Concepts from Traditional Indian Architecture to Reduce Energy Consumption in Modern Indian Architecture

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Concepts from Traditional Indian Architecture to Reduce Energy Consumption in Modern Indian Architecture

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Abstract

The unprecedented growth in population in Bangalore city, India, from 5.1 million (2001) to 11.5 million (2016), has led to an exponential increase in residential construction activities, and associated fossil fuel consumption and greenhouse gas emissions. It is vital to reduce the overall energy consumption per household in India to reduce the net environmental impact of this construction explosion.

The primary subject of this research hinges on the question: Will applying concepts from traditional Indian architecture help address the increasing energy consumption in today's modern Indian architecture? The hypothesis that examines this question is: Architectural elements and construction materials of traditional Indian houses allow for lower energy consumption profiles compared to houses that use modern non-traditional methods and materials.

I tested this hypothesis by comparing the current energy consumption, cost-benefit analysis and CO_2 emissions of traditional and modern houses by examining various parameters such as space planning, construction materials, indoor environmental performance, and energy consumption through energy simulations using Green Building Studio – an energy modeling software.

Data were collected from various sources – building plans, utility bills, interviews with owners of the houses, energy profiles for construction materials, and a Netatmo weather station. Three energy modeling methods were used to determine the annual energy use intensity and CO_2 emissions for the houses. Then an experimental energy

consumption simulation was performed on the houses by interchanging the building materials of the traditional and modern houses. A cost-benefit analysis was performed on the results of the experimental energy consumption simulation to test the hypothesis.

The results showed that the average energy consumption for the traditional houses was 18.5 KWh/m^2, and 72 KWh/m^2 for the modern houses based on standard equipment usage and the estimated utility consumption. Energy use is typically 30 % higher in the summer months for the majority of houses, as determined by actual utility bills. Energy consumption for the traditional houses (houses 1-3) increases drastically by an average of 39% when modeled with modern materials, while the modern houses modeled with traditional materials showed a 36% average decrease in energy consumption. Therefore, applying concepts from traditional Indian architecture would help reduce the increasing energy consumption in today's modern Indian architecture.

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I would finally like to thank my husband, Bharath Hemachandran, who helped me with proof reading and support at every stage of the thesis. Lastly, I would like to thank my entire family without whose encouragement and patience this research would not have been completed.

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Definition of Terms

Carbon Footprint: The total amount of greenhouse gasses that are emitted into the atmosphere each year by a person, family, building, organization, or company. A person's carbon footprint includes greenhouse gas emissions from fuel that an individual burns directly, such as by heating a home or riding in a car. It also includes greenhouse gasses that come from producing the goods or services that the individual uses, including emissions from power plants that make electricity, factories that make products, and landfills where trash gets sent (EPA, 2013).

Embodied Energy: The energy consumed by all of the processes associated with the production of a building, from the mining and processing of natural resources to manufacturing, transport and product delivery (Milne, 2013).

Energy Use Intensity (EUI): Represents the energy consumed by a building relative to its size and is expressed in KWh per square meter (Energy Star, n.d.).

EPA: Environmental Protection Agency

Greenhouse Gas (GHG): Any gas that absorbs infrared radiation in the atmosphere. Greenhouse gasses include carbon dioxide, methane, nitrous oxide, ozone, chlorofluorocarbons, hydrochlorofluorocarbons, hydrofluorocarbons, perfluorocarbons, sulfur hexafluoride (EPA, 2013).

Green building: A holistic concept that starts with the understanding that the built environment can have profound effects, both positive and negative, on the natural environment, as well as the people who inhabit buildings every day. Green building is an effort to amplify the positive and mitigate the negative of these effects throughout the entire life cycle of a building (Kriss, 2014).

INR: Indian Rupee, converts at 68 INR per USD

Specific heat: Also called specific heat capacity, is the measure of the heat energy that a substance in a unit quality absorbs or releases when the temperature increases or decreases 1K. The bigger the specific heat is, the better the stability of the indoor temperature will be. It is expressed in J/ (gm.) ("Basic Properties of Building Materials," 2011).

Thermal Capacity: The property of a material to absorb heat when it is heated and to release heat when it is cooled. It is expressed in J ("Basic Properties of Building Materials," 2011).

Thermal Comfort: The condition of mind that expresses satisfaction with the thermal environment as per the ASHRAE 55-74 Standard (Madhumathi, Radhakrishnan, &

Priya, 2014). The thermal comfort of a building has a great influence on the energy consumption of a building and the subsequent dependence on mechanical cooling (Gangwar, 2012). Various aspects such as carbon dioxide content, humidity and the temperature difference between the indoor and the outdoor air affect the indoor environment significantly and the recorded measurements are documented in the Results section. The ASHRAE Standard 55-2013 mentions that the Thermal Environmental Conditions for Human Occupancy, ranges between approximately 19°C and 29°C (Madhumathi, , 2014). The National Building Code (NBC) 2005 states that the thermal comfort of a person can be taken at 27°C. However, with proper air circulation and movement, inhabitants can tolerate temperatures up to 35°C. (Jayasudha, Dhanasekaran, & Devadas, 2014).

Thermal Conductivity: The property of a material that indicates its ability to conduct heat is known as thermal conductivity. It is expressed in W/ (m K) ("Basic Properties of Building Materials," 2011).

Thermal mass and insulation: Used to describe materials of high thermal capacitance i.e. materials which can absorb and store large quantities of heat (Autodesk Sustainability Workshop, n.d.). Thermal mass may be in the form of masonry walls, roofs, floors, or possibly embedded phase change material (Almatarneh, 2013).

Thermal Transmittance value (U): indicates the total amount of heat transmitted from outdoor air to indoor air through a given wall or roof per unit area per unit time. The lower the value of U, the higher is the insulating value of the element

Urban heat island effect: An urban heat island, or UHI, is a metropolitan area that's a lot warmer than the rural areas surrounding it. Heat is created by energy from all the people, cars, buses, and trains in big cities (National Geographic, n.d.)

Vernacular/Traditional Architecture: Unpretentious, simple, indigenous, traditional structures made of local materials and following well-tried forms and types (Prashad & Chetia, 2010).

Chapter I.

Introduction

Globalization has ushered in a new era of prosperity into present India. As cities and towns all across India are growing both in size and population at an exponential rate, construction activity is at an all-time high. Moreover, with greater numbers of people shifting from rural to urban areas, it is evident that there will be a massive increase in the number of houses to be constructed. Additionally, the government has promised to house for all by 2022, which will result in a significant increase in carbon emission into the environment (Prasad, 2016). In India, the construction sector is a major economic, social and environmental driver that has grown exponentially over the last few decades.

Sustainable design strategies and techniques focused on improving occupant comfort with minimal energy use have always been an essential component of traditional Indian architecture (Prashad & Chetia, 2010). Unfortunately, these energy-saving lessons have not been widely adopted or implemented in new construction or renovation projects throughout India. Rather than learning from India's extensive past in architecture, builders are creating poor reproductions of imported architectural techniques that may not be suitable for India (UNEP, 2010). Most present day building materials consist of large amounts of glass, feature fewer open spaces, and rely heavily on mechanical cooling and lighting, all of which can lead to an increase in the energy consumption.

The use of appropriate materials is crucial for the energy performance of buildings. Construction materials are primarily integrated into the building envelope, which is the interface between the interior of a building and its external environment (Center for Climate and Energy Solution, n.d. – a). For example, one ton of the cement, the substrate of this new urban infrastructure, equals at least one ton of carbon dioxide in the atmosphere - a key reason as to why China is now the world's leading CO_2 emitting nation. According to the United Nations Population Fund, countries like China and India will contribute more than half of global CO_2 emissions by 2050 (LeDoux, n.d.). Moreover, a report from Center for climate and energy change states that India is the fourth largest greenhouse gas (GHG) emitter, accounting for 5.8% of global emissions. India's emissions increased by 67.1% between 1990 and 2012, and are projected to grow 85 % by 2030 under a business-as-usual scenario (Center for Climate and Energy Solutions, n.d.-b). In addition, poor construction techniques lead to decreased building lifespans, so many buildings will have to be torn down and rebuilt within a decade or two (Biello, 2012).

Energy used for cooling and lighting form the largest proportion (72% in residential & 92% in commercial buildings) of total energy usage in Indian buildings (Gupta, 2003). Further, this energy usage is comparatively inefficient: "Recent studies of the energy performance of commercial buildings in India indicate that energy efficiency is poor by international standards, which has the effect of locking Indian cities into inefficient and potentially uncompetitive building stock for decades" (TERI in GEA, 2010) (UNEP, 2010).

The first step towards tackling this problem would be to understand the energy use by typical urban households (residential properties). A keen look at the profile of energy usage of urban households in India shows that energy is primarily directed towards space conditioning (45%), lighting (28%), refrigeration for storing food (13%) and the remainder for electrical appliances (14%) (UNEP, n.d.). Therefore, it is clear that targeting the top two uses of electricity is the key to reducing the energy consumption of urban households in India. This will consequently lead to significant reductions in the number of GHG emissions.

These problems have led to an ongoing debate on how to reduce the energy consumption of buildings through sustainable techniques. These strategies could significantly influence the architectural language of India, so future design and planning must be responsible and take into consideration the cultural heritage, identity and the lifestyle of its people.

Research Significance and Objectives

The goal of this thesis is to analyze current design and construction practices in Bangalore city, India, to determine how inculcating India's traditional architectural techniques may potentially provide savings in the energy consumption of buildings.

The study will compare traditional buildings with modern buildings of the same typology. The comparison will evaluate space planning, materials, indoor environmental performance, and energy consumption of traditional and modern houses. The result of the comparison will provide data to determine which type of building is more energy efficient. Moreover, the potential benefits of this research are to:

a) Establish if there is a significant saving in the energy consumption and cost between traditional vs. modern architecture.

b) Use the data to draw conclusions about sustainable architectural principles that can be a prototype for best practices in India.

c) Shape the development of new construction and the renovation of existing buildings of many Indian cities in the near future. If cost-effective, the outcome of this research may help various segments of the population to incorporate sustainable techniques into their buildings irrespective of their economic and social conditions.

Background

Buildings account for a sixth of the world's freshwater withdrawals, a quarter of its wood harvest, and two-fifths of its material and energy flows (Jamwal & Jain, 2007). Buildings contribute up to 30% of global annual greenhouse gas emissions and consume up to 40% of all energy (UNEP SBCI, 2009). This is even higher in India. According to the International Energy Agency (IEA), the construction sector accounted for 47% (highest) of India's final energy use between 1995 and 2005 (Figure 1). As per reports from IEA, about 22 million square meters of commercial buildings and 19 million square meters of residential buildings were constructed between 2004 and 2005 alone (Evans, Shui & Somasundaram, 2009).

Even at this pace of development, the urban housing shortage is estimated to be more than 29 million. Moreover, the demand for affordable housing is more likely to increase from current level to more than 38 million households by 2030 (Ramaswamy, Vilvarayanallur, & Kumar, n.d.).

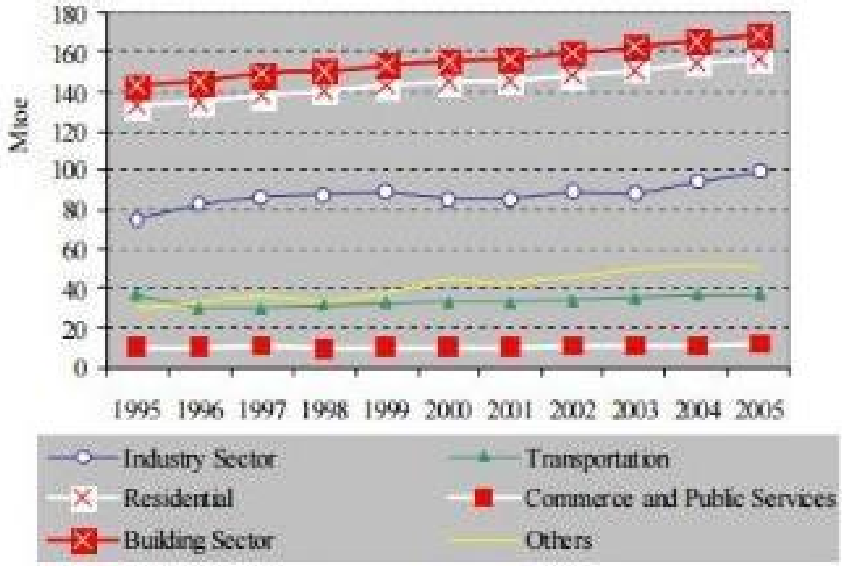


Figure 1. Energy consumption by sector in India (1995-2005). Energy consumption in this figure refers to the final energy use, which includes consumption of renewable and waste energy, the sector "Others" includes agriculture, forestry, fishing, and non-specified and non-energy use (Evans et al., 2009).

Construction Sustainability Goals and Standards Relevant to India

In the past few decades there have been numerous attempts to reduce the energy consumption of new buildings in India through the adoption of two main frameworks – LEED (Leadership in Energy and Environmental Design) and GRIHA **(**Green Rating for Integrated Habitat Assessment).

Although these frameworks provide tools to objectively assess building performance versus standard metrics (UNEP, 2010), they do not provide innovative design solutions and techniques for designers to follow. Additionally, even if these frameworks are adapted to the Indian environment, these certifications are expensive and complicated for Indian builders and individuals to follow without employing professionals with the required expertise, who are rare in the current workforce. This is especially challenging for builders that focus on creating low-income housing.

Further, even though LEED rewards buildings based on the integration of sustainable design strategies, there is no guarantee that buildings will reduce energy consumption when in operation (Menon, 2014). This is similar to a local rating tool in Singapore, Green Mark, which places a larger emphasis on installation of technologically intensive cooling units, arguing that reducing energy consumption is essential in a tropical city where air-conditioning represents a large part of electricity demand. However, some experts wonder if Singapore's approach will eventually encourage an unsustainable dependence on air conditioning as an essential design component. Often, country-specific rating tools under development in Malaysia, Indonesia, and other Southeast Asian countries may be more effective at promoting vernacular designs that emphasize passive technologies — such as optimization of shading and ventilation — and sensitivity to a building's carbon life cycle. Moreover, since the goal of sustainable rating tools is to reduce a building's environmental footprint, Deo Prasad, a professor of architecture at the University of New South Wales in Australia who has studied sustainable building policies across the Asia-Pacific region, asks an open question for Singapore: "Are you getting hooked into the energy consumption being absolutely necessary for comfort?" (Ives, 2013).

Similarly, in India, to ensure buildings qualify for LEED certification, many builders incorporate elements like photovoltaic panels, rainwater tanks, and air-conditioning systems in their construction (Research Gate, n.d.). These design strategies are in contrast with the traditional architecture of India, which has always been very sensitive and relevant to its environment through its use of climate-responsive design, use of local and sustainable materials, and the incorporation of architectural design elements that promote high quality indoor environments, such as courtyards, clusters, wind towers, roof terraces and jaalis (stone lattices), among others (Jhadhav, 2007).

Another important factor in the construction of energy efficient buildings is the choice of the materials to be used. Often, the embodied energy of the construction material is overlooked, which can have a significant impact on the non-renewable resources of the planet (Maqwood, 2015). Some materials with high embodied energy may have a longer lifespan, for example, aluminum (Branz Ltd., 2014). Therefore it is important to understand the material impact over the entire life cycle before making design decisions.

The Need for Affordable Housing and its Bearing on Energy Efficiency

In India, the majority of the Indian urban population – 92% or 73 million households -- earns less than INR 25,000 per month and most of the new housing being constructed has so far been unaffordable for them (Agarwal, Jain, & Karamchandani, 2013). There is a need for a huge undertaking to address the demand for low-cost housing in India. As per the Government of India, there is a shortage of 18.78 million homes in urban India, 95% of which is accounted for by the EWS4 (households with annual income of less than INR 1 lakh) and Low Income Group (LIG) segments (households with annual income of INR 1-2 lakh). (Agarwal, Jain, & Karamchandani, 2013). This clearly shows that designers and builders must work to not only minimize the energy consumption of buildings but also provide affordable housing solutions for all citizens. Thus, this research study aims to understand the difference in energy use between traditional and modern buildings and provide strategies to address low-cost housing in a sustainable manner.

Energy Consumption from Growth in the Residential Sector in India

Since 1991, India's economy has grown significantly and the construction sector has been one of the leading engines responsible for this growth. It contributes nearly 6.5% of the Indian Gross Domestic Product on an annual basis. Within the construction industry, commercial and residential sectors have served as the primary markets.

Despite its obvious economic benefits, the construction industry also consumes large amounts of energy throughout the construction lifecycle (UNEP, n.d.). Consequently, the carbon footprint of this industry has seen a huge rise in India. The Electrical Power Survey, conducted by the Central Electricity Authority, projects that energy consumption due to the growth of the construction sector will increase by around 8% annually in the residential sector. Since urban households primarily use electricity generated from fossil fuels, there will be a marked increase in GHG emissions (UNEP, n.d.).

Climate Change and its Impact on India

Although the effects of climate change on the planet are a subject of much debate, there are evident changes occurring in India suggesting a significant climatological shift. For example, the average temperature in India has steadily been rising in parallel with population growth. With an addition of 242 million people over the last 15 years (Figure 2) along with the relative change in the climate, India experienced the detrimental impact of temperature rise through a deadly heat wave that killed more than 2300 people in 2015 (Das, 2015). The U.N. Intergovernmental Panel on Climate Change (IPCC, n.d.) warns the country that, “India is getting hotter as humans continue to pump carbon dioxide into the atmosphere." This will increase the risk of heat-related mortality exacerbated by climate change and population increases (Atkin, 2015).

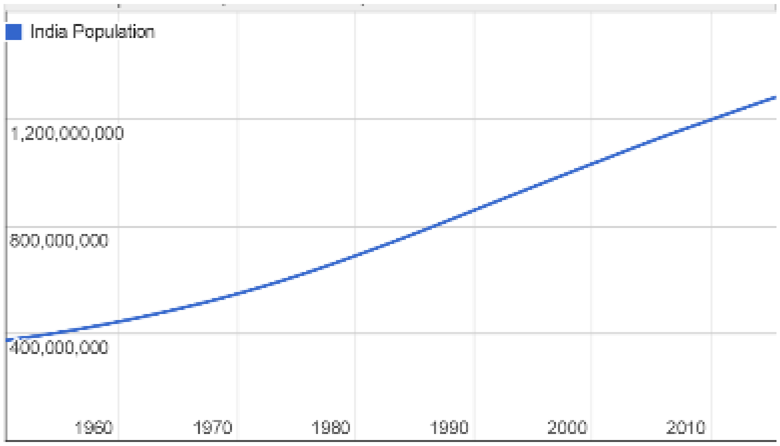


Figure 2. India population (1950-2015) showing the growth trend (Worldometer, 2015).

Bangalore as a Research Focus

Bengaluru, the IT (Information Technology) capital of India, is the focus of this research study. Over the past three decades, there have been tremendous changes in the infrastructure and building skyline resulting from the explosive population growth in the city. The population has grown from 5.1 million in 2001, to over 11.5 million people currently (Indiaonlinepages.com, n.d.). This unrestrained population growth has resulted in unimaginable pressures imposed on the infrastructure and natural resources available in the city (Figure 3) (Geospatial world, 2014). Consequently, this has given rise to a plethora of serious challenges such as lack of appropriate infrastructure, traffic congestion, and lack of basic amenities (electricity, water, and sanitation) in many localities. The exponential growth of the city has resulted in a haphazard urban development, throwing the city into shambles. Today the city has a poor reputation and is unfortunately referred to by some as the garbage city of India (Prabhu, 2016).

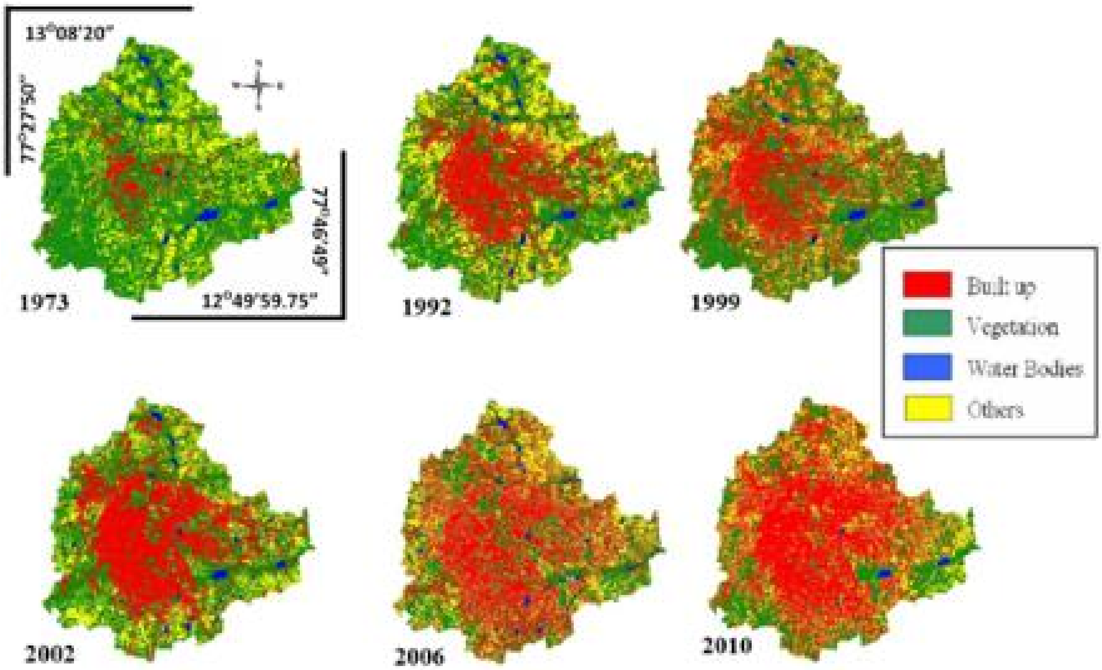
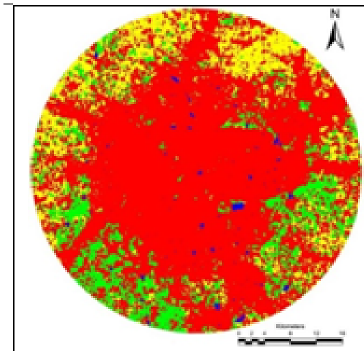


Figure 3. Land use change in the infrastructure and natural resources in Bangalore 1973-2010 (Geospatial world, 2014).

Although a large part of the allure of the city has been its pleasant climate, over the last few years many environmentalists have documented that Bengaluru's weather has changed significantly. Scorching summers, bone-chilling winters, and deluges that resemble cloudbursts are indicators that all is not well with the city's climate. Bangalore experienced its highest temperature in April 2016 with a temperature recording of 39.2 degree Celsius (Bangalore 2016). Environmentalist Naveen KS (2013) noted: “Bengaluru is experiencing an urban heat island effect. Temperature and other climatic factors within the city limits differ from its surroundings. The city also experiences varied precipitation and there are changes in the micro-climate as well”. Moreover, the urban heat island phenomenon is seen in a large number of localities within greater Bengaluru (The Times of India, 2013).

Furthermore, Bangalore showed a 584% growth in a built-up area during the last four decades with the decline of vegetation by 66% and water bodies by 74% (Geospatial world, 2014). Analysis of the temporal data reveals an increase in urban built up area of 343% from 1973 to 1992, 130% from 1992 to 1999, 107% from 1999 to 2002, 114% from 2002 to 2006, and 126% from 2006 to 2010. There have also been average annual temperature changes with an increase of ~2 to 2.5 ºC during the last decade (Geospatial world, 2014). A large part of these temperature changes can be attributed to radiation from buildings and paved roads that create heat islands, which is evident from the large number of localities with higher local temperatures.

Moreover, inadequate tree cover in the city further exacerbates the temperature increase. Urban sprawl also limits the air circulation within the city which increases the effects of the heat islands more. These negative trends are expected to continue, as the simulated land use model for 2020 shows an increase in development from 48.66 % (2012) to 70.64% (2020) (Figure 4) (Geospatial world, 2014).



Year	**2020 - Predicted**	
Land use	Area in hectares	Percent
Urban	142,381.08	70.64
Vegetation	27,316.44	13.55
Water	1491.21	0.74
Others	30,356.64	15.07

Figure 4. Predicted land use map for 2010 in Bangalore (Geospatial world, 2014).

With a total population of over 11.5 million people, Bangalore is India's third most populous city in India. The negative effects described above have worsened with the city's rapidly expanding population over the last 75 years, with over six million people added in the last 15 years (Table 1) (Indiaonlinepages.com, 2016). Bangalore's population has increased by 127% since 2001 and 37% since 2011.

Table 1. Population increase in Bangalore 1941-2016. (Indiaonlinepages.com, 2016).

Census	Population
1941	406,760
1951	778,977
1961	1,207,000
1971	1,654,999
1981	2,922,000
1991	4,130,000
2001	5,101,000
2011	8,425,970
2012	8,973,658
2013	9,556,945
2014	10,178,146
2015	10,839,725
2016	11,556,907

The boom in the construction sector is a direct consequence of the rapid urbanization of Bangalore. Blessed with a temperate climate, it has attracted many industries into the city. In the coming years; many companies, national and international, have aggressive growth plans in the city. This has lured immigration into the city as it boasts of a multi-cultural population, good educational institutions, excellent medical facilities, and a thriving social network which in turn demands a constantly upgraded physical infrastructure. Bangalore is expected to clock a 15% growth annually for residential units. By the year 2021, Bangalore's population is expected to burgeon to 14 million. (Strategic Advisory Group, 2012).

Furthermore, Bangalore has a large number of expatriates who live and work in the city. The increase in demand in the luxury sectors fuels demand for luxury constructions near their area of work. Villa projects with many facilities have sprung up to cater to this segment (Figure 5). There is high demand for high-end residential spaces in the city (Strategic Advisory Group, 2012).

14 Million

Bangalore metropolitan population by 2021.[1]

13%

average annual price appreciation rate in residential sector for last 4 years.

20,600

residential units absorbed in 2011.

4.5%

average annual residential yield rate.

100,000+

average annual addition in IT/ITeS workforce for past 2 years; expected to grow at least at this rate for next 3 years.

44,000

residential units launched in 2011 [38,700 and 5,300 in apartment and villa/row houses category respectively].

55,400

residential units available.

15%

CAGR for residential sector during 2008-11.

Figure 5. Bangalore residential market statistics: 2012 and beyond (Strategic Advisory Group, 2012).

Indian Architecture and its Influence on Climate Change

The architecture of a country plays a major role in defining its cultural heritage, identity and the lifestyle of its people. The rapid, poorly planned, and uncontrolled growth pattern in India has led to poor design decisions that do not reflect the local culture or climate. This has resulted in the unwelcome changes that have affected the culture, environment and healthy lifestyle of people (Wang, 2003).

Materials and Techniques of Traditional Architecture of India

The use of appropriate materials is crucial for the energy performance of buildings symbolized by the building envelope. A building envelope is an interface between the indoor and outdoor environment – walls, floors, roof, and foundation of a building (Center for Climate and Energy Solution, n.d. - a). Minimizing and regulating the heat transfer through the building envelope determines the heating and cooling loads. In hot climates – such as India – the building climate should be focused on reducing the heat transfer from outside. Therefore, construction materials should have a high thermal capacity (Madhumathi, Radhakrishnan, & Priya, 2014). Table 2 shows the typical materials documented in the traditional versus modern building observed.

Table 2. Old versus new building materials documented from the study samples.

	List of old building materials	**List of new building materials**
Wall	Brick, Rammed Earth, Rubble, lime, or clay plaster	RCC Block, Cement Plaster, Paint
Roof	Madras Terrace Roof, Filler Slab	Reinforced Cement Concrete slab
Floor	Red oxide or Mosaic	Vitrified Tiles/Granite/Marble
Windows	Wood frame with Jaali Mesh or Iron Bar Grill with double Glaze	Timber Frame with Single/Double Glaze
Wood	Teak	Teak, Sal, Oak

Wall construction. This contributes to the air, heat and light transmission into a space. Traditional houses have thick walls with a high thermal capacity to keep the indoors cooler in summer and warmer in winter.

Baked bricks are a traditional construction material dating back to 2700BC and are made from clayware dried in the sun or fired in brick kilns. They have been the de facto materials used to build residential buildings due to their low cost across India. Bricks provide structure, finish, acoustic comfort, thermal comfort, good indoor air quality, fire resistance, impact resistance and durability. They can contribute to improved indoor air quality by eliminating the need for paints and other finishes and the resulting volatile organic compounds (VOCs). Brick has a high life expectancy and can be reused and recycled. The thermal mass is contained within a protective layer of insulation which improves thermal regulation. Brick is non-combustible and does not emit toxic fumes (Clay Tile, n.d.).

Other traditional Indian architecture materials like rammed earth is sustainable since it is noncombustible, thermally massive, strong, durable, easy to construct, and has a low life cycle impact. Harvested from earth, it can be disposed of without damaging the environment. It is a sustainable substitute for man-made concrete (Vishnupriya, Madhumita, & Vignesh, 2014). Properties of rammed earth make it suitable for construction that aims to achieve thermal comfort at a low cost and reduced CO_2 emissions (Vishnupriya, Madhumita, & Vignesh, 2014). Well-constructed walls using rammed earth can survive thousands of years. The rammed earth section of Kyichu Lhakhang monastery has survived over 300 years (Figure 6) (Jacquin, 2012).

Figure 6. Rammed earth section of Kyichu Lhakhang monastery (Jacquin, 2012).

Rubble masonry – another common traditional wall construction material – has been used to build walls and standing structures in India since ancient times, dating back to Harappan civilization (NIOS, n.d.). It is naturally available, long lasting and with good cooling properties that can be used to construct large structures. Some popular stones are granite, marble, sandstones, etc. (NIOS, n.d.). Traditionally stone walls were constructed using lime mortar and internal plastering. Solid stone walls tend to absorb and retain heat by radiating the heat to the interior in winters, while in summer the heat is radiated externally (National Energy Services Ltd, 2010). The thermal capacity of brick and rammed earth are the least, which makes them suitable for wall construction (Table 3).

Table 3. Houses categorized by type of wall (Green Building Studio).

Materials	**Thermal Conductivity (W/mK)**	**Specific Heat (J/Kg.K)**	**Density (kg/m^3)**	**Thermal capacity (J/K)**
Clay Brick	0.54	840	1550	1302000
Rammed Earth	0.837	1046	1300	1359800
Stone	2.51	962	2300	2212600
Concrete Masonry Block	1.3	840	1800	1512000

The thermal properties of various wall construction materials used in the nine houses under study.

Mortars are the binding forces that keep the building blocks of standing structures together by providing strength and durability. Lime and gypsum mortars have been used in India for thousands of years (NIOS, n.d.). Today, cement mortar is used extensively in all modern buildings. The detrimental impact of cement has been recognized by English Heritage and Historic Scotland, and they have banned its use in all historic buildings. It encourages dampness and can destroy buildings that have stood for hundreds of years (Chapelgate Construction, n.d.).

Plasters were used both as protective and decorative elements applied on top of walls constructed using the various building blocks. Two commonly used plasters are lime and cement. Since lime is renewable, it reduces the GHG effect compared to using cement. Most of the CO_2 released during the manufacturing process of lime is re-absorbed during the lifetime of the plaster, thus being close to carbon neutral. On the other hand, cement plaster is one of the major sources of GHGs globally, as its releases of carbon dioxide into the atmosphere is not re-absorbed by cement plaster.

The thermal conductivity of lime plaster (0.52 W/mK) is lower than cement (1.5 W/mK). Since lime is also permeable, using it is a healthier option than sealed buildings using cement as it causes fewer damp problems. In a traditional stone or brick wall laid with lime mortar, the wall works as a weatherproof surface because the stone keeps the rain out, and the lime absorbs water while it is raining, and then releases it when it stops (Chapelgate Construction, n.d.).

Roof. It is a main aspect of the building envelope where solar heat gain can take place apart from walls and openings. Therefore, thermal performance of the roof is one of the most important factors for achieving indoor thermal comfort in houses designed for natural cross ventilation (Madhumathi, Radhakrishnan, & Priya, 2014).

The thermal performance of a building is affected by the solar absorbance of the roof (Madhumathi, Radhakrishnan, & Priya, 2014). The heat gain in many cases can account for 50% of the total heat gain in buildings. A light colored roof with white lime mortar is preferred since it makes the surface more reflective and thus minimizes heat absorption by the external roof surface.

Madras terrace roof is a traditional roofing system (Figure 7) that consists of wooden beams placed upon the opposite wall with steel or wooden rafters running across. Clay bricks of high density and high strength made to a size of 25mmX75mmX150mm are placed at an angle of 45 degrees diagonally to the wall and fixed with lime mortar. The angle provides more strength to the roof and terrace tiles were placed on the edge. Thereafter a 75mm thick layer of broken bricks or brick bat is laid with lime mortar, three parts brick and one part gravel and one part sand. This layer provides the compressive strength and load bearing capacity to the roof. The intermediate floor is further finished with flooring material (Figure 8) (Madhumathi, Radhakrishnan, & Priya, 2014).

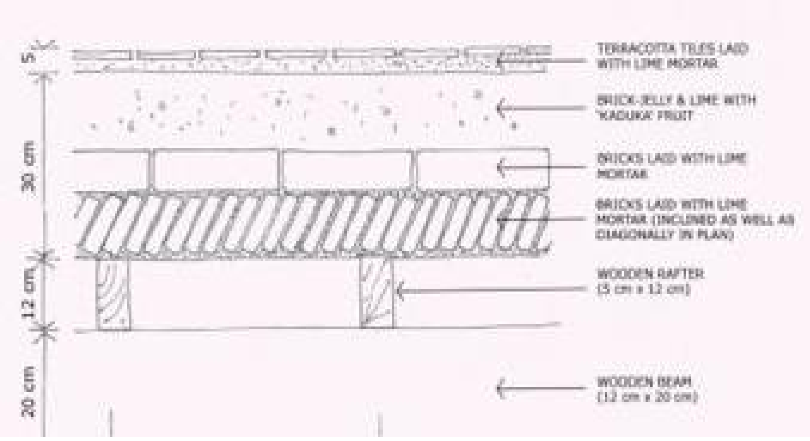


Figure 7. Section of a typical Madras terrace roof (Auroville.org, 2009).

Figure 8. Photo of Madras terrace roof.

A Filler Slab is a combination of concrete, filler material and steel ribs used for the purpose of roof construction. The filler material, Mangalore tiles, were placed between the steel ribs and concrete was poured in the gaps to set it (Figure 9). The idea is to use the filler material in the parts that are not structural, thereby reducing the cost and weight of the roof (Society for Environment Protection, n.d.).

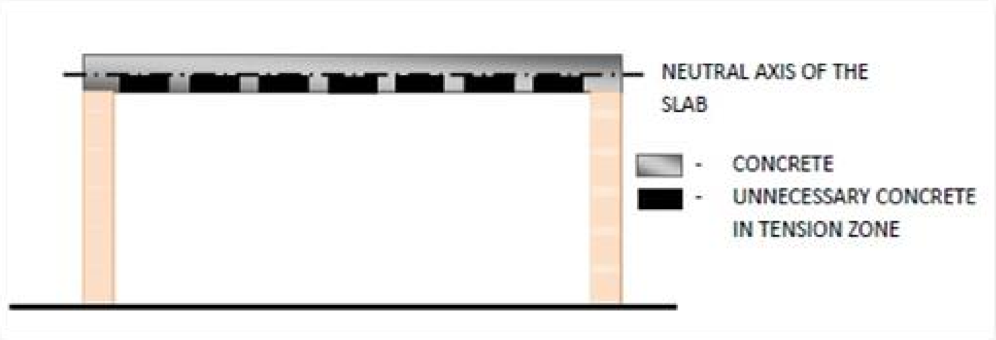


Figure 9. Section of a typical filler slab (Society for Environment Protection, n.d.).

The RRC Roof is the most common roof type used in modern India. Horizontal slabs of steel reinforced concrete between 100-500 mm are used with a layer of brick brat concrete laid on top (Figure 10). A ratio of 3:1:1 of brick bats:gravel:sand along with cement mortar is laid over the RC slab. The top surface is finished with three coats of lime mortar – tiling material for the terrace and Mangalore tiles for the sloping part. The intermediate floors are finished with flooring tiles (Khan et al, 2004).

Figure 10. Construction of an RCC slab.

Upon comparison of the three roofing systems above, the Madras roof appears to be best as it has stood the test of time with minimum or no maintenance. It doesn't need centering and facilitates faster construction. The three main components of the roof are wood, lime mortar, and clay tiles, which are all renewable resources and have a low effective thermal conductivity. They do not allow the roof surface to gain heat throughout the day and can maintain a comfortable internal temperature (Madhumathi, Radhakrishnan, & Priya, 2014). The Madras Roof has the highest thermal capacity over the other roof types (Table 4). This prevents the roof from transferring heat from the outside to the internal environment. The heat entering the roof materials during the daytime can be stored there for several hours until it flows back out to the cool night air under appropriate weather conditions and adequate thermal capacity.

Table 4. Comparison of the thermal capacity of roof types (from Green Building Studio, 2016).

Roof Materials	Specific Heat (J/kg.k)	Density (kg/m^3)	Thermal capacity (J/K)
Madras Terrace	840	2000	1680000
Filler Tile	800	1900	1520000
RCC slab	657	2300	1511000

Thermal capacity - property of material to absorb heat is shown for the three roof types observed in the nine samples under study. Higher values indicate greater ability to store the heat without transferring to the indoors.

The Madras Terrace roof also has the lowest U-Value of 1.59 W/m2k compared to the Filler slab 3.36 W/m2k and RCC slab of 3.09 W/m2k (Table 5) (Madhumathi, Radhakrishnan, & Priya, 2014). When compared to Indian Standard Code 3792-1978, which requires the maximum value of U-value not to exceed 2.33 W/m2k, only the Madras Terrace Roof falls within the permissible value (Madhumathi, Radhakrishnan, & Priya, 2014).

Table 5. U values of roof materials. U-values measure how effective a material is an insulator. The lower the U-value is, the better the material is a heat insulator (Madhumathi, Radhakrishnan, & Priya, 2014).

S. No.	Type of Roof	U Value (W/m^2 k)
1	RC Slab with lime concrete Terracing	3.09
2	Madras Terrace	1.59
3	Filler Tile	3.36
4	Thatch roof	0.35
5	Roof shading with inverted mud pots	2.04
6	Roof shading with clay tile and air space in between	1.37

Although the filler slab is a good roofing option, the concrete and steel used in the roof are not sustainable. However, the air pocket formed by the filler material can make an excellent thermal insulation layer. The clay sandwiched tiles (two layers one over the other) facilitates entrapping an air cavity between the two tiles. The filler material is left open for aesthetic purposes (Society for Environment Protection, n.d.).

Finally, RCC houses can cause an increase in indoor temperatures due to the heat transmission into space through the cement and concrete materials. Additionally, RC slabs absorb a great deal of heat which is emitted into the interior space causing discomfort to the inhabitants.

Typical Architectural Elements in Indian Architecture

The sections below detail the traditional architectural elements typically found in Indian buildings. Aspects such as site planning, massing, and orientation of buildings greatly influence the energy demand, microclimate, wind flow, natural ventilation, thermal comfort and shade of a building (Building and Construction Authority, 2010).

Orientation influences the manner in which a building receives natural daylight and ventilation. An east–west (EW) orientation helps expose a building only to diffused and indirect sunlight for the majority of the day and to direct sunlight only in the early mornings when the intensity of the UV rays is low. This helps reduce the solar heat gain of the house due to sunlight. Therefore, less energy is required to cool the house.

Site planning creates the ambiance required for the energy performance of a house. Landscaping and hardscaping around the buildings greatly influence the energy demand, microclimate, wind flow, natural ventilation, thermal comfort and shade of a building (Building and Construction Authority, 2010). The amount of open and green space and shade provided as well as material selection and treatment of roof areas are strategies that can help to mitigate these effects. The greater the amount of hardscaping present in the site, the greater the heat island effects will be (Building and Construction Authority, 2010). An important caveat to this statement is that the materials and color of the hardscaping elements increase the heat island effects proportionally. Landscaping also plays an important part in directing winds. The direction and flow of winds around the house affects the temperature of the house considerably (Building and Construction Authority, 2010).

Designing the footprint of a house is a delicate balance between an optimal and extreme building form. For example, too many jogs in the massing can lead to significant increases of hardscape (Figure 11), which increases the number of façade materials used to enclose the building, increase in building costs, surface area and a higher heat island effect (Building and Construction Authority, 2010).

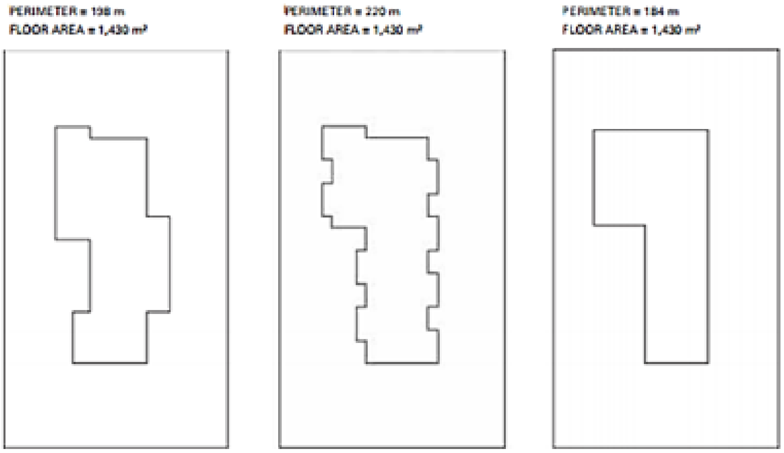


Figure 11. Comparison of building footprints with the same floor area. Building perimeter in the center is substantially more and leading to increased surface area and higher solar gain (Building and Construction Authority, 2010).

Factors like daylight, indoor environment, and energy consumption are affected by space planning (Building and Construction Authority, 2010). Additional elements such as courtyards (Figure 12), clear story windows, skylights, and jaalis contribute to the amount of natural daylight entering a building.

Traditional buildings follow a typical spatial arrangement that once formed the design basis for Indian architecture for centuries. This functional approach took into account social, economic, and cultural needs which were interwoven with climatic conditions (Jayasudha, Dhanasekaran, & Devadas, 2014).

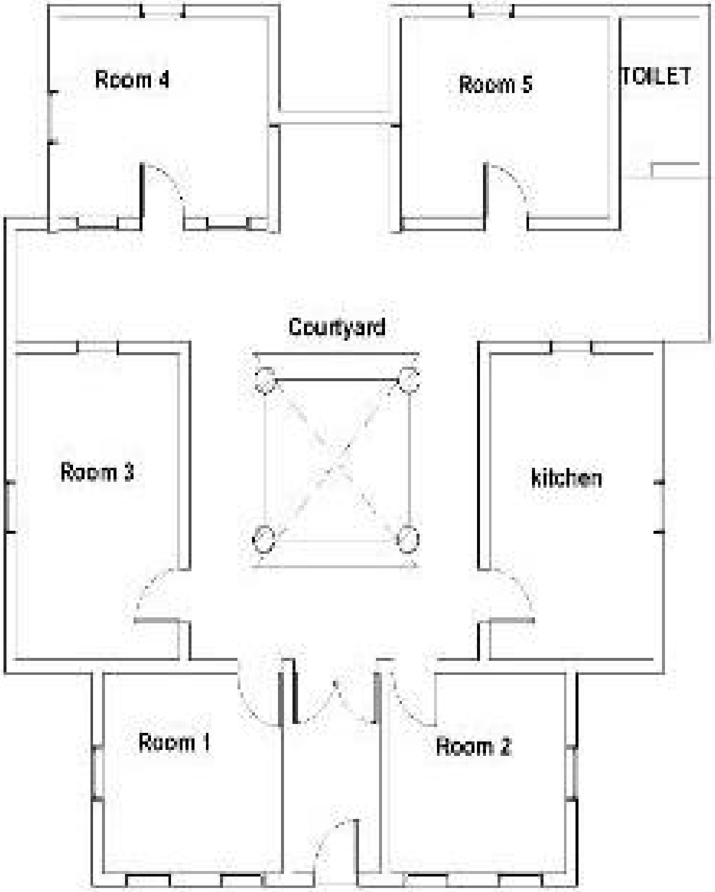


Figure 12. Central courtyard. House 2- floor plan showing the typical presence of a central courtyard usually seen extensively in traditional houses.

For example, the entrance to a traditional house sits on a high plinth leading to a verandah. This further leads to a typical living space attached to a central courtyard with rooms located on either side of the courtyard. Usually, a kitchen garden is planted behind the house with the toilets located outdoors. The plans were very symmetrical in nature with mostly an equal number of rooms on either side (Figure 12). In contrast, modern houses have no definitive space planning features and are distinctly different. Some typical features seen in the traditional houses are detailed below.

Verandah or Thinnai are often integrated into the indoor and outdoor living lifestyle by forcing inhabitants to transit between different areas in the house to move from less comfortable to more comfortable spaces. This area acted as a buffer for inner spaces to protect people from heat while functioning to provide shade (Figure 15) and as a place for organizing daily activities during the rainy season (Figure 13). Verandah often had curtains, screens or grass mats sprinkled with water on the openings to further improve the internal environment. The deep covered spaces allowed filtered light to enter the house (Prashad & Chetia, 2010).

Figure 13. Photo of a typical verandah leading to the inside of the house.

Courtyards are one of the most typical spaces in traditional houses of India. They are usually open to the sky or semi-closed spaces that form the focal point of the interiors of the house (Figure 14). The multifunctional space helps to integrate nature into the house and provide ample light from the sun (Prashad & Chetia, 2010). It is always shaded throughout the majority of the day regardless of the building's orientation.

Figure 14. Central courtyard with grills and lighting from above-allowing plenty of natural light.

Furthermore, courtyards often had vegetation and water bodies which enhanced the humidity, cooled the air by evaporation, kept dust down and provided shade for comfortable living (Prashad & Chetia, 2010). Many times they acted as a rainwater harvesting area (Figure 14) (Prashad & Chetia, 2010). This space was also used for sleeping during summers by the household.


Figure 15. Courtyard used for rainwater harvesting (Lakshamanan, n.d).

The thick walls of the houses themselves did not allow the heat from the courtyards to penetrate into the houses during the daytime. (Prashad & Chetia, 2010). This space is also referred to as a microclimate modifier (Prashad & Chetia, 2010) that enabled air movement of the space by helping the cool air to enter the space at night without radiation of heat. The heated floor of the courtyard and the wall surfaces of the buildings raises the temperature of the air present in the courtyard, which rises due to its lower density, and finally, fresh cool air enters the space.

Traditional houses have a varying ceiling height for different rooms with the living rooms usually having a double height of 5-6 meters (Prashad & Chetia, 2010). The high ceilings helped to cool the space by letting the warm air rise. This enabled the room to be cooler as internal air takes a longer time to heat up due to a higher volume of the enclosed space (Prashad & Chetia, 2010).

Openings and fenestrations affect the building performance as the openings and glazing are major heat and light exchange mediums within a building. They affect the three important aspects of a building such as heat gain, natural ventilation and natural lighting (Asia Green Buildings, 2013). Traditional houses have windows present even in the interior partition walls (Figure 16), and thus there is a continuous flow of filtered air flowing from the outside to the inside and vice versa (Ali, 2013).

Figure 16. Internal windows present in traditional houses that help with movement of filtered air.

Passive cooling

Passive cooling is a system used in the past when there were no mechanized cooling systems available. This system allows zero energy consumption while trying to improve the indoor thermal comfort. The choice of building materials used showcased the method to adjust the temperature inside a building (Asia Green Buildings, 2013). Maximizing the amount of space to be naturally ventilated is another strategy towards reducing energy demand since this requires little energy use as compared to mechanized cooling. (Building and Construction Authority, 2010).

Factors that affect the airflow within a building are materials, openings, landscaping and orientation with respect to wind direction, etc. When air with a greater velocity enters into a wider space, sudden expansion results in lowering the temperature of inside spaces. The hot air rises in a domed space and vents near the ceiling allow hot air to escape (Ali, 2013). Direct solar radiation heats up indoor air, finishing materials, and thermal mass. Interior spaces can easily overheat if exposed to excessive solar radiation (Riemer, n.d.).

Jaalis are latticed screens with ornamental patterns constructed through the use of calligraphy and geometry (Figure 17); they provided privacy for building occupants while also acting as a filter for light, heat, and wind in a building. Jaalis mostly have a low sill or are sometimes without sill so that the air could move near the floor (Ali, 2013).

Figure 17. Latticed jaali work.

Another passive cooling feature is the stepwell (Figure 18). This feature was very common in India in the past, but not widely used today. The technique involved building around a well that cools surrounding spaces through evaporative cooling. It also acts as a heat sink since the base of the building is lowered to a few meters below the ground to entrap heat within its descending set of steps. As the bodies of water encased evaporate in heat, it immediately lowers the temperature of the space around it. This process creates a cool microclimate inside the building (Asia Green Buildings, 2013).

Figure 18. Stepwell used in ancient Indian architecture.

Ventilators are manually operated openings just below the ceilings of a house. They provide a stack effect where the hot air rises and cool air takes its place. They help increase the velocity of air entering the building which further lowers the pressure and causes the hot air to escape out (Figure 19) (Prashad & Chetia, 2010).

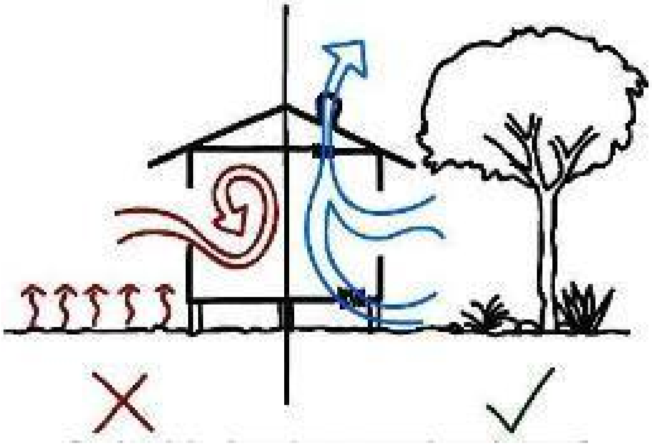


Figure 19. Section showing how clear story windows benefit air movement (Anderson, 2012). On the right, hot air escapes through a roof vent and draws cool air in convection. On the left, a lack of ventilation contributes to the stagnation of hot air.

Additionally, there used to be ample landscaping and water bodies both outside and inside houses. These helped to enhance the process of evaporation by adding moisture to the air and increasing humidity. A lot of importance was given to having good natural ventilation in the building. It is the result of differential wind forces on various building surfaces and temperature differences between outside and inside air. Various elements such as solar shade screens, deeply located windows, roof overhangs, awnings, trees and other landscaping features can also shade the indoors (Ali, 2013).

Lack of Knowledge and Experience with Sustainable Building Standards

Often, many designers/builders lack a sense of understanding of the relevance and methods of following sustainable design with respect to our local environment. Currently, green building guidelines like LEED (equivalent) are sometimes followed blindly to make Indian buildings appear sustainable, but this does not guarantee a sustainable building. For example, an article published in ‘The Hindu’- a leading newspaper in India, states that green-rated buildings are falling below the minimum benchmarks of their official star rating by the Bureau of Energy Efficiency (BEE). The data released by the Indian Green Building Council (IGBC) on the energy consumption of large commercial LEED certified buildings (Silver, Gold, and Platinum), showed they are grossly underperforming. Several of the energy rated buildings cannot qualify even for the one-star label for energy efficiency. The CSE examined green ratings and concluded that buildings rated by the IGBC and GRIHA as saving 30-50 % energy and 20-30 % water were not in compliance with these ratings (Menon, 2014).

These frameworks require a fair amount of knowledge and technical expertise to comprehend them. Unfortunately, most builders in India are not trained or do not have the technical skills to implement these standards and therefore they are largely unused. Therefore, it is very important to lay out practices and techniques that are simple, inexpensive and easy to follow. Although people are trying to find new methods to build sustainable buildings using various types of technologies, ancient practices used energy conserving techniques, which ideally can form the design basis for our future sustainable architecture.

Moreover, most Indian builders are ignoring the advantages of natural resources and local climatic conditions prevalent in a city. By mindlessly aping construction elements from other countries – such as using large glass windows, air conditioning, and unsustainable building materials and techniques – a new set of problems are created. All these green technologies end up increasing costs to the extent that buildings become unaffordable to most. This seems to indicate that India needs building standards that are regionally appropriate and cost-effective. Traditional architecture is based on the principle of “localizing” buildings which optimize natural elements and resource usage (Narain, 2014).

Evolution of Sustainable Building Policies

India has adopted multiple frameworks and policies to promote sustainable practices in the building sector. Apart from the Vaastu principle that dates back to 600 BC, some of the other frameworks that have evolved over the years are:

- The National Housing and Habitat Policy (1998) acknowledges importance of construction techniques and materials in energy conservation (Evans et al., 2009)
- The Energy Conservation Act (ECA 2001) promotes energy efficiency and conservation domestically (Evans et al., 2009)
- LEED-India (2001) is a whole-building approach to sustainability. The framework addresses sustainable efficiency in site development, water savings, energy efficiency, materials selection and indoor environmental quality (Evans et al., 2009)
- The National Building Code of India (NBC) (2005) provides guidelines for a range of structural, safety and other design issues. However, the NBC addressed energy efficiency only marginally (Evans et al., 2009)
- INTBAU – International Network for Traditional Building Architecture & Urbanism (2005) is an organization to support traditional building, maintenance of local character and create a better living environment (Prashad & Chetia, 2010)
- The Integrated Energy Policy (2006) identifies major areas with large potential for energy savings. Five of the 13 areas are related to the building sector, including building design, construction, HVAC, lighting and household appliances (Evans et al., 2009)
- ECBC (2007) is the first stand-alone national building energy code in India, but it is voluntary; ECBC establishes minimum energy efficiency

requirements for building envelope, lighting, HVAC, electrical system, water heating and pumping systems (Evans et al., 2009)

- The Green Rating for Integrated Habitat Assessment (GRIHA) promotes building design, construction, and operation with green building principles (Evans et al., 2009)

These major energy policies, standards, and frameworks have started evolving only in the last two decades.

Research Question, Hypotheses, and Specific Aims

The primary subject of this research hinges on the question: Will applying concepts from traditional Indian architecture help address the increasing energy consumption in today's modern Indian architecture? The hypothesis that examines this question is: Architectural elements and construction materials of traditional Indian houses allow for lower energy consumption profiles compared to houses that use modern non-traditional methods and materials.

The first step to test this hypothesis was to understand the usage of energy by typical urban households. The study compared traditional buildings (baselines) with modern buildings of the same typology, evaluating space planning, materials, indoor environmental performance, and energy consumption. The research was carried out through the following steps:

- Conduct building walkthroughs and assessments for the traditional and modern buildings

- Measure the indoor and the outdoor environment for the various buildings under study
- Collect building material information for the products used in the properties
- Collect utility bills for the respective buildings
- Conduct analysis of the energy consumption based on energy simulation and the utility bills collected
- Develop an energy model by interchanging the traditional and modern materials for the houses to understand the energy use of the building samples and test traditional Indian energy reduction strategies
- Conduct a cost benefit analysis between the energy consumption of a traditional building versus a modern building.

Chapter II

Methods

The first step in the study was to create a list of potential houses to explore in Bangalore. A list of six traditional buildings was set up based on the age of the buildings. Three houses were shortlisted as only these houses provided access and the required data to conduct the study. Next, a list of materials and architectural features for the houses was cataloged. Then, six modern houses were selected based on the age of construction (within 20 years of this study) and, the availability of data and access to the houses.

Data Collection

The initial step was to define various factors to be evaluated and list the manner in which they influence the energy performance of a building (Table 6). The building orientation of the houses was studied and classified based on the major axis of the building which affects the daylight and natural ventilation. Additionally, site plans and building forms were used to classify buildings.

Table 6. Factors that affect energy consumption for a house.

Factor	**Reason for collection**
Building Orientation	Natural Daylight and Ventilation received
Site Plan	Landscaping around the house, Heat Island Effect, and Thermal Comfort of the occupants
Building Form	Daylight received, Heat Island Effect, Thermal Comfort, Natural Ventilation
Construction Materials	Heat Island Effect, Thermal Comfort
Architectural Features (Traditional and Modern)	Natural Daylight and Ventilation received, Heat Island Effect, Thermal Comfort

Next, the construction materials used in the buildings identified for the study were noted and classified into traditional and modern building materials (Table 7). The next step identified the data sources for the factors listed (Table 6) along with collection and measurement methods (Table 8).

Table 7. Comparison of traditional versus modern building materials.

	List of traditional building materials	**List of modern building materials**
Wall	Brick, Rammed Earth, Rubble (Mid), lime, or clay plaster	RCC Block, Cement Plaster, Paint
Roof	Madras Terrace Roof, Filler Slab (Mid)	Reinforced Cement Concrete slab
Floor	Red oxide or Mosaic	Vitrified Tiles/Granite/Marble
Windows	Wood frame with Jaali Mesh or Iron Bar Grill with double glaze	Timber Frame with Single/Double Glaze
Wood	Teak	Teak, Sal, Oak

All traditional materials are made from renewable resources.

The house plans were measured, drafted and converted into 3D models using Revit, which were then fed into an energy modeling software – Green Building Studio – to create energy consumption simulations for every house.

During each house visit, a Netatmo Weather Station (Figure 20) was used to measure the indoor and environment parameters (Table 3). Multiple measurements across the house were taken over a period of 2 hours and averaged to limit any inconsistencies and provide a larger sample set of data. Since the houses were all visited on different days, there are variances in the outdoor temperature and humidity. However, the results collected are not dependent on one another.

Table 8. Data parameters/metrics based on factors that influence energy consumption.

Factor influencing Energy Performance	Data parameter collected	Collection/Measurement method
Building Orientation	Major Axis of a building	Compass & Building Plan
Site Plan	Landscaping type and location	Observation
	Hardscaping type, color, reflectivity, and location	Observation
Building Form	Building footprint	Building plan
Construction Material	Building construction materials (Wall, Window, Floor, Door, Roof)	Building plan, Interview with owner & Physical observation
Indoor Environment	Outdoor Temperature (°C)	Netatmo Weather Station
	Outdoor Temperature – Feels like (°C)	Netatmo Weather Station
	Indoor Temperature (°C)	Netatmo Weather Station
	CO_2 levels (ppm)	Netatmo Weather Station
	Outdoor Humidity	Netatmo Weather Station
	Indoor Humidity	Netatmo Weather Station
	Exterior Wall Area (m^2)	Building plan
	Skylight/Courtyard (Y/N)	Building plan & Physical Observation
Energy Consumption	Number of electrical appliances by type (HVAC, Lighting and Miscellaneous)	Interview with owner & Physical Observation
	Floor Area (m^2)	Building plan
	Number of Occupants	Interview with owner
	Number of Storeys	Building plan & Physical observation
	Wall Thickness (mm)	Building Plan & Site measurement
	Monthly Energy Consumption (kWh) (Dec 2015 – May 2016)	Utility bills consumption

The above parameters were measured physically during the summer months of April and May. To keep the readings consistent, all the houses were visited between12:00 pm and 3:00 pm on a typical summer day (no rain).

Additionally, the types and the number of electric and electronic appliances used in each house were listed. These were used to calculate the electricity consumption based on standard equipment usage data (Table 9).

Table 9. Typical usage of electrical and electronic appliances in Bangalore (Narasimha, Sumithra, & Reddy, n.d.).

Appliance	**Wattage**	**Usage hrs/day**
Table lamp	40	2.54
Table fan	60	4.76
Mixer	450	0.47
Refrigerator	100	22.33
Air Cooler	170	4.8
Air cond.	1500	0.81
Toaster	800	1.1
Hot Plate	1000	1.37
Kettle	1500	1.1
Electric iron	750	0.48
Geyser	3000	1.18
Immersion rod	1000	1.75
Vacuum cleaner	750	0.7
Television	100	3.93
V.C.R	40	2.14
Radio	15	2.51
Mono recorder	20	1.82
Stereo rec.	50	1.74
Elec. Heater	1000	1.72
Battery Charger	15	3.25
Washing Machine	325	0.71
Step-up Transformer	400	0.89
Water pump	750	0.68
FL20	20	1.3
FL40	40	2.63
IL15	15	2.32
IL40	40	1.56
IL60	60	2.36
IL100	100	2.72
IL25	25	1.27
Fans	100	4.45

Figure 20. Netatmo devices used to measure the indoor environment. A screenshot of the results captured from the device.

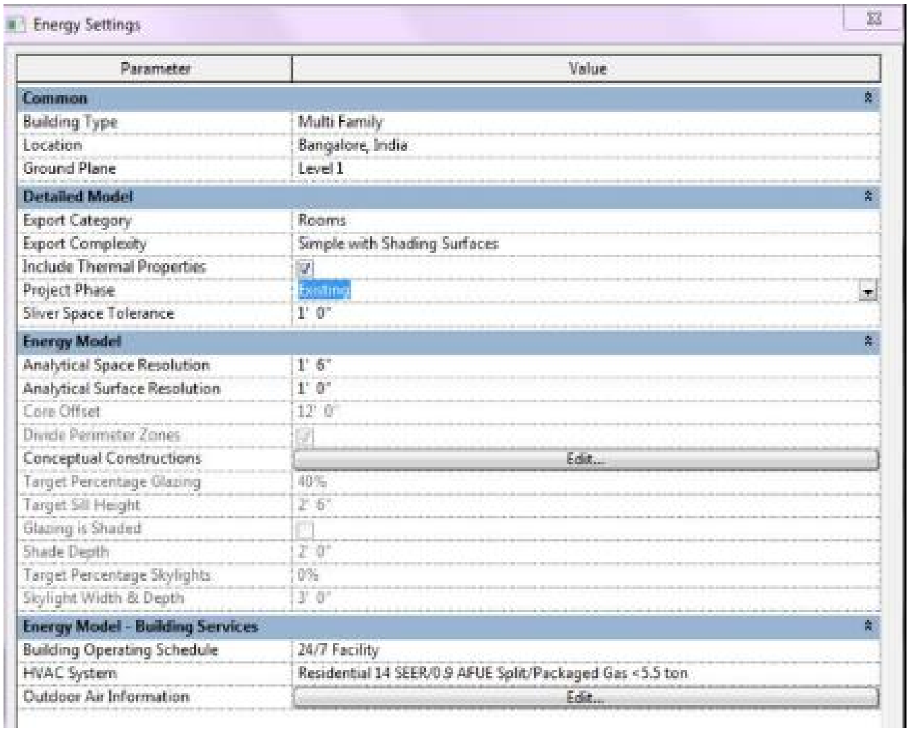
Utility bills for six months were collected to assess the power and cost per unit power consumed by a house. The bills spanned the winter (Dec 2015-Feb 2016) and summer (Mar 2016-May 2016) (Table 11) months. In India, energy consumption for a house is equal to the electricity consumption alone since gas – used for cooking – is the only other source of energy consumed.

Energy Consumption Modeling

Three types of power consumption models were used to test the hypothesis. The first model used the energy analysis software – Green Building Studio. The second model calculated power consumption based on the use of electrical and electronic appliances in each house as surveyed. The third model was a calculation based on the power consumed from utility bills for each house.

Energy Modeling using Green Building Studio

The 3D models fed into Green Building Studio ran an energy analysis simulation and generated reports for each house type for various parameters. Various parameters were configured to run a simulation (Figure 21). To contextualize the energy analysis with the local climate, the relevant location coordinates and climate information were input. The simulation modeled the annual energy consumption on a 24-hour schedule for 365 days in the year. Appendices 1 to 9 list the consolidated measurement and simulated results for each house.



Parameter	Value
Common	
Building Type	Multi Family
Location	Bangalore, India
Ground Plane	Level 1
Detailed Model	
Export Category	Rooms
Export Complexity	Simple with Shading Surfaces
Include Thermal Properties	☑
Project Phase	Existing
Sliver Space Tolerance	1' 0"
Energy Model	
Analytical Space Resolution	1' 6"
Analytical Surface Resolution	1' 0"
Core Offset	12' 0"
Divide Perimeter Zones	☑
Conceptual Constructions	Edit...
Target Percentage Glazing	40%
Target Sill Height	2' 6"
Glazing is Shaded	☐
Shade Depth	2' 0"
Target Percentage Skylights	0%
Skylight Width & Depth	3' 0"
Energy Model - Building Services	
Building Operating Schedule	24/7 Facility
HVAC System	Residential 14 SEER/0.9 AFUE Split/Packaged Gas <5.5 ton
Outdoor Air Information	Edit...

Figure 21. Key configuration settings required to run an energy analysis simulation in Green Building Studio.

The simulation produces metrics such as annual energy use intensity; monthly and annual energy consumption; annual costs; and annual carbon emissions. All of the metrics have been calculated per unit area (m^2) to facilitate comparison across the varied house sizes. Refer to Appendix 10 for all the analysis assumptions made in the software.

Calculation of Annual Energy Consumption by Appliance Use

This method involved calculating the power consumed by each house using a standardized power consumption profile for the electrical and electronic appliances surveyed (Table 10).

Table 10. Electricity consumption profile used to calculate annual energy consumption for the houses studied.

Appliance	**Quantity**	**Power Consumed (Watts)**	**Average Daily Usage (Hours)**
Fan	0	100	4.45
Air Conditioner (1.5 ton)	0	1500	0.81
Refrigerator	0	100	22.33
Immersion Rod	0	1000	1.75
Geyser	0	3000	1.18
Bulb (FL40)	0	40	2.63
Tube light (IL40)	0	40	1.56
Computer	0	100	3.00
Mixer	0	450	0.47
Water Pump	0	750	0.68
Television	0	100	3.93
Washing Machine	0	325	0.71
Radio	0	15	2.51
Electric Iron	0	750	0.48
VCR	0	40	2.14
Microwave	0	1000	1.00
Vacuum Cleaner	0	750	0.70

The average daily power consumed by each appliance was calculated using the following formula:

Average Daily Power Consumed (kW) =

Appliance Power Consumption (W) * Average Daily Usage (hrs) *

Quantity of Appliances / 1000

This number was multiplied by 365 and divided by the floor area of the house to derive the annual power consumed per unit area (m^2). The annual power consumed per unit area (kW/m^2) was then compared to see which house performed best.

Annual Energy Consumption from Utility Bills

This model used the six months' utility bills collected from each house (Table 11). The annual and the monthly energy use intensity (energy consumed per unit area) calculations were used to analyze the usage trends. The average energy use intensity for the summer versus winter months was calculated to see how the power consumption varied per house over the six month period.

One weakness of this method is that only six months' utility bills could be used due to the unavailability of bills for an extended period for all of the houses examined.

Table 11. Energy consumption (kWh) noted from utility bills.

	Winter			Summer			
	Dec	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Total Power Consumed for six months (kWh)**
House 1	416	420	423	420	358	350	2387
House 2	117	121	153	155	150	124	820
House 3	140	139	106	219	243	267	974
House 4	643	579	707	540	505	470	3444
House 5	489	431	476	632	645	645	3318
House 6	465	428	391	844	626	614	3368
House 7	582	536	595	814	821	762	4110
House 8	350	310	390	560	543	318	2471
House 9	248	280	304	410	395	225	1862

Experimental Energy Consumption

By using the energy analysis software, an experiment was conducted on the study houses where some key building materials, as previously identified (Table 12), were interchanged (old materials used in place of new and vice versa) and the simulations re-run.

Table 12. Materials interchanged between traditional and modern houses.

Area	**Typical Modern Materials Used for Traditional Construction**	**Typical Traditional Materials Used for Modern Construction**
WINDOWS	Single Glazed Sal Wood Frame	Jaali Mesh Windows
WALL	Concrete Blocks Cement/screed Plaster	Brick and Lime Mortar
ROOF	Concrete Cast In Place + Cement Plaster	Roof - Madras roof with steel rafters
FLOOR	Marble & Concrete Cast in Place with 40mm Screed	Mosaic flooring & Brick flooring
DOOR	Teak Wood	Teak Wood Frame

The simulation provided an estimate for the annual energy consumption of the interchanged materials. Given that all conditions other than the substituted materials remained constant between the two simulations, the difference in energy consumption value was used to derive the percentage difference in energy consumption between the houses in the two states. This percentage is then applied to the power consumption for appliances as previously calculated (estimated power consumption for each house listed in the Appendix section - Estimated plug load energy consumption).

The point of this experiment was to provide a definitive test of the hypothesis of this study. The outcome of this experiment compared the energy use intensity for each house under its current state and modified state. This experiment tests whether traditional materials and methods are better than the modern materials and approaches used in India today.

If the energy use intensity of the traditional houses increases significantly while the energy use intensity of the modern houses decreases, it will support the hypothesis. A reversal in the values would disprove the hypothesis. If there are no major changes in the values between the two runs, or if there are mixed results wherein some traditional houses show increases while others show decreases (likewise for the modern houses) it would mean that materials and methods may not have any bearing on the energy consumption performance of a building.

Additionally, the results of the experiment allow comparison of the carbon emissions for all the houses. If the traditional materials are better, the carbon emissions will decrease for the modern houses when substituted. Conversely, if the modern materials are better, the metric should decrease for the traditional houses post the interchange of traditional materials.

Cost Benefit Analysis

For this study to be relevant to the construction industry stakeholders, it is important to understand the financial implications of this experiment. Therefore, a basic cost-benefit analysis would enable the quantification of savings based on results of the hypothesis.

The cost-benefit analysis was calculated by using the difference in the energy expenditures between the current and the modified construction of the buildings. The calculations for the difference in energy expenditure for each house derived by multiplying the energy use intensity by the unit cost of power (INR 6.20) consumed and subtracting the annual costs of the house in its modified versus its current state.

Since the area varies for each house, the energy consumption per unit area of each house (m^2) was calculated and then converted to annual costs.

Chapter III

Results

The following section contains the quantitative and qualitative data collected from nine houses across the city of Bangalore, India (Table 13).

Table 13. Snapshot of houses on the collected parameters.

	Building Type and Age (years)	**Area (m^2)**	**Age (Years)**	**Number of stories**	**Land scape**	**Courtyard /Skylight**	**Orientation - Main Axis**
House 1	Old - 108	313	108	Ground +1	Yes	Yes	East -West
House 2	Old-130	150	130	Ground +1	Yes	Yes	East -West
House 3	Old – 50	212	50	Ground +2	Yes	Yes	Equal
House 4	Modern – 9	123	9	Ground +1	No	No	North - South
House 5	Modern - 15	186	15	Ground +2	No	No	North - South
House 6	Modern - 13	238	13	Ground +2	Yes	No	North- South
House 7	Modern - 7	77	13	Ground +1	No	No	North - South
House 8	Modern - 5	565	5	Ground +2	Yes	Yes	Equal
House 9	Modern - 5	190	5	Ground +1	No	No	East - West

After studying all the materials used in the nine houses, most of the materials utilized in the traditional houses are renewable materials whereas the newer houses tend to use processed or non-renewable materials (Table 14).

Table 14. Building materials used in each house.

	Roof	**Wall**	**Plaster**	**Wall Finish**	**Flooring**	**Wood**
House 1	Madras roof	Clay Brick	Lime	Lime wash	Mosaic	Teak
House 2	Madras roof	Rammed earth	Lime	Lime wash	Red oxide	Teak
House 3	Filler Slab	Rubble	No Plaster	Exposed Rubble	Red oxide	Teak
House 4	RCC	Concrete	Cement	Paint	Granite/Vitrified	Sal
House 5	RCC	Concrete	Cement	Paint	Granite/Vitrified	Teak
House 6	RCC	Concrete	Cement	Paint	Granite	Teak
House 7	RCC	Concrete	Cement	Paint	Vitrified	Oak
House 8	RCC	Concrete	Cement	Paint	Marble/Vitrified	Teak
House 9	RCC	Concrete	Cement	Paint	Marble	Sal

All of the houses have flat roofs except houses 2 and 3 have a combination of flat and sloped roofs. The traditional houses 1 and 2 have the Madras Terrace roof finished with Lime Mortar Plaster, while house 3 has sandwiched Mangalore tiles with the Filler Slab. These traditional roofs are about 280 mm thick and much heavier compared to the RCC roof slabs which are about 150 mm in depth.

Houses 1 and 2 have a wall thickness of 300 to 600 mm compared to the regular 230 mm walls. Furthermore, lime plaster and lime washing were used in the traditional houses 1 and 2 (Figure 23). House 3 was made of rubble and didn’t require any plaster or paint (Figure 22), whereas the modern houses 4-9 had cement plaster finished with paint (Figure 23).

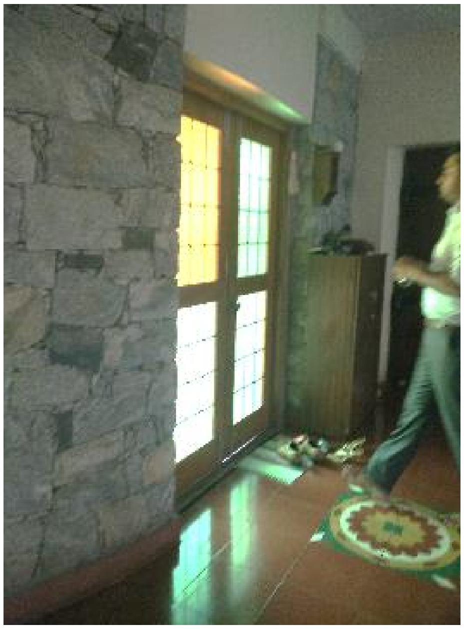


Figure 22. House 3 walls constructed with rubble masonry and no plaster.

Figure 23. Types of wall finish. House 1 (left) with lime wash and natural color pigments versus house 5 (right) with emulsion paint.

All of the traditional houses (1 to 3) have the above features (Table 13). Of the modern buildings, only houses 6 and 8 had some greenery around the building. House 8 was the only house among the modern houses to have a skylight. There was no courtyard present in any of the modern houses.

Orientation, Site Planning and Building Form

The performance of climate sensitive buildings is related to all these building site related factors: orientation, site planning, and building form.

Houses 1, 2, and 9 have an East –West (EW) orientation. Houses 3 and 8 do not have a longer ridge line for orientation since their layouts are square. Houses 4, 5, 6 and 7 have a North- South (NS) ridge line orientation (Table 13).

Figure 24. Types of landscaping. House 1 (top-left) with natural landscaping and House 8 (top-right) with a well-manicured lawn and House 6 (bottom) with a primarily hardscaped landscape.

Houses 1, 2, 3, 6 and 8 have well-designed sites with plenty of greenery and open spaces around the house (Figure 24). The traditional houses (1, 2, and 3) also have courtyards with additional landscaping. The modern houses (house 4, 5, 7 and 9) do not have any surrounding greenery (Table 13). These houses were constructed end to end of the site boundary with a minimum setback of only 3 to 4 feet (Figure 25). Houses 1, 3, 4, 5, 6, and 9 conform to the ideal façade, while house 8 has the least optimal façade from a building form perspective.

Figure 25. House 9 façade as seen with no landscaping and glazed façade in the west.

Indoor Environment

All of the typical features identified as influencing factors in the indoor building environment were noted if present for each house (Table 15).

Table 15. Indoor space planning features for the houses studied.

Typical Features	**House 1**	**House 2**	**House 3**	**House 4**	**House 5**	**House 6**	**House 7**	**House 8**	**House 9**
Courtyard	✓	✓	✓						
Skylight	✓	✓	✓					✓	
Landscape	✓	✓	✓			✓		✓	
Veranda	✓	✓							
Jaali	✓								
Clerestory	✓	✓	✓						
Glazed façade									✓
High ceiling	✓	✓	✓					✓	

The typical features that define traditional houses are listed except a glazed façade used extensively in many modern buildings.

Daylight

The traditional houses maximize the use of natural light through various methods (Table 15). The modern houses do not have large open spaces around the buildings but instead, are surrounded by other buildings on three sides and a road measuring 3m in front (Figure 25). Houses 6 and 8 had open spaces only along one side (west and south, respectively).

House 1 has a ceiling height of 5m in the living rooms with the remaining rooms having a height of 3.35m. House 2 and 3 have a ceiling height of 1m with house 2 having a central double-height courtyard and a double height kitchen. Moreover, houses 1 and 2 have windows on the interior walls, which further allows daylight to penetrate deeper into the house. The modern houses 4, 5, 6, 7, 8 and 9 had a typical ceiling height of 2.5 - 3 m throughout. House 8 had a well-situated skylight along with a double height ceiling in the central part of the house.

Thermal Comfort

The traditional houses had a cooler indoor temperature as compared to the modern houses, which had the same or slightly higher indoor temperature versus the outdoor temperature. House 1 (traditional house) showed the largest difference in the temperature, measuring 2°C cooler indoors, while house 9 showed the least difference in the temperature measuring 1.7°C warmer inside (Table 16).

All of the modern houses require some form of mechanical cooling to maintain thermal comfort. Fans used at most times of the day and air conditioners (AC) installed in the majority of the bedrooms validates the above statement. The difference in indoor temperature can be observed by comparing the thermal comfort between houses 2 and 9 since they are located adjacent to each other. The delta temperature between the inside and outside environments shows a stark difference. House 2 is approximately 1°C cooler than outside whereas house 9 is warmer than outside by almost 2°C even though the outside temperature had reduced from 31.1 to 30.5°C (30 minutes after recording the temperature for house 2) (Table 16).

Table 16. Indoor environment measurements.

	CO_2 levels (ppm)	**Outdoor Temperature (Feels Like)**	**Indoor Temperature**	**Outdoor Temperature**	**Delta temperature**	**Outdoor Humidity**	**Indoor Humidity**
House 1	710–740	41	30	32	2	58	55
House 2	724-743	41	30.3	31.1	0.8	60	53
House 3	580-600	40	29.2	30.8	1.6	59	60
House 4	940-1000	39	31.1	29.9	-1.2	61	72
House 5	830-840	38	29.3	29.2	-0.1	63	68
House 6	1015-1040	39	30.6	29.9	-0.7	61	48
House 7	1020-1060	40	30.9	30.5	-0.4	61	65
House 8	635-670	39	29.7	29.6	-0.1	65	55
House 9	800-824	39	32.2	30.5	-1.7	59	57

Readings were taken between 12 – 3 pm during summer using the Netatmo weather station.

The thermal comfort inside a house also depends on the indoor humidity level. The higher the humidity at a given temperature, the more heat the air can hold. ASHRAE

Standard 62.1-2013 recommends that relative humidity in occupied spaces be controlled to less than 65% to reduce the likelihood of conditions leading to microbial growth (ASHRAE, 2016). Although most houses showed humidity levels within the allowable amount of 65%, houses 4, 5 and 7 have a relatively higher humidity (Table 16) (The Engineering Toolbox, n.d.).

All the traditional houses (1-3) have low CO_2 levels. However, all of the modern houses (4-9), with the notable exception of house 8 (Table 16), have very high CO_2 levels. Houses 6 and 7 have an unacceptable amount of CO_2 since their readings are above 1000ppm.

Energy Consumption

The energy consumption values have been taken using the second model where consumption is calculated based on the number and types of electrical and electronic appliances used in each house (Table 17). A detail of this model for each house is present in the appendix section.

House 7 consumed the most amount of electricity per unit area while house 1 consumed the least. The average energy consumption for the traditional houses was 18.5 KWh/m^2, and the modern houses were 72 KWh/m^2.

Table 17. Annual energy consumption per unit area and cost per unit area (m^2).

	Building materials used (Old/New)	**Energy consumption (kWh/m^2)**	**Cost of consumption per unit energy per area (INR)**
House 1	Old	12.64	78.34
House 2	Old	18.65	115.66
House 3	Old	24.46	151.69
House 4	New	77.70	481.75
House 5	New	67.72	419.89
House 6	New	52.15	323.31
House 7	New	142.80	885.40
House 8	New	24.99	154.96
House 9	New	67.14	416.28

The energy consumption for the houses per unit area from actual utility bills showed that houses 4, 5, 6 and 7 have a very high energy usage compared to the rest of the houses. The traditional houses continued to show relatively lower energy usage – especially during the summer months (Mar – May) (Table 18).

Table 18. Annual electricity consumption per unit area (KWh/m2).

	Winter			**Summer**		
	Dec	**Jan**	**Feb**	**Mar**	**Apr**	**May**
House 1	1.3	1.3	1.4	1.3	1.1	1.1
House 2	0.8	0.8	1.0	1.1	1.0	0.8
House 3	0.7	0.7	0.5	1.0	1.1	1.3
House 4	5.2	4.7	5.8	4.4	4.1	3.8
House 5	2.6	2.3	2.6	3.4	3.5	3.5
House 6	2.0	1.8	1.6	3.5	2.6	2.6
House 7	7.6	7.0	7.7	10.6	10.7	9.9
House 8	0.6	0.5	0.7	1.0	1.0	0.6
House 9	1.3	1.5	1.6	2.1	2.0	1.2

Represent the typical summer and winter months (December to May), calculated as per the utility bills and divided by the area of the respective houses.

The average energy usage for the majority of the houses is higher by 30 % in the months of summer (Table 19) based on a comparison with winter months.

Table 19. Average electricity usage (kWh/m^2) for winter and summer months.

	Average winter months usage	**Average summer months usage**	**Delta %**
House 1	1.34	1.20	10%
House 2	0.87	0.95	-10%
House 3	0.61	1.15	-89%
House 4	5.23	4.11	21%
House 5	2.50	3.44	-38%
House 6	1.80	2.92	-62%
House 7	7.42	10.38	-40%
House 8	0.62	0.84	-35%
House 9	1.45	1.80	-24%

Experimental Energy Consumption

The typical materials interchanged for the experimental energy analysis are listed in Table 12). The simulation provided an estimate for the annual energy consumption for every house for both the current and the experimental version of the house with the interchanged materials.

Table 20 extends the findings of Table 19 through the inclusion of the energy consumption calculated based on the percentage increase/decrease in energy consumed based on the interchanged materials.

The results indicate that the delta increase in energy consumption per unit area was highest in house 3 with an increase of 54% while house 4 decreased by 46%. The energy consumption increases drastically for the traditional houses (houses 1-3) when constructed with modern material by an average of 39% while the modern houses (4-9), if built with traditional materials in the experimental modeling, showed an average decrease in energy consumption of 36%.

Table 20. Annual electricity consumption (kW) per unit area (square meter).

House	Current	Modified	% Increase	Delta Usage
House 1	12.64	17.84	41%	5.20
House 2	18.65	22.80	22%	4.15
House 3	24.46	37.77	54%	13.31
House 4	77.70	42.27	-46%	-35.43
House 5	67.72	42.16	-38%	-25.56
House 6	52.15	48.47	-7%	-3.68
House 7	142.80	85.96	-40%	-56.84
House 8	24.99	14.34	-43%	-10.66
House 9	67.14	36.94	-45%	-30.20

Table 21. Annual energy use intensity (kWh/m^2) from the computer simulation.

	Current	Modified	Delta	Delta %
House 1	144	172	-27.8	-19%
House 2	224	245	-21.4	-10%
House 3	106	131	-25.6	-24%
House 4	307	207	100.3	33%
House 5	251	240	11.6	5%
House 6	143	135	7.5	5%
House 7	212	159	53.1	25%
House 8	166	115	50.6	31%
House 9	195	135	60.0	31%

Negative value indicates the % decrease in energy consumption when materials interchanged

The collated results between the energy use intensity for the houses in their current states versus their modified states are listed below (Table 21). The energy consumption of the traditional houses (1-3) continues to increase when the construction materials are modified. Additionally, all of the modern houses (4-9) show a decrease in energy use when modified with traditional materials. The modern houses show an average savings of 21% with houses 4, 8 and 9 having a potential of saving 31% energy per square meter of the living space area.

Another notable result, based on the interchange experiment between the traditional and modern materials, is in CO_2 emissions. There is the potential for CO_2 emission reduction of over 30%, on average, in the modern houses as a result of modifying the building materials, whereas the traditional houses show an average increase of 22% upon material modification (Table 22).

Table 22. Comparison of the annual net CO_2 emissions (metric tons) by house in its current vs. modified states.

	Current	**Modified**	**Delta**	**Delta %**
House 1	13	16	-3	-23%
House 2	7	8	-1	-14%
House 3	7	9	-2	-29%
House 4	12	7	5	42%
House 5	14	11	3	21%
House 6	11	10	1	9%
House 7	4	2	2	50%
House 8	32	20	12	38%
House 9	11	6	5	45%

A negative value indicates the % decrease in energy consumption when materials interchanged.

Cost Benefit Analysis

On interchanging the materials, the traditional houses show an estimated average additional expenditure of 18%. The modern houses show a significant average savings of

21% in the utility bills (Table 23). House 3 shows the greatest expenditure increase of 24% while house 4 shows the greatest savings of 33%.

Table 23. Cost-benefit analysis based on energy consumption per unit area (INR) by house in its current vs. modified states.

	Current	**Modified**	**Delta**	**Delta %**
House 1	895	1067	-172	-19%
House 2	1389	1522	-133	-10%
House 3	655	814	-159	-24%
House 4	1906	1284	622	33%
House 5	1558	1486	72	5%
House 6	886	839	46	5%
House 7	1315	986	329	25%
House 8	1027	714	313	31%
House 9	1207	834	372	31%

The unit cost of power (INR 6.20 per kW).

Chapter IV

Discussion

The results of this study show that all of the traditional houses consumed lesser energy when compared to the modern houses. All the factors of space planning, design, ambiance and the lifestyle along with the construction materials and technique helped improve energy performance of traditional houses.

Key Physical Observations

The light-colored roof with white lime mortar as seen in the traditional houses makes the surface more reflective and appears to minimize heat absorption by the external roof surface. The RCC roofs used in the modern houses absorb a tremendous amount of heat (Building Construction Practices Sectional Committee, 1988) making the terraces of the modern houses hot. This heat was evident in the top floors of the modern houses under study making them extremely uncomfortable. As a result, mechanical forms of cooling were mandatory to keep the temperature amenable adding to energy consumption.

Wall materials and the plaster play an important role in heat transfer of buildings. The temperature difference between the indoor and outdoor temperatures for houses 2 and 9 (located opposite each other) illustrates this. House 2 has walls constructed of rammed earth – which has a lower heat transfer coefficient – versus house 9 with concrete walls and cement plaster with paint finish which measured higher indoor temperatures.

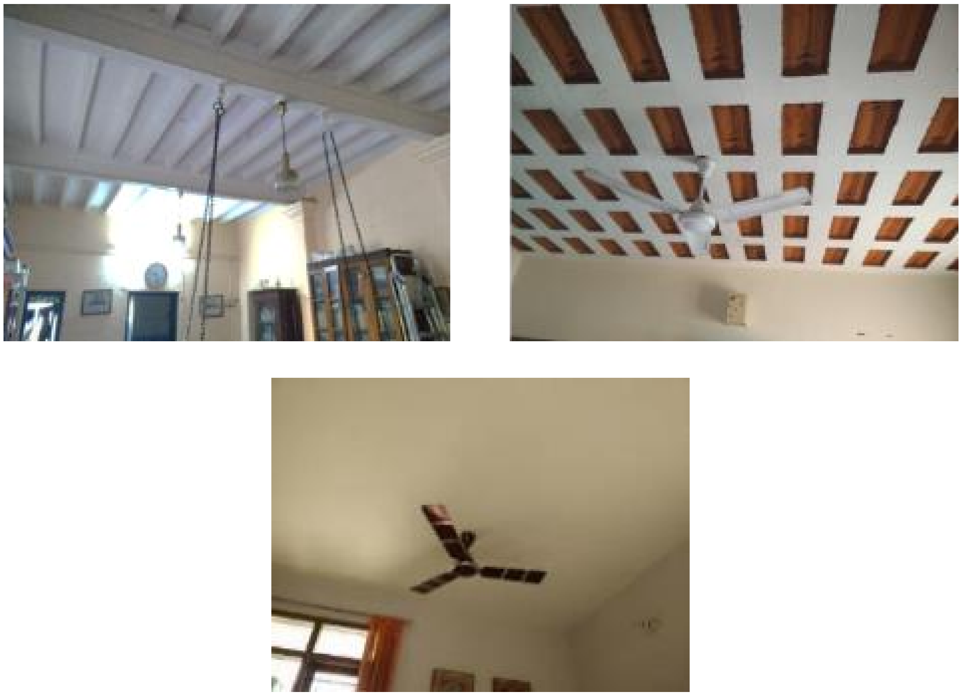


Figure 26. Types of roofs. Houses 1 (left top) with a Madras terrace roof, House 3 (right top) with a filler slab roof & House 8 (bottom) with an RCC roof.

No conclusive results can be drawn just from the construction materials (Table 13). However, insights into the materials used in traditional versus modern construction could be observed. Moreover, the materials used are necessary for the energy simulation that is created by Green Building Studio Software.

Orientation, Site Planning, and Building Form

The Building and Construction Authority states that an EW orientation is ideal for houses (Building and Construction Authority, 2010). Houses 4, 5, 6 and 7 with NS axis may require more energy to cool as opposed to houses 1, 2 and 9 with the preferred EW axis (Figure 27).

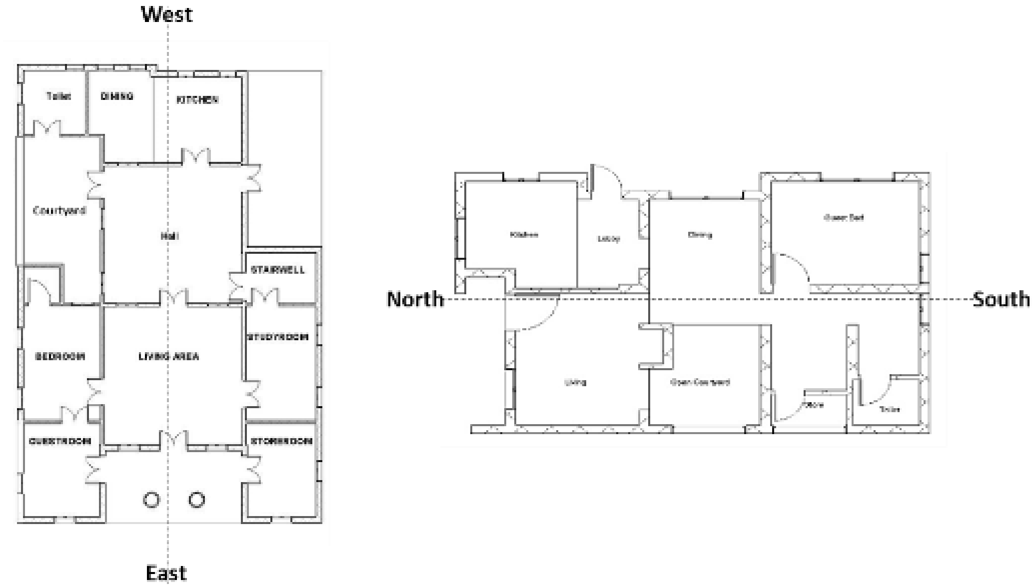


Figure 27. Building orientation of house 1 (left) with an EW axis while house 4 with an NS axis.

Although building orientation is important, the landscaping around the house, the location and types of openings, and the window to wall ratio are also vital since these also affect the solar heat gain or loss. For example, house 9 has a complete glazed west façade causing increased solar heat gain within the building. Therefore, despite having the beneficial EW ridge line, it does not have the appropriate facade treatment resulting in reduced performance.

The building footprint on the site and the treatment of various site surfaces determine the heat island effect. Houses 1, 2, 3 and 8 have well-designed sites with plenty of surrounding greenery and open spaces. This feature reduces the heat island effect for these houses. Although house 6 has some landscaping located to the west (Figure 24), the amount of hardscape increases the heat island effect.

House 1 has a linear floor plan while house 8's floor plan is irregular with a larger building perimeter (Figure 28). This probably led to an elevated quantity of construction materials required to build house 8, which hiked the construction costs of the building. Moreover, the increased number of jogs will not provide uniform distribution of light into the interior.

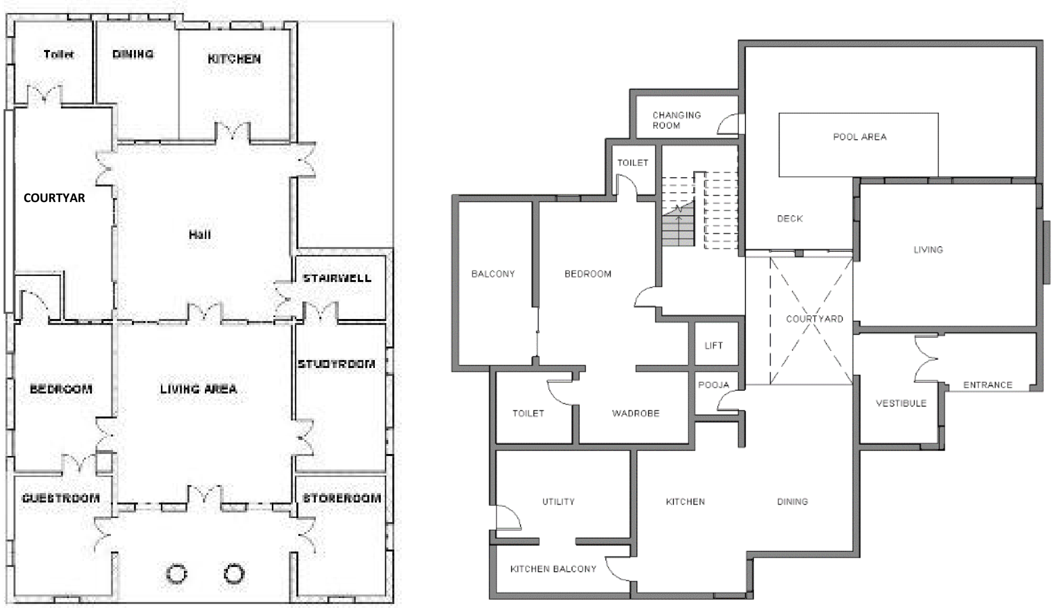


Figure 28. Comparison of building footprints. House 1 (left) has a linear plan, house 8 (right) is non-linear and greater perimeter.

Indoor Environment

Modern houses (4-9) are unable to maximize natural light, so all except house 8 required artificial lighting during daytime. Conversely, the traditional houses (1-3) had plenty of natural light indoors due to the optimal site orientation of these houses. Openings on the north-south façade allow light to enter the space without creating too much glare. Additionally, features such as courtyards, high clear-story windows, and jaalis maximize the penetration of natural daylight into traditional houses. This observation is consistent with the report published by Building and Construction Authority in Singapore (Building and Construction Authority, 2010).

Although house 9 has an ideal building orientation, it does not get adequate natural light due to the presence of a glazed façade located in the west. The glass increases the glare inside the house and only provides lighting for the room in which it is located. Houses 4, 5, 6, and 7 need artificial lighting in all the areas.

The slightly larger floor-to-floor heights and clerestory glazing above 2,100 mm enable natural light to penetrate deep into spaces of traditional houses 1, 2 and 3 (Figure 29). This is because daylight glazing is most effective above 2,100 mm. However, this can create glare into space and needs careful planning. Since houses 1 and 2 have internal windows present in each room, it further facilitates natural light and ventilation through the spaces (Figure 30).

Figure 29. House 2(left) and House 1(right) with clerestory windows emitting light into the high ceiling area.

Floor-to-ceiling glazing is not highly effective in optimizing daylight since, as in the case of house 9 (Figure 25), it results in additional solar radiation. Areas below 750 mm do not require glazing for either daylight or vision purposes. This saves glazing material costs and reduces the amount of solar radiation entering via openings (Building and Construction Authority, 2010).

The measured temperature difference (Table 15) shows that the traditional houses perform better than the modern houses in terms of insulating the indoor environment against high outdoor temperatures. Passive cooling design elements shut out excess heat entering living spaces. Solar shade screens, deep-seated windows (Figure 30), roof overhangs, awnings, trees and other landscaping features can shade the indoors from radiation. Houses 1 and 2 have deep set windows in box type frames along with grills that facilitate natural ventilation through the spaces (Figure 30).

Figure 30. House 1with deep set windows with wooden frames and grills and high ceiling height.

Courtyards also help regulate the thermal comfort of a house. Although courtyards receive direct sunlight, they are cooled by the greenery and water bodies often present in these spaces. This cooler air then spreads into other rooms with openings into the courtyard, as seen in traditional houses. All of the traditional houses studied have openings into a courtyard. Figure 12 shows the floor plan for a typical central courtyard as seen in house 2. Figure 31 illustrates the dissipation of heat during the daytime and night time through a courtyard.

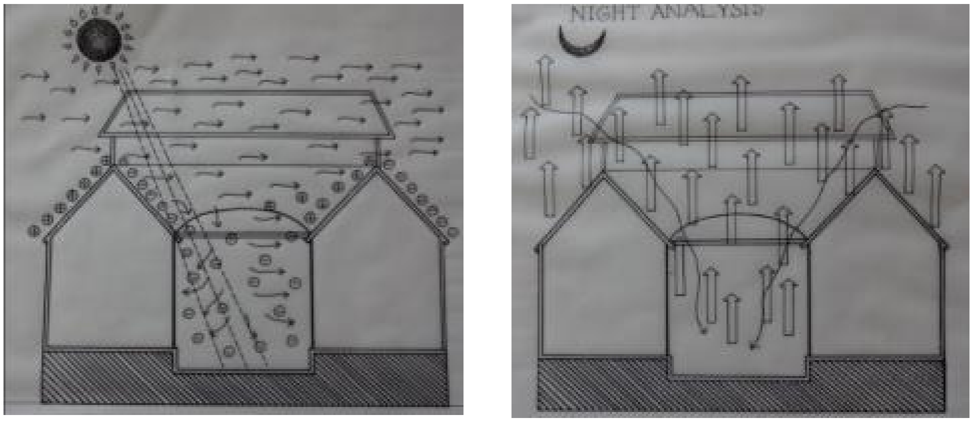


Figure 31. House section showing positive and negative energy through a courtyard house (Myneni, 2013).

The thick walls of the traditional houses (300mm – 600mm) do not allow heat from the courtyards to penetrate the houses during the daytime. (Prashad & Chetia, 2010). The courtyards in houses 1 and 2 were a more typical rectangular or square shape while house 3 had a curved wall on one side. Courtyards act as a microclimate modifier (Prashad & Chetia, 2010) that enable air movement in these houses by helping the cool air to enter at night without radiation of daytime heat (Figure 31).

Another physical feature that helps regulate the thermal comfort of a house is the presence of a high ceiling with clerestory windows. High windows and ceilings help to control the heat and light movement into space. They create a stack effect where the hot air rises continuously and cool air takes its place below. Houses 1 and 2 have high ceilings in the most commonly used areas within the house. An additional advantage of having high ceilings in a house is that the internal air takes longer to heat up due to the larger volume of the enclosed space (Prashad & Chetia, 2010). This leads to cooler indoor temperatures in rooms with higher ceilings as seen in traditional houses.

Also, houses 1, 2 and 3 have typical ventilators present which help increase the velocity of air entering due to the pressure difference caused by the exit of hot air through the ventilators (Figure 19). (Prashad & Chetia, 2010). None of the modern houses have ventilators present. Although house 8 has a skylight, it is covered with glass. While this provides natural light, it has no effect on heat regulation.

The indoor humidity level and the temperature of the air must be controlled to maintain thermal comfort. Houses 4, 5 and 7 have relatively higher humidity (Table 15). On a warm day, if the humidity inside these houses increases, the air will hold more heat. Therefore, mechanical cooling such as ACs needs to run longer to offset both the humidity and the warm air (Ames, 2011).

Various appliances and the construction materials used contribute to the amount of CO_2 present in a house. The inhabitants of houses 6 and 7 complained about having constant health issues such as frequent headaches only while they were in their houses. This could be a serious indication of sick building syndrome (Davis, n.d.). The inhabitants of these houses may need to enhance the ventilation and air flow into their buildings to remove the excess CO_2. An additional method that these houses could employ to reduce the CO_2 readings would be to increase the greenery inside and around the house (Torpy, 2013).

Energy Consumption

The results of this study show that all of the traditional houses consumed the least amount of energy and therefore spent less per unit area. Only house 8 among the new houses had an energy spend similar to the traditional houses (Table 18).

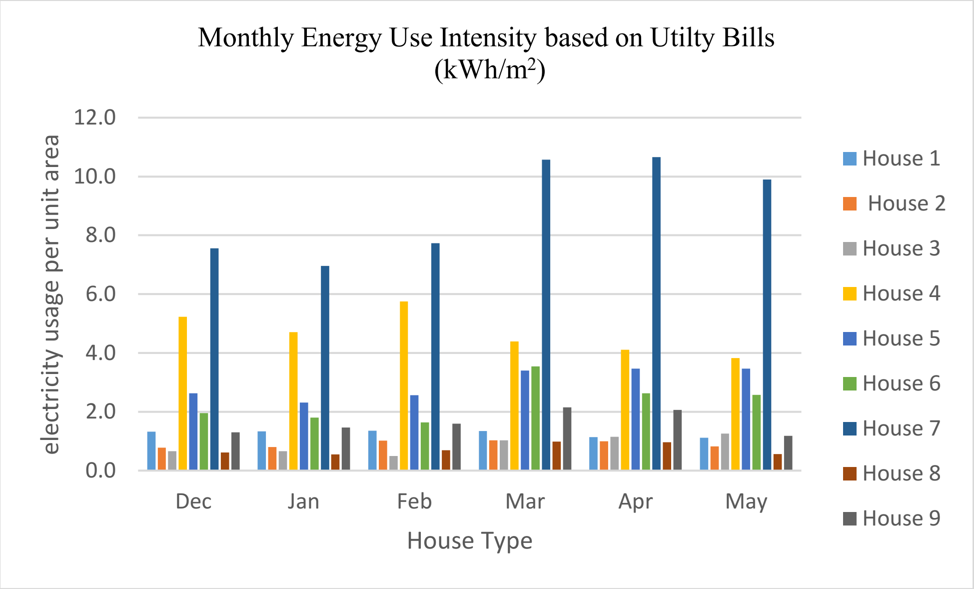


Figure 32. Energy usage per unit area based on household utility bills.

Houses 4, 5, 6, 7, and 9 score significantly higher regarding energy usage per square area (Figure 32). These houses show great potential for the use of energy saving techniques. Although the per unit area energy usage is relatively low for house 3 (Figure 32), the delta % between the average summer and winter usage is significantly higher by 89%. This could be attributed to the rubble masonry used for the construction of the house.

Further research will be required to validate the findings of this method of evaluating energy consumption. This is illustrated through various ambiguities that arise from the data captured via this method. For example, house 4 shows an anomaly of lower energy usage in summer months versus the winter months. This excess winter usage could be due to factors such as lifestyle changes, non-occupancy of the house during summer, and a higher occupancy during the winter months. Therefore, this model of calculating energy consumption may not match actual observations if use varies seasonally.

Some reasons for the utility data ambiguity are that household vary in lifestyle. Some habitually use more power than others or use different appliances. The households also hail from a wide range of socio-economic status, making it hard to compare power usage between the houses. Therefore, this model of calculating energy consumption cannot by itself create reliable observations of trends and findings.

Additionally, although each household had a certain number of people residing at the time of the survey, the number of occupants has varied over the past year due to factors such as travel, and guests visiting them. Finally, some of the houses appear to have faulty electricity meters – which may have provided incorrect consumption values in the bills. This is further evident when comparing estimated energy usage from the energy model against the actual utility bills of the houses.

Despite these challenges, there is a clear trend noticed in the nine sample houses. The energy usage per month does not vary significantly in the six months for traditional houses 1 and 2. House 2 shows a slight increase in summer usage versus winter usage, but with a small percentage difference (Table 18). Although this requires a larger data sample – with utility bills over a period of at least three years to mitigate the problems addressed above – one can assume by looking at the data in the tables above that the modern houses do not provide sufficient insulation from external temperatures. The disproportionately higher bills seen during the summer months indicate that more power was consumed then, mostly due to HVAC needs.

Experimental Energy Consumption

The experimental modeling demonstrated that the materials used to construct houses have an enormous potential for decreasing energy consumption across the board (Table 13). When the traditional building materials were substituted with modern materials, all of the traditional houses showed an increase in its energy consumption (Figure 33). This increase is possibly due to the increased energy required to cool the houses with the interchanged materials. The construction materials used have a significant impact regarding the mechanical devices used for HVAC and lighting, especially in houses 4, 5, 7 & 9.

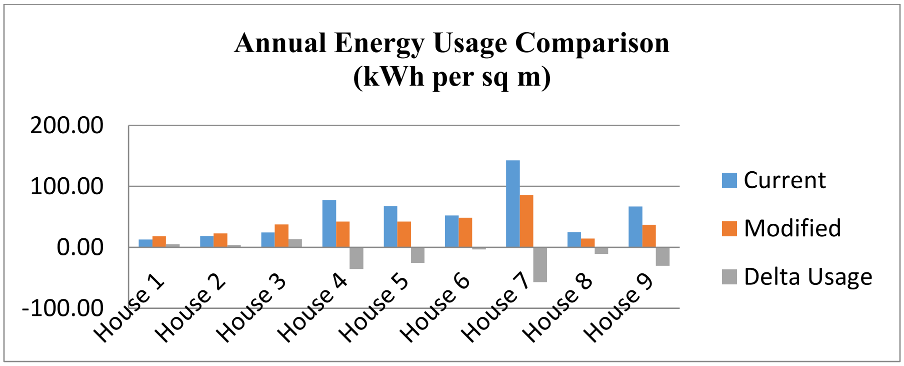


Figure 33. Annual energy use per unit area as per energy simulation model.

The energy modeling software does not take into account the number and types of appliances used in a particular house. It assumes that the houses function for all 24 hours in a day for a complete year. This is done to control for variables such as lifestyle differences, the number of occupants, and electricity usage habits between the various houses. Therefore, the energy consumed using the energy model will be much higher per unit area than we observed through the appliances in use.

The average CO_2 emission reduction potential results (Table 21) are because the traditional buildings were constructed using natural materials which are lower in embodied energy and toxicity than human-made materials. They require less processing, are less damaging to the environment and result in significantly lower CO_2 emission. When natural materials are incorporated into building products, the products become more sustainable. Thus, local traditional materials are better suited to climatic conditions (Almatarneh, 2013). The results strongly support the hypothesis that traditional materials perform better from an energy-efficiency standpoint.

Cost Benefit Analysis

Results of the study show that there is a significant saving in costs for traditional buildings and more so when substituted with modern buildings materials (Figure 34). Therefore, it is appropriate to conclude that applying concepts from traditional Indian architecture will help address the increasing energy consumption in today's modern

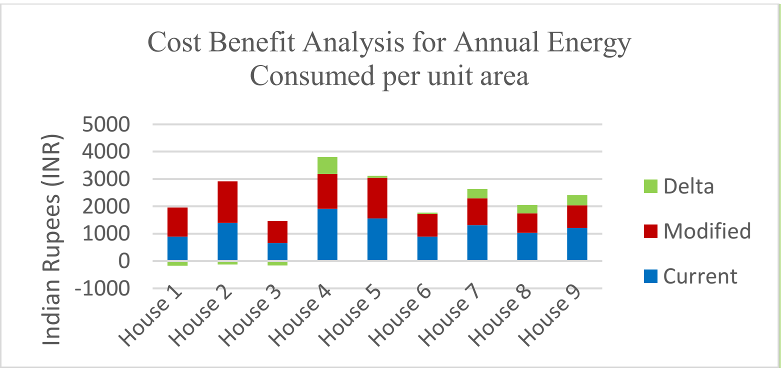


Figure 34. A cost-benefit analysis. Performed for the houses and compared by annual expenditure per household based on energy consumed from the software simulation.

Conclusions

The results of this study clearly show that buildings following traditional Indian practices consume less energy than modern construction practices. Although the results are relevant for Bangalore, they are extendable throughout all of India.

In the summer season, the measured indoor temperature in the traditional houses was cooler compared to the modern houses. Therefore, the traditional houses perform better than the modern houses in terms of insulating the indoor environment against high outdoor temperatures. Even during the peak of summer (May 2016), the traditional houses were comfortable indoors and did not require any form of mechanical cooling. The space planning and materials used for the traditional houses, and conventional openings primarily influence thermal comfort.

The average energy consumption for the traditional houses was 18.5 KWh/m^2, and 72 KWh/m^2 for the modern houses based on standard equipment usage and the estimated utility consumption. As per the actual utility bills, energy usage is typically 30 % higher in the summer months for the majority of houses. Energy consumption for the traditional houses (houses 1-3) increases drastically by an average of 39% when modeled with modern materials while the modern houses modeled with traditional materials showed a 36%average decrease in energy consumption.

Another notable result from the interchange experiment of traditional and modern materials is the CO_2 emission reduction potential of over 30% average in the modern houses if they used traditional building materials. On the other hand, the traditional houses show an average increase of 22% if they were to use modern materials. The use of natural materials in the building products make them more sustainable. Thus, local traditional materials are better suited to climatic conditions.

Traditional houses tend to be constructed with renewable materials, whereas modern houses primarily use non-renewable materials. Since renewable materials tend to have a more favorable life-cycle assessment, it would mean that they use less energy than modern materials. The materials used to construct houses could have enormous potential for decreasing energy consumption across the board. Moreover, modern houses used materials with low insulation value which resulted in higher indoor temperatures. The quantum of difference between the current versus modified materials indicates a severe need to modify the way construction is performed for modern houses.

The advantages of using traditional materials over modern materials are rather conclusive from the study data. Moreover, traditional methods of building design such as using Jaali mesh windows, courtyards, high ceilings and clerestory windows provides better natural lighting for the house. The study showed that windows above 2100mm (as seen in traditional houses) helps with deep penetration of daylight. This means that using traditional methods such as these helps reduce the energy required for lighting.

Additionally, when modern buildings are substituted with traditional materials, there is a significant saving in cost for traditional buildings. The traditional houses show an estimated average additional expenditure of 18% while the modern houses showed a significant average savings of 21% on interchanging the materials.

The modern update to housing design and construction has led to poorer performing buildings in India. The integration of traditional features like greenery around the house, courtyards, skylights, building orientation and materials used in the construction contribute to better thermal performance of houses. These result in less energy use by traditional houses as compared to the modern houses, which require more energy to modulate the indoor temperature of the house. Furthermore, the results of the study show that passive cooling techniques play an important part in the energy performance of a building. Therefore, it is important to incorporate the lessons learned from traditional design into modern design.

Further Study

Future iterations of this study would benefit from a larger sample size and collection of a minimum of three years of collected utility data. Additional data points will provide a more definitive trend on the energy consumption of households.

The houses in this study were all located in Bangalore. Since the Indian government is planning to convert and develop 100 Smart Cities in India (Bose, Praveen, 2014) soon, it will be useful to extend this study to these other cities.

Moreover, future studies in sustainable residential design and construction in India could focus on Life Cycle Assessments (LCA) of the construction materials used in residential projects. Such an analysis will provide a more holistic understanding of energy consumption of residences in Indian cities.

Appendix 1

House 1 Results

Figure 35. Floor plan of house 1. Ground floor (left) and first floor (right).

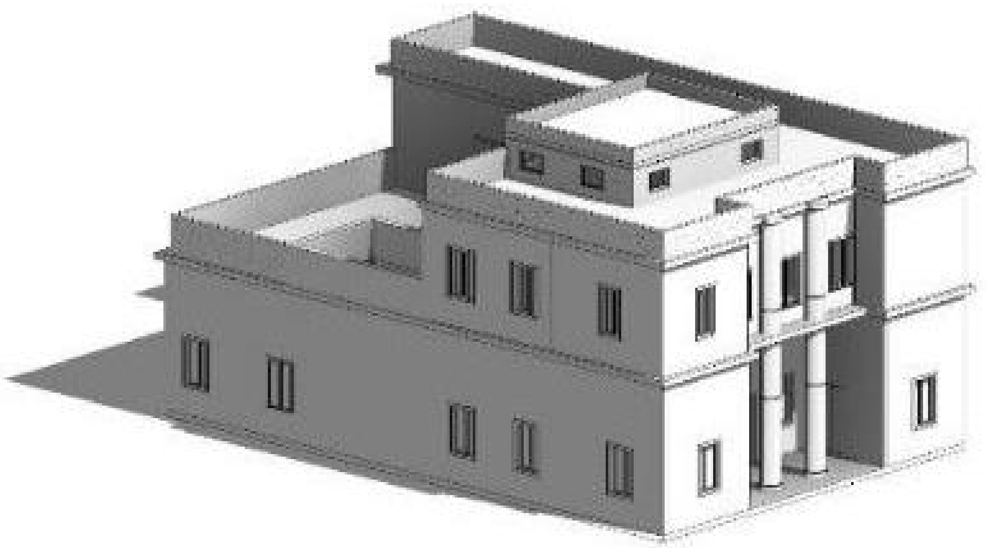


Figure 36. 3D view of house 1 created in Revit software.

Table 24. Data parameters collected for house 1 during single site visit.

Year Constructed	1908
Age (years)	108
Number of Occupants	7
Number of Storeys	Ground + 1
Skylight/Courtyard	Yes
Mechanical Cooling	2 Ceiling Fans
CO_2 levels (ppm)	710–740
Outdoor Humidity	58%
Indoor Humidity	55%
Outdoor Temperature (°C)	32
Outdoor Temperature – feels like (°C)	41
Indoor Temperature (°C)	30
Windows	Jaali Mesh Windows (Single Pane Wood)
Wall materials	Brick and Lime Mortar
Wall Thickness (mm)	300
Roof	Madras roof with steel rafters
Floor	Mosaic flooring+ Brick flooring
Door	Teak Wood Frame
Floor Area (m^2)	313
Exterior Wall Area (m^2)	461

Table 25. Actual utility energy consumption at house 1 for six months (KWh).

	Winter			Summer			
	Dec	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Total Power Consumed for six months**
House 1	416	420	423	420	358	350	2387

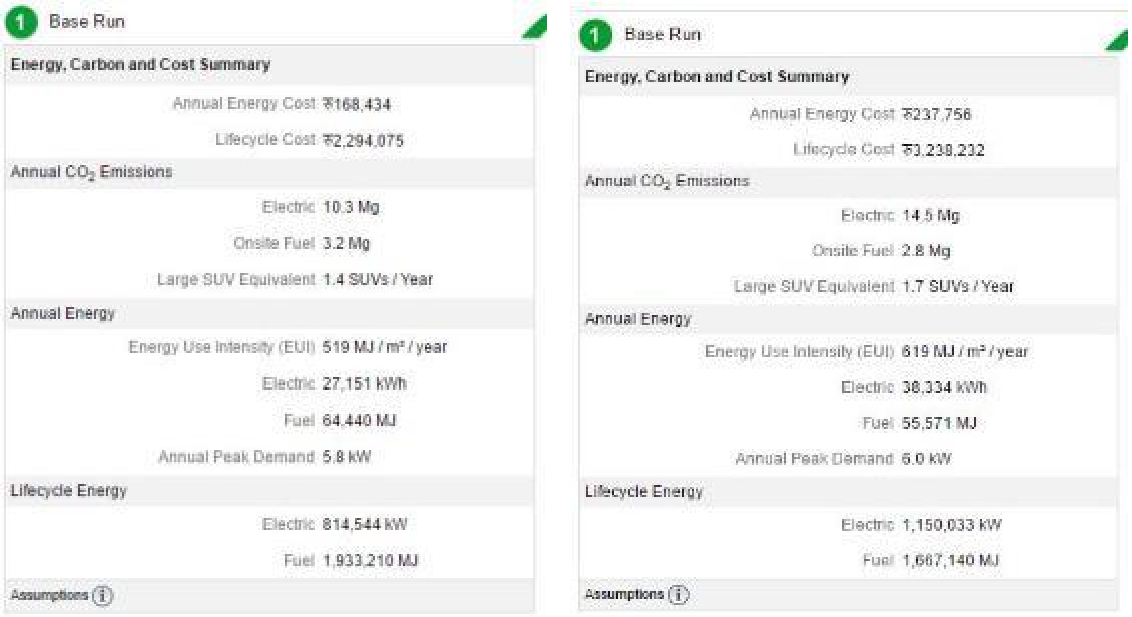
Table 26. Estimated plug load energy consumption of house 1.

Category	**Appliance**	**Quantity**	**Wattage**	**Average Daily Usage (Hours)**	**Average Daily Power Consumed (kWh)**	**Monthly Power Usage (kWh)**	**Annual Power Usage (kWh)**
HVACR	Ceiling Fan	2	100	4.45	0.45	26.70	320.40
HVACR	Air Conditioner (1.5 ton)	0	1500	0.81	1.22	0.00	0.00
HVACR	Refrigerator	1	100	22.33	2.23	66.99	803.88
HVACR	Immersion Rod	3	1000	1.18	1.18	106.20	1274.40
HVACR	Geyser	0	1000	1.18	1.18	0.00	0.00
Lighting	Bulb (FL40)	10	40	2.63	0.11	31.56	378.72
Lighting	Tube light (IL40)	22	40	1.56	0.06	41.18	494.21
Miscellaneous	Computer	1	100	3.00	0.30	9.00	108.00
Miscellaneous	Mixer	1	450	0.47	0.21	**6.35**	76.14
Miscellaneous	Water Pump	1	750	0.68	0.51	15.30	183.60
Miscellaneous	Television	1	100	3.93	0.39	11.79	141.48
Miscellaneous	Washing Machine	0	325	0.71	0.23	0.00	0.00
Miscellaneous	Radio	1	15	2.51	0.04	1.13	13.55
Miscellaneous	Electric Iron	1	750	0.48	0.36	10.80	129.60
Miscellaneous	VCR	1	40	2.14	0.09	2.57	30.82
Miscellaneous	Microwave	0	1000	1.00	1.00	0.00	0.00
Miscellaneous	Vacuum Cleaner	0	750	0.70	0.53	0.00	0.00
	Total					**329.57**	**3954.80**

Table 27. Plug load energy consumption – annual energy consumption and utility cost comparison: existing house 1 vs. modified house 1 (materials upgrade).

House 1 Annual Expenditure Analysis			
Parameter	**Current**	**Modified Materials**	**Cost Benefit**
Annual Electricity Consumed Simulation (kWh)	27150	38333	-11183.00
HVACR (kWh)	2398.68	3386.69	-988.01
Lighting (kWh)	872.93	1232.48	-359.56
Miscellaneous (kWh)	683.19	964.59	-281.40
HVACR Cost (INR)	₹ 14,872.38	₹ 20,998.26	-₹ 6,125.88
Lighting Cost (INR)	₹ 5,412.36	₹ 7,641.69	-₹ 2,229.33
Misc. Cost (INR)	₹ 4,235.94	₹ 5,980.71	-₹ 1,744.77
Annual Cost (INR)	**₹ 24,520.67**	**₹ 34,620.66**	**-₹ 10,099.99**
Floor Area (m^2)	313	313	
Annual Cost per m^2 (INR)	**₹ 78.34**	**₹ 110.61**	

Figure 37. Sample screenshot of Netatmo weather station reading.



1 Base Run

Energy, Carbon and Cost Summary

Annual Energy Cost	₹168,434
Lifecycle Cost	₹2,294,075

Annual CO_2 Emissions

Electric	10.3 Mg
Onsite Fuel	3.2 Mg
Large SUV Equivalent	1.4 SUVs / Year

Annual Energy

Energy Use Intensity (EUI)	519 MJ / m² / year
Electric	27,151 kWh
Fuel	64,440 MJ
Annual Peak Demand	5.8 kW

Lifecycle Energy

Electric	814,544 kW
Fuel	1,933,210 MJ

Assumptions ⓘ

1 Base Run

Energy, Carbon and Cost Summary

Annual Energy Cost	₹237,756
Lifecycle Cost	₹3,238,232

Annual CO_2 Emissions

Electric	14.5 Mg
Onsite Fuel	2.8 Mg
Large SUV Equivalent	1.7 SUVs / Year

Annual Energy

Energy Use Intensity (EUI)	619 MJ / m² / year
Electric	38,334 kWh
Fuel	55,571 MJ
Annual Peak Demand	6.0 kW

Lifecycle Energy

Electric	1,150,033 kW
Fuel	1,667,140 MJ

Assumptions ⓘ

Figure 38. Energy model output report for house 1. (existing-left versus modified materials-right).

Table 28. Energy model output – cost comparison of energy and fuel consumed for house 1.

	Current	Modified
Electricity Consumption	₹ 1,68,339.00	₹ 237,673.00
Fuel Consumption	₹ 95.00	₹ 82.00

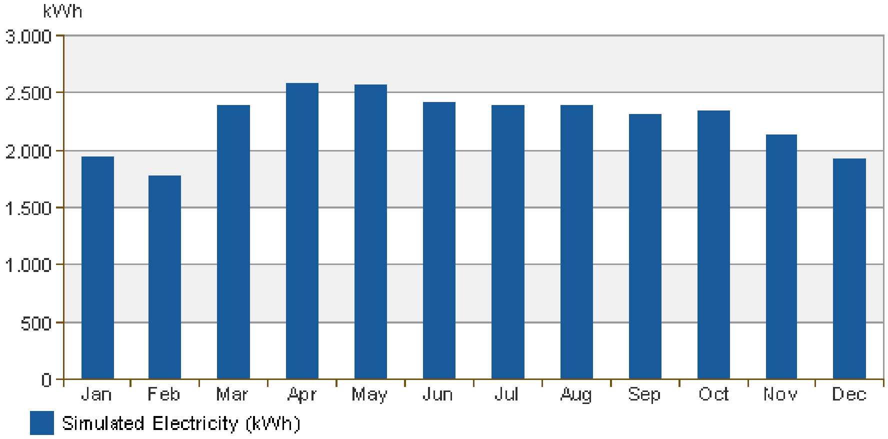


Figure 39. Energy model output – estimated existing house monthly electricity consumption for house 1.

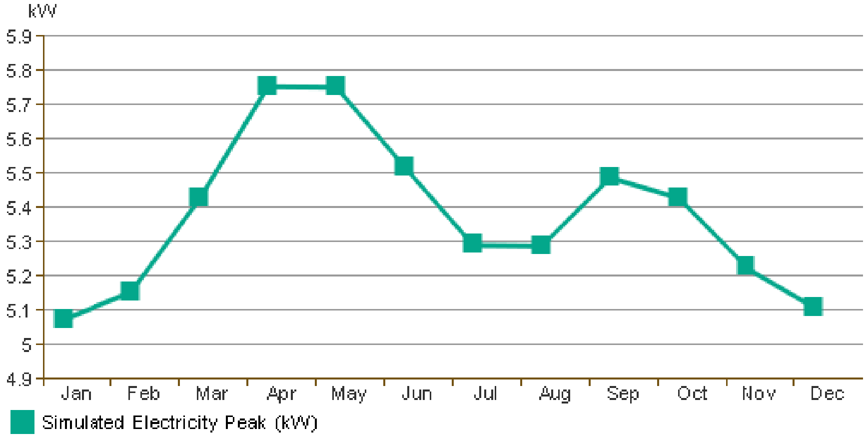


Figure 40. Existing house estimated monthly peak demand for house 1.

Table 29. Energy model output – estimated annual energy use intensity for house 1.

	Current	**Modified**
Electricity EUI (kWh/m^2/yr)	87	123
Fuel EUI (MJ/m^2/yr)	206	178
Total EUI (MJ/m^2/yr)	519	619

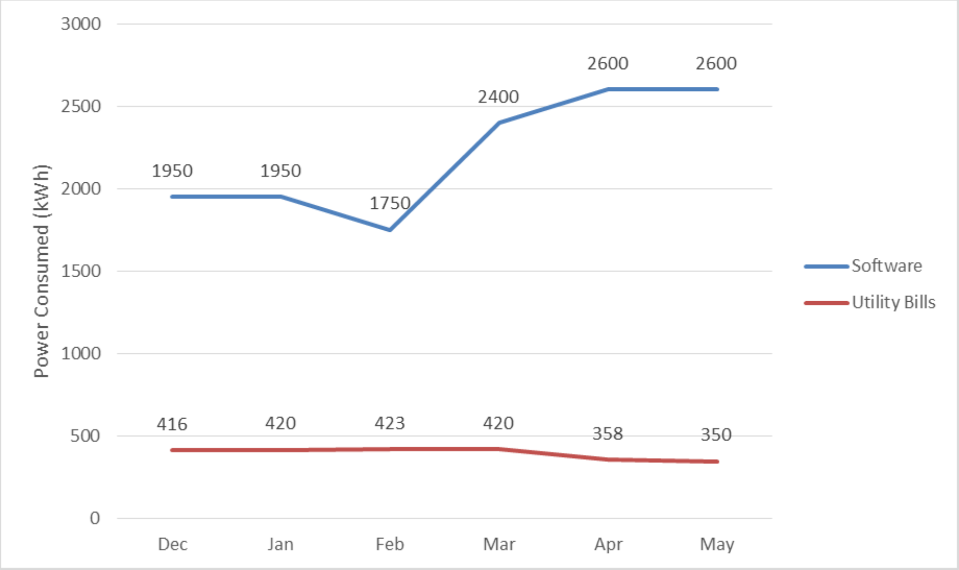


Figure 41. Comparison of the power consumed through the software versus the actual utility bills for house 1.

Appendix 2

House 2 Results

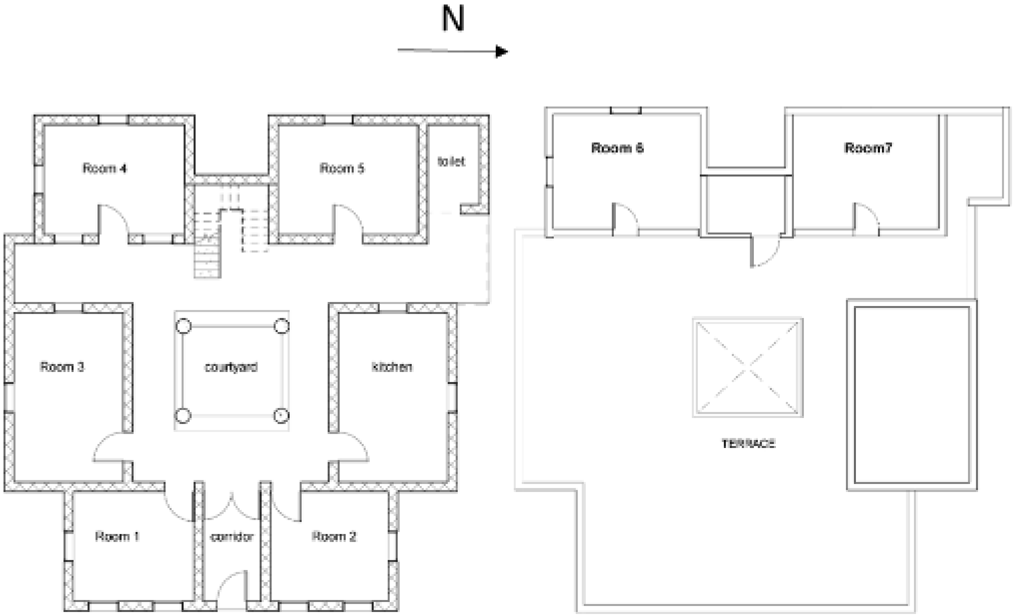


Figure 42. Floor plan of house 2. Ground floor (left), first floor (right).

Figure 43. 3D view of house 2 created in Revit software.

Table 30. Data parameters collected for house 2 during single site visit.

Year Constructed	1886
Age (years)	130
Number of Occupants	11
Number of Storeys	Ground + 1
Skylight/Courtyard	Yes
Mechanical Cooling	3 Fans
CO_2 levels (ppm)	724-743
Outdoor Humidity	60%
Indoor Humidity	64%
Outdoor Temperature (°C)	31.1
Outdoor Temperature – feels like (°C)	41
Indoor Temperature (°C)	30.3
Windows	Burma Teak Windows
Wall materials	Brick, Mud and Lime Mortar
Wall Thickness (mm)	600
Roof	Wood Rafter + Wood sheet + Mangalore tile, flat roof – Wood Rafter + Brick
Floor	Red oxide
Door	Burma Teak
Floor Area (m^2)	150
Exterior Wall Area (m^2)	371

Table 31. Actual utility energy consumption at house 2 for six months (KWh).

	Winter			**Summer**			
	Dec	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Total Power Consumed for six months**
House 2	117	121	153	155	150	124	820

Table 32. Estimated plug load energy consumption of house 2.

Category	**Applianc e`**	**Quantity**	**Wattage**	**Average Daily Usage (Hours)**	**Average Daily Power Consumed (kWh)**	**Monthly Power Usage (kWh)**	**Annual Power Usage (kWh)**
HVACR	Fan	3	100	4.45	0.45	40.05	480.60
HVACR	Air Conditioner (1.5 ton)	0	1500	0.81	1.22	0.00	0.00
HVACR	Refrigerator	1	100	22.33	2.23	66.99	803.88
HVACR	Immersion Rod	1	1000	1.18	1.18	35.40	424.80
HVACR	Geyser	0	1000	0.00	0.00	0.00	0.00
Lighting	Bulb (FL40)	5	40	2.63	0.11	15.78	189.36
Lighting	Tube light (IL40)	11	40	1.56	0.06	20.59	247.10
Miscellaneous	Computer	1	100	3.00	0.30	9.00	108.00
Miscellaneous	Mixer	1	450	0.47	0.21	6.35	76.14
Miscellaneous	Water Pump	1	750	0.68	0.51	15.30	183.60
Miscellaneous	Television	1	100	3.93	0.39	11.79	141.48
Miscellaneous	Washing Machine	0	325	0.71	0.23	0.00	0.00
Miscellaneous	Radio	1	15	2.51	0.04	1.13	13.55
Miscellaneous	Electric Iron	1	750	0.48	0.36	10.80	129.60
Miscellaneous	VCR	0	40	2.14	0.09	0.00	0.00
Miscellaneous	Microwave	0	1000	1.00	1.00	0.00	0.00
Miscellaneous	Vacuum Cleaner	0	750	0.00	0.00	0.00	0.00
	Total					**233.18**	**2798.12**

Table 33. Plug load energy consumption – annual energy consumption and utility cost comparison: existing house 2 vs. modified house 2 (materials upgrade).

House 2 Annual Expenditure Analysis			
Parameter	**Current**	**Modified Materials**	**Cost Benefit**
Annual Electricity Consumed Simulation (kWh)	17999	22000	-4001.00
HVACR (kWh)	1709.28	2089.24	-379.96
Lighting (kWh)	436.46	533.49	-97.02
Miscellaneous (kWh)	652.37	797.39	-145.02
HVACR Cost (INR)	₹ 10,597.93	₹ 12,953.75	-₹ 2,355.82
Lighting Cost (INR)	₹ 2,706.18	₹ 3,307.74	-₹ 601.56
Misc. Cost (INR)	₹ 4,044.87	₹ 4,944.01	-₹ 899.13
Annual Cost (INR)	**₹ 17,348.98**	**₹ 21,205.49**	**-₹ 3,856.51**
Floor Area (m^2)	150	150	
Annual Cost per m^2 (INR)	**₹ 115.66**	**₹ 141.37**	

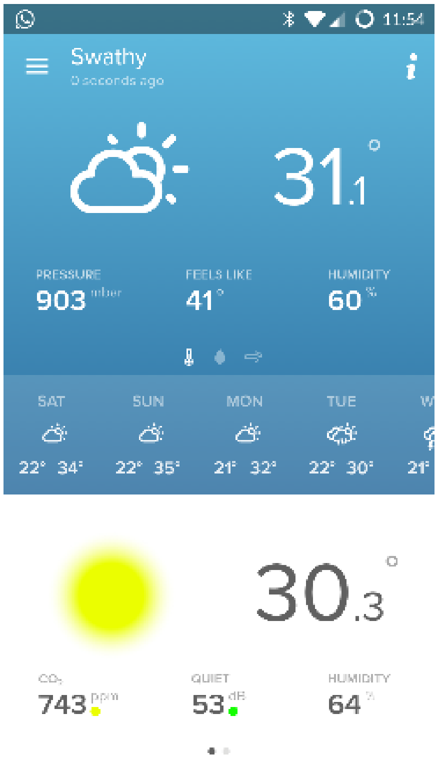
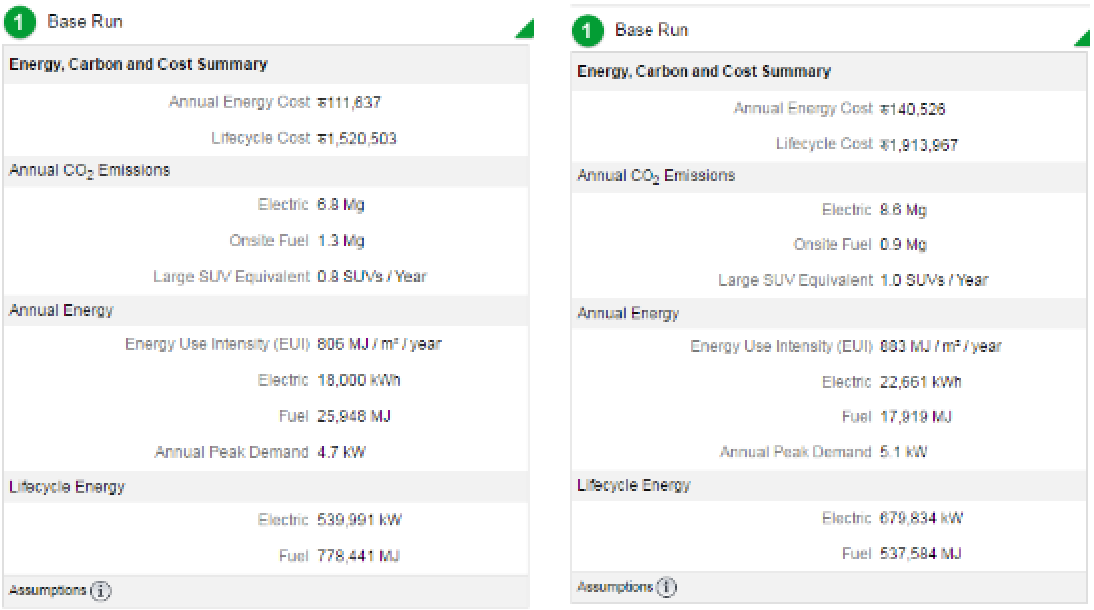


Figure 44. Sample screenshot of Netatmo weather station reading for house 2.



Energy, Carbon and Cost Summary

Annual Energy Cost ₹111,637

Lifecycle Cost ₹1,520,503

Annual CO_2 Emissions

Electric 6.8 Mg

Onsite Fuel 1.3 Mg

Large SUV Equivalent 0.8 SUVs / Year

Annual Energy

Energy Use Intensity (EUI) 806 MJ / m² / year

Electric 18,000 kWh

Fuel 25,948 MJ

Annual Peak Demand 4.7 kW

Lifecycle Energy

Electric 539,991 kW

Fuel 778,441 MJ

Energy, Carbon and Cost Summary

Annual Energy Cost ₹140,526

Lifecycle Cost ₹1,913,967

Annual CO_2 Emissions

Electric 8.6 Mg

Onsite Fuel 0.9 Mg

Large SUV Equivalent 1.0 SUVs / Year

Annual Energy

Energy Use Intensity (EUI) 883 MJ / m² / year

Electric 22,661 kWh

Fuel 17,919 MJ

Annual Peak Demand 5.1 kW

Lifecycle Energy

Electric 679,834 kW

Fuel 537,584 MJ

Figure 45. Energy model output report for house 2. (existing – left versus modified materials – right).

Table 34. Energy model output – cost comparison of energy and fuel consumed for house 2.

	Current	**Modified**
Electricity Consumption	₹ 111,598.00	₹ 140,499.00
Fuel Consumption	₹ 39.00	₹ 27.00

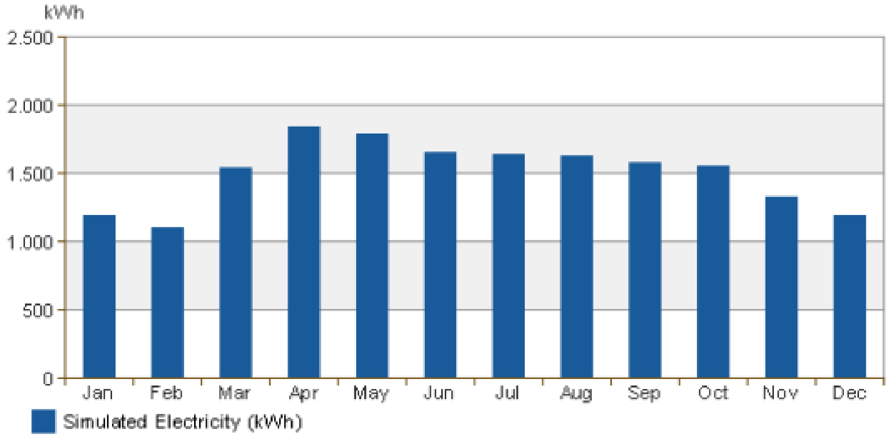


Figure 46. Energy model output– estimated existing house monthly electricity consumption for house 2.

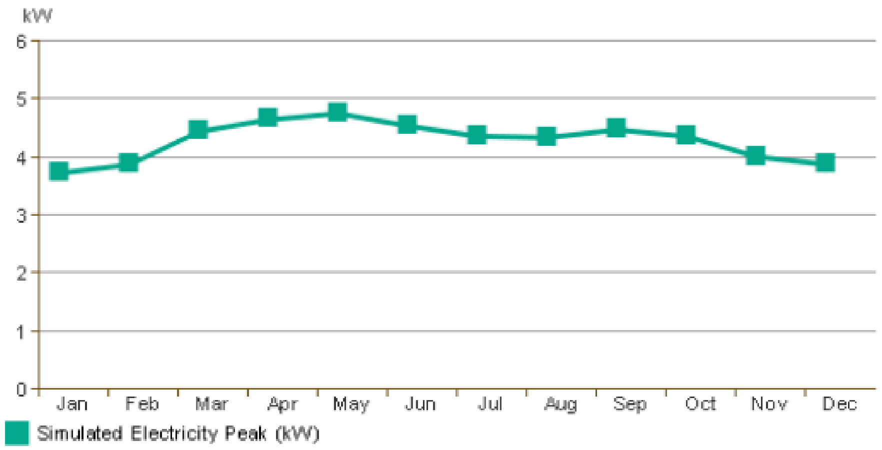


Figure 47. Existing house estimated monthly peak demand for house 2.

Table 35. Energy model output – estimated annual energy use intensity for house 2.

	Current	**Modified**
Electricity EUI (kWh/m^2/yr)	160	201
Fuel EUI (MJ/m^2/yr)	230	159
Total EUI (MJ/m^2/yr)	806	883

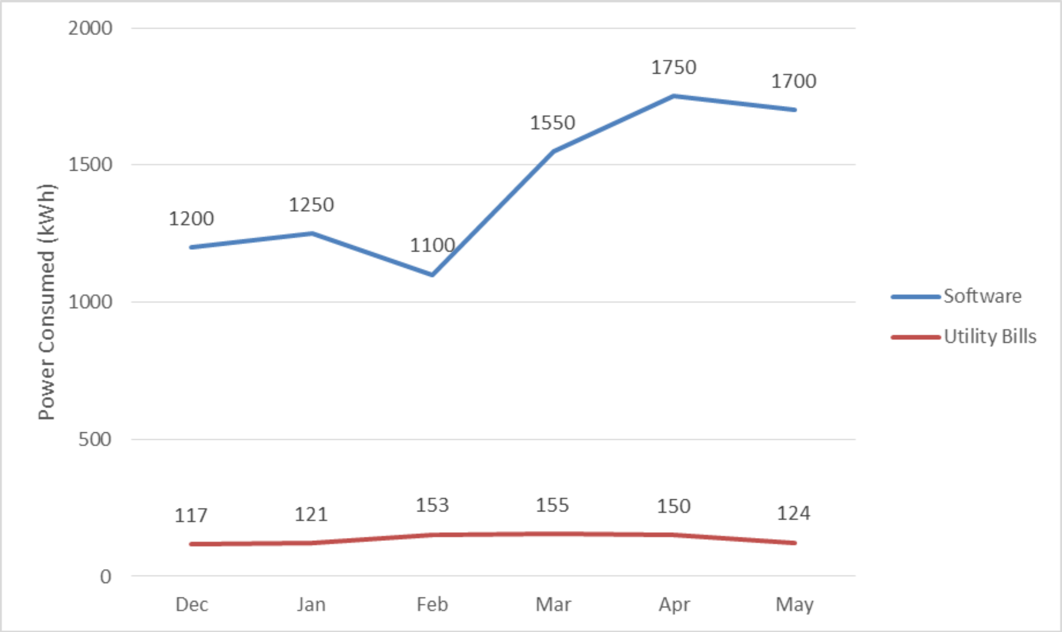


Figure 48. Comparison of the power consumed through the software versus the actual utility bills for house 2.

Appendix 3

House 3 Results

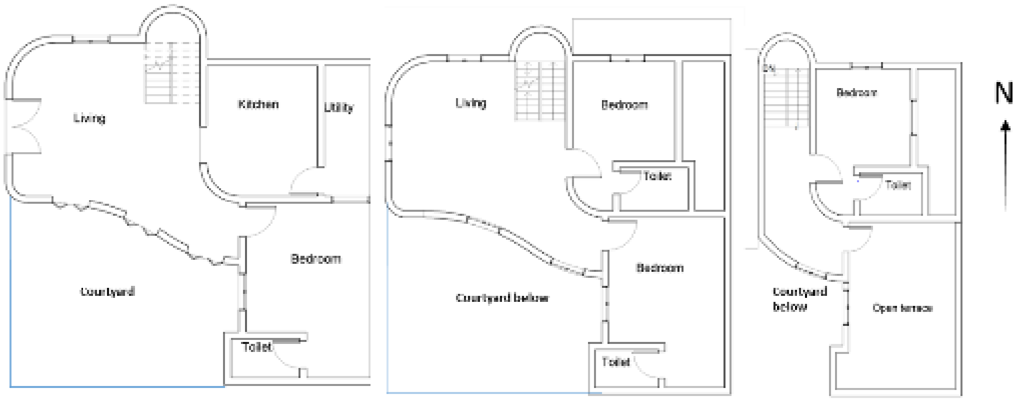


Figure 49. Floor plan of house 3. Ground floor (left), first floor (center), second floor (right).

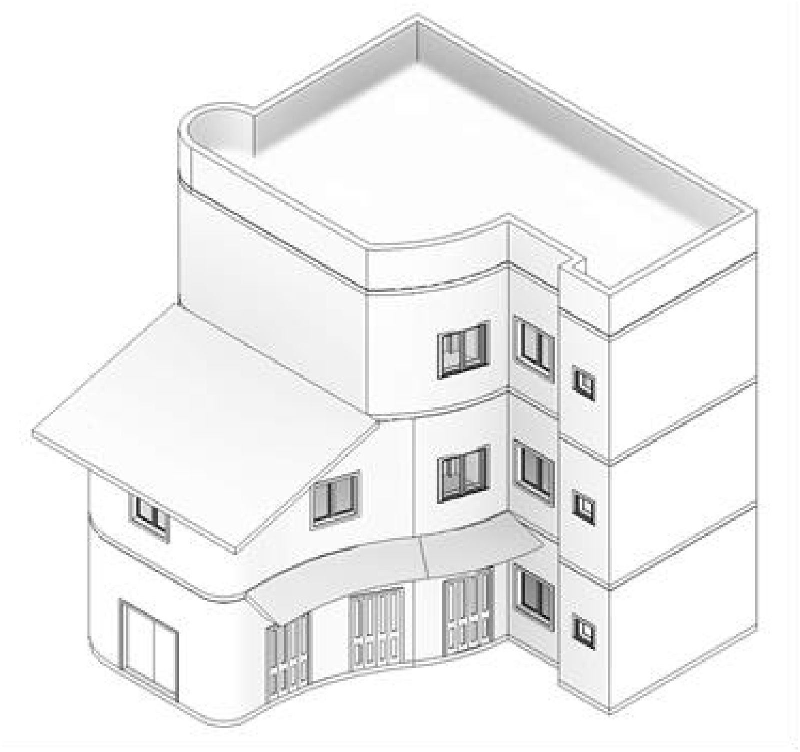


Figure 50. 3D view of house 3 created in Revit software.

Table 36. Data parameters collected for house 3 during single site visit.

Year Constructed	1965
Age (years)	51
Number of Occupants	3
Number of Storeys	Ground + 2
Skylight/Courtyard	No
Mechanical Cooling	6 Ceiling Fans, 2 AC
CO_2 levels (ppm)	580-600
Outdoor Humidity	59%
Indoor Humidity	60%
Outdoor Temperature (°C)	30.8
Outdoor Temperature – feels like (°C)	40
Indoor Temperature (°C)	29.2
Windows	Single Glazed – Teakwood
Wall materials	Laterite, Wire cut brick +Random Rubble with Load Bearing Wall
Wall Thickness (mm)	279
Roof	Filler Tile (100mm thk), Mangalore tiles with Sandwich tile
Floor	Red oxide
Door	Teakwood
Floor Area (m^2)	212
Exterior Wall Area (m^2)	351

Table 37. Actual utility energy consumption at house 3 for six months (KWh).

	Winter			Summer			
	Dec	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Total Power Consumed for six months**
House 3	140	139	106	219	243	267	974

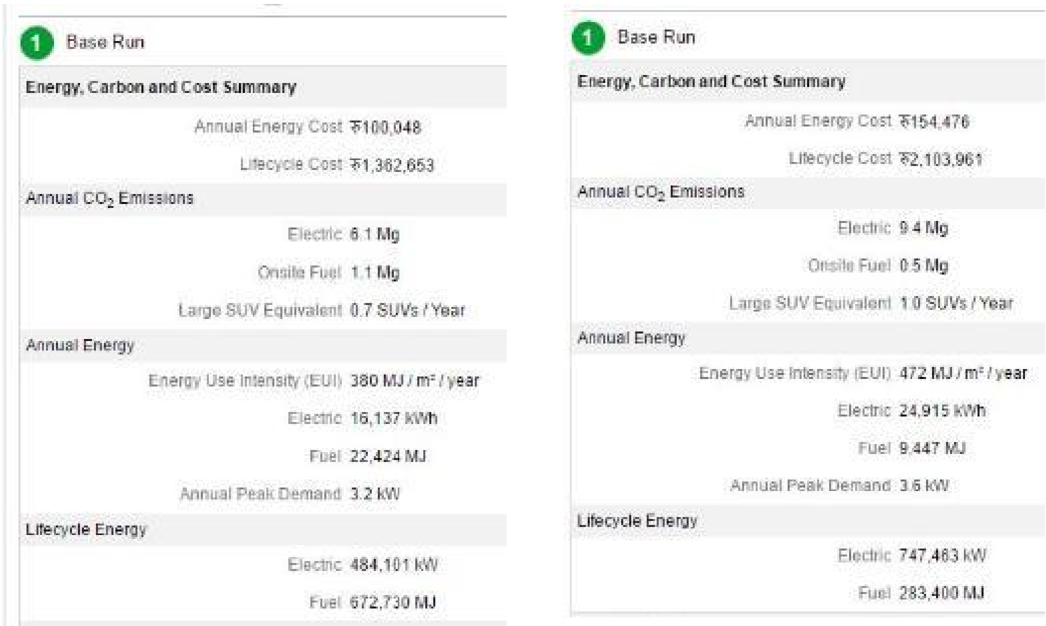
Table 38. Estimated plug load energy consumption of house 3.

Category	**Appliance**	**Quantity**	**Wattage**	**Average Daily Usage (Hours)**	**Average Daily Power Consumed (kWh)**	**Monthly Power Usage (kWh)**	**Annual Power Usage (kWh)**
HVACR	Ceiling Fan	6	100	4.45	0.45	80.10	961.20
HVACR	Air Conditioner (1.5 ton)	2	1500	0.81	1.22	72.90	874.80
HVACR	Refrigerator	1	100	22.33	2.23	66.99	803.88
HVACR	Immersion Rod	1	1000	1.18	1.18	35.40	424.80
HVACR	Geyser	0	3000	0	0.00	0.00	0.00
Lighting	Bulb (FL40)	7	40	2.63	0.11	22.09	265.10
Lighting	Tube light (IL40)	13	40	1.56	0.06	24.34	292.03
Miscellaneous	Computer	2	100	3.00	0.30	18.00	216.00
Miscellaneous	Mixer	1	450	0.47	0.21	**6.35**	76.14
Miscellaneous	Water Pump	1	750	0.68	0.51	15.30	183.60
Miscellaneous	Television	2	100	3.93	0.39	23.58	282.96
Miscellaneous	Washing Machine	1	325	0.71	0.23	6.92	83.07
Miscellaneous	Radio	1	15	2.51	0.04	1.13	13.55
Miscellaneous	Electric Iron	1	750	0.48	0.36	10.80	129.60
Miscellaneous	VCR	1	40	2.14	0.09	2.57	30.82
Miscellaneous	Microwave	1	1000	1.00	1.00	30.00	360.00
Miscellaneous	Vacuum Cleaner	1	750	0.70	0.53	15.75	189.00
	Total					**432.21**	**5186.56**

Table 39. Plug load energy consumption – annual energy consumption and utility cost comparison: existing house 3 vs. modified house 3 (materials upgrade).

House 3 Annual Expenditure Analysis			
Parameter	**Current**	**Modified Materials**	**Cost Benefit**
Annual Electricity Consumed Simulation (kWh)	16136	24914	-8778.00
HVACR (kWh)	3064.68	4731.87	-1667.19
Lighting (kWh)	557.14	860.22	-303.08
Miscellaneous (kWh)	1564.74	2415.96	-851.22
HVACR Cost (INR)	₹ 19,001.73	₹ 29,338.69	-₹ 10,336.96
Lighting Cost (INR)	₹ 3,454.37	₹ 5,333.56	-₹ 1,879.18
Misc. Cost (INR)	₹ 9,701.75	₹ 14,979.52	-₹ 5,277.76
Annual Cost (INR)	**₹ 32,157.86**	**₹ 49,651.76**	**-₹ 17,493.91**
Floor Area (m^2)	212	212	
Annual Cost per m^2 (INR)	₹ 151.69	₹ 234.21	

Figure 51. Sample screenshot of Netatmo weather station reading for house 3.



1 Base Run

Energy, Carbon and Cost Summary

Annual Energy Cost	₹100,048
Lifecycle Cost	₹1,362,653

Annual CO_2 Emissions

Electric	6.1 Mg
Onsite Fuel	1.1 Mg
Large SUV Equivalent	0.7 SUVs / Year

Annual Energy

Energy Use Intensity (EUI)	380 MJ / m² / year
Electric	16,137 kWh
Fuel	22,424 MJ
Annual Peak Demand	3.2 kW

Lifecycle Energy

Electric	484,101 kW
Fuel	672,730 MJ

1 Base Run

Energy, Carbon and Cost Summary

Annual Energy Cost	₹154,476
Lifecycle Cost	₹2,103,961

Annual CO_2 Emissions

Electric	9.4 Mg
Onsite Fuel	0.5 Mg
Large SUV Equivalent	1.0 SUVs / Year

Annual Energy

Energy Use Intensity (EUI)	472 MJ / m² / year
Electric	24,915 kWh
Fuel	9,447 MJ
Annual Peak Demand	3.6 kW

Lifecycle Energy

Electric	747,463 kW
Fuel	283,400 MJ

Figure 52. Energy model output report for house 3 (existing – left versus modified materials – right).

Table 40. Energy model output – cost comparison of energy and fuel consumed for house 3.

	Current	Modified
Electricity Consumption	₹ 100,048.00	₹ 154,475.00
Fuel Consumption	₹ 00.00	₹ 00.00

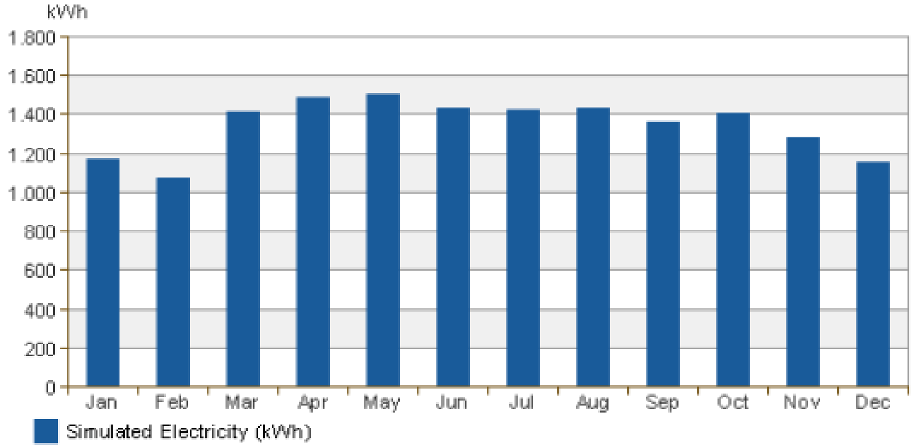


Figure 53. Energy model output – estimated existing house monthly electricity consumption for house 3.

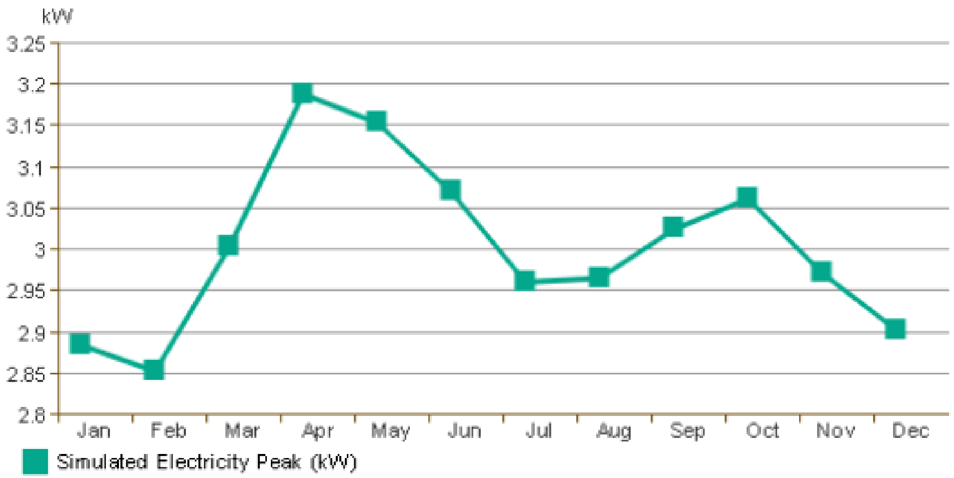


Figure 54. Existing house estimated monthly peak demand for house 3.

Table 41. Energy model output – estimated annual energy use intensity for house 3.

	Current	Modified
Electricity EUI (kWh/m^2/yr)	76	119
Fuel EUI (MJ/m^2/yr)	106	45
Total EUI (MJ/m^2/yr)	380	472

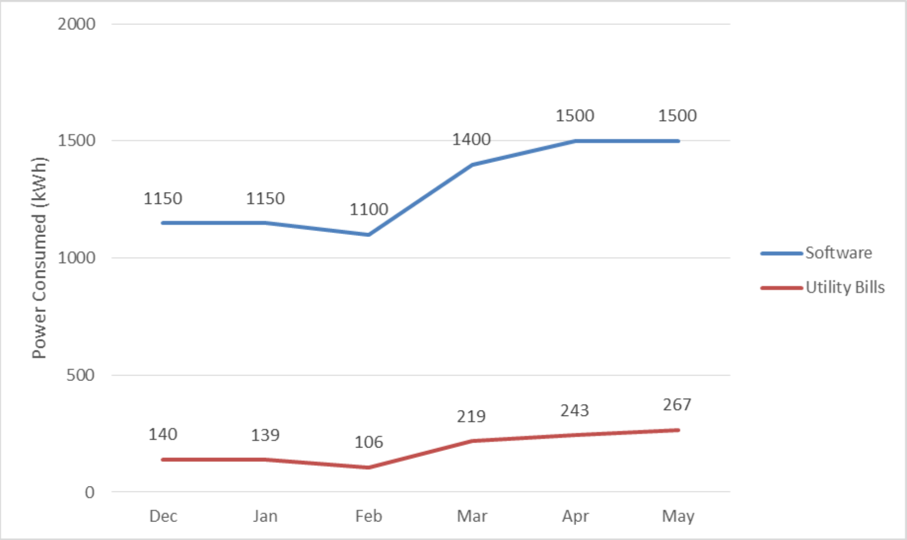


Figure 55. Comparison of the power consumed through the software versus the actual utility bills for house 3.

Appendix 4

House 4 Results

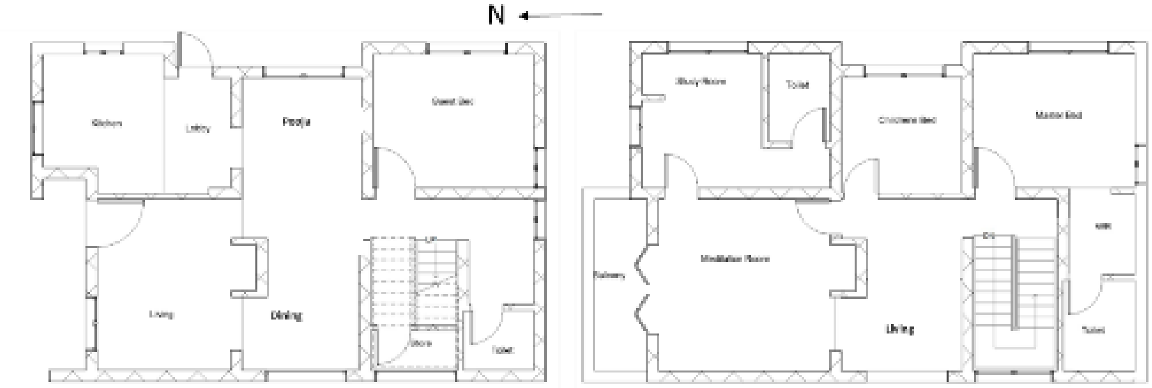


Figure 56. Floor plan for house 4. ground floor (left) and first floor (right).

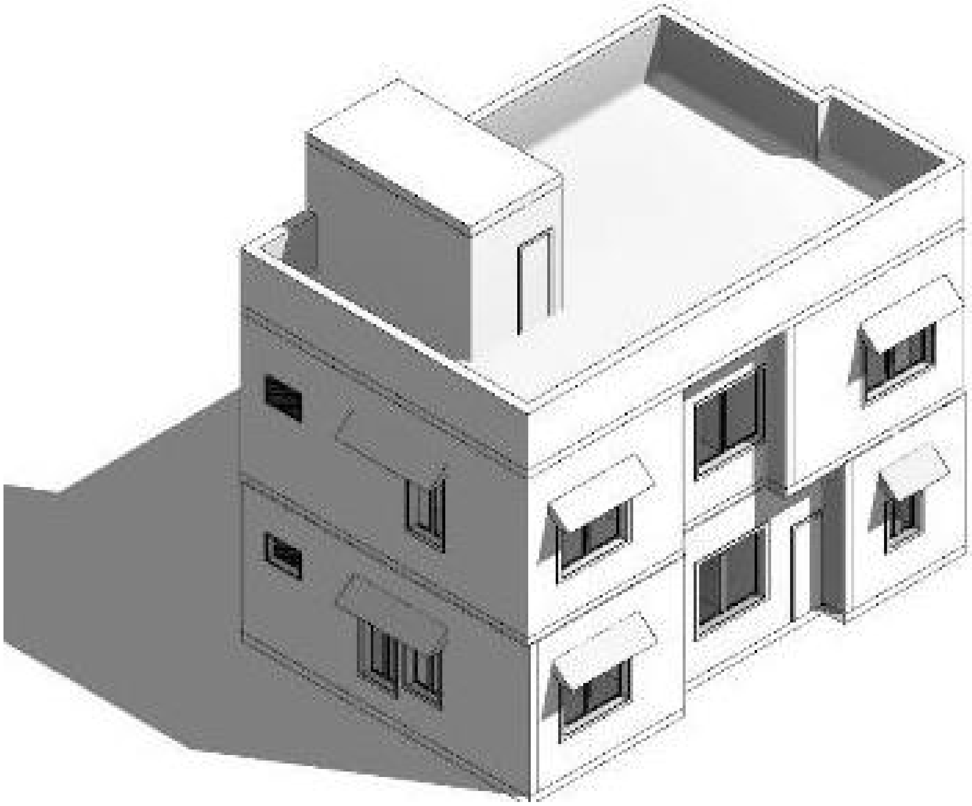


Figure 57. 3D view of house 4 created in Revit software.

Table 42. Data parameters collected for house 4 during single site visit.

Year Constructed	2007
Age (years)	9
Number of Occupants	4
Number of Storeys	Ground + 1
Skylight/Courtyard	Yes
Mechanical Cooling	7 Fans, 4 AC
CO_2 levels (ppm)	940-1000
Outdoor Humidity	61%
Indoor Humidity	72%
Direction	East
Outdoor Temperature (°C)	29.9
Outdoor Temperature – feels like (°C)	39
Indoor Temperature (°C)	31.1
Windows	Single Glazed – Plywood with Polish
Wall materials	RCC with column construction with cement Plaster
Wall Thickness (mm)	230
Roof	RCC Slab with Cement Plaster
Floor	Granite and Ceramic Tiles
Door	Plywood with Polish
Floor Area (m^2)	123
Exterior Wall Area (m^2)	239

Table 43. Actual utility energy consumption at house 4 for six months (KWh).

	Winter			Summer			
	Dec	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Total Power Consumed for six months**
House 4	643	579	707	540	505	470	3444

Table 44. Estimated plug load energy consumption of house 4.

Category	**Appliance**	**Quantity**	**Wattage**	**Average Daily Usage (Hours)**	**Average Daily Power Consumed (kWh)**	**Monthly Power Usage (kWh)**	**Annual Power Usage (kWh)**
HVACR	Ceiling Fan	7	100	4.45	0.45	93.45	1121.40
HVACR	Air Conditioner (1.5 ton)	4	1500	0.81	1.22	145.80	1749.60
HVACR	Refrigerator	1	100	22.33	2.23	66.99	803.88
HVACR	Immersion Rod	0	1000	1.75	1.75	0.00	0.00
HVACR	Geyser	3	3000	1.18	3.54	318.60	3823.20
Lighting	Bulb (FL40)	5	40	2.63	0.11	15.78	189.36
Lighting	Tube light (IL40)	17	40	1.56	0.06	31.82	381.89
Miscellaneous	Computer	1	100	3.00	0.30	9.00	108.00
Miscellaneous	Mixer	1	450	0.47	0.21	6.35	76.14
Miscellaneous	Water Pump	1	750	0.68	0.51	15.30	183.60
Miscellaneous	Television	2	100	3.93	0.39	23.58	282.96
Miscellaneous	Washing Machine	1	325	0.71	0.23	6.92	83.07
Miscellaneous	Radio	1	15	2.51	0.04	1.13	13.55
Miscellaneous	Electric Iron	1	750	0.48	0.36	10.80	129.60
Miscellaneous	VCR	2	40	2.14	0.09	5.14	61.63
Miscellaneous	Microwave	1	1000	1.00	1.00	30.00	360.00
Miscellaneous	Vacuum Cleaner	1	750	0.70	0.53	15.75	189.00
	Total					**796.41**	**9556.88**

Table 45. Plug load energy consumption - annual energy consumption and utility cost comparison: existing house 4 vs. modified house 4 (materials upgrade).

House 4 Annual Expenditure Analysis			
Parameter	**Current**	**Modified Materials**	**Cost Benefit**
Annual Electricity Consumed Simulation (kWh)	30801	16755	14046.00
HVACR (kWh)	7498.08	4078.77	3419.31
Lighting (kWh)	571.25	310.75	260.50
Miscellaneous (kWh)	1487.56	809.19	678.36
HVACR Cost (INR)	₹ 46,489.85	₹ 25,289.35	₹ 21,200.49
Lighting Cost (INR)	₹ 3,541.87	₹ 1,926.69	₹ 1,615.18
Misc. Cost (INR)	₹ 9,223.19	₹ 5,017.19	₹ 4,206.00
Annual Cost (INR)	**₹ 59,254.91**	**₹ 32,233.24**	**₹ 27,021.67**
Floor Area (m^2)	123	123	
Annual Cost per m^2 (INR)	₹ 19,751.64	₹ 10,744.41	

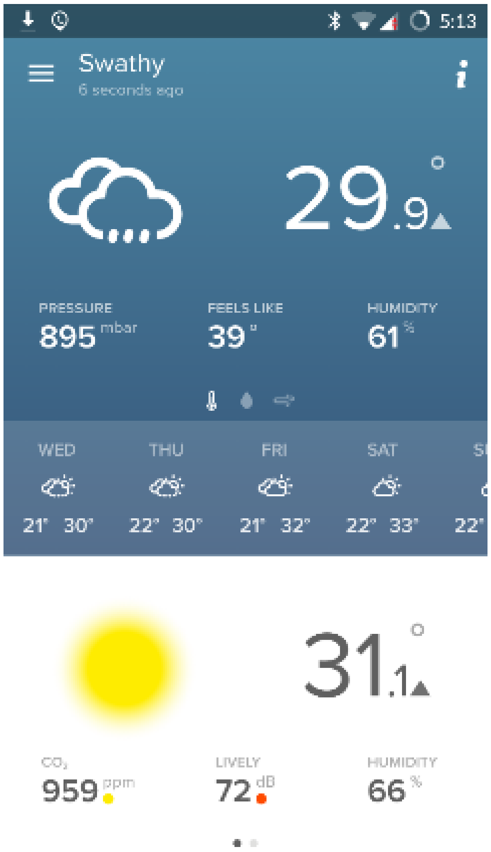
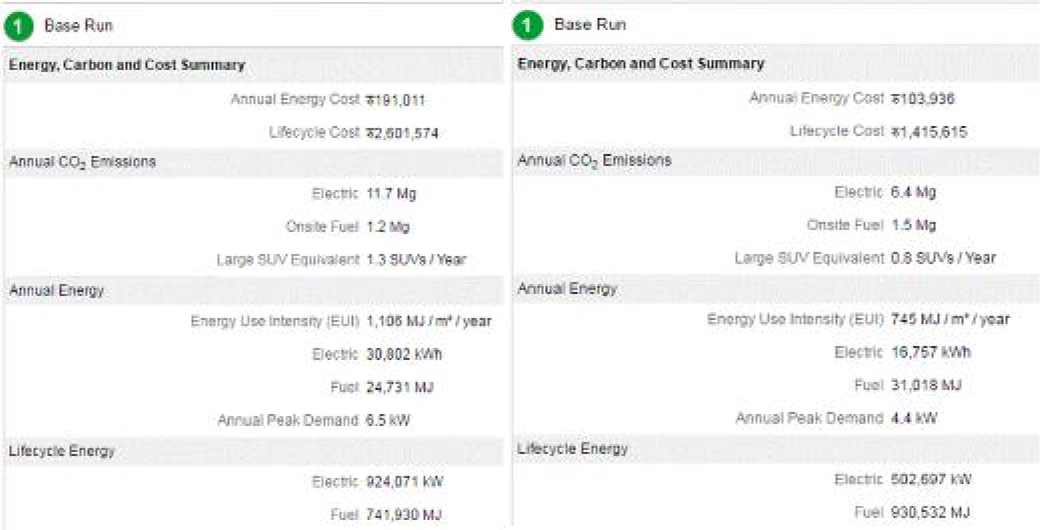


Figure 58. Sample screenshot of Netatmo weather station reading for house 4.



1 Base Run

Energy, Carbon and Cost Summary	
Annual Energy Cost	₹191,011
Lifecycle Cost	₹2,601,574
Annual CO_2 Emissions	
Electric	11.7 Mg
Onsite Fuel	1.2 Mg
Large SUV Equivalent	1.3 SUVs / Year
Annual Energy	
Energy Use Intensity (EUI)	1,106 MJ / m² / year
Electric	30,802 kWh
Fuel	24,731 MJ
Annual Peak Demand	6.5 kW
Lifecycle Energy	
Electric	924,071 kW
Fuel	741,930 MJ

1 Base Run

Energy, Carbon and Cost Summary	
Annual Energy Cost	₹103,936
Lifecycle Cost	₹1,415,615
Annual CO_2 Emissions	
Electric	6.4 Mg
Onsite Fuel	1.5 Mg
Large SUV Equivalent	0.8 SUVs / Year
Annual Energy	
Energy Use Intensity (EUI)	745 MJ / m² / year
Electric	16,757 kWh
Fuel	31,018 MJ
Annual Peak Demand	4.4 kW
Lifecycle Energy	
Electric	502,697 kW
Fuel	930,532 MJ

Figure 59. Energy model output report for house 4. (existing-left versus modified materials-right).

Table 46. Energy model output - cost comparison of energy and fuel consumed for house 4.

	Current	**Modified**
Electricity Consumption	₹ 190,975.00	₹ 103,891.00
Fuel Consumption	₹ 37.00	₹ 46.00

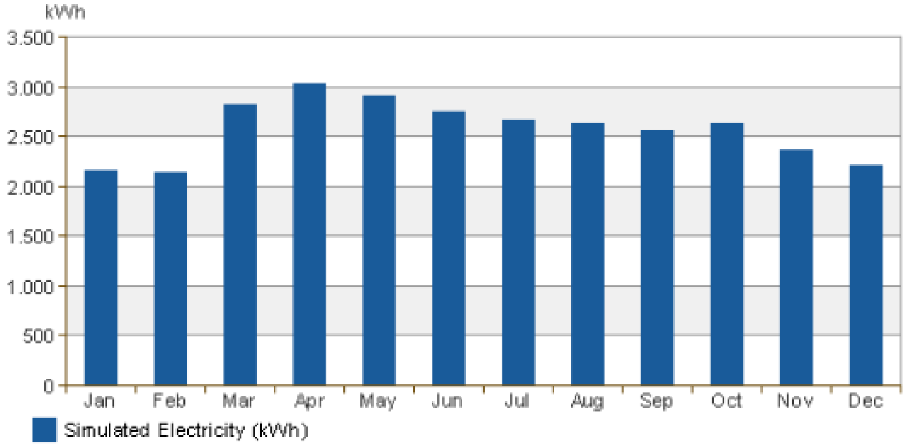


Figure 60. Energy model output – estimated existing house monthly electricity consumption for house 4.

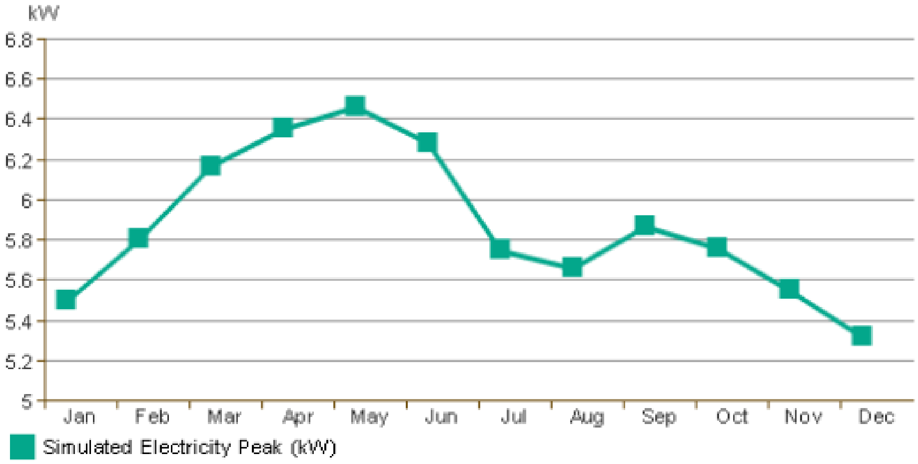


Figure 61. Existing house estimated monthly peak demand for house 4.

Table 47. Energy model output – estimated annual energy use intensity for house 4.

	Current	Modified
Electricity EUI (kWh/m^2/yr)	251	137
Fuel EUI (MJ/m^2/yr)	202	253
Total EUI (MJ/m^2/yr)	1106	745

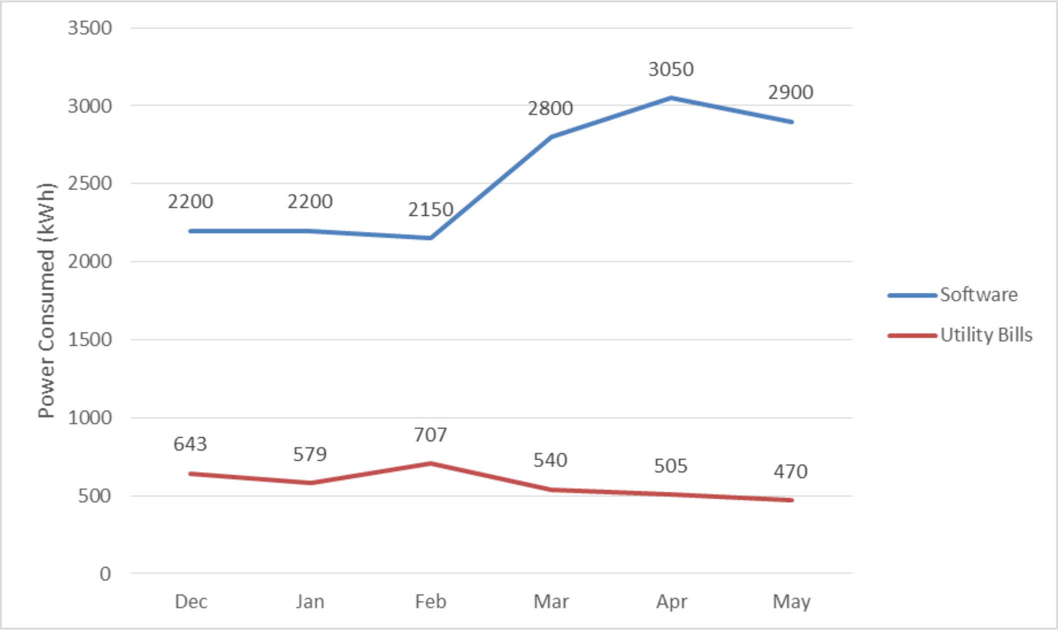


Figure 62. Comparison of the power consumed through the software versus the actual utility bills for house 4.

Appendix 5

House 5 Results

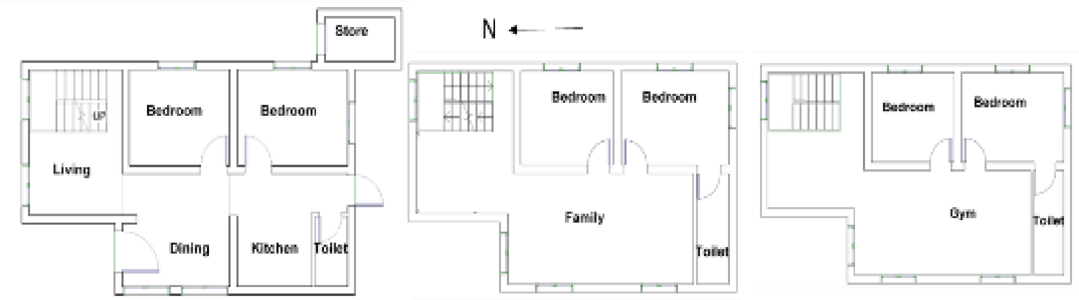


Figure 63. Floor plan for house 5. ground floor (left), first floor (center), second floor (right).

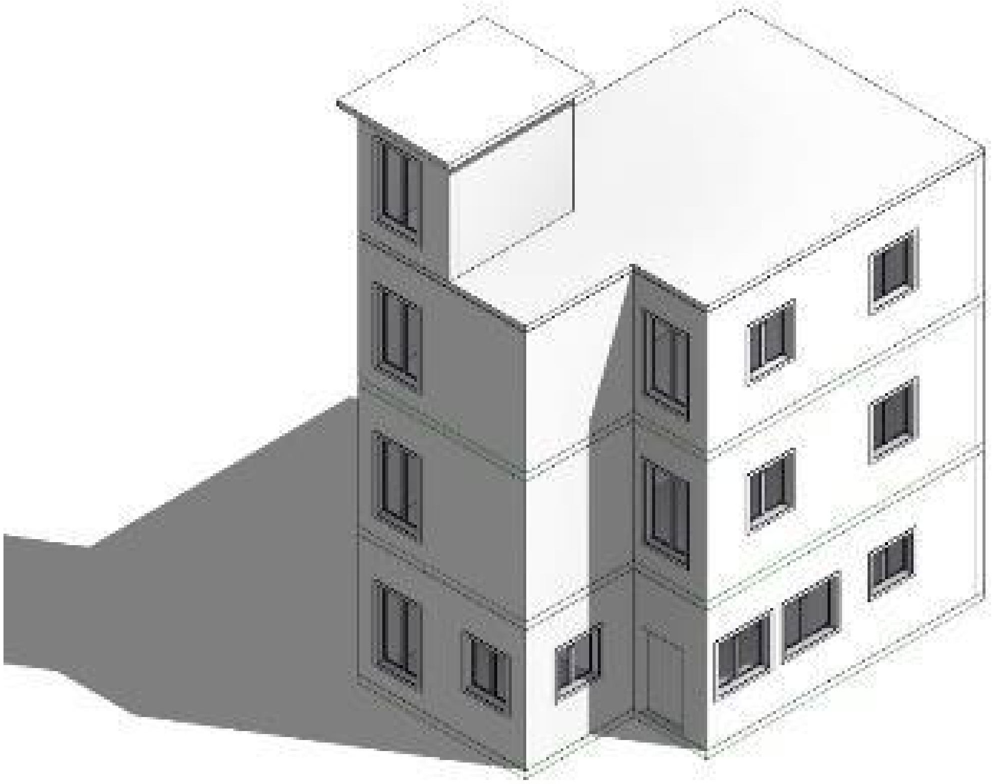


Figure 64. 3D view of house 5 created in Revit software.

Table 48. Data parameters collected for house 5 during single site visit.

Year Constructed	2001
Age (years)	15
Number of Occupants	4
Number of Storeys	Ground + 1
Skylight/Courtyard	No
Mechanical Cooling	10 Fans, 9 AC
CO_2 levels (ppm)	830-840
Outdoor Humidity	63%
Indoor Humidity	Not captured
Outdoor Temperature (°C)	29.2
Outdoor Temperature – feels like (°C)	38
Indoor Temperature (°C)	29.3
Windows	Single Glazed – Teakwood
Wall materials	RCC with column construction with cement Plaster
Wall Thickness (mm)	230
Roof	RCC Slab with Cement Plaster
Floor	Granite and Vitrified Tiles
Door	Teakwood
Floor Area (m^2)	186
Exterior Wall Area (m^2)	379

Table 49. Actual utility energy consumption at house 5 for six months (KWh).

	Winter			Summer			
	Dec	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Total Power Consumed for six months**
House 5	489	431	476	632	645	645	3318

Table 50. Estimated plug load energy consumption of house 5.

Category	**Appliance**	**Quantity**	**Wattage**	**Average Daily Usage (Hours)**	**Average Daily Power Consumed (kWh)**	**Monthly Power Usage (kWh)**	**Annual Power Usage (kWh)**
HVACR	Ceiling Fan	10	100	4.45	0.45	133.50	1602.00
HVACR	Air Conditioner (1.5 ton)	9	1500	0.81	1.22	328.05	3936.60
HVACR	Refrigerator	1	100	22.33	2.23	66.99	803.88
HVACR	Immersion Rod	0	1000	1.75	1.75	0.00	0.00
HVACR	Geyser	3	3000	1.18	3.54	318.60	3823.20
Lighting	Bulb (FL40)	5	40	2.63	0.11	15.78	189.36
Lighting	Tube light (IL40)	17	40	1.56	0.06	31.82	381.89
Miscellaneous	Computer	1	100	3.00	0.30	9.00	108.00
Miscellaneous	Mixer	1	450	0.47	0.21	**6.35**	76.14
Miscellaneous	Water Pump	1	750	0.68	0.51	15.30	183.60
Miscellaneous	Television	4	100	3.93	0.39	47.16	565.92
Miscellaneous	Washing Machine	1	325	0.71	0.23	6.92	83.07
Miscellaneous	Radio	3	15	2.51	0.04	3.39	40.66
Miscellaneous	Electric Iron	1	750	0.48	0.36	10.80	129.60
Miscellaneous	VCR	4	40	2.14	0.09	10.27	123.26
Miscellaneous	Microwave	1	1000	1.00	1.00	30.00	360.00
Miscellaneous	Vacuum Cleaner	1	750	0.70	0.53	15.75	189.00
	Total					**1049.68**	**12596.18**

Table 51. Plug load energy consumption - annual energy consumption and utility cost comparison: existing house 5 vs. modified house 5 (materials upgrade).

House 5 Annual Expenditure Analysis			
Parameter	**Current**	**Modified Materials**	**Cost Benefit**
Annual Electricity Consumed Simulation (kWh)	36379	22649	13730.00
HVACR (kWh)	10165.68	6328.99	3836.69
Lighting (kWh)	571.25	355.65	215.60
Miscellaneous (kWh)	1859.26	1157.54	701.71
HVACR Cost (INR)	₹ 63,029.59	₹ 39,241.24	₹ 23,788.35
Lighting Cost (INR)	₹ 3,541.87	₹ 2,205.11	₹ 1,336.76
Misc. Cost (INR)	₹ 11,527.82	₹ 7,177.04	₹ 4,350.78
Annual Cost (INR)	**₹ 78,099.28**	**₹ 48,623.40**	**₹ 29,475.88**
Floor Area (m^2)	186	186	
Annual Cost per m^2 (INR)	₹ 19,524.82	₹ 12,155.85	

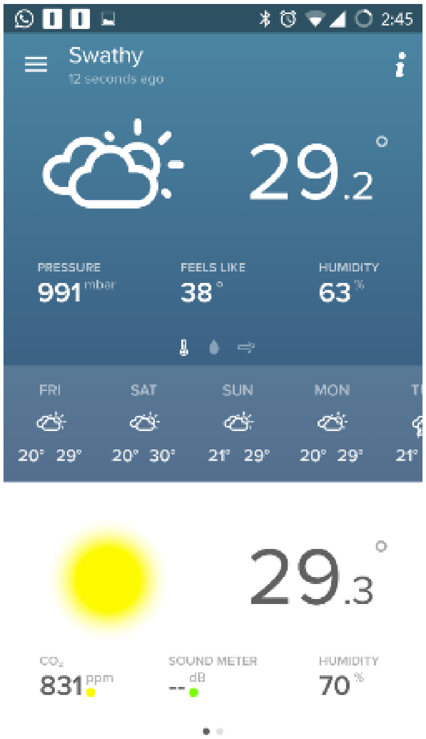
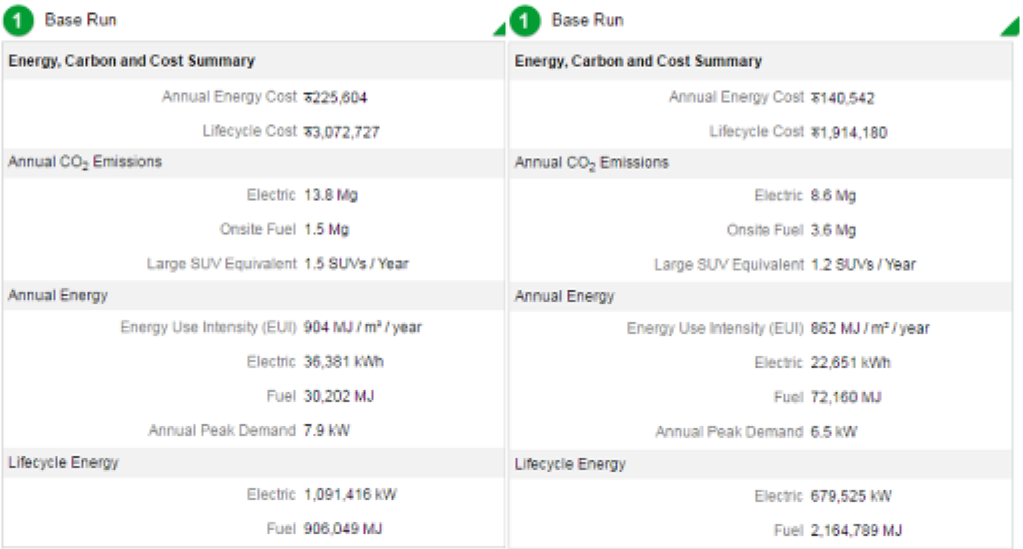


Figure 65. Sample screenshot of Netatmo weather station reading for house 5.



1 Base Run

Energy, Carbon and Cost Summary

Annual Energy Cost	₹225,604
Lifecycle Cost	₹3,072,727
Annual CO_2 Emissions	
Electric	13.8 Mg
Onsite Fuel	1.5 Mg
Large SUV Equivalent	1.5 SUVs / Year
Annual Energy	
Energy Use Intensity (EUI)	904 MJ / m² / year
Electric	36,381 kWh
Fuel	30,202 MJ
Annual Peak Demand	7.9 kW
Lifecycle Energy	
Electric	1,091,416 kW
Fuel	906,049 MJ

1 Base Run

Energy, Carbon and Cost Summary

Annual Energy Cost	₹140,542
Lifecycle Cost	₹1,914,180
Annual CO_2 Emissions	
Electric	8.6 Mg
Onsite Fuel	3.6 Mg
Large SUV Equivalent	1.2 SUVs / Year
Annual Energy	
Energy Use Intensity (EUI)	862 MJ / m² / year
Electric	22,651 kWh
Fuel	72,160 MJ
Annual Peak Demand	6.5 kW
Lifecycle Energy	
Electric	679,525 kW
Fuel	2,164,789 MJ

Figure 66. Energy model output report for house 5. (existing - left versus modified materials - right).

Table 52. Energy model output – cost comparison of energy and fuel consumed for house 5.

	Current	Modified
Electricity Consumption	₹ 225,559.00	₹ 140,435.00
Fuel Consumption	₹ 45.00	₹ 107.00

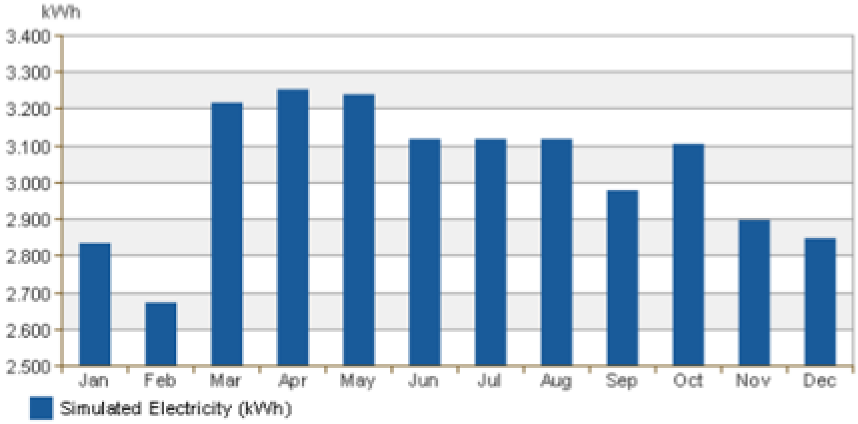


Figure 67. Energy model output – estimated existing house monthly electricity consumption for house 5.

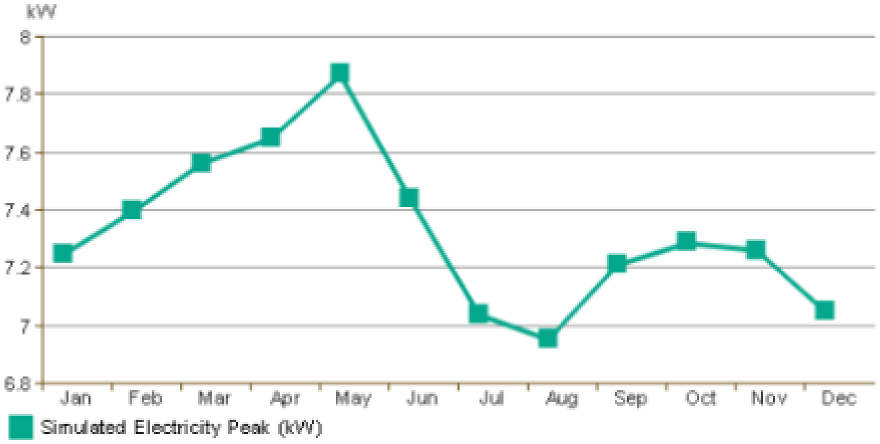


Figure 68. Existing house estimated monthly peak demand for house 5.

Table 53. Energy model output – estimated annual energy use intensity of house 5.

	Current	**Modified**
Electricity EUI (kWh/m^2/yr)	204	127
Fuel EUI (MJ/m^2/yr)	169	405
Total EUI (MJ/m^2/yr)	904	862

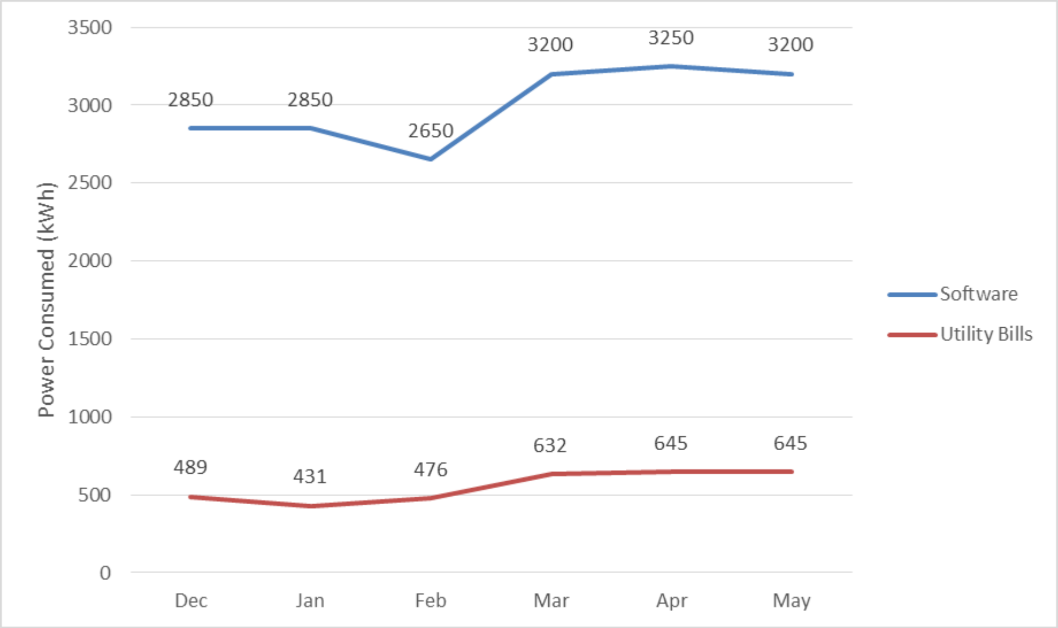


Figure 69. Comparison of the power consumed through the software versus the actual utility bills for house 5.

Appendix 6

House 6 Results

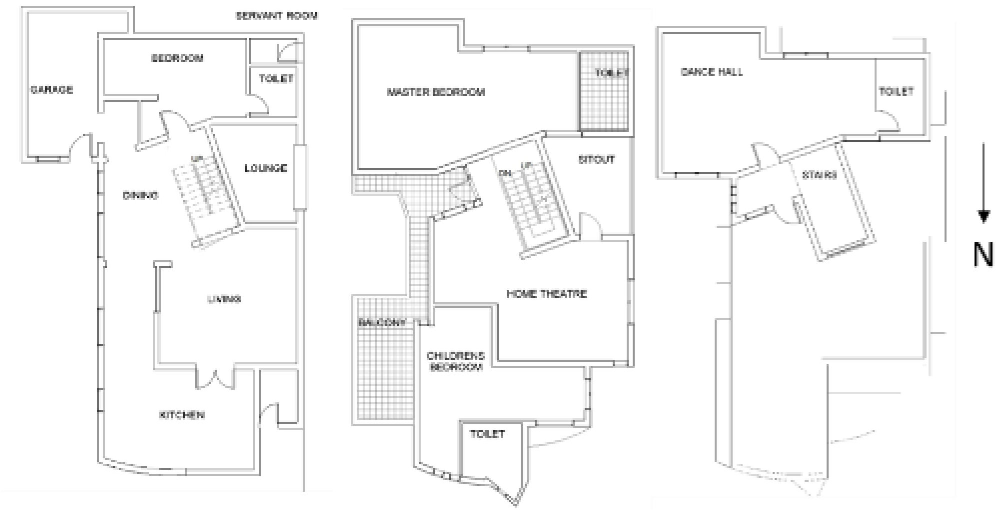


Figure 70. Floor plan of house 6. ground floor (left), first floor (center), second floor (right).

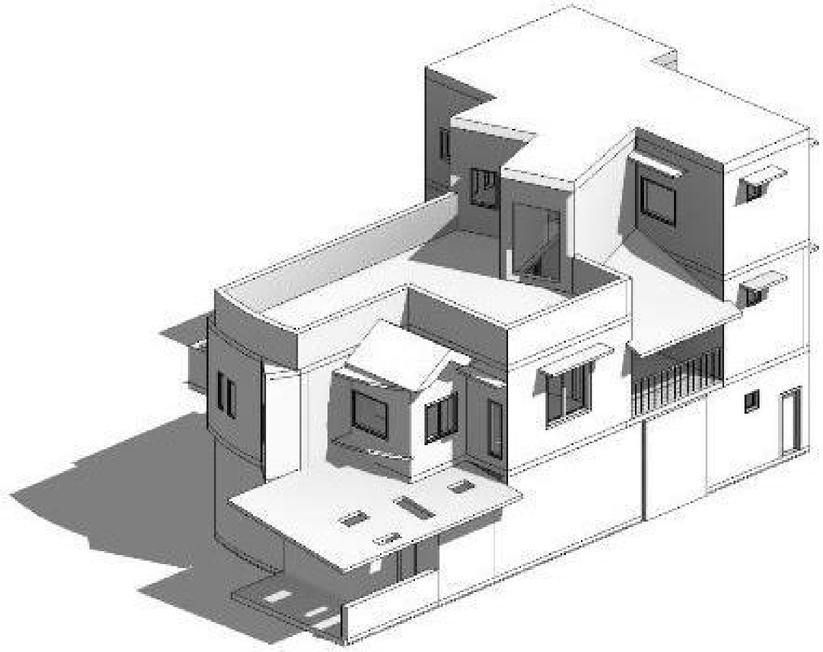


Figure 71. 3D view of house 6 created in Revit software.

Table 54. Data parameters collected for house 6 during single site visit.

Year Constructed	2009
Age (years)	7
Number of Occupants	3
Number of Storeys	Ground + 2
Skylight/Courtyard	No
Mechanical Cooling	9 Fans, 6 AC
CO_2 levels (ppm)	1015-1040
Outdoor Humidity	61%
Indoor Humidity	48%
Outdoor Temperature (°C)	29.9
Outdoor Temperature – feels like (°C)	39
Indoor Temperature (°C)	30.6
Windows	Single Glazed – Timber frame
Wall materials	Concrete with column construction with cement Plaster
Wall Thickness (mm)	230
Roof	RCC Slab with Cement Plaster
Floor	Granite
Door	Plywood
Floor Area (m^2)	238
Exterior Wall Area (m^2)	438

Table 55. Actual utility energy consumption at house 6 for six months (KWh).

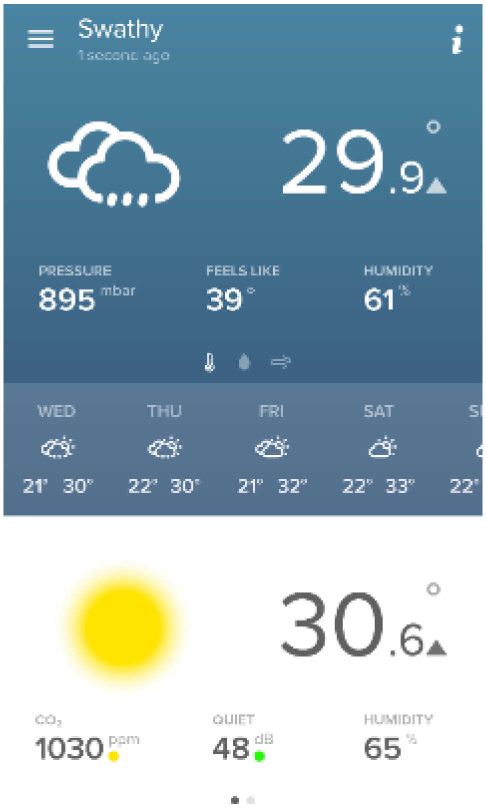
	Winter			Summer			
	Dec	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Total Power Consumed for six months**
House 6	465	428	391	844	626	614	3368

Table 56. Estimated plug load energy consumption of house 6.

Category	**Appliance**	**Quantity**	**Wattage**	**Average Daily Usage (Hours)**	**Average Daily Power Consumed (kWh)**	**Monthly Power Usage (kWh)**	**Annual Power Usage (kWh)**
HVACR	Ceiling Fan	9	100	4.45	0.45	120.15	1441.80
HVACR	Air Conditioner (1.5 ton)	6	1500	0.81	1.22	218.70	2624.40
HVACR	Refrigerator	1	100	22.33	2.23	66.99	803.88
HVACR	Immersion Rod	0	1000	1.18	1.18	0.00	0.00
HVACR	Geyser	4	3000	1.18	3.54	424.80	5097.60
Lighting	Bulb (FL40)	10	40	2.63	0.11	31.56	378.72
Lighting	Tube light (IL40)	18	40	1.56	0.06	33.70	404.35
Miscellaneous	Computer	1	100	3.00	0.30	9.00	108.00
Miscellaneous	Mixer	1	450	0.47	0.21	6.35	76.14
Miscellaneous	Water Pump	1	750	0.68	0.51	15.30	183.60
Miscellaneous	Television	3	100	3.93	0.39	35.37	424.44
Miscellaneous	Washing Machine	1	325	0.71	0.23	6.92	83.07
Miscellaneous	Radio	1	15	2.51	0.04	1.13	13.55
Miscellaneous	Electric Iron	1	750	0.48	0.36	10.80	129.60
Miscellaneous	VCR	3	40	2.14	0.09	7.70	92.45
Miscellaneous	Microwave	1	1000	1.00	1.00	30.00	360.00
Miscellaneous	Vacuum Cleaner	1	750	0.70	0.53	15.75	189.00
	Total					**1034.22**	**12410.60**

Table 57. Plug load energy consumption - annual energy consumption and utility cost comparison: existing house 6 vs. modified house 6 (materials upgrade).

House 6 Annual Expenditure Analysis			
Parameter	**Current**	**Modified Materials**	**Cost Benefit**
Annual Electricity Consumed Simulation (kWh)	28198	26208	1990.00
HVACR (kWh)	9967.68	9264.24	703.44
Lighting (kWh)	783.07	727.81	55.26
Miscellaneous (kWh)	1659.85	1542.71	117.14
HVACR Cost (INR)	₹ 61,801.94	₹ 57,440.43	₹ 4,361.51
Lighting Cost (INR)	₹ 4,855.23	₹ 4,512.58	₹ 342.65
Misc. Cost (INR)	₹ 10,291.47	₹ 9,565.18	₹ 726.29
Annual Cost (INR)	**₹ 76,948.64**	**₹ 71,518.19**	**₹ 5,430.45**
Floor Area (m^2)	238	238	
Annual Cost per m^2 (INR)	₹ 15,389.73	₹ 14,303.64	


Swathy
1second ago

29.9°

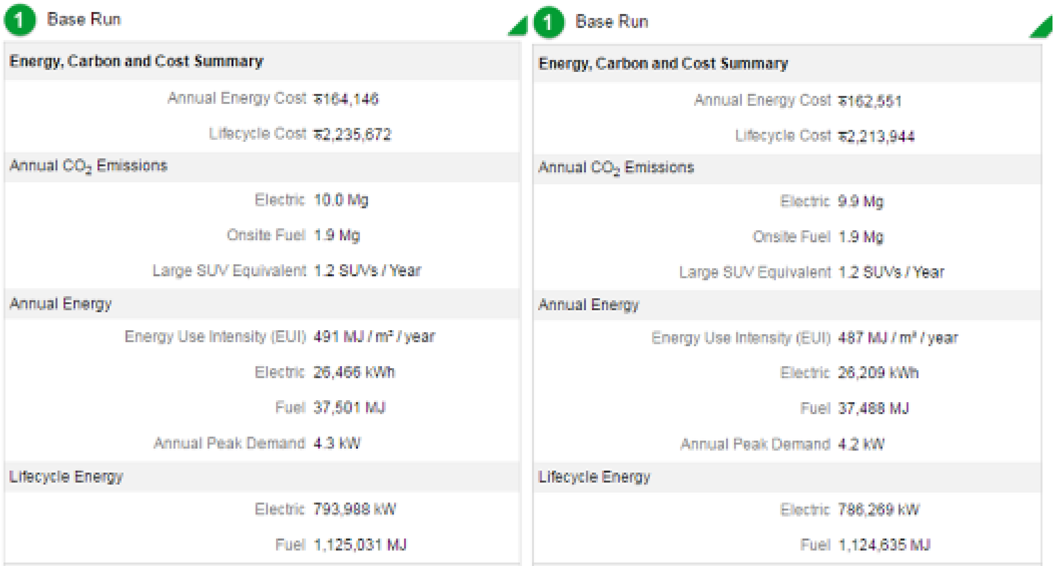
PRESSURE 895 mbar
FEELS LIKE 39°
HUMIDITY 61 %

WED	THU	FRI	SAT	
21° 30°	22° 30°	21° 32°	22° 33°	22°

30.6°

CO_2 1030 ppm
QUIET 48 dB
HUMIDITY 65 %

Figure 72. Sample Screenshot of Netatmo weather station reading for house 6.


1 Base Run

Energy, Carbon and Cost Summary

Annual Energy Cost ₹164,146

Lifecycle Cost ₹2,235,672

Annual CO_2 Emissions

Electric 10.0 Mg

Onsite Fuel 1.9 Mg

Large SUV Equivalent 1.2 SUVs / Year

Annual Energy

Energy Use Intensity (EUI) 491 MJ / m² / year

Electric 26,466 kWh

Fuel 37,501 MJ

Annual Peak Demand 4.3 kW

Lifecycle Energy

Electric 793,988 kW

Fuel 1,125,031 MJ

1 Base Run

Energy, Carbon and Cost Summary

Annual Energy Cost ₹162,551

Lifecycle Cost ₹2,213,944

Annual CO_2 Emissions

Electric 9.9 Mg

Onsite Fuel 1.9 Mg

Large SUV Equivalent 1.2 SUVs / Year

Annual Energy

Energy Use Intensity (EUI) 487 MJ / m² / year

Electric 26,209 kWh

Fuel 37,488 MJ

Annual Peak Demand 4.2 kW

Lifecycle Energy

Electric 786,269 kW

Fuel 1,124,635 MJ

Figure 73. Energy model output report for house 6. (existing - left versus modified materials - right).

Table 58. Energy model output – cost comparison of energy and fuel consumed for house 6.

	Current	**Modified**
Electricity Consumption	₹ 174,837.00	₹ 162,495.00
Fuel Consumption	₹ 56.00	₹ 55.00

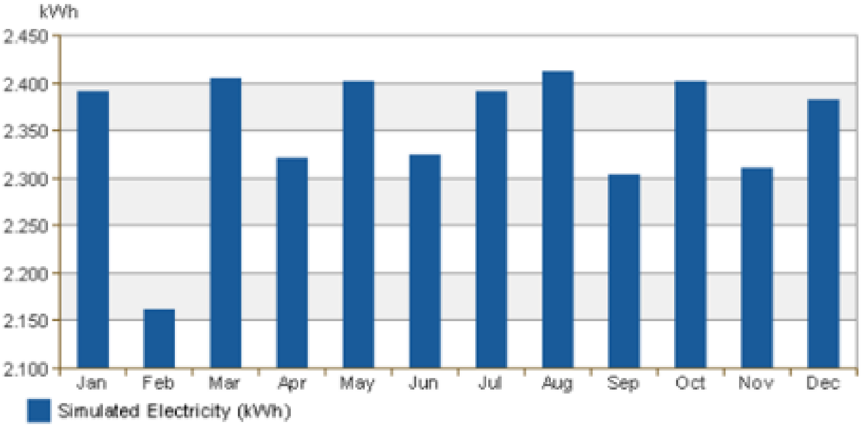


Figure 74. Energy model output – estimated existing house monthly electricity consumption for house 6.

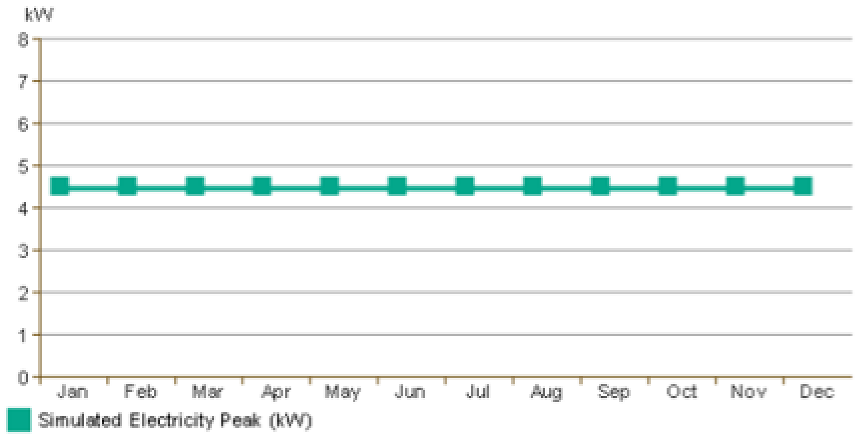


Figure 75. Existing house estimated monthly peak demand for house 6.

Table 59. Energy model output – estimated annual energy use intensity for house 6.

	Current	**Modified**
Electricity EUI (kWh/m^2/yr)	104	97
Fuel EUI (MJ/m^2/yr)	139	139
Total EUI (MJ/m^2/yr)	514	487

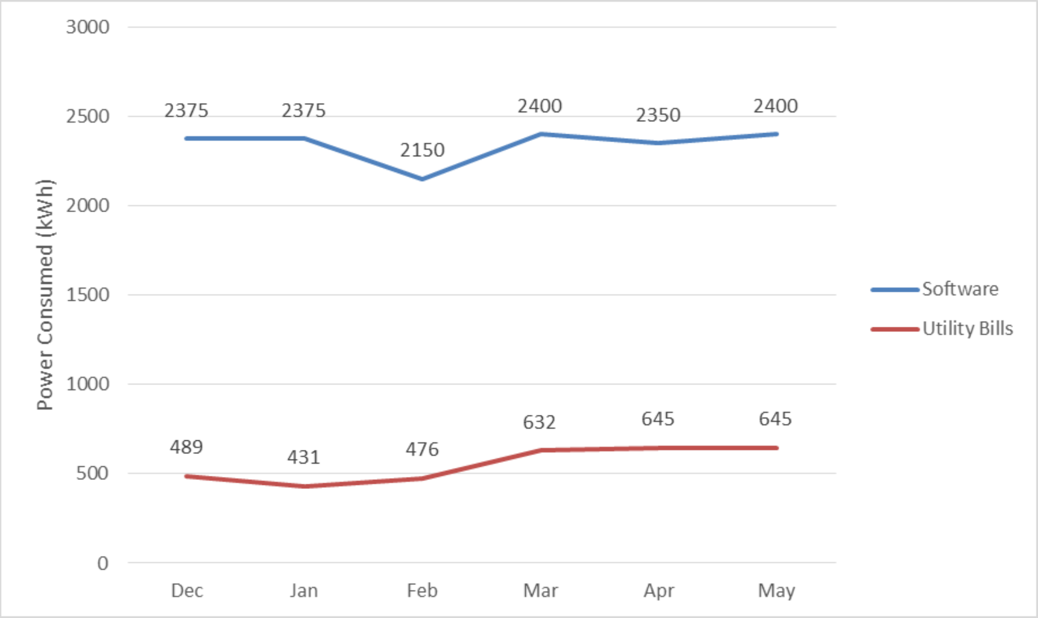


Figure 76. Comparison of the power consumed through the software versus the actual utility bills for house 6.

Appendix 7

House 7 Results

Figure 77. Floor plan for house 7. ground floor (left), first floor (right).

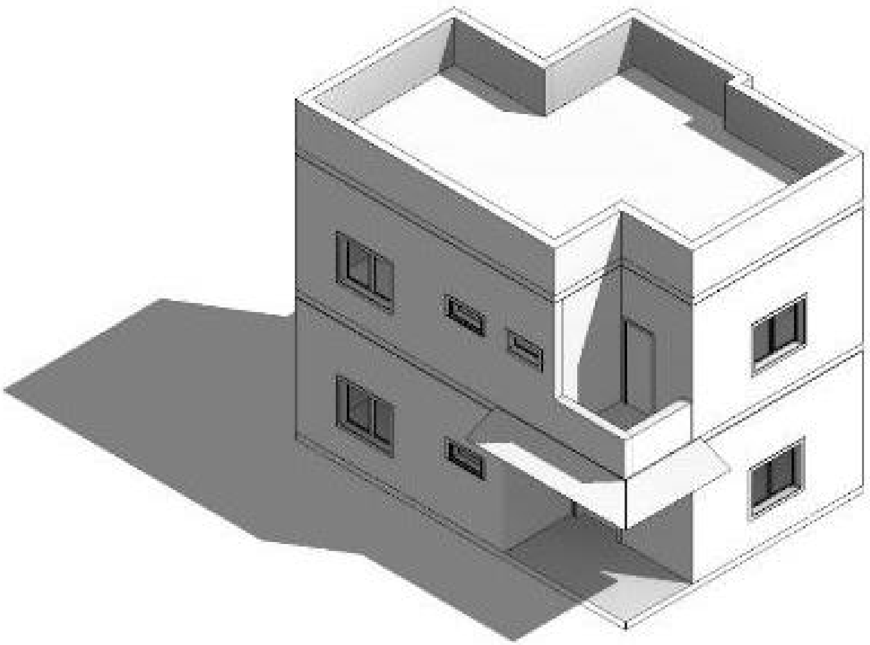


Figure 78. 3D View of house 7 created in Revit software.

Table 60. Data parameters collected for House 7 during single site visit.

Year Constructed	2003
Age (years)	13
Number of Occupants	4
Number of Storeys	Ground + 1
Skylight/Courtyard	No
Mechanical Cooling	7 Fans, 6 AC
CO_2 levels (ppm)	1020-1060
Outdoor Humidity	61%
Indoor Humidity	65%
Outdoor Temperature (°C)	30.5
Outdoor Temperature – feels like (°C)	40
Indoor Temperature (°C)	30.9
Windows	Single Glazed – Oakwood
Wall materials	Concrete block with column construction with cement Plaster
Wall Thickness (mm)	230
Roof	RCC Slab with concrete tile
Floor	Vitrified Tile
Door	Oakwood
Floor Area (m^2)	77
Exterior Wall Area (m^2)	209

Table 61. Actual utility energy consumption at house 7 for six months (KWh).

	Winter			Summer			
	Dec	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Total Power Consumed for six months**
House 7	582	536	595	814	821	762	4110

Table 62. Estimated plug load energy consumption of house 7.

Category	**Appliance**	**Quantity**	**Wattage**	**Average Daily Usage (Hours)**	**Average Daily Power Consumed (kWh)**	**Monthly Power Usage (kWh)**	**Annual Power Usage (kWh)**
HVACR	Ceiling Fan	7	100	4.45	0.45	93.45	1121.40
HVACR	Air Conditioner (1.5 ton)	6	1500	0.81	1.22	218.70	2624.40
HVACR	Refrigerator	1	100	22.33	2.23	66.99	803.88
HVACR	Immersion Rod	0	1000	1.75	1.75	0.00	0.00
HVACR	Geyser	3	3000	1.18	3.54	318.60	3823.20
Lighting	Bulb (FL40)	6	40	2.63	0.11	18.94	227.23
Lighting	Tube light (IL40)	12	40	1.56	0.06	22.46	269.57
Miscellaneous	Computer	2	100	3.00	0.30	18.00	216.00
Miscellaneous	Mixer	1	450	0.47	0.21	**6.35**	76.14
Miscellaneous	Water Pump	1	750	0.68	0.51	15.30	183.60
Miscellaneous	Television	5	100	3.93	0.39	58.95	707.40
Miscellaneous	Washing Machine	1	325	0.71	0.23	6.92	83.07
Miscellaneous	Radio	2	15	2.51	0.04	2.26	27.11
Miscellaneous	Electric Iron	1	750	0.48	0.36	10.80	129.60
Miscellaneous	VCR	5	40	2.14	0.09	12.84	154.08
Miscellaneous	Microwave	1	1000	1.00	1.00	30.00	360.00
Miscellaneous	Vacuum Cleaner	1	750	0.70	0.53	15.75	189.00
	Total					**916.31**	**10995.68**

Table 63. Plug load energy consumption - annual energy consumption and utility cost comparison: existing house 7 vs. modified house 7 (materials upgrade).

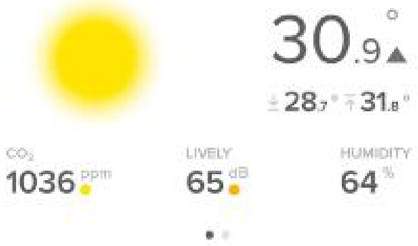
House 7 Annual Expenditure Analysis			
Parameter	**Current**	**Modified Materials**	**Cost Benefit**
Annual Electricity Consumed Simulation (kWh)	11595	6980	4615.00
HVACR (kWh)	8372.88	5040.34	3332.54
Lighting (kWh)	496.80	299.07	197.73
Miscellaneous (kWh)	2126.00	1279.82	846.18
HVACR Cost (INR)	₹ 51,913.81	₹ 31,251.26	₹ 20,662.55
Lighting Cost (INR)	₹ 3,080.28	₹ 1,854.28	₹ 1,226.00
Misc. Cost (INR)	₹ 13,181.68	₹ 7,935.16	₹ 5,246.53
Annual Cost (INR)	**₹ 68,175.77**	**₹ 41,040.70**	**₹ 27,135.07**
Floor Area (m^2)	77	77	
Annual Cost per m^2 (INR)	₹ 34,087.88	₹ 20,520.35	

Swathy
2 minutes ago

30.5°

PRESSURE 895 mbar
FEELS LIKE 40°
HUMIDITY 61 %

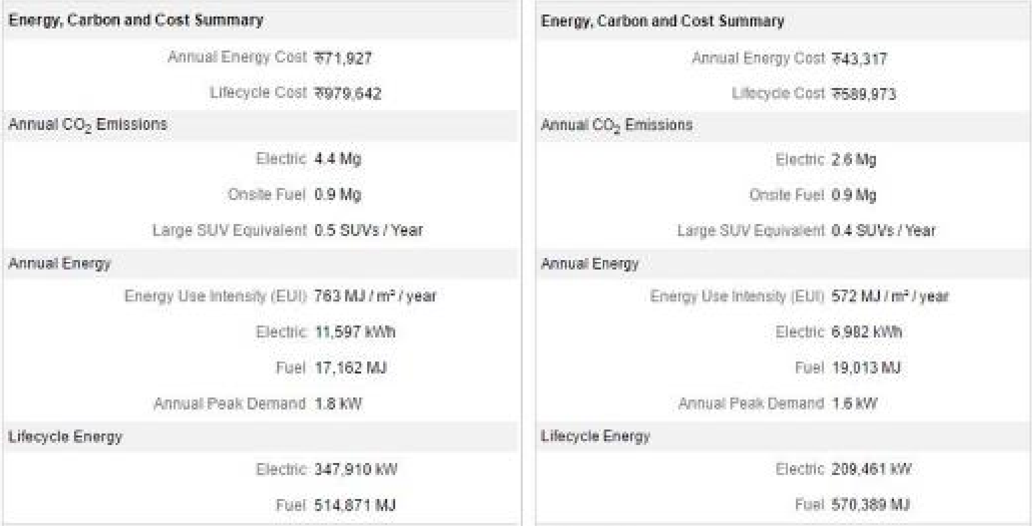
WED	THU	FRI	SAT
21° 30°	22° 30°	21° 32°	22° 33°



30.9°
28.7° 31.8°

CO₂ 1036 ppm
LIVELY 65 dB
HUMIDITY 64 %

Figure 79. Sample Screenshot of Netatmo weather station reading for house 7.



Energy, Carbon and Cost Summary

Annual Energy Cost ₹71,927
Lifecycle Cost ₹979,642

Annual CO_2 Emissions

Electric 4.4 Mg
Onsite Fuel 0.9 Mg
Large SUV Equivalent 0.5 SUVs / Year

Annual Energy

Energy Use Intensity (EUI) 763 MJ / m² / year
Electric 11,597 kWh
Fuel 17,162 MJ
Annual Peak Demand 1.8 kW

Lifecycle Energy

Electric 347,910 kW
Fuel 514,871 MJ

Energy, Carbon and Cost Summary

Annual Energy Cost ₹43,317
Lifecycle Cost ₹589,973

Annual CO_2 Emissions

Electric 2.6 Mg
Onsite Fuel 0.9 Mg
Large SUV Equivalent 0.4 SUVs / Year

Annual Energy

Energy Use Intensity (EUI) 572 MJ / m² / year
Electric 6,982 kWh
Fuel 19,013 MJ
Annual Peak Demand 1.6 kW

Lifecycle Energy

Electric 209,461 kW
Fuel 570,389 MJ

Figure 80. Energy model output report for house 7. (existing - left versus modified materials - right).

Table 64. Energy model output – cost comparison of energy and fuel consumed for house 7.

	Current	Modified
Electricity Consumption	₹ 71,901.00	₹ 43,289.00
Fuel Consumption	₹ 25.00	₹ 28.00

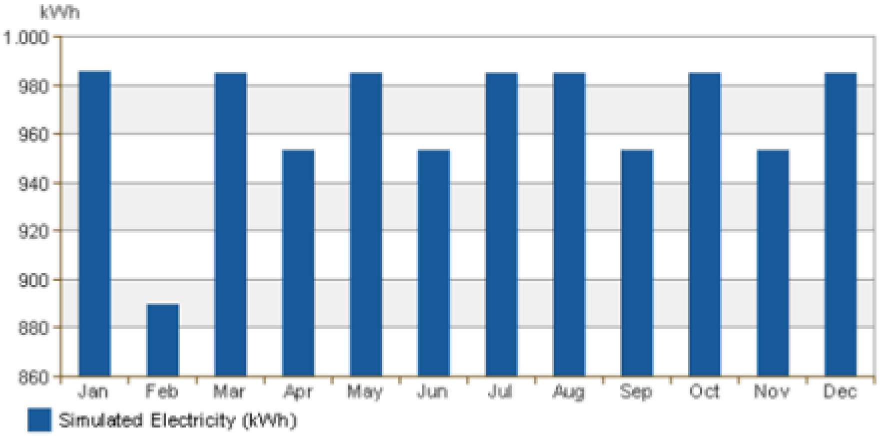


Figure 81. Energy model output – estimated existing house monthly electricity consumption for house 7.

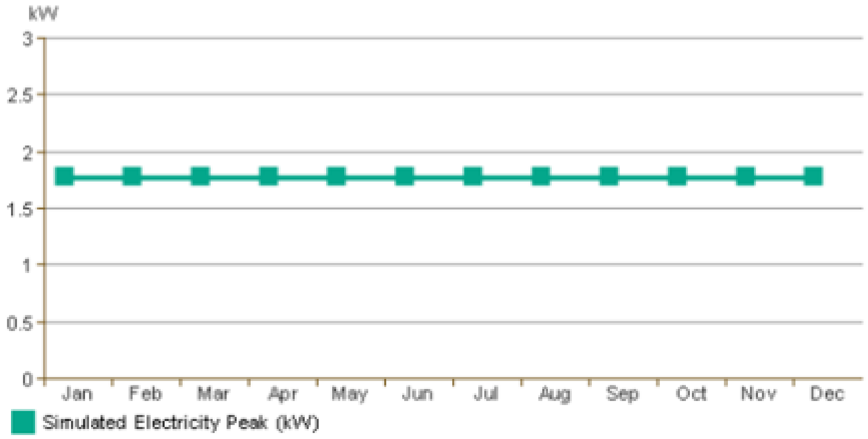


Figure 82. Existing house estimated monthly peak demand for house 7.

Table 65. Energy model output – estimated annual energy use intensity of house 7.

	Current	Modified
Electricity EUI (kWh/m^2/yr)	150	90
Fuel EUI (MJ/m^2/yr)	222	246
Total EUI (MJ/m^2/yr)	763	572

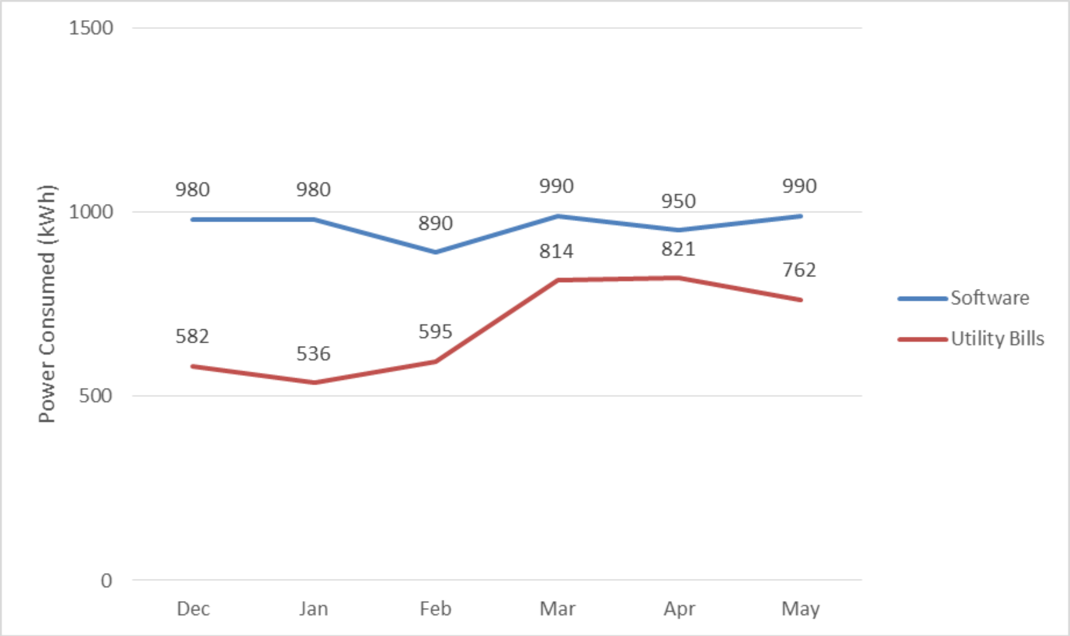


Figure 83. Comparison of the power consumed through the software versus the actual utility bills for house 7.

Appendix 8

House 8 Results

Figure 84. Floor plan of house 8. ground floor (left), first floor (right) and second floor (bottom).

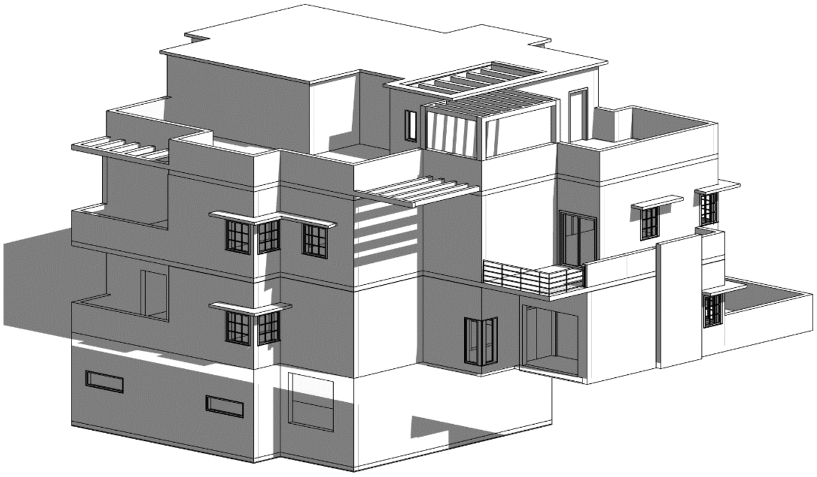


Figure 85. 3D view of house 8 created in Revit software.

Table 66. Data parameters collected for house 8 during single site visit.

Year Constructed	2003
Age (years)	06
Number of Occupants	5
Number of Storeys	Ground + 2
Skylight/Courtyard	Yes
Mechanical Cooling	8 Fans, 6 AC
CO_2 levels (ppm)	635-670
Outdoor Humidity	65%
Indoor Humidity	55%
Outdoor Temperature (°C)	29.6
Outdoor Temperature – feels like (°C)	39
Indoor Temperature (°C)	29.7
Windows	Double Glazed – Teakwood
Wall materials	RCC Constriction with column construction with cement Plaster
Wall Thickness (mm)	230
Roof	RCC Slab with Cement Plaster
Floor	Marble and Vitrified Tile
Door	Teakwood
Floor Area (m^2)	565
Exterior Wall Area (m^2)	647

Table 67. Actual utility energy consumption at house 8 for six months (KWh).

	Summer			
	Mar	**Apr**	**May**	**Total Power Consumed for 6 months**
House 8	560	543	318	2471

Table 68. Estimated plug load energy consumption of house 8.

Category	**Appliance**	**Quantity**	**Wattage**	**Average Daily Usage (Hours)**	**Average Daily Power Consumed (kWh)**	**Monthly Power Usage (kWh)**	**Annual Power Usage (kWh)**
HVACR	Ceiling Fan	8	100	4.45	0.45	106.80	1281.60
HVACR	Air Conditioner (1.5 ton)	6	1500	0.81	1.22	218.70	2624.40
HVACR	Refrigerator	1	100	22.33	2.23	66.99	803.88
HVACR	Immersion Rod	0	1000	1.75	1.75	0.00	0.00
HVACR	Geyser	5	3000	1.18	3.54	531.00	6372.00
Lighting	Bulb (FL40)	16	40	2.63	0.11	50.50	605.95
Lighting	Tube light (IL40)	29	40	1.56	0.06	54.29	651.46
Miscellaneous	Computer	2	100	3.00	0.30	18.00	216.00
Miscellaneous	Mixer	1	450	0.47	0.21	**6.35**	76.14
Miscellaneous	Water Pump	1	750	0.68	0.51	15.30	183.60
Miscellaneous	Television	3	100	3.93	0.39	35.37	424.44
Miscellaneous	Washing Machine	1	325	0.71	0.23	6.92	83.07
Miscellaneous	Radio	2	15	2.51	0.04	2.26	27.11

Miscellaneous	Electric Iron	1	750	0.48	0.36	10.80	129.60
Miscellaneous	VCR	3	40	2.14	0.09	7.70	92.45
Miscellaneous	Microwave	1	1000	1.00	1.00	30.00	360.00
Miscellaneous	Vacuum Cleaner	1	750	0.70	0.53	15.75	189.00
	Total					**1176.72**	**14120.69**

Table 69. Plug load energy consumption - annual energy consumption and utility cost comparison: existing house 8 vs. modified house 8 (materials upgrade).

House 8 Annual Expenditure Analysis			
Parameter	**Current**	**Modified Materials**	**Cost Benefit**
Annual Electricity Consumed Simulation (kWh)	84916	48712	36204.00
HVACR (kWh)	11081.88	6357.11	4724.77
Lighting (kWh)	1257.41	721.31	536.10
Miscellaneous (kWh)	1781.41	1021.90	759.50
HVACR Cost (INR)	₹ 68,710.24	₹ 39,415.58	₹ 29,294.66
Lighting Cost (INR)	₹ 10,011.94	₹ 4,472.30	₹ 5,539.64
Misc. Cost (INR)	₹ 8,829.41	₹ 6,336.03	₹ 2,493.38
Annual Cost (INR)	**₹ 87,551.60**	**₹ 50,223.91**	**₹ 37,327.69**
Floor Area (m^2)	565	565	
Annual Cost per m^2 (INR)	₹ 13,635.15	₹ 8,208.14	

Figure 86. Sample screenshot of Netatmo weather station reading for house 8.

Energy, Carbon and Cost Summary	
Annual Energy Cost	₹526,488
Lifecycle Cost	₹7,170,767
Annual CO_2 Emissions	
Electric	32.2 Mg
Onsite Fuel	1.0 Mg
Large SUV Equivalent	3.3 SUVs / Year
Annual Energy	
Energy Use Intensity (EUI)	596 MJ / m² / year
Electric	84,917 kWh
Fuel	19,374 MJ
Annual Peak Demand	15.9 kW
Lifecycle Energy	
Electric	2,547,521 kW
Fuel	581,214 MJ

Energy, Carbon and Cost Summary	
Annual Energy Cost	₹302,027
Lifecycle Cost	₹4,113,604
Annual CO_2 Emissions	
Electric	18.5 Mg
Onsite Fuel	2.5 Mg
Large SUV Equivalent	2.1 SUVs / Year
Annual Energy	
Energy Use Intensity (EUI)	414 MJ / m² / year
Electric	48,714 kWh
Fuel	50,231 MJ
Annual Peak Demand	10.6 kW
Lifecycle Energy	
Electric	1,461,416 kW
Fuel	1,506,934 MJ

Figure 87. Energy model output report for house 8. (existing - left versus modified materials - right).

Table 70. Energy model output – cost comparison of energy and fuel consumed for house 8.

	Current	Modified
Electricity Consumption	₹ 526,488.00	₹ 302,026.00
Fuel Consumption	₹ 0	₹ 1

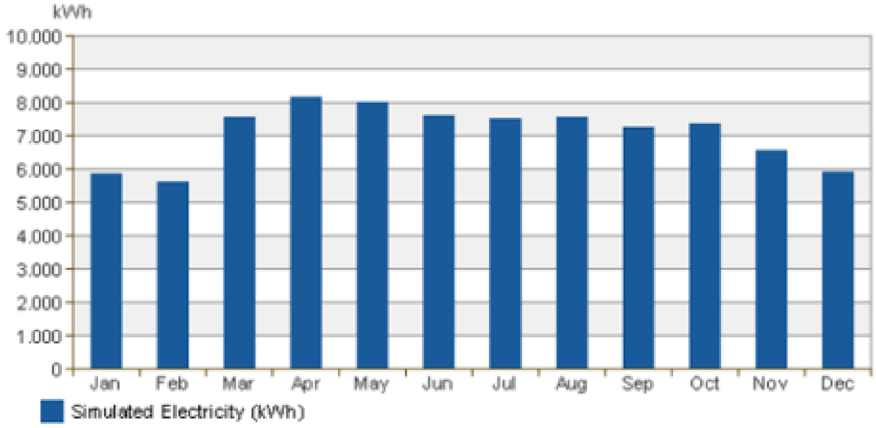


Figure 88. Energy model output – estimated existing house monthly electricity consumption for house 8.

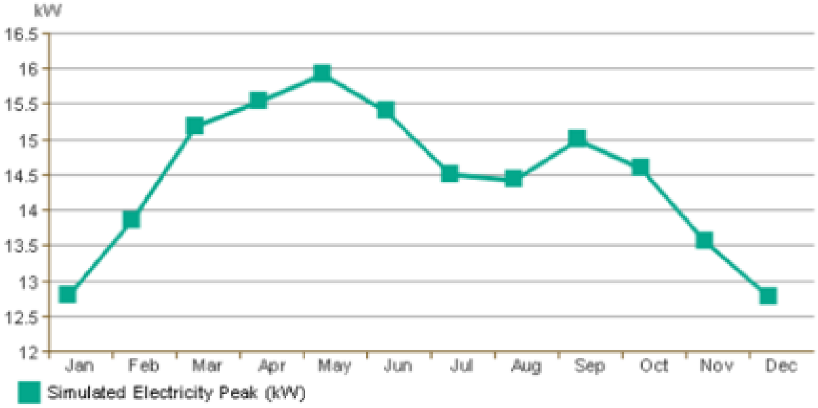


Figure 89. Existing house estimated monthly peak demand for house 8.

Table 71. Energy model output – estimated annual energy use intensity for house 8.

	Current	Modified
Electricity EUI (kWh/m^2/yr)	156	89
Fuel EUI (MJ/m^2/yr)	36	92
Total EUI (MJ/m^2/yr)	596	414

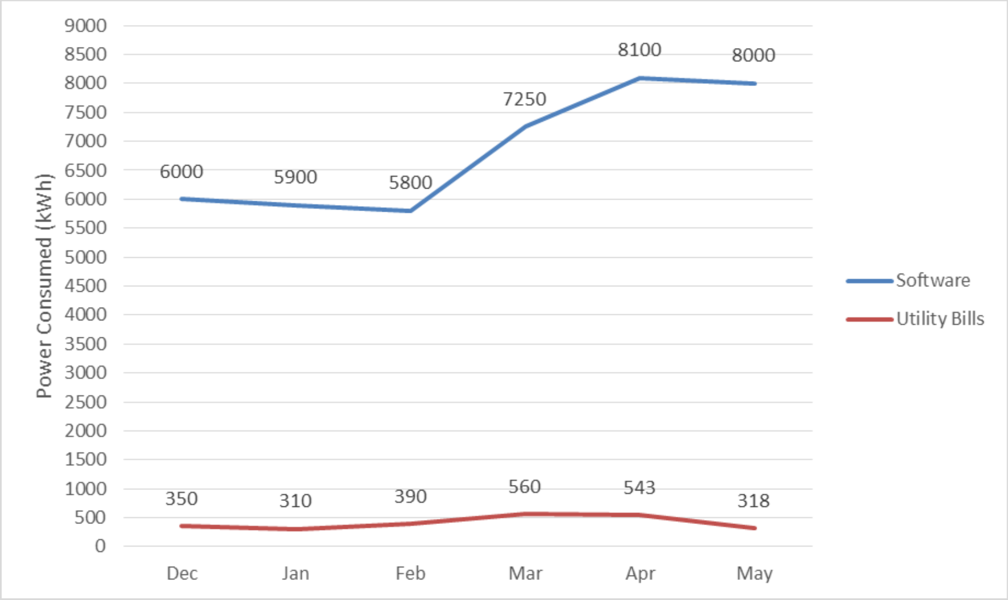


Figure 90. Comparison of the power consumed through the software versus the actual utility bills for house 8.

Appendix 9

House 9 Results

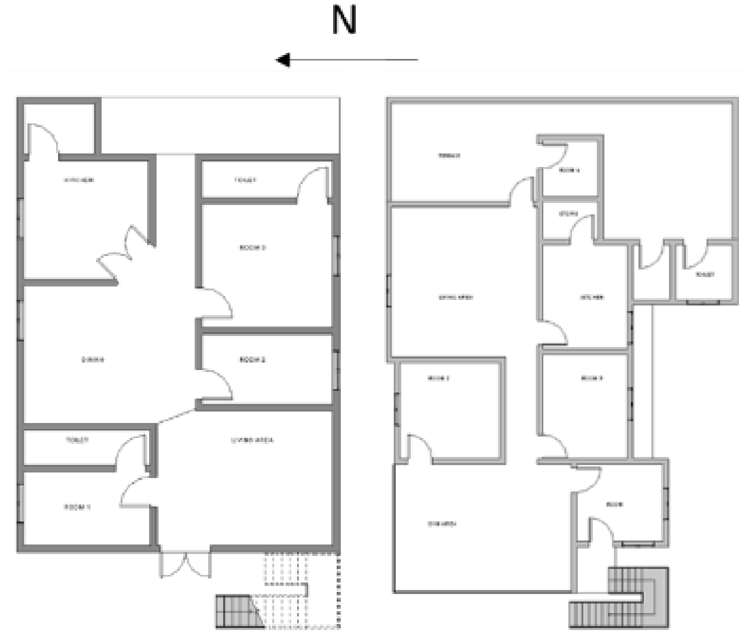


Figure 91. Floor plan of house 9. ground floor (left), first floor (right).

Figure 92. 3D view of house 9 created in Revit software.

Table 72. Data parameters collected for house 9 during single site visit.

Year Constructed	2005
Age (years)	11
Number of Occupants	5
Number of Storeys	Ground + 1
Skylight/Courtyard	No
Mechanical Cooling	10 Ceiling Fans, 5 AC
CO_2 levels (ppm)	800-824
Outdoor Humidity	59
Indoor Humidity	57
Outdoor Temperature (°C)	30.5
Outdoor Temperature – feels like (°C)	39
Indoor Temperature (°C)	32.2
Windows	Glazed – Salwood
Wall materials	RCC Constriction with column construction with cement Plaster
Wall Thickness (mm)	230
Roof	RCC Slab with Cement Plaster
Floor	Marble
Door	Salwood
Floor Area (m^2)	191
Exterior Wall Area (m^2)	301

Table 73. Actual utility energy consumption at house 9 for six months (KWh).

	Winter			**Summer**			
	Dec	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Total Power Consumed for 6 months**
House 9	248	280	304	410	395	225	1862

Table 74. Estimated plug load energy consumption of house 9.

Category	**Appliance**	**Quantity**	**Wattage**	**Average Daily Usage (Hours)**	**Average Daily Power Consumed (kWh)**	**Monthly Power Usage (kWh)**	**Annual Power Usage (kWh)**
HVACR	Ceiling Fan	10	100	4.45	0.45	133.50	1602.00
HVACR	Air Conditioner (1.5 ton)	5	1500	0.81	1.22	182.25	2187.00
HVACR	Refrigerator	1	100	22.33	2.23	66.99	803.88
HVACR	Immersion Rod	0	1000	1.75	1.75	0.00	0.00
HVACR	Geyser	4	3000	1.18	3.54	424.80	5097.60
Lighting	Bulb (FL40)	10	40	2.63	0.11	31.56	378.72
Lighting	Tube light (IL40)	18	40	1.56	0.06	33.70	404.35
Miscellaneous	Computer	3	100	3.00	0.30	27.00	324.00
Miscellaneous	Mixer	2	450	0.47	0.21	**12.69**	152.28
Miscellaneous	Water Pump	1	750	0.68	0.51	15.30	183.60
Miscellaneous	Television	2	100	3.93	0.39	23.58	282.96
Miscellaneous	Washing Machine	1	325	0.71	0.23	6.92	83.07
Miscellaneous	Radio	2	15	2.51	0.04	2.26	27.11
Miscellaneous	Electric Iron	2	750	0.48	0.36	21.60	259.20
Miscellaneous	VCR	2	40	2.14	0.09	5.14	61.63
Miscellaneous	Microwave	2	1000	1.00	1.00	60.00	720.00
Miscellaneous	Vacuum Cleaner	1	750	0.70	0.53	15.75	189.00
	Total					**1063.03**	**12756.40**

Table 75. Plug load energy consumption - annual energy consumption and utility cost comparison: existing house 9 vs. modified house 9 (materials upgrade).

House 9 Annual Expenditure Analysis			
Parameter	**Current**	**Modified Materials**	**Cost Benefit**
Annual Electricity Consumed Simulation (kWh)	27169	14948	12221.00
HVACR (kWh)	9690.48	5331.57	4358.91
Lighting (kWh)	783.07	430.84	352.24
Miscellaneous (kWh)	2282.85	1255.99	1026.86
HVACR Cost (INR)	₹ 60,083.24	₹ 33,056.95	₹ 27,026.29
Lighting Cost (INR)	₹ 4,855.23	₹ 2,671.28	₹ 2,183.95
Misc. Cost (INR)	₹ 14,154.20	₹ 7,787.44	₹ 6,366.76
Annual Cost (INR)	**₹ 79,092.67**	**₹ 43,515.67**	**₹ 35,577.00**
Floor Area (m^2)	190	190	
Annual Cost per m^2 (INR)	₹ 15,818.53	₹ 8,703.13	

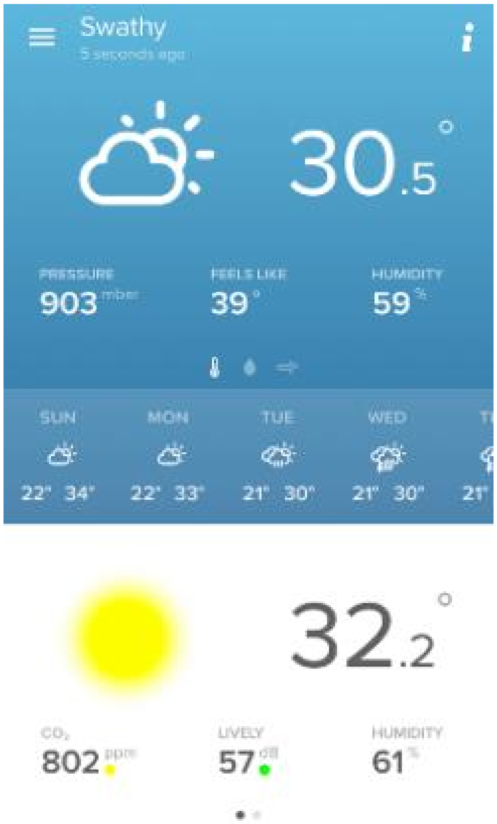
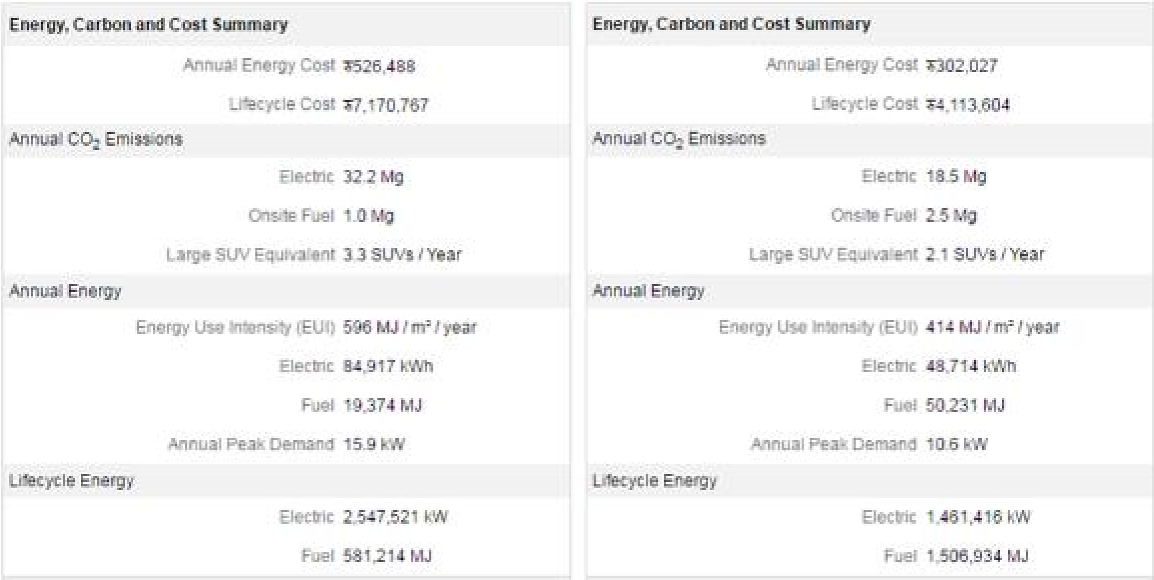


Figure 93. Sample screenshot of Netatmo weather station reading for house 9.



Energy, Carbon and Cost Summary

Annual Energy Cost	₹526,488
Lifecycle Cost	₹7,170,767
Annual CO_2 Emissions	
Electric	32.2 Mg
Onsite Fuel	1.0 Mg
Large SUV Equivalent	3.3 SUVs / Year
Annual Energy	
Energy Use Intensity (EUI)	596 MJ / m² / year
Electric	84,917 kWh
Fuel	19,374 MJ
Annual Peak Demand	15.9 kW
Lifecycle Energy	
Electric	2,547,521 kW
Fuel	581,214 MJ

Energy, Carbon and Cost Summary

Annual Energy Cost	₹302,027
Lifecycle Cost	₹4,113,604
Annual CO_2 Emissions	
Electric	18.5 Mg
Onsite Fuel	2.5 Mg
Large SUV Equivalent	2.1 SUVs / Year
Annual Energy	
Energy Use Intensity (EUI)	414 MJ / m² / year
Electric	48,714 kWh
Fuel	50,231 MJ
Annual Peak Demand	10.6 kW
Lifecycle Energy	
Electric	1,461,416 kW
Fuel	1,506,934 MJ

Figure 94. Energy model output report for house 9. (existing - left versus modified materials - right).

Table 76. Energy model output – cost comparison of energy and fuel consumed for house 9.

	Current	**Modified**
Electricity Consumption	₹ 168,462.00	₹ 92,689.00
Fuel Consumption	₹53	₹ 57

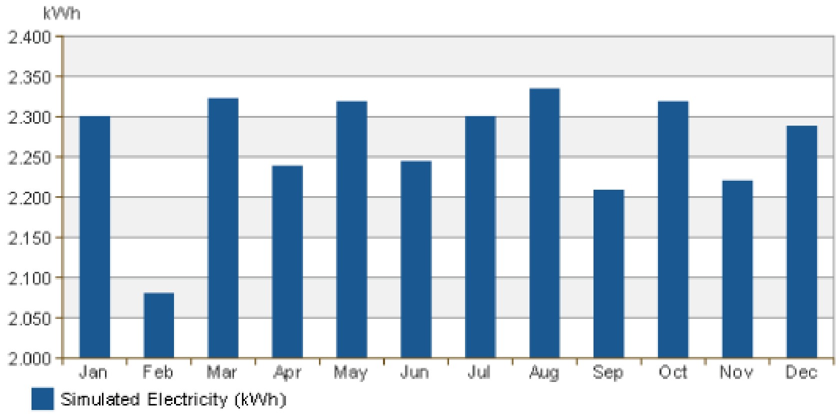


Figure 95. Energy model output – estimated existing house monthly electricity consumption for house 9.

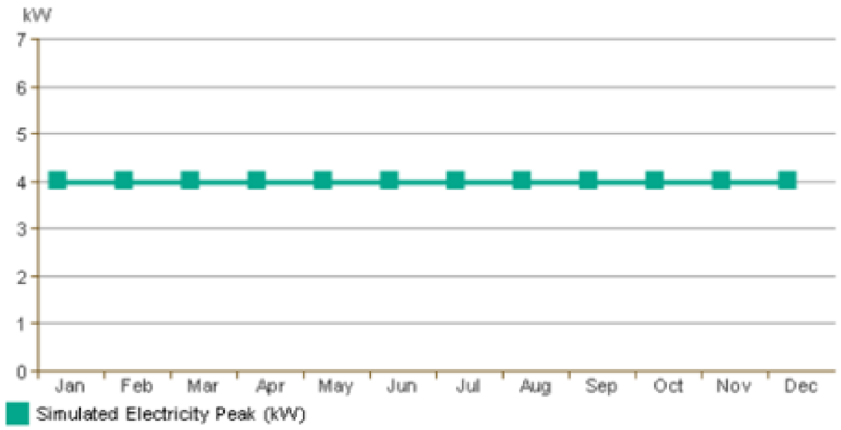


Figure 96. Existing house estimated monthly peak demand for house 9.

Table 77. Energy model output – estimated annual energy use intensity for house 9.

	Current	Modified
Electricity EUI (kWh/m^2/yr)	143	79
Fuel EUI (MJ/m^2/yr)	187	201
Total EUI (MJ/m^2/yr)	700	484

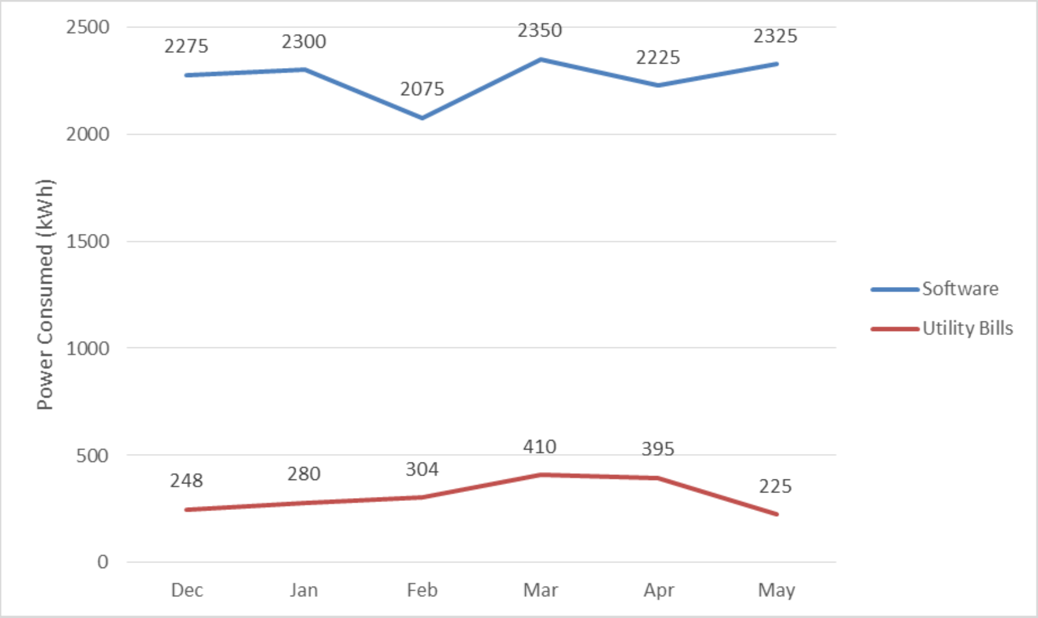


Figure 97. Comparison of the power consumed through the software versus the actual utility bills for house 9.

Appendix 10

Analysis Assumptions: Base Run Carbon Neutral Potential

- Assumptions for electric power plant sources in a region – Data for U.S. Projects was based on the US EPA EGRID 2010 (2009 Plant Level Data). Projects outside the U.S. used CARMA (Carbon Monitoring for Action) data
- To calculate carbon di oxide emissions for United States projects, Green Building Studio uses data from the U.S. Environmental Protection Agency; which has historical records for all the fuel and emissions of all power plants in the United States. Data from CARMA (Carbon Monitoring for Action) is used for projects outside of the United States
- Energy, Cost Summary and Carbon Footprint - Most building energy cost comparisons and early compliance decisions can be made using annualized energy cost and consumption information. The Energy and Carbon Results are categorized into multiple groups as seen below
- Carbon neutrality is defined here as eliminating or offsetting fossil-based electricity and fuel use. For example, if the electricity grid is 60% fossil fuel and 40% hydroelectric, reducing grid consumption by 60% and eliminating/offsetting on-site fuel use will make the project carbon neutral. Use any combination of efficiency, natural ventilation, renewable energy, carbon credits and biofuels to reach this goal
- Annual Energy Cost: The estimated total annual utility cost for all electricity and fuel used by a project. This study assumed a 24/7 working model for all the houses

- Annual carbon di oxide emissions: The sum of the annual carbon di oxide emissions of a project (Electric and Onsite Fuel). Emissions are estimated based on the on-site fuel use and the fuel sources for the electricity in the region
- Annual Energy Consumption: The estimated measure of how much electricity and fuel project may use during a typical one-year period. Note: Peak electric demand (kW) is the estimated highest electricity usage during any one hour for the year
- Carbon Neutral Potential: The amount of gas emitted before applying factors that would offset the carbon emissions, such as renewable energy. Carbon emissions are calculated by estimating the on-site fuel use and the fuel sources for the electricity in the region. For example, projects located in a region with coal powered power plants have higher carbon di oxide emissions than projects based in areas with hydroelectric power plants
  - Onsite Renewable Potential: This value is a negative number because it represents tons of carbon one can potentially remove from a project by using renewable energy rather than obtaining electricity from the utility provider. For onsite renewable potential, we calculate the Photovoltaic Potential (solar electric) and the Wind Energy Potential for your project based on the climate, and geometry of your project. Refer to the PV Analysis page to review the various assumptions used in the photovoltaic calculations
  - Natural Ventilation Potential: This value is a negative number because it represents the tons of carbon one can potentially remove from a project by taking advantage of natural ventilation to cool a building, rather than using mechanical cooling systems, which require electricity. The natural ventilation potential uses a

project's chosen climate data. Savings potential is calculated by determining whether the outdoor air temperatures are sufficient. The calculation also assumes that the building form and openings will be designed to allow for stack-effect and cross-ventilation that will result in 20 air changes per hour. The calculations do not take into account actual design opening placements

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