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Article

Aesthetic Possibilities of Building Thermal Control through Colored Envelopes

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Abstract: The possibilities of obtaining efficient building thermal control by means of colored envelopes while maintaining broad aesthetic options have been evaluated. The use of colored bilayers, where the inner layer presents strong solar absorbent or reflectance properties, while the outer layer provides visible coloration, represents a feasible way. A representative set of twenty bilayers spanning a broad color palette has been studied in two configurations, static and dynamic. The dynamic configuration allows for the switching of the inner layer between absorptive and reflective states. Simulations have been carried out in a total of nineteen locations around the world, representing the main habitable climates according to Köppen–Geiger climate classification. Comparative results between climate zones where this approach may have a significant impact have been obtained, and identification of feasible climate zones has been carried out. The use of the simpler static configuration is recommended for tropical climates, whereas the dynamic configuration could be effective in moderate climate locations (within arid or temperate climate classification). Possible savings for cold climates are negligible.

Keywords: thermal control; chromogenic; colored envelope; building energy efficiency

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1. Introduction

Currently, great efforts are being taken to reduce world energy consumption. Buildings account for a significant percentage of this consumption, especially in developed countries. In the European Union, half of energy consumption is related to heating and cooling with 80% of these loads accounted for by buildings [1] (Council of Europe, 2018). A major portion of this energy is produced through combustion of fossil fuels, increasing greenhouse effect gases, among other harming climate effects. Therefore, there is an urgent need to reduce both the percentage of fossil fuels used and, simultaneously, the building energy consumption.

Building envelopes, being the medium through which any energy exchange with the ambient environment takes place, are the most straightforward elements to modify in order to obtain a significant change in the building energy consumption profile. Passive control over solar gains through the use of outer materials with different reflection and absorption properties has been used in the past, even in traditional architecture. The use of white color paints in hot climates, which are more reflective, prevents the inner heating by reducing the need for cooling and obtaining thermal comfort inside buildings. White villages in Andalusia and on the Greek islands constitute a well-known example [2]. Seasonal energy savings can be obtained with the use of these passive solutions, although the maximization of these savings implies the use of extreme colors with purely reflective (white) or purely absorptive (black) [3] properties, which considerably limits the aesthetic options. More recently, it has been shown that, for hot climates, the use of "Cool paints" [4–8] reduces significantly the refrigeration loads in summer season. However, the results of these works for variable climates showed that the annual energy consumption was still not reduced by this type of technology, due to the passive nature of this solution, unable to adapt to the variability of climate conditions throughout the year.

Therefore, two additional features for a more extensive use of envelope color for thermal control could be convenient: a broader color palette and higher adaptability to variable external climate conditions.

Recently, the use of bilayers has been proposed in order to expand the available color gamut [9]. Chen et al. proposed the use of dyes atop reflective white substrates for efficient "colored" cool paints. In this configuration, dyes absorbing mainly in the visible region are responsible for the painting appearance, while the inner layer shows broad reflectivity over the whole solar spectrum, especially the infrared range.

In parallel, numerous investigations have been conducted in the field of adaptive materials through chromogenic technologies. While electrochromic devices (whose transmission properties are controlled through electrical pulses) are mostly investigated as windows [10–12], most of the efforts for the rest of the envelope have been focused on thermochromic materials capable of modulating their transmission according to the exterior temperature [13]). These technologies, through their controllable absorptive-reflective properties, are able to adapt to variable climate conditions [14–17], presenting energy advantages compared to static materials [18] and providing the possibility to reduce thermal loads in buildings throughout the year. Energy simulations of buildings have verified the benefits of these materials in terms of thermal load savings [19–22]. While electrochromic windows are yet to be commercialized and are slowly being implemented, thermochromic materials still suffer from fast degradation in ambient conditions, which prevents its massive use in buildings. Several investigations have been conducted to establish a diagnosis of the mechanisms that produce it [23] and the alternatives to improve the durability of these materials [24,25].

In this study, we have explored the feasibility of obtaining energy savings through the use of colored building envelopes by adding bilayers in which the inner layer provides the reflective or absorptive properties and the outer colored layer broadens the aesthetic options. Chromogenic functionality of the inner layer was assumed to allow for dual thermal control: static or dynamic. Bilayers covering a complete color gamut were obtained, and their effect on the energy performance of a building, under a representative set of different climates present worldwide, was simulated and quantified.

2. Materials and Methods

2.1. Materials and Equipment

Commercially available dyes were used (red, yellow, blue, green, white and black), together with white acrylic paint. Dyes (outer layers) were mixed in appropriate proportions and dissolved in adequate solvents (methanol, chloroform or water) in order to allow its deposition through airbrushing. Inner layers were obtained with commercially available acrylic white paint (reflective layer) and black dye (absorbent layer). Details on each composition and deposition conditions are specified in Table S1. Subsequently, these mixtures were deposited on 2×2 cm^2 glass pieces. Depositions were made by airbrushing using an Iwata High Performance Plus airbrush.

Optical characterizations of the bilayers were made with an ASD FieldSpec3 spectroradiometer, obtaining reflectivity values over the 300–2500 nm range, together with colorimetry values. Spectralon® diffuse reflectance standards (Labsphere, Inc., North Sutton, NH, USA) were used as reference.

Dwelling design and energy simulations were carried out with SketchUp and Energy Plus software (version 9.3), respectively.

2.2. Optical Characterization of Dyes and Bilayers

The studied bilayers were comprised of two independent layers, in which the outer layer provided the color, by selectively absorbing in a determined region of the visible spectrum while letting the infrared radiation pass in entirely. The inner layers were characterized by significant absorption or reflection over the whole solar spectrum. Therefore, these bilayers were intended to have a net thermal absorptive or reflective effect while offering visible coloration.

For the outer layers, eight dyes were developed spreading evenly in CIELAB color space, as shown in Figure 1. Four dyes corresponded to a* or b* values close to zero (termed Red, Yellow, Blue and Green), while the other four were situated along the diagonal lines with $a^* \cong b^*$ (termed Lime Green, Orange, Violet and Sky Blue). Additionally, white and black dyes were also studied as limiting cases, with luminance close to 100% and 0% (maximum reflection and maximum absorption, respectively) for comparison. L*a*b* coordinates of the ten dyes can be found in Table S1.

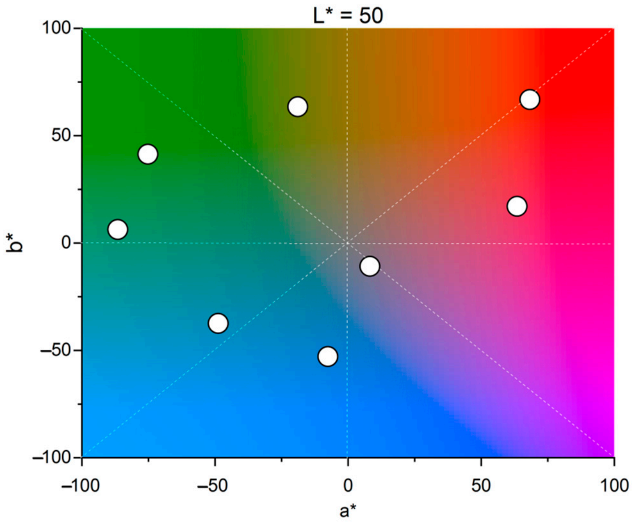


Figure 1. CIELAB coordinates for the eight dyes created projected on a L* = 50 plane.

As for the inner layers, two different layers were used. The first one, based on white acrylic paint (reflective), showed reflective characteristics along the solar spectrum, while the second one, based on black dye, showed absorbent properties along the solar spectrum.

Two groups of bilayers were deposited, consisting of the ten mentioned dyes as the outer layers combined with an absorbent or reflective inner layer, totaling twenty different bilayers. Reflectance values of each bilayer in the visible region (350–850 nm), near-IR (NIR) region (850–2500 nm) and the complete solar range (350–2500 nm) were obtained and are shown in Table 1.

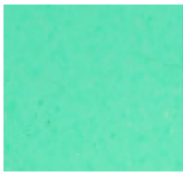
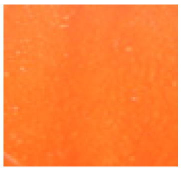
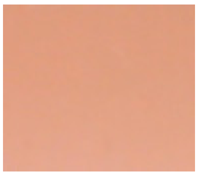
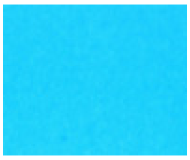
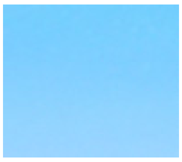
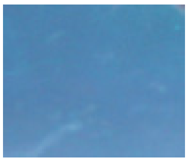
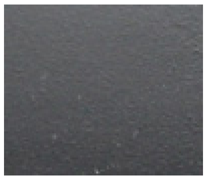
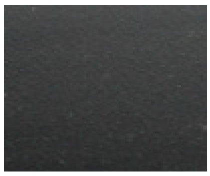
Table 1. Reflectance values of the studied bilayers in the visible, NIR and solar range both in their absorbent and reflective compositions.

Dye	Reflective Bilayer			Absorbent Bilayer			Solar Reflectance Modulation
	Visible	NIR	Solar	Visible	NIR	Solar	
Yellow	72.08	88.44	78.00	8.90	6.26	7.98	70.02
Green	31.13	85.93	50.96	2.65	4.57	3.35	47.61
Red	56.08	90.23	68.44	7.05	5.15	6.36	62.08
Blue	35.35	84.10	53.00	17.02	16.26	16.75	36.25
Sky blue	35.36	90.45	55.29	2.44	4.57	3.21	52.08
Lime Green	36.65	87.24	55.00	4.49	6.77	5.31	49.69
Orange	52.71	86.45	64.92	9.10	7.70	8.60	56.32
Violet	30.52	88.51	51.51	25.70	51.60	35.10	16.41
White	85.37	84.95	85.21	41.30	17.22	32.58	52.63
Black	10.81	9.70	10.41	1.26	1.07	1.19	9.22

It can be observed that for the reflective compositions, solar reflectance was greater than 50% for all colors (with the obvious exception of the black dye). In contrast, for absorbent compositions, solar reflectance was below 50% in all cases.

Pictures of all bilayers in their absorptive and reflective compositions, obtained under standard D65 illumination, are shown in Table 2.

Table 2. Reflective and absorptive configurations of bilayers. Pictures taken under calibrated D65 illumination.

Color	Configuration		Color	Configuration	
	Reflective	**Absorptive**		**Reflective**	**Absorptive**
Yellow			Lime Green		
Green			Orange		
Red			Violet		
Blue			White		
Sky Blue			Black		

2.3. Dwelling and Locations

A single-family two-story house was chosen for the study. The building consists of a ground floor for parking and storage use and a first floor for living. Figure 2A,B show the house blueprint and orientation.

A complete list of materials considered for enclosures and floors is shown in Table S2. Materials and building design were selected according to Spanish building regulation [26], where Barcelona was taken as the location for dwelling design. Insulation was adjusted to comply with the loads limit values allowed (32 KWh/m^2year). Thermal characteristics and properties of the dwelling are shown in Table 3. In this dwelling, six people have been considered for internal gains.

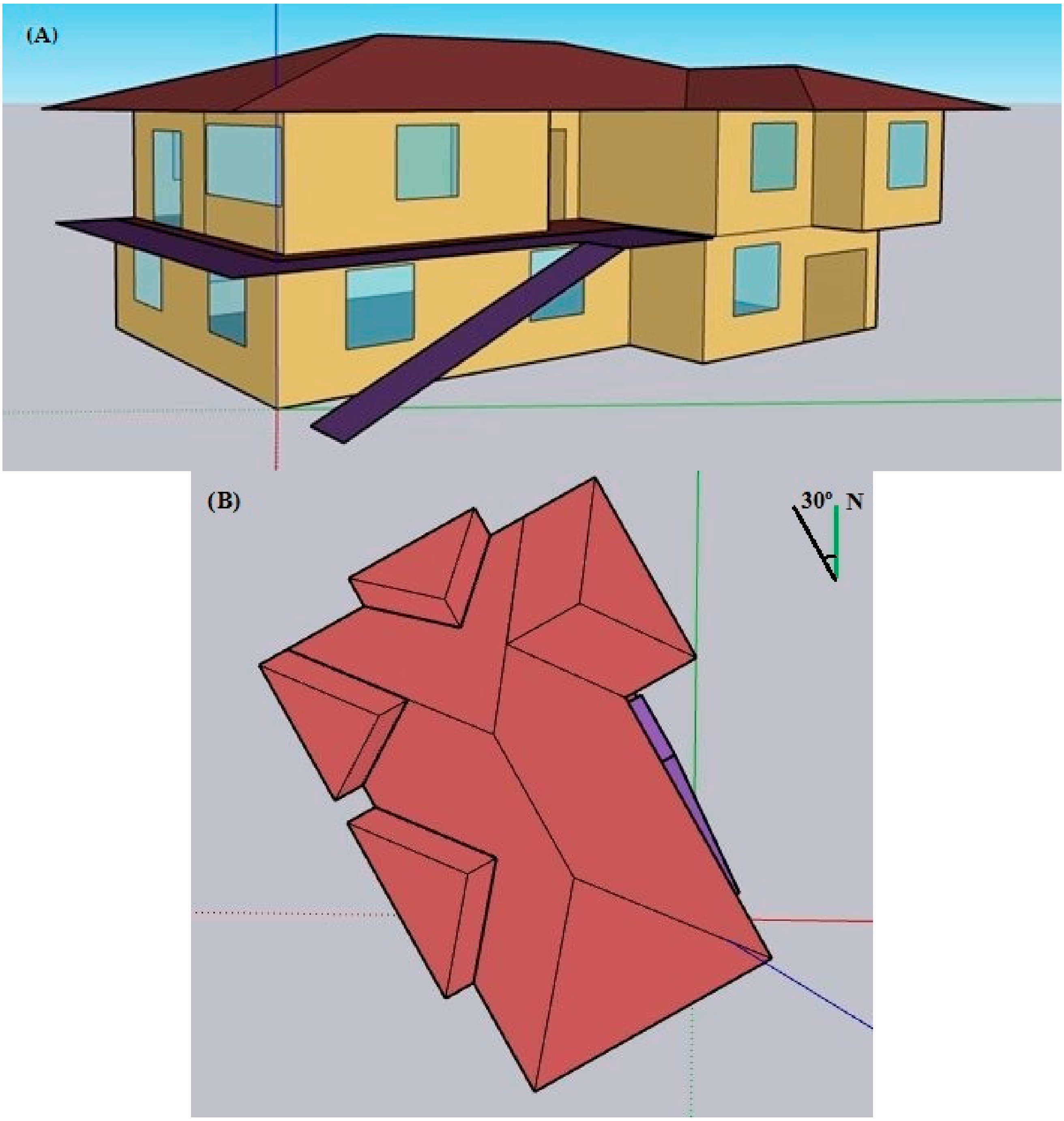


Figure 2. (**A**) House 3D rendering. (**B**) Zenithal view of the building.

Table 3. Main thermal properties of the dwelling.

Internal gains	People (W/person)	134
	Lights (W/m^2)	4
	Electric equipment (W/m^2)	2
Airflow (m^3/s)		0.044
Constant heating set point (°C)		20
Constant cooling set point (°C)		25

A set of different locations was chosen considering the largest possible variability of climate conditions. To select the set of different climates, Köppen–Geiger climate classification was used [27]. This classification shows five mayor climates: A (Tropical), B (Arid), C (Temperate), D (Cold) and E (Polar) and several sub-climates, resulting in 30 different climates. Detailed information about sub-classifications and the classification criteria can be found elsewhere [28,29]. In Figure 3, these classifications and the current worldwide climate distribution is visualized. Chosen locations for this study are situated and listed in this figure, together with the climate sub-classifications that each one belongs to.

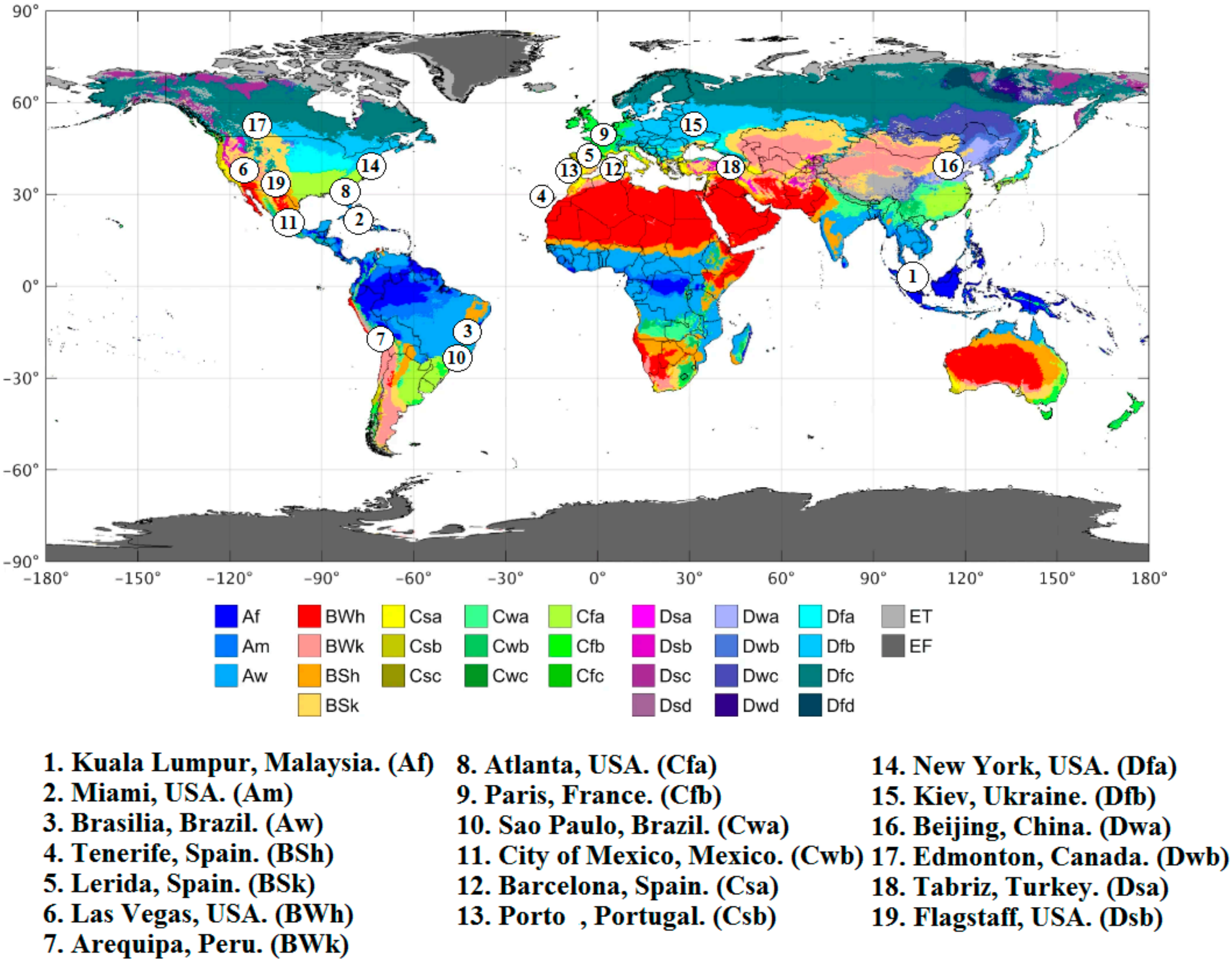


Figure 3. Köppen–Geiger climate classifications (adapted from [28]). Chosen locations are situated and listed.

In this study, those climates that are practically uninhabitable (climate E) have not been considered. In addition, very cold and almost uninhabitable climates (several climates of type C and D) whose solar radiation is almost nil (for which reflective properties of buildings are irrelevant) have also been discarded. Taking these considerations into account, a total of 19 different locations were chosen.

3. Results

Simulations and energy evaluations were carried out according to the previously described materials, dwelling and locations. For each location considered the following steps were followed:

Annual heating, ventilation, and air conditioning (HVAC) loads in each location were calculated for the "reference" conditions. The reference conditions chosen were characterized by a gray outer coloring, showing intermediate luminance and solar reflectance values (50%). Total annual values, including cooling and heating loads, are shown in the first columns of Figures S3–S21. Considering that an absorbent layer may reduce the heating loads, while a reflective layer may reduce the cooling loads, absorbent bilayers are expected to be beneficial in locations where the annual heating loads are greater than cooling loads, and reflective bilayers in the opposite case. In any case, substitution of the gray outer layer for both absorbent or reflective colored bilayer was made in each location, and the resulting annual loads obtained (Table S3): the most favorable case in each location was chosen for the study. We termed this the static thermal control.

For more precise thermal control in locations subject to great climate variations over the year, a monthly-basis analysis and simulations were performed. In these cases, the possibility of reflectivity modulation of the inner layer of the bilayer was considered through any chromogenic technology that would allow the switching between absorbent and reflective states. Reflective states were considered for months in which the cooling loads exceed the heating loads, and vice versa. We termed this the dynamic thermal control.

In all cases, simulations were performed for the complete color gamut proposed (eight colored bilayers plus white and black limit cases). Table S4 shows the chosen bilayer state for each location, for the static and dynamic cases (in this case, monthly broken down).

Annual HVAC loads (kWh/m^2 habitable) were calculated for each location in both cases (static and dynamic) and for the complete color gamut, and compared with the reference case. These results are shown in Figures S3–S21.

For each major climate (A, B, C and D), results varied widely. Therefore, results are grouped and compared according to their main climate classification. Analysis of the resulting data is presented in two ways. Firstly, absolute annual loads for each colored bilayer as a function of its solar reflectance are depicted and compared to the reference so as to visualize which configurations promote net annual savings. Secondly, percentages of annual savings are calculated to evaluate the impact in each case (in this case, where no savings were found for a particular color, there is no graphic representation). In both analyses, for the sake of clarity, just the most favorable configuration in terms of savings (whether static or dynamic) is shown.

Figure 4 comprises results obtained for climate A (Tropical) locations. This major climate is characterized by high irradiances and temperatures during all year (temperature in the coldest month > 18 °C). In this way, heating loads are non-existent. Therefore, only the static reflective configuration of bilayers was applied in all locations in this case (no dynamic configuration applied). As might be expected, a relationship between increasing reflectance values and energy savings can be found. Although the white bilayer appears as the most convenient choice, confirming the abovementioned traditional solution of "white villages", significant savings are also achieved through those bilayers with high reflective properties (red, orange and yellow colors), therefore broadening the available color palette. Savings were also present for the rest of colors (except for black), although minimum. Significant saving percentages can be found for this tropical climate locations, up to 60% in the most favorable case for Brasilia.

Figure 5 comprises the results obtained for climate B (Arid) locations. Four different subcategories can be found in this climate type termed S (steppe), W (desert), h (hot) and k (cold). Tenerife (Subcategory BSh) and Arequipa (Subcategory BWk) represent the two extreme cases within climate B type. In the first case, high irradiances along the year prevent the need for heating loads, while in the latter, colder temperatures during the year prevent the need for cooling loads. In these cases, only the static configuration (reflective configuration in Tenerife and absorbent configuration in Arequipa) was applied. Results in Tenerife are very similar to those obtained in climate A, where just the most reflective colors achieved significant savings. Interestingly, the full color gamut can be used in Arequipa obtaining significant savings, as long as an absorbent configuration bilayer is present. The lowest savings in this case corresponded to white- and violet-colored bilayers, the two cases with higher solar reflectance. Considering the low annual loads in these two locations, savings obtained can represent more than 40% in the total annual loads.

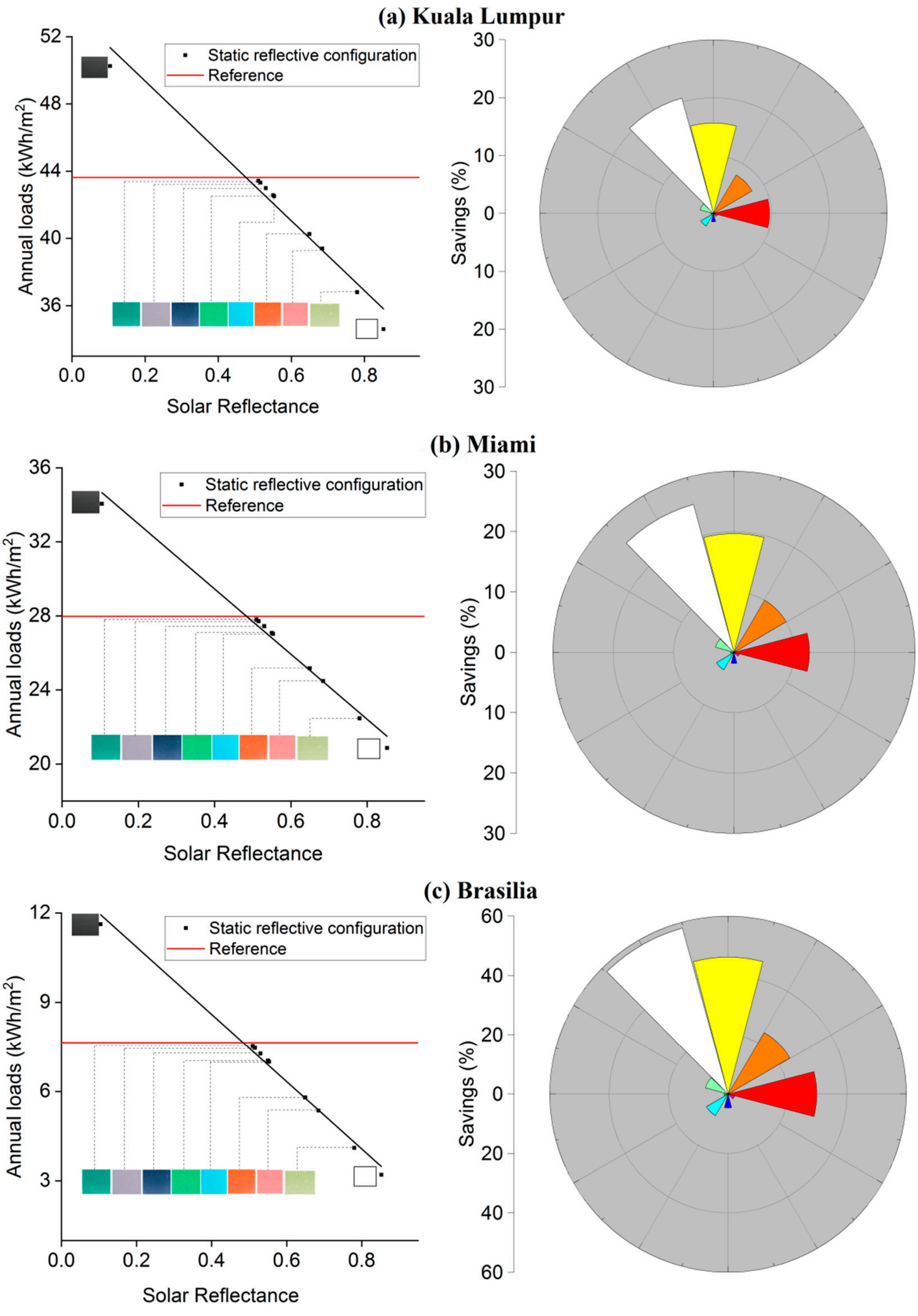


Figure 4. HVAC load savings in climate A (Tropical): (**a**) Kuala Lumpur, (**b**) Miami, (**c**) Brasilia.

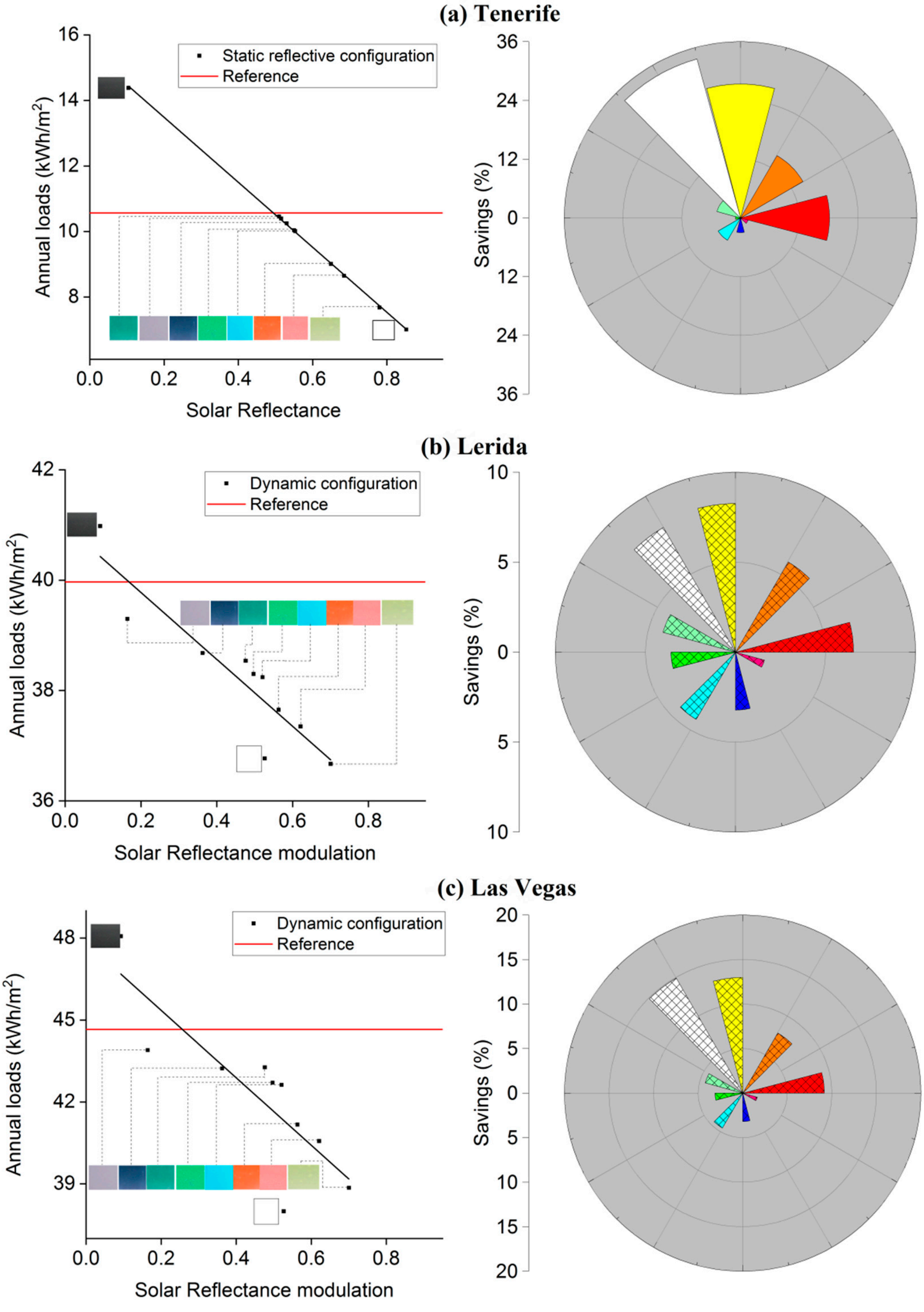


Figure 5. *Cont*.

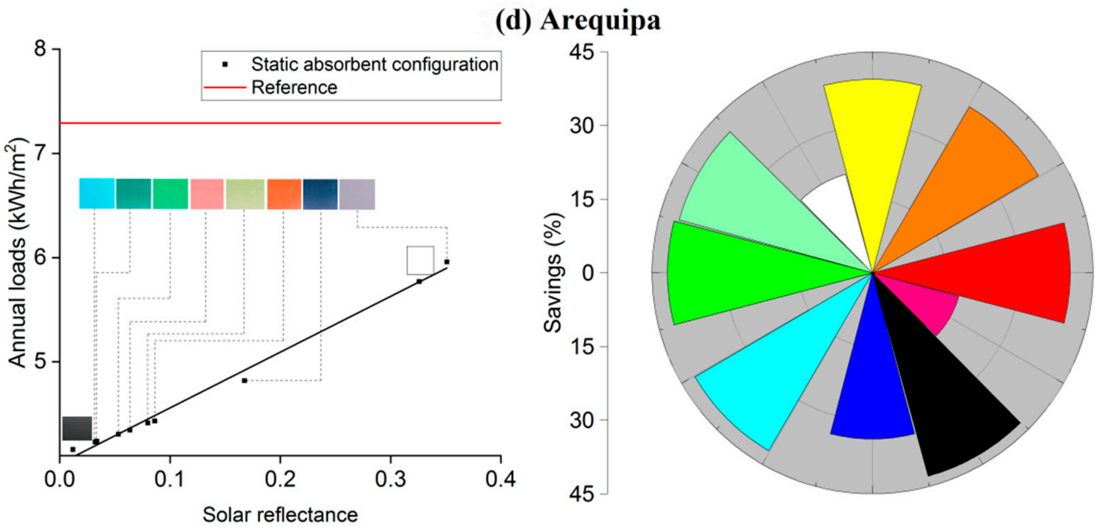


Figure 5. HVAC load savings in climate B (Arid): (**a**) Tenerife, (**b**) Lerida, (**c**) Las Vegas, (**d**) Arequipa. Right graphs: static configuration, solid color, dynamic configuration, striped color.

On the other hand, sub-climates BSk and BWh (Lerida and Las Vegas, respectively) represent situations where both heating and cooling loads are needed (Figures S7 and S8). Heating loads are predominant in Lerida (85% of the total annual HVAC loads), while cooling loads are slightly higher (60%) in Las Vegas. In these cases, the dynamic configuration presents significantly better savings than the static one. For dynamic configurations, where absorbent and reflective configurations are used depending on the heating or cooling loads, achievable savings have been represented as a function of reflectance modulation, that is, the difference between reflectance in the reflective and absorbent states. More complex relationships are found, considering that the number of months for which a certain configuration could be different depending on location, as well as the values of the reflectance modulation for each color. Nevertheless, an almost linear relation can still be found between the decreasing annual loads and increasing reflectance modulation values. An exception can be found in this behavior, corresponding to the white bilayer: a high reflectance value for its absorbent state prevents this bilayer to be an effective absorbing bilayer and makes it deviate from the rest of the colors. We have found this deviation of the white bilayer in all climates and locations where the dynamic configuration was applied.

Coming back to the cases of Lerida and Las Vegas, where dynamic configurations were applied, the full color gamut can be used in both cases, although with significantly better savings in Las Vegas, corresponding to more balanced cooling and heating loads. In this case, the absorbent configuration was needed for five months, while the reflective configuration was used for seven months. For the case of Lerida, with cooler temperatures during the year, the absorbent configuration was needed just for four months (the configurations used and specific months for each location are depicted in Table S4). With high annual loads surpassing 40 Kwh/m^2 in both cases (Lerida and Las Vegas), the savings obtainable by means of colored envelopes only reach values close to 10% at the maximum.

Figure 6 comprises results obtained for climate C (Temperate) locations. Six different subcategories can be found in this climate type, termed s (dry summer), w (dry winter), f (without dry season), a (hot summer), b (warm summer) and c (cold summer). In all cases HVAC loads include cooling and heating to a greater or lesser extent (Figures S10–S15). Therefore, the dynamic configuration was more adequate for better thermal response. The dynamic configuration allowed the use of any color (except black) to obtain energy savings. Among the six studied locations, Sao Paulo (Cwa), Barcelona (Csa) and Porto (Csb) presented very similar savings. Interestingly, these locations present a mirrored profile in their monthly reflective-absorbent configurations (see Table S4) due to the northern-southern hemispheric differences (winter months in Sao Paulo correspond to summer months in Porto and Barcelona, and vice versa). Atlanta (Cfa) showed a similar savings profile in terms of color gamut but to a greater energy extent. Although in Paris (Cfb) percentage savings are significantly lower than others (almost negligible, below 2%), it is interesting to note that it is still possible to use any envelope color maintaining lower loads than in the "reference" dwelling of the location.

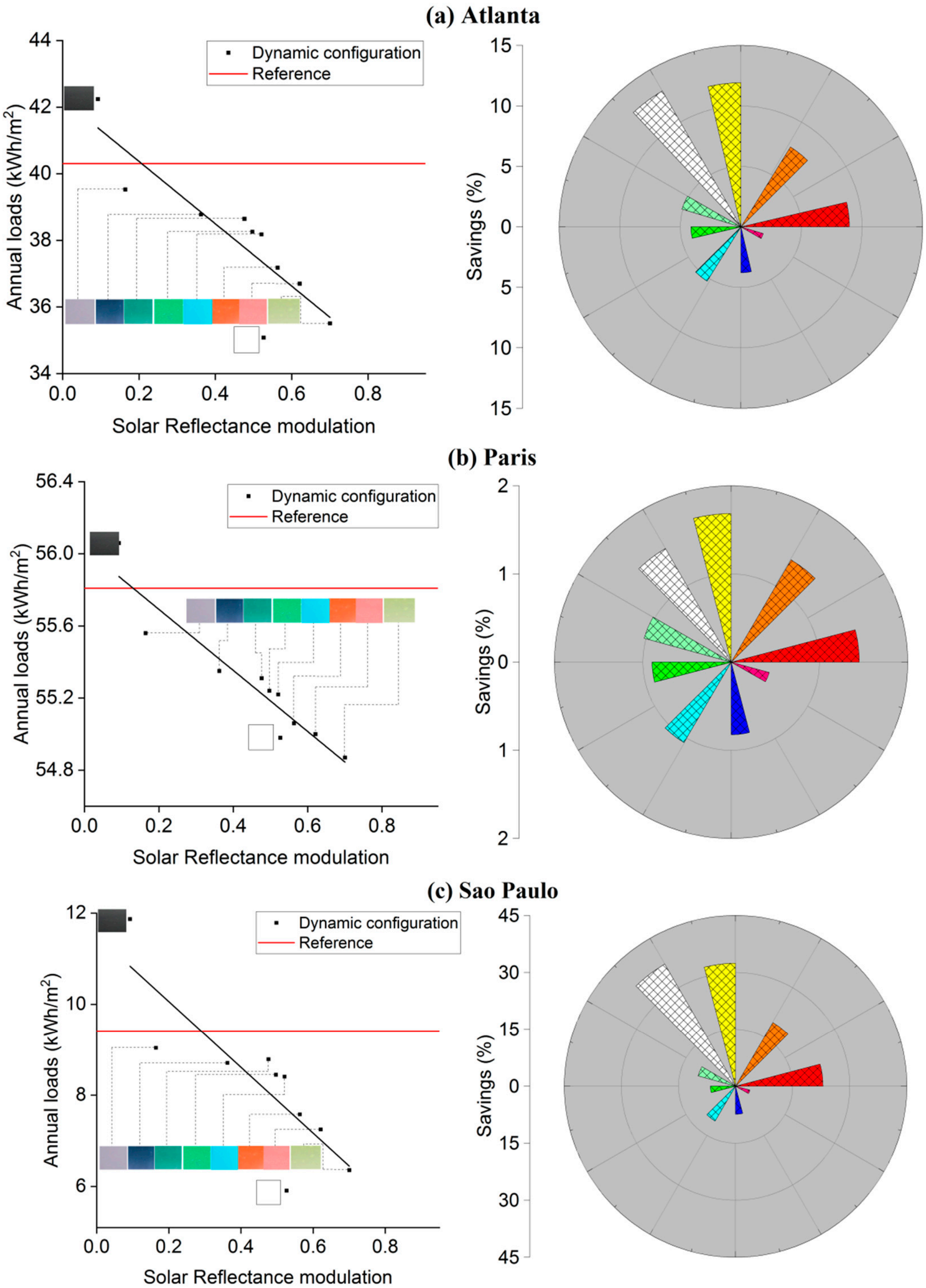


Figure 6. *Cont.*

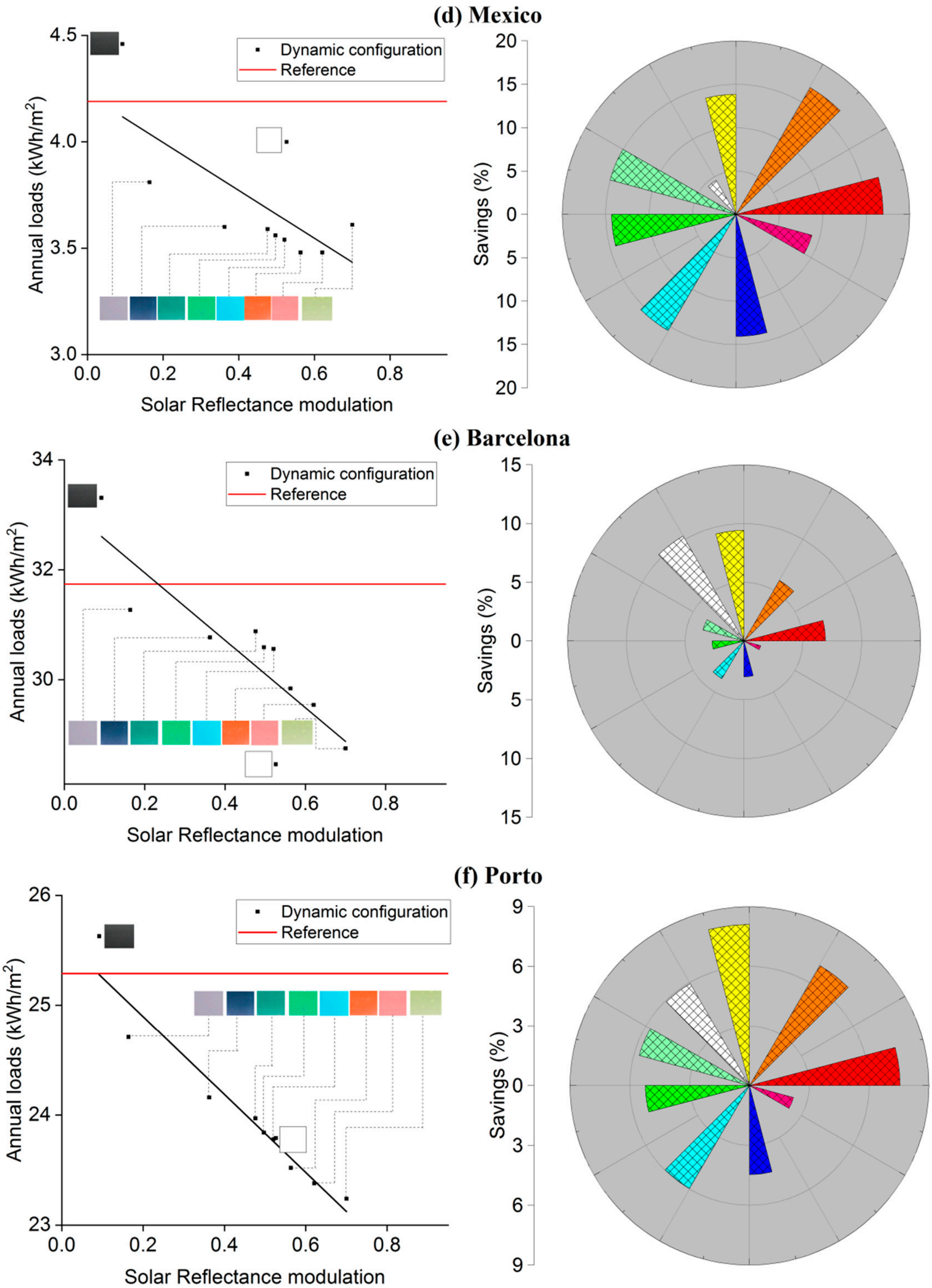


Figure 6. HVAC load savings in climate C (Temperate): (**a**) Atlanta, (**b**) Paris, (**c**) Sao Paulo, (**d**) Mexico, (**e**) Barcelona and (**f**) Porto.

Figure 7 comprises results obtained for climate D (Cold) locations. Six different subcategories were studied for this climate type, grouped under the following terms: s (dry summer), w (dry winter), f (without dry season), a (hot summer) and b (warm summer). Heating loads were predominant in HVAC loads in all cases (Figures S16–S21).

The dynamic configurations showed better thermal response than the static ones in all locations, except Edmonton and Flagstaff, where cooling loads are nil throughout the year, and the best solution is the static absorbent configuration.

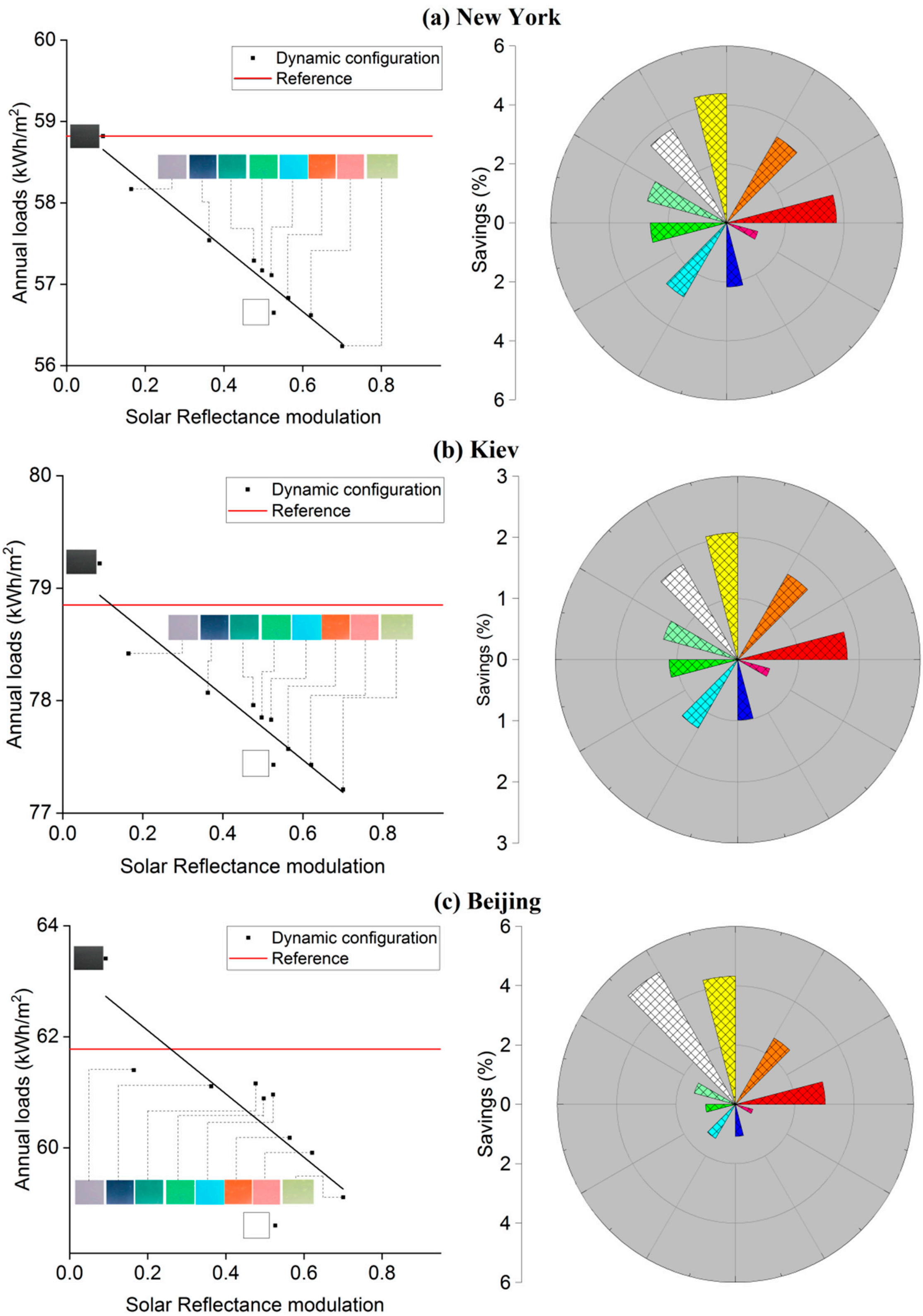


Figure 7. *Cont.*

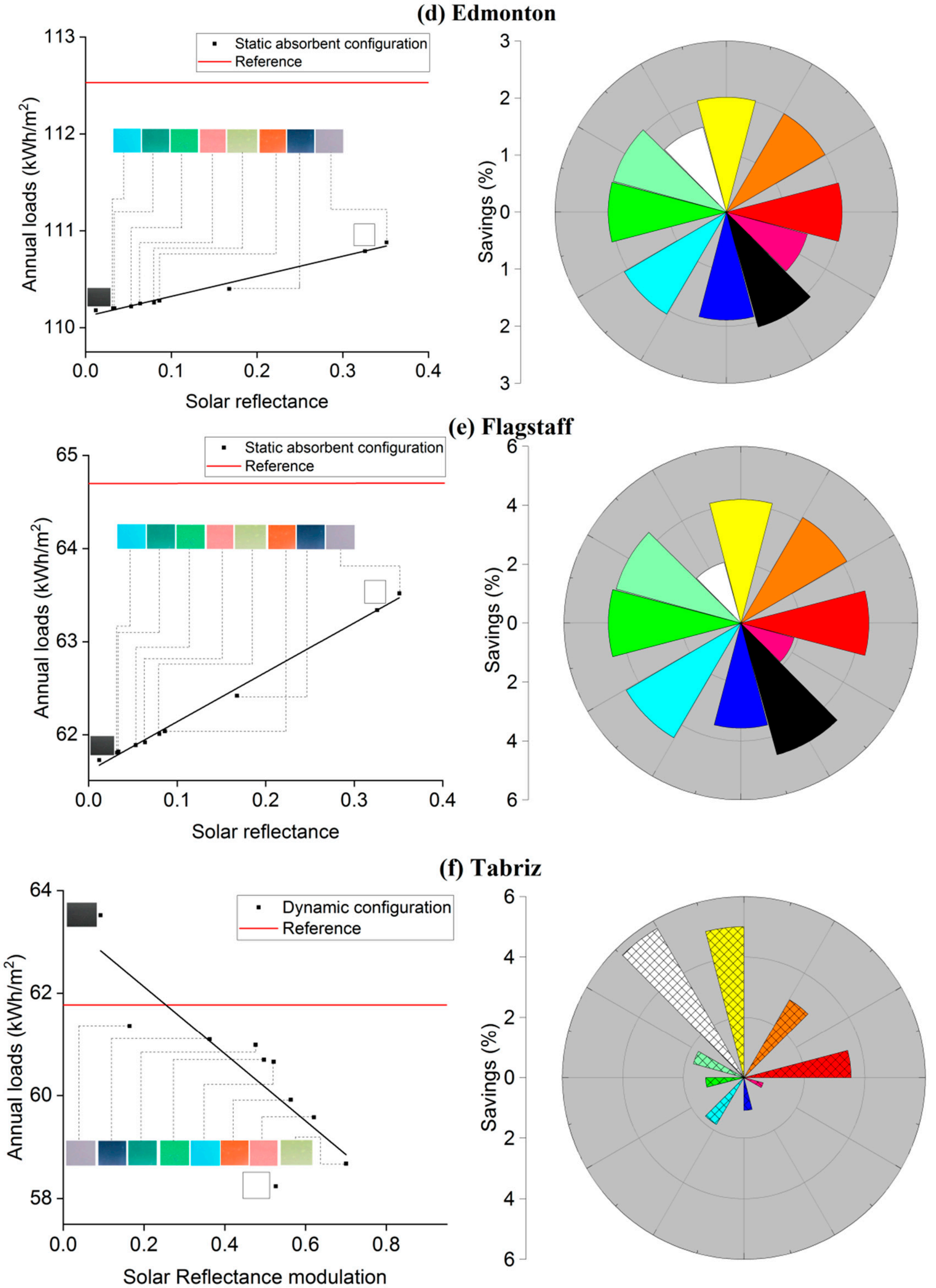


Figure 7. HVAC load savings in climate D (Cold): (**a**) New York, (**b**) Kiev, (**c**) Beijing, (**d**) Edmonton, (**e**) Flagstaff and (**f**) Tabriz. Right graphs: static configuration, solid color, dynamic configuration, striped color.

For the locations showing more "moderate" climates (within the cold D climate type), New York, Kiev, Beijing and Tabriz, minor savings (below 5% in all cases) can be obtained for the full color gamut in the dynamic configuration, whereas for the two "extreme" locations within this group, Edmonton and Flagstaff, similar savings can also be achieved, but in the static absorbent configuration.

4. Discussion

The study presents a comparative set of data intended to evaluate the influence of the use of colored bilayers (whether in the static or dynamic configurations) on possible HVAC building savings. In order to obtain the widest picture, simulations were carried out for an extensive set of climate conditions worldwide. However, some restrictions of the used model should be considered when analyzing the resulting data and established conclusions. To obtain meaningful comparative data, the same building was used for all simulations. This building was designed to comply with the Spanish regulations in a specific location, but these regulations differ for different countries. Materials needed to comply with different national regulations (or even different locations inside the same country), specially referring to insulation, are considerably different. The designed building solution may not be realistic for practical purposes in some locations, and, consequently, the interpretation of the obtained results may be modulated.

In view of these results, both climate A (Tropical) and D (cold) locations show consistent patterns. On the one hand, all locations belonging to tropical climate present significant savings exceeding 15% (the high values obtained for Brasilia, exceeding 40%, may be interpreted according to the considerable low annual loads in the reference conditions). It is interesting to note that the color gamut able to provide significant savings, besides white, is expanded towards other high reflectance colors (yellow, orange or red). These saving values may be considered realistic, as the insulation level used in the reference building (designed for colder climate conditions) exceeds those needed for these locations. In addition, it is important to note that this thermal control is obtained with static configurations: as no chromogenic control is needed, future implementation of this solution would be greatly simplified.

On the other hand, Climate D (Cold) locations also present a consistent pattern but with opposite values. None of the locations show savings above 5%, even for dynamic configurations. Moreover, a realistic building design would significantly increase insulation, lowering (or practically cancelling) any possible savings due to the bilayers. In view of these results, the use of bilayers for thermal control in the studied conditions should be discarded.

Climates B (Arid) and C (Temperate) show the largest variation in results. In the first case, when considering the extreme climate conditions (Tenerife (Subcategory BSh) and Arequipa (Subcategory BWk)) within climate B conditions, the same pattern observed in climates A or D is obtained. For warm locations (Tenerife), savings are obtained in a reflective static configuration, and the color gamut available is expanded towards yellows, oranges or reds. For colder locations, like Arequipa, significant saving percentages are obtained, but absolute values of these savings are low and, considering the effect of additional insulation for a realistic building, those savings are negligible. Similar considerations may be applied to climate C locations, Paris or Sao Paulo (even considering that a dynamic configuration was applied in both cases): negligible savings in the former case due high annual loads and the need for increasing insulation for real buildings, which would make bilayers contribution irrelevant, or very low absolute saving values due to the low annual loads needed in the latter case.

The rest of the locations in climate B or C, with intermediate annual loads (between 30–40 kWh/m^2year) and significant percentages of both cooling and heating loads constitute the most variable but interesting group. In all cases, due to interseason variability of climate conditions, the dynamic configuration is the most favorable choice. For practical implementation, where chromogenic control is needed, this would imply higher costs. Noteworthy, the color gamut able to provide savings is greatly expanded, and although colors with higher reflectivity still provide higher savings, the rest of colors simulated also provide savings to a variable extent. Saving percentages range between 5–15%. Again, as previously mentioned, significant lowering of the obtained savings may be expected in a realistic scenario due to the contribution of additional insulation required to comply with the different national regulations. Considering the need for additional insulation, an interesting approach may be considered: colored bilayers may be used to reduce the amount of insulating material in the building structure, lowering the material costs. Additional studies are needed to establish a proper balance between the costs of each solution. The lack of widespread chromogenic solutions in the market makes this approach speculative at this moment but opens the way for future studies.

5. Conclusions

The use of colored bilayers where the inner layer presents strong solar absorbent or reflectance properties, while the outer layer provides visible coloration, has been evaluated for HVAC building energy savings. A representative set of twenty bilayers spanning a broad color palette has been studied in two configurations, static and dynamic. The dynamic configuration was achieved by simulating the switching of the inner layer between absorptive and reflective states. Simulations have been carried out in a total of nineteen locations around the world representing the main habitable climates according to Köppen–Geiger climate classification.

In hot or cold climates, where there are only cooling or heating loads, the use of the static configuration of these bilayers has been proven to be more convenient than the dynamic one. In all cases, the use of bilayers broadened the envelope color gamut available while maintaining significant savings. However, the inclusion of additional insulation in a realistic building design provides possible savings due to bilayers negligible for cold climates.

On the other hand, in changing or mild climates, the use of a dynamic configuration provided the possibility of HVAC load savings practically with any color, surpassing any of the static options. Indeed, in most of these locations, static configurations are not able to provide net annual savings. These climates would offer the highest benefits for the application of chromogenic technologies capable of switching between absorbent and reflective states. Interestingly, these types of seasonal changing climates are the most common around the world and with the higher population densities.

In summary, comparative results have shown that the use of colored bilayers in building envelopes could be an efficient tool to obtain HVAC savings while maintaining broad aesthetic options for a number of climate conditions. Although the use of a restricted building model limits the direct application of obtained results, general trends can be extracted for different climate conditions worldwide, paving the way for forthcoming quantitative studies in selected locations or climates.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings13030802/s1, Table S1. Properties of dyes and inner layers, composition and color coordinates (CIELAB). Table S2. Materials used (with corresponding thicknesses), enclosures and floors of the dwelling. Listed from inside to outside. Table S3. Annual loads (kWh/m^2) for reflective and absorbent static configuration in each location. The more favorable static configuration obtained in each case in bold. (In the second column, C stands for Configuration, R for Reflective configuration and A for Absorbent configuration). Table S4. Configuration of bilayers for each location and type of simulation: static or dynamic (Monthly broken down for the dynamic case). White cells mean the reflective configuration was used for simulation, black cells, absorbent configuration. Figure S1. Different views of the building. (A) Frontal view. (B,C) Lateral views. (D) Back view. Figure S2. Building plans. (A) Ground floor plan. SI units. (B) First floor plan. SI units. Figure S3. Annual loads in Kuala Lumpur, Malaysia (Climate Af). Static simulation, s, dynamic simulation, d. Red, heating loads, blue, cooling loads. Figure S4. Annual loads in Miami, USA (Climate Am). Static simulation, s, dynamic simulation, d. Red, heating loads, blue, cooling loads. Figure S5. Annual loads in Brasilia, Brazil (Climate Aw). Static simulation, s, dynamic simulation, d. Red, heating loads, blue, cooling loads. Figure S6. Annual loads in Tenerife, Spain

(Climate Bsh). Static simulation, s, dynamic simulation, d. Red, heating loads, blue, cooling loads. Figure S7. Annual loads in Lerida, Spain (Climate Bsk). Static simulation, s, dynamic simulation, d. Red, heating loads, blue, cooling loads. Figure S8. Annual loads in Las Vegas, USA (Climate Bwh). Static simulation, s, dynamic simulation, d. Red, heating loads, blue, cooling loads. Figure S9. Annual loads in Arequipa, Peru (Climate Bwk). Static simulation, s, dynamic simulation, d. Red, heating loads, blue, cooling loads. Figure S10. Annual loads in Atlanta, USA (Climate Cfa). Static simulation, s, dynamic simulation, d. Red, heating loads, blue, cooling loads. Figure S11. Annual loads in Paris, France (Climate Cfb). Static simulation, s, dynamic simulation, d. Red, heating loads, blue, cooling loads. Figure S12. Annual loads in Sao Paulo, Brazil (Climate Cwa). Static simulation, s, dynamic simulation, d. Red, heating loads, blue, cooling loads. Figure S13. Annual loads in City of Mexico, Mexico (Climate Cwb). Static simulation, s, dynamic simulation, d. Red, heating loads, blue, cooling loads. Figure S14. Annual loads in Barcelona, Spain (Climate Csa). Static simulation, s, dynamic simulation, d. Red, heating loads, blue, cooling loads. Figure S15. Annual loads in Porto, Portugal (Climate Csb). Static simulation, s, dynamic simulation, d. Red, heating loads, blue, cooling loads. Figure S16. Annual loads in New York, USA (Climate Dfa). Static simulation, s, dynamic simulation, d. Red, heating loads, blue, cooling loads. Figure S17. Annual loads in Kiev, Ukraine (Climate Dfb). Static simulation, s, dynamic simulation, d. Red, heating loads, blue, cooling loads. Figure S18. Annual loads in Beijing, China (Climate Dwa). Static simulation, s, dynamic simulation, d. Red, heating loads, blue, cooling loads. Figure S19. Annual loads in Edmonton, Canada (Climate Dwb). Static simulation, s, dynamic simulation, d. Red, heating loads, blue, cooling loads. Figure S20. Annual loads in Tabriz, Turkey (Climate Dsa). Static simulation, s, dynamic simulation, d. Red, heating loads, blue, cooling loads. Figure S21. Annual loads in Flagstaff, USA (Climate Dsb). Static simulation, s, dynamic simulation, d. Red, heating loads, blue, cooling loads.

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Data Availability Statement: The data presented in this study will be made available on reasonable request to the corresponding author. The Following Image: Under a creative commons license was used in the graphical abstract: https://commons.wikimedia.org/wiki/File:Casa_del_C%C3%B3nsul_Alem%C3%A1n_(20200902_103833).jpg (accessed on 1 February 2023).

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