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Comparative Assessment of different Solar PV Technologies in Various Climatic Zones of India

Radhika[1] and S.K. Suman[2]

[1]M. Engg., Electrical Department, PEC University of Technology, Chandigarh–160012, India
[2]Electrical Department, PEC University of Technology, Chandigarh–160012, India
E-mail: [1] radhikaradhu12345@gmail.com, [2]sksuman@gmail.com

Abstract— *Solar energy is the cleanest, most abundant renewable energy source available. Solar energy is the best solution for energy crises, especially in developing countries where there is huge gap between demand and generation, like INDIA. In India, Solar PV is emerging power generation technology which is spreading almost in every state, every town rapidly. Also Government of India has taken several initiatives in this field and expects 100GW power from solar PV by 2020. In this paper, the performance of different PV technologies in 10 different climatic zones of India was analyzed using three different models: TerraSAS PV Array Simulator, PVWatts Calculator developed by NREL and 'SPV4ALL' from TERI. The main objective of this paper is to find out best suited PV technology with respect to the respective location from point of view of annual AC energy generated (kWh), cost of electricity generated (INR) and the payback period(years).*

1. INTRODUCTION

With the day by day advancement in technology, the energy consumption and energy requirement also increases with tremendous speed which can never be fulfilled by the centralized generation from fossil fuels. Thus for the developing country like India, the only solution is to promote the power generation from renewables. In the renewable energy resources, Solar PV is one of the cost effective as well as clean with zero emission power generation technology. Solar PV also have advantages like it support decentralized generation near to the load side with low maintenance and can be installed on rooftop of every building thus consequently it reduces the transmission loses also. Solar PV also has less payback period. As India locates between Tropic of Cancer and Equator, it has huge potential for solar with 300-330 sunny days every year with average annual temperature ranges from 25˚C – 27˚C which is almost equivalent to 5000 Trillion kWh per year which is more than India's total energy consumption per year[1].

Current Status of Solar installation in India
Current power generation from PV in India is 3000MW approximately. State-wise SPV installation [2] is given in table I.

Table 1: State wise solar installation in India

Sr. No	State/UT	Total commissioned capacity in MW till 15/12/14	Sr. No	State/UT	Total commissioned capacity in MW till 15/12/14
1	Andhra Pradesh	234.86	13	Rajasthan	839.5
2	Arunachal Pradesh	0.025	14	Tamil Nadu	104.2
3	Chhattisgarh	7.6	15	Telangana	8
4	Gujarat	929.05	16	Uttar Pradesh	29.51
5	Haryana	12.8	17	Uttarakhand	5
6	Jharkhand	16	18	West Bengal	7.21
7	Karnataka	67	19	Andaman & Nicobar	5.1
8	Kerala	0.025	20	Delhi	5.465
9	Madhya Pradesh	353.58	21	Lakshadweep	0.75
10	Maharashtra	286.9	22	Pondicherry	0.025
11	Orissa	31.5	23	Chandigarh	2
12	Punjab	55.77	24	Others	0.79

Govt. of India initiatives in PV industry
The Jawaharlal Nehru National Solar Mission is the major initiative taken by Govt. of India. The Jawaharlal Nehru National Solar Mission (JNNSM) aims at development and deployment of solar energy technologies in the country to achieve parity with grid power tariff by 2022. In this Mission (NSM), the Government of India and State Government works to promote ecologically sustainable growth while addressing India's energy security challenge. It will also constitute a major contribution by India to the global effort to meet the challenges of climate change. The objective of the National Solar Mission is to establish India as a global leader in solar energy, by creating the policy conditions for its diffusion across the country as quickly as possible. The Mission will be completed in 3-phases, straddling the remaining period of the 11^{th} Plan and first year of the 12^{th} Plan (up to 2012-13) as

Phase 1, the remaining 4 years of the 12th Plan (2013-17) as Phase 2 and the 13th Plan (2017-22) as Phase 3. The aim would be to protect Government from subsidy exposure in case expected cost reduction does not materialize or is more rapid than expected[3]. The proposed roadmap is given in table II.

Table 2: Proposd Roadmap for Solar in India

Sr. No.	Application Segment	Target for Phase 1 (2010-13)	Target for Phase 2 (2013-17)	Target for Phase 3 (2017-22)
1.	Solar collectors	7 million square meters	15 million square meters	20 million square meters
2.	Off grid solar applications	200 MW	1000MW	2000 MW
3.	Utility grid power, including roof top	1000-2000MW	4000-10,000 MW	20000 MW

In this paper different PV technologies which are globally available (monocrystalline, polycrystalline and thin-film) were compared for various climatic zones of India using three different models and the best suited PV technology for a particular location was found out. These technologies are explained as follows:

Monocrystalline

Monocrystalline PV technology is made out of the highest-grade silicon thus has the highest efficiency. The efficiency typically lies between 20-25%. Monocrydtalline solar panels are space-efficient also as they need the least space for the same output comparative to other PV technology. These panels can produce up to four times the amount of electricity produce by thin-film solar panels. These panels have better performance in low-light condition comparative to polycrystalline. These are most expensive solar panels.

Polycrystalline

Polycrystalline PV technology has the efficiency between 15-20%. Polycrystaline solar panels need more space comparative to monocrystalline and require less space comparative to thin-film for the same output. These solar panels have moderate cost. They are more affected by the temperature as compare to monocrystalline panels.

Thin-film

Thin-film PV technology have the lowest efficiency comparative to crystalline technology. The efficiency lies between 5-13%. Thin-film includes different types of solar cells which are categorized by which photovoltaic material is deposited onto the substrate:

- Amorphous silicon (a-Si)
- Cadmium telluride (CdTe)
- Copper indium gallium selenide (CIS/CIGS)
- Organic photovoltaic cells (OPC)

These three PV technologies are compared for 10 different climatic zones in India. The different climatic zones with their climatic conditions are given in table3 and their location can be shown in the fig1.

Table 3: Table for 10 Climatic Conditions in India

Sr No.	Name	Description
1	Bengaluru	Moderate
2	Bhubaneswar	Humidity, salt content in environment because of nearby coastal area
3	Chandigarh	Hot &cold
4	Delhi	Dry
5	Gujarat	Highest insolation region, high potential for solar
6	Guwahati	Cloudy
7	Kolkata	Humidity, salt content in environment because of nearby coastal area
8	Pune	Moderate
9	Rajasthan	Highest insolation region, high potential for solar
10	Tamil Nadu	Humidity, salt content in environment of nearby coastal area.

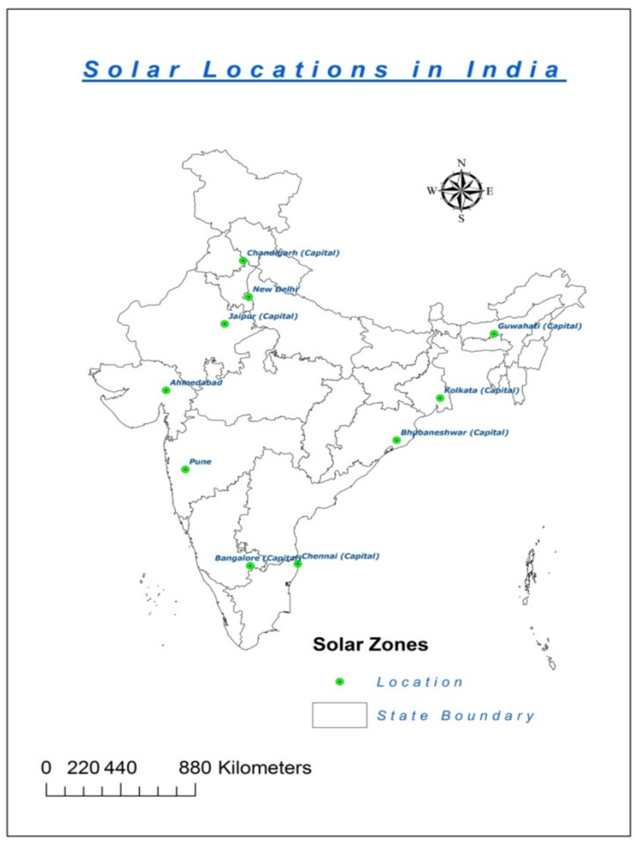

Fig. 1: Map for 10 different location in India.

2. METHODOLOGY

In the analysis, 5kWp Solar PV system for residential building with fixed array type was used. The methodology can be explained with the help of flow diagram as shown below:

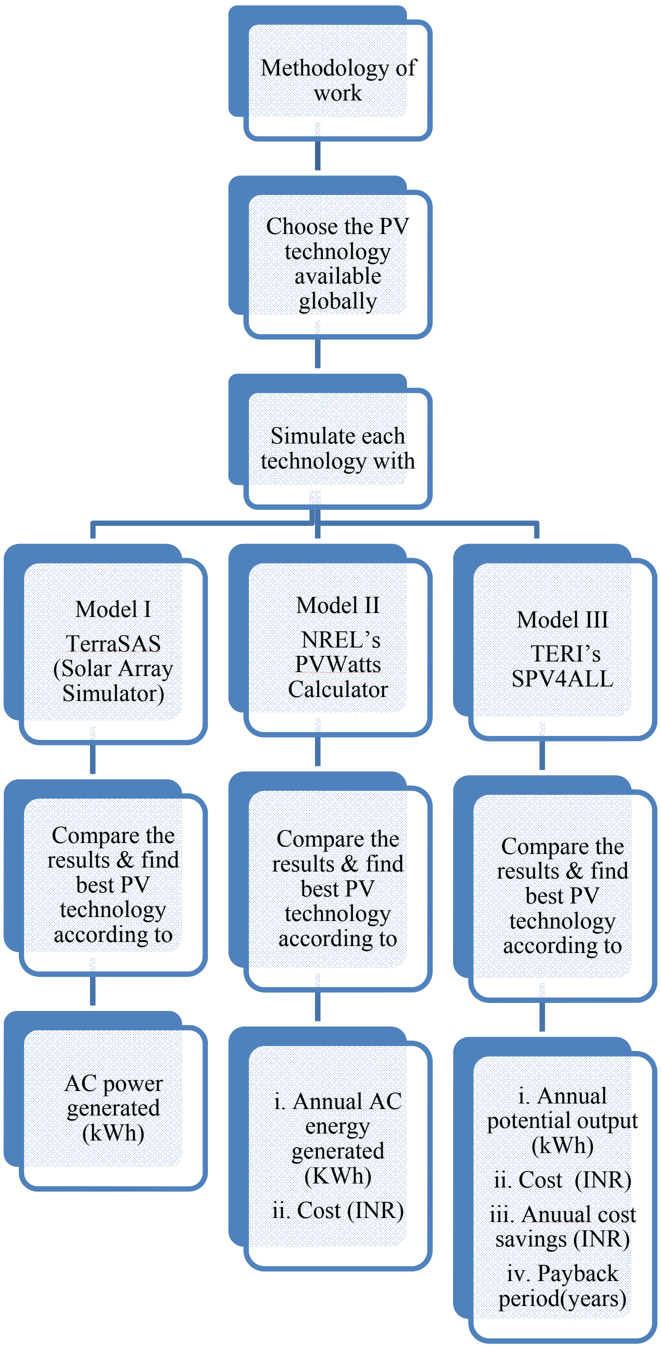

Fig. 2: Methodology of work analysis.

3. SOLAR RESOURCE DATA

Solar resource data used for the analyses is taken from NREL's website, National Renewable Energy laboratory (NREL), U.S. Energy Department. Monthly solar data from year 2002 to 2011 is available for these 10 different climatic zones[4]. How this data have been used in different models explained as follows:

Case I

TerraSAS Solar Array Simulator

In this model, for each climatic zone, latest solar data is used. In the analyses, the data for each day from 8AM till 5PM in the evening for month May in 2011 year is used for every zone.

Case II

PVWatts Calculator

As this model is generally the application designed by the NREL. It uses the same NREL solar data for each input location.

Case III

SPV4ALL

This model is the Android-based mobile phone application designed and developed by TERI (The Energy and Resources Institute). PVWatts's API is used to incorporate solar resource data and thus automatically takes up the solar resource data for each input location.

4. DETAILED ANALYSIS

a) Model I

TerraSAS Solar Array Simulator

TerraSAS stands for Terrestrial Solar Array Simulator, which is designed to provide the powerful features and ease of use. Its main design goals are:

- Import photovoltaic curves created with third party applications and also easily create the photovoltaic curves from manufacturer supplied data.
- Import irradiance / temperature profiles created in Microsoft Excel, third party applications or using real-time data acquisition from actual solar panels.
- Organize any number of curves, profiles and solar array configurations into graphic, filmstrip like pools for intuitive, easy access.
- Intuitive drag-and-drop interface to easily assign curves and profiles to individual array elements, to support accurate modeling of array shadowing patterns.
- Static and dynamic simulation preview of each configured array.
- Fully configurable real time trigger, measurement and data logging features.

- Full hardware monitoring and fault reporting system.
- Real time control of TerraSAS digital photovoltaic simulator systems (up to 100 channels).
- Real time control of standalone, desktop TerraSAS digital photovoltaic simulator units.

The different PV technologies used were monocrystalline, polycrystalline and thin-film. The electrical datasheet for these technologies is given in Table IV and its photovoltaic curves snapshot are shown in figure3.

Table 4: table for electrical characterstics of different pv Technologies

Module	Pmp(W)	Vmp(V)	Imp(I)	Voc(V)	Isc(I)	Module type
A	250	35.14	7.1123	43	7.75	polycrystalline
B	250	32.368	7.8267	37.8	8.28	monocrystalline
C	100	47.362	2.1164	58.8	2.33	Thin-film
D	100	23.646	4.397	29.04	4.8	polycrystalline

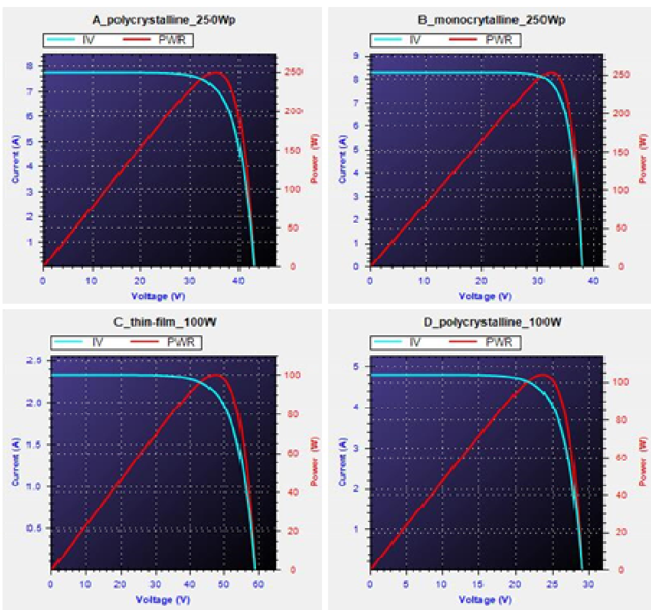

Fig. 3: Photovoltaic curves for different PV technology modules.

For the simulation, the inputs were

a. photovoltaic curve of module used,
b. irradiation profile of each climatic zone and
c. Solar array of 5kWp system (Grid-Connected).

The photovoltaic curve parameters (including V_{oc}, I_{sc},V_{mp}, I_{mp} P_{mp}) and the output which includes voltage, current and power which will now be the input to the inverter were shown. The result shows that each one PV technology has the same output in each zone shown in table V.

The snapshots of irradiation profiles and the result are shown in figure4, figure5 respectively.

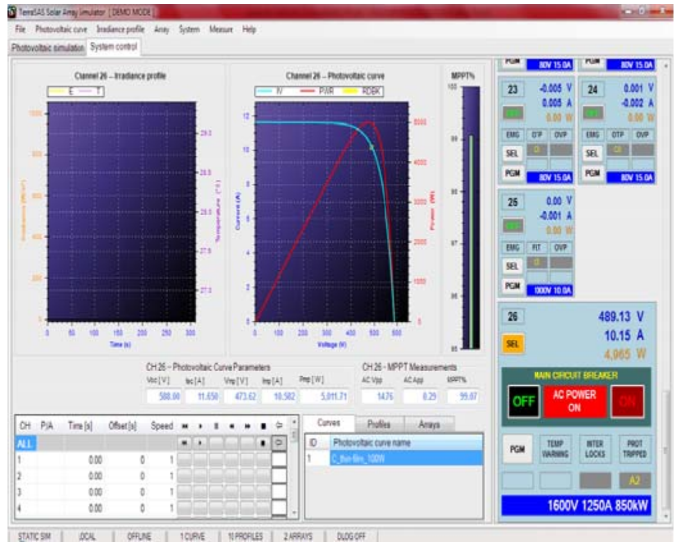

Fig. 5: Simulation result of Array C using module type C for Delhi climatic zone from 8:00 hours to 17:00 hours of each day of month May, 2011.

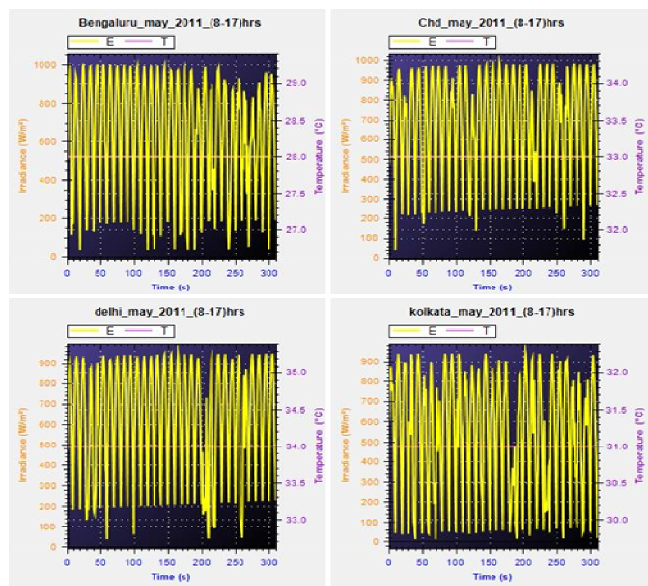

Fig. 4: Irradiation Profiles for 4 different climatic zones.

Table 5: Terrasas Results for each of 10 different climatic Zones of India

Module	Module Type	Module Wattage(Wp)	Power generated (kW) in month May,2011 for 8Hrs. to 17 Hrs. in 5kWp system
A	Polycrystalline	250	4956
B	Monocrystalline	250	5024
C	Thin-film	100	4968
D	Polycrystalline	100	5153

b) Model II

PVWatts Calculator

NREL's PVWatts Calculator is developed by the National Renewable Energy Laboratory (NREL), is a web application that estimates the electricity production of a photovoltaic system which can either be grid-connected roof- or ground-mounted. To use the calculator, provide information about the system's location, basic design parameters, and system economics. PVWatts calculates estimated values of annual and monthly electricity production, for a photovoltaic system that uses crystalline silicon or thin film photovoltaic modules [5].

For the analysis through PVWatts Calculator, the inputs were:

- System DC size (Wp)
- Module type(Standard, Premium, Thin-Film)
- Array type (Fixed, Single-axis, Dual-axis)
- System losses
- Array tilt angle
- Array azimuth angle

The system design assumptions can be redefined with three optional advanced inputs:

- DC to AC size ratio
- Inverter efficiency
- Ground coverage ratio

The value of inputs for the analysis were

- System DC size= 5kWp,
- Module type= Standard, Premium, Thin-Film
- Array type= Fixed,
- System type= Residential,
- For the array tilt angle, azimuth angle, DC to AC size ratio, Inverter efficiency etc. the by-default values were used.

The result will show the annual as well as monthly AC Energy generation, average cost of electricity purchased from utility which is INR3.63 per kWh for each zone and, initial cost which is INR127.38 per dc watt for each zone, cost of electricity generated by the system per kilowatt hour. Table VI show the AC Energy generation annually and the cost of electricity generated by the system per kilowatt hour.

Table 6: PVWatts Results for 10 different Climatic Zones in India

Location	Module Type					
	Standard		Premium		Thin-Film	
	1	2	1	2	1	2
Bengaluru	7749	6.21	7982	6.03	8229	5.84
Bhubaneswar	6970	6.90	7216	6.67	7493	6.42
Chandigarh	7220	6.66	7464	6.44	7736	6.28
Delhi	6933	6.94	7186	6.69	7478	6.43
Gujarat	7822	6.15	8135	5.91	8482	5.67
Guwahati	6506	7.39	6748	7.13	7024	6.85
Kolkata	6724	7.15	6947	6.92	7202	6.68
Pune	7675	6.27	7942	6.06	8237	5.84
Rajasthan	7764	6.2	8068	5.96	8409	5.72
Tamil Nadu	7610	6.32	7868	6.11	8150	5.90

Where

1. AC energy, kWh per year.
2. Cost of electricity generated by the system, INR per kWh.

c) Model III

SPV4ALL

Solar PV for all (“SPV4ALL”) is an initiative taken by The Energy and Resources Institute (TERI), and supported by Shakti Sustainable Energy Foundation (SSEF) to promote solar PV systems in India. The ‘SPV4ALL’ mobile application is initially developed for Android mobile devices, using which one can estimate the electricity production of a grid-connected or, off-grid solar photovoltaic system based upon few simple input parameters. To use the solar simulation tool under ‘SPV4ALL’ mobile application, one will need to select a location of interest on map either through find location or, using in-built GPS, specify the space available to install the solar PV system, and provide some basic information about the system cost, and electricity rate. ‘SPV4ALL’ mobile application calculates estimated value of electricity production, capital investment cost, CO2 savings, payback period [6].

In this model, the inputs were

- Location,
- Total solar rooftop area in meter square,
- PV technology = crystalline and thin-film,
- grid-tie system,
- PV system size = 5 kW,
- Building type = residential and
- For the efficiency, system cost per watt, electricity rate, tilt angle use the by default values.

The result show:

- Potential annual output in kWh per year,
- Total incoming solar radiation in kWh per meter square per day,
- Potential cost savings in INR,
- Annual CO_2 saving in tonnes,
- Potential system cost in INR,
- Subsidy in percentage
- Capital investment in INR,
- Payback period in years.

The solar PV output for 5kWp, residential and Grid-tie system from SPV4ALL for crystalline technology is tabulated in table VII and for thin-film technology in table8.

Table 7: Solar Pv Output for Crystalline Technology

Location	a	b	c	d	e
Bengaluru	6964.71	5.8	34823.54	30.99	5.74
Bhubaneswar	6346.27	5.29	31731.36	28.24	6.3
Chandigarh	6566.44	5.47	32832.2	29.22	6.09

Delhi	6337.12	5.28	31685.59	28.2	6.31
Gujarat	7250.13	6.04	36250.63	32.26	5.52
Guwahati	5984.27	4.99	29921.36	26.63	6.68
Kolkata	6081.26	5.07	30406.31	27.06	6.58
Pune	6974.98	5.81	34874.91	31.04	5.73
Rajasthan	7188.12	5.99	35940.61	31.99	5.56
Tamil Nadu	6973.43	5.81	34867.16	31.03	5.74

Table 8: Solar Pv Output for thin-Film Technology

Location	a	b	c	d	e
Bengaluru	6167.25	5.8	30836	27.44	5.74
Bhubaneswar	5619.62	5.29	28098	25.01	6.3
Chandigarh	5814.58	5.47	29072.91	25.87	6.09
Delhi	5611.52	5.28	28057.59	24.97	6.31
Gujarat	6419.99	6.04	32099.94	28.57	5.52
Guwahati	5299.07	4.99	26495.37	23.58	6.68
Kolkata	5384.96	5.57	26924.79	23.96	6.58
Pune	6176.35	5.81	30881.73	27.48	5.73
Rajasthan	6365.08	5.99	31825.41	28.32	5.56
Tamil Nadu	6174.97	5.81	30874.87	27.48	5.74

Where
a = Potential annual output in kWh per year
b = Total incoming solar radiation in kWh per meter square per day
c = Potential cost savings in INR,
d = Annual CO_2 saving in tonnes,
e = Payback period in years

Other outputs were as follows:

- Potential system cost for
  Crystalline= INR 4, 00,000
  Thin-film= INR 3, 54,200
  Subsidy in percentage is 30% in all cases.
- Capital investment for
  Crystalline INR 2, 00,000 and
  Thin-film INR 1, 77,100

5. CONCLUSION

From the analyses it is concluded that according to

Model I: TerraSAS Solar Array Simulator
The best PV technology is polycrystalline when we compare the system of 5kWp consisting 100Wp modules and the system consisting 250Wp modules, the best is monocrystalline for 10 climatic zones of India from the point of view of power generated.

Model II: PVWatts Calculator
It is concluded that the Thin-Film Technology is best for 10 climatic zones of India from the point of view of power generated per year. But here it contradicts the theory that thin-film technology has lowest efficiency comparative to polycrystalline and monocrystalline. This can be explained as follows

The key fact that is essentially left out of PVWatts is the area of the array. A thin-film array takes up significantly more area to get the same number of kWp. As PVWatts primary input is the number of kWp of panels, that low efficiency of the panels is rolled into that number.

The other reason for the total output per kWp is higher is that the temperature coefficient for thin-film is lower which is given in table IX. Therefore, for particularly in hot climates like in India, the thin-film panels do not lose as much power at high temperatures of operation.

Table 8: Temperation Coefficeint for different Technologies

Type	Approximate Efficiency	Module Cover	Temperature Coefficient of Power
Standard (crystalline Silicon)	15%	Glass	-0.47 %/°C
Premium (crystalline Silicon)	19%	Anti-reflective	-0.35 %/°C
Thin film	10%	Glass	-0.20 %/°C

From the point of view of cost of electricity generated by the system the standard PV technology which includes polycrystalline modules is the best for each climatic zone of India.

Model III: SPV4ALL
From the point of view of potential AC energy output, annual CO_2 savings and the potential cost savings, the crystalline technology is best for 10 climatic zones of India. From the point of view of payback period, both the technologies have same payback period.

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