Performance Evaluation of 400 kW Grid Connected Rooftop Solar Photovoltaic Power Plant Installed at SKIT, Jaipur

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Received 12.02.2019 received in revised form 28.02.2019, accepted 28.02.2019

Abstract : Due to consumption of conventional energy sources for the generation of electrical power leads to degradation of the environment. In Therefore, it is imperative to shift to renewable energy sources such as, solar energy for the generation of electricity. The generation of electrical power using renewable energy sources required good command on technical knowledge and governmental policies due to their volatility and high initial investment. In this paper, the energy in and out study has been carried out on grid connected solar photovoltaic plant (SPV) installed at SKIT, Jaipur from January 1, 2018 to June 30, 2018.The results obtained from this study are compared with previous year data 2017 on the same period. The performance of this 400 kWp plant is analyzed on the basis of parameters, namely average generated energy (kWh) per day, performance ratio (PR), capacity utilization factor (CUF), reference yield, and final yield. Daily, monthly performance parameters of the plant evaluated on this period which includes: final yield (YF) ranged from 0.998 to 4.103 h/d, reference yield ranged from, Performance ratio (PR) ranged from 34.78% to 46.97%, and Capacity utilization factor (CUF) ranged from 11.35% to 17.09%.Analysis results shows that average monthly energy production capacity is 31503.5 kWh, total production capacity through given period is 189021 kWh. The performance of the plant compared with SPV plants installed all over in India and found satisfactory.

Keywords: Solar photovoltaic system (SPV), performance ratio (PR), capacity utilization factor, final yield, Renewable energy resources (RES).

1. INTRODUCTION

Over the past decades, the increasing consumption and cost concern of electricity generation from existing conventional resources across the world have severe impact on economy of developed and developing countries. Globally, the major generation of power from conventional resources, is based on fossil fuels. The conventional resources which dominate the energy sector are on the brink of impoverishment. Conventional energy resources evolve serious impact toward ecosystem by emerging by-products in terms of global warming and the greenhouse effect. With the swift degradation of fossil fuels resources across worldwide have required an imperative search for alternative energy resources with maximum energy conversion to fulfill the present day energy demand. RET contributes in reduction of

carbon footprints results in emission free energy harvesting. It is crucial to develop new methodology and techniques for diminish cost and improve efficiency of solar power plant. India being a country lies between 8° and 37° north latitude has average annual temperature ranging between 25℃ and 27.5℃,with about 300 clear sunny days in a year and daily average solar energy incidents over India varies 4-7kWh/m2 offers great potential for utilizing solar energy.[1]

In addition, India's intended nationality determined contribution (INDC) is planning to base 40% of the total installed power generation capacity on renewable resources by 2030 with the help of international support on technology transfer and financing. The Government of India aims to reach a renewable energy capacity of 175 GW by 2022. It also has a goal to reduce the emission intensity of GDP by 33 to 35% from 2005 levels by 2030 [2].

Among various renewable energy technologies (RET), photovoltaic /solar technology is contemplated as a most suitable technology especially for distributed power generation. During 2016, at least 75 GW of solar PV capacity was added worldwide-equivalent to the installation of more than 31,000 solar panels every hour. India installed solar PV cumulative capacity in 2017 increased by 3.2 times of cumulative capacity in 2015 i.e.12289 MW [3].

Government of India is clinching the paradigm of shift in power scenario designed several policies

measures such as Jawaharlal Nehru National Solar Mission (JNNSM), Feed-in-Tariff, Accelerated Depreciation (AD), Generation Based Incentives (GBI), Renewable Purchase Obligations (RPO) and Renewable Energy Certificates (RECs) with an objective encouraging of implementation of solar PV plants [4, 5].

Performance of solar power plant affects the quality of supply in grid and reliable operation of equipment in power system. Hence, existing grid is becoming more advanced and Importance of Grid connected solar photovoltaic power plant is also increasing in modern power system. Energy fed into grid by a solar power plant depends on seasonal variation of the solar resource, losses due to temperature variation, system losses and overall losses of grid.

2. DESCRIPTION OF SPV PLANT AT SKIT, JAIPUR

Solar photovoltaic plant (SPV) of an installed capacity of 400 kW is located at SKIT, Jaipur. SPV consists of solar panels, inverters, transformers and other equipment which are further connected to the grid. The SKIT solar plant of capacity 400 kWp comprised of 1302 modules (Renesola 310 W) and all modules are arranged in parallels string and connected to the sungrow inverter installed on supporting structures, in addition to connection boxes and data logging system. The inverters are tied to the local grid via transformer & net metering system. The 400kWp solar power plant consists of following arrays:

Table 1: Array description

Array no.	*Array name*	*Array capacity (kW)*	*Inverter capacity in kW*
1	Old building1	73.2	60
2	Old building2	37.2	30
3	Girls hostel	24.8	25
4	Boyshostel1	55.36	30
5	Boys hostel2	55.36	60
6	Electrical Department	37.2	30
7	Pharmacy building	54.9	50
8	Mechanical block	62	50

2.1 Plant Layout

The capacity of plant is 400kWp.The skit plant is comprised of eight different arrays installed at different building of institute. PV modules are arranged in series and parallel string. Polycrystalline silicon type solar module power rating of 310 W and 305 W at STC. Each array is connected to different inverter. Module details and specifications of solar module with power rating 310 W are provided in Table 2 and 3 respectively.

In this paper, Performance analysis has been carried out on different arrays which are connected to different inverters. Array 1 consist 240 modules in which 10 modules in series and 24 strings are connected in parallel. Array 2 and 5 comprises of 120 modules in which 10 modules are connected in series and 12 strings are in parallel. Array 3, 4 and 7 comprises of 180 modules in which 20 modules are connected in series and 9 strings are in parallel. Similarly array 6 and 8 consist 80 and 200 modules respectively. Sungrow inverter of different ratings are used to convert DC to AC .The plant consists of three 60 KVA, two 50 KVA and three 30 KVA inverters (Sungrow make) connected to 8 arrays. Inverter specifications are shown in Table IV. The plant is located in SKIT, Jaipur, and Rajasthan, India. The plant was built and commissioned in October 27, 2015 under JNNSM.

Figure 1: Layout of SKIT plant

Table 2 : Module Details

S. No	Module make Name	Capacity (watts)
1	Renesola	305
2	Renesola	310

Table 3 : PV Module Specifications

S. No.	Parameters	Values
1	Module type	JC310M-24/Ab
2	Maximum power (P_{max})	310 W
3	Type	Polycrystalline silicon
4	Open circuit voltage (V_{OC})	45.0 V
5	Maximum power voltage (V_{mp})	37.0V
6	Short circuit current (I_{sc})	8.80 A
7	Maximum power current (I_{mp})	8.38 A
8	Maximum series fuse rating	20 A

Table 4: Inverter details and specification

S.No.	*Parameters*	*Values*
1	Type	SG50KTL-M
2	Min. MPP voltage	300 V
3	Max. MPP voltage	950V
4	Max. input voltage	1000V
5	Max. input current	4.26A
6	I_{SC} PV	4.32A
7	Rated output power	50000W
8	Rated output voltage	3 phase,400V

2.2 Location Specification

Swami Keshawanand institute of technology (SKIT), Jaipur is located at latitude 26.90° and longitude 75.80°E. The average solar direct normal irradiation (DNI) received by the plant location is of about 5.04 kWh/m^2/day. The solar irradiation data for each month is shown in fig. 2.

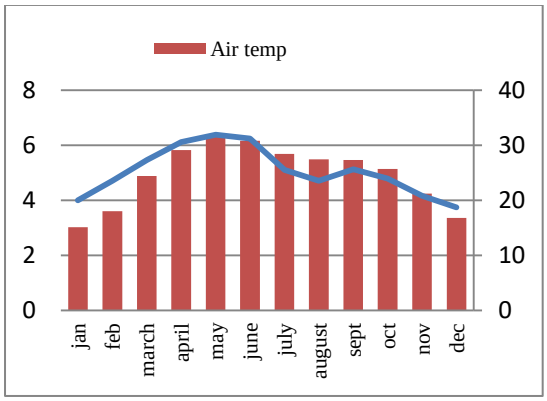

Figure 2: Inclined irradiation and ambient temperature

3. METHODOLOGY FOR SYSTEM ANALYSIS

The performance of rooftop grid connected solar photovoltaic power plant work in this paper is categorized into three stages:

1. Manually extract the parameters of power generation through SCADA system.
2. Calculate all performance parameters of solar plant.
3. Compare the performance with the PVSYST software.

3.1 Performance Parameters

The SPV plant was fully monitored & the performance of the system is evaluated by using performance parameters defined by IEC standard 61724. [4]

The technical parameters include final yield, reference yield, performance ratio (PR) and Capacity utilization factor (CUF) are calculated to assess the plant performance.

3.2 Final Yield, YF

Final yield [4] is defined as the ratio of annual, monthly or daily net AC energy output of the system to the peak power of the installed PV array at standard test conditions (STC) of 1000W/m^2 solar irradiance and 25° cell temperature.

$$Y_F = \frac{\text{System energy output, } E_{AC}(\text{kWh})}{\text{system Rated Power(kW)}} \quad (1)$$

It provides the number of hours required by the system to operate at rated power to the yield the net energy. It is the normalized value of system energy output with respect to system size. It is used to estimate the system performance in terms of solar radiation resource [5].

3.3 Reference Yield, Y_R

Reference yield is the total in-plane solar insolation Ht (kWh/m^2) divided by the array reference irradiance under STC i.e.1kW/m^2 is given by

$$Y_R = \frac{\text{Total In} - \text{Plane Solar Insolation}}{\text{Reference Irradiance}}$$

$$Y_R = \frac{H_t\ (\text{kWh/m}^2)}{H_R} \quad (2)$$

Where, H_R =1kW/m^2

3.4 Performance Ratio, PR

Performance Ratio (PR) is defined as the ratio of final yield and reference yield.PR is used to analyze the performance of system annually. It is very important parameter to determine whether system is operating as expected or not and degradation in PR value is indication of occurring some problems in system [6]. The performance ratio (PR) depends on the total losses in the system resulting from conversion operations made by different components as PV modules, inverters and cables [15].

$$PR = \frac{Final\ yield\ [Y_F]}{Reference\ Yield\ [Y_R]} \quad (3)$$

It is a dimensionless quantity. It gives information about the impact of overall system losses on the rated output. The losses include PV array losses, tilt angle losses, dust losses, shade losses, module temperature losses. This parameter is used to analyze the system performance annually and reduction of PR value is an indicator of the degradation of the system performance [7].

3.5Capacity Utilization Factor (CUF)

It is defined as the ratio of the actual annual energy output of plant to the amount of energy the solar plant would generate if it operated at full rated power for 24 hrs./day/month/year. It is dimensionless quantity. It is used to evaluate the performance of solar PV units.

$$CUF = \frac{\text{actual energy output from the PV}}{24 \times \text{No.of days of operation} \times P_{Rated}} \quad (4)$$

Solar radiation and no. of clear sunny days experienced by plant location affects the both energy generation of plant and capacity utilization factor.

4. RESULT AND DISCUSSION

In this paper, the experimental results regarding meteorological and characteristics performance parameters of 400 kW PV Rooftop solar plant installed on SKIT building for individual six months (Jan-June) of 2017 & 2018. Data of the meteorological parameters including inclined irradiation and ambient temperature were recorded on 12 min intervals in data logger.Fig.2 shows the monthly average total inclined irradiation together with monthly average ambient temperature. The maximum value of inclined radiation was in April with 415.811kWh/m^2 and the lowest in February was 180.029 kWh/m^2. Annual global horizontal radiation for the proposed plant is 2944.576kWh/m^2 and mean ambient temperature was 22.4898 ℃.

Global horizontal solar irradiance on monthly basis for one year is shown in figure 3.

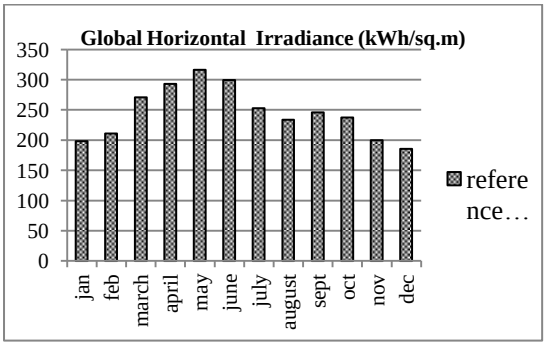

Figure 3: Solar irradiance site data

Figure 3 solar irradiance Site data showed that the average solar irradiation per month was 5.04 kWh/m2/day; the maximum value of solar irradiance was 316.448 kWh/m^2 in May and the minimum value of solar irradiance was 185.4 kWh/m^2 in December as shown in figure 3.

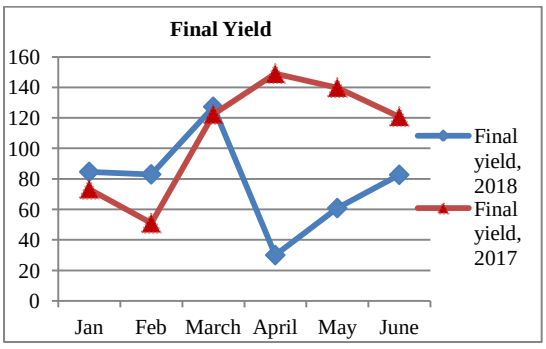

Figure 4: Final yield comparison of 2017 & 2018

Figure 4 Present comparative analysis of final yield of 2017 and 2018.Highest monthly final yield was in April 2017 and the lowest was in April 2018.

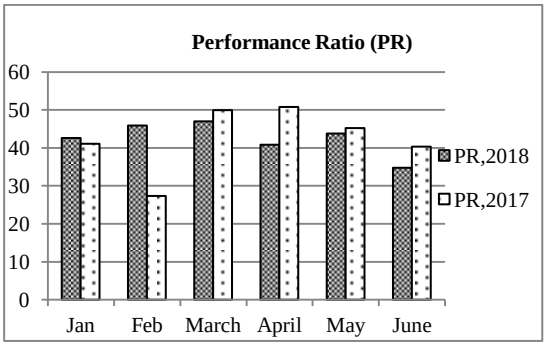

Figure 5: Comparative analysis of Monthly Performance ratio from Jan to June, 2018 & 2017

Figure 5 shows the comparative analysis of monthly performance ratio of different arrays of a PV System for six months of operation from Jan to June of 2017 & 2018. Fig.5 depicts that the minimum value of PR is obtained 27.32% in Feb of 2017 and maximum value of PR was 50.77% in April for 2017. From fig.5 we can see that all inverters have very low performance ratio for month April and May as compared to other months due to some technical problems in system.

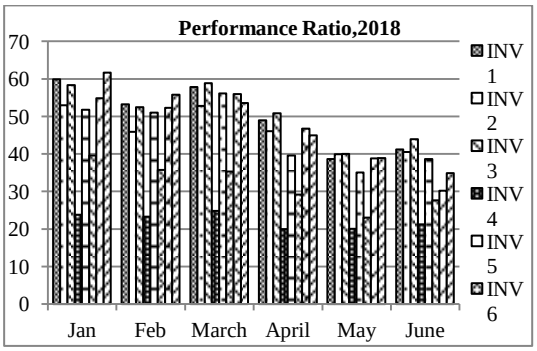

Figure 6: Monthly Performance ratio from Jan to June, 2018

Figure 6 shows monthly wise performance of all inverters of 2018.some inverters have very low performance ratio as seen in fig. There are various reasons behind the degradation of the performance of inverters in PV System:

- Variation in module temperature:
- Shading on PV modules: The infrastructure of surrounding area of the PV system may need to be design carefully as they may be surrounded by trees or building, it may cause the partially shadow effect on PV cells. Because of different solar insolation ,there may be large difference in current output in the characteristics .shadowing effect may cause long term performance degradation and

eventually severe damage to the PV cells & modules.[8]

- Lamination defects
- Mechanical stress
- Cell contact breakdown
- Wiring degradation

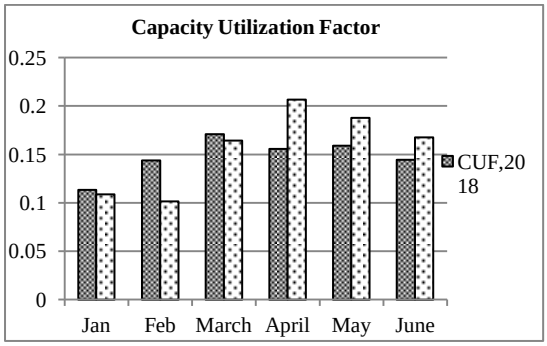

Figure 7: Comparasion of Monthly capacity utilization factor (CUF) from Jan to June, 2018 & 2017

From figure 8 we can see that inverter 3 in April has highest capacity utilization factor with 20.71 % and inverter 4 in January month has lowest value with 6.6%. A comparative analysis of results from real data and simulation data for six months (Jan, 2017 to June, 2017and January 2018 to June 2018) is presented in table no VI. This table includes all the technical parameters of all inverters which play a vital role in determining the performance of solar power plant.

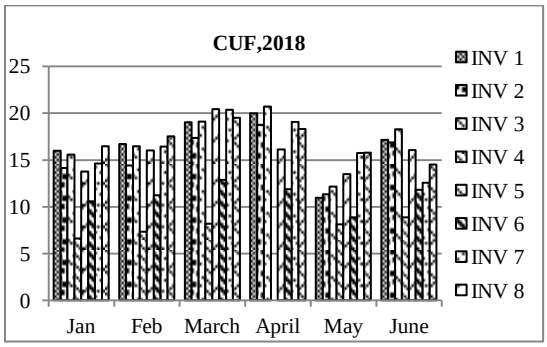

Figure 8: Monthly capacity utilization factor (CUF) from Jan to June, 2018

5. CO_2 EMISSION MITIGATION AND NET REDUCTION

The emission factor as per CEA report is taken as 0.82 $kgCO_2$/kWh for energy mix from coal .So total CO_2 emission from 400 kWp rooftop plant will be, while including transmission and distribution losses 40% and equipment losses of 20% the conversion factor will be changed to

CO_2 mitigation =1.312×480000

= 629,760 $kgCO_2$ = 629.76 tCO2/kWh annually

However there the contribution of PV technologies in GHG emission has to be taken in the consideration. A maximum range of emission has been taken from the ref [15] for polycrystalline modules is 0.569 ($kgCO_2eq$/kWh)

Table 5: Comparison of SPV plants

S.no.	Name and location of SPV plants	Tools used	Final yield (h/d)	Performance ratio (%)	Capacity factor
1	A grid connected photovoltaic park on the island of Crete [4]	PV Syst	1.96-5.07	58-73	-
2	1MW Grid connected PV system in Oman [7]	MATLAB	-	-	21.7
3	5MW Grid Connected SPV Plant Established in Karnataka [8]	PV Syst	1.96-5.07	58-73	19
4	3.6 kW Rooftop Grid Connected Photovoltaic System In Egypt [9]	-	-	-	18.12
5	Performance evaluation of a rooftop SPV plant in Northern India[10]	-	-	76.97	16.39

CO_2 emission from PV = 0.569×480000 = $kgCO_2$ = 273120 $kgCO_2eq$/kWh=273.12 tCO2/kWh

Net CO_2 avoidance from the plant will be: CO_2 emission – CO_2 mitigation

CO_2 AVOIDANCE = 356.64 TCO_2EQ/KWH ANNUALLY

6. ECONOMIC ANALYSIS

Five economic attributes, namely, benefit-cost ratio (BCR), net present worth (NPW), annuity (A), internal rate of return (IRR) and payback period (PBP) adopted from [16,17], were determined for judging the economic viability of the plant.

Economic attributes

(i) BCR: The ratio of discounted benefits to the discounted values of all costs.

(ii) NPW: It is the sum of all discounted net benefits throughout the project.

(iii) The annuity (A) of the project indicates the average net annual returns.

(iv) PBP: It is the length of time from the beginning of the project before the net benefits return the cost of capital investments.

(v) IRR: It is measure of an investment's rate of return.

Table 6: Cost of Equipment

Equipment	No of equipment	Cost (Rs)
Solar panel	1174	14384000
Inverter	8	2722923
DC &AC cables	-	262520
Distribution board and kit	1	86347
Total cost		17455770

- Operation and maintenance charges Rs.0.25/kWh
- Discount factor 12% lifetime of the system 25 years
- Preferential tariff Rs 8/Kwh

Were E is benefits from sale of units, **C** is initial value after plant

PBP is given as n,

$n = [\log [(E-M)/a] - \log [(E-M)/a]]/\log (1+a)$

NPV can be given as,

$(E-M)/a [1-(1/ (1+a))^{n} – C$

BCR is given as,

BCR=1+ NPV/C

Annuity (A) is given as,

$A=NPV/ \Sigma (1/ (1+a))^{n}$

IRR is given as,

$IRR= a_1+ (a_2-a_1) \times NPVa_1/ (NPV_{a1} - NPV_{a2})$

Where a_1 is lower discount rate = 0.12, a_2 is higher discount rate = 0.50

Power generation at the rate of 1600 kWh per day for 300 days a year comes to 480000 units annually

Cost of the system after 30% subsidy comes to Rs 12219039

O&M cost given as M -

M=Rs 0.25 /kWh × 480000= 120000

Benefits from power generated at a tariff rate of Rs 8/kWh comes to

E=480000 × 8= Rs 3840000 and a=0.12, n =25 years

Putting these values in above equation, the following attributes in Table.

Table 7: Values of economic attributes

S.No.	Attributes	Values
1	BCR	2.39
2	NPV @(12% discount)	16950130
3	NPV @(50% discount)	4779337
4	A	2158455
5	IRR(%)	41.64
6	PBP(Yr)	4.42

7. CONCLUSION

A study has been carried out to assess technical feasibility of 400kW capacity solar PV plant installed at SKIT, Jaipur. Based on the results of the experiments determination of the energy and other performance parameters of plant from January 1, 2018 to June 30, 2018, following can be concluded:

- Total half yearly energy production capacity is 189021 KWh.
- Average monthly energy output is 31503.5 KWh.
- Average monthly performance ratio is 42.46 %.
- Average monthly capacity factor is 14.80 %.
- Solar power plant reduces large amounts of emission to the environment thereby making the environment cleaner.
- The same capacity system has been simulated on Software PVSyst and compared with actual data and results found satisfactory.

8. ACKNOWLEDGEMENT

The authors would like to thank Dr. Praveen Kumar Jain, ECE Department, Dr. Akash Saxsena, EE, SKIT, Jaipur for providing access to the data logger system and greatly assisted the research. We would also like to expand our deepest gratitude to all those who are directly or indirectly involved in this work.

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Table 9: Comparative results of actual and simulation data of 2017& 2018

Month	Parametes	Inv 1	Inv 2	Inv 3	Inv 4	Inv 5	Inv 6	Inv 7	Inv 8
Jan	**Actual Data (2017)**								
	Final yield	95.415	86.645	91.999	46.432	NA	91.056	84.515	89.611
	PR	0.4809	0.4366	0.4636	0.23398	NA	0.4589	0.4259	0.4516
	CUF	0.141987	0.12893	0.13690	0.0690	NA	0.1355	0.12576	0.1333
	Actual Data (2018)								
	Final yield	107.318	81.40	89.588	38.047	72.588	70.994	101.76	114.59
	PR	0.5988	0.5299	0.5832	0.2377	0.513	0.396	0.5483	0.6172
	CUF	0.1597	0.1413	0.1555	0.066	0.134	0.1056	0.1462	0.1645
	Software Simulation								
	Final yield								
	PR	86.0	85.5	85.6	86.6	86.6	0.855	86.6	86.5
	CUF	0.2104	0.2103	0.2104	0.2111	0.2111	0.2103	0.2111	0.298
Feb	**Actual (2017)**								
	Final yield	19.494	17.508	105.885	53.271	NA	20.129	100.258	96.467
	PR	0.09239	0.0829	0.5018	0.2524	NA	0.09539	0.4751	0.46193
	CUF	0.033845	0.03039	0.1838	0.0924	NA	0.03494	0.17406	0.16921
	Actual Data (2018)								
	Final yield	84.1912	72.631	79.0524	45.626	99.88	70.05	102.53	109.59
	PR	53.2	45.89	52.44	23.28	50.9	35.75	52.33	55.81
	CUF	0.167	0.1414	0.1646	0.07312	0.16	0.1122	0.1643	0.1752
	Software Simulation								
	Final yield								
	PR	83.7	83.1	83.3	84.9	84.9	83.1	84.9	84.8
	CUF	0.2406	0.240	0.2364	0.2186	0.2186	0.24	0.2186	0.2169
March	**Actual (2017)**								
	Final yield	141.493	131.575	167.223	85.478	NA	150.411	152.323	105.022
	PR	52.24	48.58	61.74	31.56	NA	55.54	56.24	55.399
	CUF	0.19017	0.17684	0.22476	0.11489	NA	0.202165	0.204735	0.20164
	Actual Data (2018)								
	Final yield	141.498	129.11	142.01	60.807	151.96	95.69	151.52	145.9
	PR	57.84	52.78	58.85	24.859	56.11	35.33	55.95	53.51
	CUF	0.2105	0.1921	0.2113	0.0904	0.2042	0.1286	0.2036	0.1950
	Software Simulation								
	Final yield								
	PR	80.9	80.4	80.6	82.4	82.4	80.4	82.4	82.3
	CUF	0.2425	0.2423	0.2383	0.2164	0.2164	0.2423	0.2164	0.2147

April	**Actual Data(2017)**								
	Final yield	161.229	151.478	176.119	93.44	138.70	168.30	156.13	145.88
	PR	54.97	51.64	60.05	31.86	47.29	67.38	53.23	49.77
	CUF	0.2239	0.2103	0.2446	0.1297	0.1926	0.2337	0.2168	0.2026
	Actual Data (2018)								
	Final yield	38.336	36.018	39.771	NA	30.939	22.872	56.56	35.14
	PR	49.01	46.05	50.85	NA	39.56	29.18	46.75	44.94
	CUF	0.1996	0.1875	0.2071	NA	0.161	0.1188	0.1904	0.1830
	Software Simulation								
	Final yield								
	PR	79.2	78.9	78.9	80.8	80.8	78.9	80.8	80.7
	CUF	0.2343	0.2345	0.23	0.209	0.209	0.2345	0.209	0.2082
May	**Actual Data(2017)**								
	Final yield	156.12	148.978	142.30	97.99	150.86	160.291	122.95	138.79
	PR	49.33	47.80	44.97	30.96	47.65	53.18	38.85	48.85
	CUF	0.2098	0.2002	0.1912	0.1317	0.2026	0.2153	0.1652	0.185
	Actual Data (2018)								
	Final yield	55.184	57.115	61.302	40.912	68.031	44.744	79.32	79.506
	PR	38.61	39.96	40.03	20.039	35.07	23.07	38.85	38.94
	CUF	0.1437	0.1487	0.1596	0.0852	0.1349	0.0887	0.1573	0.15775
	Software Simulation								
	Final yield								
	PR	78.8	78.6	78.6	80.4	80.4	78.6	80.4	80.3
	CUF	0.2124	0.2126	0.2085	0.1966	0.1966	0.2126	0.1966	0.1951
June	**Actual Data 2017**								
	Final yield	121.639	124.67	133.56	85.278	137.09	134.79	119.67	108.75
	PR	40.61	41.62	44.59	28.47	45.77	45	39.95	36.31
	CUF	0.1689	0.1731	0.1855	0.1184	0.1904	0.1872	0.1662	0.51
	Actual Data 2018								
	Final yield	98.734	97.107	105.286	48.856	88.666	66.268	72.389	83.559
	PR	41.2	40.52	43.93	21.27	38.61	27.636	30.21	34.872
	CUF	0.1714	0.1685	0.1827	0.0885	0.1606	0.118	0.1256	0.145
	Software Simulation								
	Final yield								
	PR	80.4	80.3	80.2	81.4	81.4	80.3	81.4	81.2
	CUF	0.1880	0.1882	0.1845	0.186	0.186	0.1882	0.186	0.1850