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Parametric Study of the Impact of Windows to Wall Ratio on Reduction of Energy Consumption and Environmental Impact of a Zero-Energy Building in Different Orientations

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ABSTRACT

Nowadays, the increase of fossil fuel consumption intensifies the crucial role of architects. As buildings consume over one-third of the used energy, the society of architects is held responsible for this consumption. Therefore, the amount of energy used by a building is directly related to its design; meaning that reduction of energy consumption should be targeted at the design stage. In this research, the proper building form with the lowest energy consumption for heating, cooling, and lighting was obtained after studying different shapes in Design Builder Software, and it was concluded that the building form has a significant impact on energy consumption. After the parametric studies, the best building orientation of 60 degrees north-east and a window-wall ratio (WWR) of 40% was obtained. Moreover, the building considered for this study had annual CO_2 emissions of 30 tons, which was reduced to around 15 tons of CO_2 emissions in a year at the optimum degree and WWR, i.e. a reduction of CO_2 emissions to half of its previous amount.

1. Introduction

To date, many studies have focused on energy saving in buildings on a continuous basis and further studies are needed to use renewable energy instead of fossil fuels. In particular, the solar infinity energy source is among the other green energies without regional constraints (unlike fossil fuels) and studies of its use in construction are ongoing. When using this solar energy effectively, the transmission radiation entering the building must be properly controlled. Since the window is the main way for a building to receive the sun's radiation, it must therefore be controlled to increase lighting, cooling and heating energy, while providing thermal comfort to residents [1-4]. Mahdavi Adeli et al. [5] after in-depth studies on optimizing energy consumption in a zero-energy building, put forward various scenarios for using a zero-energy home for renewable energy and concluded that in hot climates, using a solar panel alone to achieve a zero-energy building is not enough, and wind turbines or other renewable energies should also be used. Su et al. [6] investigated the appropriate range of window to wall ratio (WWR) for different orientations of the building and the type of windows in an office building in Shanghai, China. In their study of the effects of the building's appearance, they concluded that with increasing WWR, a slight but significant (about 5 to 9%) decrease in environmental detrimental effects occurs. Azari et al. [7] examined the effects of window type, window frame materials, wall thermal resistance, window to wall ratios on the southern and northern walls of insulation materials in an office building and concluded that the optimum possible mode to reduce energy consumption and reduce environmental impacts, WWR 60% is south and WWR 10% is north. Lobaccaro et al. [8] using parametric analysis to minimize greenhouse gas emissions as well as energy consumption in a zero emission building, selected ten shapes for use in solar potential using shape optimization. Goia [9] look for window to wall optimization in various European climates with regard to office buildings built with the best technologies available to build envelope components and installations. They results show that although optimal WWR exists in each climate and orientation, many ideal values can be found in a relatively narrow range (0.30<WWR<0.45). Only southeastern facades in very cold or very hot weather require WWR values outside of this range. When adopting the worst WWR settings, overall energy consumption may increase by 5-25% compared to when using the optimal WWR. Charles et al. [10] Used a parametric study to investigate the effect of wall and ceiling insulation, airtightness, and replacement of windows on an old office building in Vancouver, Canada, and concluded that modifying them could save 45% of total energy consumption. It also reduced emissions by reducing the use of natural gas by 70 tones. Moschetti et al. [11] examined the most influential aspects of environmental and economic problems in zero-energy buildings and zero-emission, and suggested a way to solve these problems in buildings. One of their proposals was the widespread use of wood in construction, which resulted in a 30% reduction in GWP (Global Warming Potential).

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Pathirana et al. [12] investigated the effect of shape, orientation, window to wall ratio and areas on the energy consumption of lighting in approximately 300 different two-story buildings with 24 orientations in tropical climate with natural ventilation. They found that WWR changes had a greater impact on residents' thermal comfort (20 to 55 percent) than electrical energy for lighting (1.5 to 9.5 percent). Harmati et al. [13] performed a detailed analysis on improving the energy consumption performance of existing office buildings by using window to wall ratio and geometry. Their results show the impact of glass parameters on annual building energy demand. Alwetaishi [14] examined the window to wall ratio of a building at 5%, 10%, 20%, 30%, and 40%, and suggested that in addition to obtaining the worst directions in terms of southern and eastern heat, The glass to wall ratio is 10% in hot climates (both wet and dry). Zomorodian et al. [15] concluded by examining an office building with maximum thermal comfort hours and minimum energy consumption for a hot and dry environment, reducing energy consumption by 14.8%, as well as operating carbon emissions by 17%. It decreased, while embodied carbon increased by 47%. Khalesi et al. [16] studied the impact of combining a passive ventilation system and smart windows in a climate-friendly building. A 3D steady-state Reynolds-averaged Navier Stokes Computational Fluid Dynamics (RANS CFD) simulation with a Shear Stress Transport (SST) K-ω turbulence model was used to evaluate the temperature and air age distributions for two heat source and smart window cases and two ventilation openings. The results of thermal comfort analysis showed that WWR 30% and 40% are preferred for all studied windows and electrochemical glazed windows, respectively.

Based on the aforementioned, although several studies have been conducted on the effects of different building orientations on energy consumption, so far a comprehensive study has not been conducted to compare the simultaneous effects of these parameters on CO_2 and embodied reduction in hot and dry climates. It is worth noting that the suitability of the variable parameters mentioned in the walls is highly dependent on the climatic conditions of the area. In other words, if a parameter decreases or increases the absorption of solar heat, it will naturally decrease or increase the summer and winter load. Accordingly, only by determining the annual load for given climate can one comment on whether or not the orientation and ratio of window to wall in a building are appropriate. In this research, different methods of reducing CO_2 production of a zero energy building to achieve more stability are investigated.

2. Methodology

Figure 1 illustrates the use of renewable energies in the simulated building of the present study, as well as how electricity is exchanged with the grid and electricity storage (battery). As shown in Figure 1, solar energy and wind energy are continuous inputs to the building's electrical current. The important point is that, unlike thermal energy, electrical energy is not easily stored after production. For this purpose, the battery is used after generating electricity and converting it to storage. In this research, by using power generators that attach to the battery, the electricity is first stored by them (after the building has been supplied with electricity), then if the battery is charged, the surplus electricity is returned to the national network. It may also be possible to receive electricity stored in the battery at times when high energy loads are on the building and to receive electricity from the national network when the battery is fully discharged.

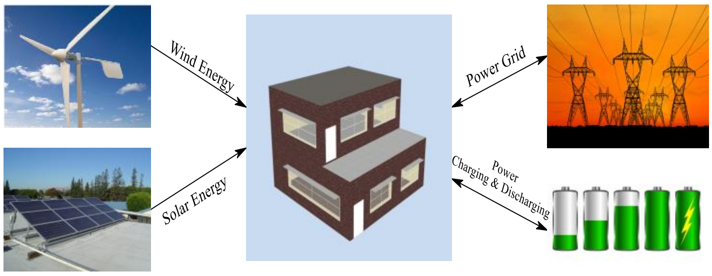


Figure1. Interchange of studied building energy with renewable resources and network

2.1. Building Model

For modeling, a two-story real-estate office building in Zahedan, Iran, with a total area of 149 square meters and a total occupied volume of 513 cubic meters, was studied. The 3D drawing of this building is shown in Figure 2. The details of the design of the model building are given in Table 1.

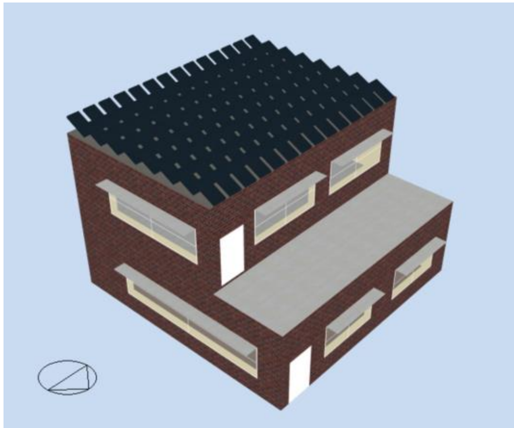


Figure2. Modeled building for analysis

Table 1 Modeled Building's Specification and Site Location.

Parameters	Values/Types
Program Version	EnergyPlus, Version 8.5.0-c87e61b44b
Hours Simulated [hrs]	8760
Weather File	Zahedan Airport - IRN ITMY WMO#=408750
Latitude [deg]	29.48
Longitude [deg]	60.91
Elevation about sea level [m]	1378
Site orientation [deg]	0
HVAC	GSHP Water to Water heat Pump, Heated Floor, Chilled Beams, Nat Vent
Lighting	Compact fluorescent (CFL)
Gross Window-Wall Ratio [%]	19.55
Window Opening Area [m^2]	50.63
Gross Wall Area [m^2]	259

As explained in the previous sections, energy production in that building should be used to supply part or all of the energy consumed for a Net-Zero Energy Building (NZEB). This generating energy consists of two general types of electric and thermal, although previous research has shown that to analyze energy in a mechanical system one can convert these energies into coefficients. As can be seen in Figure 1, due to the climate potential of Zahedan, this study uses two types of photovoltaic solar and wind energy. The specifications of the photovoltaic panel used and the turbine used in the present study are presented in Tables 2 and 3, respectively.

Table 2 Photovoltaic Panel Specifications. [5, 17-22]

Parameters	Values/Types
Total area [m^2]	54
Fraction of surface with active PV	0.9
Efficiency [%]	15
Material	Bitumen felt
Heat transfer integration	Decoupled
Inverter efficiency [%]	90
Availability schedule	On 24/7

Table 3 Wind Turbine Specifications. [5, 17-22]

Parameters	Values/Types
Rotor type	Horizontal Axis Wind Turbine
Power control	Variable Speed Fixed Pitch
Overall height [m]	11
Number of blades	3
Overall wind turbine system efficiency [%]	83.5
Availability schedule	On 24/7

Table 4 provides environmental information and thermal comfort for different seasons of the year.

The monthly diagrams of dry bubble temperature and dew point temperature are shown in Figure 4. As it can be seen, the maximum temperature of the bubble is dry in summer and the dew point is almost constant throughout the year. The same pressure is shown in Figure 5. As can be seen, the pressure changes are negligible and can be considered 87 kPa. The annual moisture level is also shown in Figure 6, which indicates that the relative humidity in the investigated building environment is not very high. The wind speed and direction are also shown in Figure 7.

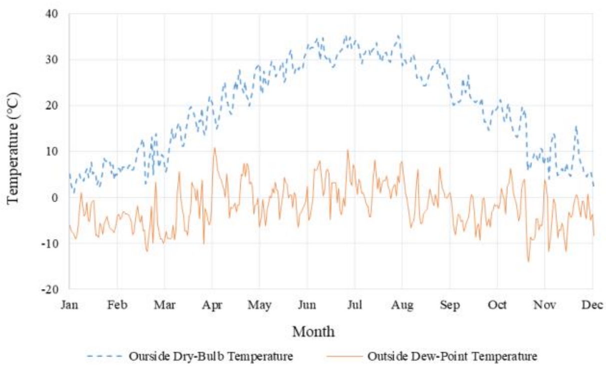


Figure4. Monthly dry-bulb and dew point temperature outside the building [5, 17-22]

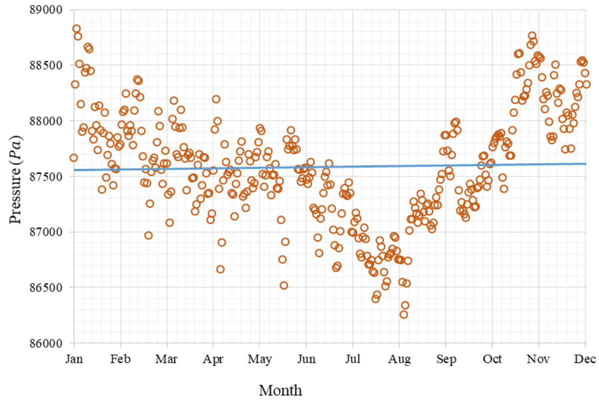


Figure5. Monthly atmospheric pressure around the modeled building [5, 17-22]

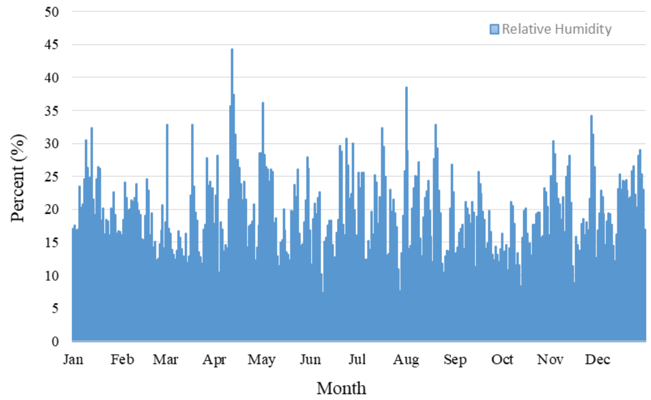


Figure6. Annual relative humidity around the modeled building [5, 17-22]

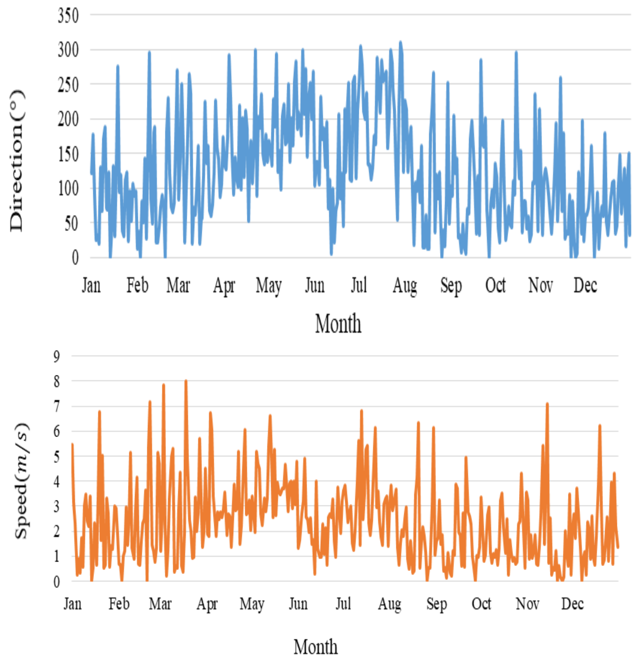


Figure7. Relative wind speed and annual wind direction around the modeled building [5, 17-22]

Table 4 Site Data and Comfort for Different Months of Year. [5], [17-22]

Data/Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Air Temp.	23.5	24.0	25.5	26.7	28.9	30.5	31.2	31.6	30.2	27.6	25.3	23.5
Radiant Temp.	24.7	25.4	27.1	28.9	31.2	32.6	33.4	33.5	32.3	29.6	26.9	24.6
Operative Temp.	24.1	24.4	26.3	27.8	30.0	31.5	32.3	32.6	31.3	28.6	26.1	24.1
Outside Dry Bulb Temp. (°C)	17.7	18.9	23.0	26.4	30.4	32.8	34.0	33.1	31.8	28.6	23.2	18.3
Outside Dew Point Temp. (°C)	9.2	11.8	15.3	18.0	22.1	24.0	26.5	27.0	24.4	20.6	13.3	11.6
Wind Speed (m/s)	2.0	2.1	3.0	2.2	3.1	2.7	3.5	3.9	3.0	1.4	1.9	2.6
Wind Direction (°)	107.1	131.0	128.3	107.8	126.6	131.0	130.1	135.1	143.3	68.2	123.4	144.5
Solar Altitude (°)	-12.8	-8.1	-1.1	6.0	11.6	14.3	13.2	8.8	2.0	-5.5	-11.5	-14.2
Solar Azimuth (°)	189.6	190.0	191.6	193.7	194.7	194.0	192.8	193.0	194.5	195.6	194.3	190.9
Atmospheric Pressure (kPa)	101.3	101.2	101.1	100.9	100.3	99.6	99.3	99.4	99.7	100.0	100.6	100.9
Direct Normal Solar (kWh)	108.3	104.6	135.7	114.7	119.1	163.4	123.0	139.7	117.1	106.6	95.0	94.8
Diffuse Horizontal Solar (kWh)	102.9	131.1	121.6	183.5	196.5	156.4	158.0	147.3	156.1	139.2	111.6	98.2

2.2. Analysis of the Total Energy Consumption

The most important loads in a residential building are cooling and heat loads. In a building, the sum of the heat dissipated and received must be equal to that given in Equation 1 [23]:

$$-Q_{HVAC} = Q_{Total\ Site\ Energy\ Consumption} = \sum_{i=1}^{Nsj} \dot{Q}_i + \sum_{i=1}^{Nsurface} h_i.A_i.(T_{si} - T_z) + \sum_{i=1}^{Nzones} m_i.c_p.(T_{zi} - T_z) + m_{\inf}.c_p.(T_{ext} - T_z) \quad (1)$$

In the above equation, $\sum_{i=1}^{Nsj} \dot{Q}_i$ is the sum of the loads caused by the internal heat transfer, $\sum_{i=1}^{Nsurface} h_i.A_i.(T_{si} - T_z)$ the heat transfer transferred by the surfaces of the different regions, $\sum_{i=1}^{Nzones} m_i.c_p.(T_{zi} - T_z)$ is the heat transfer due to the composition of the air inside the zones, and $m_{\inf}.c_p.(T_{ext} - T_z)$ is also the heat transfer caused by the exit of the air seams.

Heat transfer caused by the building components will impact the temperature of internal surfaces (T_{si}), and, hence, Equation 2 demonstrates the convective heat transfer between building surfaces and the internal air:

$$-q''_{conv} = q''_{LWX} + q''_{SW} + q''_{LWS} + q''_{sol} + q''_{ki} \quad (2)$$

Where q''_{LWX} represents the flux of radiative heat transfer between surfaces with long wavelengths, q''_{SW} shows the flux of radiative heat transfer between lights and surfaces, and q''_{LWS} is the flux of radiative heat transfer between surfaces and radiants. Moreover, q''_{sol} and q''_{ki} represent the solar radiative flux and conductive heat transfer from the building surroundings, respectively. q''_{ki} can be figured out using Equation 3:

$$q''_{ki}(t) = -Z_o T_{i,t} - \sum_{j=1}^{nz} \dot{Z}_j T_{i,t-j\delta} + Y_o T_{o,t} + \sum_{j=1}^{nz} Y_j T_{o,t-j\delta} + \sum_{j=1}^{nq} \psi_j q''_{ki,t-j\delta} \quad (3)$$

where *T* represents the temperature, *i* and *o* coefficients show the internal and external surfaces, respectively, *t* represents the time in one stage, and *Z*, *Y*, and *Ψ* show the internal, cross, and flux coefficients.

The amount of the energy required for consumption of one year to cool the interior space of the building in terms of kWh/m^2.year is determined by Equation 4:

$$CN_{usf} = \frac{1-\eta_c}{A} \times Q_{gn,c} \quad (4)$$

where η_c, A, and $Q_{gn,c}$ represent the loss coefficient in the cooling system, the total net cooled area of the building, and the total flux of the internal and solar heat gain of the building.

As seen in the building heating section, the cooling temperature should be set on a certain amount for some seasons of the year to be able to solve this equation. $Q_{gn,c}$ is figured out by Equation 5:

$$Q_{gn,c} = Q_{opq} + Q_s + Q_i \quad (5)$$

where Q_{opq} is the internal temperature caused by equipment, lights, and building occupants. Q_s represents the solar heat gained from transparent environments (e.g. windows and other transparent surfaces), while Q_i shows the solar heat gained from opaque environments.

Finally, heat loss through exterior walls is figured out by Equation 6:

$$Q_{loss} = U(T_t - T_{md}) \quad (6)$$

Where *U*, T_t, and T_{md} represent the overall temperature transfer coefficient, the fixed internal temperature, and the mean daily temperature, respectively, with T_{md} being figured by Equation 7:

$$T_{md} = \frac{T_{rad} + T_{air}}{2} \quad (7)$$

Where T_{rad} and T_{air} represent the radiative temperature and air temperature, respectively.

2.3. Calculation of the amount of Carbon Emissions in a Building

Total carbon emissions in construction of a building (E_c) is figured out by Equation 8 [24]:

$$E_c = \sum E_{mat} + \sum E_{trans} + \sum E_{site} + \sum E_{waste} \quad (8)$$

where E_{mat} is the carbon emitted from the building materials, E_{trans} is resulted from the carbon emitted during transfer, E_{site} is caused by carbon emissions through the site, and is E_{waste} the amount of carbon emitted through waste.

Equation 9 yields the carbon emitted through building materials:

$$E_{mat} = Q_{mat} \times EF_{mat} \tag{9}$$

where Q_{mat} represents the quantity of the materials and products made in the building, and EF_{mat} represents the coefficient of materials and products.

Moreover, the overall annual carbon emissions, E_{o-a}, caused by the function of the building at the time of operation with electricity consumption:

$$E_{o-a} = E_{ele-a} \tag{10}$$

$$E_{ele-a} = C_{ele-a} \times EF_{grid} \tag{11}$$

where E_{ele-a} shows the carbon emissions due to annual consumption of electrical energy, C_{ele-a} represents the annual electrical energy consumption, and EF_{grid} shows the carbon emissions coefficient for generation and distribution of electricity.

3. Results and Discussion

In Figure 8, for a building that uses photovoltaic panel and wind turbines, details of the monthly electricity consumption including the electrical energy used for occupants' activity and all equipment except lighting, the electrical energy used for lighting, the electrical energy consumption of cooling and electrical energy consumed to produce hot water. As mentioned above, due to the Zahedan city's climate, the highest energy consumption is due to the cooling energy produced in the warm seasons, with the highest cooling load for this building being 1227 kWh in July. Finally, Figure 9 compares the annual electricity consumption of the building and the annual electricity generated by renewable energy. In fact, this figure shows that the total annual energy production of the building (derived from the photovoltaic panels installed on the roof of the building as well as the wind turbine) was slightly higher than the annual energy consumption of the building, and therefore the building is in terms of consumption is zero energy building.

In Table 5, for each of the materials used in the modeled building, the values of the surface area occupied, the mass, the amount of carbon dioxide embodied and the amount of carbon dioxide equivalent produced. As can be seen, the total CO_2 is 19562.7 kg and is equivalent to 23902.2 kg. The carbon content of the exterior glass and shades is also shown in Table 6.

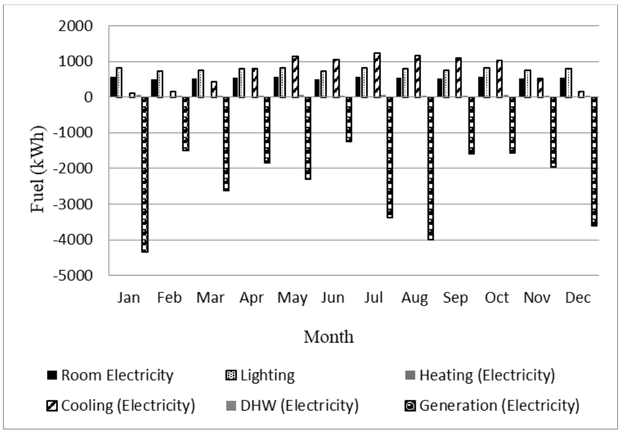


Figure8. Monthly production and consumption energy using renewable energies in zero energy building

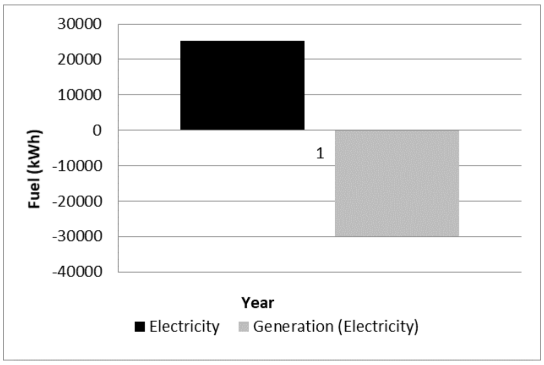


Figure9. Total energy consumption and annual energy production using renewable energies in zero energy building

Table 5 The building blocks and carbon dioxide produced.

Materials Embodied Carbon and Inventory	Area (m^2)	Mass (kg)	Embodied Carbon (kg.CO_2)	Equivalent CO_2 (kg.CO_2)
Painted Oak	4.3	107.4	0.1	0.2
Plasterboard	100.1	3640.1	1383.1	1456.2
Floor/Roof Screed	100.1	8400.1	1344.1	1344.1
Timber Flooring	100.1	1950.1	897.1	916.3
MW Glass Wool (rolls)	100.1	173.3	265.2	291.2
Urea Formaldehyde Foam	100.1	132.6	236.1	254.7
Gypsum Plastering	204.1	2651.7	1007.6	1060.6
XPS Extruded Polystyrene - CO_2 Blowing	204.1	567.5	1634.5	5437.4
Cast Concrete (Dense)	70.1	14700.1	1176.1	1176.1
Cast Concrete	100.1	20000.1	1600.1	1600.1
Concrete Block (Medium)	204.1	28557.7	2284.5	2284.5
Asphalt	100.1	2100.1	105.1	105.1
Brickwork Outer	204.1	34677.2	7629.1	7975.7
Sub Total		117658.1	19562.6	23902.1

Table 6 The local shape of building and carbon dioxide produced.

Glazing Embodied Carbon and Inventory	Area (m^2)	Embodied Carbon ($kg.CO_2$)	Equivalent CO_2 ($kg.CO_2$)
Project external glazing	50.7	946.5	946.5
Local shading	-	2531.3	2531.3
Window shading	-	2531.4	2531.1
Sub Total	50.7	6009.3	6009.4

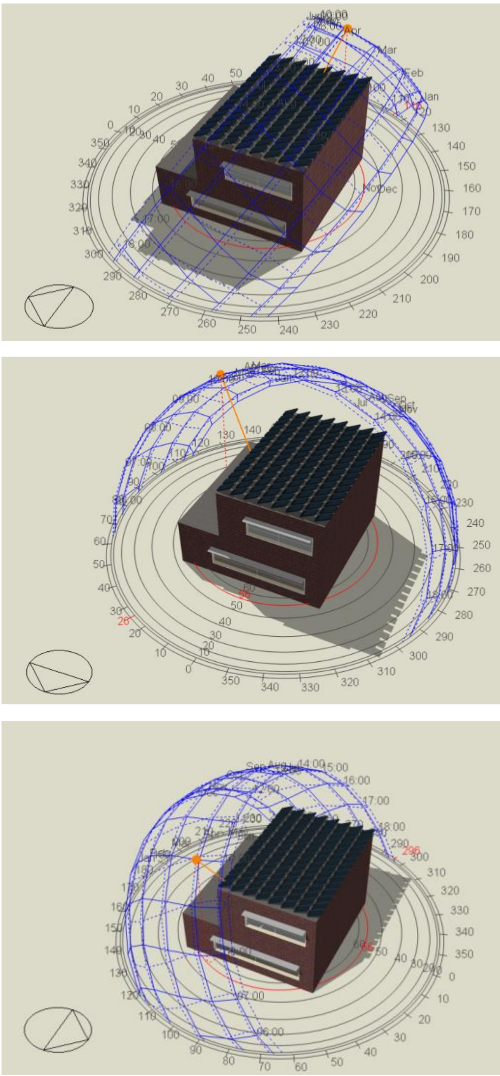
Finally, for the total area of 529 m^2 of building, the amount of embodied carbon dioxide was 25572.3 kg and the amount of carbon dioxide equivalent 29911.8 kg.

In Figure 10, the four main orientations of the building are shown on August 23rd at 10 A.M.

a

b

c



d

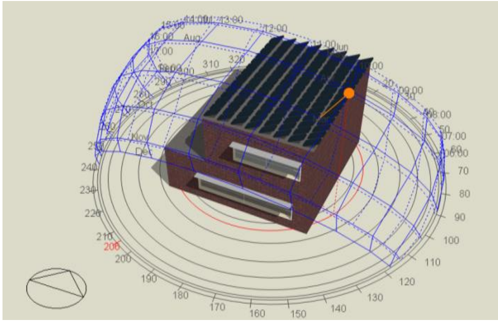
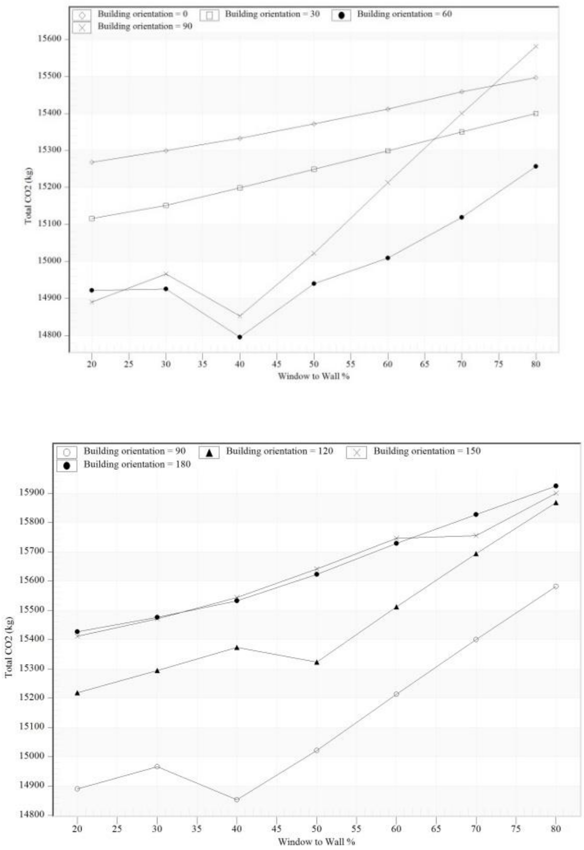


Figure10. Different orientations of the building modeled on August 23rd at 10 A.M. a) Northern orientation b) Eastern orientation c) Southern orientation d) Western orientation

In the Figure 11, Carbon dioxide production results illustrate in four different building modes in different orientations and window to wall Ratios. In the south and west orientations, carbon dioxide production is not significantly different, although the use of the WWR is recommended in these two orientations, with the minimum CO_2 production in the orientation being recommended. South/West are about 20% per annum with a rate of 15114.16 kg CO_2 annually. Also in the eastern orientation, the most suitable orientation angle of 110 degrees was obtained for WWRs of 20% and 50%, with carbon dioxide production of 15106.14 kg CO_2 and 15244.86 kg CO_2, respectively.

a

b



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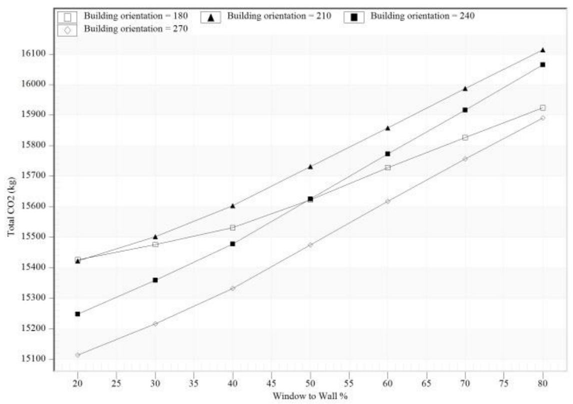

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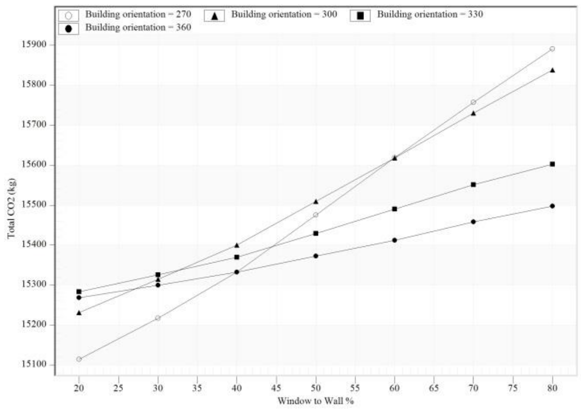

Figure11. CO_2 emissions in different orientations of the modeled building: a) north orientation; b) east orientation; c) south orientation; d) west orientation.

4. Conclusion

Since about 30% to 40% of energy demand is in most of the developed or developing countries in the building sector, so buildings are considered to be the key to the transition to sustainability in the energy sector. Due to the high consumption of electricity in buildings, these figures are usually converted to more than 40% of the primary energy and energy associated with the generated CO_2.

In this study, Annual amounts of electrical energy used for occupants of the building and all equipment except lighting, electrical energy consumed for lighting, electrical energy consumed for cooling and electrical energy consumed for hot water production, respectively, 6459.8 kWh, 9335.8 kWh, 8860.5 kWh, respectively, and 584.5 kWh, while annual electricity production is 27308.4 kWh. After parametric studies, the best positioning of the building in the north / east orientation was obtained with a 60 degrees and a WWR of 40%. Also the building considered in hot climate, since it produced CO_2 annually 29911.8 kg, it was observed that at optimum angle and ratio of window to wall, about 15 Tons of carbon dioxide production have fallen annually, which means that carbon dioxide production is halved. In the south and west orientations, carbon dioxide production is not significantly different, although the use of the WWR ratio is recommended in these two orientations, with the minimum CO_2 production in the orientation being recommended. South/West is about 20% per annum with a rate of 15114.16 kg CO_2 annually. Also in the eastern orientation, the most suitable orientation angle of 120 degrees was obtained for WWRs of 20% and 50%, with carbon dioxide production of 15106.14 kg and 15244.86, respectively.

Importantly, building orientation has almost no effect at 180 to 270 degrees, and with increasing WWR, carbon dioxide production increases.

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