CASE STUDY OF AN ENERGY EFFICIENT COMMERCIAL BUILDING: VALIDATING DESIGN INTENT & ENERGY SIMULATION RESULTS WITH MONITORED PERFORMANCE DATA

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ABASTRACT

In India, adoption of ECBC and energy-efficient building design measures in commercial buildings has remained limited due to various reasons. One of the reasons is the non-availability of good case studies of energy efficient buildings based on performance data. Such case studies are needed for convincing both government agencies (responsible for ECBC implementation) and builders and building design teams about the advantages of energy-efficient buildings. Monitoring of energy performance of buildings is a challenge due to non-installation or non- functioning energy information system (EIS) in majority of the buildings.

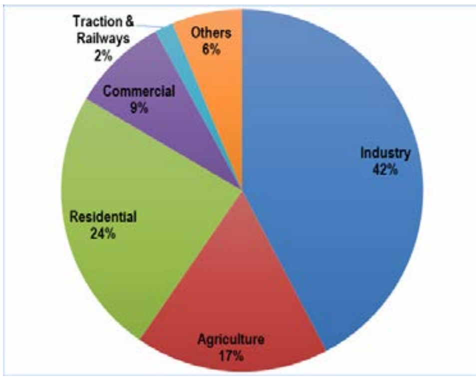
The paper presents case study of an energy efficient day-use public office building in composite climate (Jaipur). The paper provides details about:

a) Energy efficiency measures adopted in the building.
b) Results of the building energy simulation during the building design.
c) Methodology and results of the performance monitoring of the fully functional building for one-year period.
d) Results of checking compliance with ECBC

Energy efficiency measures (EEMs) for this building includes use of insulation in external walls & roof, optimized window-to-wall ratio, efficient glazing, high efficiency water cooled chiller, T5 & LED lighting and rooftop solar photovoltaic system. Since the building does not have an EIS, a monitoring methodology was developed. This consisted of (i) two-weeks detailed energy monitoring twice a year, in winter and summer season; (ii) analysis of monthly energy bills for a year; and (iii) a calibrated energy simulation model. Results show 53% of electricity is used for HVAC annually, while 31% of electricity is used for office equipment and 6% for artificial lighting. The difference in simulated performance (EPI: 53 kWh/m^2.y) and measured performance (EPI: 43 kWh/m^2.y) is explained.

INTRODUCTION

India as an emerging market economy is witnessing a significant increase in energy consumption. The total installed capacity for electricity generation in the country was ~350 GW (as on 31.03.2016), and has increased at a compound annual growth rate (CAGR) of 8.52% in last decade (Energy Statistics, 2017). Total installed capacity is estimated to increase to ~1145 GW by 2047 (IESS, 2015) under 'Determined Effort Scenario' (i.e. level of effort which is deemed most achievable by the implementation of current policies and programmes of the government).



Buildings are the second largest consumer of electricity in India after industries (Figure 1). Overall, buildings sector accounts for 33% (24% residential & 9% commercial) of the electricity consumption (Energy Statistics, 2017).

Figure 1: Electricity Consumption in India (sector-wise)

Projections under different scenarios (Figure 2), show that the electricity consumption for the residential sector is expected to increase 6-13 times from 2012- 2047 and 7-11 times for the commercial sector in the same time frame (IESS, 2015). This increase of electricity

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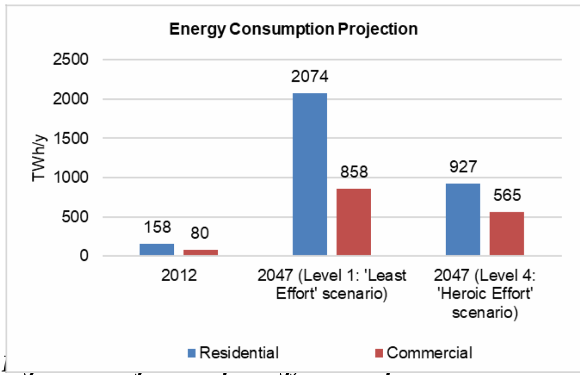
consumption in buildings is primarily attributed to the increase in building stock with residential sector built-up area expected to increase by ~4 times, while commercial sector by ~13 times, during 2012 to 2047 (Figure 3) (IESS, 2015), expansion of electrification in rural areas as well as to the increased intensity of electricity consumption in urban buildings, mainly due to rapid growth of air conditioning.



(Level 4) and worst (Level 1) scenario

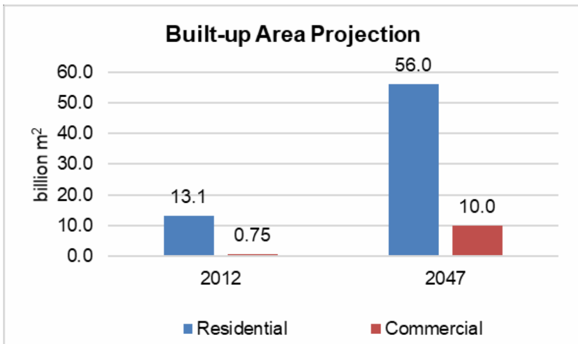


Figure 3: Projection of built-up area

The difference between the "Least Effort Scenario" (i.e. projections assuming past trends continue) & "Heroic Effort Scenario" (i.e. heightened efficiency numbers, leading up to the physically best attainable in due course) (Figure 2) shows that there is a large potential of reducing the overall energy consumption in building by ~50% by the year 2047.

Regulatory efforts in India have focused on commercial building energy efficiency. The Bureau of Energy Efficiency (BEE) developed Energy Conservation Building Code (ECBC) in 2007 to address energy efficiency in new and large commercial / institutional buildings. However, ECBC adoption is voluntary and becomes mandatory in the state after notification by respective state government. As of now, 10 states have notified ECBC and established ECBC cells in 5 states; but actual implementation of the code has remained challenging.

Mandatory building energy efficiency codes like ECBC are considered essential for mainstreaming building energy efficiency in new buildings in emerging economies. Further, it has been noted that world-wide the building energy efficiency codes have better acceptance in the cold climate regions as compared to warm climate regions (Liu et.al. 2010). There are several challenges in the implementation of building energy efficiency codes in the emerging economies and a multi-pronged approach is needed for successful implementation.

Development of good quality case studies of energy-efficient commercial buildings is one of the key components of this multi-pronged strategy, particularly for countries like India which falls in warm climate region. Most of the existing case studies on energy efficient commercial buildings in India are based on building energy simulation results and not on actual monitored energy performance of the building. Due to this reason, there is a lack of confidence and a certain degree of distrust amongst the builders/developers and building designers about the effectiveness of ECBC, building energy efficiency design measures and the results of building energy simulations.

This paper presents a case study of a commercial building. The paper provides details about:

a) Energy efficiency measures adopted in the building.
b) Results of the building energy simulation during the building design.
c) Methodology and results of the performance monitoring of the fully functional building for one-year period.
d) Results of checking compliance with ECBC

Building Design

About the building: The building (Figure 4 and Figure 5) is the head office of the Rajasthan Forest Department, situated in Jaipur (composite climate).

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Figure 4: Aranya Bhawan

Key details of this building are:

- Built-up area: ~10,000 m^2 (excluding basement parking and service area)
- Number of floors: Five (G+4) + one basement level for parking and services
- Number of users: 344
- Types of spaces: Offices, museum, library, auditorium, guest rooms
- Building has three wings with the floor plans as shown below.

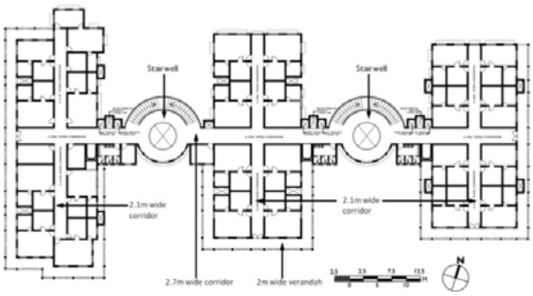

Figure 5: Ground floor plan of the building

- Project timeline & key steps
    - A design workshop for energy-efficient design with key project team members was organised at the design stage in December 2012. This workshop resulted in identification & selection of energy efficiency measures (EEMs) as well as building energy simulation to quantify energy savings.
    - Construction of the building was carried out from 2013 – March 2015.
    - The building was inaugurated in March 2015 and fully occupied by April 2015. Energy monitoring of the building was done in 2015-2016.

Energy efficiency measures & renewable energy system implemented: During the design workshop, the main emphasis was on reducing heat gains, improving day lighting, energy efficient lighting and cooling systems and integration of renewable energy. Following EEMs were agreed upon and implemented during construction stage. The EEMs include:

- Roof insulation (Figure 6): Roof of this building is insulated with 40 mm polyurethane foam (PUF) resulting a U-value of 0.6 W/m^2.K. Also, light coloured terrazzo tiles at top was incorporated to have high reflectivity.

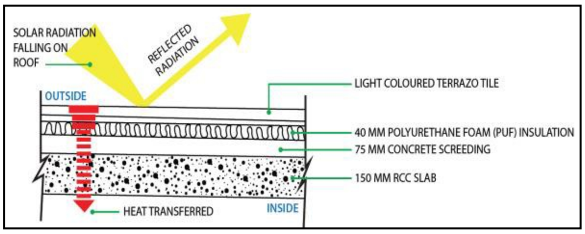

Figure 6: Roof insulation details

- Wall insulation (Figure 7): External wall constructed as cavity wall filled with insulation. A 50 mm extruded polystyrene (XPS) insulation was used, resulting a U-value of 0.5 W/m^2.K (without taking account thermal bridging).

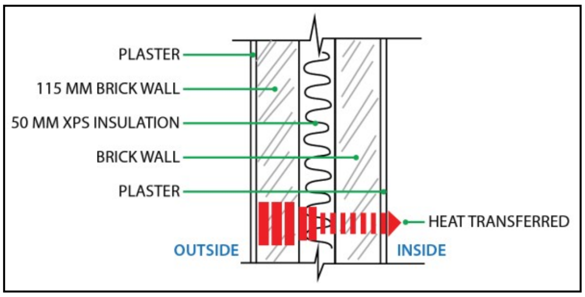

Figure 7: Wall insulation details

- Efficient glazing (Figure 8): Double glazed unit (6-12-6 mm) with U-value: 1.8 W/m^2.K, SHGC: 0.24 & VLT: 36% was used to reduce heat gains and get enough daylight. Relatively shallow floor plate (15 m deep) of the building helped in daylighting.

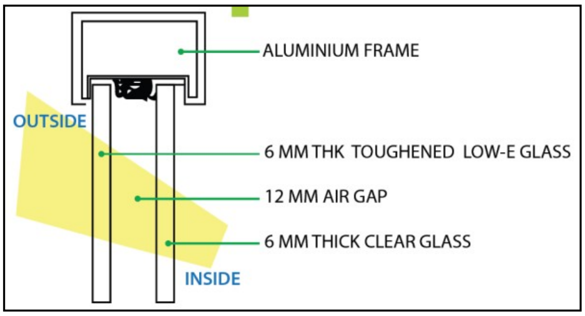

Figure 8: Glazing details

- Energy efficient lighting: LEDs and T5 were used to achieve a lighting power density (LPD) of ~6 W/m^2.

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- Energy efficient cooling system: A centralised high efficiency water-cooled chiller (COP: 5.8) was implemented for air-conditioning the building. Given the water scarcity in Jaipur, a sewage treatment plant (capacity: 15 m^3/d) was installed and treated waste water is used for the cooling towers.
- Solar photovoltaic (SPV) system: A 45kW$_p$ grid-connected roof-top SPV system (Figure 9) with net metering is installed to meet part of the building energy requirement. It should be noted that the contribution of solar PV system has not been included in the EPI calculations during energy simulations.

Figure 9: SPV system at the rooftop

The energy simulation of the building was carried out using DesignBuilder software to quantify the benefits of the integration of EEMs. The key results of the energy simulation were:

- Reduction in cooling system size: The cooling system size was reduced from 230 TR (before the design workshop) to 165 TR (after the integration of EEMs), which is a 28% reduction in the cooling system size (Figure 10).

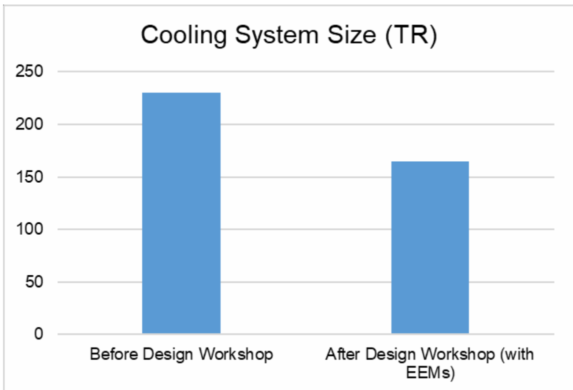

Figure 10: Reduction in cooling system size with EEMs

- Reduction in energy consumption: The energy performance index (EPI) was reduced from 77 kWh/m^2.y to 53 kWh/m^2.y (31% reduction) after considering EEMs in energy simulation (Figure 11). This does not include the energy generated from SPV system.

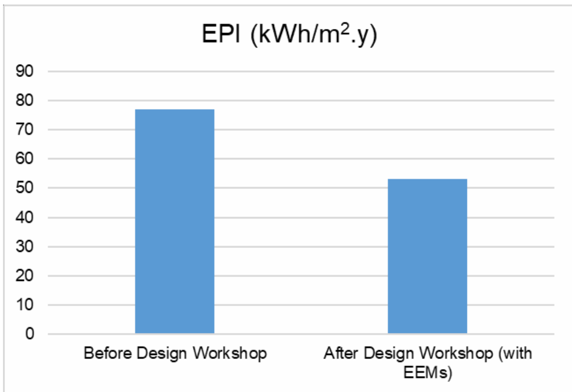

Figure 11: Reduction in EPI size with EEMs (SPV contribution not included)

ENERGY MONITORING

Energy monitoring of the building was done to understand the actual energy performance of the building and to compare it with the estimated energy performance through energy simulation. As the building does not have an EIS, the methodology for energy monitoring involved.

Collection of Electricity Bill

Monthly electricity bills for a period of one year (May 2015 to April 2016) were collected. Using this data monthly and annual EPI of the building was calculated. The billing data was also cross-checked with the data from the log book maintained by the building operation team on the hours of usage of HVAC system and periodic readings of the electricity meter.

Seasonal Energy Monitoring

The objective of the detailed seasonal energy monitoring was (1) to get break-up of energy consumption for different end-uses (e.g. HVAC, lighting, equipment, etc.), and (2) to identify further energy saving opportunities by measuring the performance of different systems (e.g. chillers, pumps, fans, lighting fixtures etc.).

Detailed energy monitoring for two weeks in winter and two weeks in summer was done. Winter monitoring was done for a duration of two weeks in January 2016. During this period, the HVAC system was not operational. Except HVAC system data, all measurements were done. In addition, data on building usage such as number of people, occupancy schedule, schedule of operation for lighting and other systems was gathered. Summer monitoring was for a duration of two weeks in May 2016. During summer, all the

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measurements were done as the HVAC system was fully operational.

Prior to actual energy monitoring, a detailed monitoring plan was prepared. Architectural drawings, HVAC schematic and electrical schematic was studied in detail to prepare a draft monitoring plan (Figure 12). A visit to the building was done to exactly identify the different measurement points, instruments needed, measurement frequency and other details to be collected.

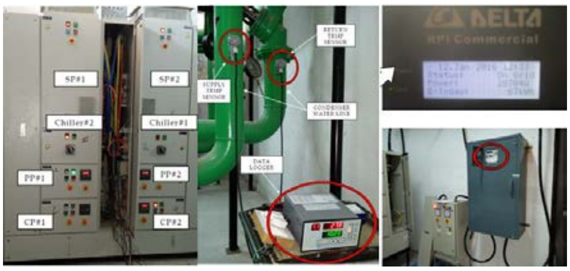

Figure 12: Identification of monitoring points

Monitoring plan for building included three levels of data monitoring and collection

Level 1: Continuous data logging with an interval of 15 min. or less: Energy loggers were installed at electricity distribution panel to continuous log the HVAC and non-HVAC loads. In addition, data logging was done for HVAC system components which included power for each operational chillers, condenser water flow, condenser water in and out temperature, power for air handling units, ambient air temperature and relative humidity. This data was used to calculate the HVAC energy break-up in AHU and Chiller plant and to calculate the chiller coefficient of performance (COP).

Level 2: Spot measurement of parameters (2 times per day: 1100-1230 hrs, 1430-1630 hrs): The key aim of this task was to find an approximate energy break-up of non-HVAC loads which included lighting (office spaces, corridor & exterior), office equipment, STP & miscellaneous (lift, water pump, basement ventilation fan, etc.). Measurement points on multiple electricity distribution panel were identified for the same.

Spot measurements of electrical power was done for primary chilled water pump, secondary chilled water pump, condenser pump and cooling tower fan to get further break-up of chiller plant energy consumption.

Spot measurements were also made for indoor lighting levels and artificial lighting power to understand the daylight penetration in spaces and lighting energy.

Level 3: Data collection (from hourly panel reading, through records or through interaction): Energy generated from SPV system, from DG set was collected to get energy supply from these systems.

Figure 13: Photographs during the monitoring

Table 1 shows the list of instruments used during the monitoring, its make and measured parameter.

Table 1: List of instruments used during monitoring

Sr. No	Name of Instruments	Make	Measurement
1	Single CT power meter	MECO	Snap shot power measurement
2	Three CT power analyzer	ORACLE	Power Data Logging
3	Three CT power analyzer	Krykard	Power Data Logging
4	Swing Psychrometer	JRM	DBT & WBT
5	Lux meter	TES 1332 A	Illumination levels
6	Surface contact type temperature sensor	Libratherm	Measurement of surface temperature on condenser water header
7	Head mount temperature sensor	Libratherm	Measurement of water temperature through thermowell
8	8 Channel Temperature Logger	Libratherm	Logging of water temperature readings
9	8 Channel Temperature Logger + %RH logger	Libratherm	Logging of Ambient Temperature + water temperature + %RH
10	Ambient temperature + %RH sensor	Libratherm	Ambient Temperature + %RH
11	Ultrasonic Water Flow meter	Essiflo	Data logging of Water flow through main header of condenser
12	Infrared temperature gun	Testo	Measurement of Envelope temperature

Calibrated Energy Simulation Model

Based on the information gathered, detailed specification of equipment and performance measurement of systems; an energy simulation model

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(using VisualDOE) was prepared. Calibration of simulation model was done:

- Against the monthly energy bills to match the monthly energy consumption
- Against the energy consumption of different end-uses (lighting, equipment, HVAC, etc.) for the detailed monitoring period i.e. two weeks of January and two weeks of May

The objective of this model was: (1) to calculate the break-up of energy consumption for different end-uses round the year as the detailed monitoring was done only for a total of four weeks duration and (2) to calculate the energy saving through the additional measures identified during the monitoring period.

ECBC Compliance

'Whole building performance method' was followed for ECBC compliance check. This requires preparation of energy simulation model for two cases

(1) ECBC Prescriptive and (2) As Designed. All the simulation inputs, (e.g. wall U-value, roof U-value, fenestration SHGC, VLT & U-value, lighting power density, HVAC system COP, etc.) for 'ECBC Prescriptive' case, were taken as defined in ECBC. For the 'As Designed' case, all the simulation inputs were taken as designed capacity and design specification. Inputs on building operation (e.g. thermostat setpoints, schedules, internal gains, occupant loads, etc.) were kept same for both cases. In addition, all the mandatory requirements were checked for ECBC compliance.

Actual energy performance of building may not match to the 'As Designed' case due difference in user behaviour and difference in actual performance of various systems.

RESULTS AND DISCUSSIONS

Comparison of energy performance (Simulation vs actual)

The simulated EPI during the charrette (December 2012) was 53 kWh/m^2.y as compared to the actual EPI (monitored data for May-15 to Apr-16) of 43 kWh/m^2.y. Figure 14 shows the comparison of monthly EPI for these two cases.

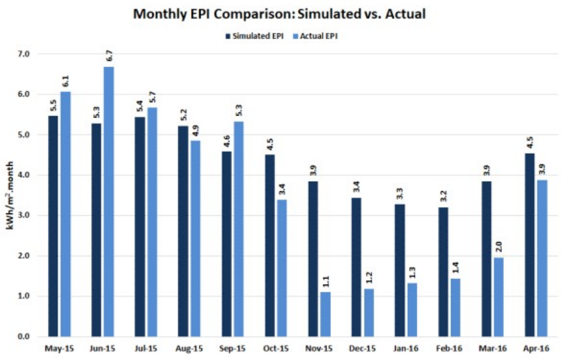

Figure 14: Simulated and actual monthly EPI

Key reasons for these differences are:

- The simulation was done using the ISHRAE weather data file which gives the hourly data for a year with long term measured data. Weather conditions for the monitoring period may have differences as compared to the data considered in the energy simulation.
- During monitoring it was observed that the HVAC remained OFF during the period November - Mid March, while in simulation, the HVAC system was considered operational during this period.
- The artificial lighting energy consumed in winter (Nov-Feb) was also less than that estimated in the charrette due to better use of daylight.
- During the simulation, only weekends (Saturday & Sunday) were considered as holidays, whereas in actual there were 20-30 additional holidays.

All the findings of energy monitoring (actual schedule for occupancy, lighting, equipment, HVAC system performance) were used to prepare a 'calibrated energy simulation model' as explained in subsequent sections.

Energy supply and consumption

Figure 15 gives the break-up of energy supply from grid & SPV system. DG set was hardly used during this period and thus does not feature here. SPV system of 25 kW_p capacity was installed in October-2015 and subsequently the installed capacity was increased to 45 kW_p in January-2016 and later net metering was done in April-2016. Therefore, during May-15 to April-2016, only ~6% of energy was supplied through SPV system and ~94% was drawn through the grid. However, is it estimated that contribution of energy from SPV system would increase to ~20% (considering the present energy consumption and energy generation from 45 kWp system for a year).

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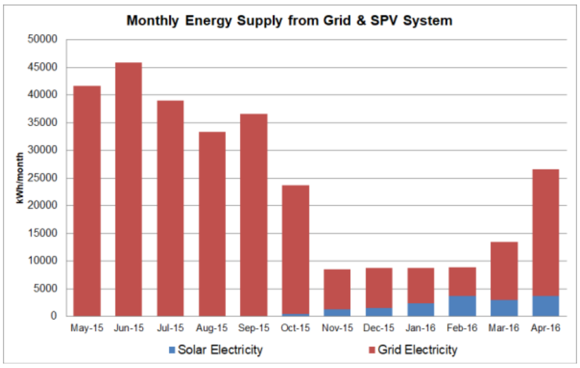

Figure 15: Energy supply break-up

Figure 16 & Figure 17 gives the annual and monthly break-up of energy consumption for different end- uses, respectively.

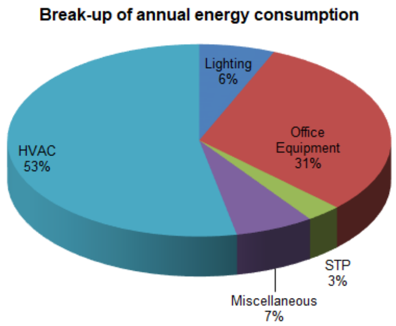

Figure 16: Break-up of annual energy consumption

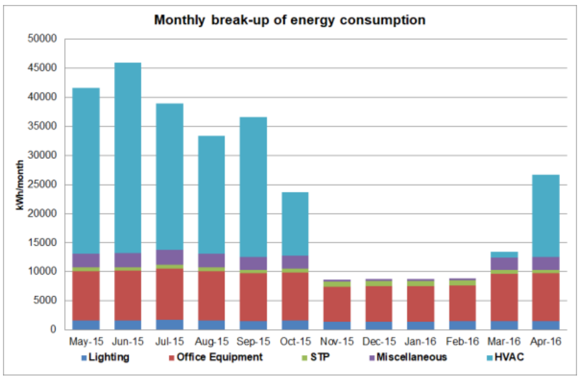

Figure 17: Break-up of energy consumption (Monthly)

Annually, HVAC consumes maximum energy and accounts for 53% of the electricity consumed. Office equipment consumes 31% of the annual electricity with artificial lighting consuming 6%. November- 2015 to mid of March-2016, the HVAC system remained off. Total monthly consumption peaks in June due to peak energy consumption by the HVAC system.

Seasonal energy break-up

Figure 18 and Figure 19 show the break-up of energy consumption during the winter (Nov-Feb) and summer (Mar-Oct) months, respectively. During the winter office equipment consume maximum (69%) amount of energy while in summer HVAC accounts for maximum (60%) energy consumption.

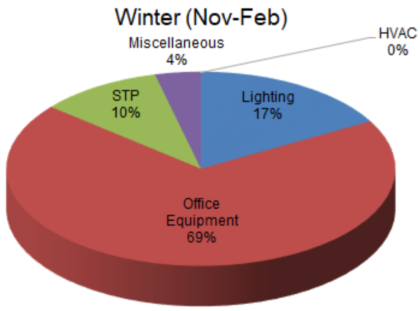

Figure 18: Break-up of energy consumption in winter

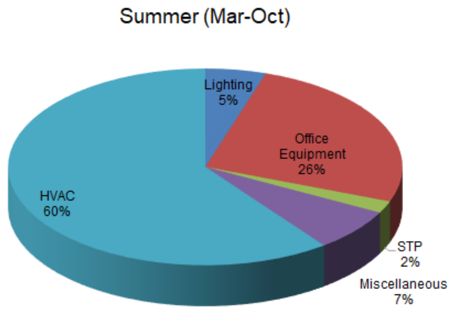

Figure 19: Break-up of energy consumption in summer

HVAC system performance

Figure 20 shows the measured COP of two operational chillers day-wise. The average COP of Chiller#1 was 7.4, while for Chiller#2 it was 5.5. Although cooling water temperature delivered to Chiller#2 was same as Chiller#1; but the "Condenser Approach" was found to be 4.5°C; as compared to the "Condenser Approach" of 2°C for Chiller#1. Due to this higher "Condenser Approach" for Chiller#2, the condensing pressure of refrigerant was higher as compared to that of Chiller#1 and therefore, performance of Chiller#2 was found to be low.

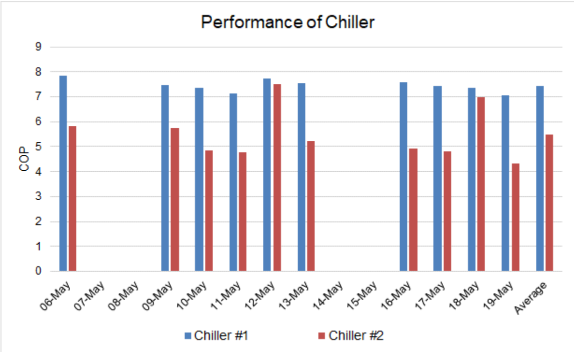

Figure 20: Measured chiller performance

Figure 21 shows the COP of overall HVAC plant (including chiller, pumps & cooling tower) for the monitoring period. It varied from 3.6 to 4.6 during the monitoring period and the average COP was calculated as 4.1.

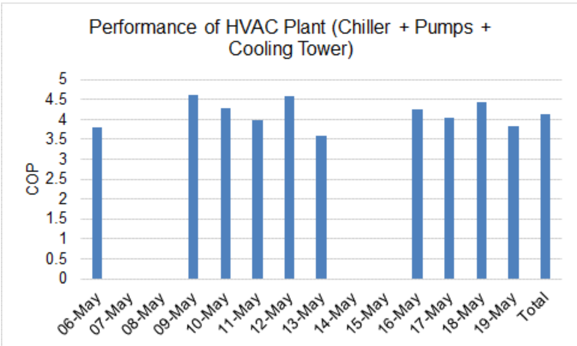

Figure 21: HVAC plant performance

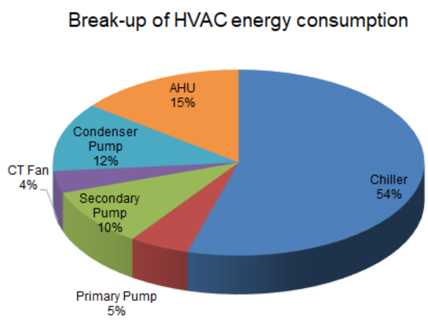

Figure 22: Break-up of HVAC energy consumption

Figure 22 shows the break-up of HVAC energy consumption. Chillers account for the 54% of HVAC energy while AHU consume 15% of it.

Daylighting measurement

Figure 23 shows the sample spaces (total 9 spaces) for which daylight measurement (lux levels) was done. The measurement was done once during winter and summer monitoring.

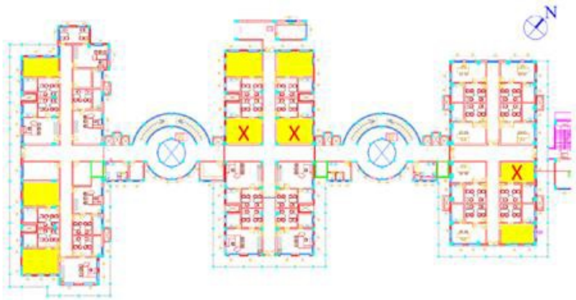

Figure 23: Sample spaces for daylight measurement

Out of these 9 spaces, 3 spaces (marked as 'X') had average daylight of ~30 lux and required artificial lighting. This was mainly due shading by adjacent staircase block. Other 6 spaces had average daylight of ~300 lux and did not require any artificial lighting.

Further Energy Saving Opportunities

Energy monitoring identified few additional measures which can further help in energy saving. The saving potential of these additional measures is estimated through energy simulation (by adding these measures in the 'calibrated energy simulation model'). These measures are:

- Reduction of contract demand from 500 kVA to 400 kVA as the recorded demand did not exceed 300 kVA.
- Improve condenser approach for under-performing chiller by cleaning the condenser tubes and maintaining water quality.
- Improve cooling tower efficiency.
- Replace condenser water pumps & primary chilled water pump with revised capacity (pressure & flow).

Energy savings through these additional measures is estimated to be ~10,000 kWh/y.

ECBC Compliance Analysis Results

Following the 'whole building performance method', energy simulation was done for 'ECBC Prescriptive' case and 'As Designed' case to check whether the design of the building is ECBC compliant or not. Figure 24 shows that the energy consumption of 'As Designed' case is ~20% less as compared to 'ECBC Prescriptive' case; confirming that the building is an ECBC compliant building.

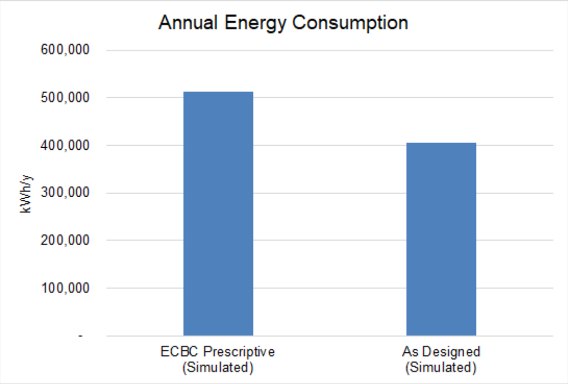

Figure 24: Energy consumption results for ECBC compliance

BEE also has a star rating programme for existing buildings based on one energy consumption (EPI) data for a complete year. For day-use office building in composite climate (e.g. Jaipur), a building with an EPI < 90 kWh/m^2.y, gets a five-star (maximum) rating. With an EPI of 43 kWh/m^2.y, The building easily qualifies for five-star rating under BEE's star rating programme.

Cost Benefit Analysis

Cost of construction before design workshop was estimated to be Rs 300 million, while the actual cost of construction after implementing all EEMs (except SPV system) was Rs 306 million. The increase in capital cost was only 2% while energy saving estimated to be 44%; thereby resulting in a payback period of 2.5-3.0 years.

CONCLUSION

Good quality case studies based on monitored energy performance are needed for mainstreaming ECBC in the country. The paper presents case study of an office building at Jaipur and cover:

a) Energy efficiency measures adopted in the building.
b) Results of the building energy simulation during the building design.
c) Methodology and results of the performance monitoring of the fully functional building for one-year period.
d) Results of checking compliance with ECBC

Energy efficiency measures (EEMs) for this building includes use of insulation in external walls & roof, optimized window-to-wall ratio, efficient glazing, high efficiency water cooled screw chiller, T5 &LED lighting and rooftop solar photovoltaic system. Since the building does not have an EIS, a monitoring methodology was developed. This consisted of (i) two-weeks detailed energy monitoring twice a year, in winter and summer season; (ii) analysis of monthly energy bills for a year; and (iii) a calibrated energy simulation model. Results show 53% of electricity is used for HVAC annually, while 31% of electricity is used for office equipment and 6% for artificial lighting. The difference in simulated performance (EPI: 53 kWh/m^2.y) and measured performance (EPI: 43 kWh/m^2.y) is explained.

The case study shows that for building without an EIS, using a customised energy monitoring methodology, one can get quite good understanding of energy performance of building, break-up of energy for end- uses and performance of systems; also identify possibilities of further improvement in energy performance.

There is a need to have many such case studies. This would help in motivating builders / developers and other building sector professional to adopt energy efficiency measures in their projects, having more ECBC compliant buildings.

ACKNOWLEDGEMENT

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