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Research Article

Design and feasibility analysis of a solar PV array installation during the construction of high-rise residential buildings

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Abstract: Effective energy utilization is a key parameter to meet the increasing global energy demand, and this paper proposes to install a solar PV array during the construction of a high-rise building. Electrical energy auditing is an essential tool for the planning and installation of solar PV systems. The outcome of energy auditing and the space availability are subsequently utilized for planning the sequential installation of solar PV systems in the four segments of the construction process. Several challenges in harnessing and utilizing solar energy during the construction, along with the strategic utilization of solar PV energy are presented for the benefit of building owners after the completion of the construction process. A case study (seven 200 m high rise buildings and associated facilities) is considered to validate the proposed energy-efficient construction process, and the same is compared with the conventional construction process. From the comparison, a significant reduction in the power drawn from the grid during the construction process is noticed. It has been found from the simulation results that an estimated annual energy of 7377 MWh is generated from the 3.63 MW roof-top solar PV systems. Further, a techno-economic assessment of the proposed solar PV system is drawn to bring out the financial benefits to the contractor, and the owners of the newly constructed high-rise residential buildings. Embracing sustainability in buildings with energy-efficient construction practices in large construction projects can substantially minimize the impact of environmental pollution.

Keywords: *Electrical energy auditing, Energy-efficient construction, Green-house gas mitigation, Performance indices, Solar PV system*

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Nomenclature	
BHK	Bedroom, hall, and kitchen
n	Number of Concrete grades (e.g. M5, M10 etc.) utilized for construction activity
Q	Quantity of the concrete batch produced by Concrete batching plant
Q_n	Quantity of grade-n concrete in a specific month.
ERS	Energy meter Reading of the concrete batching plant at the Start of batching
ERE	Energy meter Reading of the concrete batching plant at the End of the batching.
E	Energy consumption for 1cu.m of concrete produced from Concrete batching plant.
E_{avg}	Energy consumption factor for the type-I variable load.
K	Energy consumed by the type-II variable load for 1 hour of its operation.
K_{avg}	Energy consumption factor for the type-II variable load.
EMR	Energy Meter Reading of type-II variable load.
HMR	Hour Meter Reading of type-II variable load.
N_{BP}	Time of operation (in hours) of Boom Placer for a specific month
N_{PH}	Time of operation (in hours) of Passenger Hoist for a specific month
N_{TC}	Time of operation (in hours) of Tower Crane for a specific month
P_i	Installed capacity of the solar PV system
k	Month number
G_M	Monthly Energy generated by the Roof-top solar PV system (in kWh)
I	Cumulative insolation (in kWh/sq.m)
N_{PO}	Number of Operational solar PV modules.

1. INTRODUCTION

The development of infrastructure plays a critical influence on national economies throughout the world. The objective of various government initiatives in the environment, energy, and economic performance; is intended to achieve sustainable buildings by 2030. Soon, when sustainable buildings with energy-efficient construction practices are more common, the employment of renewable sources of energy for construction shall gain more importance. The prime motive in incorporating sustainable technologies in the building sector is to maintain or improve the standards of human living without depleting natural resources. The market for sustainable buildings is evolving as a developing business that may reduce some negative impact on the earth's natural resources and global environmental sustainability [1]. In the last few decades, governments and businesses began to adopt more sustainable dimensions in their policies to assess their levels of Corporate Social Responsibility (CSR) [2]. The rapidly growing world energy usage has already raised concerns over supply difficulties, exhaustion of energy resources, and substantial environmental impacts such as ozone layer depletion, global warming, climate change.

By utilizing passive solar strategies and active solar technologies, the energy consumption of the high-rise building can be significantly condensed [3-4]. A building consumes a lot of resources and energy during the entire life cycle. [5-6] Typically, the construction cycle of a building can be divided into the following phases: extraction of required raw materials, processing and manufacturing of construction materials, transportation, and installation of building materials. Presently, there are plenty of research works assessing the energy consumption and environmental impacts of buildings, but few encompass the energy analysis in the construction process. However, this was limited to various stages of material extraction, production, and transportation and did not include on-site construction processes [7-9]. Calculation of the Life-Cycle Cost (LCC) considers the cost of energy utilized in the construction process. The energy consumption during construction is not well understood because of its fragmented nature and involvement of many parties during the construction phase [10]. Construction site energy managers must follow a systematic energy auditing procedure to ascertain the electricity demand in the construction process and suggest relevant measures and techniques to achieve electrical energy efficiency in construction activities. Energy auditing of an academic building in Kuwait has found that the energy performances are likely dependent upon energy management practices. Considerable savings in the electricity bill could be achieved by implementing energy auditing [11]

Energy-efficient construction practice is the process of employing renewable energy instead of entirely relying on conventional grid power during the construction process. Design and performance analysis are one of the most critical aspects of any solar PV installations. The performance of several solar power plants is determined in terms of performance ratio (PR), capacity utilization factor (CUF), energy yields, and losses [12-16]. Awareness about the connections between social, economic, and the environment, as well as nature and construction practices, is increased among people of this generation [17]. In constructing a sustainable building, the materials used, as well as the energy utilized, should be measured to ascertain the total effect of new infrastructure have on the environment [18]. The perception of sustainable buildings and energy-efficient buildings are often used interchangeably. The non-sustainable materials used in the construction sector are equipped with a high value of embodied energy [19]. It is estimated that the building sector alone emits about 45 percent of greenhouse gases [20].

With proper implementation of guidelines, energy-efficiency in the construction could be practiced at the design stage of the construction project [21]. There are many footraces to incorporate sustainability in buildings. The significant difficulty is high investment costs that are associated with energy-efficient construction practice compared to conventional practice. Risks associated with unforeseen expenses in the construction process can also become a problem in embracing energy-efficient construction. The development of energy-efficient construction practice is usually dependent on the client's willingness to own a project. Implementation of energy-efficiency in construction is linked with several factors that relate to supply, available knowledge as well as methods, cost, and value of that sustainable project. Most construction industries in developing countries face problems in practicing environmental sustainability and energy-efficiency during construction [22].

However, none of the past researches have attempted to study the impact of installing solar systems during the construction. Such an integrated approach of PV array installation in line with the building construction, to minimise, the construction energy cost has not been attempted so far in the construction sector. In this work, the feasibility of installing a solar PV system in the construction site is assessed by using PVsyst V6.85 simulation software. PVsyst tool is used to design the solar PV system and estimate the potential of solar energy for a specific location. The high-rise apartments were used as a case study to study the impact of installing a solar array at the construction stage. Energy auditing during the construction of these apartments is performed to ascertain the annual energy requirement in the construction process. To minimize the energy requirement in the construction process, the installation of the solar PV system in four segments is proposed during the span of high-rise buildings construction. Such PV installation intends to reduce the consumption of electric energy during the construction stage and mean to result in net-zero operation later. The proposed approach is to harness and utilize solar energy for the construction activities with the available spaces at each stage of the construction. The complete performance analysis, economic analysis associated with the solar PV system will bring out the significance of such installations during the construction phase of the project. Figure 1 represents the methodology adopted in the energy-efficient construction process.

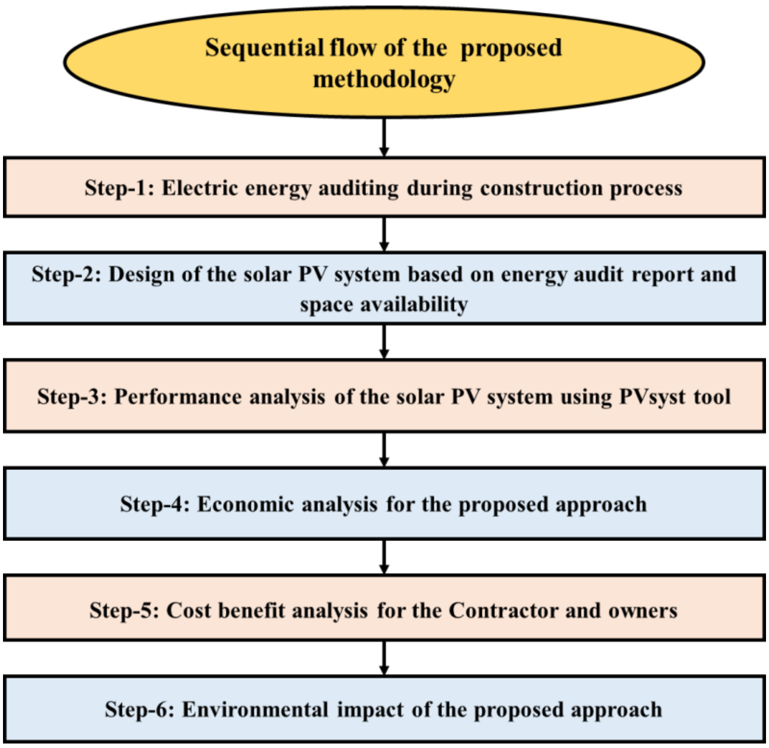


Figure 1. Methodology

2. DETAILS OF THE CONSTRUCTION PROJECT

The site is located at a latitude of 19.0760° N and longitude of 72.8777° E in Mumbai, India. Figure 2 presents the high-rise residential building layout with seven towers (A, B, C, D, E, F, G) each consisting of 61 floors designed for 3 BHK and 4 BHK flats and, eight non-towers (K, L, M, N, O, P, Q, R) each of 5 floors and 3 basements which are exclusively designed for vehicle parking and amenities. The entire project is spread across an area of 51133 sq.m. The construction is planned for two phases, with five towers and six non-towers in the phase-1 construction, two towers and two non-towers in the phase-2 construction. The timespan allocated for completion of phase-1 construction is four years, followed by two years for phase-2 construction.

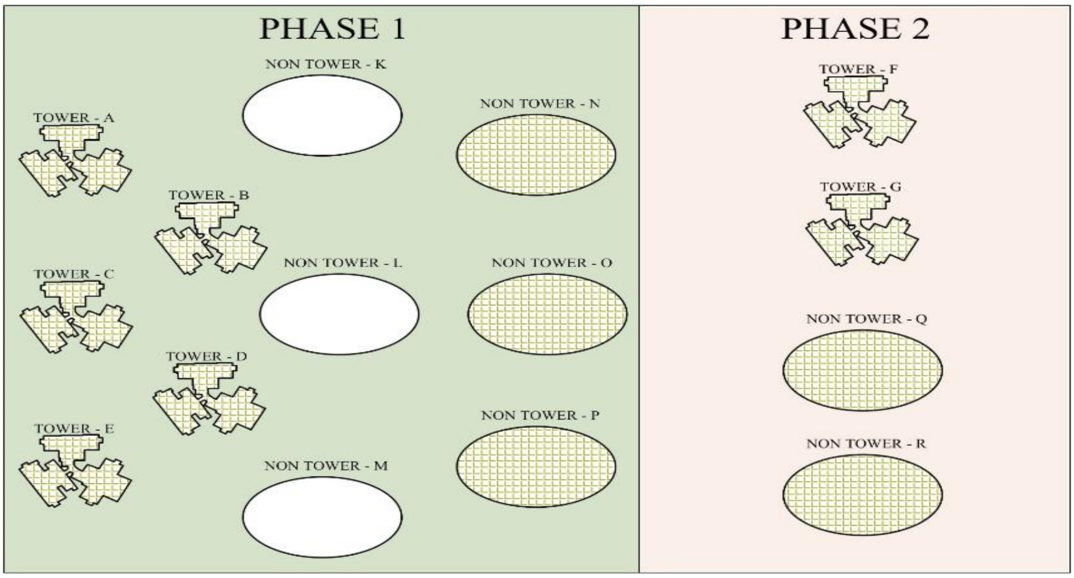


Figure 2. The layout of the High-rise residential building project

2.1 Energy Auditing (EA)

Energy auditing (EA) is the process of monitoring the energy required for construction and suggesting methods for efficient and effective energy usage. Energy auditing of the construction process of high-rise residential buildings pertains to the electrical energy consumption of the construction equipment. The activities involved in the EA process are site inspection of undergoing processes in various departments, analysis of the extracted data to estimate the grid energy drawn by the construction site, and suggesting various measures and techniques that minimize the on-site energy consumption. Energy auditing during the construction process is the essential parameter for the implementation of energy-efficient construction. The solar PV system is designed based on energy auditing results and space availability. Design and techno-economic analysis of the solar PV system are carried by using a PVsyst simulator. The impact of solar PV installation during the construction is assessed, and cost-benefit analysis for the contractor and the owners are presented. Further, the amount of GHG mitigation from the proposed approach is elaborated.

2.1.1. Variable load equipment

Loads having variable monthly energy consumption are classified as variable loads.

(I) Type-I variable load: Concrete Batching Plant (CBP)

It is the construction equipment used to produce the desired grade of concrete, e.g., M5, M10, M15, etc. The process of measuring the raw materials of concrete (cement, sand, aggregates, water, and admixtures) before mixing is known as batching. Batching of various concrete grades is automated in the CBP control room. The total power rating of the CBP used in the construction process is 210 kW. The energy meter is installed in the control room to monitor overall CBP energy consumption. Energy consumption for 1cu.m of various concrete grades vary since the quantity of raw materials mixed to produce desired concrete grade is different. Based on control room data, the quantity of various grades of concrete manufactured every month is noted, and monthly energy consumption from CBP is calculated.

II) Type-II variable load:It consists of boom placer, passenger hoist, and tower crane

(a)Boom Placer (BP):

It is an equipment used to pump concrete from the transit mixer to the construction area. Boom placers are mounted with concrete pump and use remote-controlled articulating robotic arm (called a boom) to place concrete accurately. The concrete pump consists of a 30 kW three-phase squirrel cage induction motor.

(b)Passenger Hoist (PH):

Passenger Hoist is a vertical vehicle used for transporting people and goods in an under-constructed high-rise building. It consists of 22 kW three-phase squirrel cage induction motor.

(c)Tower Crane (TC):

In most of the construction projects, materials and structural members are required to be raised from the ground level to the height where they are required to be placed, and this lifting is done with the help of Tower cranes. It consists of a 55.3 kW three-phase squirrel cage induction motor.

2.1.2. Constant load equipment

Loads having constant monthly energy consumption such as (i) Bar bending machines (ii) Bar cutting machines (iii) Welding machines (iv) Other loads from labor colony, site office, site lighting, stores & quality lab (Lighting loads, Fans, ACs, and Computers) are classified as Constant load equipment.

3. DESIGN OF PV INSTALLATIONS

PV systems are installed in four segments during the entire construction process in the areas shown in Figures 3-6, wherein the dotted outline indicates the facility during the construction stage, whereas the thick outline indicates the facility with the completion of structural work.

(A) *Segment-1 solar PV installation*

It is implemented at the beginning of the phase-1 construction activity. The area allotted for phase-2 construction is utilized for several processes (like storage of materials, formwork yard, etc.) during the phase-1 activity. Hence only 10% of phase-2 area (i.e., 1920 sq.m) will be utilized for the installation of ground-mounted solar PV panels. Ground-mounted solar PV panels are installed in the 1920 sq.m area.

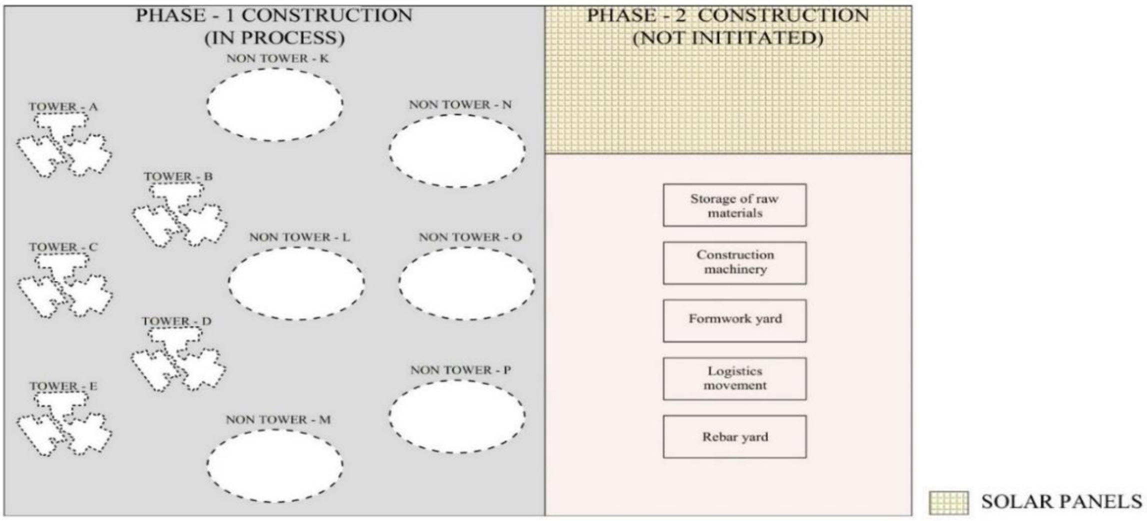


Figure 3. Segment-1 installation of a solar PV system

(B) *Segment-2 solar PV installation*

It is implemented at the beginning of the third year of phase-1 construction activity. Construction of Non-towers N, O, P each of 5 levels will be completed after two years of Phase-1 construction. Hence roof-top solar PV modules on Non-towers N, O, and P are installed. Non-towers are entirely used only for vehicular parking and amenities, hence 80% roof-top area of Non-towers N, O, P (9920 sq.m) is utilized for roof-top solar PV installation. Hence, in Segment-2, solar installations on the roof-top of non-towers N, O, P, and already operational ground-mounted solar PV panels in the phase-2 area add up to 11840 sq.m.

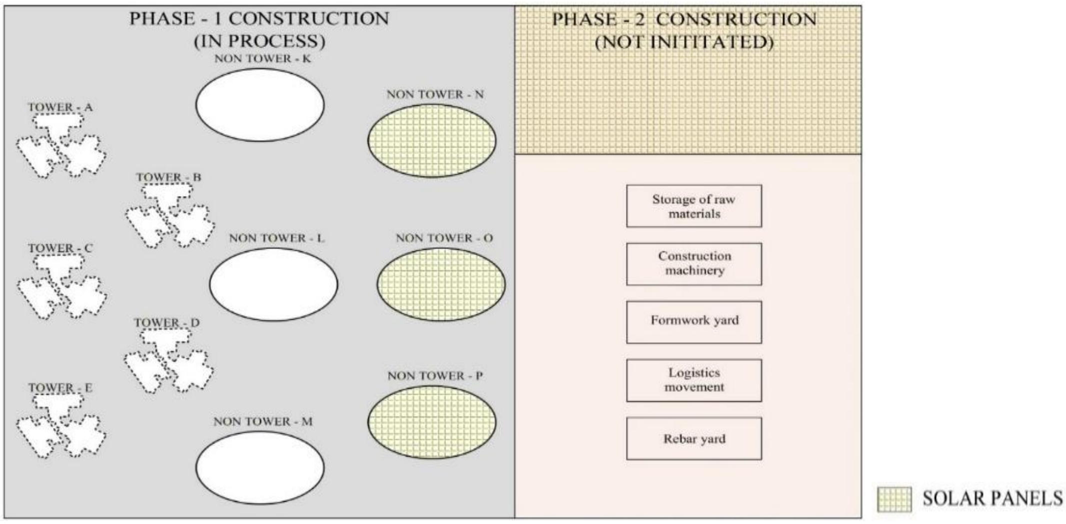


Figure 4. Segment-2 installation of a solar PV system

(C) *Segment-3 solar PV installation*

It is implemented at the beginning of the phase-2 activity. Construction of 5 towers (A, B, C, D, E) along with 6 Non-towers (K, L, M, N, O, P) as part of phase-1 will be completed by the end of 4 years, and subsequently, phase-2 construction commences. Hence, the 1920 sq.m ground-mounted solar PV system erected in the area marked for phase-2 construction is transferred and installed in the roof-top of constructed towers (A, B, C, D, and E). It is assumed that only 60% roof-top area of Towers A, B, C, D, E (3750 sq.m) is utilized for installation of roof-top Solar PV system, along with previously installed roof-top Solar PV system on Non-towers N, O, P (9920 sq.m). Hence, in Segment-3 13670 sq.m area will be utilized for the installation of a roof-top solar PV array.

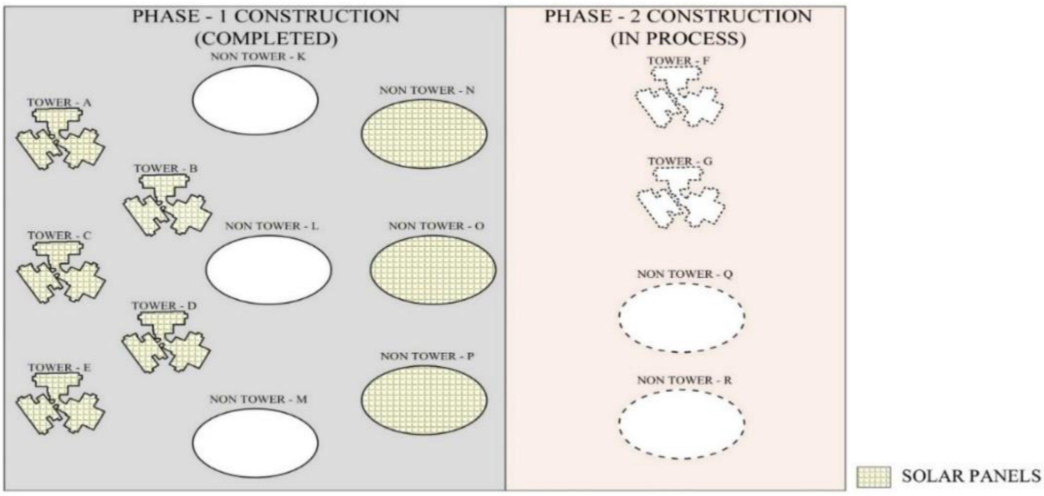


Figure 5. Segment-3 installation of a solar PV system

(D) *Segment-4 solar PV installation*

It is implemented at the end of the phase-2 construction activity. In Segment-4, the installation of roof-top solar PV panels on 7 Towers (A, B, C, D, E, F,G) and 5 Non-towers (N, O, P, Q, R) is planned to span a total area of 28530 sq.m.

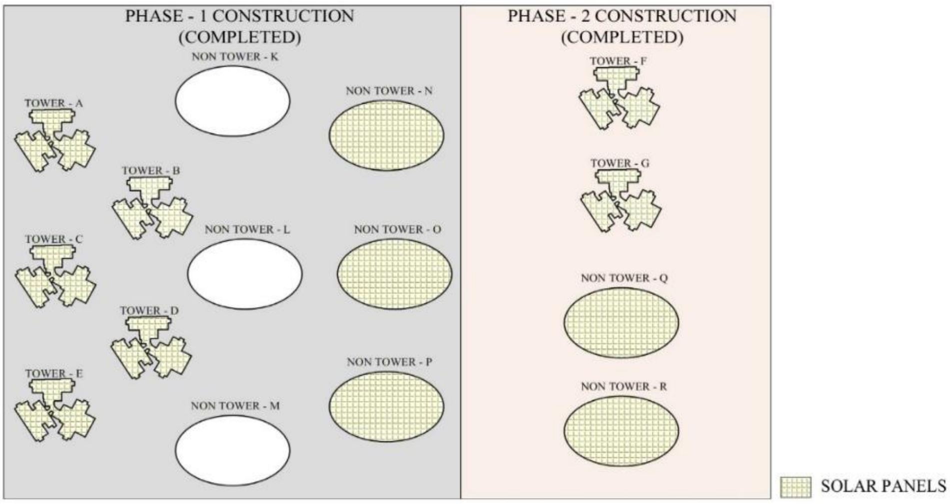


Figure 6. Segment-4 installation of a solar PV system

In each segment, the number of panels gets added up, and ultimately 28530 sq. m area of the solar PV system will be installed on the roof-top of the newly constructed high-rise residential building. The segmented installation of PV array shall result in the reduction of electricity bills at the construction stage itself.

3.1. Block Diagram

The schematic diagram of the solar PV system is shown in Figure 7. It consists of solar PV panels, grid interfacing inverters, and smart meter. The generated energy from the solar PV system is utilized for construction activity. If the generated energy is more than the requirement, the energy is exported to the grid. If the solar PV system does not meet the energy requirement, electrical energy is imported from the grid. The net meter is used in the solar PV system to record the kWh exported to the grid and kWh imported from the grid to the control center. The contractor is paid a Feed-In-Tariff (FIT) for the electricity exported to the grid.

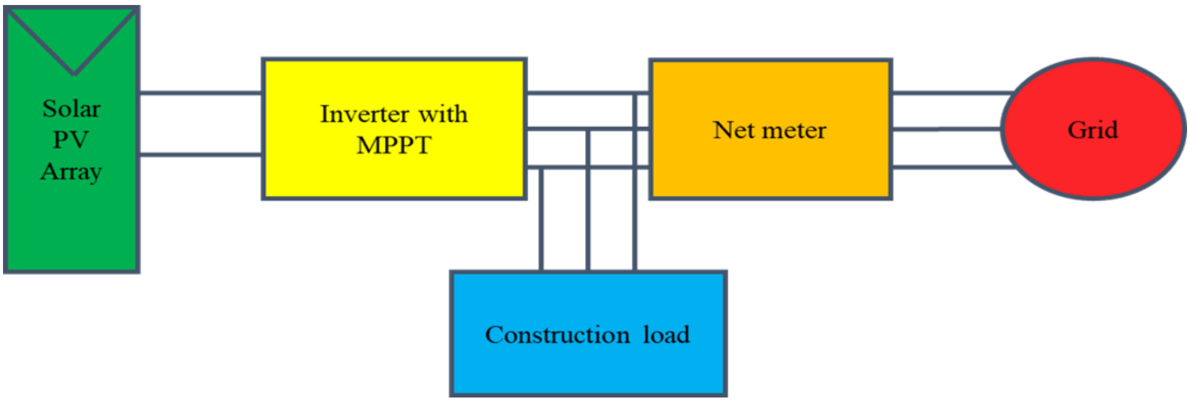


Figure 7. Schematic diagram of the solar PV system

4. RESULTS AND DISCUSSION

In this section the results obtained from the energy auditing, PV array sizing and PV array performance results are presented.

4.1. Energy Auditing (Phase-1 & Phase-2 Construction)

The procedure followed to audit the various construction loads are unique which are clearly displayed in the following sections. Phase-1 construction consists of construction of towers (A, B, C, D, E) and non-towers (K, L, M, N, O, P). Various equipment used in the phase-1 construction process is audited. The Phase-2 construction activities consist of the construction of towers (F, G) and non-towers (Q, R), which commence immediately after the completion of phase-1.

A) Type-1 Variable loads:

A set of three samples (also called a batch in construction) has been taken for each concrete grade, and the energy consumption factor (E_{avg}) is assessed by taking the average of three batches.

Where, E_{avg} represents average electrical energy consumption for 1cu.m of concrete produced from CBP, also known as energy consumption factor of type-I variable load. Energy consumption of Type-I variable load is a function of E_{avg} of a specific concrete grade and its quantity. Six concrete grades (M5, M10, M50, M60, M70, and M80) are utilized for the construction of high-rise residential buildings. Table 1 provides the data computation process to calculate E_{avg} for type-1 variable loads.

$$E = \frac{\text{ERE-ERS}}{Q} \tag{1}$$

$$E_{avg} = \frac{E_{batch-1} + E_{batch-2} + E_{batch-3}}{3} \tag{2}$$

$$\text{Monthly energy consumption of CBP} = \sum_{grade-1}^{grade-n} \text{E}_{\text{avg}} \text{ of grade concrete } \times Q_n \tag{3}$$

Table 1. Average energy consumption of concrete grades used in the site

Concrete Grade	Parameter	Batch-1	Batch-2	Batch-3	E_{avg}
M5	Q (in cu.m)	3	2	2	0.318
	ERS (in kWh)	15531.29	15732.62	15762.54	
	ERE (in kWh)	15532.25	15733.26	15763.18	
	E (in kWh/cu.m)	0.3178	0.3165	0.3198	
M10	Q (in cu.m)	2	2	2	0.2848
	ERS (in kWh)	15670.85	15856.87	15920.67	
	ERE (in kWh)	15671.43	15857.45	15921.23	
	E (in kWh/cu.m)	0.2883	0.2867	0.2795	
M50	Q (in cu.m)	2	2	2	0.2706
	ERS (in kWh)	15665.76	15423.79	15999.42	
	ERE (in kWh)	15666.31	15424.32	15999.96	
	E (in kWh/cu.m)	0.2766	0.2653	0.27	
M60	Q (in cu.m)	2	2	2	0.3691
	ERS (in kWh)	15628.24	15734.65	15787.67	
	ERE (in kWh)	15628.98	15735.4	15788.4	
	E (in kWh/cu.m)	0.3688	0.3765	0.362	
M70	Q (in cu.m)	2	2	2	0.2934
	ERS (in kWh)	15582.02	15435.09	15555.45	
	ERE (in kWh)	15582.6	15435.68	15556.02	
	E (in kWh)	0.2928	0.2999	0.2876	
M80	Q (in cu.m)	3	2	2	0.2918
	ERS (in kWh)	15649.96	15256.93	15732.84	
	ERE (in kWh)	15650.54	15257.51	15733.43	
	E (in kWh/cu.m)	0.2912	0.2875	0.2967	

B) Type-2 Variable loads

Energy meter installed in each equipment (e.g., TC, BP, and PH) indicates the amount of electrical energy consumption in kWh, whereas the Hour meter indicates the number of hours the equipment is under operation. Energy meter readings and hour meter readings for each equipment are recorded at 8 AM for eight consecutive days. The difference between two consecutive day readings gives the total amount of energy consumed and the time of operation of the equipment for every 24 hours. Table 2 provides the data computation process to calculate K_{avg} for type-2 variable loads.

$$EMR_{sample\ i} = EMR_{day(i+1)} - EMR_{day(i)} \tag{4}$$

$$HMR_{sample\ i} = HMR_{day(i+1)} - HMR_{day(i)} \tag{5}$$

Where i represents the number of samples taken, in this manner, 7 samples of EMR and HMR of the equipment are taken, and the ratio of EMR and HMR gives the parameter (K), which is constant for equipment.

$$K = \frac{EMR}{HMR} \tag{6}$$

Data analysis is done using 7 samples to obtain accurate results. K_{avg} is calculated by averaging K for all 7 samples.

$$K_{avg} = \frac{K_{sample\ 1} + K_{sample\ 2} + K_{sample\ 3} + K_{sample\ 4} + K_{sample\ 5} + K_{sample\ 6} + K_{sample\ 7}}{7} \tag{7}$$

K_{avg} represents the average energy consumption of Type-II variable loads for 1 hour of its operation. Table 2 provides the data computation process to calculate K_{avg} for tower A, and non-tower N. Energy consumption of the Type-II variable load is assessed using K_{avg} (Energy consumption factor) and operating time (N_{TC}, N_{PH}, N_{BP}). Table 3 represents the K_{avg} details for the type-II variable loads.

$$\text{Monthly Energy consumption of BP} = \sum_{grade-1}^{grade-n} \mathrm{K}_{\text{avg of BP}} \times \text{NBP} \tag{8}$$

$$\text{Monthly Energy consumption of PH} = \sum_{grade-1}^{grade-n} \mathrm{K}_{\text{avg of PH}} \times \text{NPH} \tag{9}$$

$$\text{Monthly Energy consumption of TC} = \sum_{grade-1}^{grade-n} \mathrm{K}_{\text{avg of TC}} \times \text{NTC} \tag{10}$$

All three type-II variable load equipment (BP, PH, TC) are allocated for all towers and non-towers construction except for non-towers K, L, M. Hence 8 units each of BP, PH, and TC are utilized in phase-1 construction activity and 4 units each of BP, PH, and TC are utilized for phase-2 construction activity. Table 4 represents the total energy consumed by variable loads (type-I and type-II).

$$Energy\ consumption\ of\ constant\ loads = Power\ rating \times Time\ of\ operation \tag{11}$$

$$E = \frac{\text{ERE-ERS}}{Q} \tag{12}$$

Table 3 represents the K_{avg} details of various type-2 variable loads. Total electrical energy consumption for variable and constant loads for phase-1 construction is displayed in Table-4 and Table-5 respectively.

Consolidated energy drawn from all the loads in phase-1 and phase-2 construction are displayed in Table-6 and Table-7 respectively.

Table 2. $K_{a\ vg}$ Computation procedure for Tower A and Non-tower

Facilities	Equipment	Parameter	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample7
TOWER A	TC	EMR (in kWh)	36.00	18.30	18.41	27.66	29.40	26.32	31.28
		HMR(in hours)	2.00	1.00	1.00	1.50	1.60	1.44	1.70
		K	18.00	18.30	18.41	18.44	18.38	18.28	18.40
		K_{avg}				18.3157			
	PH	EMR (in kWh)	24.90	24.60	12.30	12.37	18.63	24.96	22.68
		HMR(in hours)	2.00	2.00	1.00	1.00	1.50	2.00	1.80
		K	12.45	12.30	12.30	12.37	12.42	12.48	12.60
		K_{avg}				12.4171			
	BP	EMR (in kWh)	67.69	0.32	35.07	35.24	42.40	10.55	12.70
		HMR(in hours)	6.28	0.03	3.26	3.30	4.00	1.00	1.20
		K	10.78	10.67	10.76	10.68	10.60	10.55	10.58
		K_{avg}				10.66			
NON-TOWER N	TC	EMR (in kWh)	35.30	70.88	45.99	38.87	42.33	52.62	58.64
		HMR(in hours)	2.00	4.00	2.60	2.20	2.40	3.00	3.30
		K	17.65	17.72	17.69	17.67	17.64	17.54	17.77
		K_{avg}				17.6685			
	PH	EMR (in kWh)	32.20	25.96	20.94	25.32	27.39	26.71	19.02
		HMR(in hours)	5.00	4.00	3.40	4.00	4.30	4.20	3.00
		K	6.44	6.49	6.16	6.33	6.37	6.36	6.34
		K_{avg}				6.3557			
	BP	EMR (in kWh)	19.21	38.87	39.04	38.98	34.32	36.92	30.45
		HMR(in hours)	3.40	6.76	7.01	6.90	6.00	6.50	5.40
		K	5.65	5.75	5.57	5.65	5.72	5.68	5.64
		K_{avg}				5.6657			

Table 3. K_{avg} details of type-2 variable loads

Facility	K_{avg} of TC	K_{avg} of PH	K_{avg} of BP
Tower-A	18.32	12.42	10.66
Tower-B	18.67	12.45	10.54
Tower-C	18.66	12.11	10.91
Tower-D	18.23	12.06	10.96
Tower-E	18.11	12.56	10.47
Non-tower N	17.67	6.36	5.67
Non-tower O	17.98	6.42	5.21
Non-tower P	17.87	6.39	5.92

Table 4. Electrical energy consumption of variable loads for phase-1 construction activity

Month	Energy consumed by CBP load (kWh)	Energy consumed by PH load (kWh)	Energy consumed by TC load (kWh)	Energy consumed by BP load (kWh)	Energyconsumed by variable loads (kWh)
January	265.25	11853.6	19257.84	12328.96	43705.65
February	543.36	9196.72	17361.2	11373.92	38475.2
March	659.85	16043.2	16631.76	17104.32	50439.13
April	909.69	13999.52	19257.84	6077.68	40244.73
May	444.57	6028.96	11963.2	5817.2	24253.93
June	819.47	5824.56	11379.6	3386.08	21409.71
July	685.27	5926.8	10358.32	2170.56	19140.95
August	723.24	1839.28	19111.92	2604.72	24279.16
September	1018.48	6846.48	13130.32	3646.56	24641.84
October	1153.25	9298.96	17215.28	11460.72	39128.21
November	1049.89	11751.36	16777.6	9637.44	39216.29
December	1581.83	8379.28	13713.92	11981.68	35656.71

Table 5. Energy consumption of constant loads for phase-1 construction activity

Constant loads	Total Power rating (kW)	Monthly Energy consumption (kWh)
Labor colony	35.62	24120.4
Site office	75.88	25,073.58
Site lighting	27.29	9788.4
Stores & quality lab	9.46	1594.86
Bar bending machine (9)	3.7	999
Bar cutting machine (9)	3.7	999
Welding machines (10)	10	8631
Total	165.65	71206.24

Table 6. Total site electrical energy consumption for phase-1 construction activity

Month	Variable loads (kWh)	Constant loads (kWh)	Total Energy consumption (kWh)
January	43705.65	71206.24	114911.9
February	38475.2	71206.24	109681.4
March	50439.13	71206.24	121645.4
April	40244.73	71206.24	111451
May	24253.93	71206.24	95460.17
June	21409.71	71206.24	92615.95
July	19140.95	71206.24	90347.19
August	24279.16	71206.24	95485.4
September	24641.84	71206.24	95848.08
October	39128.21	71206.24	110334.5
November	39216.29	71206.24	110422.5
December	35656.71	71206.24	106863
Total	400591.51	854474.88	1255066.49

Table 7. Total site electrical energy consumption for phase-2 construction activity

Month	Variable loads (kWh)	Constant loads (kWh)	Total (kWh)
January	20812.21	52565.02	73377.23
February	17488.72	52565.02	70053.74
March	23792.04	52565.02	76357.06
April	19164.15	52565.02	71729.17
May	11549.49	52565.02	64114.51
June	20596.19	52565.02	73161.21
July	20610.48	52565.02	73175.5
August	20625.24	52565.02	73190.26
September	20640.00	52565.02	73205.02
October	20654.29	52565.02	73219.31
November	20669.05	52565.02	73234.07
December	20683.33	52565.02	73248.35
Total	237285.18	630780.24	8,68,065.42

After completion of the energy audit for both the phases of construction, it is concluded that 1255 MWh of annual electrical energy is estimated to have been utilized for 4 years of phase-1 construction, and 868 MWh of annual electrical energy is estimated to have been utilized during the 2 years of phase-2 construction.

4.2. Solar PV System Sizing and Installation

Solar PV panels are installed in four segments during the span of six years of the entire construction process. The availability of the space for the installation of solar PV panels varies as the construction progresses, which is a significant constraint to be considered in this approach. Installation of panels commences after the completion of the structural part of the building. Subsequent to the completion of the project, the panels are installed permanently on the roof-top of the constructed buildings. Four distinct segments in the construction process are identified. The entire construction process is divided into four segments for ascertaining the available areas for the installation of panels, as shown in Table 8. The details of the area available during each segment are described in the following sub-sections.

This initiative will target to minimize the electricity bill during the construction phase for the contractor and after the construction phase for the owners. The critical aspect here is utilizing green energy in the construction process. Detailed information about the type and rating of equipment used in the installation of solar PV panels as obtained from PVsyst simulation is demonstrated in Table 9.

Table 8. Detailed information on solar PV installation

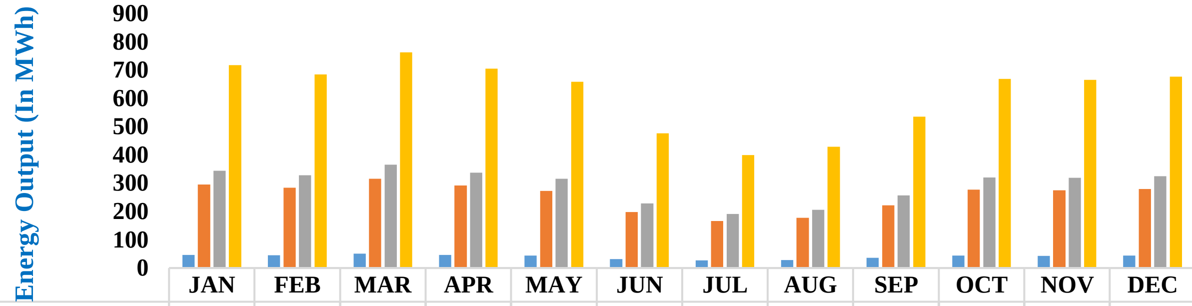
Stage in construction	Status of solar PV installation	Location of solar PV installation	Area available for PV installation	Segment
Installation of Solar PV panels during Phase-1 construction				
Beginning of Phase-1 construction	New installation	phase-2 construction area (ground-mounted)	1920 sq.m	1
Structure completed for Non-towers: N, O, P	New installation Already Operational	Non-towers: N, O, P (roof-top) phase-2 construction area (ground-mounted)	11840 sq.m	2
Installation of Solar PV panels during Phase-2 construction				
Structure completed for Towers: A, B, C, D, E	New installation Already Operational	Towers: A, B, C, D, E (roof-top) Non-towers: N, O, P (roof-top)	13670 sq.m	3
Installation of Solar PV panels after completion of entire construction				
Structure completed for Non-towers: Q, R & Towers: F, G	New installation Already Operational	Non-towers: Q, R (roof-top) & Towers: F, G (roof-top) Non-towers: N, O, P (roof-top) & Towers: A, B, C, D, E (roof-top)	28530 sq.m	4

Table 9. PV system sizing details

System Parameters		Segment-1 solar PV installation	Segment-2 solar PV installation	Segment-3 solar PV installation	Segment-4 solar PV installation
Capacity of solar PV system		275 kW	1.54 MW	1.76 MW	3.63 MW
Annual kWh generated from the solar PV system		487.1 MWh	3057 MWh	3535 MWh	7377 MWh
PV field orientation	tilt	30^0	30^0	30^0	30^0
	azimuth	0^0	0^0	0^0	0^0
PV module	N_{PO}	968	6040	6972	14553
	Nominal power (Wp)	320	320	320	320
Inverter pack	N_{IO}	22	28	32	66
	AC Nominal power (KW)	55	55	55	55

4.3. Performance of the Solar PV System

Assessment of performance parameters is used to ascertain the feasibility of the installation of the solar PV system on the constructed buildings. The performance indices of the roof-top solar PV system on the constructed buildings are made based on PVsyst simulations. Figure 8-10 represent the predicted energy output, predicted PR, and predicted CUF, respectively. Figure 8 demonstrates the variation of energy output in various months of a year. In the segment-4 solar PV installation, the maximum energy generated in March is 762.3 MWh, and the lowest energy generated in July is 399.8 MWh. The standard power output of the PV array depends on several parameters, such as array temperature, ambient temperature, solar irradiance, and wind variation in the site. Technical specifications of the solar PV module and string inverter are provided in Appendix 1 and 2.



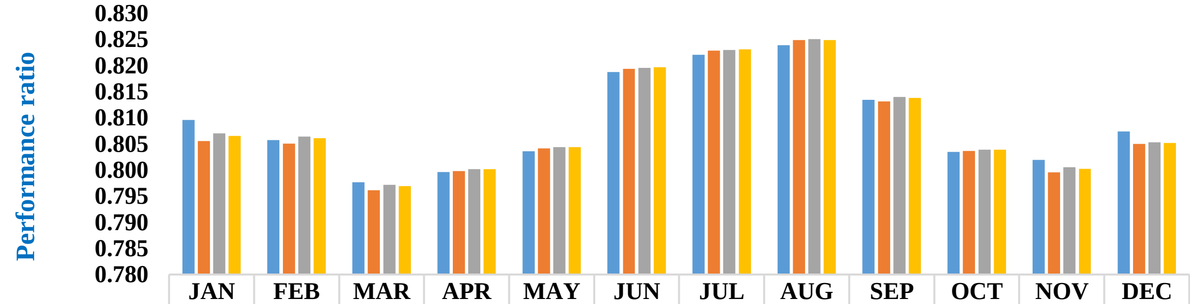
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
SEGMENT-1	46.5	45.3	50.8	46.9	43.8	31.7	26.6	28.5	35.6	44.5	43.4	43.6
SEGMENT-2	295.7	284.0	316.1	292.2	273.1	197.5	165.9	178.1	222.1	277.6	275.1	279.0
SEGMENT-3	343.7	327.8	365.3	337.4	315.3	228.0	191.5	205.6	256.6	320.5	318.8	324.3
SEGMENT-4	717.0	684.0	762.3	704.3	658.2	476.0	399.8	429.1	535.5	669.0	665.2	676.8

Month

Figure 8. Energy output of the solar PV system

4.3.1. Performance ratio (PR)

It is the ratio of final yields to the reference yields. It represents the overall effect of losses on PV arrays. This factor is used to determine if the system is operating as expected. Higher PR ascertains the effectiveness of plant operation. Figure 9 demonstrates the performance ratio of the solar PV system. In the Segment-4 solar PV installation, the highest PR is observed in August, and the lowest PR is observed in March. PR is a system-dependent quantity and does not gets affected by solar irradiance.



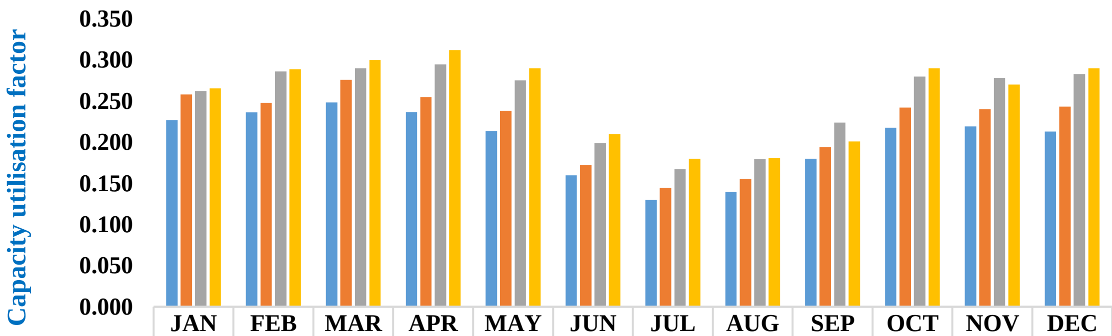
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
SEGMENT-1	0.810	0.806	0.798	0.800	0.804	0.819	0.822	0.824	0.813	0.803	0.802	0.807
SEGMENT-2	0.806	0.805	0.796	0.800	0.804	0.819	0.823	0.825	0.813	0.804	0.800	0.805
SEGMENT-3	0.807	0.806	0.797	0.800	0.804	0.820	0.823	0.825	0.814	0.804	0.801	0.805
SEGMENT-4	0.807	0.806	0.797	0.800	0.804	0.820	0.823	0.825	0.814	0.804	0.800	0.805

Month

Figure 9. Performance ratio of the solar PV system

4.3.2. Capacity utilization factor (CUF)

It is the ratio of actual generated energy to the theoretically possible maximum energy from the PV system for 24 hours for a period of 1 month. It represents the energy delivered by a power generation plant. If the solar PV system delivers rated power continuously, the capacity utilization factor would be unity. Factors that affect the CUF are solar irradiance and the number of clear sunny days experienced by the installed solar PV array. Figure 10 demonstrates the capacity utilization factor of the solar PV system.



	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
SEGMENT-1	0.227	0.236	0.248	0.237	0.214	0.160	0.130	0.139	0.180	0.218	0.219	0.213
SEGMENT-2	0.258	0.248	0.276	0.255	0.238	0.172	0.145	0.155	0.194	0.242	0.240	0.244
SEGMENT-3	0.262	0.286	0.290	0.294	0.275	0.199	0.167	0.179	0.224	0.280	0.278	0.283
SEGMENT-4	0.265	0.289	0.300	0.312	0.290	0.210	0.180	0.181	0.201	0.290	0.270	0.290

Month

Figure 10. CUF of the solar PV system

In the segment-4 solar PV installation, the highest CUF is observed in March is the result of high irradiance and more clear sunny days in the prevailing summer season, and the lowest CUF is observed in June, July , August and September is the result of low irradiance and less clear sunny days due to monsoon season.

$$\mathrm{CUF} = \frac{G_M}{(\mathrm{Pi} * \text{number of days in a month} \times 24)} \qquad (13)$$

4.4. Benefits of Solar PV Installation in Construction Site

A) Reduction in power drawn by grid due to solar PV system during construction and cost savings for the contractor

The contractor can benefit almost 38.81 % of the electricity cost at the end of the first year of construction if the segment-1 solar PV system is operational. Refer Table 10 for details of percentage reduction in energy drawn from the grid for segment-1, segment-2, and segment-3 installation. The annual site energy consumption for the construction process (C_A) and annual solar energy generated by the solar PV system (G_A) are important findings to estimate the reduction in electrical energy consumption for construction, which is ultimately reflected in the reduction in construction cost. The Commercial electricity unit cost for Mumbai, India, is $ 0.15/kWh.

$$Percentage\ reduction\ of\ energy\ drawn\ from\ grid = \frac{GA}{CA} \times 100 \qquad (14)$$

$$Cost\ savings\ for\ contractor\ with\ the\ installation\ of\ solar\ PV\ system = G_A \times 0.15 \qquad (15)$$

The percentage reduction of the energy drawn from the grid is only estimated for the segment-1 installation of the solar PV system. After the implementation of segment-2 installation, the contractor need not spend any expense as part of the electricity bill since generation is more than the demand. After segment 2 and 3 installations of solar PV, the contractor gains revenue for the excess units exported to the grid.

Table 10. Percentage reduction of power drawn from the electric grid

Year	Solar PV installation	C_A (kWh)	G_A (kWh)	Reduction of energy drawn from the grid with the solar PV system (in %)	Cost savings (in $)
1	Segment-1	12,55,066	4,87,100	38.81	73,065
2		12,55,066	4,87,100	38.81	73,065
3	Segment-2	12,55,066	30,57,000	-	4,58,550
4		12,55,066	30,57,000	-	4,58,550
5	Segment-3	8,68,065.42	35,35,000	-	5,30,250
6		8,68,065.42	35,35,000	-	5,30,250

Total cost savings for the contractor during the construction period is $ 21,23,730.

B) Reduction in power drawn by grid due to Solar PV system after construction and cost benefits for the owners

The installation of a solar PV system is ultimately attributed to benefit flat owners. PVsyst simulation software estimates the annual power generation from the fully installed roof-top solar PV system as 73,77,000 kWh. Total cost-benefit (in $) for each flat owner is the summation of annual cost-benefit for 20 years since solar PV panel is expected to function for 20 years efficiently after utilization during the construction period. While evaluating the cost-benefit analysis of flat owners, it is assumed that unit cost for power received from grid and unit cost for power exported to the grid is considered the same (i.e., $ 0.14/kWh).

- Total number of flats in high-rise residential building project = 2562
- Annual generated energy from the solar PV system = 73,77,000 kWh
- Annual units shared by each flat owner = $\frac{7377000 \text{ kWh}}{2562}$ = 2950.8 kWh
- Cost-benefit for each flat owner = 2950.8 kWh × $ 0.15 × 20 = $ 8852.4

4.4.1. Economic analysis of the proposed solar PV system

This economic analysis does not have any payback period since the total investment cost is levied from the customers at the time of flat booking. In this manner, both the contractor and the flat owner benefit from this initiative. The 320 Wp Adani-make solar PV module and 55 kW ac Huawei make string inverter is considered to perform economic analysis, which is displayed in Table 11. In economic analysis, the segment-wise solar PV system investment cost is calculated for all four segments. There are various types of costs which are encountered in economic analysis.

1) Cost of support/integration of PV panels (C_1)
2) Cost of setting and wiring per panel (C_2)
3) Cost of unskilled workers (C_3)
4) Cost of engineering and technical staff (C_4)
5) Total miscellaneous cost (C_5)
6) Investment cost on solar PV panels (C_{pv})
7) Investment cost on Inverters (C_i)

Table 11.The total initial investment in solar PV system

Type of cost	Segment-1 solar PV installation		Segment-2 solar PV installation		Segment-3 solar PV installation		Segment-4 solar PV installation	
	Quantity	Cost ($)	Quantity	Cost ($)	Quantity	Cost ($)	Quantity	Cost ($)
Cpv ($115/unit)	968	1,11,320	5072	5,83,280	932	107180	7581	8,71,815
Ci ($ 1500/unit)	22	33,000	6	9000	4	6000	34	51,000
C_1 ($ 30/panel)	968	29,040	5072	15,12,160	6972	209160	7581	2,27,430
C_2 ($ 4/panel)	968	3872	5072	20288	6972	27888	7581	30,324
C_3($200/person)		1000		1000		1000		1000
C_4($1000/person)		6000		6000		6000		6000
C_5		4000		4000		8000		4000
Total investment cost ($)		1,88,232		21,35,728		3,65,228		11,91,569

- The total investment cost for installation of all four segments = $ 38,80,757
- Number of three-BHK flats ($ 4,71,430/three-BHK flat) = 2013
- Number of four-BHK flats ($ 6,28,600/four-BHK flat) = 549
- Total number of flats = 2562
- Extra amount levied from each flat owner to render benefits of roof-top solar PV System = $ 38,80,757/2562=$ 1514.73

The excess miscellaneous cost considered in segment-3 solar PV installation is due to shifting of Solar PV panels from ground to rooftop. The amount incurred by each flat owner in order the render the benefits of reduction in electricity bill is $ 1514.73, which is 0.321 % of the flat purchase cost for three-BHK flat owners and 0.24 % of the flat purchase cost for the four-BHK flat owner. The total cost-benefit for each flat owner is estimated to be $ 8852.4, which is 1.877 % of the flat purchase cost for the three-BHK flat owner and 1.4 % of the flat purchase cost for the four-BHK flat owner. Since the benefit obtained is higher than the amount invested for this scheme, the contractor will undoubtedly use these figures as a mathematical tool to advertise the advantage in the long run.

4.4.2. Challenges, and advantages of solar PV installation during the construction process

The idea of energy-efficient construction with the utilization of solar energy rather than conventional grid power for the construction process is the new dimension in the construction sector. There are several challenges and immense cost-benefits both for contractors and owners to install solar PV panels in the construction site to harness and utilize renewable energy for the construction process.

4.4.3. Challenges in harnessing solar energy for construction

A proper solar panel maintenance team is allocated for daily cleaning of ground-mounted solar panels and roof-top solar panels since the construction site is prone to large amounts of dust. The ground-mounted solar panels are operational for only segment-1 and segment-2 installation. Later these ground-mounted panels are shifted to roof-top of constructed facilities as part of the segment-3 installation. Hence, utmost care is taken to shift these ground-mounted panels to roof-top of the constructed buildings.

Dedicate the ground-mounted solar panel area as the restricted zone for construction workers and site engineers. A temporary control center is required to set up in the construction site office to monitor and assess the performance of the operational solar PV system. Reserve miscellaneous cost for any unanticipated damages to components of the solar PV system during the construction process. The idea to harness and utilise renewable energy in the construction process is applicable only for large construction projects. Though the investment cost of solar PV systems during the construction period appears quite high for the contractor to invest, 100 % investment can be withdrawn from the flat owners at the time of flat booking.

4.4.4. Environmental impact of the energy-efficient construction practice

The amount of GHG (Greenhouse gas) emissions that can be reduced with the operation of a solar PV system for power generation is known as GHG mitigation. In India, almost 62.8 % of electrical energy generation is attributed to thermal power generating stations. Thermal power plants liberate enormous amounts of GHG emissions (carbon dioxide, Sulphur dioxide, and nitrous oxides) into the environment. Generation of one unit (kWh) electrical energy from thermal power plants produces 980 g of carbon dioxide 1.24 g of Sulphur dioxide, 2.59 g of nitrogen oxide, and 68 g of ash [23-26]. Generating adequate power from solar PV systems can reduce GHG emissions into the environment and hence can minimize environmental hazards wiz—global warming, ozone layer depletion, etc. The simulation reports of solar PV system for high-rise residential building is considered to ascertain the GHG mitigation. GHG mitigation for the high-rise residential building project with the installation of the solar PV system at Mumbai, India, has resulted in 7229.4 tons of CO_2, 501.6 tons of fly ash, 9.14 tons of SO_2, and 19.1 tons of NO_x.

4.4.5. Comparison of energy-efficient construction practice with conventional construction practice

Growing energy demand is the most significant global issue that must be addressed now. Utilization of renewable energy in all sectors of life can minimize the energy crises and environmental pollution. Table 12 represents the comparison of energy-efficient construction practice with conventional construction practice.

Table 12. Comparison between conventional construction process and energy efficient practice

SI .No	Energy-efficient construction practice	Conventional construction practice
1	Reduction in power drawn from the grid is achieved, and hence burden on the conventional power generation (Thermal, hydro, etc.) is minimized.	There is no reduction in the burden on the grid with conventional construction practice.
2	Environmental pollution can be minimized with the application of energy-efficient construction practices.	This practice contributes to environmental pollution.
3	Cost-benefits can be achieved for the contractor with the application of energy-efficient construction practices.	No additional cost-benefits are achieved with conventional construction practice.

4. CONCLUSION

Energy auditing during the construction process of a high-rise building is performed to estimate the annual energy consumption of the site for phase-1 and phase-2 construction activity. The energy auditing findings are utilised to determine the value of solar PV installation in high-rise building construction. It has been established that the proposed energy-efficient construction of energy consumption from the grid is significantly reduced. The presented effective planning strategy of solar installations in four segments, synchronous with the phase-1 and phase-2 construction activities confirms the feasibility of the proposal. Design and performance of the solar PV system has been carried out by using PVsyst simulation software. Simulation results amply confirm that the proposed solar PV system is capable of generating 487.1 MWh/year after segment-1 installation of 275 kWp capacity, 3057 MWh/year after segment-2 installation of 1.54 MWp capacity, 3535 MWh/year after segment-3 PV installation of 1.76 MWp capacity and 7377 MWh/year after segment-4 PV installation of 3.63 MWp capacity.

Further, performance parameters such as annual average performance ratio (0.807) and annual average capacity utilisation factor (0.26) are also determined for the 3.63 MW roof-top solar PV system.

Complete financial benefits for the contractor and flat owners, along with challenges involved in energy-efficient construction is presented. It is predicted that a contractor can save almost 38.81 % of the electricity bill in the first two years of construction activity with just segment-1 installation of a 275 kWp ground-mounted solar PV system. The comparison drawn for the Environmental impact with the energy-efficient construction practice, conventional construction demonstrates the usefulness of the proposed approach. This construction paradigm can be adopted by the design engineers in the building sector to minimise energy costs during construction.

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APPENDICES

Appendix 1

Technical specification of 320 W_p solar PV module

PV Module	Specifications
Type cell material	Monocrystalline
Make	Adani
Model1	ASP-7 -AAA
Maximum power (P_{max})	320 Wp
Open circuit voltage (V_{oc})	45.5 V
Short circuit current (I_{sc})	9.3 A
Voltage at maximum peak(V_{mp})	36.41 V
Current at maximum power (I_{mp})	8.79 A
Number cell in module	72
Module efficiency %	16.32

Appendix 2

Technical specification of 55 kW ac string inverter

String inverter	Specifications
Make	Huawei
Model	Sun2000-43KTL
Maximum number of inputs	8
Maximum DC usable power	53500 W
Maximum input voltage	1100 V
Maximum current per MPPT	22 A
Maximum short circuit current per MPPT	30 A
Minimum start input voltage	250 V
MPPT operating voltage range	200 V – 1000 V
Rated input voltage	750 V
Number of MPP trackers	4
Rated AC active power	43000 W
Maximum AC apparent power	52500 VA
Maximum AC active power ($\cos \varphi = 1$)	52500 W
Rated output voltage	288 V/500 V,3W +PE