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# Transformation of a University Building into a Zero Energy Building in Mediterranean Climate

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**A B S T R A C T**

In the context of environmental policy, the EU has launched a series of initiatives aimed at increasing the use of energy efficiency, as it has pledged to reduce energy consumption by 20%, compared with projected levels of growth of $CO_2$ emissions into the atmosphere by 2020. In Greece $CO_2$ emission levels in the atmosphere have risen significantly over the past two decades [45]. For the year 2011, $CO_2$ emissions per person in Greece correspond to 7.56 metric tons. According to the data, this increase in emissions is reflected to a 151.2% above from the levels of 1980 and a 756% increase from 1960 levels. The building sector consumes the largest amount of energy in Greece, therefore constitutes the most important source of $CO_2$ emissions. The energy upgrade of the building sector produces multiple benefits such as reduced energy consumption, which is consistent with the reduction of air pollution. Additionally, there is a significant improvement at the interior comfort conditions of the building, which promotes productivity and occupant health. Moreover, because of the large number of educational buildings in the country, the energy consumption of them present a significant amount of the country's total energy consumption and simultaneously has the effect of increasing the costs paid by the state budget for the operation and maintenance of public buildings. The investigation of alternative methods to reduce energy consumption in educational buildings is an important approach for sustainability and economic development of the country over time. The purpose of this paper is to study and evaluate the energy saving methods of a university building in Mediterranean climate with significant energy consumption. Additionally, through Building Information Modeling (BIM) and Computational Fluid Dynamics (CFD) software, studies considering the contribution of passive heating and cooling techniques were conducted, in order to minimize energy consumption in pursuit of desirable interior thermal comfort conditions.

## 1. Introduction

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The energy consumption of educational buildings in Greece, because of the large number in the country, represent a significant amount of the country's total energy consumption and simultaneously has the effect of increasing the costs paid by the state budget for the operation and maintenance of public buildings. Exploring alternatives to reduce energy use in educational buildings is an important approach for sustainability and economic development of the country over time. Also, an important point in this study is the fact that the internal comfort conditions of university and school buildings designed to improve thermal conditions and air quality inside the classrooms, resulting in the improvement of educational activities [13]. At Greek educational buildings, the energy that is consumed is used primarily to meet the needs for heating and lighting, and afterward to operate the equipment. The energy consumption for space cooling, is limited as most school buildings are not in operation during the summer season and thus, many of them do not use A/C equipment, except in some cases, staff offices are equipped with local A/C units. According to a study conducted in 1995 in Greece [22], the average annual energy consumption of school buildings, based on measurements of buildings in different climatic regions and whereas taking into consideration measurement data from 65,000 classrooms, energy consumption was estimated at about 92 kWh/m$^2$ for space heating, but in many cases reaching 100 and even up to 200 kWh/m$^2$. According to the "Greek Regulation for the Energy Efficiency of Buildings" [27], there are four climatic zones in Greece, where A' climate zone represents the high temperature regions and the D' climatic zone the colder areas. According to a study [21], the average annual energy consumption in school buildings is about 95 kWh/m$^2$, which is distributed to about 68 kWh/m$^2$ for heating and 27 kWh/m$^2$ for electricity.

The purpose of this paper is to study and evaluate the energy saving potential at a university building with significant energy consumption. Additionally, studies to consider the contribution of passive heating and cooling techniques, in order to minimize energy consumption in pursuit of achieving the desirable interior thermal comfort conditions has been conducted. The building which is examined in this work belongs to the building complex of the Democritus University of Thrace (D.U.TH.) in Xanthi, climatic zone C' [27]. The building presents significant energy consumption, as it was built during the period 1972-1973, before enactment of the Thermal Insulation Regulation in 1979 and shows a complete lack of thermal insulation at the building envelope. Also, the building is glazed with single glass windows in aluminium frames, which increases the thermal losses.

The objective of the paper is the study and the investigation of the best feasible sustainable solutions to achieve minimal energy consumption of the building, with the main criterion the desired internal comfort conditions.

**Table 1.** General geometrical building data

| Number of floors: Four floors | |
|---|---|
| Total building area: 3,087 m$^2$ | Total building volume: 10,866 m$^3$ |
| Heated surface: 2,634 m$^2$ | Heated volume: 9,273 m$^3$ |
| Unheated surface: 457 m$^2$ | Unheated volume: 1,593 m$^3$ |
| Average standard floor height: 3.52 m | Ground floor height: 3.52 m |
| Average floor-window height: 0.80 m | Total building volume: 10,866 m$^3$ |

## 2. Methodology

For the upcoming results, the aforesaid building has been studied with the help of BIM and CFD software to

evaluate the energy consumption during operation and also to explore variety of energy upgrade scenarios of the building in order to reduce energy consumption, while simultaneously the contribution of passive heating and cooling techniques at the building is considered.

### 2.1. Modeling and Simulations

The building energy assessment studies were carried out with the Revit software. Furthermore, Green Building Studio (GBS) was used for deeper analysis of the energy assessment results so to describe in detail the energy consumption in every case (ANSI/ASHRAE Standard 140 approved software). In parallel, Ecotect software was used for further investigation of the climatic conditions of the region. Subsequently, studies for the transmitted sunlight to the interior of the building using the computational analysis tool "Lighting Analysis" for Revit were conducted, to investigate the optimal visible transmission of sunlight permeability. In addition, a solar study with the computational tool "Solar Analysis" for Revit software has been conducted so it could be imprinted the energy channeled to the building surfaces through solar radiation during the year, according to the climatic conditions of the region, in order to study the performance and effectiveness of passive heating and cooling techniques at the particular building. Furthermore, a study on fluid dynamics with CFD Flex software, to analyze the contribution of passive heating and cooling techniques at the interiors has been conducted, using the Solar Analysis data, the internal conditions as obtained from the GBS and the weather data from Autodesk Climate Server. Supplementary, three-dimensional drawing software AutoCAD and Inventor Professional, aiming the detailed design of the structure were used in order to investigate the flow of air at the CFD software.

## 3. Description of the Building

The building belongs to the building complex of the D.U.TH. School of Engineering in Xanthi, Greece and it consists of four levels, namely ground floor and three floors,

**Table 2.** Opaque structural elements of the building

| Structural elements | Thickness (mm) | Thermal Transmittance U-value W/(m$^2$ K) | Thermal Mass (kJ/K) |
|---|---|---|---|
| Masonry S-W-E | 250 | 4.17 | 35.10 |
| Masonry N | 120 | 8.72 | 16.85 |
| Masonry Stairway | 290 | 3.57 | 40.71 |
| Glass blocks | 120 | 3.45 | 8.76 |
| Ground floor | 300 | 3.45 | 42.12 |
| Roof | 350 | 3.23 | 63.26 |

also a basement in a part of the building coverage. The long axis of the rectangular building is oriented along the axis SE - NW, while the main façade is oriented southwest. The building includes classrooms, offices and public areas. The classrooms are located in the SE side while the NW is occupied by the circulation space. The façade is covered by glass, of 1.70m high -reclining windows or glazed façade- from the height of 0.80 from the floor. All areas are heated except the basement. The building does not have thermal insulation on external or internal sides nor at the roof. General geometrical building data are given in Table 1.

**Table 3.** Transparent structural elements of the building

| Glazing Type | Visible Light Transmittance | Solar Heat Gain Coefficient | Thermal Transmittance U-value W/(m$^2$ K) |
|---|---|---|---|
| Single glazing (4 mm) aluminum frame | 0.72 | 0.76 | 5.90 |

### *3.1. Photographic depiction of the building*

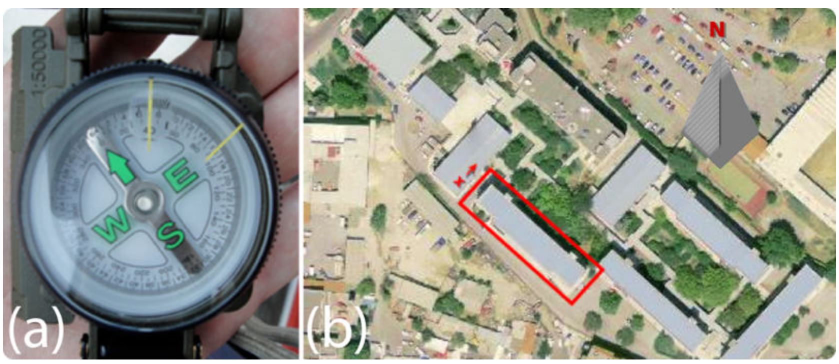



**Figure 1.** (a) Orientation of the building, with the compass mounted in position 'X' on the topographic plan, (b) Topographical plan of the building of the Democritus University at the School of Engineering in Xanthi

The building consists of prefabricated elements which do not have thermal insulation. The opaque structural elements made of reinforced concrete. The list of the opaque and transparent structural elements of the building are reported in Table 2 and Table 3 respectively.

### *3.2. Thermal Zones*

For the energy evaluation of the building, it is determined the separation of the premises to individual thermal zones depending on their use, in accordance to meet the operating conditions of the Technical Chamber of Greece Guidelines [26]. The thermal zones were considered as illustrated in Figure 2.

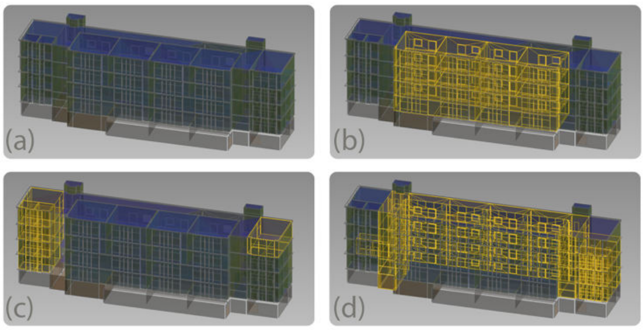



**Figure 2.** Thermal zones of the building: (a) Building Analysis Model (b) 1st Thermal Zone: Classrooms, (c) 2nd Thermal Zone: Offices, (d) 3rd Thermal Zone: Corridors & WC

## 4. Climatic Data of the Study Area

The reference building, is located in the northeastern Greece in the city of Xanthi, with latitude 41°8'0" North and longitude 24°53'0" East. The region has a continental climate with cold winters and hot summers. According to TOTEE 20701-1 [26], the building belongs to C' climatic zone. The climatic conditions of the area, as received from the

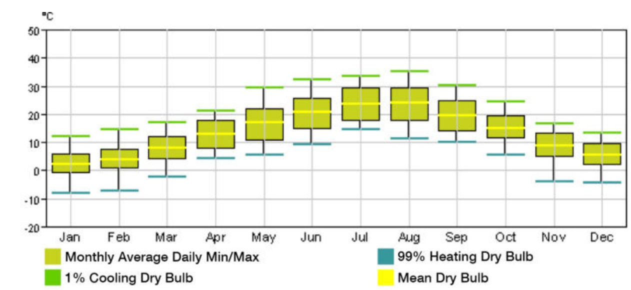



**Figure 3.** Monthly temperatures of the study area. Note that the extreme high and low temperatures recorded in 1% of the time on historical data.

Autodesk Climate Server for the forthcoming studies, in Figures 3-7.

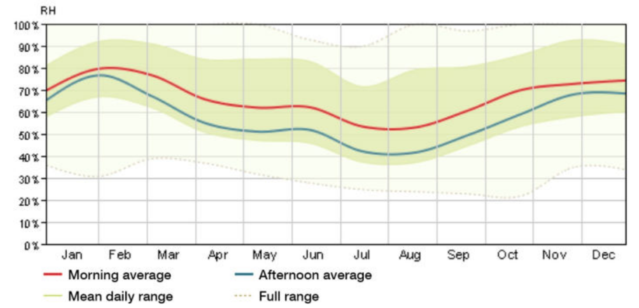
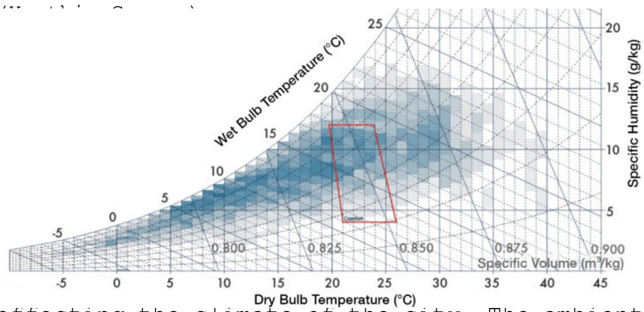



**Figure 4.** Monthly humidity variation


**Figure 5.** Psychometric Chart of the Region

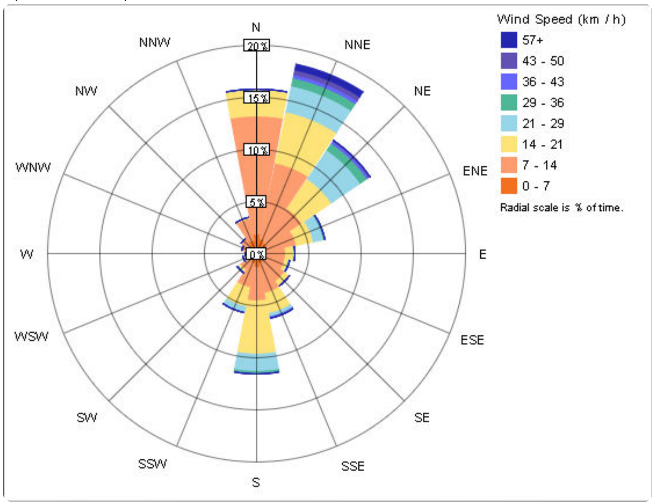



affecting the climate of the city. The ambient temperature of the prefecture ranges from -4 °C during winter to 36 °C during summer. During winter, the dry bulb temperature is at -4 °C while similar are the measurements of the wet bulb thermometer because of the increased humidity. During summer, the average dry bulb temperature is at 36 °C and the average wet bulb temperature is at 23 °C. The average daily temperature range is about 13 °C. The ambient temperature in the city ranges from -1 °C during winter to 32 °C during summer, while extreme temperatures have been measured in the range of -8 °C to 38 °C (Note that the extreme high and low temperatures as shown in Figure

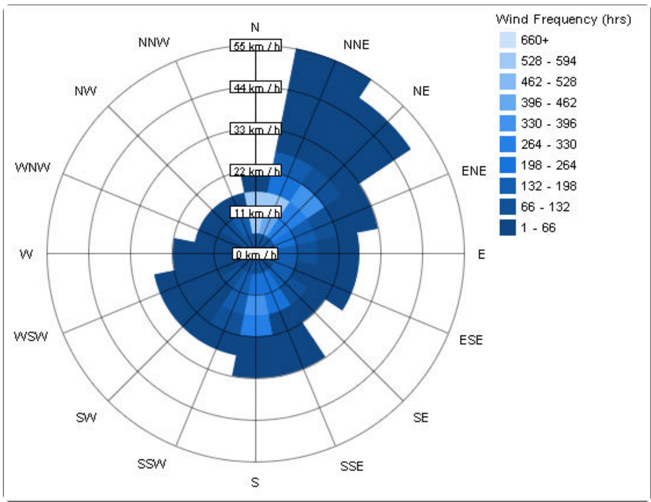
**Figure 6.** Annual speed distribution wind rose (the wind speed range, each category of km/h corresponding to the Beaufort scale 1-8)



3, recorded in 1% of the time on historical data). Highest winds frequency occurs mainly during the winter months from the north-northeast direction. Moreover, from the same direction there are recorded the highest speeds in the annual wind rose, which reach up to eighth category on Beaufort scale (>57km/h).




According to the climatic variations of the region, a humid climate during the winter months is observed with the peak in moisture levels noted during February and as the




intensity of direct solar radiation increases during the summer months, the climate becomes drier. In the annual frequency temperatures diagram, a low frequency of thermal comfort temperatures (20 °C - 26 °C) is observed in the study area. The winds in the region are mostly north-orientated during the winter

**Figure 7.** Annual frequency distribution wind rose

months, while during spring, a contribution from the easterly and southerly winds is observed and as summer approaches prevailing the southerly and milder winds. The relative humidity of the region during summer afternoons ranges at around 40%, while increasing during the winter months and culminates during the months of January and February, where exceeds the levels of 75% during the afternoon.

In the psychometric diagram of the Xanthi region (through Ecotect software) it is illustrated the thermal comfort zone. This area is covered by 19% of the region's climate, which means that the remaining 81% of climatic conditions belong to undesirable thermal comfort zone. Consequently, it is requested the study and implement of heating and cooling techniques of the interiors to achieve the desirable thermal comfort conditions.

## 5. Evaluation of the Energy Performance of the Building

For the evaluation of the energy performance of the building's existing condition, are listed the characteristics of the heating and cooling system, as well as the lighting fixtures system.

### *5.1. Existing Condition*

The actual central heating system meets the needs for space heating of the building complex of the D.U.TH. School of Engineering. The installation is composed of two boiler-oil burner units (high temperature 70-90 °C), with central two-pipe distribution network, with 13mm thick insulation. The total power of boiler-burner is 2,000,000 kcal/h or 2,326kW, from which 332.3kW corresponds to meet the needs for the study building. The thermal efficiency of the boiler-burner according to the exhaust gas analysis, was estimated by energy audit at $n_{gm}$ = 91% (D.U.TH. Technical Service, 2016). Overall, the oil supply of the two burners is equivalent to 175 lit/h (D.U.TH. Technical Service, 2016).

According to KENAK [26], with a view to obtaining the desired internal temperature conditions during operation of the building which is equivalent to 13 hours a day, 5 days a week and a heating period from 15/10 to 30/4, approximately 130 days of heating system operation. In 13-hour operation of the building, at the existing condition, the consumption of the building is equivalent to about 35,750 litres of heating oil per year. In the energy assessment of the building using the Revit software to evaluate the existing condition, for heating system considered an oil burner with two-pipe distribution network and power 348.8 kW or 300,000 kcal/h, 12 bar spray pressure of oil with efficiency 91% and a maximum operating temperature of 90 °C. For the calculation of the maximum required heat output of the heating unit it is given the equation from TOTEE 20701-1[26]:

**Table 4.** Annual energy consumption and specific energy consumption of building's existing condition

| Energy | Percentage | kWh | Cost | Specific energy consumption per year (kWh/m²/yr) | Metric tons $CO_2$ / year |
|---|---|---|---|---|---|
| Lighting | 20% | 86,749 | €13,012 | | |
| Equipment | 9% | 41,579 | €6,237 | | |
| HVAC Systems | 6% | 24,636 | €4,271 | | |
| Electricity | 35% | 152,964 | €22,945 | 58 | 151 |
| Fossil fuels | 65% | 288,278 | €32,589 | 109 | 76 |
| **Total** | **100%** | **441,242** | **€56,109** | **167** | **227** |

$$P_{gen} = A \cdot Um \cdot \Delta T \cdot 2{,}5$$

$P_{gen}$: (W) is the estimated maximum required heat output of the heating unit of the building,

A : ($m^2$), is the total actual outer surface of the building envelope (walls, openings, ceilings), which is exposed to the outside air. For the reference building $A=4557m^2$

Um : (W(m²K)) is the maximum permitted average rate of heat transfer to the entire surface A. For the area of Xanthi is 3,5 W(m²K) for old buildings before the Greek Regulation of Thermal Insulation.

ΔT : (°C) the temperature difference for the design of the system for Xanthi 23 °C (C' Climatic Zone)

2,5 : overall surcharge coefficient which includes loads of ventilation and surcharge rates due to intermittent operation, distribution network losses, etc.

The thermal power boiler $P_{gen}$ for the reference building should be 917kW. The proportion of the installed capacity of heating systems corresponds to 332.3kW. Therefore, the actual installed capacity of the boiler is less than the maximum estimated $P_{gen}$. For this reason, we take over-dimensioning rate $n_{g1}$=1 and the factor $n_{g2}$ (boiler condition), is taken $n_{g2}$=1 [26]:, given that the boiler is in a relatively good condition. Thus, the total thermal efficiency of boiler-burner unit, is calculated:

$$n_{gen} = n_{gm} \cdot n_{g1} \cdot n_{g2}$$

$$n_{gm} \cdot n_{g1} \cdot n_{g2} = 0{,}91 \cdot 1 \cdot 1 = 0{,}91 = 91\%$$

In the building's offices (2nd thermal zone), there are located autonomous 12 local air-conditioners, with cooling power 12,000btu/h each (3.5kW). There is not central air distribution network thus there are not any distribution losses. The total cooling capacity installed is 42kW. Since there are no specifications and standards for the units, the energy efficiency ratio of the heat pump is taken EER = 2.0, as defined in TOTEE 20701-1 [26] and received efficiency $n_{em}$ = 0.93:

$$n_{em,t} = \frac{n_{em}}{f_{im} \cdot f_{hydr}}$$

For $f_{im}$ = 0.97 (for intermittent operation) and $f_{hydr}$ = 1 (system with hydraulic balance), the efficiency of terminal units calculated $n_{em,t}$ = 0.96. The consumption of the lighting system has been obtained into account for higher education building. From TOTEE 20701-1 [26], has been received 500 lux light level for higher education classrooms and office spaces (16 W/m$^2$) and 200 lux light levels for corridors and WC (6.4 W/m$^2$).

For the energy costs, the electricity prices of €0.15/kWh and heating oil of €0.9/lit were considered (D.U.TH. Financial Management Administration for the years 2013 to 2015). Emissions of carbon dioxide to the atmosphere, were calculated with values, 9,89x10$^{-4}$ metric tons $CO_2$/kWh for electricity consumption and 2,64x10$^{-4}$ metric tons $CO_2$/kWh for fossil fuel consumption (Greek Ministry of Environment, 2016).

### *5.2. Energy assessment results of existing condition*

The results from the energy simulation of the existing condition are summarized at Table 4 in terms of the monthly energy consumption, the cost thereof, the annual energy consumption, the percentage of energy consumption per use and fuel, its percentage proportion, the specific energy consumption and the annual $CO_2$ emissions.

## 6. Energy Renovation Measures

In this paragraph, it is described the energy assessment of the building by applying thermal insulation at building's envelope and glazing upgrade, taking into account the building's operating conditions as recommended from the TOTEE 20701-1 [26] for University building. The thermal insulation for this study chosen to be the graphite expanded polystyrene (FIBRAN GRAFIT EPS80) after a comparative research on relative materials to market prices and thermal properties, with Thermal conductivity (λ): 0,0320 W/(m·K), Specific heat capacity: 1,4900 J/(g·°C) and Density: 23,00 kg/m³. The list of the opaque and transparent structural elements after the renovation are reported in Table 5 and Table 6 respectively.

**Table 5.** Opaque structural elements of the building after renovation

| Structural elements | Thickness (mm) | Insulation Thickness (mm) | Thermal Transmittance U-value W/(m$^2$ K) | Thermal Mass (kJ/K) |
|---|---|---|---|---|
| Masonry S-E-W | 250 | 70 | 0.41 | 35.32 |
| Masonry N | 120 | 70 | 0.43 | 17.07 |
| Basement Masonry | 250 | 30 | 0.68 | 35.23 |
| Basement Masonry | 120 | 30 | 0.70 | 16.95 |
| Floor | 300 | 35 | 0.72 | 42.23 |
| Roof | 350 | 70 | 0.40 | 63.75 |

**Table 6.** Transparent structural elements of the building after renovation

| Glazing Type (A, B, C, D) | Visible Light Transmittance | Solar Heat Gain Coefficient | Thermal Transmittance U-value W/(m$^2$ K) |
|---|---|---|---|
| Double glazing (4-16-4mm) with Argon | 0.62 | 0.62 | 1.99 |

### *6.1. Daylight analysis*

Concerning the replacing of the glazing of the building, in order to achieve optimal energy performance of the building, a study of transmitted sunlight diffusion analysis of the building's existing transparent surfaces has been conducted, in order to; the frame replacement have both the desired thermal performance and optimal visible transmission of sunlight permeability resulting to less energy consumption during the diurnal operation of the building's lighting systems.

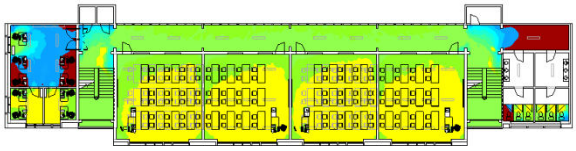
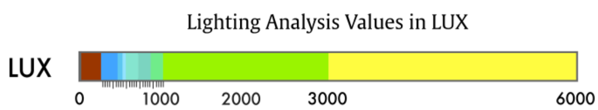


**Figure 10.** Daylight distribution in interior spaces at building's existing condition on the second floor

**Figure 11.** Daylight distribution in interior spaces at building's existing condition on the third floor



Lighting Analysis tool for Revit, uses LEED v4 EQc7 to determine the impact of daylighting within the building. The analysis illustrates illuminance levels at the interiors for 9 a.m. and 3 p.m., both on a clear-sky day, within 15 days of the equinox (21 September) that represent the clearest sky condition using typical meteorological year data. LEED v4

**Figure 8.** Daylight distribution in interior spaces at building's existing condition on the ground floor

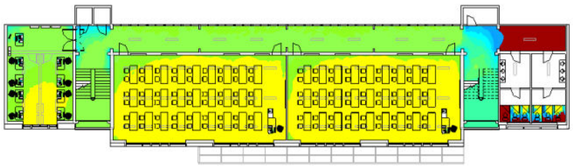


**Figure 9.** Daylight distribution in interior spaces at building's existing condition on the first floor

0 1000 2000 3000 6000

From the results of the daylight distribution in interior spaces, it is concluded that the sunlight transmission could be improved at the office spaces of the second and third floor while glazing replacing. By replacing the windows at east oriented office space on the third floor, (with dimensions 812.5x800mm) with larger transparent surfaces (dimensions 812.5x1700mm), it could be achieved a better daylight distribution into the area. Additionally, the consolidation of west-oriented office spaces, or replacement areas/spots of the walls with glass blocks could achieve a better daylight distribution inside the spaces.

The results of the daylight distribution in interior spaces of the second and third floor are illustrated afterwards, after the replacement of windows at the east oriented office space on the third floor and

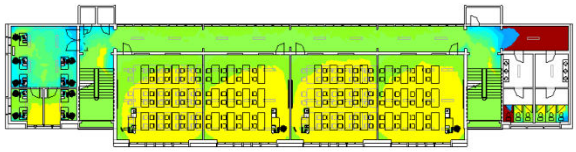


**Figure 13.** Daylight distribution in interior spaces after glazing replacement on the second floor

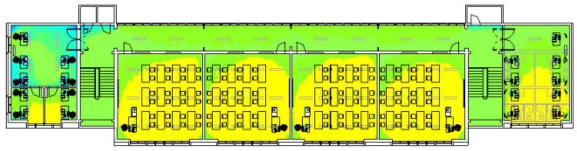


**Figure 14.** Daylight distribution in interior spaces after glazing replacement on the third floor

installation of glass blocks at the interior of the west oriented office areas.

**Table 7.** Daylight distribution in interior spaces results on the existing condition of the building*

| 9am, 17 September | 3pm, 17 September |
|---|---|
| Included area below lower threshold: 15% | Included area below lower threshold: 6% |
| Included area passing threshold limits: 73% | Included area passing threshold limits: 94% |
| Included area above upper threshold: 12% | Included area above upper threshold: 0% |
| Notes: | |
| LEED requires that both analysis times meet passing criteria of at least 75% | |
| Result: | FAIL |

*As obtained by Lighting Analysis tool for Revit software

**Figure 12.** Suggested replacement of the windows at the east oriented office space on the third floor

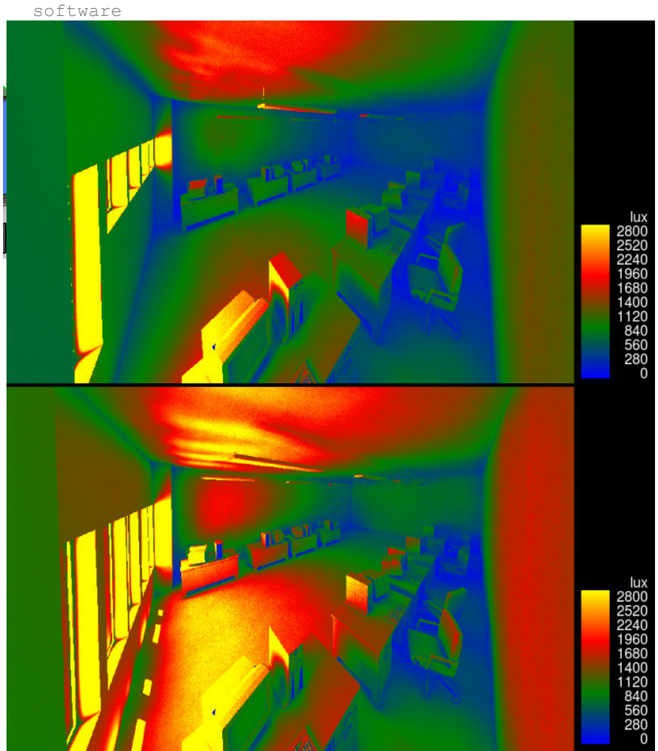


**Table 9.** Technical characteristics of heat pump*

| Properties | Measurement Unit | Performance |
|---|---|---|
| Thermal Power (0/35 °C, 5K spread) | kW | 290 |
| Power Supply | V/PH/HZ | 380V/3hp/50 hz |
| COP (efficiency factor) | $m^3/h$ | 5.8 |
| Water supply | Lt/h | 25 |
| Hot water production (60 °C) | °C | 3,835 |
| Maximum temp. water outlet | | 85 |

*Viessmann Limited, Allendorf, Germany, 2016

**Table 8.** Daylight distribution in interior spaces results after glazing replacement*

| 9am, 17 September | 3pm, 17 September |
|---|---|
| GHI:387, DNI:581, DHI:83W/$m^2$ | GHI:460, DNI:635, DHI:86W/$m^2$ |
| Included area below lower threshold: 12% | Included area below lower threshold: 3% |
| Included area passing threshold limits: 76% | Included area passing threshold limits: 97% |
| Included area above upper threshold: 12% | Included area above upper threshold: 0% |

Notes:
LEED requires that both analysis times meet passing criteria of at least 75%

Result: PASS

*As obtained by Lighting Analysis tool for Revit software

**Table 10.** Difference in energy consumption with LED lamps

| Fixture type | Existing fixtures* | LED fixtures** |
|---|---|---|
| Lighting power per unit area of 500 lux (W/$m^2$) | 16 | 5.3 |
| Lighting power per unit area of 200 lux (W/$m^2$) | 6.4 | 1.2 |

*KENAK, 2016 [27]
**Philips lighting Athens, Greece, 2016

From the results after the glazing upgrade and the interior wall configurations at office spaces in the second and third floor with glass blocks, we conclude that it is possible to achieve better sunlight transmission inside the building, as also it is approved with LEED certification for adequate daylight distribution in interior spaces.

Furthermore, an illuminance analysis of the office space at the third-floor was conducted, where it is observed that the aforementioned space presents poor daylight distribution with the existing transparent structural elements and after glazing replacement indicates a significant improvement (Figure 15), with analysis data: September 17 and clear sky at 13:00 (Autumnal equinox).

The cost of thermal insulation of Graphite Expanded Polystyrene (FIBRAN GRAFIT EPS80) were obtained (Prima materials Xanthi, Greece, 2016) as:

- for 70mm the price €6.32/1000x500mm
- for 35mm the price €3.16/1000x500mm
- for 30mm the price €2.70/1000x500mm

The cost for materials and labor placement of thermal insulation of graphite expanded polystyrene to the walls costs €35/m², to the roof €60/m² while the flooring is priced by €50/m² (Intermonosis Xanthi, Greece 2016).

For the cost of glazing upgrade of the building, were obtained (Altec Xanthi, Greece, 2016):

- 840x1700mm: €180.2/piece
- 812.5x1700mm: €174.3/piece
- 800x1700mm: €171.6/piece
- 812.5x800mm: €107.9/piece

## 6.2. *Mechanical equipment and Lighting fixtures*

To meet the needs for space heating and cooling, a heat pump to evaluate the energy performance has been considered through Revit software with the technical characteristics as described in Table 9.

The specific heat pump was selected for the

**Figure 15.** Illuminance analysis at internal space in the east oriented office area on the third floor, before and after the glazing replacement.

high temperatures provide a water outlet to 85 °C to meet the heating demands for large spaces with small radiators or heating systems with terminal fan units (fancoil).

Additionally, for the forthcoming energy assessment, were taken into consideration LED lighting fixtures for illuminating the interior of the building. The energy consumption during operation provides a significant reduction in both the lighting requirements of the spaces of 500lux (classrooms and offices) and for lighting areas with requirements of 200lux (corridors and WC). More specifically below it is detailed the energy difference from conventional lamps with LED lamps in Table 10.

**Figure 17** Detail of the Sunshade awnings, above the openings of the building on the south facade

The cost for the heat pump with the specific requirements is €97,946 (Viessmann Limited, Allendorf, Germany, 2016). The LED lighting fixtures for 500lux and 200lux luminous intensity cost respectively €120/piece and

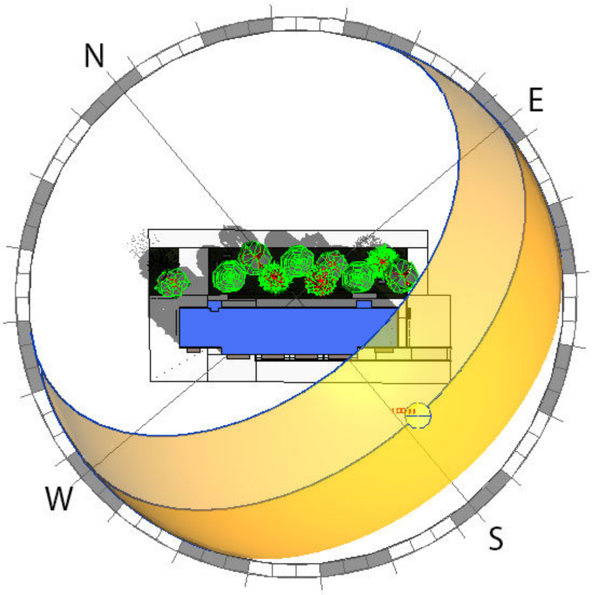


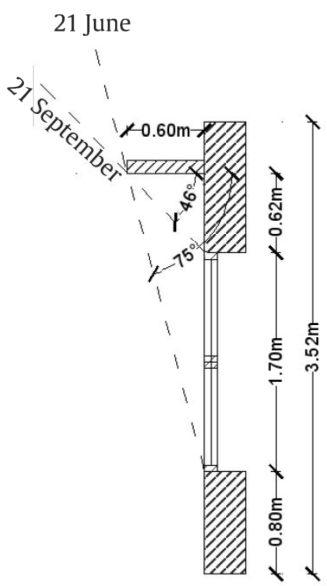

**Figure 16.** Solar path & orientation of the

€90/piece (Philips lighting Athens, Greece, 2016).

*6.3. Solar Analysis*

In order to study the efficiency and effectiveness of passive heating and cooling techniques in this building, a solar incident radiation study was conducted, with purpose to imprint the energy channeled to the building surfaces through solar radiation. In Figures 16 to 19 the solar radiation analysis is illustrated.

*6.4. Sunshade Awnings*




In order to achieve the desired thermal comfort conditions in the interior spaces of the building during summer, but also reaping the benefits from heat gains during the winter, it is suggested to fit sunshade awnings on the south facade, 0.63 cm above the openings of the building, with 10cm width thickness. The shades are proposed to the specific dimensions according to the longitude and latitude of the study area, so as to obscure the openings of the building from the vernal equinox on March 21 until the autumnal equinox on September 21.

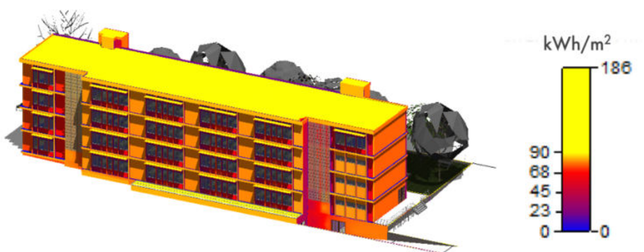
*6.5. Solar Incident Radiation Analysis Results*

The effects of solar incident radiation analysis in the building's surfaces are more significant during the periods:

- December 10 to January 10, where we observe the winter solstice (December 21)
- June 10 to July 10, where there is the summer solstice (June 21)

During the winter solstice, where the highest position of the sun at noon is at 24,75° gradient, the solar incident radiation on the horizontal surfaces of the building is equal to 50 kWh/$m^2$, while at the south-orientated vertical surfaces ranges from 50 to 63 kWh/$m^2$. The areas of the vertical walls in which Trombe walls suggested to be installed, the solar radiation incident is equal to 63 kWh/$m^2$. After the sunshade awnings has been placed, at the areas of the vertical walls in which Trombe walls suggested to be installed, a similar solar incidence to the analysis it is observed, equal to 63 kWh/$m^2$. This is because the angle of inclination of the sun is less than 40°, so the awnings may not affect the of solar incident radiation on the vertical surfaces of the building (Figure 18).

During the summer solstice, where the highest position of the sun at noon is 71,65° gradient of the Earth's surface, the solar incident radiation on horizontal surfaces of the building is equal to 186 kWh/$m^2$, while at the south-orientated vertical surfaces ranges from 65 to 80 kWh/$m^2$. The areas of the vertical walls in which Trombe walls suggested to be installed, the solar radiation incident is equal to 80 kWh/$m^2$. After the sunshade awnings has been placed, at the areas of the vertical walls in which Trombe walls suggested to be installed, a reduction of solar incident it is observed, equal to 10 kWh/$m^2$, so the incident radiation is equivalent to 70 kWh/$m^2$ after a 13% shading caused by the awnings (Figure 19).



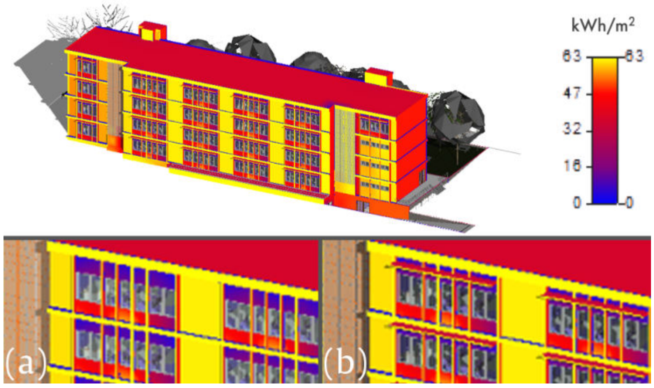



**Figure 18.** Solar incident radiation analysis on building surfaces with sunshade awnings during the period 10th of December until 10th of January. (a, b) Detail of the vertical surfaces before and after the sunshade awnings respectively.

T[illegible]ic modules in kWh

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | **Total** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [illegible] (kWh/m²) | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 160 | 142 | 126 | 99 | 78 | 61 | **1404** |
| PV Energy Production (kWh) | 6,853 | | 10,187 | 12,040 | 14,170 | 16,763 | 14,818 | 13,151 | 11,669 | 9,169 | 7,224 | 5,649 | **130,027** |

To avoid shading on the Trombe wall elements, it is recommended to be adapted sunshade awnings with adjustable parts to be adjusted depending on the time period and the desired solar incident radiation.

## 6.6. Photovoltaic Installation

**Figure 19.** Solar incident radiation analysis on building surfaces with sunshade awnings during the period 10th of June until 10th of July. (a, b) Detail of the vertical surfaces before and after the sunshade awnings respectively.

In the context of reducing $CO_2$ emissions to the atmosphere from energy consumption during the operation of the building, it is recommended the installation of photovoltaics at the building's roof with the characteristics as described in Table 11.

The available area of the roof for PV installation equals to 688,32m². In order to maximize the potential energy production from the solar panels, it is proposed to construct a metal base, with 11% gradient facing south, in order to put as much elements as possible, while at the same time achieving the shade avoidance by the south elements.

According to the photovoltaic installation guide, the minimum distance between arrays to avoid shading, equals to twice the distance from the height of the element towards the southern point. According to these fact, the final available area for the photovoltaic

**Table 11.** Technical characteristics of photovoltaic module

| Properties | Symbol | Measurement Unit | Performance |
|---|---|---|---|
| Maximum power | Pmax | W | [illegible] |
| Efficiency | η | | 19.70% |
| Rated voltage | Vmpp | V | 40.5 |
| Rated current | Impp | A | 6.05 |
| Open-circuit voltage | Voc | V | 48.8 |
| Short circuit current | Isc | A | 6.43 |
| Dimensions | | | 1600x800x46mm |

installation equals to 625m² where it is possible to be installed 354 photovoltaic modules, which correspond to 470.11m² of solar radiation absorbable surface. The monthly energy production from photovoltaic modules is described in Table 12.

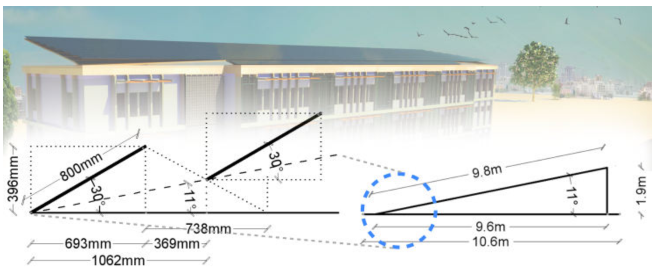



**Figure 20.** Detail of photovoltaic modules installation

**Table 13.** Opaque structural elements of the Trombe wall

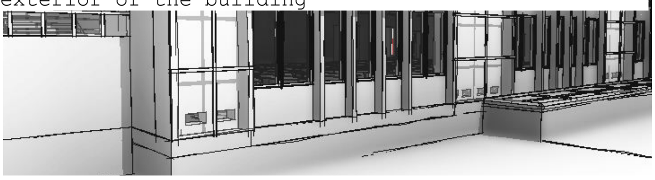
| Structural element | Thermal mass (mm) | Thermal insulation (mm) | U-value W/(m²K) | Thermal mass (kJ/K) |
|---|---|---|---|---|
| Trombe wall | 250 | 70 | 0.41 | 35.32 |

## 7. Trombe Walls

In the context of minimizing the energy consumption of the building, a study for the contribution of thermal mass thermosyphon flow walls (Trombe, 1960), which were annexed to the southern classrooms of the building, to the heating and cooling of the interior was carried out. To the concrete thermal mass walls, have been placed adjustable vents and their exterior is dyed with black color for maximum concentration of solar radiation, while is applied glazing within 30cm from the thermal mass of the masonry, as defined the optimal distance by 1/10 of the wall height [28]. To exploit the phenomenon of thermosyphon flow within the Trombe walls, while avoiding heat loss during winter and excess heat during the summer months, it is proposed the application of 7cm thermal insulation at the vertical thermal storage wall elements, from the side of the interiors. Therefore, it is exploited the function of heat storage Trombe walls while at the same time, it is given the option of using the passive heating and cooling to achieve the desired thermal conditions within the building [9],[17].

**Figure 21.** Illustration of Trombe walls at the interior of the building

**Figure 22.** Illustration of Trombe walls at the exterior of the building



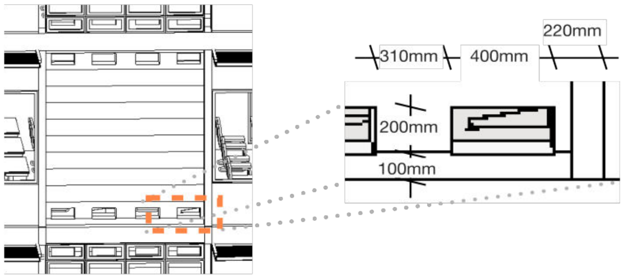



**Figure 23.** Detail of Trombe wall vent

At the walls which will be attached components in order to function as Trombe walls, have been created adjustable vents with dimensions 200x400mm in the lower and higher positions of the walls, having a distance of 10cm from the top and bottom edges of the walls and 31cm between them.

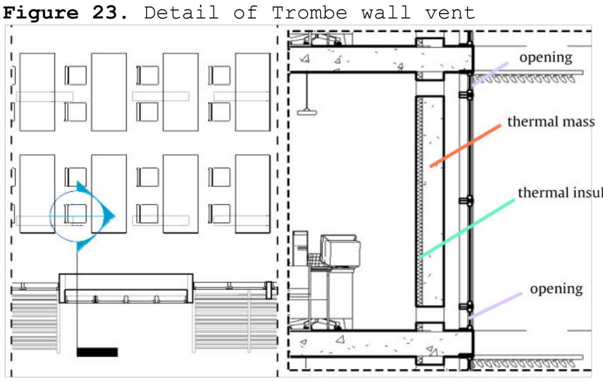



**Figure 24.** Trombe wall detail

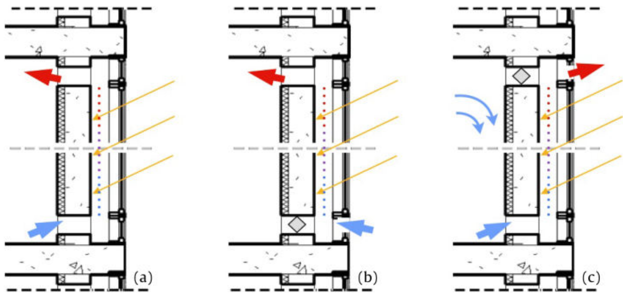
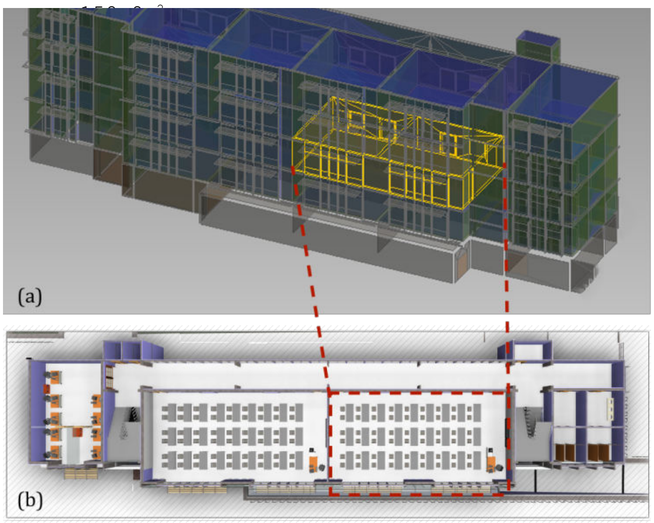



**Figure 25.** (a) Winter function of Trombe wall (b) Winter function introducing fresh air (c) Summer

During the winter, the sun heats the cool air entering through the lower vent of the thermal storage wall and injects from the highest vent to the interior, after the air molecules have passed from the space of the thermal mass which is exposed to the solar radiation, resulting the increase of their temperature. It is also possible the introduction of fresh air to the interior, where the air molecules at their entry way, passing from the thermal mass exposed to solar radiation, increasing their temperature.

During the summer, the thermal storage wall enhances the natural cooling effect, as it is drawing the cool air entering from an opposite opening and then expel the hot air from the upper opening of the frame utilizing the

**Figure 26.** Illustration of the CFD simulation area (a) 3D representation of the classroom's location, (b) Plan of the first floor of the building highlighting the location of the classroom with




phenomenon of natural draft.

### *7.1. CFD simulation in the classroom during winter*

In order to determine the contribution of thermal storage walls in the internal conditions of the building, Computational Fluid Dynamics simulations were performed with CFD Flex software in the classrooms. In the following figures are illustrated the distribution of the air temperature at the interior and at the surfaces of the classroom. In addition, it is presented the range of air velocity and airflow within the room, during the winter operation of Trombe walls.

The simulation was conducted during the winter solstice 21st of December at 13:00 with clear sky and outdoor air temperature 10 °C. From the Figures 27a and 27b, it is obvious the contribution of windows and Trombe walls to the heating of the room. Specifically, the thermal storage walls increase the average indoor air temperature by 3 °C, from 15 °C to 18 °C, resulting the reduction of the mechanical heating by the equipment, and thus the decrease of energy consumption of the space by 26% during the day.

The airflow inside the space, caused by the thermosyphon flow phenomenon, can also be determined by applying the Bernoulli equation. For simplicity, it could be assumed that the density and the temperature of the air in the gap varies linearly with height. The mean

**Table 14.** Transparent structural elements of the Trombe wall

| Glazing Type | Visible light Transmittance | Solar Heat Gain Coefficient | U-value W/(m$^2$K) |
|---|---|---|---|
| Single Glazing | 0.90 | 0.86 | 5.54 |

velocity of the air inside the space ($v_A$) equals to [14]:

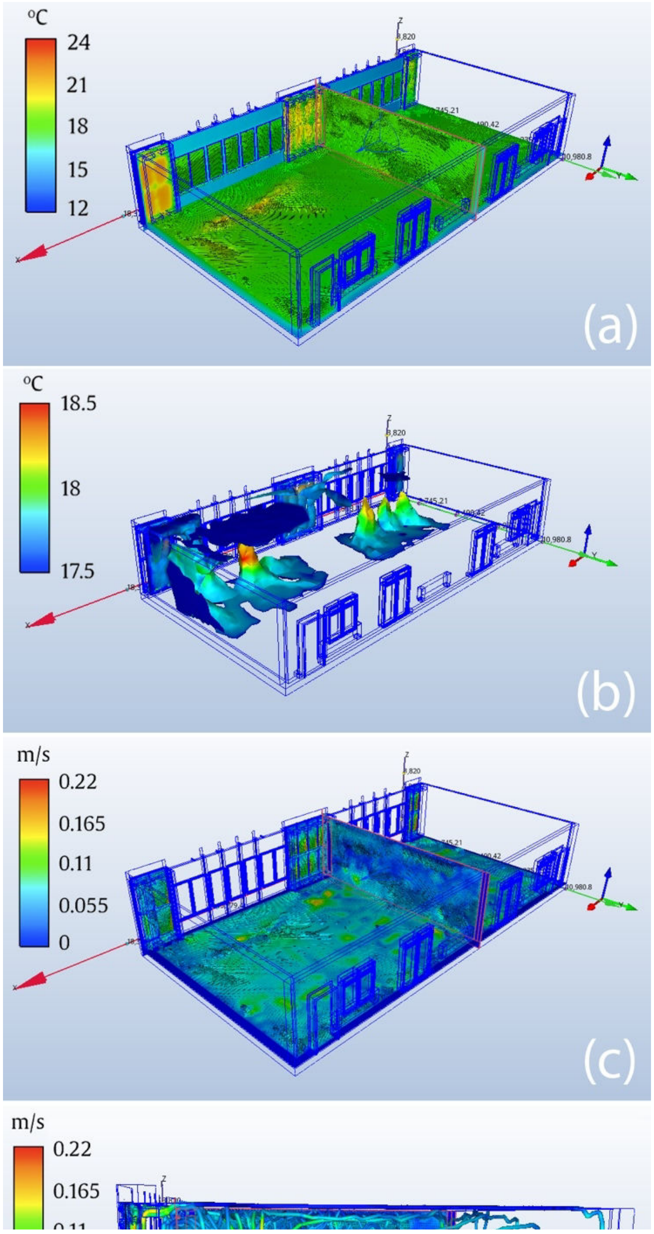



**Figure 27.** CFD simulation in the classroom during winter (a) Surface temperature distribution and air temperature in the classroom, (b) Maximum air temperature distribution in the classroom, (c) Range of air velocity within the classroom, (d) Three-dimensional representation of the airflow within the classroom

$$v_A = \sqrt{\frac{2\Delta P}{\rho\left(C_1\left(\frac{A_e}{A_{in}}\right)^2 + f\frac{H}{e} + C_2\left(\frac{A_e}{A_{out}}\right)^2\right)}}$$ , where

$\Delta P$: pressure difference
$\rho$: friction coefficient within the gap
$A_e$: cross sectional area of the gap ($m^2$)
$A_{in}$: entrance area at the gap ($m^2$)
$A_{out}$: outlet region area of the gap ($m^2$)
$C_1$: factor input pressure loss in the gap
$C_2$: output pressure loss coefficient through the gap
the values of $C_1$ & $C_2$ are fixed to be 1.5 and 1.0, respectively for f = 0.056 (Chen, Z.D., et al., 2003)
H: Trombe wall height (m)

As it is observed, the air velocity presents emphasis at the area near the Trombe wall, with a maximum 0,22m/s and an average velocity 0.12m/s, results that meet the criteria for air velocity at internal comfort conditions [29]. Furthermore, it is resulting the rise of the air temperature inside the room, as it is illustrated at the distribution of air temperature Figures 27c and 27d.

### *7.2. CFD simulation during winter introducing fresh air*

Furthermore, a CFD simulation during the winter function of Trombe wall introducing fresh air was conducted, resulting the distribution of air temperature at the interior and at the surfaces of the classroom, as also the range of airflow and air velocity within the classroom, as illustrated in the following Figures 28a-28d.

This simulation was conducted during the winter solstice 21st of December 13:00 with clear sky, outdoor air temperature 10 °C and an import of air volume from the lower opening of glazing through the upper vent of the Trombe wall equal to 0.01 $m^3$/s.

It is observed a slight temperature rise of about 1.3 °C, from 15 °C to 16.3 °C during introducing fresh air, resulting a reduction to the consumption of energy for the operation of the space, by about 11% during midday.

Also, it is presented the maximum internal ambient air temperature, wherein the flow of heat that occurs into the space mainly heats the upper air layers to the direction of the opposite surface, creating a long flow circle and consequently a lower contribution to the heating of the room, comparatively with the operation of thermal mass wall with both internal vents open.

As it is illustrated, the air velocity presents emphasis on the upper area of the vents of the thermal storage wall, with

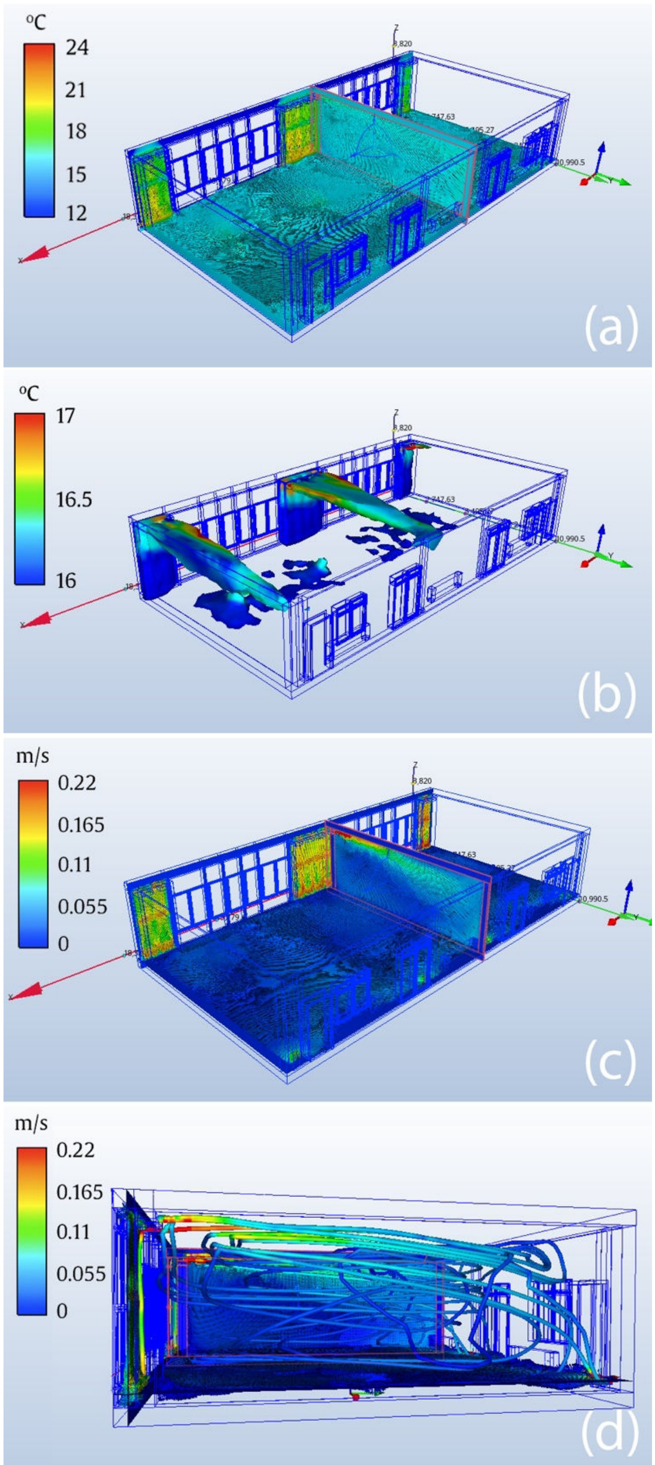



**Figure 28.** CFD simulation in the classroom during winter introducing fresh air (a) Surface temperature distribution and air temperature in the classroom, (b) Maximum air temperature distribution in the classroom, (c) Range of air velocity within the classroom, (d) Three-dimensional representation of the airflow within the classroom

maximum 0,25m/s and average velocity 0.08m/s, within the desired air velocity to meet the criteria for internal comfort conditions [29].

### 7.3. CFD simulation in the classroom during summer

In addition, a CFD simulation during the summer function of Trombe wall was conducted. The low opening at the internal wall and top opening at the external glazing of the Trombe wall are assumed open. The top opening on the room wall adjacent to north oriented corridor is also assumed open.

This simulation was conducted during the summer solstice 21st June at 13:00 with clear sky and outdoor air temperature 34 °C. An import of air volume equal to 0.01 $m^3/s$, coming from the northern located and shaded corridor that has already lower temperature than the interior of the southern located classroom, lowers classroom's air temperature.

A small decrease of temperature at approximately 1 °C, from 30 °C to 29 °C is obtained, resulting to reduction of cooling energy consumption of the space by 22% during midday.

The phenomenon of natural draft, caused by the thermal storage wall and an opposite opening, is illustrated in the minimum air temperature figure, where the incoming air molecules from the northern part of the building removing the heated air temperature out of the interior room.

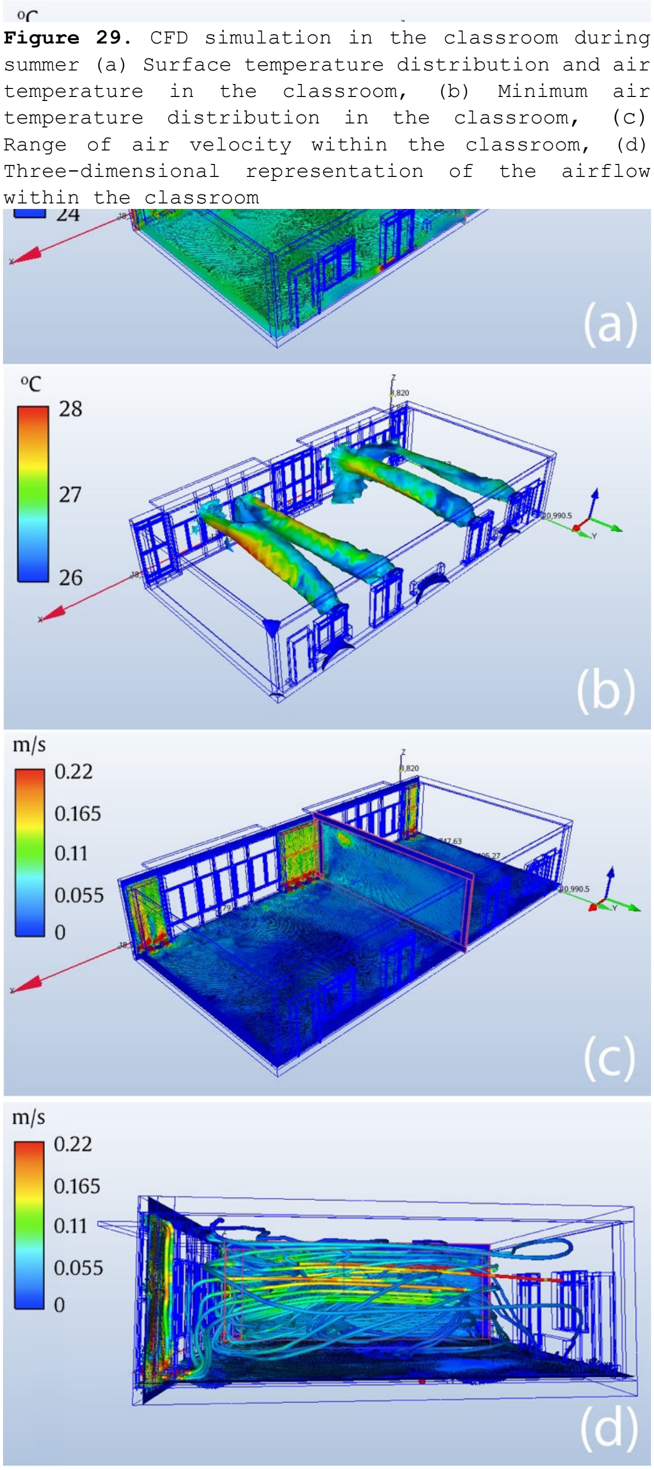
Thereafter it is observed a widespread airflow, with a maximum 0,27m/s and average velocity 0.14m/s, within the desired air velocity to meet the criteria for internal comfort conditions [29].

## 8. Energy Renovation Results

The results from the energy simulation of the building by applying thermal insulation at building's envelope, glazing upgrade, LED lighting fixtures, heat pump, photovoltaics and applications of passive heating and cooling techniques, are summarized at Table 15 in terms of the monthly energy consumption, the cost thereof, the annual energy consumption, the percentage of energy consumption per use and fuel, its percentage proportion, the specific energy consumption and the annual $CO_2$ emissions.

### 8.1. Cost of Energy Upgrades

**Figure 29.** CFD simulation in the classroom during summer (a) Surface temperature distribution and air temperature in the classroom, (b) Minimum air temperature distribution in the classroom, (c) Range of air velocity within the classroom, (d) Three-dimensional representation of the airflow within the classroom




The surface of the building which is to be covered with 70mm thermal insulator represents 1551.64$m^2$ and the underground surfaces which is to be covered with 30mm equals to 188.67m$^2$. According to the 2016 market prices, the cost for the implementation of the thermal insulation around the outside of the walls of the building and at the interior of the basement wall is €103,797. The cost for the insulation of the roof of the building which is to be covered with 70mm insulating material corresponds to 688.32m$^2$ and the floor which is to be covered with 35mm equals to 799.92m$^2$. According to the 2016 market prices, the cost for the implementation of the roof and the floor of the building thermal insulation is €85,598. The total cost of thermal insulation to the walls, the roof and the floor of the building is €189,695.

For the glazing upgrade, the costs for 160 windows with dimensions 840x1700mm with a north orientation equals to €28,832. For 78 windows with a south orientation and 8 west orientation with dimensions 812.5x1700mm, the cost is €14,990. For 56 windows, south oriented with dimensions 800x1700mm the cost is € 9,610 and for 18 south-facing windows with dimensions 812.5x800mm the cost is equal to €1,942. The total cost for the building's glazing upgrade corresponds to €55,374.

For the needs of lighting to the building spaces, it is needed to be installed 164 LED fixtures covering 500lux and 52 fixtures to cover 200lux lighting demands. The cost of the lighting fixtures equals to €24,360.

The cost of the heat pump is €97,946.

The total cost of upgrading LED lamps and installation of heat pump is €122,306.

The cost of the glazing for the Trombe walls is €8.760.

The cost for the sunshade awnings with adjustable parts is €3,498.

The cost of 354 photovoltaic modules is €86,730, while the cost of 295 modules (so to equal the energy consumption with the energy generation) equals to €72,275. The installation cost for the PV is €7,080 and €5,900 respectively.

Overall, the cost of upgrading with the complete PV capacity system is €461,106, alternatively with the reduced installation equals to €446,106.

## 9. Results

In this chapter aggregated assessments results are presented, where is referenced for each stage of energy upgrade in Table 16.

Summarizing the data from Table 16, a gradual reduction of energy consumption it is distinguished while increasing the thermal insulation of the building with a view to prevent the thermal losses. Moreover, it is noticeable that excess electricity generation occurs from the PV installation on the roof of the building in the last simulation scenario, also covering the electricity needs of the previous scenario, where Trombe walls are not part of the building.

From the data of Table 16, the energy consumption and the cost savings are concluded, resulting from the building's operation.

**Table 15.** Annual energy consumption and specific energy consumption after building's energy upgrade

| Energy | Percentage | kWh | Cost | Specific energy consumption per year (kWh/m$^2$/yr) | Metric tons $CO_2$ / year |
|---|---|---|---|---|---|
| Lighting | 26% | 27,998 | €4,200 | | |
| Equipment | 38% | 41,579 | €6,237 | | |
| HVAC Systems | 36% | 38,750 | €5,812 | | |
| Electricity | 100% | 108,327 | €16,249 | 41 | 107 |
| Fossil fuels | 0% | 0 | €0 | 0 | 0 |
| Renewable energy | 120% | 130,027 | - | 49 | -129 |
| **Total** | **0%** | **-21,700** | **-€2,170*** | **-8** | **-21** |
| Total without LED | - | 36,317 | €5,448 | 14 | 37 |

* pricing of electricity produced by photovoltaic equals to 100 €/MWh (Greek Ministry of Environment, 2016)

### *9.1. Costs and payback time of energy upgrades*

Thereafter, the summarized energy consumption, the operation expenses, the cost of each energy upgrade and the payback time for each case is illustrated in Table 17.

Also, the payback period it is indicated, corresponding to the operation of the building as determined according to its use by the TOTEE 20701-1 [26].

As it is illustrated in Table 17, the payback period of the integrated building envelope energy upgrade, including glazing upgrade, installation of heat pump, LED fixtures, sunshade awnings, Trombe walls and the installation of photovoltaic modules corresponds to 8 years.

Significantly conclusions from the observation of the Table 16 and Table 17 are obtained, where the building's operating expenses over 30 years are presented. After building's envelope thermal insulation, installation of heat pump and LED fixtures, the operating expenses for 30 years are equal to €589,080, while the costs for the specific energy upgrade is €354,273, resulting to total costs over 30 years equal to €943,353 (Figure 30).

In the case of the integrated energy upgrade with simultaneous implementation of passive design techniques and installation of photovoltaics for energy generation, the energy upgrade cost corresponds to €458,861, while the operating expenses over 30 years equals up to -€65,100 (profit over PV energy generation) resulting to total costs over 30 years equal to €396,641.

In conclusion, the energy upgrade on the building's envelope in order to minimize the thermal losses, the replacement of mechanical equipment and electrical systems to reduce building's energy consumption, have the effect to reduce building operating expenses and energy consumption, but in the long term they prove costly solutions.

Progressing a step further, introducing energy generation from renewable energy sources and in this case the installation of photovoltaic modules in a building which has undergone energy upgrades, so that the energy consumption has been minimized replacing the heating system with a more efficient system and applications of passive heating and cooling techniques for greater energy savings, it is demonstrated as an economically and environmentally sustainable solution.

The integrated energy upgrade may it appears the more expensive solution at its inception, but in the long term, beyond the payback time, the building presents negative operating expenses, which provides economical profit for the building's self-preservation.

Subsequently the annual building operating expenses in each case over 30 years is presented, as firstly the upgrade cost was added, in Figure 30.

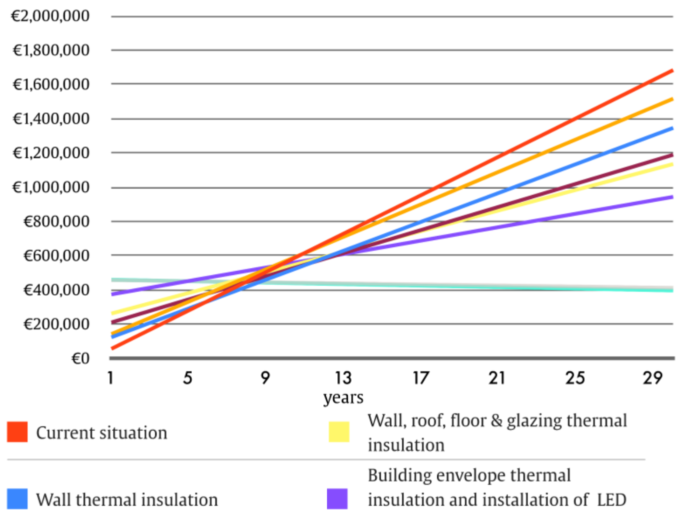



**Figure 30.** Annual building operating expenses in each case over 30 years, as firstly the upgrade cost

**Table 16.** Annual consumption and specific energy consum

| Energy assessment | Energy | Per | | | |
|---|---|---|---|---|---|
| Existing condition of the building | Electrical | 35% | 152,964 | €22,945 | 58 |
| | Fossil fuels | 65% | 288,278 | €32,589 | 109 |
| | Total | 100% | 441,242 | €56,109 | 167 |
| Wall thermal insulation | Electrical | 35% | 148,061 | €22,209 | 56 |
| | Fossil fuels | 53% | 169,714 | €19,933 | 64 |
| | Total | 100% | 317,775 | €42,142 | 121 |
| Roof & floor thermal insulation | Electrical | 40% | 149,875 | €22,481 | 57 |
| | Fossil fuels | 60% | 223,120 | €24,895 | 85 |
| | Total | 100% | 372,995 | €47,376 | 142 |
| Wall, roof & floor thermal insulation | Electrical | 57% | 144,475 | €21,671 | 55 |
| | Fossil fuels | 43% | 108,219 | €12,074 | 41 |
| | Total | 100% | 252,694 | €33,745 | 96 |
| Wall, roof, floor & thermal insulation and glazing upgrade | Electrical | 62% | 138,741 | €20,811 | 53 |
| | Fossil fuels | 38% | 83,253 | €9,289 | 32 |
| | Total | 100% | 221,994 | €30,100 | 85 |
| Building's envelope thermal insulation and installation of LED fixtures & heat pump | Electrical | 100% | 130,907 | €19,636 | 50 |
| | Fossil fuels | 0% | 0 | €0 | 0 |
| | Total | 100% | 130,907 | €19,636 | 50 |
| | Total without LED | - | 188,924 | €28,339 | 72 |
| Application of passive heating & cooling techniques in the classrooms and installation of photovoltaics | Electrical | 100% | 114,382 | €17,157 | 43 |
| | Fossil fuels | 0% | 0 | €0 | 0 |
| | Renewable energy | 114% | 130,027 | - | -49 |
| | Total | 0% | -15,645 | -€1,564* | -6 |
| | Total without LED | - | 42,372 | €6,356 | 16 |
| Application of passive heating & cooling techniques in classrooms & offices & installation of photovoltaics | Electrical | 100% | 108,327 | €16,249 | 41 |
| | Fossil fuels | 0% | 0 | €0 | 0 |
| | Renewable energy | 120% | 130,027 | - | 49 |
| | Total | 0% | -21,700 | -€2,170* | -8 |
| | Total without LED | - | 36,317 | €5,448 | 14 |

* pricing of electricity produced by photovoltaic equals to 100 €/MWh (Greek Ministry of Environment, 2016)

**Table 17.** Energy consumption and building operating expenses over 30 years

| Assessment | Energy | kWh | Total cost |
|---|---|---|---|
| Current situation (2016) | Electrical<br>Fossil fuels | 4,588,920<br>8,648,340 | €1,683,270 |
| Wall thermal insulation | Electrical<br>Fossil fuels | 4,441,830<br>5,091,420 | €1,264,260 |
| Roof & floor thermal insulation | Electrical<br>Fossil fuels | 4,496,250<br>6,693,600 | €1,421,280 |
| Wall, roof & floor thermal insulation | Electrical<br>Fossil fuels | 4,334,250<br>3,246,570 | €1,012,350 |
| Wall, roof, floor & glazing thermal insulation | Electrical<br>Fossil fuels | 4,162,230<br>2,497,590 | €903,000 |
| Building envelope thermal insulation and installation of LED fixtures & heat pump | Electrical<br>Fossil fuels | 3,927,210<br>0 | €589,080 |
| Application of passive heating & cooling techniques in the classrooms & PV installation | Electrical<br>Fossil fuels<br>Renewable energy | 3,431,460<br>0<br>3,900,810 | -€46,920 |
| Application of passive heating & cooling techniques in the classrooms & offices & PV installation | Electrical<br>Fossil fuels<br>Renewable energy | 3,249,810<br>0<br>3,900,810 | -€65,100 |

**Table 18.** Cost & payback-time of the energy upgrades

| Energy upgrade | Energy consumption (kWh) | Operating expenses € | Upgrade costs € | Energy saving rate | Payback (years) |
|---|---|---|---|---|---|
| Current situation (2016) | 441,242 | €56,109 | - | - | - |
| Wall thermal insulation | 317,775 | €42,142 | €81,542 | 27.98% | 2 |
| Roof & floor thermal insulation | 372,995 | €47,376 | €95,051 | 15.47% | 2 |
| Wall, roof & floor thermal insulation | 252,694 | €33,745 | €176,593 | 42.73% | 3 |
| Wall, roof, floor & glazing thermal insulation | 221,994 | €30,100 | €231,967 | 49.69% | 4 |
| Building envelope thermal insulation & installation of heat pump | 188,924 | €28,339 | €256,327 | 57.18% | 5 |
| Building envelope thermal insulation and installation of LED fixtures & heat pump | 130,907 | €19,636 | €354,273 | 70.33% | 6 |
| Application of passive heating & cooling techniques in the classrooms & PV installation | -15,645 | -€1,564 | €458,861 | 103.55% | 8 |
| Application of passive heating & cooling techniques in the classrooms & offices & PV installation | -21,700 | -€2,170 | €461,741 | 104.92% | 8 |

## 10. Environmental Impact

For the needs of recording carbon dioxide emissions into the atmosphere, for Greece, according to the total domestic way of energy production, calculated in metric tons by the values: $2.64*10^{-4}$/kWh for the heating oil and $9.89*10^{-4}$/kWh for electricity (Greek Ministry of Environment, 2016).

The referred building, pollutes the atmosphere with 227 metric tons of $CO_2$ annually. During the building's energy upgrades, $CO_2$ emitted pollutants to the atmosphere gradually reduced as shown in Table 19.

From the data of the Table 19, after application of thermal insulation on the building's envelope, glazing upgrade, installation of heat pump, LED fixtures, Trombe walls and installation of photovoltaic systems, it is observed that the emissions of $CO_2$ in the atmosphere reduced by up to 109% compared with the pollutants of the existing condition.

Notably the point that the oil boiler is replaced by the heat pump, where an increase in $CO_2$ emissions is observed compared to the energy assessment after thermal insulation at the building's envelope with the oil burner, wherein higher energy consumption is observed. The fact, that the energy assessment with the heat pump shows bigger environmental impact, occurs due to the high pollutant emissions coefficient from electricity.

It is a fact that for the Greek region, the largest requirements of buildings energy consumption occur for the space heating. Under the condition that in a building is exclusively used electricity for heating,

**Table 19.** $CO_2$ percentage reduction in the atmosphere

| Energy upgrade | Energy consumption (kWh) | $CO_2$ emissions in metric tons / year | $CO_2$ percentage reduction |
|---|---|---|---|
| Current situation (2016) | 441,242 | 227 | - |
| Wall thermal insulation | 317,775 | 191 | 16% |
| Roof & floor thermal insulation | 372,995 | 207 | 9% |
| Wall, roof & floor thermal insulation | 252,694 | 171 | 25% |
| Wall, roof, floor & glazing thermal insulation | 221,994 | 159 | 30% |
| Building envelope thermal insulation & installation of heat pump | 188,924 | 187 | 18% |
| Building envelope thermal insulation and installation of LED fixtures & heat pump | 130,907 | 129 | 43% |
| Application of passive heating & cooling techniques in the classrooms & offices & PV | -21,700 | -21 | 109% |

significantly benefits are appearing by the installation of energy generation systems from renewable sources and in particular photovoltaic systems. In the area of Greece a significant energy potential it is observed through photovoltaics, even during winter, when the demand for heating is increased. Consequently, the significant energy production from renewable sources is aimed at balancing the energy consumption in relation with the produced energy, resulting in the reduction of $CO_2$ emissions released into the atmosphere from the buildings during their operation.

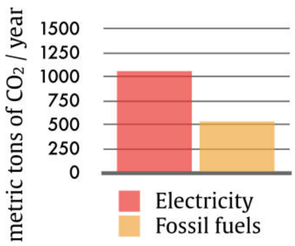
At national level, the production of energy from renewable sources corresponding to 19% of the total energy production (World Bank, 2013). The $CO_2$ emissions by the consumption of electricity in Greece, corresponding to $9.89*10^{-4}$/kWh metric tons [26].

In America, the power rate without carbon emissions is equivalent to 32% of the total energy produced, so that the $CO_2$ emissions during the electricity production, corresponds to $6.89*10^{-4}$/kWh metric tons [36]. This fact proves that a holistic approach to the energy sector at a national level, integrating more renewable energy sources in the total electricity production of the country, will significantly reduce the emissions of carbon dioxide in the atmosphere.

The building complex of the Democritus University of Thrace in Xanthi, where the study building belongs, emits into the atmosphere of about 1,589 metric tons per year, as illustrated in Table 20.

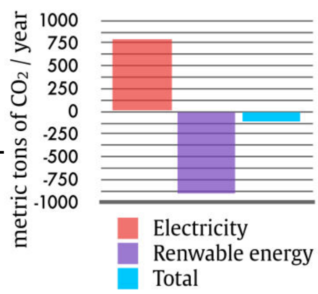
**Table 20.** Annual carbon emissions of the building complex of the D.U.TH. School of Engineering

| Energy | metric tons $CO_2$/year |
|---|---|
| Electricity | 1,057 |
| Fossil fuels | 532 |
| Total | 1,589 |




In a potential energy upgrade of the whole building complex of the School of Engineering in Xanthi, in a similar manner as was investigated in the reference building, $CO_2$ emissions in the atmosphere would have been reduced significantly, reaching the negative -112, which means that not only will not cause pollution to the atmosphere of the region , but it would be produced excess energy, which will be fed into the electricity grid of the city, saving additional $CO_2$ emissions from the energy consumption of the local residents, as illustrated in Table 21.

**Table 21.** Annual carbon emissions of the building complex of the D.U.TH. School of Engineering after energy upgrade



| Energy | metric tons $CO_2$/year |
|---|---|
| Electricity | 791 |
| Fossil fuels | 0 |
| Renewable energy | -903 |
| Total | -112 |

Observing the Tables 20 and 21, it is concluded the reduction of 1,589 metric tons of $CO_2$ and simultaneously, a supply of energy to the electrical grid of the city, generated by the photovoltaic modules on the roofs of the building complex of the School of Engineering, thus reducing additional 112 metric tons of $CO_2$ from the consumption of the residents at the study region.

The city of Xanthi, with a population of 109,627 residents, causing pollution to the atmosphere of the area equal to 446 kt $CO_2$ per year, which corresponds to 4,068 kg $CO_2$ per capita [32].

After the aforementioned energy upgrade of the building complex, it is observed a reduction to the emissions within the city from 446 kt, to 444 kt $CO_2$. This fact redounds to the environmental impact, reducing $CO_2$ emissions to 4,052 kg $CO_2$ per capita, namely 16 kg $CO_2$ per capita annually, a reduction equivalent to 0.39%.

This demonstrates how complex and multifaceted is the environmental approach of a region. It has to be focused on blocks and units with significant amounts of energy consumption but also in the contribution of renewable energy sources in the total energy production rate, to improve the environmental impact of a region.

## 11. Conclusions

The building sector consumes the largest amount of energy in Greece, therefore represents the most important source of $CO_2$ emissions. The energy upgrade of the building sector generates multiple benefits such as reduced energy consumption, which is consistent with the reduction of air pollution. Additionally, there is a significant improvement at the interior comfort conditions of the building, which promotes productivity and occupant health.

Moreover, because of the large number of educational buildings in the country, the energy consumption of them present a significant amount of the country's total energy consumption and simultaneously has the effect of increasing the costs paid by the state budget for the operation and maintenance of public buildings. The investigating of alternatives to reduce energy consumption in educational buildings is an important approach for sustainability and economic development of the country over time.

Also, an important point in this study is the fact that the internal comfort conditions of university and school buildings, contribute significantly in the learning abilities of the students [13]. Energy upgrading of educational buildings aims to improve the thermal conditions and air quality inside the classrooms, resulting in the improvement of educational activities.

In this study, after the energy consumption assessments and the CFD simulations to investigate the energy consumption of the building and the contribution of passive heating and cooling techniques, the following conclusions were ascertained:

- the thermal insulation applied to walls of the building reduces its energy consumption by 27.98%, resulting in 2-year payback time and the reduction of the $CO_2$ emissions into the atmosphere by 16%
- the application of thermal insulation at the roof and floor of the building reduces its energy consumption by 15.47%, resulting in 2-year payback time and the reduction of the $CO_2$ emissions into the atmosphere by 9%
- the thermal insulation applied to walls, roof and floor of the building reduces its energy consumption by 43.73%, resulting in 3-year payback time and the reduction of the $CO_2$ emissions into the atmosphere by 25%
- the application of thermal insulation at the building's envelope and the glazing upgrade reduces its energy consumption by 49.69%, resulting in 4-year payback time and the reduction of the $CO_2$ emissions into the atmosphere by 30%
- the replacement of the oil boiler with a heat pump for the needs of space heating of the building in combination with the thermal insulation of the building envelope and the glazing upgrade, reduces the energy consumption of the building by 57.18%. Moreover, the replacement of lighting systems with LED fixtures, reduces by

13.15% more the energy consumption of the building, achieving a total energy reduction of 70.33%, resulting a 6-year payback time and the reduction of the $CO_2$ emissions into the atmosphere by 43%

- the contribution of the sunshade awnings on the south-facing building, lead to an overall reduction of 29% of the heating loads during the period from March to September. Moreover, from the simulations within the classrooms with computational fluid dynamics software, it is demonstrated that the application of thermal mass walls with thermosyphon flow (Trombe walls), resulting in a reduction of the energy consumption at the rate:
  - 26% for space heating during the winter season with the function of recycling the indoor air
  - 11% for space heating during the winter season introducing fresh air, that as it passes through the thermal mass increases its temperature
  - 22% for the cooling of spaces during the summer, since the air flow caused by the effect of natural draft, removes the heat within the room, while simultaneously renewing the internal air.
- Supplementary, the installation of photovoltaic modules on the roof of the building generates 130,027kWh electricity annually and can meet the energy needs of the building up to 120%, under the condition that Trombe walls have been installed at classroom and office spaces of the building. The total payback time of the renovation corresponds to 8 years, with an environmental impact the reduction of $CO_2$ emissions in the atmosphere by 109%.

The reference building during operation has a specific energy consumption of 167 kWh/m$^2$/yr. In a study which have been investigated the average energy consumption of educational buildings in C' climate zone in Greece, has been found the average energy consumption of 123,31 kWh/m$^2$/yr for the space heating and 14,31 kWh/m$^2$/yr for electricity consumption, a total of 137.62 kWh/m$^2$/yr [7]. After the integrated energy upgrade, the specific energy consumption of the building is up to -8 kWh/m$^2$/yr.

In conclusion, it is demonstrated that the energy upgrading of the built environment, will bring significant environmental and economical benefits, while at the same time, improving the internal conditions of the buildings, with significant benefits in productivity and occupant health.

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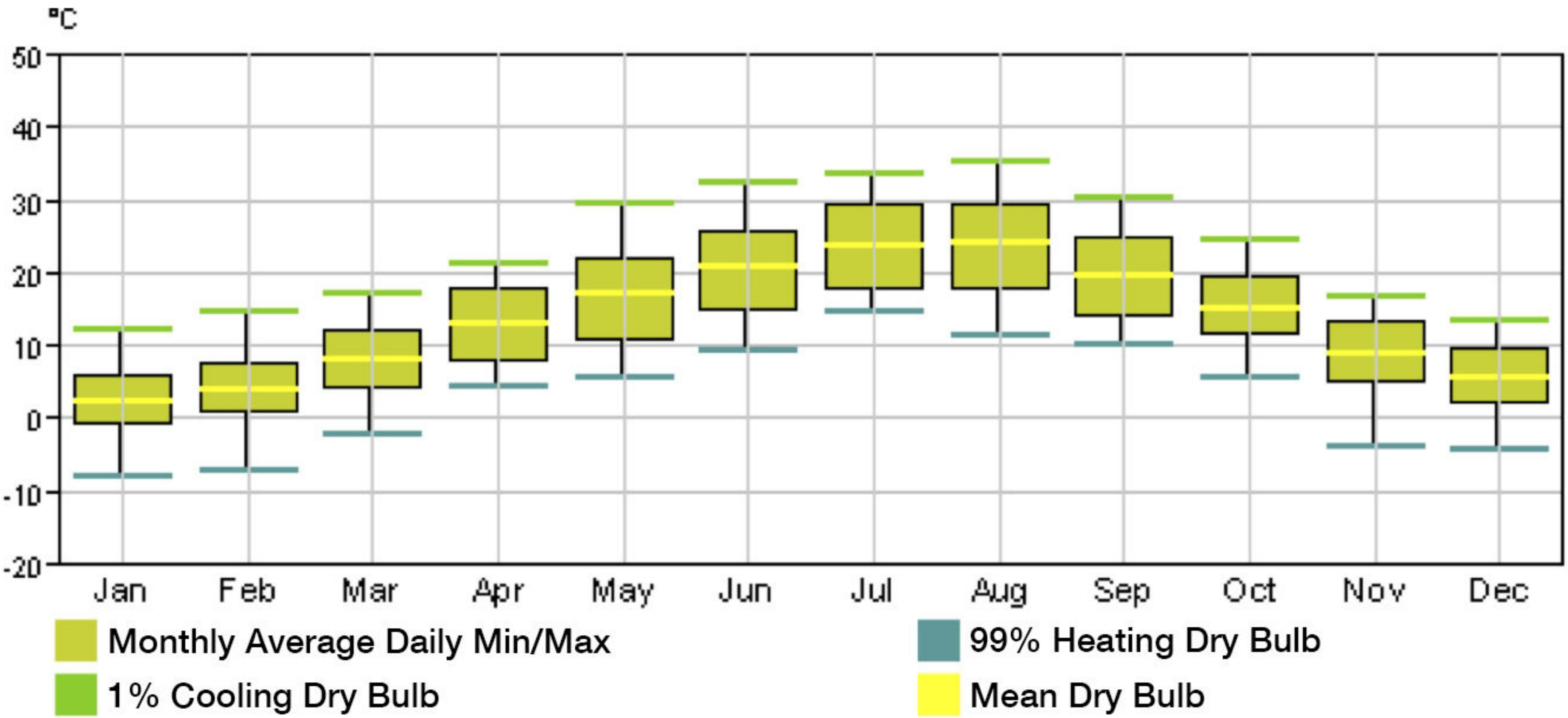
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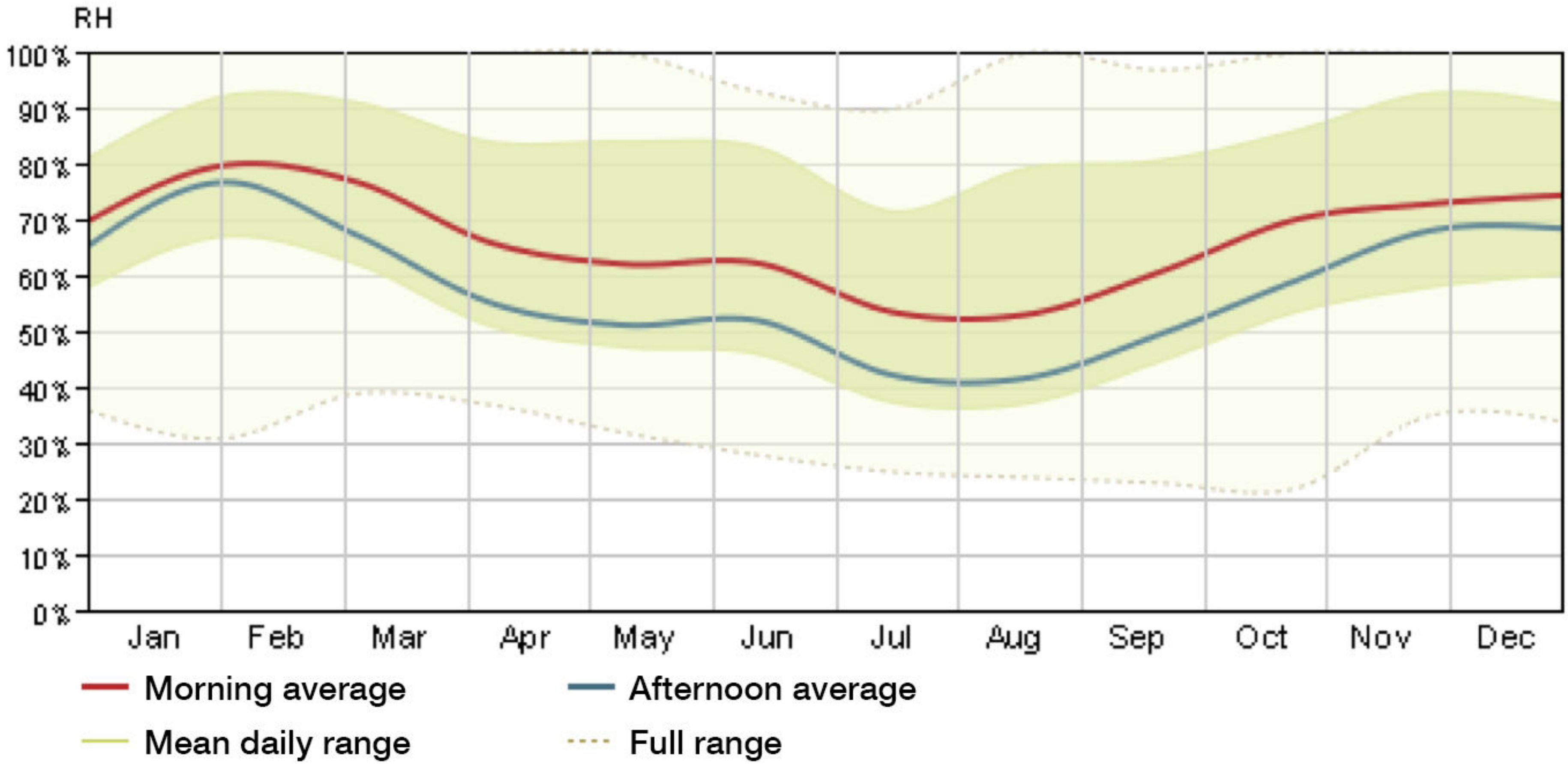
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