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Evaluation of the energy performance for a nZEB office building under specific climatic conditions

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Abstract

This paper presents the results from simulation work regarding the design of a net zero energy office building with a mixed-mode ventilation system which assures the thermal comfort of the occupants according to the ASHRAE 55/2010 Standard, with a rational consumption of energy and a minimal environmental impact. This was a particular difficult task as the studied city, New Delhi, is one of the most polluted in the world. The study relied on the use of easily accessible building materials and customary Air Conditioning (AC) equipment, in order to meet the requirements. For this purpose, three different AC systems had been selected: a Chilled Beams (CB) system, a Fan Coil Units (FCU) system, and a Variable Refrigerant Flow (VRF) system. All the simulations have been performed within the Design Builder platform, a user-friendly interface of the Energy Plus software. The chilled beams AC system came on top of the energy performance ranking, with 4,6 % less energy consumption than the fan coil units system and 2,3 % less than the variable refrigerant system, for a payback period of 11,3 years. As for the energy production, 160 modules of photovoltaic panels with a total energy yield of 64260 [kWh/year] were used to cover the building electrical needs (lighting and appliances).

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Keywords: Embodied energy; design builder; electrical consumption; life cycle cost analysis

1. Introduction

India's economy and population are rapidly increasing, so, in order to meet the national's energy needs, careful planning is required. The building sector accounts for: 40% energy use, 42% water consumption, 40% solid waste,

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50% raw material use, 50% of air pollution, 42% greenhouse gases and 50% water pollution. By studying the energy consumption evolution from 2004 to 2010, an increase of 53% can be observed whereas the CO_2 emissions grew with 47% [1,2].

According to the World Health Organization, New Delhi is the most polluted city in the world, with the highest concentration of particulate matters (PM) smaller than 2,5 micro-meters (µm), also called PM 2,5. On 9 May 2015 the average carbon dioxide level touched a record level of 404 ppm, with 15% per cent higher than the ideal value of 350 ppm. These values are a direct consequence of the continuous expansion of India's population (1,2 billion people), the rapid economic development and the improved lifestyle that includes the intensive use of air conditioning (AC) units.

India is already responsible for 10,34 % of the total worldwide CO_2 emissions from the cooling sector. Without immediate actions it will exponentially increase and will not only continue to pollute the air, but will increase the energy consumption of the buildings (Fig.1).

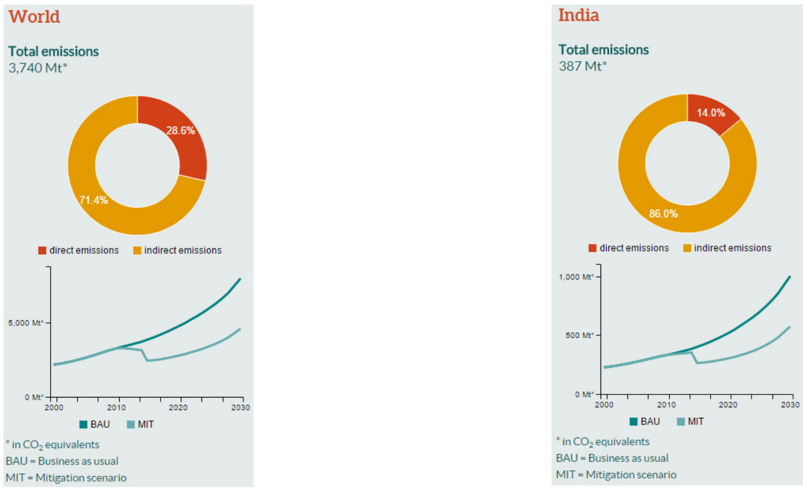

Fig.1. Carbon emissions from the cooling sector according to http://www.green-cooling-initiative.org/

This study concentrates on energy efficient measures that proved to be cost effective in a Life Cycle Cost Analysis, in order to cope with the rapid increase of greenhouse gas emissions. The study started with the analysis of the weather file, of the glazing and building fabric, then focusing on the most commonly used AC systems in India. The main goal was to design an nZEB office building with mixed-mode ventilation able to assure the comfort of the occupants according to ASHRAE 55/2010 Standard, with a rational consumption of energy and a minimal environmental impact. Several authors had focused on this subject [3,4,5]. All the simulations of the building energy consumptions have been performed by using the Design Builder software.

2. Methods and results

In order to meet all the criteria required by the ASHRAE 55/2010 Standard, special consideration was accorded to the building fabric, but also to the ventilation and AC systems. For all the simulations performed within the Design Builder software, the natural ventilation was turned on when the indoor temperature became greater than 23°C and the outdoor one became lower than 26 °C. The indoor temperature was set at 25°C, for a relative humidity of 59%, and the equipment was controlled solely on the base of the operative temperature.

The study started with a multi criteria analysis of multiple glazing types. The 1st window option was considered to be the most economical, with a payback time period of 5,3 years. As for the opaque building fabric, a Life Cycle Cost Analysis (LCCA) concluded that the type 3 (concrete), with a density of 600 kg/m³ offers the best performance at the lowest cost. As a result, a U value of 0,30 W/m²K was selected. Finally a comparative study of 3 AC systems was conducted to determine the optimal solution in terms of annual energy savings. The selected systems were:

1. Chilled Beams (CB), using indoor air induction and cooling of mixed air,
2. Fan Coil Units (FCU) system, using terminal units supplied with chilled water, and
3. Variable Refrigerant Flow (VRF) system, using direct expansion cooling.

The energy modelling of the building was done by using the Energy Plus software via the Design Builder interface. Energy Plus is developed by the U.S. Department of Energy and is designed to create simulations of buildings thermal behaviour, including the energy flows crossing them, so an optimal solution can be found. It focuses only on the simulation and does not contain a graphical interface.

Design Builder (DB) provides a graphical interface for Energy Plus and it uses its advanced energy modelling tools in a user friendly format. It contains various tools from energy modelling to daylight calculations and computational fluid dynamics (CFD) that can be easily used by architects or engineers in all stages of the design, without extensive knowledge in this field.

System Advisor Model (SAM) makes performance predictions and cost of energy estimates for grid-connected power projects based on installation and operating costs and system design parameters that are specified as inputs to the model. The software was used design the photovoltaic panels and the solar panels for domestic hot water production.

3. Building Design

The building selected for the study is located in New Delhi, India's capital. It is a 3-storey office building with a central atrium and a structure made of reinforced concrete pillars and beams. It has 70 occupants, office equipment and follows the occupancy pattern of a typical office building with differences between weekdays and weekends. Due to its shape and spatial configuration, the building has to achieve not only optimal indoor comfort criteria, but also the premises of an nZEB or energy-positive building.

The proposed site is located in the southern part of New Delhi city. All the distances taken on the map are measured via safe pedestrian way and prove that all the building users do not need to use their personal car to arrive at work as there is a residential area and bus station in close proximity. It was assumed that the occupants leave nearby or commute by bus so, no greenhouse gas emissions result from the building user transport (figure 2 and figure 3).

Fig.2. Building location

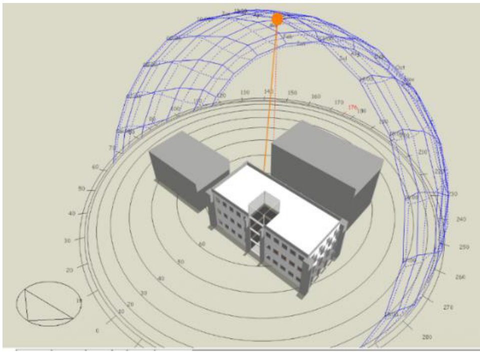

Fig.3. Site view

Each floor was divided into 2 equal office spaces connected by a circulation space and a stair house (figure 4). The Ground Floor and 1st Floor offices shelter 12 persons each and the 2nd floor only 11, while each floor has 1 laser printer and 1 overhead projector. The lighting is controlled by 2 natural daylight sensors located in each office, covering the room space. The central atrium is built entirely on glass.

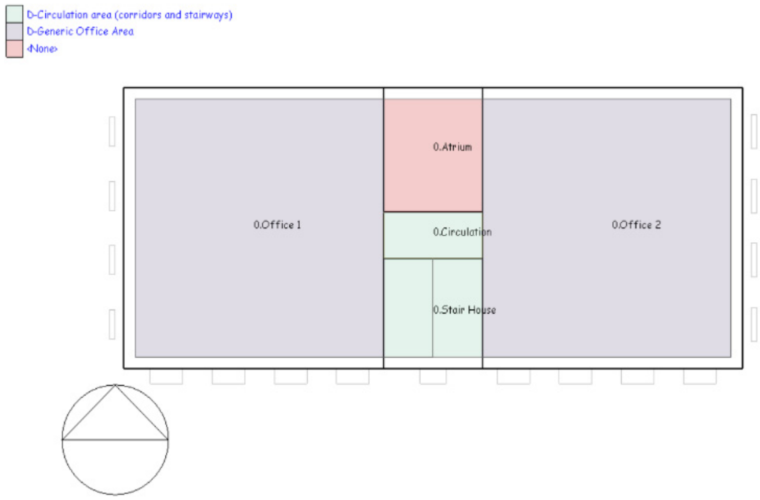

Fig.4. Typical floor plan

The building was designed to be Energy Conservation Building Code (ECBC) compliant [6]. The window-to-wall ratio (WWR) was set at 40%, with differences between orientations: on the North side 50% to benefit from natural daylight, on South and East 35% and on West, were the solar radiation is more intense, only 30%. The southern windows are shaded by overhangs and the eastern and western windows by louvers. All the windows are equipped with internal roller blinds used for glare control.

4. Local climate analysis

The New Delhi climate presents high variations between summer and winter in terms of temperature and humidity. The outdoor temperature varies annually from 6°C to 43°C, with an average of 25°C and a maximum recorded temperature of 49°C. In order to understand and to adapt architectural and energy efficient measures appropriate to his climate, the Climate Consultant software was used to analyse the weather file.

As it could be seen in the figure 5, the shading system is the design strategy with the biggest impact on the building cooling load during summer time. The external shading devices were carefully selected in order to shade the windows during the long hot summers and to allow the sun rays to enter the building during the winter time. Also, natural ventilation can be used to assure comfort for 854 hours per year, but this is limited only to winter time, as the external temperature exceeds by far the comfort range during the summer days.

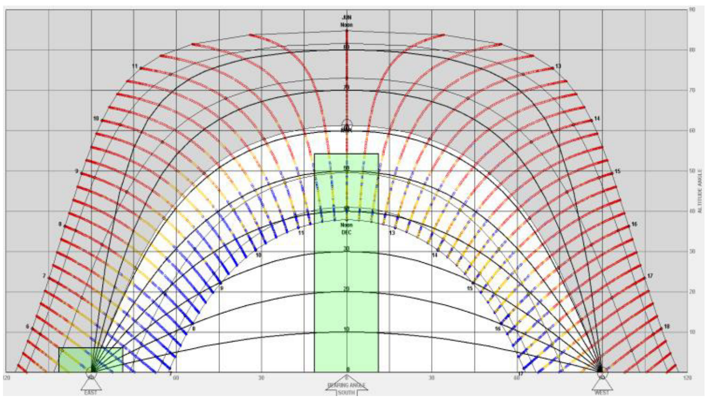

Fig.5. Climate Consultant Shading Mask study

5. The glazing system

Special consideration was given to the glazing system as it allows solar heat gains to enter the space. Five different types of windows were taken into consideration: 3 double glazing and 2 triple glazing. All of them were chosen to be ECBC compliant: SHGC<0,25, U<3,3 W/m²K, and a minimum daylight factor of 2. The Solar Heat Gain Coefficient (SHGC) was recalculated taking into account the external shading devices as well as a 30 cm retreatment of the windows from the facades plan. The office external windows have a wooden frame with a U value of 2,104 W/m²K and the atrium ones have an aluminium frame with thermal break and a U value of 1,801 W/m²K.

The energy modelling was conducted as follows:

- The indoor temperature was set at 25°C – only for the offices, the other spaces are not cooled;
- The schedules, occupancy and heat gains were set as for the design conditions ;
- The ventilation system used is a constant air volume one with a direct expansion cooling coil with a COP of 3,7, plus and a rotary heat exchanger with an efficiency of 65% that operates in a free cooling mode between 20°C and 26°C;
- The artificial lighting was designed to assure the following light intensities: 500 lx on the working plane for the offices and 150 lx for the other spaces;
- The artificial lighting is controlled by 2 daylight sensors located on the north and south part of each office;
- The natural ventilation is turned on for the exterior windows when the indoor temperature is greater than 23°C and the outdoor one is smaller than 26°C. The atrium is naturally ventilated when the indoor temperature is greater than 18°C. The internal windows are operated in the same time as the external ones, thus allowing a chimney effect through the atrium [7];
- All the equipment and the natural ventilation are controlled by the operative temperature and all the simulations were performed with 10 time steps per hour.

In figure 6 is shown a comparison between the 5 different glazing systems in terms of electrical consumptions for cooling purposes.

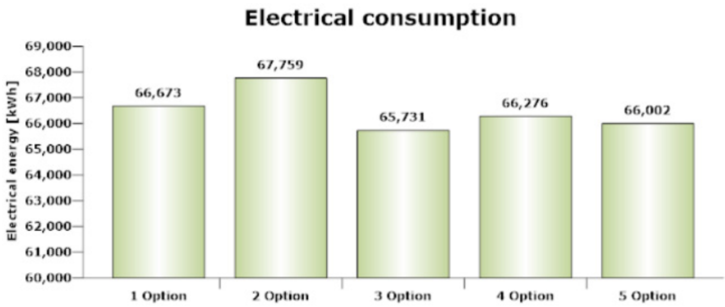

Fig.6. Electrical energy consumption for the 5 studied windows

The 3rd option seems to be the most efficient one with an energy reduction of 300 kWh compared to the nearest one and smaller with 2000 kWh than the most inefficient.

The daylight study was conducted for the whole building but the results were analysed only for the Eastern office from the ground floor. This zone presents the lowest daylight factors due to the shading from the neighbouring buildings. All the windows comply with the daylight factor requirement of minimum 2, exception making the 3rd option which was cut down from the list.

The determinant factor in choosing the optimal glazing is the Life Cycle Cost Analysis [8,9], which was conducted for a period of 20 years and considered all the investment, maintenance and disposal costs. The graph (figure 7) was represented on a 7-years period to be more easily to read. The most feasible option is the first one not only from an economical point of view, but from an environmental one too, as it contains embodied energy equivalent to 6443 $kgCO_2$, with 200 $kgCO_2$, less than the triple glazing option.

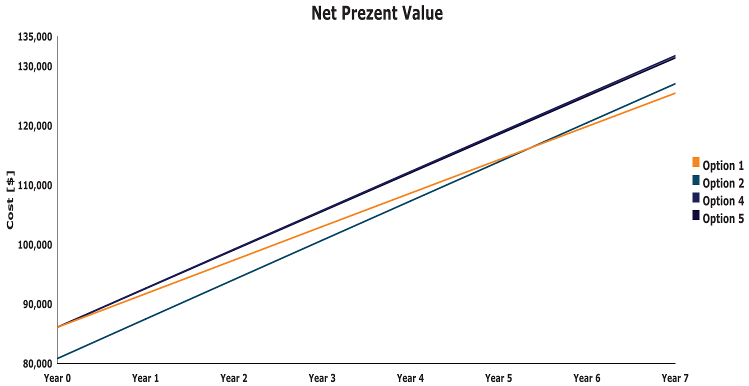

Fig.7. Result of the LCCA study for the windows considered

6. The opaque elements

The opaque construction elements (external walls and terrace), were treated in a similar manner like the glazing. Initially 3 different types of insulation were considered: polystyrene, stone wool and cellulose. The polystyrene was eliminated due to its high embodied energy (3,26 kg_{echi} CO2 /kg). The cellulose, although has a small embodied energy (0,37 kg_{echi} CO2/kg), is not fireproof and was also eliminated due to its fire risk, especially in the hot climate of New Delhi where the external temperature could reach 49°C. All the exposed areas were painted white to reflect as much solar radiation as possible.

The structure of the building is made out of concrete pillars and beams. The external walls are composed of concrete bricks. In order to find the most suitable type, 3 different options of concrete type were used with different densities and different wall U values [10]. The thickness of the insulation was changed in order to keep the same U value for all the cases, taking into account and the thermal bridges.

An LCCA analysis was conducted for a period of 20 years for the 3 options of concrete type. The variant with the lowest density presents the lowest Net Present Value (NPV), making it the most suitable element although it has the biggest energy consumption. The sum of the embodied energy of the second and third options has a lower value than the first option (figure 8 and figure 9).

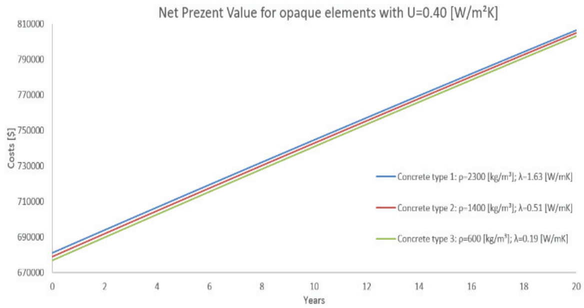

Fig.8. NPV of the 3 options

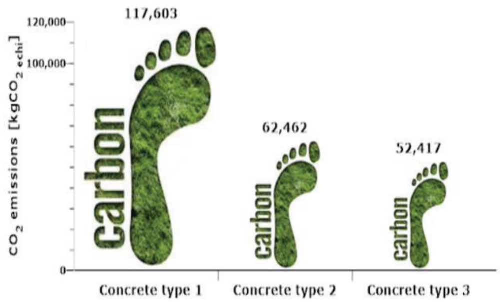

Fig.9. Embodied energy of the 3 options

The concrete type 3 was chosen for further study with altered U values. The most sustainable variant is the one with U=0,30 W/m²K as it presents both the lowest consumption of energy and the lowest embodied energy.

7. The HVAC system

7.1. Modelling assumptions for the HVAC systems

The HVAC systems contribute to 31% of the total energy use in India. In 2005 the total office space surface was estimated at 290 million m² and it's expected to increase to 2000 million m² by 2030. This study concentrates on common types of HVAC systems that are used in India. Accordingly, 3 different AC systems were chosen: Chilled Beams (CB), Fan Coil Units (FCU) and Variable Refrigerant Flow (VRF), in order to analyse their efficiency [11]. The energy modelling was conducted as follows:

- The systems were design based on the thermal load supplied by Design Builder;
- The Air Handling Units are identical in all the cases and assure the fresh air, with a flow of 10 l/s*pers.;
- The rotary heat recovery unit has an efficiency of 84% and works in free cooling mode (20-26°C);
- The cooling coil has a COP of 3,7 and cools the air to 16°C limiting the absolute humidity to 12 g/kg;
- The chiller of the FCU's and chilled beams has a COP of 3,8, the only difference between the 2 systems being the water flow and chilled water temperature → 7°C for the FCU and 14°C for the chilled beams;
- The condenser of the VRF system is evaporative cooled with a COP of 4,2;

7.2. Results of the HVAC systems simulation

The equipment and artificial lighting remained unchanged in all scenarios as they do not depend on the mechanical systems. Significant changes occurred on the on the fans+pumps category, with a 1300 kWh difference between the chilled beams (CB) and fan coil units (FCU) (figure 10).

Related to the CB electrical consumption, the FCU system consumes with 4,59% more energy, whereas VRF system reports only 2,33% increase in energy consumption (figure 10). Although the chiller has a lower COP than the condenser unit, it has a better performance explained by the performance curves of the two devices. The 7°C chilled water temperature difference between the CB system and the FCU system lowered the compressors electrical consumption with almost 1500 kWh, for the CB case.

There are no significant differences between de numbers of discomfort hours of the 3 systems as per ASHRAE 55 Standard. All of them comply with the exception of a few discomfort hours per year.

The most suitable system is the CB one, with a payback period of 11,3 years (figure 11). It also offers the best performance despite its investment cost.

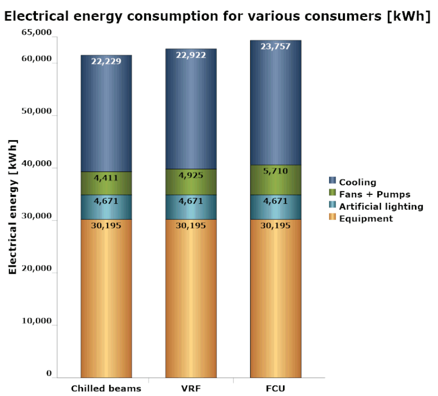

Fig.10. Electrical consumption of the 3 AC systems

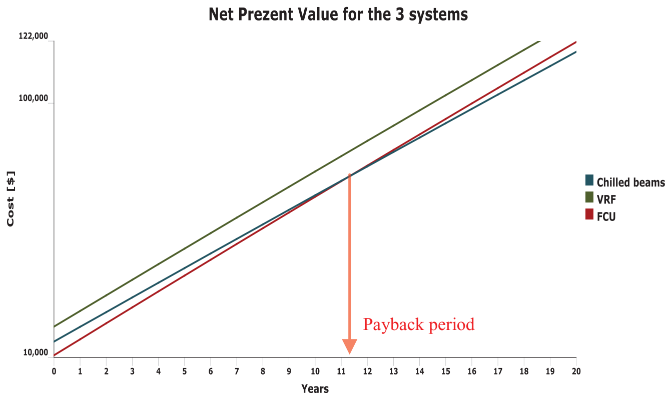

Fig.11. LCCA analysis of the 3 AC systems

8. Simulations results

The values presented in the figure 12 are reported to the conditioned area. The biggest electricity consumer is the equipment which half of the energy. It is followed by the cooling (including fans and pumps) with a ratio of 42% and the artificial lighting with only 8%. The average Indian office building consumes 216 kWh/m²year of electricity whereas this building consumes only 137 kWh/m²year (36% less).

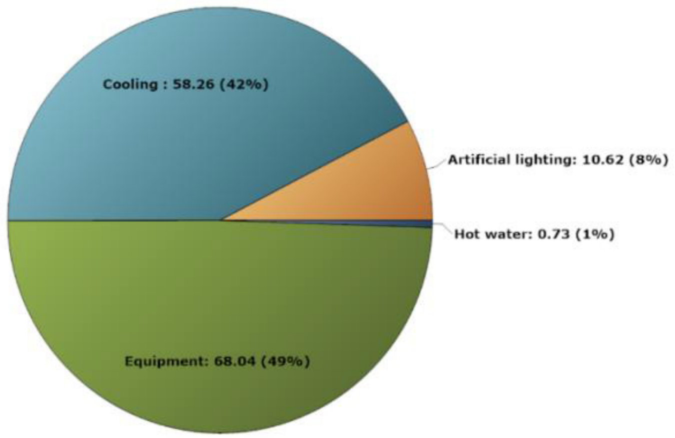

Fig.12. Electrical consumption

The building obtained the net/nearly zero energy building (nZEB) status as it produces more energy in a year that it consumes (figure 13). A total of 64260 kWh of electrical energy are produced whereas only 61086 kWh are consumed, the remaining 3174 kWh are sold to the local energy supplier. On a monthly basis, the positive energy balance is maintained only for the winter months where the cooling energy is greatly diminished. The month of May presents the highest energy consumption, due to its positioning between April, who has the most intense solar radiation and June, who has the highest temperature.

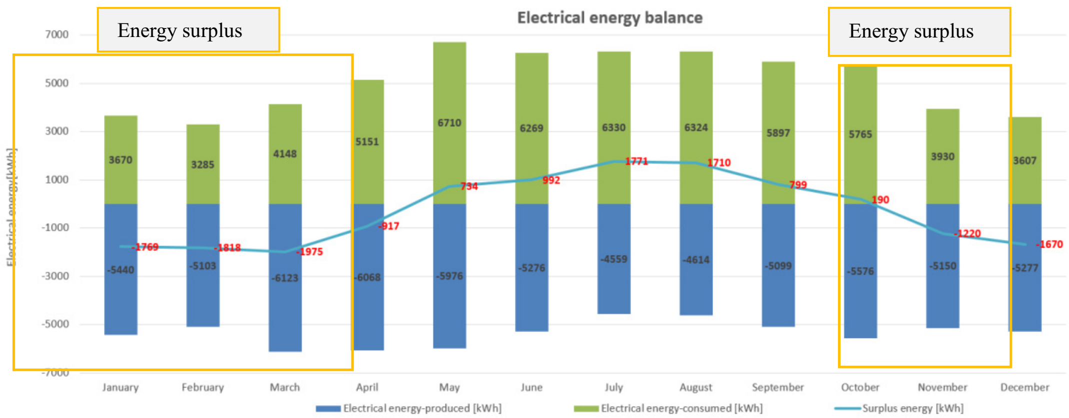

Fig.13. Annual electrical energy balance for the building studied

9. Conclusions

In this paper were presented the results from simulation work regarding the design of a net zero energy office building with a mixed-mode ventilation system which assures the comfort of the occupants according to the

ASHRAE 55 Standard, with rational consumption of energy and minimal environmental impact. A special attention was given to the indoor space comfort, which is really a combination of factors that includes day lighting and artificial lighting, indoor environmental quality and temperature.

An analysis of system performance on a monthly basis confirmed the proper implementation of the system and highlighted the performance of energy efficient systems. The building appears to be energy positive, as the total energy consumption of the HVAC systems and building users, is overcome by the energy production. Regarding the environmental impact, the building will be carbon neutral.

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