Techno-Economic Analysis & Optimal Sizing of Rooftops Photovoltaic Utilizability: a Case Study for UET Taxila

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Techno-Economic Analysis & Optimal Sizing of Rooftops Photovoltaic Utilizability: A Case Study for UET Taxila

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***Abstract*—This research aims to highlight the viability of Rooftop Photovoltaics (RPV) which have gained a nominal importance due to techno-economic & environmental benefits with better levelized cost of energy. To identify the proposed RPV size and cost PSO and PVsyst are used with inclusion of shading effects and climatic conditions. Results are compared which leads to decision of optimal size, economic viability and dependence of the energy utilization for RPV system. The current study is being carried out at the main campus of University of Engineering and Technology (UET), Taxila whose strategic location will be highly useful in north region of Pakistan, in addition to this various parameter are also analyzed in this feasibility of RPV system such as PR, Lifespan and Carbon footprints reduction which makes it a strong reason for adoption RPV for public sector buildings.**

Keywords*—*Rooftop Photovoltaic (RPV), Photovoltaic System (PVsyst), Particle Swarm Optimization (PSO), Performance Ratio (PR)

I. INTRODUCTION

Due to numerous challenges with fossil fuel-based power generation, such as increasing fuel costs, the natural resource depletion and greenhouse gas emissions, renewable energy resources (RERs) have rapidly acquired importance [1]. In fact, among all renewable energy sources, the sun is one of the most pivotal sources because it is cost-free, clean, replenishable and abundant. Owing to their various benefits, including their ease of use, long life span, variety in size and power and high ecological sustainability, Rooftop photovoltaic (RPV) systems have attracted a great deal of attention in domestic, educational, industrial and commercial, applications [2-5]. Pakistan has an enormous potential for using solar energy to generate electricity; According to a recent World Bank study, Pakistan's current energy demand might be satisfied by solar panels being installed on just 0.071% of the country's entire territory [6]. The study has already informed the Pakistan's government's targets for solar and wind, set at 20% of total capacity by 2025 and 30% by 2030 and has helped dispel concerns over integrating much higher percentages of variable generation [6]. Hence to the low utilization of solar energy, the government has set a goal to raise it through the construction of a rooftop solar power plant [7].

Buildings are among the most feasible and viable uses for solar PV systems [8]. Due to variations in structural and architectural traits, the rooftop PV use in buildings may range significantly from one to the next. In order to determine the chances for Solar PV use at any specific location, qualitative and quantitative evaluation of building rooftop conditions are very crucial [9]. Rooftop PV is the ideal renewable energy option for this region out of all the others renewable energy resources [10]. RPV installations also provide financial savings and capital security. This is because it is easy to calculate the RPV system's energy costs throughout the course of its normal lifetime.

In [9] Ahsan et al. have made an investigation for 3943.5kWp upon utilization of public sector buildings of NED to meet the energy demand and reduce environmental emissions with the support of remotely sensed software PV*SOL. The area that might be used for PV installation was calculated by identifying the constraints, their corresponding coefficients, and utilization factors. A financial analysis was also conducted, and the levelized cost of energy, the discounted payback period, the benefit to cost ratio were all evaluated. Annual yield was proposed as 1336.6 kWh/kWp. It may be concluded that the PV system is a practical choice for use in university buildings[9],[11]. The sizing of the RPV system requires a significant amount of information and environmental data. The available area, load distribution, and climatic variables [12],[13].

In photovoltaics energy systems, grid connected mode allows to balance the energy. In [14] M. Tamoor et al examined different PV modules with variable size, power ratings, and approximately similar efficiency in two specified and unique places keeping the fixed area. This study revealed the fact that choosing the proper type and size of PV modules can result in a large amount of energy loss when constructing an On-Grid solar system, which can waste a lot of energy. As well as cost of energy will also impact w.r.t to roof/ground coverage ratio GCR. Additionally, there are markets for carbon offsets that are both voluntary and mandated programs. Markets for compliance are created and regulated by mandatory regional, national, and international carbon reduction regimes [15-18].

In [19] the authors present a method to size an off-grid PV generator without a storage device in order to maximize the economic profitability of this system. This method is based on estimating the net present value (NPV) for different PV generation power while taking into account economic parameters like self-consumption electricity and electricity sell to the grid. To get the ideal sizing of isolated PV systems, the authors employed the PSO algorithm.

The rest of the paper comprises of following sections as outlined, Section II indicates the formulation of the research problem. In Section III, the mathematical modelling of the RPV is shown in detail. Results and discussion of computed results are discussed in Section IV, however conclusions are presented in Section V.

II. PROBLEM FORMULATION

Due to limited areas on rooftop RPV system are becoming most viable solution to fulfil the energy demand, therefore the given methodology analyzes the location and available area of all rooftops of the campus vicinity. To determine the size of the RPV system PSO and PVsyst will be utilizing as mentioned in section III.

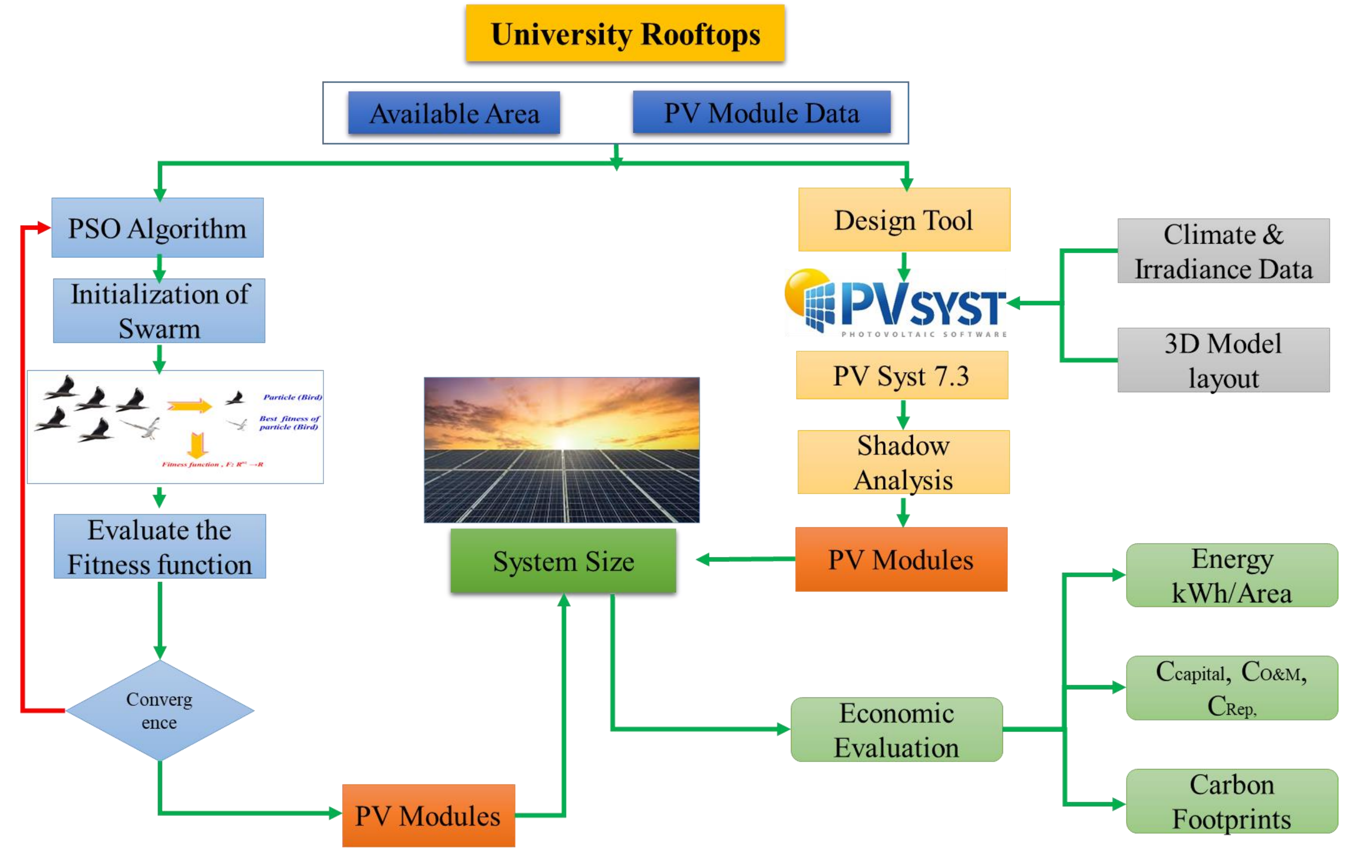

Fig. 1. Flow chart for proposed approach for RPVs

A. *Photovoltaic potential & Site constriants*

The site which are considered for RPV feasibility is the main campus of UET Taxila, which are located in the north region of Pakistan where average output of PVs are shownsare given as 33.76747⁰ N, 72.82208⁰ E. The estimated total solar energy potential for Pakistan is 2900 GW [4].

In Fig 2 Photo voltaic potential has been shown which represent the 4.28kWh/kWp lies in north region i-e campus lying in Taxila. Climatic conditions for particular site has been catered through meteonorm 8.0 [20].

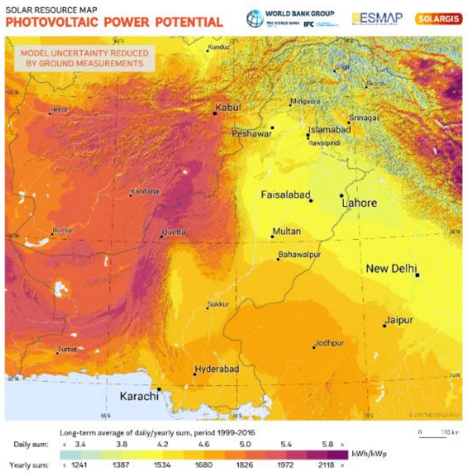

Fig. 2. Photovoltaic Power Potential Energy in Pakistan (KWh/KWp) https://globalsolaratlas.info/download/pakistan

Fig. 3. 3D Model of all rootfops of Campus

B. Shading Analysis & Area Utilization

Shading effect is one of most lethal effect on the PV panels which directly reduce the output performance and loss in energy number, similarly constant shadow cause hotspot on the modules, therefore shading effect has been performed on sketchup and PVsyst softwares. These tools helps to analyses the near & far shading on the modules. On the basis of remotely sensed tool PVsyst shading coefficient help to utilize the available area effectively. PV utilizable area (PVUA) can be determine through this equation which is shown in Table 1.

$$PVUA = U_{factor} \times A_{total} \quad (1)$$

where, U_{factor} is utilization factor and A_{total} shows total area of rooftop, while total utilizable area consumed by all rooftops of campus is 38727m^2.

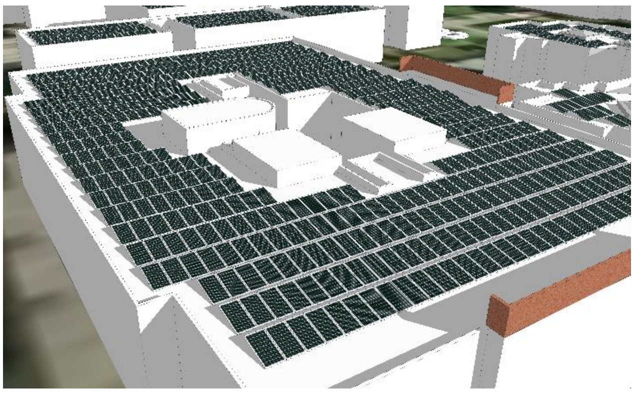

Fig. 4. 3D model of UET campus's rooftops

Table :I Available Area of All Departments of UET Campus

Sr.No	Departments	Area (m^2)	Hostels & Other	Area (m^2)
i.	Software	2,865.47	Q Hall	2,366.50
ii.	Mechanical	3,375.09	I Hall	1,774.40
iii.	Electrical	2,951.94	JB-Hayan Hall	1,214.14
iv.	Admin	840.95	AB Hall	2,655.64
v.	Ibn-e-Sina Block	2,505.36	Ali Hall	1,068.10
vi.	Telecom	2,392.99	Bilal Mosque	1,893.03
vii.	Computer Science	1,960.05	Bus Parking Shed	1,650.00
viii.	Civil	2,974.50	Car Parking shed	770.50
ix.	Environmental	450.00	Dispensary/Misc	1,806.60
x.	Electronic Lab	673.06	Ayesha Hall	892.93
xi.	Library	1,100.00	Guest House	546.43
Total Available Area for RPV			**38,727.62**	

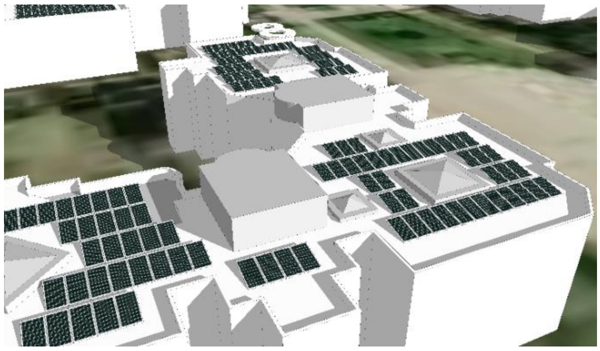

Fig. 5. 3D Model for shading analysis of all hurdles & effects

III. MATHEMATICAL MODELLING OF RPV SYSTEMS

To model the RPV sizing two methods are utilized for this Particle swarm optimization and Pvsyst are used to find the best RPV size and cost which are elaborated in below

A) Particle Swarm Optimization

A population-based stochastic optimization method developed on the basis of meta heuristics method known as particle swarm optimization (PSO). Simple concept, easy implementation, robustness to control parameters, and computational efficiency makes it unique among other algorithms, which is solely based on velocity of the particle. After determining how many swarms and iterations have developed, the particles are distributed randomly around the search space. The velocity of a particle in the swarm at iteration j + 1 can be calculated using the following equation.

$$u_r^{j+1} = w_r u_r^{j+1} + a_1(rand\ pbest_r^{j+1} - D_r^j) + a_2(rand\ gbest - D_r^j \quad (2)$$

whereas u_r^j designates the velocity of the particle number r at the iteration number j, $pbest_r^j$ is the best position of particle r while $gbest$ represents the best position globally through the search space at iteration j, D_r^j denotes the current position of particle r, w_r^j shows the inertial weight, a_1, a_2 are some positive parameters whose range can be determine from 0.5 to 2 [21]. The updated status of particle is denoted by D_r^{j+1}, which is linked to existing position D_r^j and velocity u_r^{j+1} as expressed as follows:-

$$D_r^{j+1} = D_r^j + u_r^{j+1} \quad (3)$$

However, the maximum velocity u_{max} of the particle r can be obtained by the following eq.

$$u_r^{j+1} = \left\{ \begin{matrix} u_r^{j+1} u_r^{j+1} < u_{max} \\ u_{max} u_r^{j+1} \geq u_{max} \\ -u_{max} u_r^{j+1} \leq -u_{max} \end{matrix} \right\} \quad (4)$$

B) Sizing of Rooftop Photovoltaics

The temperature of the surrounding environment and sun irradiation affect the output power of PV. PV output power is modelled using the normal distribution [22]. The rated power of RPV module is given at standard test condition (STC) but the output of PV will varies in real scenario, so it can be calculated as [23].

$$PV_{gen}=P_{STC}\times\frac{I_{measure}}{I_{PV\_STC}}\times\left(1+\chi\left(T_{mod}-T_{s\_air}\right)\right) \quad (5)$$

Where PV_{gen} *and* P_{STC} are PV module power at measured irradiance $I_{measure}$ and irradiance I_{PV_STC} at STC, χ is temperature coefficient and T_{mod} *and* T_{s_air} are module cell and surrounding air temperature.

C) Objective Function for RPV Sizing.

The objective function for optimal sizing will be given as:

$$f_{obj} = C_{capital} + C_{o\&m} + C_{rep} - C_{salvage} \quad (6)$$

In above euquation, $C_{capital}$ indicates the capital cost for RPV system. Similarly $C_{o\&m}, C_{rep}, C_{salvage}$ are operation and maintenance cost, replacement cost, & salvage cost respectively.

$$C_{capital} = (C_{PVWatts} \times N_{PV} \times \eta \times H_{max}) + (C_{INV} \times N_{INV} \times P_{INV}) \quad (7)$$

The capital cost can be calculated from the installation of RPV system, where $C_{PVWatts}, C_{INV}$ are designated for modules and inverter cost ($US/Watt), η is the efficiency of single module which are being used in campus, H_{max} is the peak value of solar irradiance, P_{INV} shows inverter power while N_{PV}, N_{INV} are the no of modules and inverters respectively in Eq 9.

$$C_{o\&m} = (C_{PVinitial}+C_{pvo\&m}) \times K_f + (C_{INVinitial}+C_{INVo\&m}) \times K_f \quad (8)$$

where $C_{PVinitial}, C_{INVinitial}$ indicates initial costs, $C_{pvo\&m}, C_{INVo\&m}$ are maintenance costs of PV modules & Inverter in ($US/W) respectively, while K_f, represents reduction factor as renewable components prices are gradually decline. The reduction factor will be

$$K_f = \left(\frac{1}{(i+1)^c}\right) \quad (9)$$

i indicates interest rate and c= 1/T, T is the time duration for project.

$$i = \left(\frac{I_n - I_i}{I_i + 1}\right) \quad (10)$$

I_n is normal interest and I_i is annual inflation interest rate. RPV systems, C_{rep} replacement cost will be applicable only if all components on PV Plant are being utilized after project lifetime as per below equation.

$$C_{rep} = C_{PVWatts} \times C_{PV-rep} + C_{INV} \times C_{INV-rep} \quad (11)$$

$C_{PVWatts}$ represent the Cost of PV module, N_{PV} no of modules which are being utilized on rooftops, C_{INV} is the cost of inverters and N_{INV} are the no of inverters.

$$C_{salavge} = [T_{ls} - (T - T_{ls} \times round\left(\frac{T}{T_{ls}}\right))]/T_{ls} \times C_{rep} \quad (12)$$

where T_{ls} indicates the life span of the whole system equipment and components and round function help to achieve the nearest integer[24].

IV. RESULTS & DISCUSSION

This section elaborates the results from the simulation of RPV system Table II represent the system size and area utilization of each rooftop. Table III & IV indicates the PV Module variability and efficiency respectively.

Table :II Area & System size of RPV of UET Campus

Sr.#	**Departments**	**Modules (No)**	**RPV (kW)**	**Area (m^2)**
i.	Software	558	315.3	2,865.47
ii.	Mechanical	648	366.1	3,375.09
iii.	Electrical	612	345.8	2,951.94
iv.	Admin	114	64.4	840.95
v.	Ibn-e-Sina Block	540	305.1	2,505.36
vi.	Telecom	468	264.4	2,392.99
vii.	Dispensary & Misc	324	183.1	1,806.60
viii.	Civil	666	376.3	2,974.50
ix.	Environmental	48	27.1	450.00
x.	Electronic Lab	132	74.6	673.06
xi.	Library	180	101.7	1,100.00
xii.	Q Hall	346	195.5	2,366.50
xiii.	I Hall	234	132.2	1,774.40
xiv.	Jabir Bin Hayan Hall	234	132.2	1,214.14
xv.	AB Hall	468	264.4	2,655.64
xvi.	Ali Hall	162	91.5	1,068.10
xvii.	Bilal Mosque	324	183.1	1,893.03
xviii.	Bus Parking Shed	396	223.7	1,650.00
xix.	Car Parking shed	162	91.5	770.50
xx.	Computer Science	378	213.6	1,960.05
xxi.	Ayesha Hall	162	91.5	892.93
xxii.	Guest House	95	53.7	546.43
Total RPV System Size		**7,251**	**4,096.82**	**38,727.6**

Table :III Comparison of PVsyst on three types of modules

Parameters	**Model**	**JKM 565N-72HL4**	**LR5-72HPH-545**	**JAM-72S30-545**
PV Modules	No	7251	7251	7251
Efficiency	%	21.87	21.3	21.1
Inverters	No	33	32	32
System Size	kWp	4096.82	3951.795	3951.795
Area	m^2	38727.6	38727.6	38727.6
Cost	$	2,057,513.1	1,984,679.2	1,984,679.2
Specific Production	kWh/K Wp/ Year	1564	1541	1532
Obtained Energy	MWh	6406.06	5985.06	5913.86

Table :IV Comparison of PSO and PVsyst

Parameters	**UoM**	**PSO**	**PVsyst**
No of PV Modules	No	6,989	7,251
Area	m^2	39,212	38,727
No of Inverters	No	32.5	33
System Size	kWp	3948.78	4,096.82
Annual Energy/Area	KWh/m^2	157.61	163.68
Cost	$	1,983,167.58	2,057,513.13

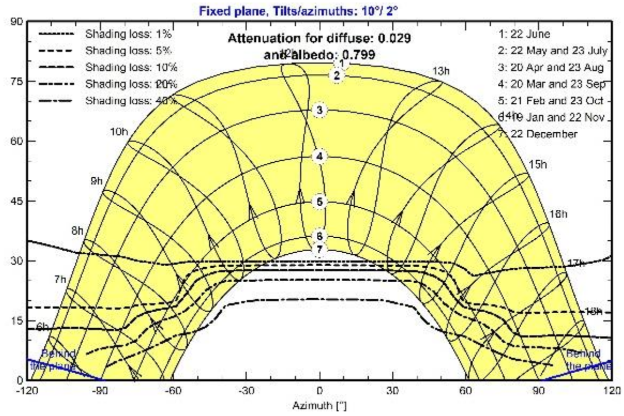

Fig. 6. Path of sun and shading loss w.r.t tilt /azimuth

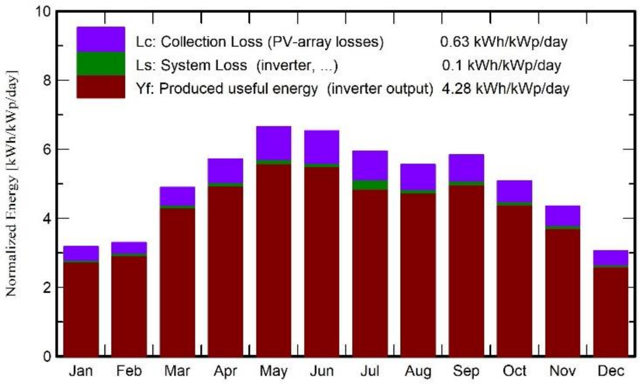

Fig. 7. Normalized energy production and system losses considering

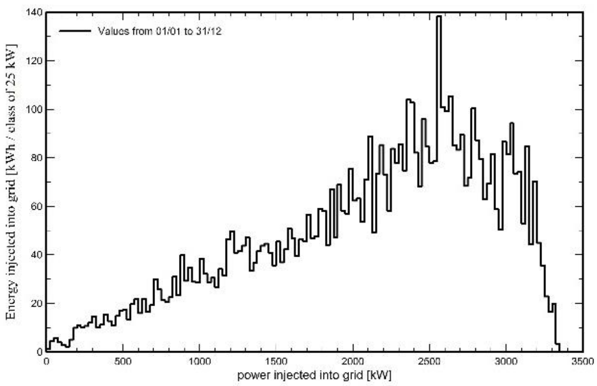

Fig. 8. Energy injection in to existing electrical network

Table:V Results table of 4.09MW simulation

Year	GlobHor	T_Amb	GlobInc	GlobEff	E_out	PR
	kWh/m²	°C	kWh/m²	kWh/m²	GWh	ratio
Jan	82.6	10.29	98.6	93	0.348	0.861
Feb	83.1	13.22	92.3	87.8	0.336	0.889
Mar	140.2	18.93	151.6	144.8	0.547	0.881
Apr	165.2	23.95	171.7	164.2	0.608	0.864
May	203.7	29.84	206.1	197.6	0.711	0.842
Jun	195.9	31.49	196	187.7	0.676	0.842
Jul	183.3	30.58	184.1	176.1	0.617	0.818
Aug	168.3	29.18	172.2	164.6	0.603	0.854
Sep	163.4	27.13	175	167.5	0.613	0.855
Oct	139.5	22.96	157.5	150.9	0.559	0.866
Nov	107.9	16.15	130.7	123.8	0.457	0.855
Dec	78.8	11.59	94.8	89.2	0.331	0.852
Total	**1712.1**	**22.15**	**1830.5**	**1747.2**	**6.406**	**0.854**

A) Performance Ratio

Performance ratio is an important evaluation criterion because it provides information about the total losses that occurred during the conversion of DC to AC power. It is ratio of obtained yield and reference of expected yield of RPV system as shown in Eq 15 and Fig. 9 such research should be conducted in conjunction with thermal comfort levels. Calculations are based on Standard IEC EN 61724. The representation for reference yield can be described as in equation.

$$PR = \frac{E_{obtained}+E_{supp}}{PV_{sys}\times Global_{incl}\times[1+\square\,(T_{module_{act}}-T_{module_{sim}})]} \quad (13)$$

whereas, $E_{obtained}$ shows monthly measured output at RPV Plant, E_{supp} is sum of daily suppressed energy, $Global_{incl}$ indicates monthly accumulated irradiation measured in solar field, T_{module_act} is monthly average temperature measured in RPV field, $T_{module_{sim}}$ is monthly average temperature, $\square$ represent temperature co-efficient for power of specified RPV module.

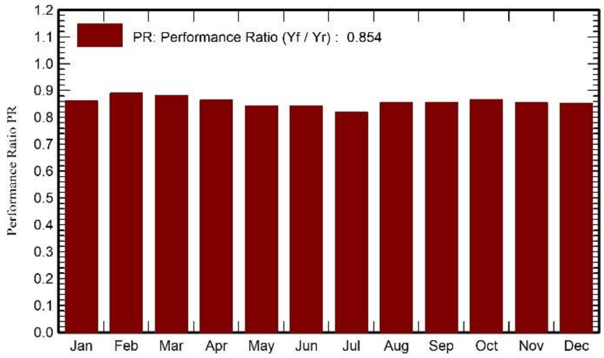

Fig. 9. Performance Ratio for proposed RPV

B) Energy Potential & Economic Analysis

Energy simulation results with respect to the global incident rays are shown in Table V. It includes Economic Analysis which has been made on the basis of obtained values of the E_{out} through table shown in Table V.

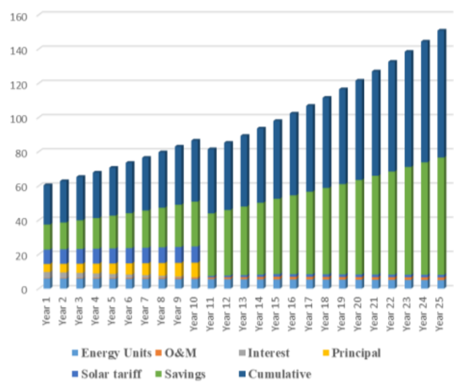

Fig. 10. Energy Saving and Economic Analysis

C) *Capaicty of Utlization Factor*

The ratio of the solar power project's actual annual energy production to its annual equivalent output of energy at rated capacity of RPV called capacity utilization factor. This can be expressed in below equation.

$$PVC_{uf} = \frac{\frac{E_{Annual}}{kWp}}{No\ of\ Days\ in\ Year\ \times 24} \quad (14)$$

E_{Annual} is total energy produced per kWh/year while PVC_{uf} represent utilization factor. In our case study of 4.096MW PVC_{uf} is 17.85% which is obtained from the above equation.

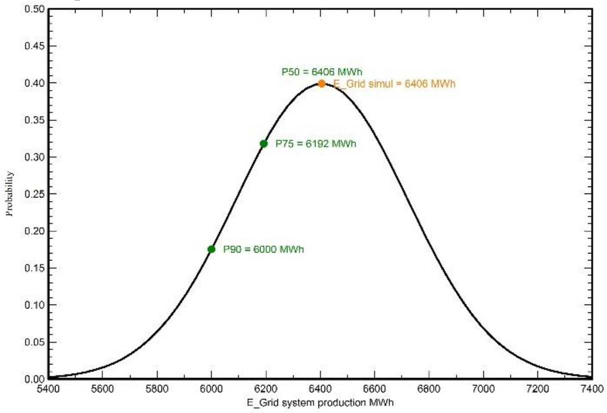

Fig. 11. Refers to Table 3 For expected energy output.

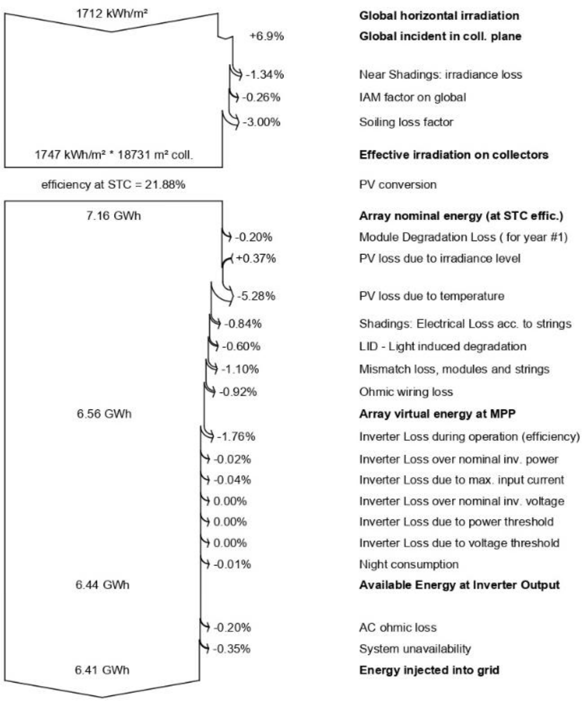

Fig. 12. Loss Diagram of 4.096MW RPV Plant

D) *Reduction of Carbon Footprints*

RPV has a significant role in reduction of carbon footprints. In addition to this renewable initiative government of Pakistan are encouraging to adopt PVs on large scale and get carbon credits in return [25]. This can be expressed in the given equation for reduction of carbon footprints.

$$CO_{2\,red} = CO_{2\,emission} - CO_{2\,mitigation} \quad (15)$$

$$= (E_{emboided} \times F_{em}) - (E_{obtained} \times F_{em}) \quad (16)$$

$$Carbon_{credit} = Net\ CO_{2\,red} \times F_c \quad (17)$$

whereas, $E_{emboided}$ represent the energy which is being utilize the for manufacturing of PV, $E_{obtained}$ is the total energy obtained from the PVs while F_{em} is emission factor, therefore $Carbon_{credit}$ can be calculated by multiplication of cost factor F_c with $CO_{2\,red}$ which indicates as net reduction in CO_2.

V. CONCLUSION

This research analyzes the limitations of the photovoltaics utilization on the rooftops of university buildings and includes thorough technical, economic, and environmental assessments. Thus to lessen its load reduction and provide hands-on training in PV systems, UET Taxila in Pakistan whose strategic location will be highly useful in north region for this study of RPV system. The relevance of choosing a strategic location with annual receiving the 4.28kWh/m^2 shows that region has abundant solar energy utilization potential. The total utilizable area which has been determined for RPV is 38,727.6m^2 in Table III & IV. The specific production which is 1564kWh/kWp from PVsysyt. The simulation results depicts that rooftops of Campus have system 4.096MWp RPV power plant potential which can produce 6406 MWh/Year, with specific production of 1564kWh/kWp/year with 17.85% PVC_{uf} and levelized cost of energy is 0.04USD/kWh. The proposed methods has utilized two different tools ie PVsyst and PSO, while sizing of RPV decide the economic viability and dependence of the energy utilization. Carbon footprints also reduce by 4036 tons of CO_2 may also a strong justification for adoptionn of RPV for public sector building. Photovoltaics are becoming most viable option for rooftops to relieve the country from current energy crisis. The acquired result indicates the proposed RPVs economic viability and its capacity to meet university requirement for the main campus is enough for upcoming years.

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