}(\bar{X}_N - 3400)\right) = 1 - \alpha$$

Substituting the values of N, σ_X and $\bar{X}_N$,

$$\mathbb{P}(t_{N-1,\alpha} \geq 1.30987) = 1 - \alpha$$

Using excel, we obtained the value for the $\mathbb{P}(t_{N-1,\alpha} \geq 1.30987) = 0.89974 = 0.900\ \ (3\ s.f.)$

In simple words, the dehydrator functioning continuously for any week has a confidence level of 90.0% even in the worst-case scenario where α is 0.100 (round off to 3 s.f.). As such, for any week in a year, the dehydrator can fulfil its purpose with a confidence level of at least 90.0%.

Dehydrator Prototype

Assumptions

To design our product, we assumed an efficiency of 14% for the solar panels based on the hands-on activity (HOA) 6 done in Design Energy System (DES). Furthermore, we assumed negligible energy losses within the circuit.

Specifications

Number of fans and solar panels

From our data, the minimum solar irradiance required for the dehydrator is 3400W/m^2.

Specification of each fan: 12V, 0.15A

Since we want the fans to be in use for 24 hrs:

Power required for 1 fan for 24 hrs: $12 * 0.15 * 24 = 43.2Wh$

Ideal number of fans (estimated based on size of prototype): 3

Specifications of the solar panel: 395*345*17mm, 14% efficiency (Based on HOA 6 in DES)

Power output of 1 solar panel: $3400 * \frac{395}{1000} * \frac{345}{1000} * 0.14 = 64.867\ Wh\ (5\ s.f.)$

Therefore, for 1 solar panel, the number of fans that can be powered: 1.5

For 3 fans, the number of solar panels required: $\frac{3}{1.5} = 2$

Battery Size

From 2016 to 2020, the greatest number of days that did not reach 3400W/m^2 was 6 days, from 10th to 15th January 2018. This is the worst case in the 5 years. (See Appendix D)

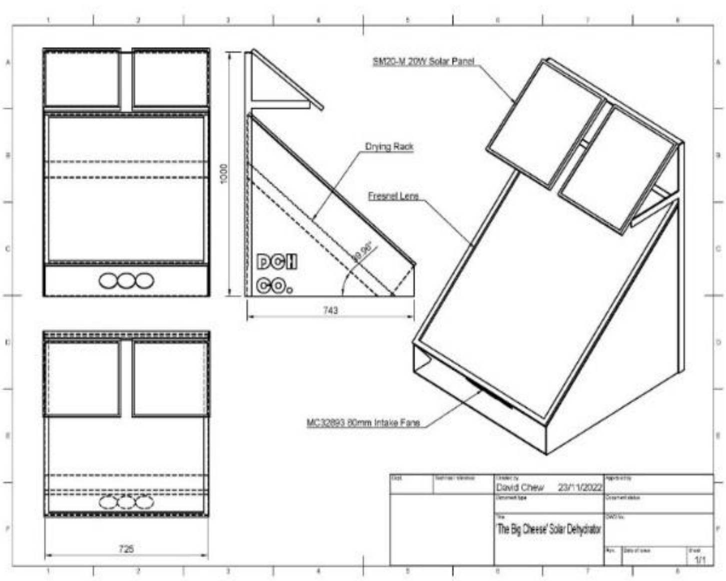
The solar irradiance deficit for the 6 days from (3400x6) = 11307 W/m^2.

Converting solar irradiance deficit to power supplied by the battery: $11307 * \frac{395}{1000} * \frac{345}{1000} * 0.14 = 215.7205\ Wh$

Therefore, we would like our battery to be able to hold at least 216Wh.

For a 12V battery (12V to power the fans), the capacity of the battery ≥ 18Ah.

Prototype



Based on the above requirements, a prototype was designed. A Fresnel lens was used as the sun-facing surface of the dehydrator to concentrate solar radiation in the centre of the drying rack to increase the drying rate of small quantities of food items placed there. The surface and drying rack were also given a 40^o angle (with reference to the ground) to be approximately normal to the direction of sunlight during the time and date of the experiment based on data we had, and to promote free convection of the contained hot air. The drying rack consists of a layer of corrugated zinc painted black to maximise heat absorption and convection (to the contained air), and a welded aluminium mesh for the food to be placed on. The dehydrator body was constructed from a thin plywood shell and polyfoam for insulation. (Full size image in Appendix D)

Cost Analysis

(See Appendix E):

A Bill of Materials (BOM) was created using the prices of parts and materials. The total cost is S$348.65. Assuming a worst-case dehydration time of 48 hours per batch (Lindsey, 2022), 15 batches can be dehydrated per month. An excel file was created to vary the weight and price of the fruit. With these factors, we estimated the rough Return on Investment Period (ROI) (the number of cycles after which we dehydrate an amount of food worth the initial cost of the dehydrator).

For our test case, for 90% availability (of the dehydrator) and 1.96 kg of mangos per batch, we found out that the ROI is 12 dehydration cycles; that is, we can dehydrate S$348.65 worth of mangos in 12 cycles. Therefore, if the dehydrator were to be used continuously except during it's down time, its construction cost expressed in retail value of food dehydrated will be made up in less than 1 month. (0.89 months: 27 days.)

The estimated food loss would be about S$39.12 per month based on our test case. This loss is the value of food that could not be dehydrated due to downtime, which is assumed to have been lost; it has no value.

Analysis of Prototype

(See Appendix F):

The prototype was tested for 2 hours from 10am to 12pm. A wet sponge was used as a stand in for food. The sponge had a dry weight of 5g, an initial wet weight of 27g, and a final weight of 9g after the test; 81.8% of the water was evaporated during the test.

The prototype was allowed to run with only free convection from 10am to 11am, where it achieved a max temperature of 89.2°C, and a mean temperature of 63.0°C. Looking at the 10.30am to 11am when the solar irradiance peaked, the mean temperature was 77.4°C.

The fans were turned on from 11am to 11.30am, which reduced the mean temperature to 52.6°C. The fans were switched off at 11.30am, after which the mean temperature returned to 66.1°C from 11.30am to 12pm.

The prototype was then left under the sun until 3.38pm and a mean temperature of 53.9 °C and a max temperature of 89.2 °C was obtained. However, this data is not as accurate as in the later periods of the data testing, the sunlight was occluded by the FabLab (neighbouring building).

Humidity data was considered unreliable as the sensor read 0% humidity when temperatures exceeded 80°C. (It may have been unable to accurately measure at such high temperature)

Temperatures exceeding 60°C are not optimal for dehydration, resulting in the dehydrator requiring forced convection during regular usage to control the temperature. However, the volume of airflow generated by the fans for the prototype caused excessive heat loss where the mean temperature fell to 46.1°C. This temperature is also not optimal for dehydration. Optimal temperatures for the dehydrator ranges from 50 °C to 60 °C.

From these findings, a new prototype iteration is recommended with fewer fans with further research needed for that prototype to provide more optimal airflow that prevents both excessive heat loss and excessive temperature.

Conclusion

To reduce the food wastage in Singapore, a solar powered dehydrator is employed. The requirement of the dehydrator would be to work continuously for a week. From the analysis, it was determined that a system comprising of 2 20W solar panels, 3 80mm, 1.8W fans, and 1 20Ah battery is appropriate to fulfil this requirement. However, to improve performance, it is recommended that further iterations of the prototype be built and tested with a lower number of fans to better control the internal air temperature of the dehydrator.

In prototyping the dehydrator, three methods were used to analyse the data for solar irradiance. These methods are percentiles, Q-Q plots, and confidence levels to determine how often the dehydrator can work continuously over a week.

The main method employed for data analysis is using percentile to help determine the specifications we would like for our dehydration and using confidence level to help us to determine the probability of our dehydrator fulfilling its requirement. Using the worst weeks, we concluded that our dehydrator would work continuously for a week with a 90% confidence level.

Overall, with this 90% confidence level, it is estimated that the resultant design will have a Return-on-Investment period of 27 days. After which, it can dehydrate up to S$390.06 worth of produce per month, with only S$39.12 being lost due to downtime. As such, the dehydrator is very valuable over the long term as it can recover up to S$390.06 worth of produce every month even in the worst conditions. Over time, food wastage will decrease as the community pick up on dehydrating expiring foods. By dealing with food wastage on the consumer level, it will directly impact the chain of food wastage as consumers have to buy less food and supermarkets have to stock less food. As a result, the problem of food wastage will decrease over time, ceteris paribus.

Appendix A

Monthly Histograms

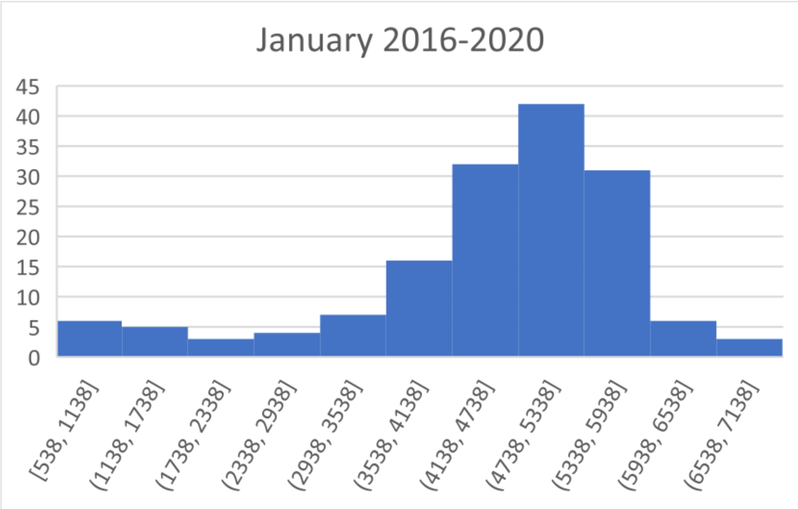


Figure A1: Daily Average Solar Irradiance for All January 2016 – 2020

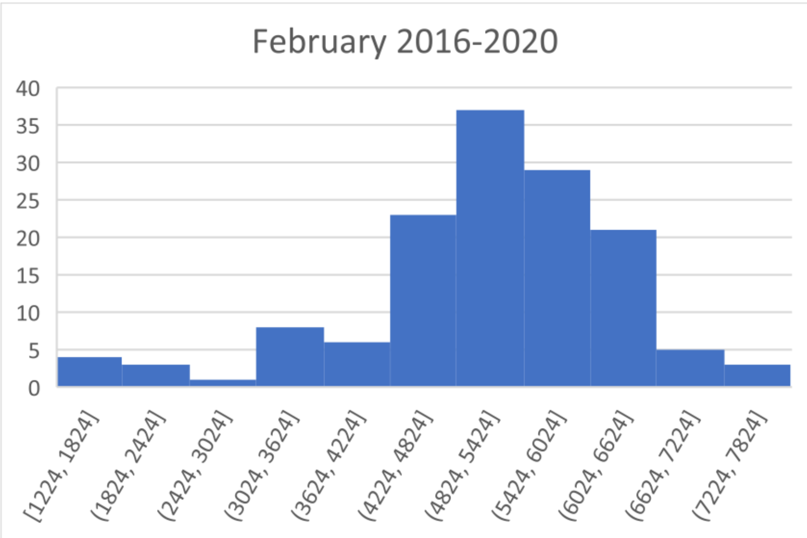


Figure A2: Daily Average Solar Irradiance for All February 2016 – 2020

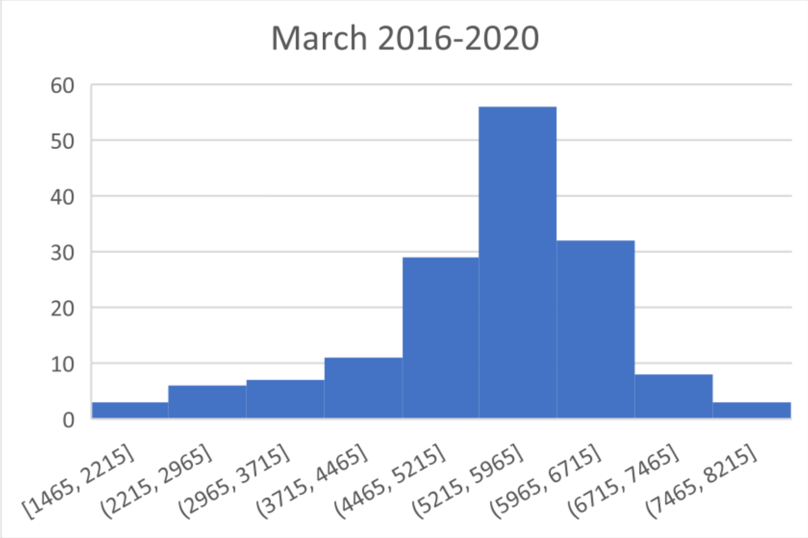


Figure A3: Daily Average Solar Irradiance for All March 2016 – 2020

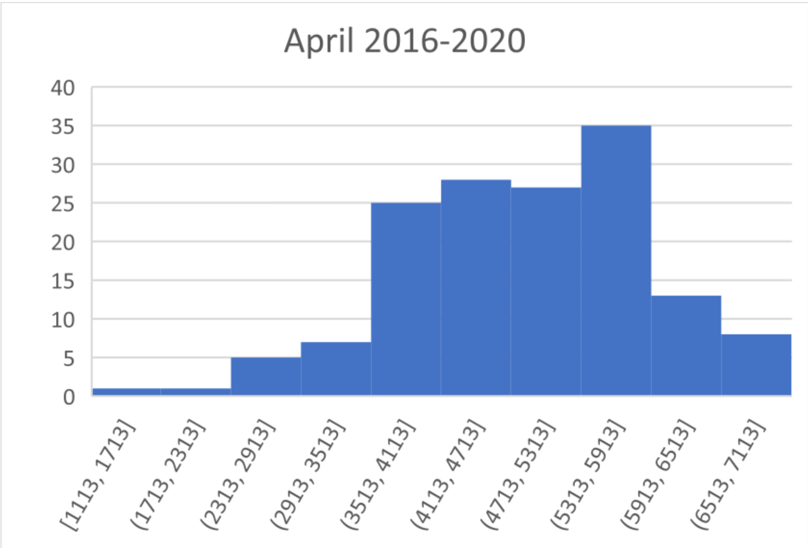


Figure A4: Daily Average Solar Irradiance for All April 2016 – 2020

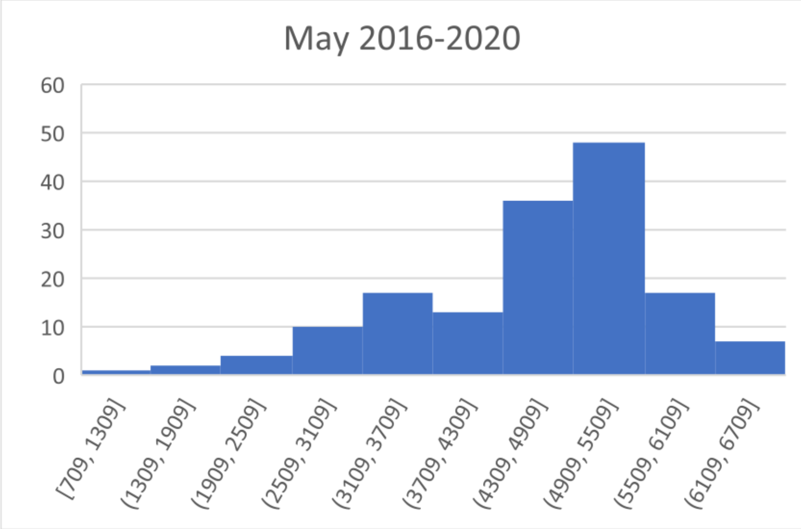


Figure A5: Daily Average Solar Irradiance for All May 2016 – 2020

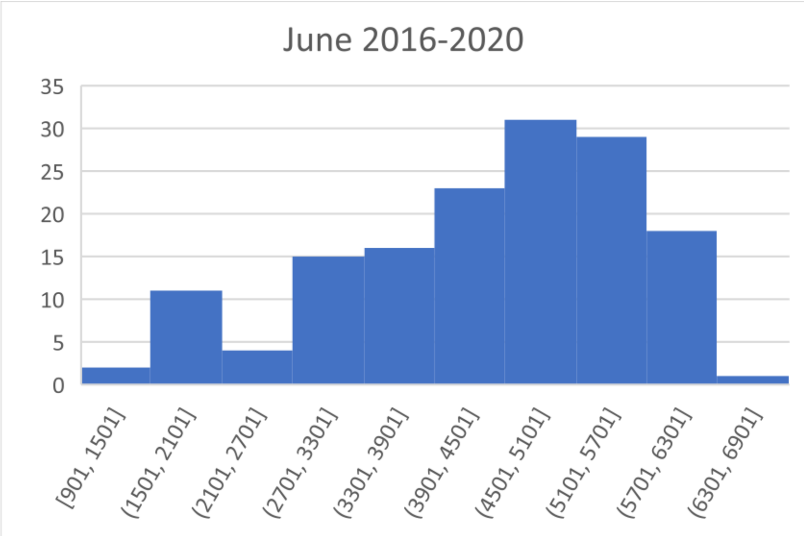


Figure A6: Daily Average Solar Irradiance for All June 2016 – 2020

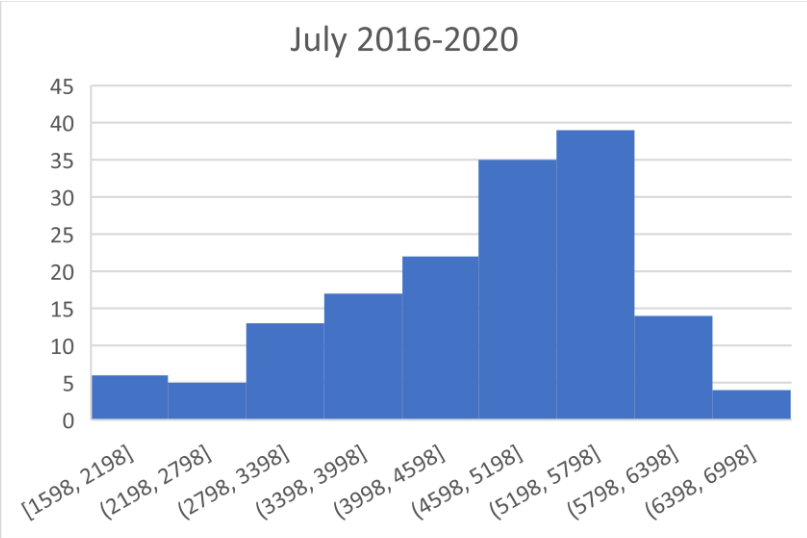


Figure A7: Daily Average Solar Irradiance for All July 2016 – 2020

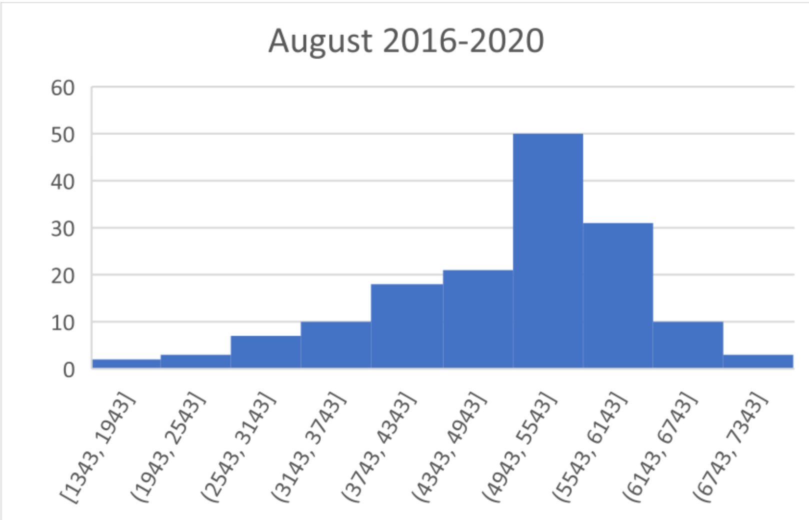


Figure A8: Daily Average Solar Irradiance for All August 2016 – 2020

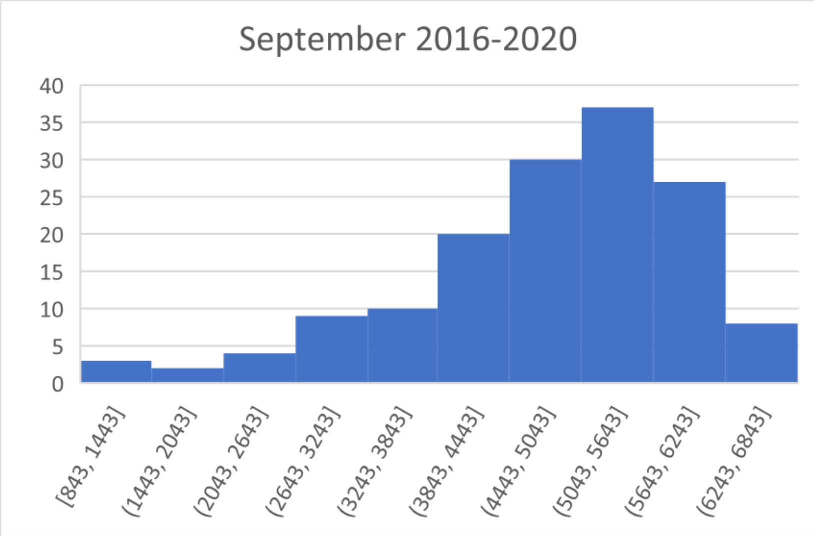


Figure A9: Daily Average Solar Irradiance for All September 2016 – 2020

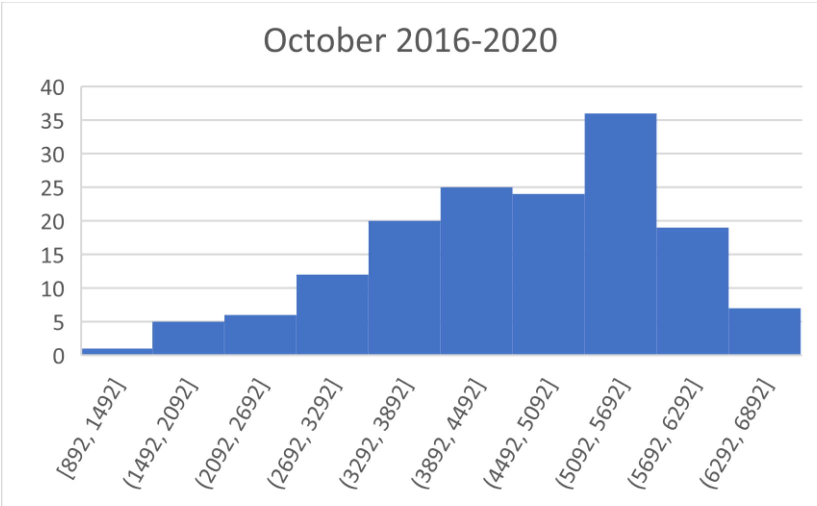


Figure A10: Daily Average Solar Irradiance for All October 2016 – 2020

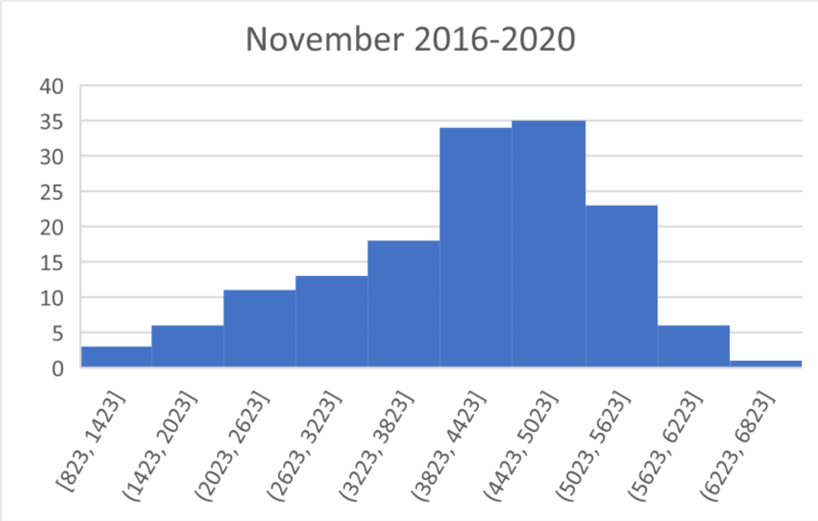


Figure A11: Daily Average Solar Irradiance for All November 2016 – 2020

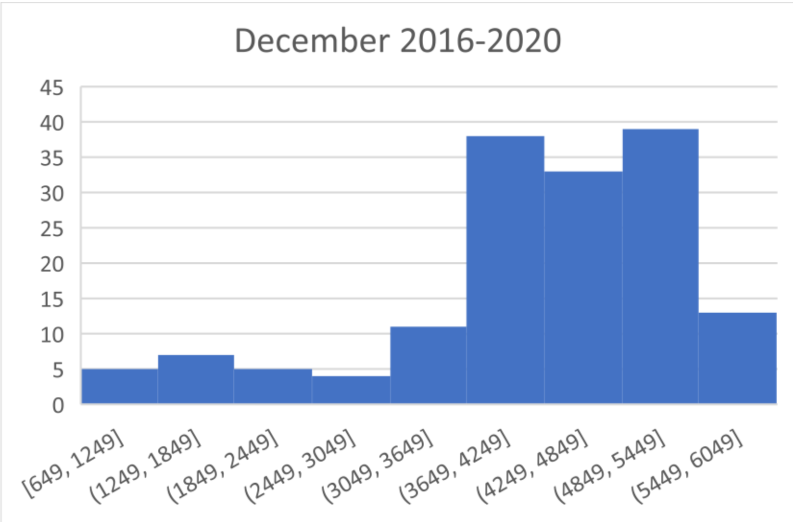


Figure A12: Daily Average Solar Irradiance for All December 2016 – 2020

Appendix B

Q-Q plot

To establish a confidence level, we investigated the type of distribution for the data set.

Using i = the number of weeks in the year (for i = 1, 2, 3, …, 52) and the x_i = data values of the daily average sum of the GHI in the week, we had plotted the x_i against $\varphi^{-1}\left(\frac{i}{n+1}\right)$ quantile to get 5 Q-Q plots for each year (The figures are shown in the excel sheet and the appendix). However, all the scatter plots do not form a straight trendline. This shows that the data cannot be modelled by a normal distribution.

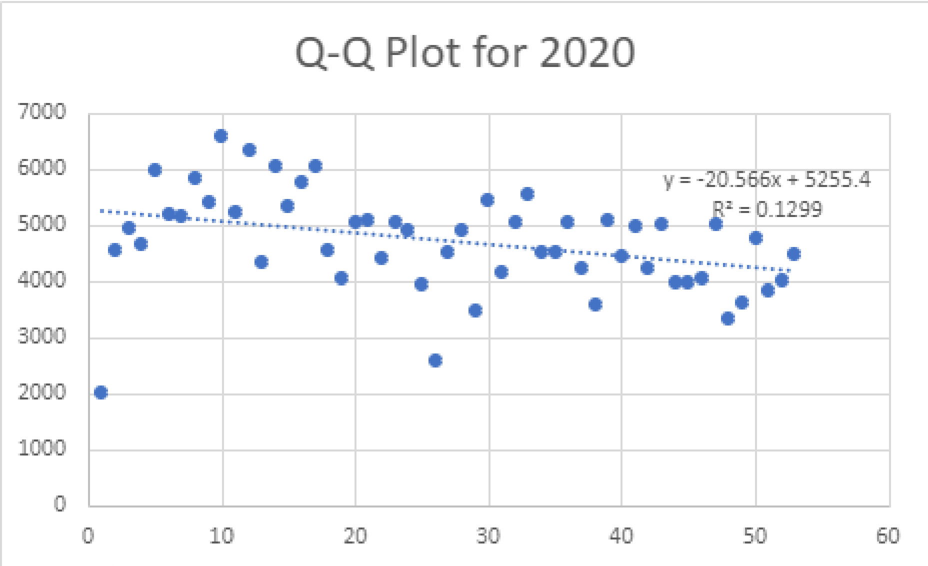


Figure B1. Q-Q Plot for 2020

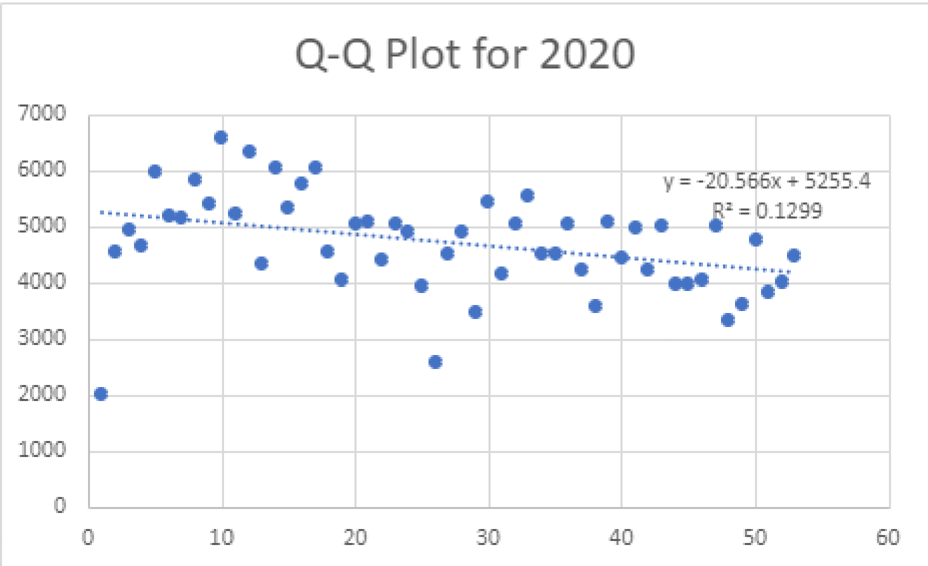


Figure B2. Q-Q Plot for 2019

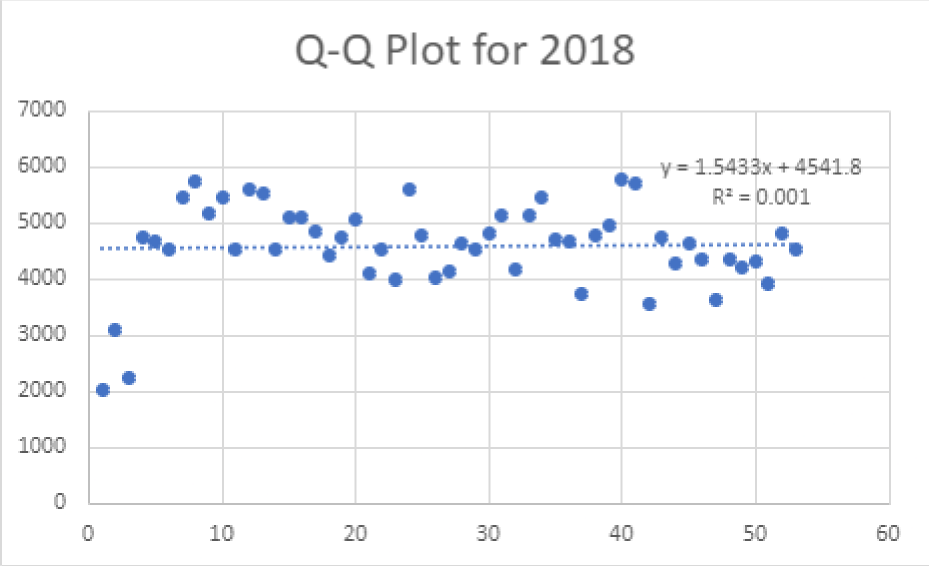


Figure B3. Q-Q Plot for 2018

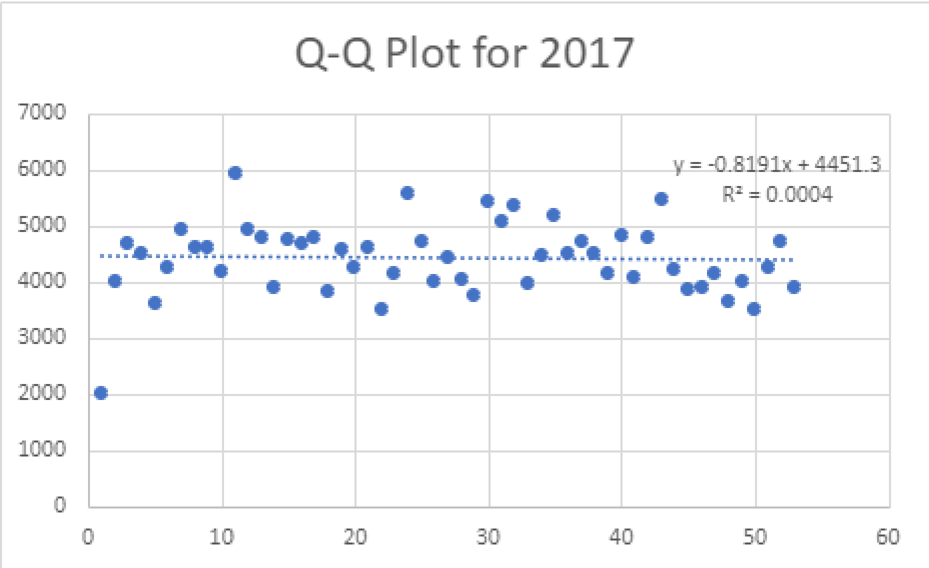


Figure B4. Q-Q Plot for 2017

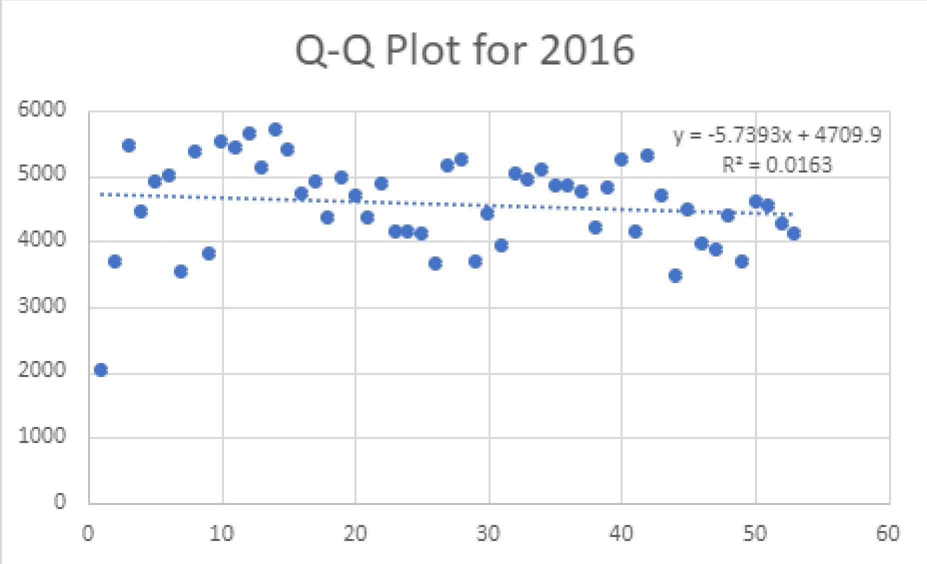


Figure B4. Q-Q Plot for 2016

Appendix C

Confidence Intervals

z	2020	2019	2018	2017	2016
1	4565	4981	3074.5714	4044.7143	3671.1429
2	4950.8571	5401.8571	2249.7143	4724.5714	5453.2857
3	4672.5714	4510.7143	4735.1429	4518	4431
4	5999.2857	4558.8571	4668.2857	3621.1429	4890.4286
5	5196.5714	5604.2857	4503.8571	4293.1429	4995.1429
6	5152.5714	5879.4286	5450.1429	4951.8571	3532.8571
7	5849.8571	5117.2857	5737.2857	4640.7143	5354.2857
8	5422.4286	5666.1429	5169.2857	4627.4286	3806.1429
9	6593.4286	5333.4286	5443.4286	4209.1429	5510.7143
10	5224.5714	5384.7143	4501.5714	5950.7143	5419.7143
11	6320.8571	6576.8571	5601.7143	4971.4286	5638.7143
12	4348.7143	5461.5714	5511	4822	5114.2857
13	6050.2857	5057.5714	4526.8571	3923.5714	5707.8571
14	5353.5714	5571.2857	5099.2857	4791.1429	5385.1429
15	5758.7143	4730	5094.2857	4716.1429	4721.8571
16	6063.8571	4794.5714	4846.1429	4810.4286	4898.5714
17	4544	3803.1429	4426.5714	3856.2857	4365.5714
18	4057.5714	4449.7143	4739.2857	4597.4286	4971.7143
19	5058.7143	4536.1429	5045.5714	4288.7143	4677.1429
20	5096.1429	4707.8571	4096.5714	4636.8571	4345.1429
21	4424.4286	4979.2857	4514.7143	3523.4286	4881
22	5044.5714	4710.1429	3729.1429	4162.8571	4141.7143
23	4922.2857	3617.1429	5197.7143	5590.7143	4150.1429
24	3933.1429	4369.1429	4374.1429	4758.7143	4110
25	2603.1429	3974.5714	3602.7143	4034.7143	3645.7143
26	4507.7143	4627.5714	3264.5714	4460.7143	5144
27	4912.5714	4794.8571	4627.7143	4081.7143	5232.8571
28	3479.5714	4920.1429	4517.5714	3782.1429	3686.8571
29	5455.1429	5069.5714	4797.5714	5445.1429	4410.7143
30	4147	5166	5130.8571	5118.2857	3932.1429
31	5064.4286	6004.5714	4161.1429	5388.1429	5014.1429
32	5540.4286	5065.1429	5141.8571	4010.5714	4941.8571
33	4507.2857	5219	5452.4286	4511.5714	5101.1429
34	4535.4286	5235.2857	4694.5714	5190.4286	4845.4286
35	5036.8571	5023.2857	4651.5714	4540.8571	4852.2857
36	4247.5714	5253.4286	3747.4286	4740	4761.5714
37	3595.8571	5174.8571	4763.7143	4534.8571	4193.1429
38	5077.5714	5611	4948.7143	4185.8571	4798.8571
39	4436.1429	4672.2857	5780.1429	4851	5240.4286
40	4984.1429	4380.5714	5688.7143	4109.4286	4125.5714
41	4239.5714	5456.7143	3568.1429	4813.2857	5296.2857
42	5010.4286	5052.5714	4745.4286	5487.1429	4683.7143
43	3989.7143	4046.2857	4279.2857	4231.2857	3463.8571
44	3993	4776.4286	4636.5714	3884.2857	4468.7143
45	4049.4286	4605.2857	4333.7143	3915.2857	3948.2857
46	5029.8571	4717.2857	3625.2857	4165.1429	3872.4286
47	3332.4286	3430.1429	4342	3667	4380.5714
48	3608.7143	4247.7143	4198.5714	4028.7143	3680.2857
49	4760.4286	3746.4286	4309.7143	3542.1429	4594.4286
50	3852.4286	2203	3920	4295.7143	4523
51	4003.1429	4316.1429	4796	4751.1429	4272.1429
52	4483.2857	5225.7143	4515.5714	3931.5714	4111

Figure C1. The X_{ij} used are highlighted in yellow

Appendix D

Prototype - Dehydrator Specifications

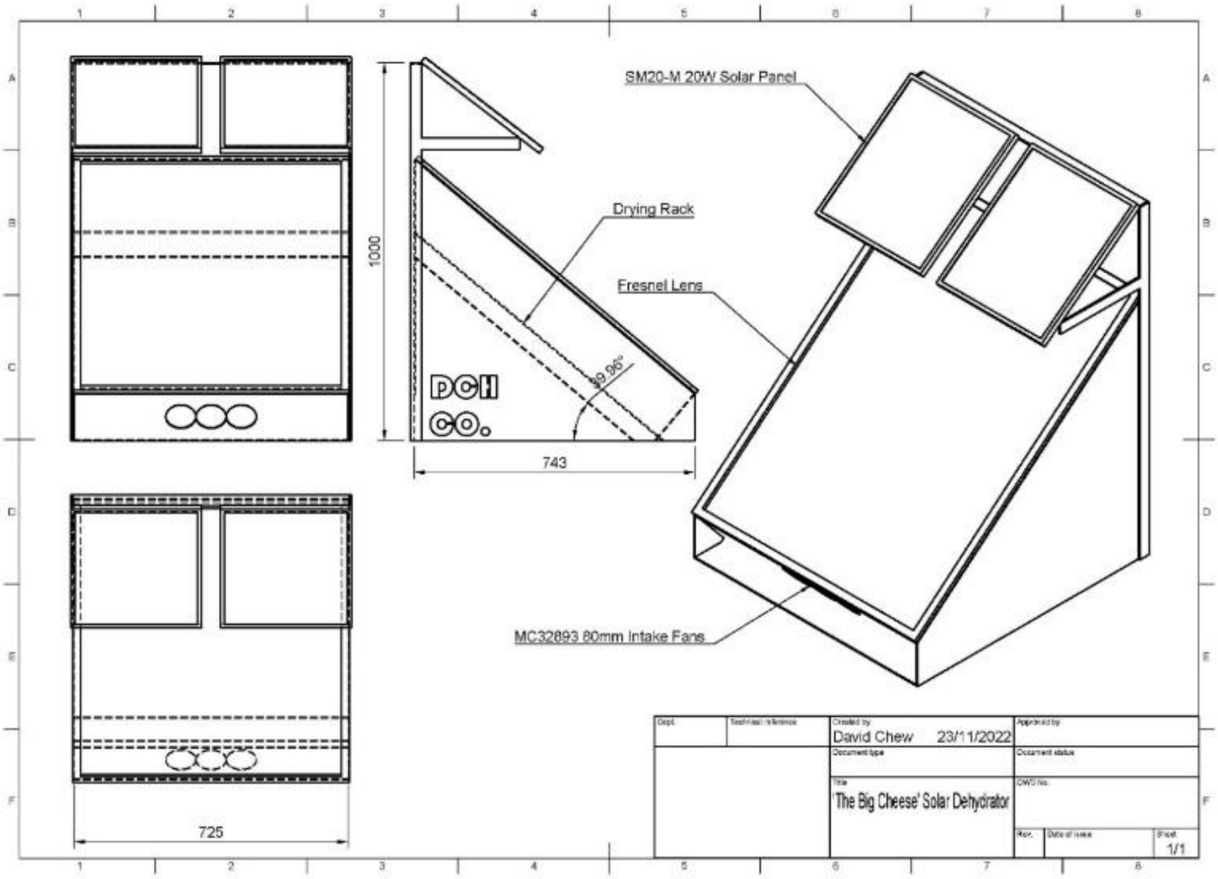


Figure D1. Dehydrator Schematic Diagram

Prototype - Battery Size

From 2016 to 2020, the greatest number of days that did not reach **3400W/m²** was 6 days, from 10th to 15th January 2018.

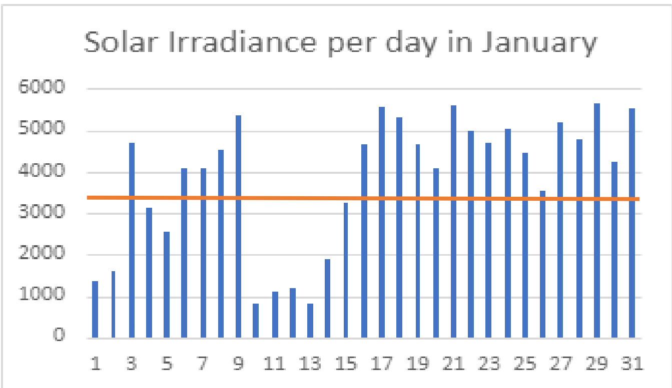


Figure D2: Daily Solar Irradiance in January 2018

Appendix E

Cost Analysis

DEHYDRATOR BILL OF MATERIALS					
Category	Item	Model	Quantity (nos.)	Unit Cost (SGD)	Total Cost (SGD)
Electrical	Solar Panel	Phaesun 20W	2	84.27	168.54
Electrical	Solar Charge Controller	aostorer-1728115624	1	9.57	9.57
Electrical	Fan	MC32893 80mm 12V 0.15A	3	4.02	12.06
Electrical	Battery	Yangtze Battery 6 fm 20 12V 20Ah	1	23.46	23.46
Electrical	Wiring	Estimated length required	1	2.00	2.00
Housing	Fresnel Lens	Solar Fresnel Lens C, Rudra Solar	1	100.00	100.00
Housing	Plywood	5mm, estimated area required	1	9.80	9.80
Housing	Polyfoam	25mm, estimated area required	1	6.50	6.50
Housing	Corrugated Zinc Sheet	NA, estimated area required	1	13.22	13.22
Housing	Welded Aluminium Mesh	1/2" Grid, estimated area required	1	3.50	3.50
				Total Cost (SGD)	**348.65**

Figure E1: Bill of Materials and Total Cost of Dehydrator Design

ROI CALCULATOR	
Item	Mango
Cost per kg (SGD)	12.23
Density (kg/m^3)	1000
Slice Thickness (mm)	6
Packing Density (%)	70
Bed Size (m^2)	0.5625
Product Mass (kg)	2.3625
Product Value (SGD)	28.893375
Drying Time (day)	2
Availability (%)	90
Batches per month	13.5
Value Dried Per Month (SGD)	**390.06**
Value Dried Per Year(SGD)	**4680.73**
Return on Investment Period (mth)	**0.893835557**
ROI Period (dehydration cycles)	**12.06678001**
EXPECTED LOSS	
Batches per year	162
Batches lost every year	16.2486
Expected Value Lost every year (SGD)	**469.48**
Expected Value Lost every month (SGD)	**39.12**

Figure E2: ROI (dehydration cycles) and Expected Loss

Appendix F

Analysis of Prototype

We will be using the solar irradiance from the flat panel. Since interference was allowed, we constantly changed the dehydrator such that it faced the sun. Therefore, as we tested the dehydrator from 10am to 3.38pm, there was a significant change in the direction of the sun, thus we will be using the flat panel to standardise and average out the solar irradiance.

Based on the data, we speculate that the power time graph is very erratic mainly because since there was a high amount of activity during the setup and testing process, when people were walking around, they had unknowingly blocked the solar panel, resulting in an immediate dip in the power output. This can be seen as during 1.30pm to 2.30pm, there was significantly lesser fluctuation as everyone left the testing site. We are unable to say the same for 10.30-11.30am as even though most people left, my group stayed and had unknowingly also blocked the solar panels when wandering around to look at the other groups' dehydrators.

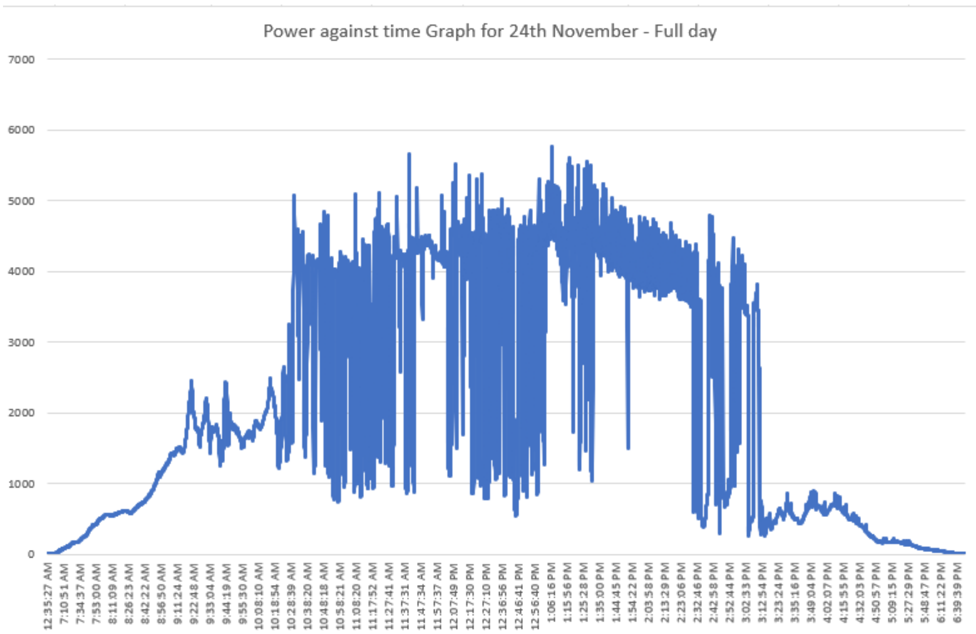


Figure F1: Power against time Graph for 24th November - Full day

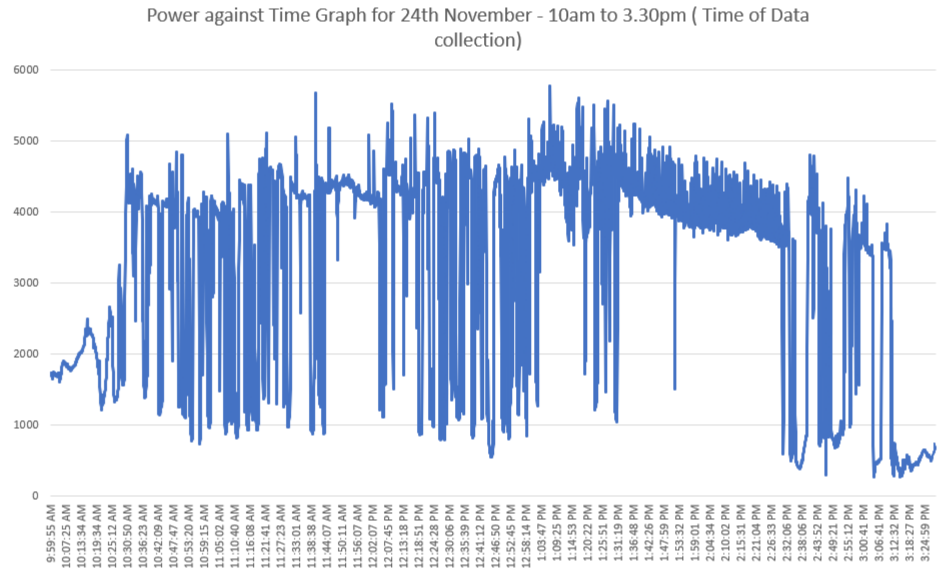


Figure F2: Power against Time Graph for 24th November - 10am to 3.30pm (Time of Data collection)

From 10am - 11am, the fans were off. The temperatures rose when high solar irradiance was (as seen by the high-power output by the solar panel). The fluctuations were due to the opening of the dehydrator to look at the insides and when there was cloud.

From 11am to 11.30am, the fans were on. Due to forced convection, the temperatures of the prototype dropped.

From 11.30am to 1.30pm, the fans were off, and the dehydrator was left alone with little interference. The only interference occurred when the dehydrator was open to remove the sponge around 12.10pm (there was a drop). Another thing too note is from 12.30pm onwards, our dehydrator was no longer pointing in the direction of the sun, which affected the amount of light focused by the Fresnel lens, leading to a lower temperature.

From 1.30pm to 3.38pm, the fans were on, resulting in a further drop in the temperatures of the prototype. At around 2.10pm, the sunlight was occluded by the FabLab building, leading to a further drop.

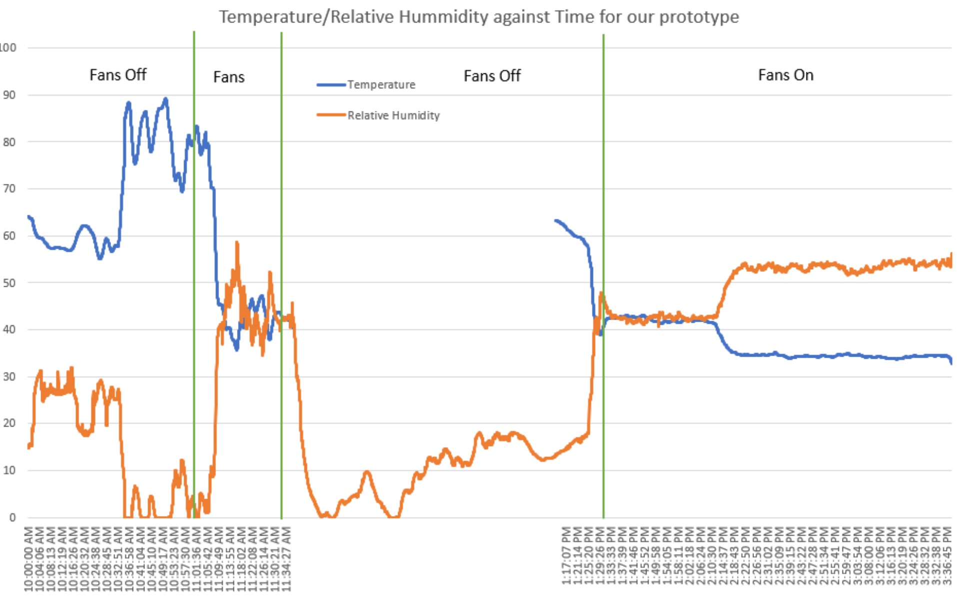


Figure F3: Temperature/Relative Humidity against Time for our prototype

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