# Optimization of Coupled Building Roof Solar Reflectance and Thermal Insulation Level for Annual Energy Saving Under Different Climate Zones

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## Abstract

The aim of this work is to assess building energy performance optimization potential of cool roof solutions in different climate conditions worldwide through dynamic thermal-energy simulation and optimization analysis. Moreover, given the dependence of roof performance on insulation level, the influence of roof insulation variation on optimum roof solar reflectance is evaluated. Therefore, the multi-dimensional optimization of combined building roof solar reflectance capability and thermal insulation level is carried out to minimize annual energy consumption for air-conditioning of standard ASHRAE building model for small offices, in each considered climate zone. Findings of this research highlight how the classic approach of super-insulated buildings for energy saving needs to be reframed for the office case, by integrating other passive solutions for truly environmentally friendly and comfortable buildings.

*Keywords: Cool Roof, Solar Reflectance, Thermal Insulation, Building energy saving, Optimization*

## 1. Introduction

Cool roofs are a widely acknowledged strategy for building thermal-energy performance improvement, by acting mainly on energy requirement for cooling (Levinson and Akbari, 2010; Pisello, 2017) and Urban Heat Island (UHI) phenomenon mitigation (Akbari and Kolokotsa, 2016; Santamouris et al., 2017). In fact, given their high solar reflectance and thermal emissivity properties, compared to conventional construction materials, cool materials are able to decrease heat release to the outdoor urban environment and to the indoor ambient air Santamouris, 2015).

However, the effectiveness of cool roofs along the whole year is affected by building boundary conditions, including envelope characteristics, building end-use, and climate conditions. For instance, the use of such materials in heating-dominated regions may generate penalties in terms of heating energy use in winter (Hosseini and Akbari, 2014; Kolokotroni et al., 2013). With the aim of estimating the impact of using cool roofs under different climatic conditions, Synnefa et al. (2007) simulated the heating and cooling load of residential building in 27 cities around the world. For the case study locations, the heating penalty was shown to be lower than the cooling load reduction. Hosseini and Akbari (2016), instead, focused on cold climates and demonstrated that cool roofs provided annual energy savings in all considered climates for the simulated prototype office and retail buildings. Considering researches focused cool roofs performance in Italian climate context, Costanzo et al. (2013) showed the suitability of cool roofs for the reduction of building annual energy consumption in three Italian cities and with different insulation levels. They stated that the use of such materials in heating-dominated regions should be preliminarily evaluated in association with high insulation levels and very efficient heating systems. Instead, Zinzi et al. (2014) defined an energy-rating scheme for cool roofs application in residential buildings in different Italian climate zones based on numerical calculation results.

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As regards building envelope characteristics, a key parameter influencing benefits achievable through cool roofs is the level of roof insulation (Daouas, 2016). The effect of cool roofs in improving building indoor thermal comfort conditions was found less important with low thermal transmittance roofing systems (Synnefa et al., 2007; Di Giuseppe and D'Orazio, 2015). On the other hand, Smith et al. (2012) stressed that in temperate climates standard energy saving approaches, e.g. lowering thermal transmittance, while useful may be unnecessary, unless other parameters are poorly designed. A further study carried out in a hot-arid climate (Radhi et al., 2017), demonstrated that the difference in heat gains through the roof with and without thermal insulation is lower when a cool roof is implemented that with other roof systems.

Given the significant interaction between roof coating optical properties and sub-roof insulation level in affecting building energy efficiency, different optimization studies involving these two envelope characteristics were carried out. For instance, Gentle et al. (2011) performed a systematic analysis of the combined effect of three roof parameters, i.e. solar albedo, thermal emittance, and sub-roof R-value. Cool roofs were shown to optimize cost and environmental benefits when the sub-roof R-value is tailored to the spectral properties of the roof. Moreover, the impact on energy saving of an additional PCMs layer in the roof was assessed (Aguilar et al., 2013). Farhan et al. (2016), instead, developed a BIM-based approach to decide the most effective technology to be implemented to reduce $CO_2$ emission and improve the thermal comfort level of residential buildings. Through a two-step experimental and numerical analysis, Ramamurthy et al. (2015a, 2015b) studied the joint influence of roof albedo and insulation on its energy performance. They highlighted that both albedo and insulation thickness play a significant role in reducing the combined heating and cooling load attributable to the roof, and that wintertime penalties of cool roofs are negligible compared to summertime benefits. Similarly, Arumugam et al. (2015) optimized the interaction of this two roof characteristics in different Indian climate zones via energy simulation and parametric analysis. The insulation thickness increase was demonstrated to provide incremental benefits in energy savings which were reduced after a limit.

## 2. Motivation

Building upon the previous literature, the purpose of this work is to contribute in defining a method for assessing the effectiveness of implementing cool roofs in different climate zones in terms of annual energy saving of the HVAC system, with varying different boundary conditions. Given the consolidated research about cool roofs performance as passive cooling technique and the awareness of the influence of roof R-value on their effectiveness, acknowledged by a variety of scientific contributions worldwide, this study proposes a replicable method for enhancing building thermal-energy performance by optimizing roof configuration. In particular, roof solar reflectance capability and thermal insulation level are considered as key drivers influencing roof performance. Therefore, the optimum combination of solar reflectance value and insulation layer thickness for minimizing building annual energy consumption for air-conditioning is evaluated in different international climate zones. The procedure consists of an integrated and timesaving approach based on the coupling of dynamic simulation and optimization analysis.

Finally, this work is aimed at filling the gap between theory and practice by providing indications for the effective use of roof coatings in buildings, by taking into account mainly their energy efficiency. Therefore, findings on cool roofs effectiveness, which are usually referred to case specific experimental campaigns, can be generalized with varying boundary conditions. In fact, the general proposed procedure can be replicated in a variety of climate contexts in the world. Therefore, guidelines for the efficient implementation of cool roofs in different climate conditions can be developed based on findings of this work.

## 3. Methodology

The methodology presented in this work is based on numerical analysis via dynamic energy simulation and optimization. In particular, the optimum roof configuration is investigated with the aim of minimizing building annual energy consumption for heating and cooling with varying climate zone conditions. The two roof characteristics selected as variables affecting building energy performance are the coating solar reflectance and the thermal insulation layer thickness. The range of considered roof solar reflectance ($\rho_{\text{solar}}$) values for the study varies from 0.1, i.e. dark roof, to 0.8, i.e. cool roof. Regarding roof thermal insulation, standard expanded polystyrene (EPS), i.e. characterized by thermal conductivity equal to 0.04 W/m K, is used considering a thickness range ($I_{thermal}$) from 0.01 m to 0.25 m. The minimum thickness value is not 0, but very close to, because this value is not allowed by the simulation software.

For the purpose of this study, different climate zones worldwide are considered as case study weather conditions and the ASHRAE standard building model for small office building (ASHRAE,2016) is used as case study building, when modifying only the envelope components thermal transmittance (U-value) with varying the climate zone. Firstly, one-dimensional optimization analysis is carried out when varying the sole roof solar reflectance or thermal insulation thickness. When varying the thermal insulation level, two different roof solar reflectance scenarios are defined: “standard roof”, where $\rho_{solar}$ value is left equal the value of the ASHRAE prototype model (ASHRAE,2016) , i.e. 0.3, and “cool roof”, where $\rho_{solar}$ value is set equal to 0.8. Therefore, the sensitivity of building annual energy consumption to each parameter variation is evaluated to assess their separate contribution in different climate zones. One-dimensional optimization analysis is carried out only for six cities that representative of six defined heating degree days (HDD) ranges. Such ranges are reported in detail in the following section 4 (Fig. 2). Secondly, multi-dimensional optimization analysis is performed to define the optimum roof configuration by coupling solar reflectance capability and thermal insulation level in each considered climate condition. The methodology procedure is summarized in Fig. 1.

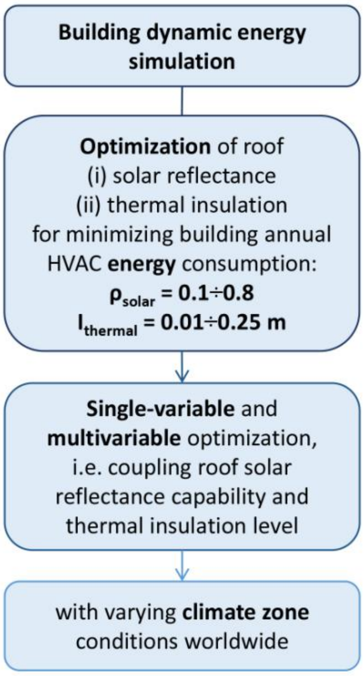

**Fig. 1: Methodology implemented in the work**

### 3.1. Numerical modeling

To perform the numerical analysis, the acknowledged simulation engine EnergyPlus v8.4 (Crawley et al., 2000) is used to develop the dynamic energy simulations. EnergyPlus is a whole-building thermal-energy simulation program (Crawley et al., 2001), based on previous validated BLAST and DOE-2 programs. EnergyPlus includes many advanced modeling tools, such as heat balance load calculations, integrated loads, user-configurable HVAC system description, system and plant calculations in same time step, simple input and output data formats, simulation of materials with variable thermal properties, etc. Further capabilities that give power to this calculation engine are advanced fenestration analysis as well as general envelope calculations (outside and inside surface convection algorithms), advanced infiltration, ventilation, room air and multi-zone airflow calculations, environmental emissions and developed economic evaluation including energy costs, and life cycle costs. Additionally, it includes several developed human thermal comfort algorithms for analyzing occupants’ thermal well-being and indoor air quality.

In this study, the conduction transfer function (CTF) algorithm is selected among the available calculation algorithms to calculate transient heat conduction transfer (U.S. DOE, 2016).

### 3.2. Optimization

For the additional optimization analysis, the generic optimization program GenOpt v3.1.1 (Wetter, 2000) is selected. This tool is capable of solving building energy performance related optimization problems developed with dynamic simulation software. It can be coupled with several simulation engines, including EnergyPlus. GenOpt performs optimization of a user-defined objective function, such as, for instance, annual energy consumption, which depends on selected independent variables. The objective function is expressed as a target quantity or a relation that has to be minimized or maximized. Generally, GenOpt optimization problems are described as shown in eq. 1:

$$min_{x \in X} f(x) \qquad \text{(eq. 1)}$$

where $f: X \rightarrow \mathbf{R}$ is the user-specified objective function that measures the system performance and $x_1, x_2 \in X \subset \boldsymbol{R}^n$ is the set of user-specified design parameters set for the independent variables. In this study, the optimization design parameters are roof solar reflectance and thermal insulation thickness, which are considered as independent continuous variables. Therefore, any value on the real line between lower and upper bounds can be used, as shown in eq. 2:

$$X = \left\{ x \in \boldsymbol{R}^n \middle| l^i \leq x^i \leq u^i, i \in \{1, \dots, n\} \right\} \qquad \text{(eq. 2)}$$

where $l \in \mathbf{R}^n$ and $u \in \mathbf{R}^n$ are the lower and upper bound, respectively, for design options and $-\infty \leq l^i < u^i \leq \infty$ for $i \in \{1, \dots, n\}$.

The objective function is defined to minimize building annual energy consumption for air-conditioning by finding out the optimum values for roof solar reflectance or thermal insulation level, in one-dimensional optimization analysis, and the optimum combination of roof solar reflectance capability and thermal insulation, in multi-dimensional optimization procedure (eq. 3).

$$f(x) = E_{total}(x_1, x_2) \qquad \text{(eq. 3)}$$

Various integrated mathematical optimization algorithms are available to be chosen in GenOpt. In the present work, the Generalized Pattern Search (GPS) implementation of the Hooke-Jeeves algorithm is used for both one- and multi-dimensional optimization analysis. Multiple starting points are selected to avoid falling in local optima (Evins, 2013).

## 4. Case study

### 4.1. Climate zones

To perform the study for a variety of climate conditions worldwide, 28 cities representing different climate zones according to the international Köppen-Geiger classification (Kottek et al., 2006), including temperate, tropical, continental, and arid conditions, are simulated. The cities, selected based on (Synnefa et al., 2007), are listed in Tab. 1, which indicates the climate zone and the heating degree days (HDD) for each city.

### 4.2. Case study building

For the purpose of the application of the above-defined methodology, the ASHRAE validated standard building model for small office building (ASHRAE, 2016), characterized by high internal heat gains, is selected. The standard case study office building model presents a single-floor rectangular prism shape. A single-floor building model is selected because of the major influence of roof properties on the floor just below it. Moreover, office buildings are suitable for the installation of cool roofs (Hosseini and Akbari, 2016).The external walls are wood-framed with intermediate insulating layer, while the roof presents wood joints, EPS insulation, added to achieve acceptable roof U-value in the different climates, and coating asphalt shingles. The main building envelope features (Winiarski et al., 2007) are summarized in Fig. 2. The building is equipped with air-source heat pump and gas furnace as back up. The air distribution is constant air volume, with one unit per occupied thermal zone (Winiarski et al., 2006). Heating and cooling set-point temperatures are set equal to 20°C and 26°C, respectively, according to EN 15251:2007 (2007). Internal heat gains, due to lighting and equipment, are equal to about 15.6 W/m$^2$ in the whole building (ASHRAE, 2016).

The main envelope components, i.e. external wall, roof, and window, of the standard ASHRAE model are modified in terms of their thermal properties, to achieve suitable thermal transmittances in each climate zone. Values are set in each climate zone according to the indications of the Italian current building regulation (Repubblica Italiana, 2015). The Italian regulation defines the maximum acceptable U-values for the external envelope components in a zone with varying the HDD. According to these general indications, U-values are set based on the HDD of each selected city. The thermal transmittance values of the different envelope components are adjusted by modifying the thickness of the thermal insulation in the opaque components and the window layers of the standard models (when necessary), in order to be as close as possible to the limit value. The final U-values defined in each climate zone are summarized in Fig. 2. Furthermore, the specific model inputs in terms of site location and design days for each climate scenario are implemented according to the EnergyPlus weather files (U.S. DOE's BTO, 2016).

**Tab. 1: Selected cities and corresponding climate zones (Kottek et al., 2006) and HDD**

| **Zone (Köppen-Geiger)** | **City** | **HDD** |
|---|---|---|
| **Aw**: Tropical wet and dry | Rio de Janeiro, Brazil<br>Miami, USA | 5<br>128 |
| **BWh**: Hot desert climate | Abu Dhabi, UEA<br>Cairo, Egypt | 31<br>393 |
| **BSh**: Hot semi-arid climate | New Delhi, India | 271 |
| **BSk**: Cold semi-arid climate | Tehran, Iran<br>Thessaloniki, Greece | 1495<br>1057 |
| **Cfa**: Humid subtropical climate | Sydney, Australia<br>Tokyo, Japan<br>Buenos Aires, Argentina | 717<br>2388<br>1212 |
| **Cfb**: Temperate oceanic climate | Johannesburg, South Africa<br>Paris, France | 1099<br>2643 |
| **Cwb**: Subtropical highland climate | Mexico City, Mexico<br>Nairobi, Kenya | 954<br>155 |
| **Csa**: Hot-summer Mediterranean climate | Athens, Greece<br>Barcelona, Spain<br>Palermo, Italy<br>Rome, Italy<br>Casablanca, Morocco<br>Ankara, Turkey | 477<br>1388<br>751<br>1415<br>845<br>3299 |
| **Csb**: Warm-summer Mediterranean climate | Porto, Portugal<br>San Francisco, USA | 1496<br>2653 |
| **Dfa**: Hot-summer humid continental climate | Beijing, China<br>New York, USA | 2866<br>4750 |
| **Dfb**: Warm-summer humid continental climate | Moscow, Russia<br>Montreal, Quebec, Canada | 4748<br>4861 |
| **Dfc**: Subarctic climate | Tarvisio, Italy<br>Tampere, Finland | 3959<br>4068 |

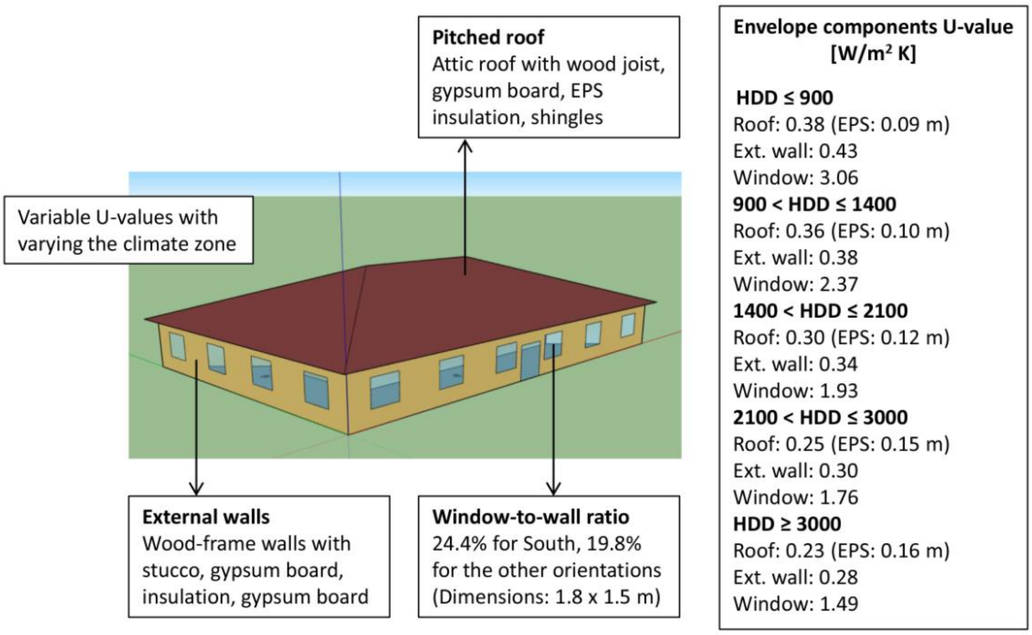

**Fig. 2: Case study small office building model and envelope characteristics**

# 5. Results

## 5.1. Sensitivity to roof solar reflectance variation

Firstly, the one-dimensional optimization of roof solar reflectance in the climate conditions of six selected cities representative of the HDD ranges defined in Fig. 2, i.e. Abu Dhabi, Palermo, Buenos Aires, Rome, Paris, and Tampere, is carried out. Results show that in a standard small office building the optimum roof solar reflectance corresponds to the maximum available cool capability, namely 0.8, in almost all climates except that in the almost totally heating dominated subarctic zone of Tampere (Finland). Accordingly, the configuration characterized by the lowest performance is the dark roof, i.e. $\rho_{solar}$ equal to 0.1, in all climate zones except Tampere, where the situation is inverted and $\rho_{solar} = 0.1$ results to be the optimum value.

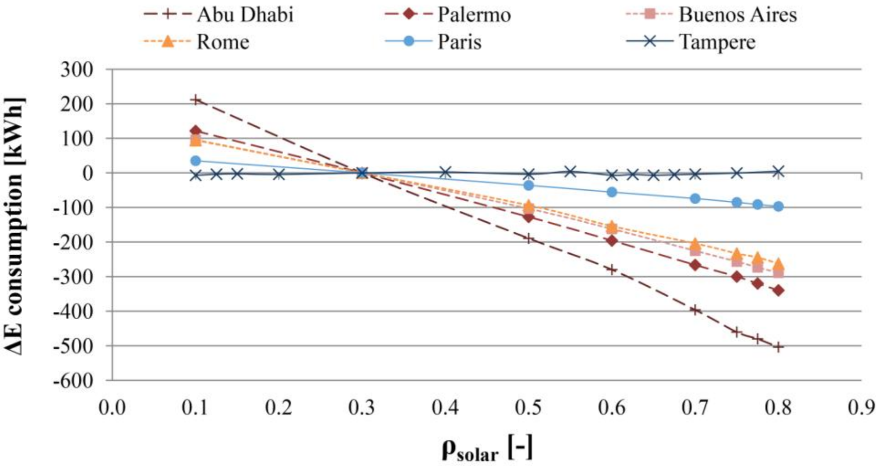

**Fig. 3: Total building HVAC energy consumption difference variation with varying only roof solar reflectance in the selected climate zones**

Moreover, the sensitivity of annual building energy performance to roof solar reflectance variation in the different climate zones is assessed. Fig. 3 depicts the trend of total HVAC energy consumption difference ($\Delta E$) between roof $\rho_{solar}$ scenarios in the considered range (0.1 ÷ 0.8) and the "standard roof" ($\rho_{solar} = 0.3$) for each selected case study city. Trend lines demonstrate how the influence of roof solar reflectance is mostly perceived in hot and warm climate conditions, which are totally or mainly cooling dominated. The difference in terms of annual HVAC energy need of the office building is equal to 3.7%, corresponding to about 716 kWh, 5.2% (461 kWh), 5.9% (384 kWh), and 4.3% (357 kWh) in Abu Dhabi, Palermo, Buenos Aires, and Rome, respectively, between $\rho_{solar}$ equal to 0.8 (optimum) and 0.1 (worst). Whereas, in Paris and Tampere, the building annual HVAC ΔE consumption variation trend is flatter (in particular in the subarctic city) with energy savings equal to about 132 kWh (3.7%) and 12 kWh (0.1%), respectively, between the optimum and worst $\rho_{solar}$.

### 5.2. Sensitivity to roof thermal insulation level variation

To analyze the impact of roof thermal insulation on the energy performance of the office building, the same one-dimensional optimization method is applied in the six selected representative cities by varying only the roof thermal insulation level. As previously mentioned, two different scenarios are considered for the roof solar reflectance, i.e. (i) "standard roof" and (ii) "cool roof".

As regards models with "standard roof", i.e. $\rho_{solar}$ equal to 0.3, the maximum available roof thermal insulation thickness of 0.25 m is found to be the optimum value in all considered climates. However, the thermal insulation level variation is mainly perceived in extreme climate conditions, namely in Abu Dhabi and Tampere, as depicted in Fig. 4, which reports the trend of total HVAC ΔE consumption between roof $I_{thermal}$ scenarios in the considered range (0.01 ÷ 0.25) and the "standard roof" ($I_{thermal}$ according to HDD) for each case study city. In Abu Dhabi and Tampere the annual HVAC energy savings in the case study building are equal to 3.2% (about 615 kWh) and 5.6% (526 kWh), respectively, between $I_{thermal}$ equal to 0.25 (optimum) and 0.01 (worst). On the contrary, in temperate and milder climates, especially in those cooling dominated, the building annual HVAC energy need is only reduced by 2.7% (about 242 kWh), 3.0% (195 kWh), 1.7% (142 kWh), and 5.3% (194 kWh) in zone Palermo, Buenos Aires, Rome, and Paris, respectively, with the optimum and worst $I_{thermal}$.

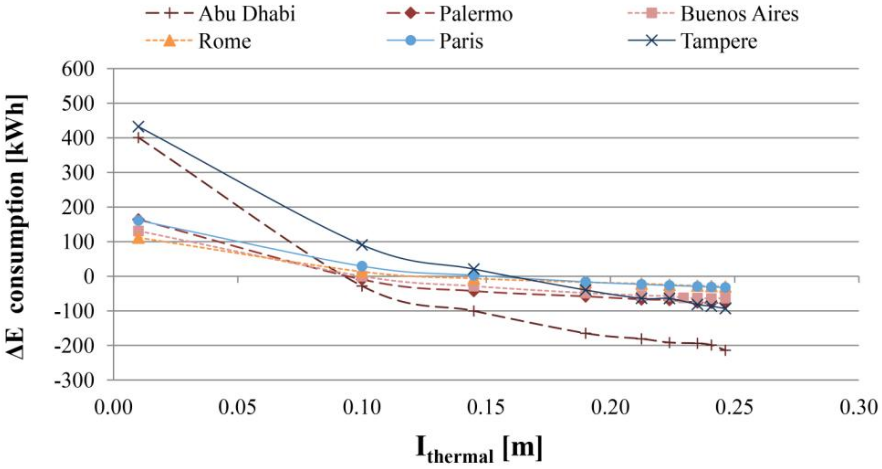

**Fig. 4: Total building HVAC energy consumption difference variation with varying only roof thermal insulation thickness in the selected climate zones with "standard roof"**

On the contrary, in the models with "cool roof", i.e. $\rho_{solar}$ equal to 0.8, the annual HVAC energy consumption is minimized by applying the thinnest thermal insulation (0.01 m) as roof layer in milder climates, i.e. Palermo, Buenos Aires, Rome. Instead, in extremely hot conditions, i.e. Abu Dhabi, the optimum is increased up to 0.04 m. Finally, in heating dominated climates, namely Paris and Tampere, the optimum corresponds to the maximum available value, i.e. 0.25 m. Nevertheless, the trend of annual HVAC energy need variation is flatter (Fig. 5) and the roof thermal insulation optimization is less significant, except that in extreme cold conditions, i.e. Tampere. In fact, the cooling load is predominant in all other case study climate contexts. Accordingly, in Palermo, Buenos Aires, Rome, and Paris about 2% benefit (138 kWh, 118 kWh, 171 kWh, and 62 kWh, respectively) is observed in terms of total energy saving, while in Abu Dhabi only 0.2% (42 kWh), between the optimum and worst $I_{thermal}$. Conversely, in Tampere the HVAC energy consumption reduction increases up to 5.9%, corresponding to about 556 kWh, between $I_{thermal}$ equal to 0.25 (optimum) and 0.01 (worst).

It has to be noticed that the annual HVAC energy consumption of the case study building is more affected by roof solar reflectance variation than thermal insulation level variation, in the considered cities, except that in the coldest climate conditions.

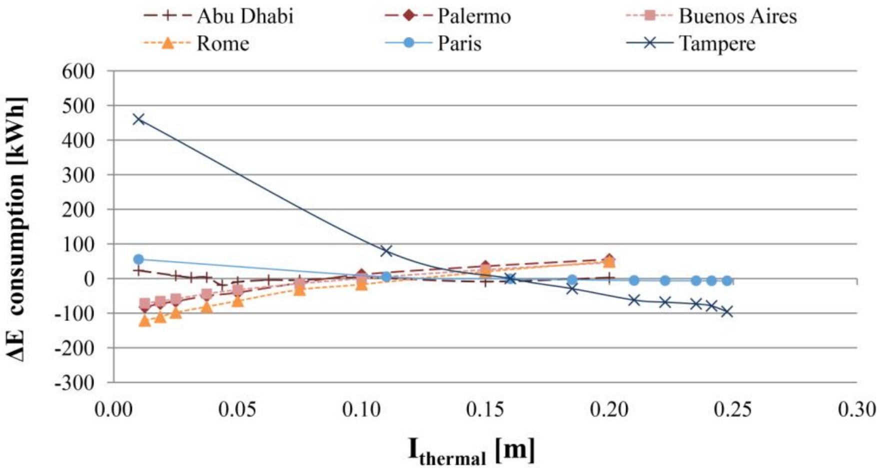

**Fig. 5: Total building HVAC energy consumption difference variation with varying only roof thermal insulation thickness in the selected climate zones with "cool roof"**

### *5.3. Optimum roof configuration with varying climate zone*

Results of the multi-dimensional optimization analysis are reported in Fig. 6 and Tab. 2 for all the simulated case study climate conditions. In particular, Tab. 2 shows the optimum roof configuration (i.e. combination of $\rho_{solar}$ and $I_{thermal}$) in each city and the corresponding total, heating, and cooling energy consumption. The roof configuration which minimizes building annual HVAC energy consumption is mostly characterized by high solar reflectance ($\rho_{solar}$ equal to 0.8), except in the three coldest cities, while the optimum insulation level is more variable with varying the climate context. In temperate and Mediterranean zones, $I_{thermal}$ is almost negligible, since values between 0.01 and 0.04 m are found to optimize the roof energy performance (Tab. 2). On the contrary, in the extremely hot zones a suitable thermal insulation level is required to minimize heat gains. On the other hand, in the colder zones, the maximum available $I_{thermal}$ equal to 0.25 m is required to reduce heating energy losses through the roof. Therefore, Tab. 2 shows how in the majority of considered climate zones, i.e. milder, the optimum roof configuration in order to minimize annual HVAC energy consumption involves the combination of high solar reflectance capability and low insulation level (blue rectangle).

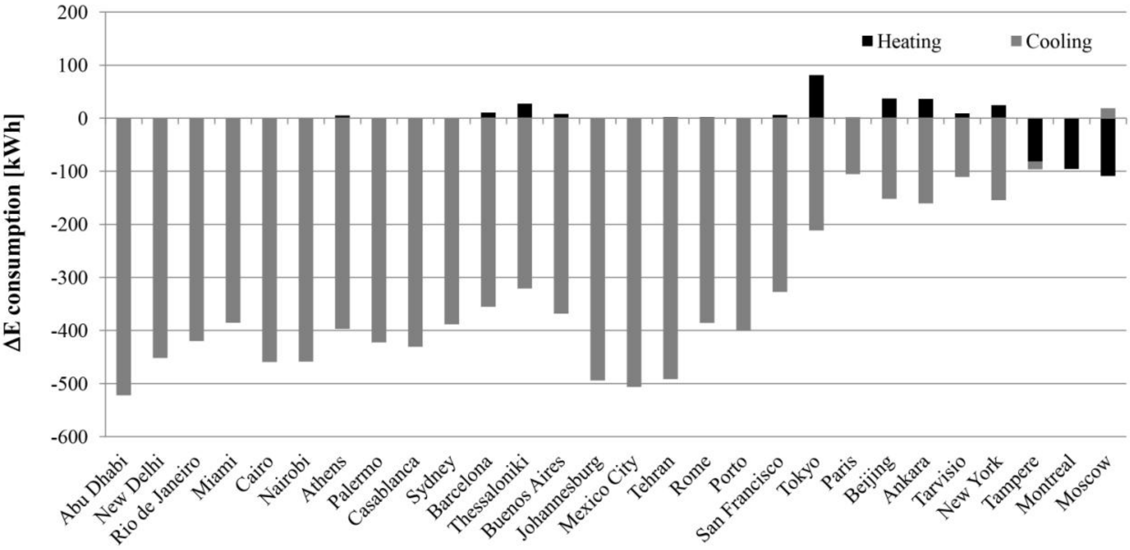

**Fig. 6: Building HVAC energy consumption difference between the optimum and the "standard roof" configuration in each climate zone, reporting the separate contributions for heating and cooling**

Moreover, Fig. 6 depicts the ΔE in terms of heating and cooling energy need between the "standard", i.e.

characterized by $\rho_{solar}$ = 0.3 and $I_{thermal}$ according to the regulation (Repubblica Italiana, 2015) depending on HDD, and the optimum roof configuration in each climate. The comparison of annual HVAC energy saving with the optimum roof configuration, with respect to the "standard", demonstrates how the optimization of combination of roof solar reflectance and thermal insulation generates non-negligible annual energy saving in all considered climate conditions. However, benefits are mainly perceived in cooling dominated climates. Office building annual energy consumption for air-conditioning is reduced by about 1% to 11%. The maximum achievable actual energy saving is equal to 522 kWh, 507 kWh, 493 kWh, and 490 kWh, in Abu Dhabi, Mexico City, Johannesburg, and Tehran, respectively, always in terms of cooling energy consumption. On the contrary, the energy need reduction decreases up to 90 kWh, 95 kWh, and 97 kWh in the coldest Moscow, Montreal, and Tampere, respectively, in terms of heating energy saving. In general, the cooling load is predominant in almost all considered climate conditions, due to building end-use and associated high internal gains too.

**Tab. 2: Optimum roof configuration and corresponding heating, cooling, and total HVAC energy consumption for the case study building in each climate**

| City | Optimum $\rho_{solar}$ [-] | Optimum $I_{thermal}$ [m] | Heating [kWh] | Cooling [kWh] | Total HVAC [kWh] |
|---|---|---|---|---|---|
| Abu Dhabi, UEA | 0.8 | 0.11 | 0 | 18513 | 18513 |
| New Delhi, India | 0.8 | 0.09 | 0 | 15685 | 15685 |
| Rio de Janeiro, Brazil | 0.8 | 0.03 | 0 | 13815 | 13815 |
| Miami, USA | 0.8 | 0.01 | 1 | 14077 | 14078 |
| Cairo, Egypt | 0.8 | 0.01 | 0 | 10897 | 10897 |
| Nairobi, Kenya | 0.8 | 0.01 | 0 | 8028 | 8028 |
| Athens, Greece | 0.8 | 0.01 | 35 | 7397 | 7432 |
| Palermo, Italy | 0.8 | 0.01 | 0 | 8345 | 8345 |
| Casablanca, Morocco | 0.8 | 0.01 | 18 | 7591 | 7609 |
| Sydney, Australia | 0.8 | 0.01 | 5 | 6902 | 6907 |
| Barcelona, Spain | 0.8 | 0.01 | 80 | 5523 | 5603 |
| Thessaloniki, Greece | 0.8 | 0.01 | 225 | 5504 | 5729 |
| Buenos Aires, Argentina | 0.8 | 0.01 | 106 | 5977 | 6083 |
| Johannesburg, South Africa | 0.8 | 0.01 | 56 | 6154 | 6210 |
| Mexico City, Mexico | 0.8 | 0.01 | 5 | 6253 | 6258 |
| Tehran, Iran | 0.8 | 0.01 | 312 | 10934 | 11246 |
| Rome, Italy | 0.8 | 0.01 | 106 | 7707 | 7813 |
| Porto, Portugal | 0.8 | 0.01 | 44 | 6292 | 6336 |
| San Francisco, USA | 0.8 | 0.01 | 39 | 2571 | 2610 |
| Tokyo, Japan | 0.8 | 0.04 | 786 | 4308 | 5094 |
| Paris, France | 0.8 | 0.25 | 1050 | 2350 | 3400 |
| Beijing, China | 0.8 | 0.25 | 2143 | 4864 | 7007 |
| Ankara, Turkey | 0.8 | 0.25 | 1871 | 3007 | 4878 |
| Tarvisio, Italy | 0.8 | 0.25 | 3094 | 2187 | 5280 |
| New York, USA | 0.8 | 0.24 | 1539 | 4440 | 5979 |
| Tampere, Finland | 0.4 | 0.25 | 7437 | 1416 | 8853 |
| Montreal, Quebec, Canada | 0.2 | 0.24 | 8406 | 2816 | 11222 |
| Moscow, Russia | 0.1 | 0.25 | 7610 | 2192 | 9802 |

## 6. Discussion

Findings of the above mentioned analyses show that, in order to minimize the annual energy consumption for air-conditioning in a standard small office building worldwide, roof solar reflectance plays a significant role.

Roof thermal insulation level is also important, yet mainly in heating dominated climates or extreme climate conditions. However, in accordance with existing works in literature (Radhi et al., 2017), when coupling cool roof and thermal insulation capability, the role of roof insulation in improving building energy performance becomes negligible, for the case study building in the majority of considered climate zones. In fact, office buildings are characterized by high internal gains, and, therefore, heating load is dampened down by such heat gains, while cooling load becomes predominant also in heating dominated climate contexts. However, in the coldest zones, a consistent insulating layer is required to limit the significant heating energy need.

Thermal insulation level increase provides benefits mainly in terms of heating load reduction. Therefore, when implementing a “standard roof”, characterized by higher external heat gains with respect to the “cool roof”, high thermal insulation provides significant benefits in terms of both cooling and heating energy saving. On the other hand, in the “cool roof” scenario, the cooling load is already minimized by the positive passive cooling effect due to the low roof coating solar absorptance. In this scenario, although high thermal insulation level provides positive effect in the cold season (heating load reduction), the cooling load is even increased when thick insulating layers are implemented. Since, in the case study building typology, i.e. office building, the cooling load is predominant, the annual HVAC energy consumption is generally minimized with low thermal insulation thickness, with the exception of the coldest climates. Accordingly, building annual HVAC energy consumption is more sensitive to roof solar reflectance variation, with respect to roof thermal insulation variation. Moreover, when “cool roof” is applied over the building, the effect of thermal insulation variation is less significant, except that in extremely cold conditions, because in the case study building the heating need is generally a small percentage of the annual HVAC energy requirement.

In milder climate contexts, characterized by hot summer and mild/cold winter, the expected optimum roof configuration, i.e. combination of roof solar reflectance and thermal insulation, would be with high solar reflectance, which minimizes the cooling energy consumption, and maximum available thermal insulating layer thickness, which minimizes the heating energy consumption. Nevertheless, due to the predominance of cooling load in the case study building typology (characterized by high internal gains) and to the penalties in terms of cooling need associated to high insulation levels, the optimum configuration is characterized by maximum solar reflectance and minimum thermal insulation.

## 7. Conclusions and future developments

In this work, a replicable method for optimizing the combination of cool roof and roof thermal insulation as passive strategies for building energy efficiency in different climate contexts is proposed. To this aim, optimization analysis based on dynamic thermal-energy simulation is carried out with the final purpose of minimizing annual energy requirement for air-conditioning by optimizing the roof configuration of a small office building in different climate contexts worldwide. In particular the combination of two key parameters affecting roof energy performance is taken into account, i.e. solar reflectance and thermal insulation thickness.

Results show that between the two considered roof characteristics, solar reflectance capability mostly affects building energy performance. Moreover, “cool roof” optimizes the annual HVAC energy consumption of the case study building in the majority of climate conditions. On the other hand, building energy performance is more sensitive to roof thermal insulation variation when a low reflectance “standard roof” is implemented. Nevertheless, when considering the combination of roof solar reflectance capability and thermal insulation level, the optimum configuration is characterized by high cool capability, i.e. $R_{solar}$ equal to 0.8, and low insulating layer thickness, i.e. $I_{thermal}$ between 0.01 and 0.04 m, in the majority of climate zones (milder zones). The exception is represented by the extremely hot and the coldest considered climate zones, where an insulating layer up to 0.11 m and 0.25 m is required, in the hottest and the coldest zones, respectively, to limit the significant thermal energy gains or losses through the roof. All in all, the optimum combination of roof solar reflectance capability and thermal insulation level provides the maximum annual energy saving.

Although the present study refers to selected climate zones, reliable indications are provided also for other regions in the world with similar climate classifications. Moreover, the same analysis procedure is reproducible for other climate conditions. In addition, findings of this work highlight how both climate conditions and further boundary conditions affecting building energy performance, namely end-use and envelope characteristics, e.g. coating optic-energy properties, have to be taken into account simultaneously when targeting building envelope thermal requirements. Given the promising multivariable optimization results of this paper, future developments of this work can be the investigation of economic and life-cycle benefits associated to coupling cool roof and thermal insulation design of building envelopes. Furthermore, this optimization methodology can be implemented to study the influence of further building boundary conditions in the optimum roof configuration, e.g. end-use, type of HVAC system, occupancy, internal gains. The final goal is to develop guidelines for the efficient implementation of cool roofs in different climate conditions.

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