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Bi-Facial Solar Tower for Telecom Base Stations

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Abstract: This paper proposes overcoming space constraints in solar projects by employing bi-facial PV (BPV) systems and flexible installations. The simulation study, conducted for a telecom operator's off-grid base stations in Bangladesh, demonstrates that deploying four vertical mini solar towers with bi-facial panels can significantly enhance solar harvesting, potentially leading to up to 50% annual diesel savings. This translates to an estimated 0.7 million USD[1] in savings for 290 off-grid base stations. The paper also includes a financial analysis comparing two solution options, highlighting the practicality of the proposed mini solar tower framework for addressing space limitations.

Keywords: *Bi-facial, Solar tower, Solar energy, telecom base stations, BPV*

1. Introduction:

The evolution of telecommunications technology, spanning 2G to 3G, 4G, and now 5G over the past 30 years, has led to continuous changes. Unlike expectations, new technologies only partially replace their predecessors due to factors like ecosystem readiness and handset availability. This results in telecom base stations supporting multiple access technologies simultaneously, leading to a continuous increase in energy consumption driven by amplifiers, digital signal processors (DSP), and transmitters.

With a surge in mobile penetration in countries like Bangladesh, the telecom infrastructure faces challenges in meeting the growing energy demand. The space for installing solar panels on rooftop base transceiver station (BTS) rooms is limited. This, coupled with uneven rural electrification rates, often requires adding or replacing diesel generators to meet energy requirements.

Solar energy production per square meter must be enhanced to overcome these challenges. Bi-facial PV (BPV) panels, capable of harnessing both direct and reflected sunlight, offer a promising solution. Arranging these panels in mini solar towers maximizes energy production while minimizing rooftop space requirements.

[1] All USD amounts are expressed in $2018 unless otherwise mentioned

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Existing research highlights the significant potential of bi-facial technology to increase electric power generation compared to mono-facial cells. Cuevas et al. (1982) found that BPV panels could add an extra 42%–63% to power output compared to a conventional ground-mounted panel [1], while Raina et al. (2022) stated that a BPV system could offer 25%–30% additional power output when installed in an optimized configuration [2]. Bi-facial technology shows promise for its higher energy harvesting capability and flexible installation options, whether slanted or vertical [3], especially when constrained horizontal spaces. This increase in power density reduces area-related costs and lowers rental and interconnection accessory expenses.

Several successful global projects, like those by Earthon, MegaCell, and others [4], demonstrate the effectiveness of bi-facial PV systems in increasing energy production. However, a systematic approach is essential for implementing such solutions for a telecom operator in Bangladesh. This paper outlines the methodological approach, proposed systems, prototype tower design, and simulation results, concluding with suggestions for future work.

2. Methodology

Nineteen telecom base stations from 1180 deployed off-grid and poor grid sites belonging to a telecom operator in Bangladesh were selected for this study. Among these, 290 sites are categorized as off-grid, primarily powered by diesel generators supplemented by solar photovoltaic systems and batteries. The remaining 890 sites fall under the poor grid, facing challenges related to grid availability and outage restoration time, and are also equipped with photovoltaic solar systems to ensure base station uptime.

A simulation tool hosted at Purdue University [5] estimates monthly solar energy for mono-facial and bi-facial scenarios. This tool accurately models and optimizes bifacial module performance based on various installation parameters and ground albedo coefficients. The financial viability of bifacial technology can be evaluated by comparing location-specific energy yields of bifacial and mono-facial modules.

Due to the absence of connected DC loggers at existing base sites, solar and diesel energy measurements were obtained from site-specific data provided by the operator. This data included connected load values, monthly utility bills, the diesel generator's specifications, kVA ratings, site-specific loading factors, efficiency figures, and the diesel generator's runtime and fuel consumption. A comparison between simulated and collected energy data revealed a close alignment between the selected 19 sites. The annual DC energy requirement minus diesel energy production for off-grid sites closely matched simulated mono-facial photovoltaic energy. Similarly, for poor grid sites, the total DC energy requirement minus calculated utility bill energy is closely equated to simulated mono-facial energy. It is worth noting that the load for all sites remained constant throughout the three-month observation period.

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3. Data

Table 3 presents a 3-month average summary of the energy contribution from different sources for the selected 19 base station sites. The analysis reveals that, for the off-grid type (rows 1-9), these sites could achieve an average solar energy contribution of 20% of their annual energy requirement, which is comparatively higher than other scenarios. The higher operational expenses from diesel generators prompted the operator to secure additional space rental near these sites. This led to a capacity increase in the solar system from the initial 3.1KWp to 5.1KWp, implemented 2-3 years after the initial deployment. Conversely, for the remaining poor grid sites (rows 10-19) where additional space could not be obtained, the average solar harvesting capacity remains at 10%, addressing a lesser portion of the total annual requirement for the base station sites.

Table 1: Source-wise energy contribution for the selected 19 base station sites in Bangladesh

Sl	Site Name	Category	Number of solar Modules	Total Solar Capacity (kWp)	Solar Annual Energy yield (kWh)	Connected load (kW)	Solar Contribution	Diesel Contribution
1	Bogra	Off-grid	17	5.1	6815	3.75	21%	79%
2	Gaibandha	Off-grid	17	5.1	6812	3.75	21%	79%
3	Maulvibazar	Off-grid	17	5.1	6350	3.75	19%	81%
4	Chittagong	Off-grid	17	5.1	6551	3.75	20%	80%
5	Borguna	Off-grid	27	8.1	9905	3.75	30%	70%
6	Barishal	Off-grid	17	5.1	6386	6	12%	88%
7	Barishal	Off-grid	30	8	11270	3.75	34%	66%
8	Jamalpur	Off-grid	17	5.1	6689	3.75	20%	80%
9	Kurigram	Off-grid	17	5.1	6798	3.75	21%	79%
10	Dinajpur	Poor grid	10	3	4129	3.75	13%	0%
11	Pabna	Poor grid	10	3	3887	6	7%	0%
12	Chagalnaiya	Poor grid	10	3	3824	4.5	10%	0%
13	Comilla	Poor grid	10	3	3805	7.5	6%	0%
14	Gazipur	Poor grid	10	3	3812	6	7%	0%
15	Munshiganj	Poor grid	10	3	3812	3.75	12%	0%
16	Faridpur	Poor grid	10	3	3823	4.5	10%	0%
17	Patuakhali	Poor grid	10	3	3702	7.5	6%	0%
18	Habiganj	Poor grid	10	3	3759	7.5	6%	0%
19	Habiganj	Poor grid	10	3	3759	7.5	6%	0%

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4. Strategic Considerations

The delay in securing additional space for the expansion of the photovoltaic system often compels reliance on non-renewable energy sources, a scenario common in new green-field solar projects. In the telecom context, the significant impact of powering off-grid sites with diesel generators is evident through heightened diesel consumption, increased carbon dioxide emissions, and elevated operational costs associated with fuel handling and transportation. In the case of poor grid sites, where solar systems aim to provide backup during grid failures, the challenge lies in addressing the less stable grid conditions in remote areas. During cyclones and storm months (April to June) [6], grid fault isolation and outage restoration times can extend up to 8-9 hours, posing a risk of revenue loss for operators in those critical months. Increasing solar harvesting in these operational sites without requiring additional land or rooftop space could prompt operators to reconsider solar energy as a mainstream source. While operators anticipate grid modernization under government-initiated projects, the uncertainty of timelines necessitates a proactive business approach. A potential business case can be established for remote poor-grid areas by conducting a levelized cost comparison between solar and poor-grid options, facilitating quicker decision-making. A collaborative effort involving all operators, including tower-co companies responsible for renting telecom site infrastructure, can be employed to adopt the proposed solution outlined in this paper.

5. Existing vs. Proposed infrastructures

Table 2 details the specifications of the current solar infrastructure at telecom base stations, distinguishing between off-grid and poor-grid sites. Both categories utilize mono-facial technology, with capacities of 5.1 kWp and 3 kWp. The off-grid site comprises 17 panels, each with a 300 Wp capacity, while the poor-grid site has 10 panels with the same specifications. Panel dimensions for both are 2x1 meters. The off-grid site occupies 34 square meters of rooftop space, and the poor-grid site uses 20 square meters. Both sites exhibit an efficiency of 15%, resulting in an annual energy generation of 6,628 kWh for the off-grid site and 3,831 kWh for the poor-grid site. Consequently, the energy density for the occupied rooftop area is 195 kWh/m2 for the off-grid site and 192 kWh/m2 for the poor-grid site.

Table 2: Existing Rooftop Solar Power Specifications

Item	Off-Grid Site Solar Power Specs	Poor-Grid Site Solar Power Specs
Technology	Mono-Facial	Mono-Facial
Total Capacity	5.1kWp	3kWp
Number of Panels	17	10
Per Panel Capacity	300 Wp	300 Wp

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Panel Dimension (mxm)	2x1	2x1
Occupied Rooftop area (m2)	34	20
Efficiency (%)	15	15
Annual Average Energy (kWh)	6628	3831
Energy density (kWh/m2) in terms of occupied rooftop area	195	192

Table 3 outlines the specifications for two proposed bi-facial solar tower solutions: Option A and Option B. Both options employ bi-facial technology but differ in total capacity and configuration. Option A, with a total capacity of 10 kW, consists of 28 panels, each with a 362 Wp capacity, arranged on four solar mini towers, each standing at a height of 5.25 meters. The required bi-facial solar tower space is 8 square meters, while the rooftop space is calculated at 27.6 square meters. Notably, the maximum tower-to-tower distance is assumed to be the tower height for complete shadowing avoidance.

Table 3: Proposed Bi-facial Solar Tower Specifications

Item	Proposed solution (Option A)	Proposed solution (Option B)
Technology	Bi-facial	Bi-facial
Total Capacity	10 kWp	14.4 kWp
Number of Panels	28	40
Per Panel Capacity	362 Wp	362 Wp
Panel Dimension (m*m)	1.7m*1m	1.7m*1m
Number of Solar Mini Towers	4	4
Mini Solar Tower Height (meter)	5.25	7.5
Required Bifacial solar tower space (m2)	8	8
Required rooftop area (m2)	5.25m*5.25m=27.6	7.5m*7.5m=56.2
Efficiency (%)	21.7	21.7
Annual Average Energy (kWh)	15600	22296
Energy density (kWh/m2) in terms of the required rooftop area	566	396

With an efficiency of 21.7%, simulation results indicate that Option A yields an annual average energy of 15,600 kWh, resulting in an energy density of 566 kWh/m2 for the rooftop space.

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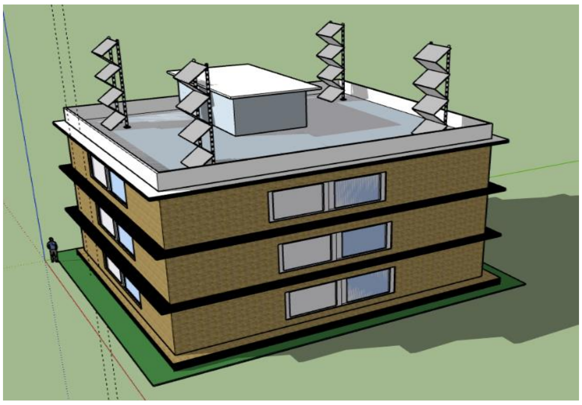
Conversely, Option B features a higher total capacity of 14.4 kWp, comprising 40 panels with the same specifications as Option A. The four mini-towers stand taller at 7.5 meters, occupying 8 square meters of bi-facial solar tower space and 56.2 square meters of rooftop space. With an identical efficiency of 21.7%, simulation results show that Option B generates an annual average energy of 22,296 kWh, resulting in energy harvesting of 396 kWh/m2 for the rooftop space. Comparing the energy density for the rooftop space between existing and proposed infrastructure reveals a 190% increase for Option A and a 103% increase for Option B in the off-grid site. Option A increases the energy density by 195% for the poor-grid site, and Option B increases it by 106%.



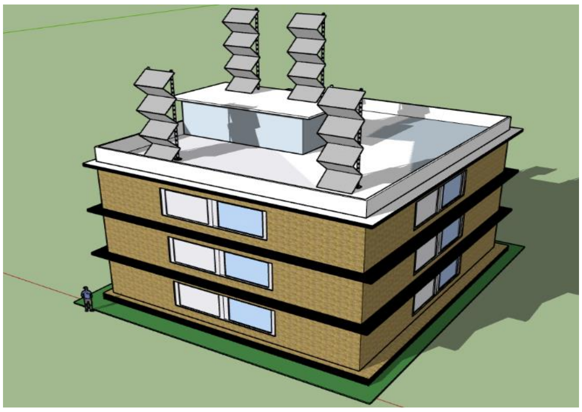


Figure 1: Four towers on the house owner's roof. Figure 2: Two towers on top of the BTS room

6. Design considerations

Table 3 presents the potential expansion of existing solar capacity (3 kWp or 5 kWp) to 10 kWp to 14.4 kWp using bifacial solar towers. However, a single tower accommodating 28 to 40 modules would require substantial structural and steel support, including guy support, resulting in increased wind pressure. To mitigate this, the proposed solution involves distributing the capacity among four mini solar towers, significantly reducing rooftop space compared to the previous setup and doubling the apparent energy density for rooftop space.

6.1 Orientation

Maintaining a specific distance between the towers is crucial to prevent shading. In urban areas of Bangladesh, where typical building heights are around 20 meters, telecom operators rent rooftop space for GSM/microwave antennas or construct a BTS room (3.65m*3.65m). Ideally, the solar towers should be placed in the four corners of the owner's rooftop (Figure 1) to avoid potential shading issues. Alternatively, if the house owner is unwilling to host all four towers or the space is pre-occupied, two towers could be installed at the top of the BTS room (Figure

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2). Each mini solar tower has a footprint of only 2 square meters, similar to the GSM/microwave antenna pole mount requirement. Positioning the four solar towers as additional poles during space requirement discussions with house/land owners or tower-co vs. operators could facilitate smoother negotiations and positive outcomes. Another viable option involves integrating bifacial panels into the existing 42m communication tower (Figure 3).

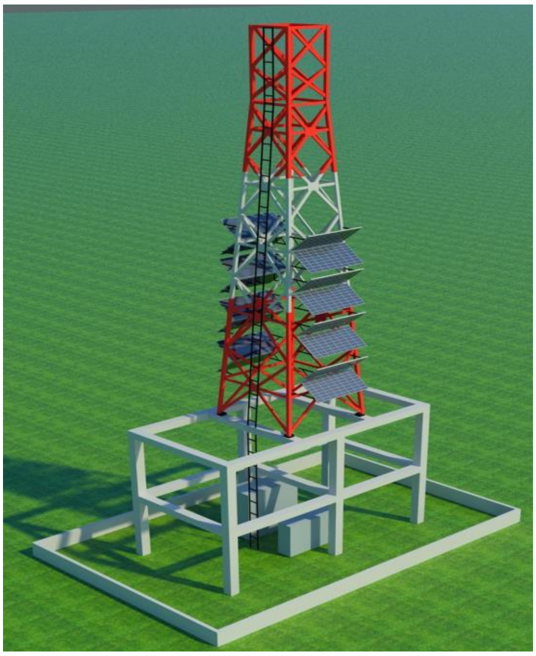

Figure 3: Installing bi-facial panels in the existing 42m communication tower

6.2 Stress ratio

The telecom operator, with approximately 400 towers ranging from 40m to 62m, was analyzed in a specific site named DPCRBR in Dinajpur, featuring a pre-existing 42m tower. Utilizing the national wind map, a maximum wind speed of 130km/hr was determined for the site. Employing MS Tower V6 [7], the analysis considered factors such as self-weight, wind pressure on all sections, and the weight of existing GSM and microwave antennas. The objective was to assess the tower's designed stress ratio in response to the proposed installation of 14 bi-facial panels. Steel sections were evaluated for strength, with values of 400Mpa and 275Mpa in certain parts. The findings indicate that the existing communication tower has the load-bearing capacity for additional solar panels, making it a potential candidate for bi-facial panel installations, particularly in lower segments not typically occupied by telecom antennas.

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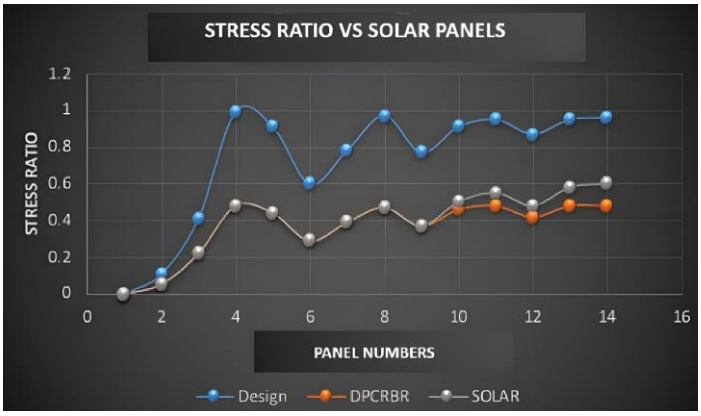

Figure 4: Stress Ratio of 42m Communication Tower with Bi-facial Panels

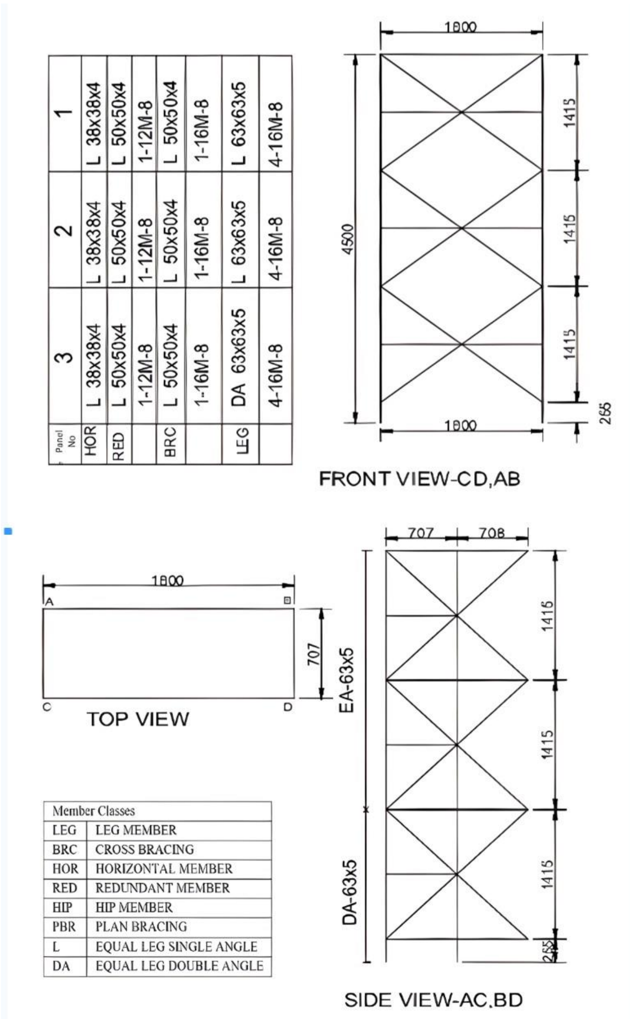

Figure 4: Six-panel solar tower design with dimensions in mm

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6.3 Wind load

During the structural design analysis, several factors are taken into account. Wind load calculations for the tower are based on BS 8100 part 1 and 3 standards. The average rooftop level is assumed to be 20m. Site locations across 19 areas are analyzed using the Bangladesh wind speed map, with the maximum speed of 210km/hr selected for the mini solar tower design (Figure 4). MS Tower V6 software [7] is utilized for wind load calculations. A maximum of 10 bi-facial slanted panels are considered. Structural sections are constructed from steel with a yield strength value of 275 MPa; all bolts are grade 8.8.

7. Energy yield estimation

Distinct input parameters were employed in the simulation tool hosted at Purdue University to assess the energy yield (kWh/m2) from the existing mono-facial system and the proposed bi-facial system [5]. The parameters for the mono-facial simulation include latitude-longitude for 19 sites, a 1m module height (with dimensions 2x1m), an elevation of 3m (considered as the minimum value for single-story buildings at all sites), an azimuth angle of 180 degrees (south-facing), and a tilt angle based on each site's latitude. The efficiency figure for the existing mono-facial panels is assumed to be 15%, according to the operator's datasheet.

For the bi-facial simulation, key parameters include a bi-facility of 90 (as per Prism Bi362 data sheet [8]), front side efficiency of 21.7%, a fixed tilt of 45 degrees following the proposed design (Figure 4), and a ground albedo of 0.25 for the green field (grass), typical for Bangladesh terrain [9]. The proposed module height remains the same per the manufacturer's datasheet [8], and the azimuth is consistent with the mono-facial setup (180 degrees, south-facing).

The simulator output, kWh/m2, every month for each site, provides 456 data points for analysis (19 sites * 12 months * 2 types). For actual usable energy calculation, a system performance ratio of 75% is considered, with the following loss assumptions: inverter loss (8%), temperature loss (8%), DC cable loss (2%), AC cable loss (2%), shading (3%), weak irradiation loss (3%), and loss due to dust & snow (2%).

Tables 4 and 5 summarize the energy contribution of the two proposed solar tower options. Option A exhibits an average increase of 30% in solar harvesting for off-grid sites, while Option B shows a potential increase of up to 50%. In the case of poor-grid sites, the contribution rises from a single-digit 9% annual energy contribution to 30% for Option A and 50% for Option B.

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Table 4: Site-specific energy yield for proposed (Option A) solar tower

SI	Site Name	Site ID	Category	Option-A Annual Output (kWh/m2)	Number of Modules	Solar Annual Energy yield (kWh)	Connected load (kW)	Solar Contribution
1	Bogra	BOCTN1	Off-grid	456	28	16278	3.75	50%
2	Gaibandha	GBKMR1	Off-grid	457	28	16331	3.75	50%
3	Maulvibazar	MBFTP2	Off-grid	427	28	15230	3.75	46%
4	Chittagong	CGGMH1	Off-grid	437	28	15591	3.75	47%
5	Borguna	BRPGT3	Off-grid	415	28	14833	3.75	45%
6	Barishal	BSDDP1	Off-grid	426	28	15197	6	29%
7	Barishal	BSDSH1	Off-grid	426	28	15197	3.75	46%
8	Jamalpur	JPMBN2	Off-grid	449	28	16029	3.75	49%
9	Kurigram	KGDTV3	Off-grid	458	28	16350	3.75	50%
10	Dinajpur	DPCRBR	Poor grid	471	28	16818	3.75	51%
11	Pabna	PBDSR1	Poor grid	441	28	15745	6	30%
12	Chagalnaiya	CGBAH2	Poor grid	434	28	15486	4.5	39%

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13	Comilla	CMELT2	Poor grid	433	28	15441	7.5	24%
14	Gazipur	GPULS1	Poor grid	434	28	15477	6	29%
15	Munshiganj	MNMRC1	Poor grid	433	28	15456	3.75	47%
16	Faridpur	FPBBR1	Poor grid	434	28	15487	4.5	39%
17	Patuakhali.	PTBOG1	Poor grid	419	28	14970	7.5	23%
18	Habiganj	HGMAD1	Poor grid	429	28	15312	7.5	23%
19	Habiganj	HGPAN1	Poor grid	429	28	15312	7.5	23%

Table 5: Site-specific energy yield for proposed (Option B) solar tower

SI	Site Name	Site ID	Category	Option-B Annual Output (kWh/m2)	Number of Modules	Solar Annual Energy yield (kWh)	Connected load (KW)	Solar Contribution
1	Bogra	BOCTN1	Off-grid	456	40	23256	3.75	71%
2	Gaibandha	GBKMR1	Off-grid	457	40	23256	3.75	71%
3	Maulvibazar	MBFTP2	Off-grid	427	40	23256	3.75	71%
4	Chittagong	CGGMH1	Off-grid	437	40	23256	3.75	71%

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5	Borguna	BRPGT3	Off-grid	415	40	23256	3.75	71%
6	Barishal	BSDDP1	Off-grid	426	40	23256	6	44%
7	Barishal	BSDSH1	Off-grid	426	40	23256	3.75	71%
8	Jamalpur	JPMBN2	Off-grid	449	40	23256	3.75	71%
9	Kurigram	KGDTV3	Off-grid	458	40	23256	3.75	71%
10	Dinajpur	DPCRBR	Poor grid	471	40	23256	3.75	71%
11	Pabna	PBDSR1	Poor grid	441	40	23256	6	44%
12	Chagalnaiya	CGBAH2	Poor grid	434	40	23256	4.5	59%
13	Comilla	CMELT2	Poor grid	433	40	23256	7.5	35%
14	Gazipur	GPULS1	Poor grid	434	40	23256	6	44%
15	Munshiganj	MNMRC1	Poor grid	433	40	23256	3.75	71%
16	Faridpur	FPBBR1	Poor grid	434	40	23256	4.5	59%
17	Patuakhali	PTBOG1	Poor grid	419	40	23256	7.5	35%
18	Habiganj	HGMAD1	Poor grid	429	40	23256	7.5	35%
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8. Cost-benefit analysis

8.1 Off-grid site

For the off-grid site, the annual diesel cost is calculated using three months of site data from the operator. Specifically, a 30kVA diesel generator operates at approximately a 65% loading factor, with an average daily runtime of around 4.5 hours. The financial impact of the proposed solution with Option A (30% diesel cost saving) and Option B (50% diesel cost saving) could potentially lead to annual savings of USD 0.42 million and 0.71 million, respectively, considering 290 off-grid sites for a single mobile operator. Extrapolating these figures nationwide across all operators would result in significantly higher savings. The RET screen simulation [10] indicates that the Benefit-Cost Ratio for Option A solar tower is 3.05, and Option B is 2.37 (Table 6), underscoring the viability of implementing solar towers.

Table 6: Viability of Bi-facial Solar Tower Installation

	Unit	Option-A	Option-B
After-tax IRR - equity	%	16.3%	20.4%
After-tax IRR - assets	%	10.5%	13.5%
Simple payback	Year	8.8	7.3
Equity payback	Year	8.3	6.4
Net Present Value (NPV)	USD	10100	21250
Annual life cycle savings	USD/years	950	2000
Benefit-Cost (B-C) ratio		2.37	3.05
CO2 Emission reduction	ton/site/year	5	7.9

8.2 Poor grid site

The financial feasibility analysis for the poor grid sites is approached differently, comprising 890 locations without diesel generators but equipped with a 3kWp photovoltaic system and poor grid connectivity. The existing 3kWp system, coupled with an 8-hour battery backup, faces challenges in managing outages during the stormy weather that prevails for four months. Despite this, operators are hesitant to expand the existing solar infrastructure for two reasons: limited space around the BTS site or high rental/land prices and the perceived lower grid costs.

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To address this, a comparison of the levelized cost has been conducted using NREL's Levelized Cost of Energy Calculator [11] between bi-facial solar tower solutions and the poor grid condition, assuming that the tower will not require additional land space at the existing BTS sites. To err on the side of caution, the levelized cost calculator [11] considers a fuel cost escalation rate of 3%, although the last 10 years' rate analysis suggests it is 5%. Additionally, the lifetime of solar cells is conservatively estimated to be 10 years even though practical longevity is approaching 20 years. Despite these conservative considerations favoring the grid, the analysis still indicates that the levelized cost for the bi-facial solar tower is lower by 1 USD compared to the grid. This supports the rationale for investing in solar energy even at poor grid sites.

9. Conclusion

In conclusion, the analysis of deploying bi-facial solar towers at both operator-owned towers and site rooftops demonstrates promising potential, particularly in scenarios where limited space poses a challenge for efficient solar energy harvesting. The case study of a telecom operator presented here highlights the multifaceted benefits of opting for bi-facial solar towers over mono-facial counterparts. These advantages extend beyond direct savings in diesel consumption, including reduced space rental costs. The financial viability of both options has been thoroughly examined, revealing payback periods of 7 and 8 years, with the levelized cost projected to be lower than grid costs in the next decade.

Practical considerations, including the structural design for holding bi-facial panels on towers, have been analyzed, accounting for factors such as wind speed. A sample rooftop mini solar tower design has been proposed, along with an assessment of the tolerance limit of an existing 42m telecom tower for potential bi-facial panel installation. However, it is essential to acknowledge that simulated bi-facial production from a vertical tower may experience deviations due to site-specific shadowing factors. The uneven incident light at the rear side of the panel, resulting from specific shadowing effects, can lead to cell-wise current mismatch, impacting overall power and efficiency. To mitigate this, painting the rooftop surface white may enhance the albedo factor, preventing uneven current flow across the cells. For non-rooftop installations, considering additional ground reflector material is an option. Still, factors such as site location, reflector material cost, and surroundings are critical in deciding whether to implement this additional layer.

For the selected telecom operator in Bangladesh, with 290 off-grid sites and 860 sites facing poor grid conditions, all equipped with solar PV since 2012, the proposed approach suggests prioritizing off-grid sites for the transition to bi-facial technology. The recommendation is not

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an immediate replacement of all systems but rather a strategic re-use of existing mono-facial systems in new off-grid sites or as module expansions in poor-grid locations. This phased implementation aims to optimize energy harvesting efficiency while considering the telecom operator's specific operational and financial context.

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