Sustainable Campus with PEVs and Microgrid

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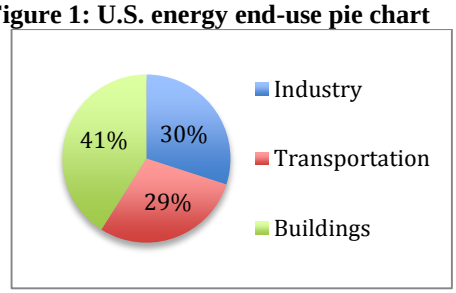
ABSTRACT

Market penetration of electric vehicles (EVs) is gaining momentum, as is the move towards increasingly distributed, clean and renewable electricity sources. EV charging shifts a significant portion of transportation energy use onto building electricity meters. Hence, integration strategies for energy-efficiency in buildings and transport sectors are of increasing importance. This paper focuses on a portion of that integration: the analysis of an optimal interaction of EVs with a building-serving transformer, and coupling it to a microgrid that includes PV, a fuel cell and a natural gas micro-turbine. The test-case is the Nanyang Technological University (NTU), Singapore campus. The system under study is the Laboratory of Clean Energy Research (LaCER) Lab that houses the award winning Microgrid Energy Management System (MG-EMS) project. The paper analyses three different case scenarios to estimate the number of EVs that can be supported by the building transformer serving LaCER. An approximation of the actual load data collected for the building into different time intervals is performed for a transformer loss of life (LOL) calculation. The additional EV loads that can be supported by the transformer with and without the microgrid are analyzed. The numbers of possible EVs that can be charged at any given time under the three scenarios are also determined. The possibility of using EV fleet at NTU campus to achieve demand response capability and intermittent PV output leveling through vehicle to grid (V2G) technology and building energy management systems is also explored.

Introduction

Improving energy efficiency in buildings and transportation, which together constitute two-thirds of energy end-use in the U.S., as shown in Figure 1, has traditionally followed parallel strategies; however, that situation needs to change.

Figure 1: U.S. energy end-use pie chart



Source: U.S. Department of Energy (DOE), *2012 Buildings Energy Data Book*, Section 1.1.1, 2012.

In California, for instance, transportation accounts for 40 percent of the state's greenhouse gas emissions. The California Air Resources Board's Jan 2012 Advanced Clean Car Package now requires automakers to cut emissions from all new vehicles in half by 2025, and it anticipates a total of 1.4 million zero-emission and plug-in hybrid vehicles (PHEV) on the road in California by 2025. It also stipulates that by 2025, 15% of all new cars and trucks sold be powered by batteries, hydrogen fuel cells, or other technology that produces little or no air pollution. PHEVs and Electric Vehicles (EVs) have the greatest potential for widespread market penetration and the literature indicates that most PHEV charging will likely occur at buildings and homes during off-peak hours (Electric Power Research Institute 2007). Analysis shows that PHEV's will increase residential building energy loads by 13% and electricity use by 55% for a 2010 vintage home (Rohloff, Roberts & Goldstein, 2010). The additional load implications will adversely affect building energy targets, especially the U.S. 2030 Buildings Challenge which sets goals at a 60% reduction in energy use by 2015, 90% reduction by 2030 and 100% (Zero Net Energy) by 2035. On the other hand, effective management of PHEVs in conjunction with the grid could have mutually beneficial impacts. It is estimated by the International Energy Agency (IEA) that electrified transport could reduce GHG emissions by 30% around the world by 2050.

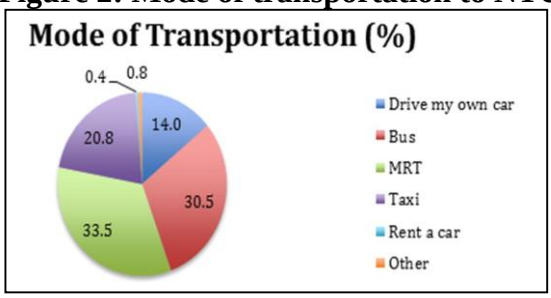
Singapore has also set aggressive transport and buildings energy efficiency goals and has a targeted National Climate Change Policy. Its hot tropical climate, lack of natural resources and expanding economy pose interesting energy challenges. Transportation and buildings have been major sources of green-house-gases emissions (GHG), contributing 18% and 17% respectively. There were about 950,000 motorized vehicles in Singapore at the end of 2010, while the total population is just over 5 million. (Source: Land Transport Authority-Singapore). Singapore is actively considering deployment of EVs and launched its EV test-bed program in June 2011 to assess the benefits and feasibility of adopting EVs in Singapore. This program incentivizes purchase of EVs through the Enhanced Transport Technology Innovation and Development Scheme (TIDES+), which allows a waiver on all vehicular taxes for the test-bed participant, making the EV 50-60% cheaper. In return, the participant is obligated to log in key data such as number of passengers in the EV, weather conditions and air-conditioning status via a smart device located within the EV for every trip.

EVs have ranges usually between 90km to 160km (56 miles to 100 miles), which is well within limit of the average travel distances of 55km (34 miles) in Singapore (LTA), and therefore is less cause for 'range anxiety'. Here, electricity is generated using predominantly imported natural gas; current well-to-wheel emissions estimates from automakers show about 66% reduction in carbon emissions when switching from a gasoline car to an equivalent-size EV (Source: Renault-Nissan). Singapore is actively looking at renewable energy resources such as solar energy to diversify its fuel mix and also reduce its environmental impact. This makes the future case for EVs even stronger. As part of the EV test-bed program, Bosch is tasked to design, develop and deploy up to 60 normal charging stations (full charge within 7-8 hours) and 3 quick charging stations (full charge within 30-45 minutes), and the charging infrastructure will be scaled up to match the take-up rate of EVs for the test-bed. However, the capability of the power distribution network to support the EVs has to be verified and the corresponding impacts of additional loads in the form on the distribution system are to be determined.

The Nanyang Technical University (NTU) is one of Singapore's two largest public universities with the biggest campus, with 200 hectares area, with 30,000 students and 6,000 faculty and staff. NTU announced its Campus Master Plan in February 2011, whereby it

established its intention to become a mini-city, with adoption of energy efficient and sustainable technologies, and possibly including provisions for EVs (electric buses, cars and bikes) for transportation. A recent survey[1] conducted on the campus revealed that the majority of the travel around the campus is already made using shuttle bus service. (Fig 2)

Figure 2: Mode of transportation to NTU



Two-thirds of respondents travel by public transport to NTU, and use three different shuttle routes within campus (Route-A, Route-B and Route-C) and one route (Route-D) connects the campus to Pioneer Mass Rapid Transport (MRT, Singapore's metro system) station. The energy consumption and CO_2 emissions of the shuttle buses on campus is tabulated in Table 1. The campus has a hilly terrain, making it more amenable to PHEVs, and suitable for harvesting energy through regenerative braking and hence the efficiency gain will be high. This scenario is also more favorable when compared to diesel-powered buses, which have high CO_2 emissions.

Figure 3: NTU campus photos showing the hilly terrain and commuters waiting for shuttle bus

Table 1: Energy consumption and CO_2 emissions of shuttle buses on campus (per day)

Route	Daily Average Bus km Travelled	Total Energy Consumption in kWh	Total Tail Pipe CO_2 emissions in kg	Total CO_2 emissions in kg
Shuttle Bus-A	208	595	125	144
Shuttle Bus-B	203	478	121	140
Shuttle Bus-C	430	1220	256	294

[1] Survey conducted by the Energy Research Institute @NTU in January 2012 with 108 respondents including staff and students on NTU campus

Proposed Methodology

There are numerous methods in the literature that can be used to determine the impact of electrification on transportation; however, few studies have estimated the number of EVs that can be deployed with current power generation capacity (Ipakchi & Albuyeh, 2009), or estimated the total power generation requirement for a stipulated EV fleet percentage (Shrestha & Ang, 2007). No proper methodology exists in the literature for estimating the capacity of distribution transformers to support the EV fleet. Each distribution transformer has different capacity and characteristics that determines the amount of EVs it can handle at any given time. The distribution transformers are the weakest links of a power system because of their relatively low capacity and low operating voltage. Due to the additional load created by EVs, the distribution transformers are relatively stressed more than any other equipment in the distribution system (Masoum, Moses & Smedley, 2011). Hence estimating the capability of distribution transformers to support EVs is important in order to determine the capability of whole system. The loss of life (LOL) of the distribution transformer is an important factor to consider as it is directly related to reliability and economics of the system (Gong et al. 2011). Any premature/unexpected failure of the distribution transformer is not only associated with replacement cost but also the revenue loss due to supply interruption. A study on the capacity of the transformer will provide the amount of additional EV loads that can be supported by the transformer such that the additional load has minimal effect on the transformer's life expectancy. The decision on the amount of LOL allowed will be taken by the power system operators, in the case of NTU it is the Office of Development and Facilities Management.

A methodology is now proposed for estimating the number of EVs that a transformer can support and also study the impact of penetration of a microgrid on the number of EVs. The 60kVA transformer serving NTU's Laboratory of Clean Energy Research (LaCER) is taken as the test case. LaCER houses an award winning[2] Microgrid Energy Management System (MG-EMS) project. The microgrid prototype incorporates software applications that manage sensing data and perform load and generation management. A number of traditional and renewable energy sources, namely synchronous generators, solar PVs, wind turbines, fuel cells and battery banks are installed in the microgrid setup (see Table 3). (Fuel cell and micro turbine are operated during morning and evening peak periods.) Control algorithms are implemented to allow both grid connection and islanded operations of the microgrid. A Low-Voltage (LV) Distribution panel is simulated as industrial/commercial and housing loads as part of the microgrid. The hardware components including On-Line Tap Changers (OLTCs), circuit breakers and relays of the whole system are controlled by MG-EMS in a server. The developed microgrid and the MG-EMS server system will be used in the future for test-bedding EV management and control schemes. It is therefore important to analyze the load capacity of the transformer serving LaCER and estimate the number of EVs it can support. Furthermore, using smart charging, the voltage regulation, power losses and harmonics can be maintained within required limits (Clement, Haesen & Driesen, 2010; Deilami et al. 2010 & 2011). Tables 2 and 3 describe the transformer and microgrid parameters.

[2] Best Innovation in Green Engineering Award, ASEAN Virtual Instrumentation Applications Contest Singapore, 20 October 2010.

Table 2: Transformer parameters

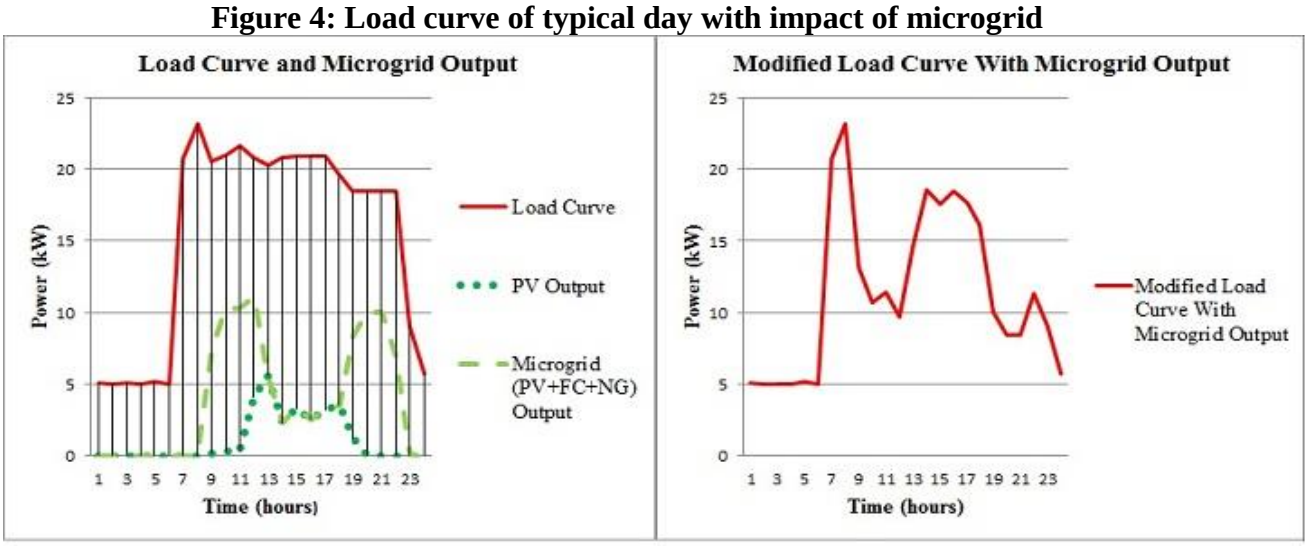
Life of transformer (Hours):	180000
Ambient temperature (°C):	30
Rated load (kVA):	60
Ratio of full load loss and no load loss:	4.5
Empirical constant M:	0.7
Empirical constant N:	0.7
Top oil temperature rise over ambient at rated load (°C):	45
Hotspot temperature rise over top oil, at rated load (°C):	35
Oil thermal time constant for rated load (Hours):	4.89

Table 3: Microgrid parameters

Source	Output Power	Operating Hours (based on Peak period)
Solar PV	10kW peak	Actual output based on solar radiation
Fuel cell (FC)	5kW continuous	8.00 to 11.30 hours and 18.30 to 21.30 hours
Natural Gas Micro Turbine	5kW continuous	8.00 to 11.30 hours and 18.30 to 21.30 hours

In order to obtain the maximum number of EVs, the LOL of the transformer's insulation is analyzed. The transformer load data obtained for a period of 30 days spread over 3 months is used for the analysis. Since the transformer is supplying power to a building used for educational purposes, its load profile is similar to a commercial building, significant since mid-sized commercial buildings are attractive hosts for Distributed Energy Resources (DER) adoption. Load curve for a typical day and impact of penetration of microgrid are shown in Figure 4.

Figure 4: Load curve of typical day with impact of microgrid



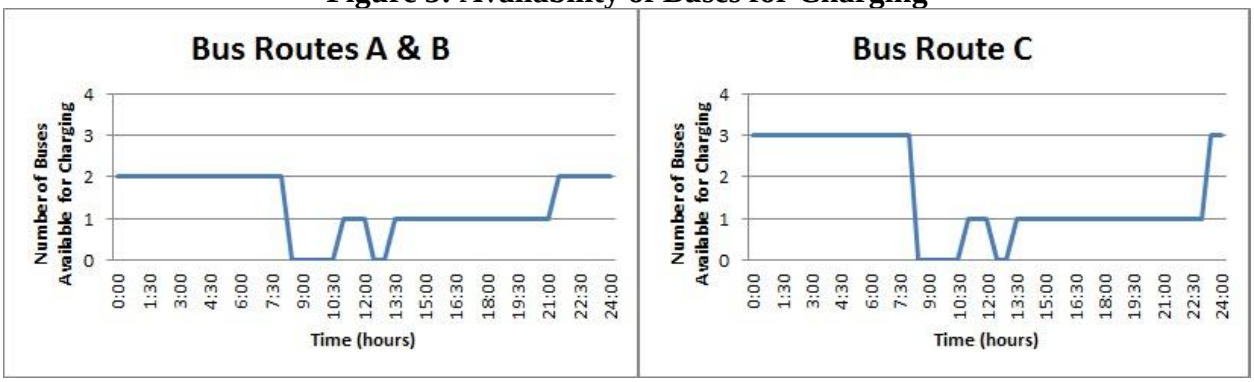
Since the life of the transformer's insulation depends on its average load during a particular period rather than the instantaneous load, approximation of the actual load curve into time intervals is needed. The approximation of the load curve is obtained by:

$$L = \sqrt{\frac{L_1^2 t_1 + L_2^2 t_2 + L_3^2 t_3 + \cdots + L_n^2 t_n}{t_1 + t_2 + t_3 + \cdots + t_n}} \qquad (1)$$

where L_1, L_2, etc. are the various load steps in percentage per unit ,in actual power (kVA) or in current (A), and N is the total number of loads considered. t1, t2, etc. are the respective durations of these loads in minutes.

The intervals for the load approximation are decided based on a number of factors. Firstly, the starting time of the off-peak period of the load curve, which is approximately 22:00 hours, is considered. Secondly, the approximate time required for the transformer insulation to cool down to the desired temperature is taken to be approximately 2 hours. Thirdly, the average charging time required for the electric vehicles is taken to be around 6-10 hours to reach 100% state of charge (SOC). Finally, the availability of the electric vehicles for charging is also considered. Currently, there are 2 buses in service each for routes A and B, and 3 buses for route C. Although there are multiple numbers of buses per route and varying schedules (see Fig 5), for the sake of analysis in this paper the estimation of the EV fleet considers only 1 route A bus to be charged at the charging station located at LaCER.

Figure 5: Availability of Buses for Charging



An approximated load curve is shown in Figure 6, where Interval 1 is from 00:00-08:00 hours, Interval 2 is 08:00-11:30 hours, Interval 3 is 11:30-15:00 hours, Interval 4 is 15:00-18:30 hours, Interval 5 is 18:30-22:00 hours and Interval 6 is 22:00-00:00 hours. The time duration during which the load is normal/medium (08:00-22:00 hours) is further divided into four intervals to clearly visualize the impact of the microgrid. Further, the energy that the transformer can supply with the allowed LOL can be calculated using the algorithm as shown in Figure 7.

Figure 6: Approximated load curves with and without microgrid

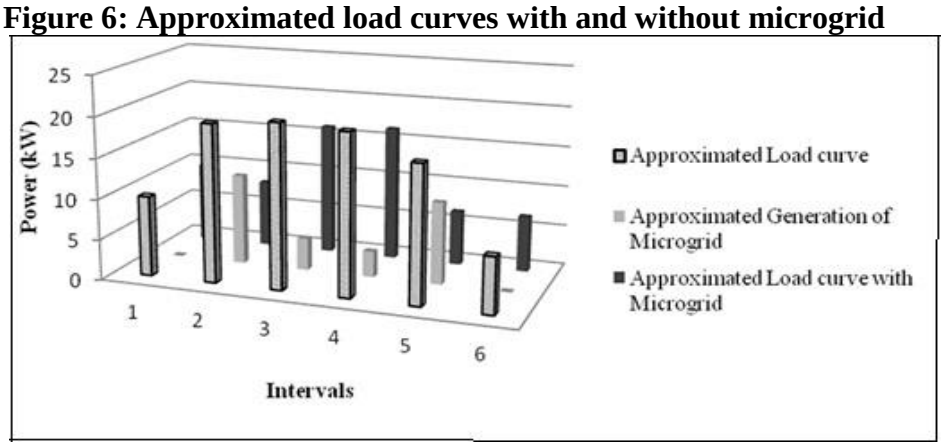
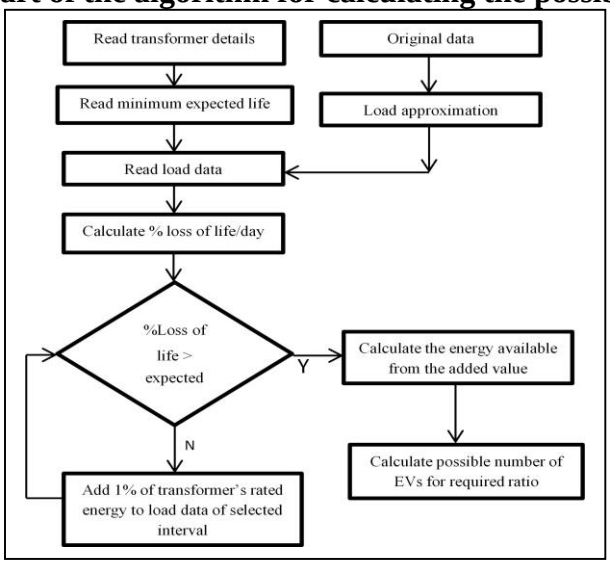


Figure 7: Flow chart of the algorithm for calculating the possible number of EVs



The calculated energy will be used to estimate the possible number of EVs that can be charged using that transformer at any given time. The transformer LOL is determined by

$$F_{AA} = \exp^{\left[\frac{1500}{383} - \frac{1500}{\Theta_H + 273}\right]} \tag{2}$$

$$F_{EQA} = \frac{\Sigma_{n=1}^{N} F_{AA} \cdot n \cdot \Delta t_n}{\Sigma_{n=1}^{N} \Delta t_n} \tag{3}$$

$$\%LOL = \frac{F_{EQA} \cdot 24 \cdot 100}{Expected\ Insulation\ Life} \tag{4}$$

F_{EQA} is the equivalent aging factor for the total time period,
n is index of the time interval, t,
N is total number of time intervals,
$F_{AA,n}$ is aging acceleration factor for the temperature which exists during the time interval t_n,
t_n is time interval, hours,
Θ_H is the winding hotspot temperature, °C.

The winding hotspot temperature is calculated using the method explained in Annexure C of IEEE Std C57.91-1995. However, if some actual measurements are made using devices[3] then more accurate results can be obtained. While calculating the energy available, the LOL is calculated for every day (base LOL) and the average for 30 days of the calculated LOL is verified in order to ensure that the added energy is within the limits of the expected value.

EV Fleet Estimation based on Transformer LOL Calculation

Maximum possible number of EVs is analyzed for:

1. Case 1: 10% additional LOL with only overnight charging at time intervals 1 and 6.
2. Case 2: 20% additional LOL with 24 hour charging, where during the night only one shuttle bus and a few other vehicles can be charged; during the day a few vehicles can be charged.

[3] Devices such as mentioned at (http://www.bplglobal.net/eng/knowledgecenter/download.aspx?id=393)

3. Case 3: 20% additional LOL with 24 hours charging including the impact of the microgrid where output from PV and 60 kWh from fuel cell and micro turbine is considered.

All the calculations made for finding the maximum possible number of EVs are based on the conservative approach rather than the optimized approach. Only an energy-based calculation is performed where the rating, number, and type of chargers are not considered in the simulation model.

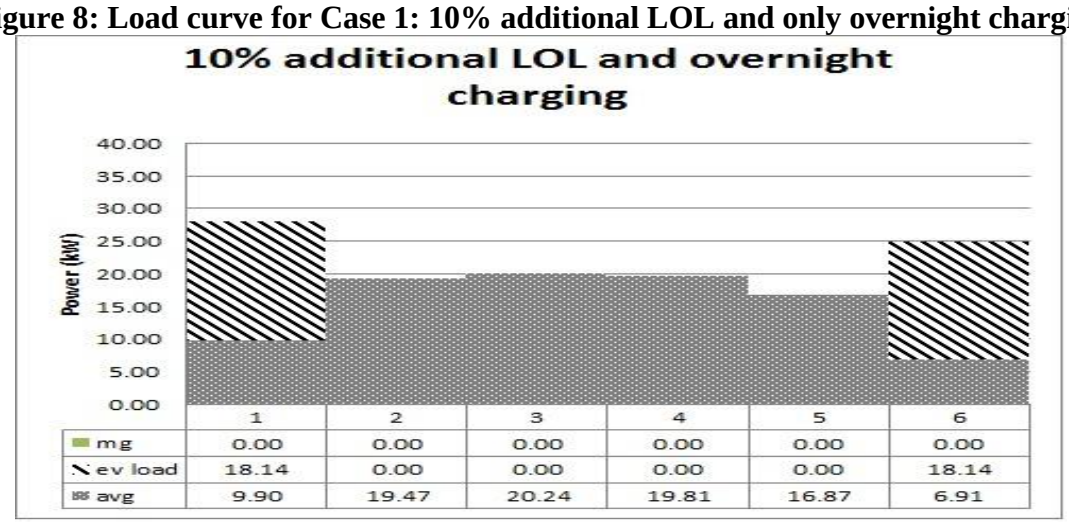
Figure 8 shows the additional EV loads that can be supported by the transformer in Case 1. The transformer can support up to 18.144 kW additional loads during this time interval.

Figure 9 shows the additional EV loads that can be supported by the transformer in Case 2. The transformer can support up to 18.144 kW additional EV loads during time intervals 1 and 6 while 11.726 kW additional EV loads can be supported during time intervals 2 to 5.

Figure 10 shows the additional EV loads that can be supported by the transformer in Case 3. This analysis takes into consideration the impact of the microgrid on the transformer capacity--with the PV output as well as a combined 60 kWh output of the fuel cell and micro turbine. The fuel cell and micro turbine are operated only during intervals morning and evening peak periods, i.e. time intervals 2 and 5. The output of the PV supports the grid during intervals 2 to 4 based on actual solar radiation data[4]. The microgrid output totals approximately 11 kW, 4 kW, 3 kW and 10 kW during intervals 2, 3, 4, and 5 respectively. Considering the impact of the microgrid, the transformer can support an average of 17.4 kW of additional EV loads throughout the day.

The number of EVs that can be charged under each case is shown in Table 4. It can be clearly seen that the microgrid has significant impact on the number of EVs that can be supported with an increase of approximately 33% (considering EV cars) compared to without the microgrid coming online. Note that a specific fleet was not chosen for this analysis; instead the number of each type of vehicle was analyzed.

Figure 8: Load curve for Case 1: 10% additional LOL and only overnight charging



[4] (http://nwsp.ntu.edu.sg/weather/portal_download.php)

Figure 9: Load curve for Case 2: 20% additional LOL and 24 hours charging

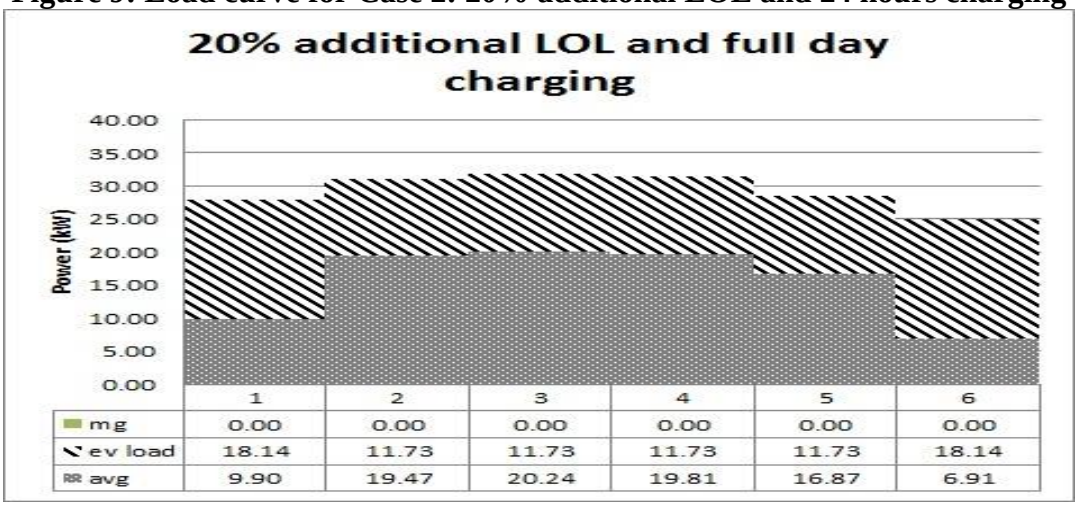


Figure 10: Load curve for Case 3: 20% additional LOL, 24 hours charging with microgrid

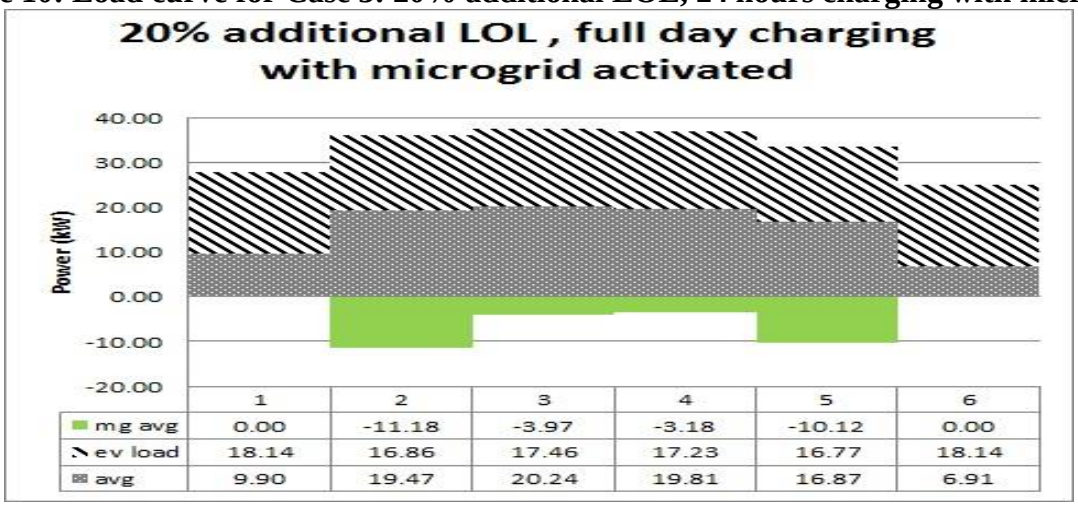


Table 4: Estimated number EVs for different case scenario

Scenario		Cars	Motorcycles	Quad/tricycle	E-moped	Bicycle
Case 1	Total EVs	13	68	33	119	318
	Total EVs with 1 A-bus	3	16	8	29	76
Case 2	Total EVs	25	130	63	227	606
	Total EVs with 1 A-bus	15	78	38	137	364
Case 3	Total EVs	30	156	76	274	730
	Total EVs with 1 A-bus	20	105	51	183	488

The numbers shown in Table 4 are estimation for the number of each type of vehicle where no combination of vehicles (fleet) is considered. For example in Case 1, either 13 cars or 68 motorcycles or 33 quad/tricycles or 119 e-mopeds or 318 bicycles can be charged. When one route-A shuttle bus is charged then the change in numbers are indicated in second row of Case 1. The difference between Case 1 and Case 2 gives the number of vehicles that can be charged during daytime. The difference between case 2 and case 3 will give the impact of microgrid.

Vehicle to Grid Technology

Electrification of transportation not only improves efficiency over an internal combustion engine, it also decreases the carbon footprint of the transportation sector. When parked, EV batteries could be used to let electricity flow from the car back to the power lines, adding value to the utilities. This Vehicle-to-Grid (V2G) technology can provide the short bursts of power used to correct imbalances in the electric power grid and can also be used to level the fluctuations inherent in DERs such as solar and wind energies.

All major industrial and commercial consumers in Singapore, including large buildings purchase power from the utility or gencos/retailers on a 30-minute maximum demand interval, with a contracted capacity to meet maximum demand. The contracted capacity is the declared purchasing capacity of the consumer. The consumer will be charged 50% more if the declared contracted capacity is exceeded. On the other hand, if actual usage is less, the consumer will still be billed according to the contracted capacity. The tariff details for High Tension Small (HTS) Supplies usage charges are given in Table 5.

Table 5: Average Peak Period Charge for HTS Supplies

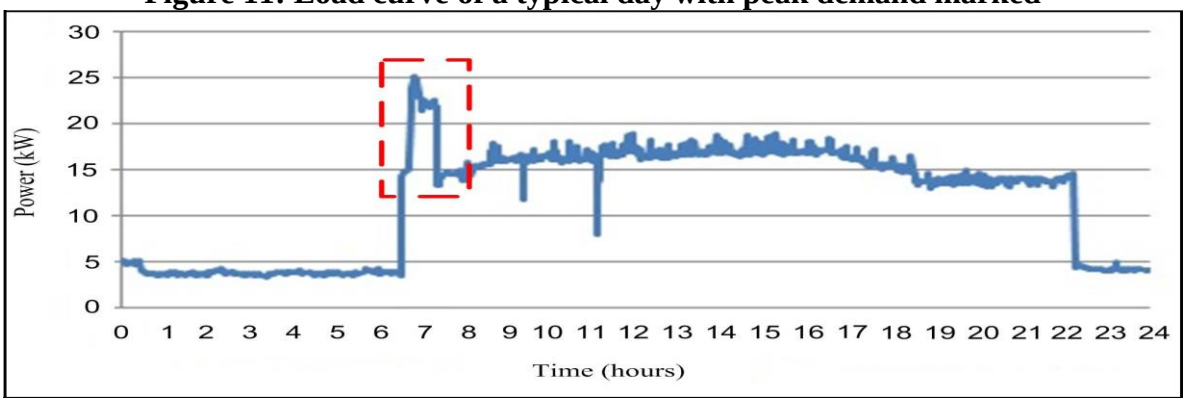
Usage charge	With effect from April 2011 (with 7% GST)
Contracted capacity charge	S$7.45/kW (Monthly rachet)
Un-contracted capacity charge	S$11.17/kW (Monthly rachet)
Peak period charge (0700-2300 hours)	S$0.2578/kWh
Off-peak period charge (2300-0700 hours)	S$0.1581/kWh
Reactive power charge	S$0.0063/kVArh

Various Building Energy Management Systems (BEMS) are being implemented in buildings to ensure that contracted capacity is not exceeded and to reduce energy consumption through energy efficiency measures. One potential function of the EVs is to provide load shifting/leveling capability by storing extra energy at times of low load demand and supplying the stored energy during periods of heavy load demand. Moreover with the presence of DERs as a part of BEMS, the storage devices become inevitable to counter the intermittent nature of DERs. The availability of EVs, which represents a huge energy storage device, that sits parked and unused for long periods of time is an added advantage for BEMS. Furthermore, the batteries used in EVs usually have fast response that performs better than other current energy storage devices. EVs and BEMS can work to reap the benefit of lower cost off-peak power and counter the disadvantage of high energy storage cost. This can also result in improving the utilization factor/load factor of the transformer while the whole system can be more dynamic and efficient.

Taking the typical LaCER's load curve, the microgrid advantage for EVs can be clearly explained. It is assumed that one shuttle bus (Route-A) with battery capacity of 120 kWh is charged overnight during intervals 6 and 1, while 3 cars with battery capacity of 16 kWh and 5 motorcycles with battery capacity of 2 kWh are charged during intervals 2, 3 and 4. Figure 11 shows the load curve of a typical day. The peak demand occurs between 6:45 to 7:20 hours. During this period, the shuttle bus is available for discharging to level the peak load. Energy demand during this interval is around 3 kWh, but on some days it can reach 7-8 kWh. Nonetheless, this energy demand is less than 10% of total energy of the shuttle bus battery

capacity. Therefore, discharging the battery at a rate of C/10 or less will not affect its performance and a charge-discharge cycle 10% of DOD (if at all used) will not affect the life the of battery to a great extent. Therefore, the peak demand can be decreased considerably, which reduces the cost of operation of the buildings and improves energy efficiency. During daytime, it would not be wise to level the peak demand using the battery as the penetration of solar power will have much higher savings. EVs as an energy storage device can also be used to level the intermittent output of the PV system.

Figure 11: Load curve of a typical day with peak demand marked



Conclusion

In this paper, a method for estimating the number EVs that a transformer can support based on the important factor of insulation loss of life (LOL) calculation was developed. An algorithm for finding the maximum number of EVs was presented that can be used for other studies. The advantage of coupling a microgrid with the transformer and its impact on the number of EVs that can be supported was also presented. Using the microgrid prototype at LaCER Labs as a test case, it was observed that the transformer can support an average of 17.4 kW of additional EV loads throughout a typical day. This equates to the capacity of charging 30 EV cars, or 20 EV cars plus one bus per 24-hour period. The microgrid has a significant impact on the number of EVs that can be supported with an increase of approximately 33% (considering EV cars) compared to without the microgrid. The possibility of using EVs at the NTU campus to achieve demand response capability and intermittent PV output leveling through vehicle to grid (V2G) technology and building energy management systems was also discussed. In order to optimally deploy an EV fleet, additional research needs to be conducted specifically on reduction of utility costs via load shifting by using the EV as the mobile energy storage in the microgrid. Additionally, business models must be developed wherein a rental EV company can receive reimbursement for helping arbitrage the buildings' operations cost, and for car battery degradation, that can partially offset their mobile storage investment.

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CLIMATE-SPECIFIC MODELING AND ANALYSIS FOR BEST-PRACTICE INDIAN OFFICE BUILDINGS

ABSTRACT

This paper describes the methodology and results of building energy modeling to validate and quantify the energy savings from conservation measures in medium-sized office buildings in four different climate zones in India. We present the different energy measures and their expected and simulated performances and discuss the results and the influence of climate.

INTRODUCTION

Total primary energy demand in India in 2009 represented 5.5% of world energy demand and was predicted to increase by 8.6% by 2035 (Ahn & Graczyk, 2012). In addition to an exponential rise in energy demand, India already faces several energy challenges. These include: low grid availability, quality, and reliability (Pargal & Banerjee, 2014); significant energy imports (Yadav, 2014); and entrenched use of non-renewable, fossil-fuel sources (Ministry of Power - Government of India, 2013).

In India, the building sector is currently the second-largest energy consumer (29% of total energy demand) and is growing rapidly by 8% annually (Ahn & Graczyk, 2012). Although the building sector represents less than one-third of the total energy consumed in India, the savings potential is significant. India's Energy Conservation Building Code (ECBC) currently provides non-compulsory guidance. Simulation models indicate that "ECBC-compliant buildings can use 40 to 60% less energy than conventional buildings" (Ministry of Power - Government of India, 2007).

Simple improvements in building design and systems could increase energy efficiency, which would be an important step forward in addressing India's energy challenges.

Preceding work (Singh, Sartor, & Ghatikar, 2013) focused on identifying features of existing "best in class" Indian office buildings and listing measures of expected energy savings compared to energy use in conventional buildings. Although the case studies of pragmatic solutions and realistic benchmarks in that previous study are valuable, they cannot be used to differentiate the impact of individual energy measures.

As an alternative to collecting measured data, we use building energy simulation (BES) to model the impact of incremental energy-conservation measures. This allows us to evaluate the impact of individual measures on energy consumption and occupant comfort. BES can also fill gaps in measured building performance data, for example when the savings generated by a particular solution have not been measured in all of India's climate zones.

Such simulation studies have been performed in other geographical areas with climates similar to India's, such as Saudi Arabia (Iqbal & Al-Homoud, 2006) and sub-tropical Australia (Rahman, Rasul & Khan, 2010). Both of these studies used a real building to calibrate their models before simulating the potential savings from different energy conservative measures. In India, Manu et. al (2011), Dhaka et. al (2012), and Tulsyan et. al (2012) compared the performance of a conventional Indian building to an ECBC-compliant building but did not investigate further improvements to buildings.

In this work, we propose energy conservation measures that go beyond code compliance and that are rarely investigated in simulation work, such as radiant cooling, night flush, and mixed-mode ventilation. Unlike other studies, this study uses a generic medium-size office building in four different climate zones, to get more translatable results than those obtained using buildings that have specific uses, designs and external environments. The energy conservation measures might be applied in practice differently from the way they are modeled, or in buildings with different uses or designs. However, the goal of this study is not to predict exact savings but to identify solutions that have significant impact in the Indian context and to gain an understanding of the relative energy savings from these solutions. This, in turn, will inform future energy-efficient building guidelines.

METHODOLOGY

This research is conducted in two phases. In the first phase, we create two baseline models: business as usual (BAU) and ECBC-compliant. In the second phase, we use these two baseline models to analyze the impact on occupant comfort and energy consumption of incrementally implementing carefully selected, state-of-the-art design and efficiency improvements

that have been applied in existing energy-efficient buildings in India.

The strategies are added one by one, cumulatively, to create a best-practice building. The order in which the strategies are implemented prioritizes reducing loads before implementating solutions to reduce the energy cost of meeting those loads. The strategies modeled are:

- Optimizing building envelope orientation and fenestration to reduce external loads while maintaining significant daylighting
- Reducing electric lighting and plug loads
- Using night flushing and natural ventilation when available to promote "free" cooling
- Using high-performance heating, ventilation, and air-conditioning (HVAC) system architecture that decouples ventilation and cooling. In analyzing this efficiency measure, we study compare the savings from radiant ceiling and variable-refrigerant flow (VRF) systems.

Simulation program

We used EnergyPlus 7.2 for modeling. EnergyPlus is a recognized whole-building energy-simulation program used worldwide, with more than 85,000 copies downloaded since it was first released in April 2001. The program includes various models for energy-flow transfer and HVAC systems. Although the validity of the whole-building models generated by EnergyPlus is a subject of discussion (Neto & Fiorelli, 2008) (Ko & No, 2015), this work covers only subsets of the tool's functionality that have been previously validated (Olsen & Chen, 2002), (Sunman, Marston, & Baumann, 2013).

Model input parameters

We distinguish three types of input parameters in our model:

- Parameters specific to the building, such as occupancy, geometry, or envelope materials
- Parameters specific to the performance of building systems, such as HVAC equipment size or the heating or cooling setpoints
- Established parameters, such as the properties of the building materials used

We chose parameters specific to the building by consulting experts on Indian buildings, with the objective of developing a model of a typical medium-sized Indian office building.

We chose and tuned the parameters related to systems performance to optimize occupant comfort. Real systems might work with different, not ideal parameters, but a fixed comfort level in the model's output leaves energy consumption as the only comparison value. This reduces the variability in modeled HVAC behavior and simplifies the analysis of the results.

The established parameters are taken from conventional building libraries, specifically the medium-sized office building models distributed by the U.S. Department of Energy (DOE) (Deru et al., 2011).

Climate zone

India's climate is typically divided into five zones that exhibit different temperatures, humidity, and solar irradiation. The five zones are designated as follows:

- "Hot and dry" climate in the Northwest region
- "Warm and humid" climate along the Indian Ocean coast
- "Composite" climate in the center, inland of the country
- "Temperate" climate around Bangalore
- "Cold" climate in the north and other elevated areas

This study focuses primarily on reducing cooling loads, which dominate the energy demand in India's buildings. Therefore, we do not include the cold climate zone, which hosts only a small part of the country's building stock. For the four other climate zones, we use weather data provided by India's Department of Energy for the following cities:

- Jaipur, Rajahstan, for the "Hot and Dry" climate
- Mumbai, Maharashtra, for the "Warm and Humid" climate
- New Delhi, Delhi, for the "Composite" climate
- Bangalore, Karnataka, for the "Temperate" climate

Outputs

All of the models are simulated for an entire year. The three main types of outputs are:

- Comfort level
- Heat gains
- Energy consumption

Results for these three outputs are calculated as hourly averages at the zone and whole-building levels. The comfort-level assessment uses either the Fanger model (Fanger, 1967) for fully conditioned zones or the Brager model (De Dear & Brager, 2002) for naturally ventilated zones. Because the models are optimized to meet comfort requirements in every building zone at any time, this output is used mainly for validation. Nonetheless, in some of the early, energy-intensive design options simulated, it is not possible to meet our comfort target.

We analyze heat gains, both external and internal, to identify those that could be reduced to decrease the cooling load.

Energy consumption is the final metric used to assess building performance. When occupant comfort is maintained, energy use is used to characterize the building's operation. We investigate five categories of

end uses: heating, cooling, ventilation, lighting, and plug loads.

MODELS

This study uses 44 optimized models corresponding to one "typical" baseline building, one code-compliant (ECBC) baseline building, and nine independent best-practices energy-conservation measures in four different climate zones.

The models for a given building in different climate zones are built using the same EnergyPlus objects but different input parameters, typically for wall composition, window properties, and HVAC equipment size with variations for code compliance (when applicable) or maintaining occupant comfort. Occupancy, geometry, and building use remain unchanged from one climate zone to another.

Baseline models

The baseline models represent a four-story, medium-size office building with four perimeters and one core zone per floor. The buliding dimensions are:

- North and south façade length: 50m each
- East and west façade length: 33m each
- Floor-to-floor height: 3.95m
- Ceiling height: 2.74m
- Perimeter zone depth: 6m

This generic geometry is based on the DOE reference model for medium-sized office building (Deru et al., 2011); other parameters of the model building represent common practice for new office buildings in India.

The typical building structure in the model has brick walls and concrete slabs, with a U-value of 2.18 $W \cdot m^{-2} \cdot K^{-1}$. Windows make up 80% of the envelope and are composed of single glazing modules with a low solar heat gain coefficient: U-value of 5.62 $W \cdot m^{-2} \cdot K^{-}1$ and Solar Heat Gain Coefficient (SHGC) of 48%. The building is a high-occupant-density, single-shift office with the following parameters:

- Lighting and plug-load power density are 15 watts per square meter (W/m^2) and 10.8W/m^2 respectively.
- Occupant density is 10 m^2/person.
- Occupancy starts at 7am and ends at 11pm on weekdays, with full occupancy between 9am and 6pm.

The HVAC system is a central air-handling unit (AHU) that provides air to all zones. The AHU includes an economizer, a supply and return fan, and a water-based cooling coil associated with a chiller and cooling tower. In each zone – one core and four perimeter zones per floor – a variable-air-volume (VAV) box controls the inflow and provides potential reheat. The chiller has a coefficient of performance (COP) of 5.8, representing the minimum requirement for centrifugal chillers that dominate the Indian market for high-capacity chillers (PACE-D Technical Assistance Program, 2014). Most Indian buildings are not equipped with heating equipment, but analysis of our simulation results shows that a small heater is required to maintain optimal comfort on certain days in the typical and code-compliant buildings.

The code-compliant baseline building is identical to the typical building with some parameters updated to conform to code: walls are insulated (U-value of 0.44 $W \cdot m^{-2} \cdot K^{-1}$, window-to-wall ratio is reduced to 50%, and windows are double paned (U-value of 3.30 $W \cdot m^{-2} \cdot K^{-1}$ and SHGC of 22%) with shading. Lighting power density is reduced to 10.8 W/m^2.

Energy-conservation measure models

We studied nine different energy-conservation measures that were added incrementally to previous model iterations except when new measures are not compatible with previous ones. Figure 1 shows the measures studied. Blocks that are grouped together share the same purpose:

1. Reducing external gains
2. Reducing internal gains
3. Promoting external losses
4. Decoupling cooling and ventilation

The arrows show how preceding modules are used in subsequent measures.

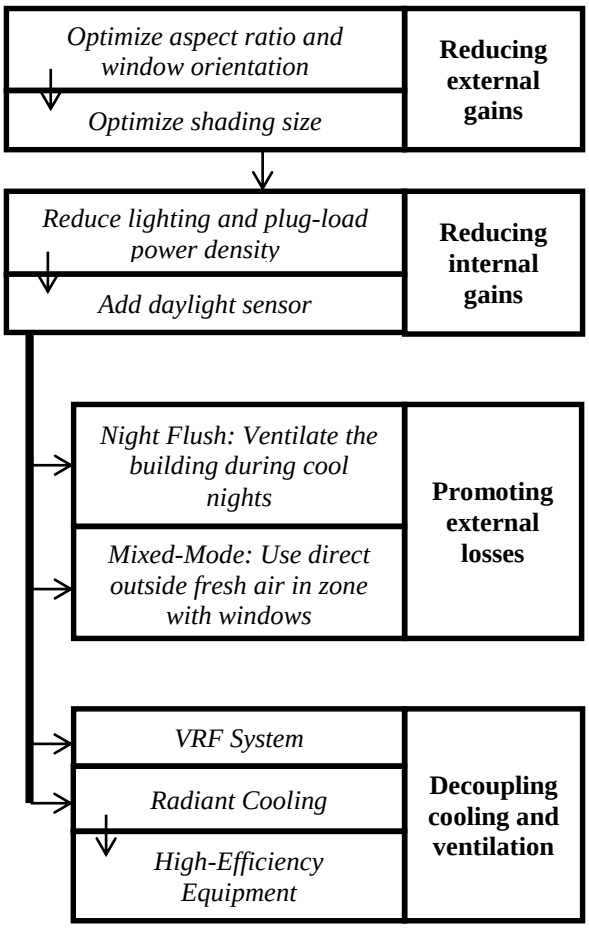

Figure 1 Energy-Conservation Measures

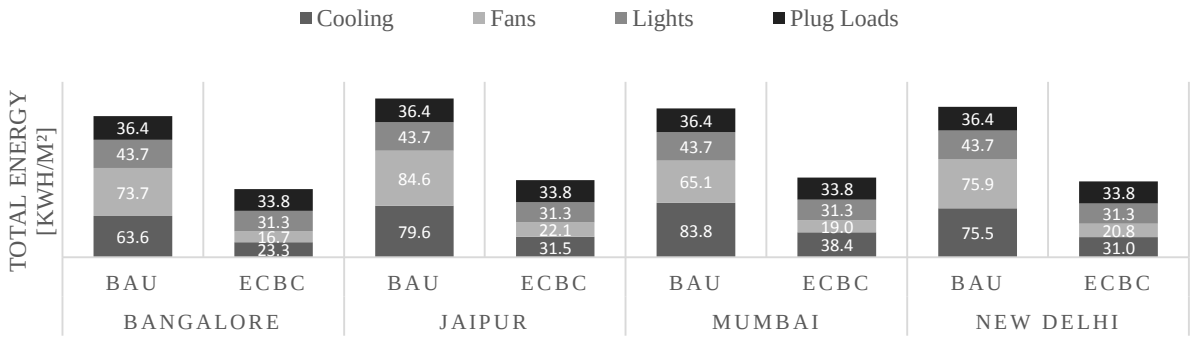

Figure 2 Energy consumption per end use for the baseline models

RESULTS

Baseline

The typical (or BAU) and code-compliant (ECBC) buildings are simulated for a whole year using the weather data from four different climate zones: hot and dry (Jaipur), warm and humid (Mumbai), composite (New Delhi), and temperate (Bangalore). Figure 2 shows the outputs.

Despite the diverse outdoor conditions of the four climate zones, the overall energy performance index (EPI), given by the energy consumption per square meter, remains similar for all cities. For a given building, only the cooling and ventilation end uses change from one location to another. The lighting and plug loads are independent of the climate. The fan consumption is greater in hotter climates despite ventilation requirements being the same for a given occupancy. We find that this is because, in all of these models, the cooling loads are met exclusively by the air system.

Table 1
EPI [kWh/m²] for Indian office building from data collection and simulation work

Data Collection (Best-Practice Guide)		250	150
Simulation	**Bangalore**	219	105
	Jaipur	253	121
	Mumbai	230	123
	New Delhi	241	119

The savings resulting from increasing efficiency from the BAU to the ECBC case come solely from a reduction in the energy use associated with air conditioning (labeled “cooling” and “fans” in Figure 2). The savings in the cooling demand result in part from use of shading, which reduces heat gain from the windows by 75%, and in part from a reduction in the window-to-wall ratio and solar heat gain coefficients. Cooling demand reductions result from an almost 100% reduction in heat gains from the walls, achieved by the addition of wall insulation.

The EPI results in Table 1 are congruent with the first version of the Best Practice Guide, which was developed based on measured data collected from actual buildings. In addition, the 47% to 52% reduction in EPI in code-compliant buildings compared to typical buildings is consistent with the conclusion of the ECBC User Guide.

Reducing external gains

The first measures we implement to save energy in our models are related to the building’s orientation and fenestration.

Although the south façade makes the largest contribution to total solar energy received , buildings should be oriented such that the north and south façades are the longest and only façades with glazing. In the summer, when cooling demand is greatest, the west and east façades receive more solar energy than the south. Direct solar radiation from the west and east has a low solar elevation, making it more difficult to shade whereas overhangs are sufficient to block the higher-elevation sunlight from the south.

When we optimize the aspect ratio of the building from 1.5 to 4 so that the south and north façades dominate and reduce the overall window-to-wall ratio by 30%, we see a 40% decrease in annual solar heat gains. Although solar heat gains are not the dominant component of the cooling load, this reduction in solar heat gain translates to a 12% decrease in cooling and fan energy consumption. It should also be noted that solar heat gains are not always detrimental to energy use; they provide beneficial heating during occasional cold days.

When we add adequate shading to the windows with consideration of the solar trajectory at each location (Parekh & Dadia, 2014), the cooling and fan consumption drops to 16% of the consumption in a code-compliant equivalent building. The interior lights are controlled on a schedule independant of exterior conditions, so lighting consumption did not change. When we include the cooling and fan reduction in the whole-building energy consumption, the resulting savings increase from 7% to 10%.

Reducing internal gains

The building's electrical equipment has a double effect on the energy consumption: it directly consumes electricity, and it uses this energy to create heat, which increases the cooling load and therefore the HVAC system energy consumption. In the previous iteration of the simluation with optimized envelope performance, the electrical equipment (lighting and plug loads) consumes 55% of the total energy used and accounts for 70% of the total heat gain.

Improved management of office electrical equipment and lighting, including turning off unused equipment and unneeded lights, can drastically reduce energy use.

Simulating improved electricity load management based on use or occupant movement would require a complex behavioral model. To simplify this simulation, we reduce the power density of lighting and plug loads based on input from interviewed experts and best-in-class buildings data. In parallel, we add daylight sensors that dim the artificial lighting when natural sunlight is available, and maintain illuminance to 300 lux. The use of increased daylighting is promoted by the optimized envelope in the previous model.

The results confirm that reducing lighting power density by 50% and plug load power by 25% reduces annual lighting and plug load energy consumption by 50% and 25%, respectively. Daylighting sensors and controls reduce lighting electricity consumption further, to 20% of its initial value.

The effect of lighting and plug-load reduction on cooling loads is substantial: total annual heat gains (both external and internal) are reduced by 36%, which reduces HVAC demand by 33%. Figure 3 shows how the measures reduce heat gains from lighting and electrical equipment (averaged for all four climates).

Overall, adoption of simple, effective energy management reduces building energy consumption by 38% to 48%. These ideal savings can only be achieved if the plug-load and lighting reduction strategies are carried out by every building occupant.

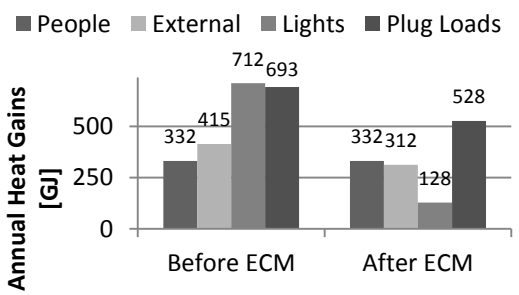

Figure 3 Annual heat gains by source, before and after load management

Promoting external losses

After integrating building envelope and internal gains measures in the two model iterations described above, we find that cooling and ventilation loads still represent about 40% of annual consumption. Another simple way to reduce cooling energy consumption is to use outside fresh air when available. We apply two different measures based on that premise: night flushing and changeover mixed-mode ventilation.

Night flushing which is used to actively (with fans) or passively (by motorized or operable windows) ventilate the building at night when the outside air is colder than the inside air. Although cooling and ventilation demand is lowest at night, this process can help quickly cool the building mass below the occupancy comfort setpoint; that cooling affects building temperature throughout the following day, reducing the cooling requirements.

The results of night flushing vary depending on outdoor conditions. In the hottest climate zones like Jaipur or New Delhi, night flushing produces few to no savings. Only the temperate climate shows significant savings from night flushing, a 24% reduction in cooling and fan consumption, as a result of colder night in summer.

The significant savings obtained in Bangalore would only be achievable in a building with a heavy structure, as is the case in the model building. The model building's walls and floors are made of high-inertia materials such as brick and concrete, with a thermal capacity ranging from 100 $kJ \cdot m^{-2} \cdot K^{-1}$ for internal floors to 400 $kJ \cdot m^{-2} \cdot K^{-1}$ for external walls. When night flushing is used in a building with a light structure, such as a steel-framed building with a capacity ranging from 10 to 40 $kJ \cdot m^{-2} \cdot K^{-1}$, fan and cooling energy savings dropped to 7% in the temperate climate.

The second method of reducing cooling and loads is changeover mixed-mode ventilation, which is an extension of night flushing applied during the daytime. In this approach, if the outside air temperature is lower than the inside air temperature, and the inside air temperature is higher than the minimum requirements for comfort, the mechanical ventilation is shut down, and windows are opened. Mechanical cooling is turned back on when the comfort conditions cannot be meet with fresh air.

Occupants report that naturally ventilated spaces are more comfortable than those that are mechanically ventilated (Brager, Ring, & Powell, 2000). Therefore, for the models integrating mixed-mode spaces, we introduce a different comfort definition using the Brager model (De Dear & Brager, 2002). Brager has shown that, in naturally ventilated spaces, comfort can be closely connected to a weighted average of the exterior temperature over the preceding weeks. Other studies have shown that this observation can be extended to occupants transitioning from naturally to mechanically ventilated spaces.

Although we might expect the savings from mixed-mode ventilation to be similar to those from night flushing, the above redefinition of comfort allows greater flexibility and so delivers greater savings in climates with low seasonal temperature variability than in climates with a high daily temperature variability. In other words, in climates where it is hot all year round, people typically have higher heat tolerance and find hotter environments more comfortable than is the case for people in more variable climates.

The lowest seasonal variability is in the temperate and warm and humid climates of Bangalore and Mumbai. In these climates, simulation shows that the integration of mixed-mode zones in more than 82% of the conditioned area reduces cooling demand by 43% and 41%, respectively.

The composite and hot and dry climates of New Delhi and Jaipur show lesser but still important savings from incorporation of mixed-mode ventilation, with a cooling demand reduction of 23%.

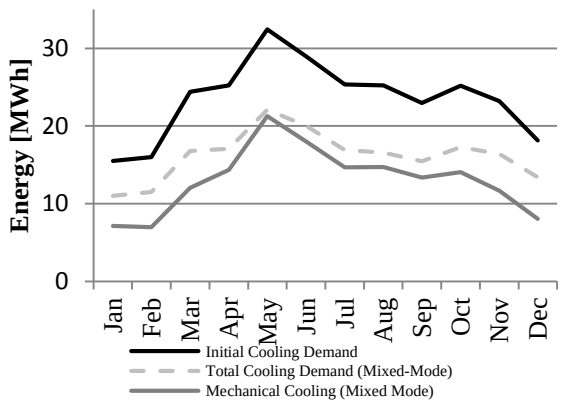

Figure 4 Comparison of cooling demand for fully conditioned and mixed-mode buildings in Mumbai

Figure 4 shows that cooling energy savings come mainly from modifiying the temperature setpoint definition (the difference between the black continuous line and the dotted grey line), and the "free cooling" from natural ventilation operation has less impact on savings (the difference between the dotted grey line and the continuous one). Therefore, we conclude that the comfort definition is the dominant contributing factor to the energy savings. However, these results are highly dependant on the validity of the comfort model used.

Decoupling cooling and ventilation

VRF HVAC technology uses a refrigerant loop for space cooling. The loop is composed of an outdoor unit with condenser and cooling towers for heat removal, and one or multiple evaporators in the different conditioned spaces to cool down the indoor air. The benefit of this type of system is that it decentralizes air cooling and decouples it from the ventilation. This allows a considerable reduction in ventilation equipment size compared to conventional systems. With a centralized, conventional air-conditioning system, air-supply temperature is determined by the cooling demand of one master zone. If the cooling demand for zones on the same loop varies significantly, a centralized system won't be able to satisfy all demands and will cause over-ventilation, overcooling or unnecessary reheating in one or multiple zones.

VRF systems eliminate those problems and provide the required cooling for each zone. Moreover, in comparison to other decoupling solutions such as radiant cooling, VRF systems are assumed (Thornton & Wagner, 2012) to have a lower construction and operating cost with a higher degree of decentralized control. This type of system can be a good alternative for retrofits (slab radiant systems are more difficult to adapt to an existing design).

When we replace conventional VAV space-cooling systems with VRF systems in our simulations, and replaced the COP from 5.8 to 4 to account for a less efficient system (PACE-D Technical Assistance Program, 2014), the results confirm our expectations that cooling and ventilation consumption are considerably reduced in every climate. The reduction is greatest in climates that have significant cooling needs; the higher the cooling demand, the greater the savings, as shown in Figure 5. Savings in cooling equipment energy use range from 20% to 26%, and savings in fan energy use range from 38% to 51%.

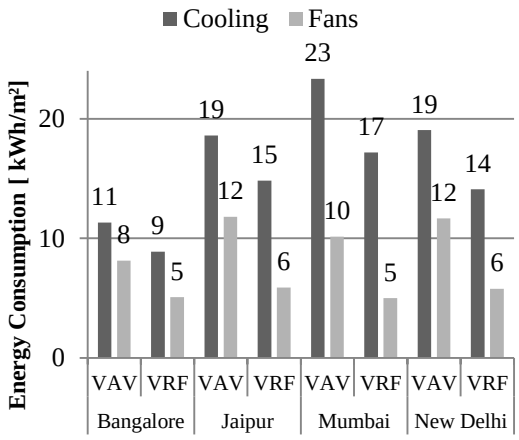

Figure 5 Cooling and fan energy consumption in VAV and VRF systems

High-temperature cooling

A second alternative for decoupling cooling and ventilation is to use hydronic, high-temperature cooling, such as radiant panel systems. Radiant panel cooling can be expensive and is not suitable for all retrofit applications. It also requires large installations

that don't fit every building design. However, radiant panel cooling has one key advantage over VRF: because of the large surface area of a radiant panel system, a higher temperature can be used for radiant cooling than can be used in a VRF system. When water is used as the thermal fluid, the volume transported is less than required in a conventional air system, which saves fluid-transport energy use. Occupants also report that radiant cooling is more comfortable and gentler than other systems (Feustel & Stetiu, 1995).

We updated the cooling equipment coefficient of performance (COP) in our modes from 4 to 5.8 to account for the better fluid medium and higher supply temperature in the radiant panel system.

Results show that when fan use is limited to providing minimum ventilation in occupied spaces, fan energy consumption is reduced to 4kWh/m². Cooling consumption under the radiant panel scenario is also lower than in the VRF scenario, with savings ranging from 33% to 46%, mainly because of the radiant system's better COP. We should note that, although the modeled radiant panels are controlled to prevent condensation, water vapor flows are not fully integrated in the models. Actual performance might be reduced in humid climates.

Best HVAC suite

Finally, we maximize the energy-use reduction in our scenarios by incorporating the best-in-class HVAC equipment for a medium-sized office building in India. In this model, we combine a radiant system with naturally ventilated spaces and high-efficiency magnetic bearing chillers (COP 7).

The result is buildings with minimal cooling and fan energy consumption. The majority of total building energy demand comes from lighting, plug loads, and service hot water (representing from 60% to 75% of total energy, depending on climate).

Table 2
EPI per climate and building performance for models that include best-in-class HVAC equipment

EPI [kWh/m²]	Typical	ECBC	Best
Bangalore Temperate	219	105	45
Jaipur Hot and Dry	253	121	53
Mumbai Warm and Humid	230	123	53
New Delhi Composite	241	119	53

Table 2 shows total energy consumption for baseline and best models per climate. The best models show a total energy savings of 77% to 79% compared to typical buildings, and 55% to 57% compared to code-compliant buildings.

CONCLUSION

In this study, we simulate the cumulative addition of a series of energy-conservation measures to a typical Indian medium-sized office building to determine the efficiency impact of each measure.

In the real world, a building's energy consumption depends heavily on the building's use and the external environment in which the building operates; therefore, it is difficult to compare the performances and effect of efficiency improvements in two different buildings, particularly when they are in two different climates. Building simulation allows us to create the same environment for every modeling run and understand the effect of each improvement modeled based on an apples-to-apples comparison.

Our results provide high-level, climate-specific guidance about which energy-saving strategies are likely to have a greater chance of success and which ones probably will not be effective in particular climate zones in India.

- In a temperate climate like Bangalore (or Pune), it may not be worth investing in radiant panels because a similar level of energy benefits can be achieved through mixed-mode operations. A VRF system is similarly effective in this climate zone.
- The simulations for hot dry weather such as Jaipur (or Ahmedabad) show that a radiant system is effective, providing 25% savings over an optimized VAV system with a good envelope and reduced lighting power density and plug loads.
- In hot and humid areas such as Mumbai (or Chennai), an optimal modeled performance can be attained using a radiant system. Mixed-mode and VRF systems also save significant energy.
- In a composite climate such as New Delhi (or Chandigarh or Hyderabad), a radiant model provided optimal savings of 24% over an optimized VAV system with a good envelope and reduced lighting power density and plug loads.

This study also provides insight into the theoretical limits of the energy-savings potential of energy-efficiency strategies. We found that, through a series of improvements, it is possible to reduce a building's EPI by 75% compared to a building with typical design, and by more than 50% compared to a builing that meets current energy code. This shows that buildings in India can strive toward more aggressive targets than those outlined in the ECBC.

The simulation data in this study are consistent with benchmarked energy-performance data collected from various office buildings in India (Singh, Sartor, & Ghatikar, 2013). These data on the effectiveness of various energy-efficiency strategies can be used to develop a robust set of target metrics for office buildings.

Future work will focus on evolving from climate-specific to building-specific studies, developing an interactive tool for building practitionners.

ACKNOWLEDGMENT

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