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ABSTRACT

In this paper, the energy and environmental impacts of a passive retrofit action, involving the installation, on an office building, of a second-skin system with the external layer made of a PVC-coated polyester fabric, were evaluated in terms of primary energy saving and carbon dioxide equivalent emissions. The primary energy consumption and the carbon dioxide equivalent emissions associated with the considered case studies were evaluated through the dynamic simulation software TRNSYS, across a whole year. The study was carried out considering five cities (Athens, Barcelona, Lisbon, Marseille and Naples) in five different countries in southern Europe upon varying the orientation of the two main façades of building (north-south and east-west orientation were considered). The office building was modeled in detail considering different construction characteristics upon varying the country. The simulation results highlight that the best results in terms of PES (equal to 22.4%) in Naples, while the best results in terms of CO2 (equal to 32.0 Mgc02eq) were obtained when the building is located in Athens. In addition, the adoption of the proposed passive lightweight retrofit solution allowed the reduction of both cooling and thermal yearly energy demand up to 57.7% (Marseille) and 17.8% (Barcelona), respectively.

1. INTRODUCTION

Nowadays, the building sector represents about 40% of the global energy consumption and about one-third of global greenhouse gases (GHG) emissions [1]. The European Union (EU) has set itself targets to progressively reduce its greenhouse gas emissions by 2050 [2]. Moreover, the vast majority of the existing non-residential EU building stock has been built before 1990 and almost the 55% of this stock has yet to be renovated [3, 4]; the problem is especially emphasized in the southern European area, where the combination of a hot summer climate, future increasing trends, and the probability of heatwaves strongly affects the indoor/outdoor comfort and the overall energy consumption [5]. This geographical scenario is characterized by old building stock with poor energy efficiency due to deterioration of the building components during the time or backwashdom in the constructions’ standards over the decades (i.e. thermal transmittance of the envelope, the efficiency of the energy systems, etc.) [3, 4, 6]. Therefore, the reduction of the energy consumption in such buildings has been one of the main topics in the policies issued by the EU for the building sector [7, 8], effectively scheduling for the member states a set of goals for the renovation of these assets. In this context, these EU Directives have been developed to introduce several requirements for new and existing buildings. Accordingly, researchers and designers should optimize all possible aspects (heating and cooling system, regulation criteria, building envelope, shadowing components, etc.). Different products and systems have been studies to investigate the improvement of the buildings' energy efficiency in southern European countries. Several parameters are involved in the buildings’ energy consumption, such as external conditions, the characteristics of the envelope and the behavior of the occupants. The analysis of a building’s energy performance requires substantial input data describing detailed constructions, environmental conditions, thermo-physical properties, building geometry, and control strategies [9].

A recent research [10] suggests that the annual energy consumption of an office in Greece could be reduced by 33% as a result of changing envelope components features, like cooling set-point, natural ventilation strategies, glazing g-value and window-to-wall ratio. In France [11], a single-family house (built before 1974) was simulated through retrofit parameters, namely: ventilation, window glazing type, wall insulation, loft insulation, ground slab and infiltration, which lead to significant energy saving as well as cost reduction. An innovative design was considered in Spain [12] for retrofitting approach that makes the façade as an active element to dehumidify the ventilation air before entering the indoor environment and leads to lower energy consumption in both Mediterranean and Subtropical climates. In [13], the authors have presented retrofitting facades by applying solar passive technologies in Portugal that lead to improve the thermal comfort, more energy saving and lower greenhouse gas emissions. Finally, a comprehensive approach to optimizing the energy design of building envelopes in Italy [14] indicated the energy performance increase, economic
benefits and thermal comfort simultaneously.

In general, the improvement of the energy performances of old existing buildings could be carried out by means of active and passive refurbishment actions [15]. Active actions include the installation of renewable energy generation technologies (i.e. PV systems), the replacement or redesign of the heating/cooling systems or the installation of different HVAC technologies. Passive actions, conversely, aim either to better managing the thermal gains and the energy losses of the building, or to increase the use of natural heating, cooling and lighting. Intuitively, the building envelope plays a key role in the effectiveness of passive actions. Among the different passive refurbishment actions that are possible to implement on existing buildings, the ventilated façade systems, and, in general, the Second-Skin systems (SS systems), seems to offer a good compromise in terms of ease of installation, performance and cost effectiveness [16]. The SS systems consists of an additional second skin layer hanged on the surface of the external building wall, with an air cavity in-between. Consequently, thanks to their simple structure, the SS systems are well suited adopt new materials as SS layer. Among these, the most interesting ones seem to be tensile and membrane-like materials, due to their lightweight and flexible nature [17]. Based on their characteristics, they are well-suited for both new and existing buildings, providing for thermal comfort through passive cooling/heating and thus reducing the energy consumption and the GHG emissions.

In recent years, different numerical models have been developed and tested by means of dedicated simulation software as TRNSYS, DOE-2, BLAST, Energy Plus, and SPARK. However, the buildings’ energy performances are commonly evaluated through steady-state models [9].

In this work, the assessment of the energy and environmental impacts of a passive retrofit action on an existing office building, in terms of reduction of primary energy consumption and carbon dioxide equivalent emissions, were carried out using the dynamic simulation software TRNSYS [18], across a whole year. The refurbishment action involves the installation of a SS system, in which the external layer is made of a light and flexible PVC-coated polyester fabric, on the whole building. The study has been carried out considering five cities in five different countries in the Mediterranean biogeographical region (Greece, Spain, Portugal, France and Italy), and varying the orientation of the building. Moreover, different construction characteristics have been considered for each country: the reference buildings’ envelopes were characterized according to each country building stock context, while the refurbishment models were built according to the legal energy requirements of five different EU countries and based on their national standard for the existing building energy performances.

2. BUILDING MODELING

The study is focused on an office building and it is aimed at both proposing a general operational methodology and highlighting a best practice for retrofit actions in the Southern European territorial context. The software TRNSYS 18 has been used to evaluate the potential benefit achievable in an office building refurbishment using a PVC-coated polyester fabric as material in a SS system in terms of primary energy saving and reduction of carbon dioxide equivalent emissions.

The reference building investigated in this research has been modeled in SketchUp 3D-modeling software on the basis of a “typical” office building from the IEA Annex 27 activity [19]. It consists of seven floors, each with a floor area of 661 m² and 4.13 m height. The building has been simulated considering two different orientations for the two main façades, north-south (Figure 1a) and east-west (Figure1b).

The windows were implemented only on the two main façades considering different Windows-to-Wall Ratio (WWR) as suggested by [20], and reported in Table 1.

| Table 1. WWR for the two main façades upon varying the building orientation |
|--------------------------|--------------------------|
|                          | North-south orientation  | East-west orientation |
| North façade             | 0.37                     | 0.33                    |
| South façade             | 0.27                     | 0.34                    |

The geometrical model has been then imported in TRNSYS in order to characterize the envelope, the internal gains, the infiltration rate and the set point for the cooling and heating systems. The study was carried out in five cities located in five different countries in the Mediterranean biogeographical region [21]:
- Athens (GR, 37°58′0″N - 23°43′0″E);
- Barcelona (ES, 41°23′0″N - 2°11′0″E);
- Lisbon (PT, 38°43′30.96″N - 9°0′0.07″W);
- Marseille (FR, 43°17′47″N - 5°22′12″E);
- Naples (IT, 40°50′N - 14°15′E).

The monthly trends of the external air temperatures and average global horizontal radiation have been compared upon varying the different locations. Figure 2 reports the minimum, average and maximum outside temperature ($T_{min}/T_{avg}/T_{max}$) as well as the average global horizontal solar radiation ($G_{avg}$) of the five considered cities. This figure shows that: (i) the lowest value of $T_{min}$ is achieved in Marseille (-3.2°C), while the highest value of $T_{max}$ is achieved in Athens (37.9°C), (ii) the highest value of $G_{avg}$ is achieved in Athens (165.6 W/m²) while the lowest one is achieved in Marseille (141.8 W/m²).

The envelope has been characterized differently in terms of thermal transmittance (U-value) of both opaque and transparent surfaces for each location. [22] provided an insight on the characteristics of the envelope of the European office buildings in different decades. The U-values implemented in this study are related to the 1980-1990 decade, which, as reported by [4], is the period when most of the non-residential European buildings were built, thus requiring a refurbishment. Table 2 summarizes the implemented U-values.
In TRNSYS, the reference building has been simulated though Type 56. Table 3 reports the common simulation parameters [20, 23-25]. In addition, a specific EnergyPlus weather data file [26] is considered to simulate the weather conditions of each city. In order to guarantee a comfortable indoor air temperature (see Table 3) two commercial parallel-connected electric heat pump (EHP) devices for each flat, split type air conditioning system, have been used for the indoor air temperature and the cooling system operation. The authors presented and experimentally validated in [16]. The comparison between the experimental and the numerical data showed good reliability of this numerical model, with an RMSE of 0.5°C and 0.4°C for the indoor air temperature and the temperature of the air cavity, respectively [16].

Table 2. U-values of the office buildings for each location

<table>
<thead>
<tr>
<th>Location</th>
<th>Surface</th>
<th>U-value (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Athens (GR)</td>
<td>Vertical Walls</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>Roof</td>
<td>0.70</td>
</tr>
<tr>
<td></td>
<td>Floor</td>
<td>0.70</td>
</tr>
<tr>
<td></td>
<td>Windows</td>
<td>3.70</td>
</tr>
<tr>
<td>Barcelona (ES)</td>
<td>Vertical Walls</td>
<td>1.80</td>
</tr>
<tr>
<td></td>
<td>Roof</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Floor</td>
<td>2.00</td>
</tr>
<tr>
<td></td>
<td>Windows</td>
<td>3.30</td>
</tr>
<tr>
<td>Lisbon (PT)</td>
<td>Vertical Walls</td>
<td>1.50</td>
</tr>
<tr>
<td></td>
<td>Roof</td>
<td>2.70</td>
</tr>
<tr>
<td></td>
<td>Floor</td>
<td>2.00</td>
</tr>
<tr>
<td></td>
<td>Windows</td>
<td>4.40</td>
</tr>
<tr>
<td>Marseille (FR)</td>
<td>Vertical Walls</td>
<td>1.20</td>
</tr>
<tr>
<td></td>
<td>Roof</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>Floor</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Windows</td>
<td>3.40</td>
</tr>
<tr>
<td>Naples (IT)</td>
<td>Vertical Walls</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>Roof</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>Floor</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>Windows</td>
<td>4.20</td>
</tr>
</tbody>
</table>

The insulation layer (Expanded PolyStyrene - EPS, l= 0.041 W/mK) has been set differently upon varying location, in order to reach the U-value thresholds highlighted by the legislation on the performance of the building envelope of each country. In each refurbishment cases, the SS system (consisting of the SS external layer, a 10cm deep air cavity and an insulation layer on the external surface of the existing external wall) integrating the PVC fabric as external layer, has been implemented on the whole reference building, in both orientations, while the other surfaces have been left as in the original reference cases.

Table 3. Summary of the simulations’ parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Detail</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infiltration</td>
<td>Air changes per hour</td>
<td>0.6 h⁻¹</td>
</tr>
<tr>
<td>Occupancy</td>
<td>Workhours</td>
<td>8.00 – 17.00 h</td>
</tr>
<tr>
<td>Heating system</td>
<td>Workhours set point</td>
<td>20°C</td>
</tr>
<tr>
<td></td>
<td>Night-time set point</td>
<td>15°C</td>
</tr>
<tr>
<td></td>
<td>Operation period</td>
<td>16 Nov/30 Mar</td>
</tr>
<tr>
<td>COP</td>
<td></td>
<td>2.67</td>
</tr>
<tr>
<td>Cooling system</td>
<td>Workhours set point</td>
<td>26°C</td>
</tr>
<tr>
<td></td>
<td>Night-time set point</td>
<td>29°C</td>
</tr>
<tr>
<td></td>
<td>Operation period</td>
<td>1 Apr/15 Nov</td>
</tr>
<tr>
<td>EER</td>
<td></td>
<td>2.41</td>
</tr>
<tr>
<td>Lighting system</td>
<td>During workhours</td>
<td>7.5 W/m²</td>
</tr>
<tr>
<td></td>
<td>During night-time</td>
<td>0.0 W/m²</td>
</tr>
<tr>
<td>Equipment</td>
<td>During workhours</td>
<td>10.0 W/m²</td>
</tr>
<tr>
<td></td>
<td>During night-time</td>
<td>1.0 W/m²</td>
</tr>
<tr>
<td>People</td>
<td>During workhours</td>
<td>11.5 W/m²</td>
</tr>
</tbody>
</table>

Table 4. Summary of the case studies for each location

<table>
<thead>
<tr>
<th>Location</th>
<th>Case study</th>
<th>SEPS (m)</th>
<th>Walls U-value (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Athens, Zone B</td>
<td>Case 0R_AT &amp; Case 1R_AT</td>
<td>-</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>Case 0R_AT &amp; Case 1R_AT</td>
<td>0.025</td>
<td>0.50</td>
</tr>
<tr>
<td>Barcelona, Zone C2</td>
<td>Case 0R BA &amp; Case 1R BA</td>
<td>-</td>
<td>1.80</td>
</tr>
<tr>
<td></td>
<td>Case 0R BA &amp; Case 1R BA</td>
<td>0.055</td>
<td>0.49</td>
</tr>
<tr>
<td>Lisbon, Zone 1/3</td>
<td>Case 0R LI &amp; Case 1R LI</td>
<td>-</td>
<td>1.50</td>
</tr>
<tr>
<td></td>
<td>Case 0R LI &amp; Case 1R LI</td>
<td>0.048</td>
<td>0.50</td>
</tr>
<tr>
<td>Marseille, Zone H3</td>
<td>Case 0R MA &amp; Case 1R MA</td>
<td>-</td>
<td>1.20</td>
</tr>
<tr>
<td></td>
<td>Case 0R MA &amp; Case 1R MA</td>
<td>0.062</td>
<td>0.40</td>
</tr>
<tr>
<td>Naples, Zone C</td>
<td>Case 0R NA &amp; Case 1R NA</td>
<td>-</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>Case 0R NA &amp; Case 1R NA</td>
<td>0.056</td>
<td>0.36</td>
</tr>
</tbody>
</table>

In this section the methodology used to compare the proposed cases has been compared with the reference cases from energy and environmental points of view.

3. METHODOLOGY
The energy comparison between the proposed case (PC) and the reference case (RC) has been performed considering the primary energy consumption through the index PES (Primary Energy Saving) [16, 33]:

\[
PES = \left[ \left( E_p^{RC} - E_p^{PC} \right) / E_p^{RC} \right] \cdot 100
\]

where \( E_p^{RC} \) is the primary energy associated with the cases with reference cases (Cases 0 and 1 see Table 4), while \( E_p^{PC} \) is the primary energy associated with each of the proposed cases (Cases 0R and 1R, see Table 4). A positive value of the index PES indicates that the proposed refurbishment actions allow for a primary energy reduction in comparison to the reference case.

The values of the \( E_p^{RC} \) and \( E_p^{PC} \) are calculated as reported below:

\[
E_p^{RC} = \frac{E_{th}^{RC} + E_{cool}^{RC} + E_{el, equipment} + E_{el, lighting}}{COP + EER} \left[ \frac{1}{\eta_{PP}} \right]
\]

\[
E_p^{PC} = \frac{E_{th}^{PC} + E_{cool}^{PC} + E_{el, equipment} + E_{el, lighting}}{COP + EER} \left[ \frac{1}{\eta_{PP}} \right]
\]

where, \( \eta_{PP} \) is the power plants' average efficiency.

A different value of \( \eta_{PP} \) for each location is assumed according to [33, 34]. The environmental comparison between the proposed case (PC) and the reference case (RC) has been performed considering the reduction of carbon dioxide equivalent emission (\( \Delta CO_2 \)) [16, 33]

\[
\Delta CO_2 = m_{CO_2,eq}^{RC} - m_{CO_2,eq}^{PC}
\]

where, \( m_{CO_2,eq}^{RC} \) is the mass of the dioxide equivalent emission associated with the reference cases (Cases 0 and 1 see Table 4), while \( m_{CO_2,eq}^{PC} \) is the one associated with each of the five proposed cases (Cases 0R and 1R, see Table 4). A positive value of \( \Delta CO_2 \) indicates that the proposed refurbishment actions reduce the carbon dioxide equivalent emission with respect to the reference case.

The values of the \( m_{CO_2,eq}^{PC} \) and \( m_{CO_2,eq}^{RC} \) are calculated as reported below:

\[
m_{CO_2,eq}^{RC} = \alpha \left( \frac{E_{th}^{RC} + E_{cool}^{RC} + E_{el, equipment} + E_{el, lighting}}{COP + EER} \right)
\]

\[
m_{CO_2,eq}^{PC} = \alpha \left( \frac{E_{th}^{PC} + E_{cool}^{PC} + E_{el, equipment} + E_{el, lighting}}{COP + EER} \right)
\]

where \( \alpha \) is the \( CO_2 \) equivalent emission factor for electricity production. Five different values of \( \alpha \) are assumed according to [35]. Table 5 reports the values of \( \eta_{PP} \) and \( \alpha \) for each location [33-35].

Table 5. Values of \( \eta_{PP} \) and \( \alpha \) considered for each location

<table>
<thead>
<tr>
<th>City</th>
<th>( \eta_{PP} )</th>
<th>( \alpha )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Athens (GR)</td>
<td>0.425</td>
<td>0.54901</td>
</tr>
<tr>
<td>Barcelona (ES)</td>
<td>0.376</td>
<td>0.22066</td>
</tr>
<tr>
<td>Lisbon (PT)</td>
<td>0.410</td>
<td>0.25255</td>
</tr>
<tr>
<td>Marseille (FR)</td>
<td>0.601</td>
<td>0.03895</td>
</tr>
<tr>
<td>Naples (IT)</td>
<td>0.465</td>
<td>0.33854</td>
</tr>
</tbody>
</table>

This table highlights that the values of \( \eta_{PP} \) range from a minimum equal to 0.376 (Marseille) to a maximum value of 0.601 (Marseille), while the values of \( \alpha \) vary between 0.03895 kg \( CO_2,eq/kWh_d \) and specific 0.54901 kg \( CO_2,eq/kWh_d \) for Marseille and Athens, respectively.

4. RESULTS AND DISCUSSION

This section reports the simulation results; in particular, those related to the heating and cooling energy demands associated with the whole building as well as the primary energy saving and the reduction of carbon dioxide equivalent emission have been discussed in detail.

Figures 3a and 3b show the values of PES (Eq. (1)) and \( \Delta CO_2 \) (Eq. (4)) upon varying the refurbishment case and the location. Figures 4a-e report the thermal and cooling energy flows associated with the whole office building as a function of the refurbishment case and month of the year for each location. In particular, in Figures 4a-e both thermal and cooling energy flows associated with the simulation cases with the main façades of the building oriented north-south are reported in black, while the energy flows associated to the simulation cases with the main façades of the building oriented east-west are reported in red.

Table 6 reports both the specific cooling and thermal energy yearly demand associated with the whole office building upon varying the location and the case study.

The results reported in Figures 3 and 4, as well as Table 6 highlight that:

- the effects of weather data, the construction characteristics of reference building, the threshold U-value as well as the orientation of the building are not negligible;
- all the proposed cases (Cases 0R and 1R, Table 4) allow for a reduction of both the primary energy consumption as well as the \( CO_2 \) equivalent emissions in comparison to the reference cases for each location (Cases 0 and 1, Table 4);
- whatever the location, the adoption of SS systems returns the best results when the main façades of the building are oriented east-west (Cases 1R, Table 4), in terms of reduction of both of primary energy consumption and \( CO_2 \) equivalent emissions, in comparison to the reference cases (Cases 1, Table 4);
- the values of PES range from a minimum of 15.4% in Lisbon (Case 0R_LI) and a maximum equal to 22.4% in Naples (Case 1R_NA);
- the values of \( \Delta CO_2 \) range from a minimum of 1.8 Mg \( CO_2,eq \) (Case 0R for Marseille) and a maximum equal to 32.0...
MgCO$_2$,eq (Case 1R for Athens), these significant differences are mainly due to the fact that different CO$_2$ equivalent emission factors for the electricity production have been considered (see Table 5);

• considering the north-south orientation, the best value of PES is returned by the retrofit case in Barcelona (Case 0R_BA), equal to 17.6%, thanks to a significant reduction of both the cooling and thermal energy demand, in comparison to the reference case, of about 51.1% and 17.3%, respectively;

• Case 1R_NA does not return the best reduction of cooling and thermal energy demand among the east-west oriented cases (equal to 54.7% and 5.8%, respectively); however, the value of $h_{pp}$ equal to 0.465 allows for the best results in terms of PES (equal to 22.4%) among the east-west oriented cases (see Table 4);

• in terms of cooling energy demand reduction, the best results for both north-south and east-west orientation cases are returned in Athens, equal to 21.1 kWh/m$^2$/year and 30.1 kWh/m$^2$/year, respectively;

• the worst results in terms of cooling energy demand reduction are returned in Lisbon (equal to 15.5 kWh/m$^2$/year) when the two main building façades are north-south oriented, and in Barcelona (equal to 21.5 kWh/m$^2$/year) when the main façades are oriented east-west;

• in terms of thermal energy demand reduction, the best results for both north-south and east-west orientation cases are returned in Barcelona, and equal to 7.3 kWh/m$^2$/year and 7.5 kWh/m$^2$/year, respectively;

• the worst results in terms of thermal energy demand reduction are returned in Athens for the east-west orientation, and equal to 0.3 kWh/m$^2$/year, while in the north-south orientation, there is actually a slight increase of thermal energy demand, equal to 0.2 kWh/m$^2$/year.

**Figure 3.** Values of a) PES and b) $\Delta$CO$_2$ varying the location
Table 6. Annual specific cooling and thermal energy demand associated to the whole office building upon varying the case study

<table>
<thead>
<tr>
<th>Case Study</th>
<th>Cooling energy demand for space cooling (kWh/m²/year)</th>
<th>Thermal energy demand for space heating (kWh/m²/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Athens</td>
<td>Barcelona</td>
</tr>
<tr>
<td>Case 0</td>
<td>48.6</td>
<td>30.9</td>
</tr>
<tr>
<td>Case 1</td>
<td>60.7</td>
<td>38.6</td>
</tr>
<tr>
<td>Case 0R</td>
<td>27.5</td>
<td>15.1</td>
</tr>
<tr>
<td>Case 1R</td>
<td>30.7</td>
<td>17.1</td>
</tr>
</tbody>
</table>

5. CONCLUSIONS

In this paper, the impacts of a passive retrofit action, involving the installation, on an office building, of a second-skin system with the external layer made of a PVC-coated polyester fabric, were evaluated in terms of primary energy saving and carbon dioxide equivalent emissions upon varying both weather conditions (Athens, Barcelona, Lisbon, Marseille and Naples were considered) and orientation of the two main façades of the building (north-south and east-west orientation were considered). The simulation results highlight that the best results in terms of PES and were achieved when the building is east-west oriented. In particular, the simulation returned the maximum value of PES (equal to 22.4%) for the Case 1R_NA, while the best results in terms of ΔCO₂ (equal to 32.0 MgCO₂eq) were obtained when the building is located in Athens (Case 1R_AT). In addition, the adoption of the proposed passive lightweight and non-impacting retrofit...
solution allowed the reduction of both cooling and thermal yearly energy demand up to 57.7% (Case 1R_MA) and 17.8% (Case 1R_BA), respectively.

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energy and environmental feasibility of a polygeneration
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[35] Country specific electricity grid greenhouse gas emission
factors, Carbon Footprint Ltd, Basingstoke, Hampshire,

NOMENCLATURE

COP Coefficient of performance (-)
E Energy (kWh)
EER Energy efficiency ratio (-)
EPS Expanded Polystyrene
G Global horizontal radiation (W/m²)
GHG Greenhouse gases
m Mass
PC Proposed case

PES Primary Energy Saving (%)
RC Reference case
RMSE Root Mean Square Error (°C)
s Thickness
SS Second-Skin
T Temperature (°C)
U-value Thermal transmittance (W/m²K)
WWR Windows-to-Wall Ratio (-)

Greek symbols

α CO₂ equivalent emission factor for the
electricity production (kgCO₂eq/kWhₘₑ)
Δ Difference
η Efficiency (%)
λ Thermal conductivity (W/mK)

Subscripts

avg Average
CO₂,eq Carbon dioxide equivalent emission
electricity
el Electricity
p Primary energy
PP Power plant
th thermal

Superscripts

PC Proposed case
RC Reference case