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Feasibility Analysis of Mono-facial Photovoltaic System in Ahmedabad

Jainil Prakashkumar Patel[1], Priyank Vipulbhai Patel[2], Shrey Tushar Patel[3]

[1,2,3] Mechanical Engineering, Ahmedabad University, Gujarat.

Abstract - *The Photo Voltaic cells can be used to generate high amount of energy. The performance of Photo Voltaic modules gets affected by various external factors like ambient temperature, wind speed, humidity, and clearness index of the day, and sometimes wind direction as well. To incorporate the influence of these factors on PV system, the overall productivity from four different PV technologies like Mono-crystalline, Multi crystalline, Thin-film, and HIT have been compared. The Global Irradiance data have been procured from Indian Meteorological Department, Pune, while its diffused and reflected components are calculated from various estimation models. The study shows the daily unit generation and efficiency of each module and also includes the operating cost, maintenance cost, and carbon-reducing the capacity of modules as well. Finally, by calculating the payback period of each technology it was found that Multi crystalline PV technology turns out to be the most efficient technology with maximum power generation and is the least cost-intensive. It was also analyzed that Mono-crystalline technology contributes most to CO_2 reduction but its operating and maintenance cost is much higher, while thin-film technology is the least efficient. Therefore, ultimately the Multi-crystalline PV technology turns out to be the most promising and feasible option out of all the four technologies analyzed, particularly for the location of Sabarmati river banks, Ahmedabad.*

Key Words: Solar panels, Renewable energy, Photo Voltaic Systems

1. INTRODUCTION

The amount of energy and its related services required for the social and economic development of people is increasing. The resource of fossil fuels which was used to be the primary source of energy for humans since centuries is now depleting. Moreover, the burning of fossil fuels to generate electricity causes great harm to the environment by producing pollution ranging from the release of greenhouse gases leading to climate change to health-endangering particles leading to deadly diseases. Increasing demand for energy along with population increment has led government authorities to shift from conventional sources of energy to non-conventional sources. Returning to renewable sources is a superlative approach to mitigating climate change. With the launch of the sustainable development goals by the United Nations, every nation went on policies and laws of sustainable development. Affordable and Clean Energy is one of the UN sustainable goals which shows awareness and motivation in people globally for shifting to clean energy sources. Also, renewable energy is derived from energy sources that can be replenished in one human lifetime, making it virtually inexhaustible. Furthermore, it does not release any harmful greenhouse gases during the production of energy and hence making it the cleanest and most viable solution to prevent climate change. However, among the most widely used renewable sources of energy, solar energy has proved to be the most beneficial source of energy as it is the cleanest and greenest energy source, helps in reducing electricity bills and, has low maintenance costs compared to its alternatives and offers a plethora of applications. Solar energy is nothing but the radiance energy reaching the earth's surface in the form of sunlight. The approximate amount of solar energy reaching the earth's atmosphere is about 1360W/m^2; but, due to the reflection and losses to atmosphere effects, maximum solar power reaching earth's surface is 1000W/m^2. To signify the importance of solar energy, approximately 1.5*1018 kWh of solar energy reaches the earth surface annually which is more 10,000 times the world's total energy use. We utilize the solar energy coming in the form of electromagnetic waves in mainly two forms, visible waveform region by solar photovoltaic and infrared waveform by solar thermal. The image mentioned below represents the solar radiation map of India. It is apparent from the map that entire country is rich in solar energy potential, but the particular state of Gujarat 10 is receiving hefty number of solar radiations which makes it best possible location to test and try different PV technologies for their efficiency and power generation capabilities. Also, the intensity of Orange color represents the solar energy potential (kWh) of that location, darker the color the more solar energy available in that particular region. The Ministry of New and Renewable Energy Sources of India is committed to promote the green sources of energy and to mitigate the emission of CO2. Among the available renewable energy sources, India has very favourable conditions for utilizing the solar energy and it promises to setup one of the largest PV solar energy markets in the world. Gujarat government has set a target of 30,000 MW of renewable energy generation by 2022 from the current 9,670 MW in 2019 which includes 6,880 MW of wind energy and 2,654 MW of solar energy. In January 2019, the government announced that solar power generation will be increased by 3,000MW annually. In the Gujarat government's new 2021 policy for solar energy, the condition of 50% sanction load has been scrapped and now an individual can produce solar power as per their requirement without any limits. It encourages installation of small and medium scale solar projects on residential and commercial premises. The consumer can give rooftop or premises on lease to produce energy without any load restrictions and can sell surplus power at a tariff of 2.25 per unit. Also, Gujarat is set to get India's largest renewable energy generation park with capacity of 30GW near Kutch district. Projects like Narmada canal solar power production can be established in one or other way which also helps in saving water.

Our purpose in this project is to do theoretical analysis of Photovoltaic system along with its installation and cost analysis on the bank of Sabarmati River. We will study the conditions around the desired area, factors affecting solar panel in its way of generating energy and will come up with the best estimation for the same and also analyse the feasibility for the same. In near future, conventional sources are not going to exhaust but Climate change effects are real concern nowadays and shifting to solar energy for electricity purposes would be beneficial to the human kind.

2. Calculations

2.1 Basic Solar Parameters

$\delta = 23.45 * sin[(360/365)(284+n)]$

δ = Declination angle which is defined as the angular distance of the sun's rays north or south of the equator. If a line is extended from the centre of the Sun and projected upon Earth's equatorial plane, the angle between these two lines gives the declination angle. Due to the tilt of the earth's axis, the declination angle varies from 23.5° on Summer solstice and -23.5° on winter solstice and on equinoxes, the declination angle is zero.

n = Number of days in a year counted from 1st January.

As the earth's orbital velocity varies throughout the year, the civil day which is exactly equal to 24 hours varies slightly from the solar day which is approximately equal to 24hours. This variation is called Equation of time (EOT). It may be considered constant for a given day and an approximate equation to calculate EOT is given by Duffie and Beckman,

$EOT = 3.82 \times (0.000075 + 0.001868 * \cos(B) - 0.032077 * \sin(B) - 0.014615 * \cos(2B) - 0.04089 * \sin(2B))$

Where 'B' is a constant used in equation of time (°) and is calculated as $B=(360/365)(n-1)$

The Hour angle is the angle by which the earth must rotate to bring the meridian of a point directly in line with the sun's rays. It is measured exactly from the noon according to the local solar time. Thus, at noon, the hour angle is zero, before noon it is a positive number and after noon it is a negative number. Duffie and Beckman provided the following equation to calculate hour angle,

$\omega = (t_s - 12) * 15$

Where, 'ts' is the local solar time in hours is obtained as,

$t_s = t_c + (\lambda/15) - Z_c + EOT$

Where, 'tc' is the local clock time in hours 'λ' is the longitude of the location and 'Zc' is the time zone.

3. Irradiation

3.1 Global Horizontal Irradiance (GHI) - It is the radiation reaching the surface of earth and can be considered as total amount of shortwave radiation received by a horizontal surface on the ground.

$GHI = DHI + DNI cos\theta_z$

Where, θz=Hourly Zenith Angle defined as the vertical angle between Sun's rays and a line perpendicular to the horizontal plane through the point and can be calculated as,

$\theta z = cos^{-1}(\sin\delta \sin\phi + \cos\delta \cos\phi \cos\omega)$

3.2 Direct Normal Irradiance (DNI) – The radiations which falls on the plane that is perpendicular to the vector joining centre of the earth and sun and which does not interact with the atmosphere are called direct normal radiations. It plays an important part in PV systems and is measured by a Pyrheliometer whose receiving surface is kept normal to the solar radiations. Seyed Abbas Mousavi Maleki proposed parametric models to calculate direct normal irradiation,

$DNI = GHI - DHI/cos\theta_z$

3.3 Diffuse Horizontal Irradiance (DHI) – It is the part of DNI which gets dispersed/scattered by the particles present in the atmosphere or the radiations which are reflected back from the ground called as albedo. It is measured by a shaded pyranometer. It becomes a difficult task to gather such data because of high prices of measuring equipment, therefore number of mathematical models are already defined to estimate diffuse radiation on horizontal surfaces. Particularly in this research project the Decomposition model proposed by Muneer is utilized which is formed on the basis of correlation between total along with diffuse radiation on horizontal surface as a function of hourly clearness index (K_t). The correlation is as follows;

For $0 < K_t < 0.175$,

$DHI = (0.95) * GHI$

For $0.175 < K_t < 0.755$;

$DHI = (0.9698 + 0.4353K_t - 3.4499K_t^2 + 2.1888K_t^3) * GHI$

For $0.775 < K_t < 1$,

$DHI = (0.26) * GHI$

Where, GHI is available from procured data and K_t is Clearness index which is a measure of the effects on atmosphere in an isolated place. It is defined as the ratio of Global horizontal irradiation to the extra-terrestrial radiation and it varies according to the time of the year, climatic conditions and geographical location of a place. K_t is calculated from Homer's equation,

$K_t = H_{avg} / H_{0,avg}$

Where, H_{avg} = Monthly average radiation on earth's horizontal surface,

H_{avg} is derived from procured data;

$H_{0,avg}$ = the extra-terrestrial horizontal radiation, the radiation on the top of the earth's atmosphere.

If the latitude of any given place is known, $H_{o,avg}$ can be calculated for any month of the year from equations given by HOMER. The technique homer uses to calculate Monthly Average Extra-terrestrial Radiation **(**$H_{o,avg}$**)** is given below;

Following equation is used to calculate intensity of solar radiation on top of earth's atmosphere,

$G_{on} = G_{sc}[1 + 0.033*\cos(360n/365)]$

G_{sc} = Solar constant [1367 W/m^2]

n = day of the year calculated from 1st January

The total daily extra-terrestrial radiation per square meter is given by following equation,

$H_0 = (24/\pi)*G_{on}[cos\o*cos\delta*sin\omega s\{\pi*\omega s/180^\circ\}*sin\o*sin\delta]$

Where, ωs = Sunset Hour angle

$\omega s = cos^{-1}[\tan(\emptyset)*\tan(\delta)]$

ø = latitude angle for location chosen for research and can be taken as constant throughout the year.

δ = Declination angle

Now, as average daily extra-terrestrial radiation (H_0) is calculated, by the below mentioned Homer's equation, the average extra-terrestrial horizontal radiation for the month can be calculated as $K_t = H_{avg} / H_{0,avg}$.

Proceeding further, as all the necessary values to find the clearness index (K_t) are obtained, K_t can be derived by substituting them in above given equation. Finally, with clearness index (K_t) and GHI, the diffuse horizontal irradiance (DHI) can be calculated from correlation given by Muneer.

Therefore, all the solar radiations on horizontal surfaces are now calculated. But, in order to estimate PV cell temperature, the In-plane solar irradiance (IPOA) is necessary. Now by incorporating Badescu's model for transposition of radiations from horizontal surfaces to tilted surfaces it becomes possible to calculate Beam radiation, Reflected radiation and diffuse radiations on tilted surface.

3.4 In-Plane Irradiance

Most of the solar irradiation data available from the meteorological ground stations are of global solar irradiation on horizontal surface (GHI). However, for determining the performance of the PV module, the plane of array (POA) irradiance, i.e., solar irradiance incident on the module is required, whose data is frequently not available. Certain models have been developed under the name "Transposition Models" for determining the POA irradiance. Badescu estimated a model for diffused solar radiation on tilted surfaces in which the total radiation falling on tilted surfaces was given by,

$HT = HbRb + Hg\rho[(1-cos\beta t)/2] + Hd[(3 + cos2\beta t)/4]$

Here, H_T = In-plane solar irradiance (I_{POA}) which will be used to calculate PV cell temperature.

Where, H_b = Monthly average of daily beam radiation on horizontal surface (DNI)

$R_b = cos\theta/cos\theta z$

Hg = total solar radiation on horizontal surface (GHI)

ρ = ground albedo which depends on the type of ground surface

H_d = diffuse radiation on horizontal surface (DHI)

β_t = tilt angle of surface kept constant = 0.9*Latitude angle(ø)

4. Cell Temperature

To assess the efficiency of PV installations it becomes pivotal to estimate the PV module temperature accurately. As solar cells are semi-conductors their characteristic power curve is affected significantly by cell temperature. With increasing module temperature, the open-circuit voltage decreases significantly while there is not much increase in short-circuit current, as a result due to increased cell temperature the efficiency of PV system decreases. Therefore, to predict the PV cell temperature accurately various scholar have developed the model that parametrize the physical relation between cell temperature, In-plane irradiance (IPOA), wind speed, ambient temperature and in some cases wind direction too. After a comprehensive assessment of different research papers, the correlation presented by Kurtz to calculate cell temperature was used in this study

$Tc = Ta + I\cdot e - 3.473 - 0.0594[vw]$

Where;

Ta = Ambient temperature [from procured data]

I = In-plane irradiance (IPOA) [calculated above]

Vw = Local wind speed [from procured data]

5. Power Calculations

Determining the efficiency of a panel is extremely important in order to choose the superlative panels for our photovoltaic system. In order to calculate the efficiency of the solar module, individual I-V parameters such as short-circuit current (Iscs), open-circuit voltage (Vocs), maximum power (Pmax), maximum current (Imps), maximum voltage (Vmps) and fill factor (FF) has to be taken into consideration. These parameters can be obtained in the data sheet of the selected module but they are obtained under standard testing conditions i.e. (Irradiation =1000W/m2 and Ambient temperature = 25° Celsius).

However, there is a significant variation in the irradiance and ambient temperature throughout the year from the standard conditions which is visible from the collected data. Hence, these parameters cannot be considered directly to calculate the efficiency. This is where the degradation rates of the module come into the picture. Using the module temperature coefficients of short-circuit current, open-circuit voltage and maximum power; α, β and γ respectively, the voltage and current for each month can be estimated. The values of these degradation factors along with other parameters of the selected module are mentioned in the annexure.

The equations mentioned in the research done by R. Ayazare used to determine the new I-V parameters,

$Isc(G,Tc)= Iscs*G/Gs*[1+\alpha(Tc-Ts)]$

$Imp(G,Tc)=Imps*G/Gs*[1+\alpha(Tc-Ts)]$

$Voc(Tc)= Vocs + \beta(Tc-Ts)$

$Vmp(Tc)= Vmps + \beta(Tc-Ts)$

Where, I_{SCS}, I_{MPS}, V_{OCS}, and V_{MPS} are obtained from the datasheet of a module provided by the manufacturer. G and T_C are the total irradiation and cell temperature. Gs and Ts are the irradiation and surrounding temperature at standard testing conditions. Further, calculations of the fill factor and Power for the module is done.

$Fill\ Factor\ (FF)= (Pmax/Isc*Voc) = (Vmp*Imp/Isc*Voc)$

$Power\ (Pm)= FF*Voc*Isc$

Finally, the panel efficiency determines the power output of a solar panel per unit area. Maximum efficiency of a solar panel can be given by the following equation,

$Maximum\ efficiency = (Maximum\ Power\ output) / (Incident\ radiation*Area\ of\ collector) * 100\ \%$

Incident radiation is assumed as 1000 W/m^2 under standard test conditions that the manufacturers use.

7. Results and Discussion

Sabarmati Riverfront area near Usmanpura, Ahmedabad is selected as the site for this particular research project. Latitude and Longitude for this site are 23.04277° and 72.5727° respectively and the time zone is +5.5 GMT. This site is near the river as a result the temperature here remains lower than rest of the city.

Cell temperature is very much sensitive to the ambient temperature and wind speed. Ambient temperature increases during March to June and it is highest in the month of May. December to February is winter and July to September is monsoon. Particularly in October which marks the end of monsoon, ambient temperature rises.

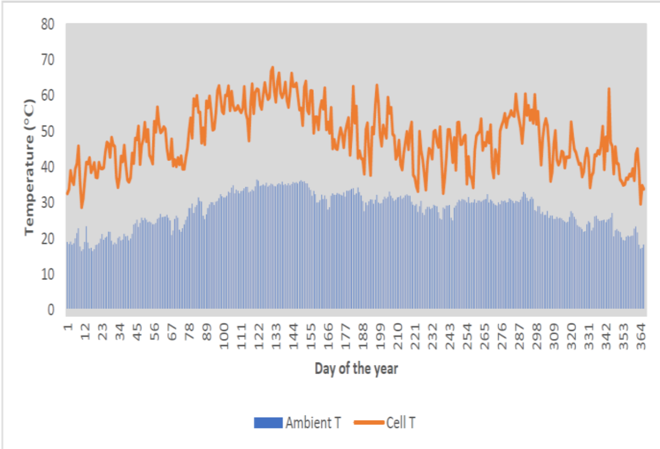

Figure 1 - Daily ambient and cell temperature

Four types of PV cell technologies, Mono-crystalline cells, Multi-crystalline cells, thin-film cells and HIT cells were selected for this study. Their specifications are attached in annexure. It is ostensible that multi-crystalline and thin-film cells will produce lesser number of units per day but there are variations in this when other parameters like energy losses are considered. HIT stands for Heterojunction with Intrinsic Thin-film. This type of cells are combination of monocrystalline cells and amorphous silicon thin-film. Monocrystalline layer is sandwiched between two a-Si layers. This particular technology improves the behaviour of cells with temperature and hence the efficiency of the cell. This advanced technology is relatively new in the market and thus expensive.

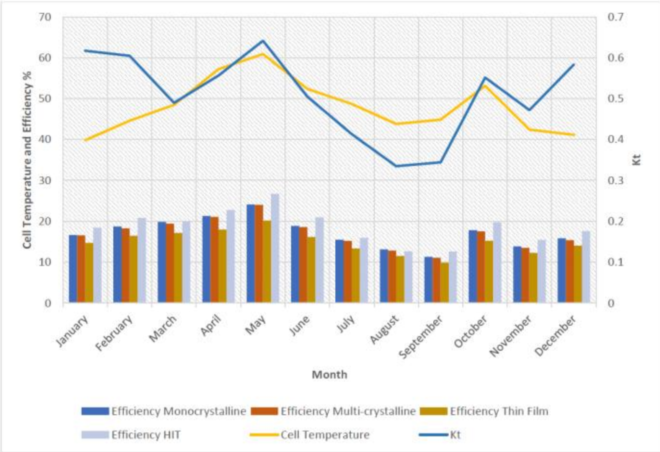

Figure 2 - Efficiency variation with cell temperature and clearness index

In this, seasonal variation in efficiency is clearly observed. In monsoon season, efficiency decreases, it is highest in the month of May. Spectral Radiometer would be helpful in predicting in-plane irradiance for particular site and this will improve the results.

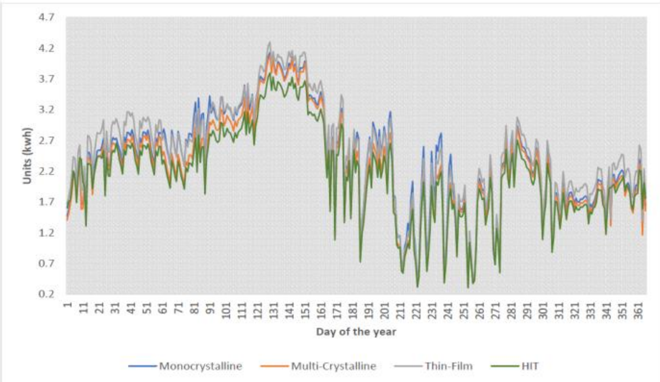

Figure 3 - Daily Unit generation

Power generation by single module is higher in thin-film is higher compared to others. Also, a point to be noted that this particularly chosen panel has higher rated power relatively. HIT panels have lowest rated power but still manages to generate good amount of power.

Even if thin film cells generates more units, it's efficiency is the least. Monocrystalline and multi-crystalline has got much of similar numbers but monocrystalline cells produce more power and also looks more efficient than later. Also, HIT panels have the highest efficiency among all due to its lower degradation coefficient.

7.1 Design of 100KW Photovoltaic System

To design 100KW PV system, Solar panel requirement of each technology is calculated below.

Table 1 - Module Requirement for 100KW System

	Monocrystalline	Multi-crystalline	Thin Film	HIT
Pmax	365	345	420	340
	273.9726027	289.8550725	238.095	294.11
Panel required	274	290	238	294

Central Inverter of Delta Electronics of 125kw capacity is taken for this. The conversion efficiency of the inverter is 96% rated in datasheet.

Here Light induced degradation factor is not included. It will not occur in Thin-Film and HIT technology. It will be less in monocrystalline and highest in multi-crystalline modules. For monocrystalline it is taken 0.75% and for lateral it is 1.5%. After computing everything we get below listed results.

Table 2 – Monthly Unit Generation (MWh)

	Mono-crystalline	Multi-crystalline	Thin-Film	HIT
January	15.49	15.65	15.06	16.37
February	17.53	17.82	16.8	17.63
March	19.55	17.85	16.65	17.51
April	22.06	21.78	19.49	21.03
May	27.14	28.15	24.7	27.01
June	18.79	19.31	17.51	18.74
July	15.5	14.39	13.29	14.05
August	11.72	10	9.46	9.89
September	9.36	9.54	8.91	9.36
October	16.49	16.93	15.42	16.45
November	11.52	11.68	11.11	11.55
December	13.51	13.66	13.09	14.14
Total Units	198.66	196.75	181.49	193.74

It is evident that Mono-crystalline technology is performing better than the other two when considering 100kW system. Also, Mono-crystalline panels appear to be more efficient. Although Multi-crystalline generates 196.67 MWh of power and Mono-crystalline generates 196.86MWh of power. HIT has also good amount of generation. The unit difference between both technologies is about 1910kWh.

Table 3 - Price Comparison

	Monocrystalline	Multi-crystalline	Thin Film	HIT
Price per module	9125	7590	173 (USD)	340 (USD)
GST/VAT (%)	5	5	5	5
Total (INR)	9581.25	7969.5	13313.1285	26164.53
Inverter	Delta Inverter (Central) 3,57,000* (INR)			
Annual Operations and Maintenance Cost (INR)	83,482	74,059	99,780	2,35,496
Total cost (INR)	29,82,762	26,68,65	35,26,024	80,49,872

Mounting costs and other miscellaneous initial costs have not been included in this as of now. 3% of the system cost is assumed as Operation and Maintenance cost, and it is increasing at rate of 3% annually.

With these calculations, payback period for monocrystalline technology is 3.7 years, for multi-crystalline technology, it is 3.3 years for Thin-film system, it is 4.8 years. Because of costly HIT panels, it is 10.2 years.

Yearly Degradation for Adani's each technology is rated at 0.68% and First Solar's values is rated at 0.5% in the datasheet. Panasonic's panels are rated for as low as 0.45%. Adani products have 12 Years of performance warranty as per datasheets. So, the power output for 12 years is considered and is listed below.

Table 4 – Power generation for 12 years (MWh)

Power	Mono-crystalline	Multi-crystalline	Thin-Film	HIT
Year 1	198.66	196.75	181.49	193.74
Year 2	197.31	195.41	180.58	192.87
Year 3	195.97	194.08	179.68	192
Year 4	194.63	192.76	178.78	191.14
Year 5	193	191	178	190
Year 6	192	190	177	189
Year 7	190.69	189	176	188.57
Year 8	189.39	187.57	175.23	187.72
Year 9	188.1	186.3	174.36	186.87
Year 10	186.83	185.03	173.49	186.03
Year 11	185.56	183.77	172.62	185.2
Year 12	184.29	182.52	171.76	184.36
Total	2296.73	2274.64	2119	2268.1

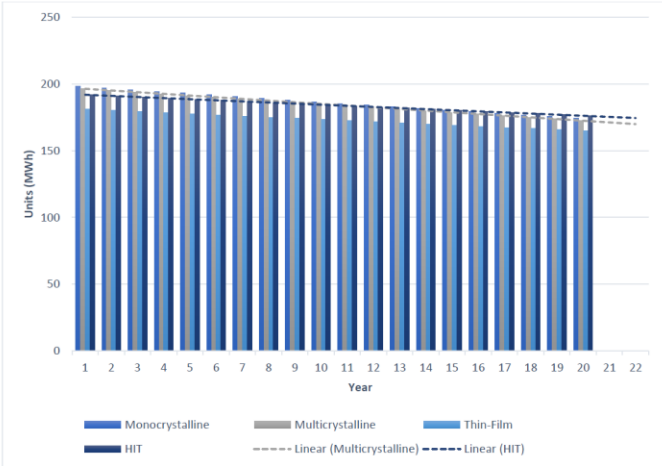

Figure 4 - Yearly degradation for 20 Years

In the above graph, it is observed that HIT system's power output surpasses multi-crystalline system's from 9th year and monocrystalline from 12th year. This proves HIT's great cell temperature behavior.

Total cost at the end of 12 years including operations and maintenance costs as well is **42,51,993** for *Mono-crystalline* PV System, **38,04,151** for *Multi-crystalline* PV System **50,26,55** for *Thin-Film* PV System and **1,14,76,479** rupees for *HIT* PV System.

For Mono-crystalline, LCOE is **1.72**Rs/KWh, for Multi-crystalline its **1.54**Rs/KWh and for Thin-Film, its **2.2**Rs/KWh. Being the costliest, HIT has currently 5.05Rs/KWh.

Although considering energy selling price at 4.3 rupees per unit in Gujarat as of May 2021, it will cost us around 84 lakhs in 12 years to produce the energy which these panels are providing. It makes the LCOE for this energy source about **4.54**Rs/KWh.

Considering CO2 reduction factor as 0.82 tonnes/MWh, at the end of 20 years, CO2 reduction by them is shown below.

Table 5 – Carbon Reduction in tonnes

Year	Mono-crystalline	Multi-crystalline	Thin-Film	HIT
1	198.66	196.75	181.49	192.17
2	197.31	195.41	180.58	191.31
3	195.96	194.08	179.68	190.45
4	194.63	192.76	178.78	189.59
5	193	191	178	188.74
6	192	190	177	187.89
7	191	189	176.11	187.04
8	189.39	187.57	175.23	186.2

9	188.1	186.3	174.36	185.36
10	186.82	185.03	173.49	184.53
11	185.55	183.77	172.62	183.7
12	184.29	182.52	171.75	182.87
13	183.04	181.28	170.9	182.05
14	181.79	180.05	170.04	181.23
15	180.56	178.82	169.19	180.41
16	179.33	177.61	168.35	179.6
17	178.11	176.4	167.5	178.79
18	176.9	175.2	166.67	177.99
19	175.7	174.01	165.83	177.19
20	174.5	172.82	165	176.39
Total	3726.65	3690.82	3462.4	3683.4

HIT system's CO2 reduction also improves after 12th year while comparing to multi- crystalline and after 15th year while comparing to monocrystalline.

8. Conclusion

The cost of Monocrystalline technology is more than Multi-crystalline. On the contrary, the life time carbon reduction of Monocrystalline technology is greater than other two and is about 18 tons more than multi-crystalline. As it is having high initial cost and larger payback period than multi-crystalline, choosing monocrystalline over multi-crystalline is not justified.

Thin film technology is said to be the cheapest around the globe, but in country like India there are very scarce amount of distributers of this particular technology and if required it must be imported which makes its initial cost much higher than other two readily available technologies. Further, it is having the least efficiency amongst all and is contributing very less in carbon reduction, making its payback period much more than other two. Therefore, thin film was the least preferable alternative out of all. 40

HIT panels have significant efficiency about 21% and is very much suitable for region having higher temperature. But as it is advanced and relatively new, the panel cost is way higher than any other. Also, they are not available in India. Thus, initial cost is significantly high for this particular. It is a great choice if there is lesser price for module.

The most efficient technology is Multi-crystalline as it is having least initial cost, and is generating almost equal power to that of monocrystalline. Its carbon reduction capacity is also marginally less than monocrystalline and has the least payback period.

Table 5 - Summary

	Mono-crystalline	Multi-crystalline	Thin-film	HIT
Power Capacity (kW)	100	100	100	100
No. of panels required	274	290	238	294
Initial cost of setup (INR)	29,82,762	26,68,655	35,26,024	80,49,872
Annual electricity generated (MWh)	198.66	196.75	181.49	192.19
Pay-back period (Years)	3	3	5	10.02
Levelized cost of electricity (LCOE) (Rs/kWh)	2	2	2	4.9
Lifetime saving (INR)	70,75,725	73,13,015	56,43,984	-
Annual Carbon reduction (tonnes)	162.9	161.33	148.82	158.86
Lifetime carbon reduction (tonnes) (12 Years)	1883.32	1865.2	1737.58	1859.91

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BIOGRAPHIES

Mr. Jainil Prakashkumar Patel, has completed his Bachelor of Technology in Mechanical Engineering from School of Engineering and Applied Science, Ahmedabad University.

Mr. Priyank Vipulbhai Patel, has completed his Bachelor of Technology in Mechanical Engineering from School of Engineering and Applied Science, Ahmedabad University.

Mr. Shrey Tushar Patel, has completed his Bachelor of Technology in Mechanical Engineering from School of Engineering and Applied Science, Ahmedabad University.