A Simulation-Based Assessment of Technologies to Reduce Heat Emissions from Buildings

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Abstract

Heat emissions from buildings are part of anthropogenic heat leading to urban overheating. This paper aims to assess how technologies (i.e., energy conservation measures - ECMs), used to decrease energy use, may also reduce heat emissions from buildings. This study employs the physics-based engine EnergyPlus to simulate the main components of heat emissions from buildings to ambient air: envelope, zone, and systems. Hourly simulations are run for IECC single- and multi-family reference models with three representative climates: Miami, Baltimore, and Chicago. The results show that the performance of ECMs varies among weather, seasons, and residential typologies. Particularly, some ECMs (i.e., cool coatings, heat pumps, additional insulation, energy-awareness occupants) show a strong decrease in heat emissions, yet they are not always correlated with proportional decreases in energy use. When all ECMs are combined, the reductions are larger on heat emissions (89%) than on site energy (65%) from the base cases. During summer in Miami, the combination of ECMs shows a decrease in heat emissions from the building surface component of 80% during daytime, 92% for the HVAC component and a counterbalanced increase in the zone component of 88%, bringing to a daily decrease in total heat emissions. The main contributions of this study are quantifying how typical ECMs influence residential building heat emissions using EnergyPlus simulations and informing urban planners and stakeholders on prioritizing measures for mitigating urban overheating problems.

Keywords: Heat Emissions; Building Performance Simulation; Urban overheating; Anthropogenic Heat

1. Introduction

Almost in all dense urban areas, temperatures are higher than in the surrounding rural areas [1–3]. This phenomenon is known as the urban heat island (UHI) effect [4]. In the last decade, UHI mitigation became a central driver of regulatory plans because of its aggravation linked to climate change and heatwaves [5,6]. The increase of temperatures of the central areas of cities has a direct effect on the energy consumption of buildings (i.e., decreasing the heating energy demand but substantially increasing the cooling energy demand [7]) and, particularly during summer, on the use of outdoor areas such as urban plazas and streets [8]. Urban form [9], buildings geometry [10] and streets morphology [11], the thermal characteristics of the materials used [12], the presence of green [13,14] and blue [15] infrastructures are all among the main elements that influence the UHI effect. The resulting sum of all these aspects affects the humidity and temperature of the outdoor air and the velocity and path of airflows in the urban context [16]. Especially, buildings play a fundamental role in the UHI mitigation [17–19], representing a large part of the anthropogenic heat emission in cities, together with industry and transport [20,21]. Buildings emit heat to the ambient air as sensible and latent heat. Airflow from buildings to the urban environment due to exfiltration, natural and mechanical ventilation, as well as convective and radiative heat from the exterior surfaces of the envelope, and heat rejection from HVAC systems dump heat to the urban environment.

In several prior studies, the heat emissions from buildings to ambient air are assumed to be equal to the energy consumption [22]. This, however, is an assumption proved to be unrealistic and simplistic [23,24]. Numerous researchers started to better understand the relation between heat emissions and strategies to minimize them. Especially, different studies are focused on the quantification and effect of measures on the radiative exchange of surfaces (e.g., cool roofs [7], cool facades [5]) or on altering the heat released in time with phase change materials [25] or structural heat storages [26].

Traditionally, there are three main approaches to handle the heat emissions from buildings: (1) quantification via inventories, (2) quantification via heat energy balances and (3) quantification via building energy models [20]. In the inventory approaches [27–30], surveyed or registered energy data are converted into heat emissions, usually neglecting heat storage, time delays, and the difference between sensible and latent heat. The heat emission data are then distributed among buildings based on various indexes (e.g., the density of population and district gross domestic product [31], statistics related to the typology of buildings [32]). Quantification via heat energy balances [33,34] defines a control volume including the buildings covered in the study, tracking all the energy inlets and outlets via measurements and approximations. The difference between the inlets and outlets is supposed to be equal to the heat emissions from the part of the city under study. Quantification via building energy models [35], exploits high spatial and temporal resolution methods already verified. Numerous thorough studies exploit traditional building energy modelling (BEM) to study a specific aspect of heat emission [36]. Some tools (e.g., Rayman [37], SOLWEIG [38], ENVI-met [39], or CityComfort+ [40]) are specifically designed to calculate the effect of buildings on the microclimate but the buildings are usually simplified as heat emitters. In BEM, direct integration between the calculation of the energy consumption with a physics-based quantification of the heat emission from buildings was still missing. Thanks to EnergyPlus version 9.2, a first step to integrating the energy consumption and heat emission assessments have been made [24], opening the possibility to study in detail the effects of a large set of strategies both on the energy uses and heat emissions with high temporal detail.

This study aims to understand if the new algorithms implemented by EnergyPlus, may prove useful to compare different ECMs, typically selected for energy saving purposes only, from the point of view of waste heat reductions, broadening the understanding of the best solutions to take at building level to reduce urban overheating. This work is an essential component of a broader research topic where urban assessment of the effect of ECMs is performed. Starting from the intial findings of this work, future studies will be performed, using bottom-up physics-based urban building energy modelling tools [41] to, eventually, assess the effects of heat emissions from buildings on the urban environment and microclimate [42], based on dynamic energy simulations at the urban scale.

2. Methods

For this study, the novel physics-based heat balance model implemented in EnergyPlus version 9.2 is exploited, to study the heat emission from a building to ambient air [24]. The calculation method assesses the heat emission to ambient air released by three main components: the envelope, the spaces (i.e., zones), and the systems.

In the calculation, for each timestep, the heat emission to air from the envelope ($Q_{emi,surf}$) includes the convective heat calculated with the difference in temperature between the external surface of the envelope (T_{surf} (K)) and the outdoor air ($T_{out}(K)$) and the convection heat transfer coefficient of the surface (H_c $(W/(m^2K))$, and the radiative heat absorbed by the air (e.g., moisture and dust) [24], following Equation 1:

$$Q_{emi,surf} = (H_c + H_r) \cdot A \cdot \left(T_{surf} - T_{out}\right) \quad [W] \quad (1)$$

in which H_r $(W/(m^2K))$ is the linearized equivalent heat transfer coefficient of the outer surface thermal radiation to the particles and dust in the ambient air, A (m^2) is the surface area.

While the total heat released into the ambient air by the exfiltration air from the zones ($Q_{exf,zone}$) and the exhaust air from the zones ($Q_{exh,zone}$) is based on the mass flow rates due to exhaust fans and exfiltration from the envelope and the difference in internal and external moist air specific enthalpy. Following Equation 2 and Equation 3:

$$Q_{exf,zone} = m_{exf} \cdot (h_{zone} - h_{out}) \quad [W] \quad (2)$$

$$Q_{exh,zone} = m_{exh} \cdot (h_{zone} - h_{out}) \quad [W] \quad (3)$$

in which m_{exf} $(\frac{g}{s})$ is the mass flow rate of the exfiltration air, m_{exh} $(\frac{g}{s})$ is the mass flow rate of exhaust airflow from the zone, and h_{zone} $(\frac{J}{g})$ and h_{out} $(\frac{J}{g})$ are the specific enthalpies of the air in the zone and outdoor moist air.

Lastly, the component of the heat emission towards air regarding the HVAC system is divided into two elements. The first one is related to the air relief by the Air Handling Unit (AHU) (Q_{AHU}) and again exploits the difference in relief and external moist air specific enthalpy and the mass flow rate of the relief air, following *Equation 4*:

$$Q_{AHU} = m_{AHU} \cdot \left(h_{AHU\_out} - h_{out}\right) \quad [W] \quad (4)$$

in which m_{AHU} $(\frac{g}{s})$ is the mass flow rate of the relief air from the AHU and h_{AHU_out} $(\frac{J}{g})$ and h_{out} $(\frac{J}{g})$ are the specific enthalpies of the AHU outlet air and outdoor moist air. The other element (e.g., heat rejection from cooling towers, heat from air-cooled condensers) is strictly linked to the type of system used in the model and specific detail can be found in the Engineering Reference [43]. To give some examples, for a gas-powered combustion unit, the heat emission toward air is given by the difference between the fuel generated heat and the fuel heat supply. While, for an air-cooled condensing unit, the heat emission is given by the sum between the cooling rate and the electric power of the condenser fan and compressor. The method is presented in previous publications [21,24] and the details of the calculations can be found in the Engineering reference of EnergyPlus [43].

In this paper we compare a base case with different ECMs implementation scenarios, in three U.S. climates: Chicago – cold winter and hot summer, Baltimore – mild winter and hot summer, and Miami – cooling only year-round. This gives the opportunity to better understand the impact of the ECMs on the heat emission of the building to the surrounding ambient air in different climatic conditions.

2.1. Weather datasets

Table 1 describes the main features of the weather in three selected reference cities for the discussed climate zones: Miami, Baltimore, and Chicago. The three locations are characterized by different climatic conditions, exploited to give a good overview of the impact of ECMs in different climates. They show different Heating Degree Days (HDD) (i.e., 83.3, 2594.4, 3556.2 for Miami, Baltimore and Chicago respectively) and Cooling Degree Days (CDD) (i.e., 2275.8, 663.1, 449.4). Miami is classified as a tropical monsoon climate (Am) in the Köppen climate classification [44] that corresponds to the class 1A in U.S. DOE climate classification [45]. Thus, its climate is relatively warm all year long, with a yearly average dry bulb temperature of 24°C and a maximum difference between monthly average of 9°C, registered between July (with an average of 28°C) and January (with an average of 19°C). Baltimore climate is classified as a humid subtropical climate (Cfa) according to Köppen [44] that corresponds to class 4A for U.S. DOE [45]. It is characterized by warm and moist summer months but relatively cold winter months. The registered yearly average dry bulb temperature is 12.8°C and a maximum difference between monthly average of 25°C, registered between July (average of 25°C) and January (average of 0°C). Lastly, Chicago is classified as hot summer continental climate (Dfa) according to Köppen [44], corresponding to 5A for U.S. DOE [45], with hot summers and snowy winters. In particular, the yearly average dry bulb temperature is 9.7°C and a maximum difference between monthly average of 28°C, registered between July (with an average of 24°C) and January (with an average of -4°C).

Table 1: Main characteristics of the weather datasets of the three U.S. cities

Location	Miami, Florida, U.S.	Baltimore, Maryland, U.S.	Chicago, Illinois, U.S.

Data Source	TMY3 722020 WMO	TMY3 724060 WMO	TMY3 725300 WMO
Köppen climate classification [44]	Am	Cfa	Dfa
U.S. DOE climate classification [45]	1A	4A	5A
Location	25.82° N 80.3° W	39.17° N 76.68° E	41.98° N 87.92° W
Elevation [m]	11	45	201
Yearly average dry bulb temperature [°C]	24	12.8	9.7
Maximum difference between monthly average [°C]	9	25	28
HDD [respect to 18.5°C]	83.3	2594.4	3556.2
CDD [respect to 18.5°C]	2275.8	663.1	449.4

2.2. Base case Models

2.2.1. General description

The Residential Prototype Building Models used in this study are developed by the Pacific Northwest National Laboratory (PNNL) [46]. They are calibrated building models used by the International Energy Conservation Code (IECC) to assess new versions of the code and for the proposal of code changes. Two base prototypes are available and exploited for this study: single-family (SF) detached house and multi-family (MF) low-rise apartment building. Various possibilities for the system types (i.e., Electric Resistance, Gas Furnace, Oil Furnace or Heat Pump), foundation types (slab, crawlspace, heated basement, unheated basement), climatic conditions, and vintages are available. The models for SF and MF buildings are chosen with climate zone 1, 4, and 5 with a moisture regime A, gas furnace as heating system, slab as the type of foundation, and IECC of 2006. In *Table 2*, the main characteristics of the models are described briefly. The models can be directly downloaded from the U.S. DOE website [46].

It has to be noted that the models represent typical residential buildings with split air-conditioning systems (i.e., no central AHU or fan). By consequence, the three variables that will compose the heat emission from the building are: (i) Surface Heat Emission to Air, (ii) Zone Exfiltration Heat Loss, (iii) HVAC System Heat Rejection Energy.

Table 2: Main characteristics and settings of the models

Characteristic	**Common to all models**		
Simulation	EnergyPlus Version: 9.3 Terrain: Suburbs Solar distribution: Full Exterior Number of Timesteps per hour: 4 Maximum and minimum warmup days: 25, 6		
Systems	Heating system: Gas heating coil (furnace) Burner efficiency of the heating coil: 0.8 Heating setpoint: 22.22 ℃ Cooling system: Direct expansion cooling coil with the condensing unit Cooling COP: 4.07 for Baltimore and Miami, 3.97 for Chicago Cooling setpoint: 23.88℃ Systems schedule: Always ON Water Heater loss coefficient to ambient Temperature: 6.28 W/K		
Infiltration rate	Conditioned zones: ~ 1 ach Attic: ~ 3 ach		
Characteristic	**Single-family detached house**		**Multi-family low-rise apartment building**
General Model	Total Building Area: 331 m^2 Net Conditioned Building Area: 220 m^2 Unconditioned Building Area: 110 m^2 Number of thermal zones: 2 Number of floors: 2		Total Building Area: 2899 m^2 Net Conditioned Building Area: 2007 m^2 Unconditioned Building Area: 892 m^2 Number of thermal zones: 20 Number of floors: 3
Characteristic	**Miami**	**Baltimore**	**Chicago**

Thermal transmittance (overall heat transfer coefficients)	Exterior wall: 0.5322 W/(m^2 K) Exterior floor on the ground SF: 1.702 W/(m^2 K) Exterior floor on the ground MF: 0.4 W/(m^2 K) Ceiling SF: 0.213 W/(m^2 K) Ceiling MF: 0.1983 W/(m^2 K) Exterior Roof: 5.358 W/(m^2 K)	Exterior wall: 0.5322 W/(m^2 K) Exterior floor on the ground SF: 1.702W/(m^2 K) Exterior floor on the ground MF: 0.291 W/(m^2 K) Ceiling SF: 0.1787 W/(m^2 K) Ceiling MF: 0.1593 W/(m^2 K) Exterior Roof: 5.358 W/(m^2 K)	Exterior wall: 0.3837 W/(m^2 K) Exterior floor on the ground SF: 1.702 W/(m^2 K) Exterior floor on the ground MF: 0.1944 W/(m^2 K) Ceiling SF: 0.1787 W/(m^2 K) Ceiling MF: 0.1593 W/(m^2 K) Exterior Roof: 5.358 W/(m^2 K)
Window glazing	U-value 6.813 W/(m^2 K) g-value 0.3344	U-value 2.271 W/(m^2 K) g-value 0.3344	U-value 1.987 W/(m^2 K) g-value 0.3344

2.2.2. Simulation results of the base case models

Figure 1 shows a comparison between the annual total site energy and the annual total heat emission by components. The highest values for both the annual site energy for the two types of buildings are registered for the climate of Chicago. An opposite trend for the heat emission is registered with the highest heat emission to air for Miami. For all cases the heat emission is larger than the site energy by an average factor of 3.2, but with the highest peak of 6.2 for the Miami SF case and the lowest of 2.0 for the Chicago MF case. On average the lowest ratio is registered for Chicago, in which the heat emissions are 2.5 times the site energy, the highest is registered in Miami (an average of 4.9 times), and a medium is registered for Baltimore (an average of 2.8 times). The Annual Site Energy of the SF houses, with an average of 430.64 MJ/m^2 equivalent to 119.6 kWh/m^2, is lower than those of the MF models, with an average of 523.2 MJ/m^2 equivalent to 145.3 kWh/m^2.

In general, the SF detached house shows a higher share of heat emission from the envelope. This is due to the highest envelope-area-to-volume ratio. The envelope component, on average, accounts for 72% of the total heat emission, with the highest 80% for the Miami SF model and a minimum of 63% for the Chicago MF model. The Exfiltration component accounts for an average of 8.6 % with a minimum of -9% for the Miami MF model (negative because during summer the outdoor air enthalpy is higher than the exhaust air), and a maximum of 22% for the MF model of Chicago. The HVAC reject component accounts for an average of 19.1 %, with a minimum value registered for the Chicago SF model of 9.6 % and a maximum of 39% for the Miami MF model.

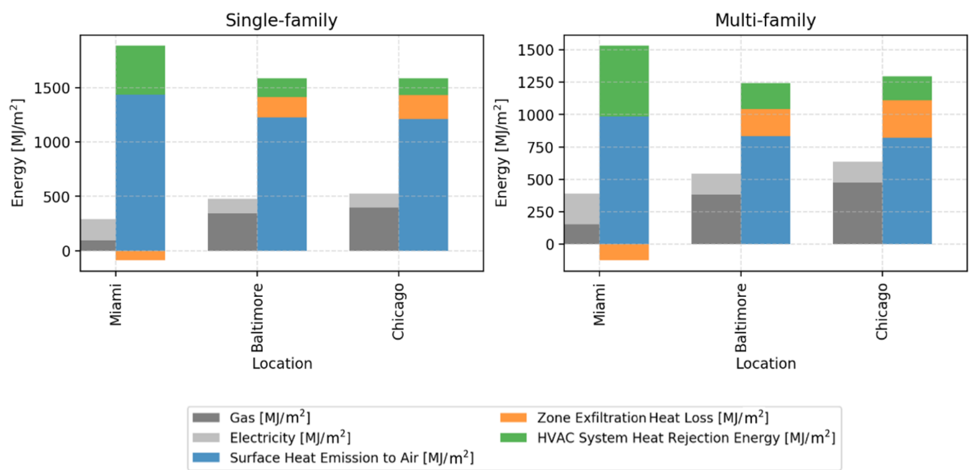


Figure 1: Yearly simulation results of the base case models regarding the site energy and the heat emission by component

To better understand the dynamics of the heat emission from buildings, in *Figure 2*, the monthly heat emissions from the base case are reported. In all cases, the heat emissions increase during summer. This confirms the idea that the higher the solar radiation and/or the outdoor temperature, the smaller will be the Zone exhaust/exfiltration air and HVAC relief air heat emission components, but the envelope component will be larger [24]. The Miami models are characterized by a flatter monthly curve; this is because the different components play negative and positive roles in the total heat emission, thus, a balance is reached. Generally, for the building typologies characterized by this trend, the peaks of heat emission are registered around July, while for Miami, the highest peak is reached in August. The site energy for the case study of Miami is quite flat because its weather is quite constant all over the year (with maximum difference between monthly averages of 9°C). Baltimore and Chicago, characterized by more defined seasons, show large differences in terms of site energy, especially in the gas use (used to heat the internal spaces). For all the models a slight increase in electricity consumption due to the cooling system activation is registered in the warmest month. For all models the heat emission from the building is always larger than the site energy. Only for the months of January and December for the Baltimore and Chicago models, the two values are comparable.

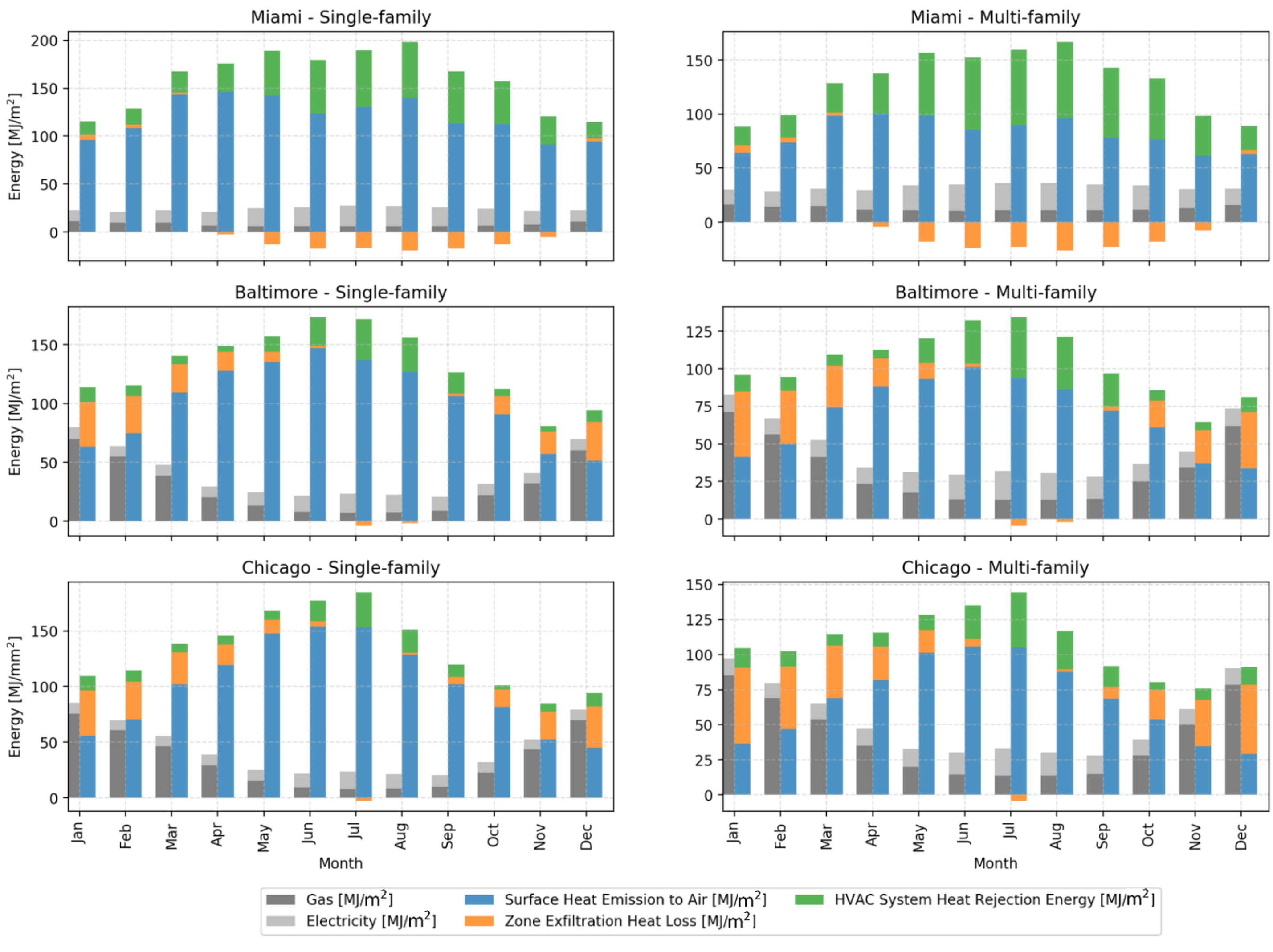


Figure 2: Monthly simulation result of the base case models regarding the site energy and the heat emission by component

2.3. ECMs scenarios

We chose a suite of typical ECMs in residential buildings, listed in *Table 3*, to implement in EnergyPlus, representing energy retrofits. Particularly, they are divided into four main categories that impact differently on the heat emission components: internal loads, envelope, systems, and occupants' behaviour. The first one includes two ECMs that aim to decrease the internal loads of the building, corresponding to a plug load upgrade (usually due to renovation of the electric appliances) and the replacement of the existing lights with a more efficient one (e.g., LED lights). Even if they will have an overall effect on all the components, the direct and main impact of these ECMs is on the HVAC component, because the systems will use more energy during the heating season and less during the cooling one to maintain the comfort conditions. The second category regards the envelope. Four ECMs are implemented: application of 20 cm of the high-resistivity insulation layer, application of high reflectivity coatings on the exterior surface of the building, the replacement of the window, and the addition of air sealing to decrease the infiltration rate. The first three have a direct impact on the HVAC and Envelope components because they change the energy balance of the exterior constructions. While the change in the infiltration rate changes the HVAC and Zone components because it decreases the airflow exchange directly between inside and outside. The third category regards the systems. Four common ECMs are developed: improving the insulation of the water tank, increasing the efficiency of the cooling and heating system, and upgrading the whole system to a heat pump with an electric water heater. Of course, all these ECMs will have a direct impact on the HVAC component of the heat emission. The last category simplifies the modelling of energy-aware occupants modifying the basic parameters related to indoor thermal comfort. In particular, the thermostat setpoint is adjusted to 19 °C for heating and 26 °C for cooling, a thermostat schedule is added, and the natural ventilation is decreased according to the occupancy schedule. The first two ECMs regarding occupants changing the indoor comfort conditions, thus, they impact on all the heat emission components. While the change in natural ventilation, as the change in the infiltration rate, impacts the HVAC and ZONE components.

Table 3: Common Energy Conservation Measures used in the residential sector

List of implemented ECMs			**Direct influence on:**	**Implementation in EnergyPlus**	**ECM code**
Internal Loads	Plug Loads	Plug Load Upgrade	HVAC	-25% Electric Equipment loads	ECM 1
	Lighting	Replace existing lighting	HVAC	-25% Lighting loads	ECM 2
Envelope	Opaque	Apply Insulation	HVAC + ENVELOPE	Add 20 cm of R30 insulation to Exterior Wall, Exterior Floor, Exterior Roof	ECM 3
		Apply Cool Wall Coating	HVAC + ENVELOPE	Add High Reflectivity coating (Absorptance = 0.2) to Exterior Wall, Exterior Floor, Exterior Roof	ECM 4
	Windows	Replace window	HVAC + ENVELOPE	U-factor = 0.25 W/m2K and SHGC = 0.2	ECM 5
	Infiltration	Add Air Sealing to Seal Leaks	HVAC + ZONE	Drop to 0.3 ach the infiltration rate respect to Baseline changing the effective leakage area	ECM 6
Systems	Service Hot Water	Improve Water Tank Insulation	HVAC	Decrease to 1.23 W/K the Off/On Cycle Loss Coefficient to Ambient Temperature	ECM 7
	Cooling	Efficiency upgrade	HVAC	Gross Rated Cooling COP = 5	ECM 8
	Heating	Efficiency Upgrade	HVAC	Burner Efficiency of Coil:Heating: Fuel = 0.92	ECM 9
	Whole System	Heat Pump	HVAC	Substitute the Heating, Cooling system with a Heat Pump and Electric Water Heater	ECM 10
Occupants Behaviour	Comfort	Increase comfort dead band	HVAC + ZONE + ENVELOPE	Heating setpoint = 19 °C, Cooling setpoint = 26 °C	ECM 11
		Thermostat schedule	HVAC + ZONE + ENVELOPE	19/26 until 9:00, 15/30 until 17:00, 19/26 until 24:00	ECM 12
	Ventilation	Natural Ventilation schedule	HVAC + ZONE	Ventilation is decreased according to the occupancy schedule	ECM 13

A code is assigned to each ECM (last column of *Table 3*), and they are combined to produce energy conservation scenarios reported in *Table 4*. To each of these scenarios, a short name is assigned that will be used in the presentation of the results. In particular: LOAD is a case in which the two ECMs decreasing the internal loads are combined, INSUL is the case with the application of the insulation and replacement of windows, COOL represents the case with the high-reflective coatings on exterior constructions (i.e., called cool coatings), EXF is the case with the addition of Air Sealing to Seal Leaks, SHW regards the case with the increase of insulation of the water tank, CS and HS are two cases with the increase in efficiency of the Cooling and Heating system respectively, HP is the case with the installation of a Heat Pump, OB regards the modelling of energy-aware occupants. Finally, the last case "ALL" is the combination of all the ECMs to be compared with the base case scenario to understand the potential impact of the heat emission from the building to ambient air.

Table 4: Combinations of the Energy Conservation Measures in cases

ECM code	Case 1 LOAD	Case 2 INSUL	Case 3 COOL	Case 4 EXF	Case 5 SHW	Case 6 CS	Case 7 HS	Case 8 HP	Case 9 OB	Case 10 ALL
ECM 1	X									X
ECM 2	X									X
ECM 3		X								X
ECM 4			X							X
ECM 5		X								X
ECM 6				X						X
ECM 7					X					X
ECM 8						X				
ECM 9							X			
ECM 10								X		X
ECM 11									X	X
ECM 12									X	X
ECM 13									X	X

3. Results

The first aim of the analysis is to directly compare the reduction of heat emission and site energy savings of each ECM. The purpose is to understand if the change in site energy is directly correlated with a proportional decrease in heat emissions from the building to ambient air.

Figure 3 collects the ratios between resulting site energy and heat emission of the cases with the implemented ECM and the base cases. In general, with exception of Case 3 (reflective coatings), for a decrease in site energy, a smaller decrease in heat emission is registered. However, the extent of these decrements is different. They range from a relatively null impact (i.e., Case 1, Case 5 and Case 6 and 7, respectively, a decrease of the internal loads, the improve water tank insulation and the systems efficiency upgrade) to quite effective strategies (e.g., Case 8 and Case 9, respectively, installation of a Heat Pump and energy-aware occupants). Some of the Miami Cases (e.g., 1,4,5,6) are characterized by a site energy ratio of around 0.91-0.95. It means that the implemented ECMs bring to a saving in the site energy of around 5-10%. This, in terms of heat emission, corresponds to smaller decreases (around 1-3%). Other Miami Cases (e.g., 8 and 9), even if have a larger impact on the site energy (around 20-25% of decrease), show a heat emission decrease around 3-7%. While Case 7 does not have a strong impact on the site energy (0.99 ratio) nor on the heat emission (ratio of 1, meaning no significant reduction). All the general trends are confirmed also for Baltimore and Chicago. The use of a heat pump is more effective in Baltimore climate than Chicago, but for both cases the effect is much larger than for Miami with least heating loads or lowest HDD.

Case 3, the implementation of high reflective coatings on the exterior surfaces, has a different result from all the other cases. This ECM, in all models, does not show a significant reduction in the site energy (even an increase for Baltimore and Chicago models). However, it has a large positive impact on heat emissions. The reduction is, on average, around 26% for the SF models and around 36% for the MF models. However, in this study, an overestimation of the positive effect of the cool coatings can be expected. The models are set in an open field, without considering other surrounding reflecting or shading buildings or objects (e.g., trees, vehicles, streets, etc.). In a more complex environment, especially with the massive use of reflective coatings, a large amount of radiation reflected from other buildings or objects could reach the modelled building, changing its energy balance. Moreover, the surface fouling of the reflecting coatings should be taken into consideration if proper maintenance is not guaranteed, causing an increase of absorptance. By consequence, the radiation that the building in an urban context receives from the environment is not just solar radiation, but it could be far more complex than in the open field. Particularly, if all the surrounding buildings make use of cool roofs and walls the result could be very different from the currently simulated. This is a limitation of the current study that can be addressed in the future with simulations of heat emissions from buildings in an urban environment considering inter-building effects.

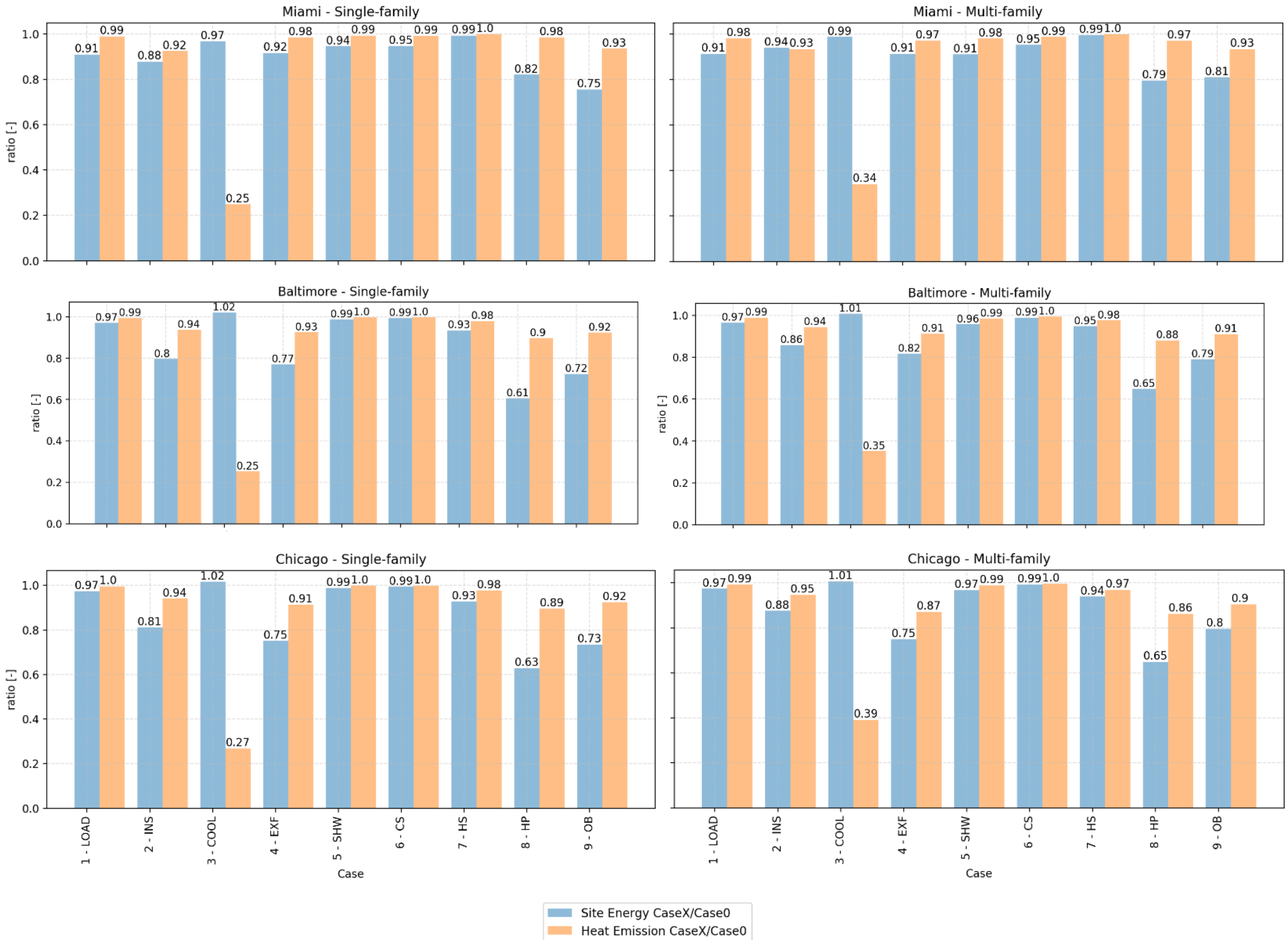


Figure 3: Comparison of the different cases with the base case, it shows the ratio of the case with the implemented ECM and the base case for the site energy and the heat emission.

To better understand not only the impact of each ECM on the annual results but also how they change the heat emission mix, *Figure 4* shows the components that form the total annual heat emission. A few ECMs change drastically the components mix of the heat emission. Case 3 (cool coatings) shows that the envelope component is greatly reduced due to the reflection of most solar heat by the exterior surfaces which cools down the exterior surfaces. This means that the temperature of external surfaces is, on average, very similar to that of the ambient air. For Miami, another ECM that changes the mix is the energy-aware occupants, increasing the zone exfiltration heat emission and decreasing the HVAC reject heat emission. In particular, the components related to the zone exfiltration are almost zero due to a wider indoor temperature comfort range. This means that the condition of the internal air is very similar to the ambient air and this is visible also in the decrease of the HVAC related emission (i.e., due to the consequent decrease of cooling the internal spaces). Lastly, for colder climates (i.e., Baltimore and Chicago), the installation of a reversible heat pump decreases sensibly the heat emissions from the HVAC component, bringing it to zero for the Chicago climate. This is because, in a year, negative and positive values of these components are present, thus, the final annual heat emission results in a small number.

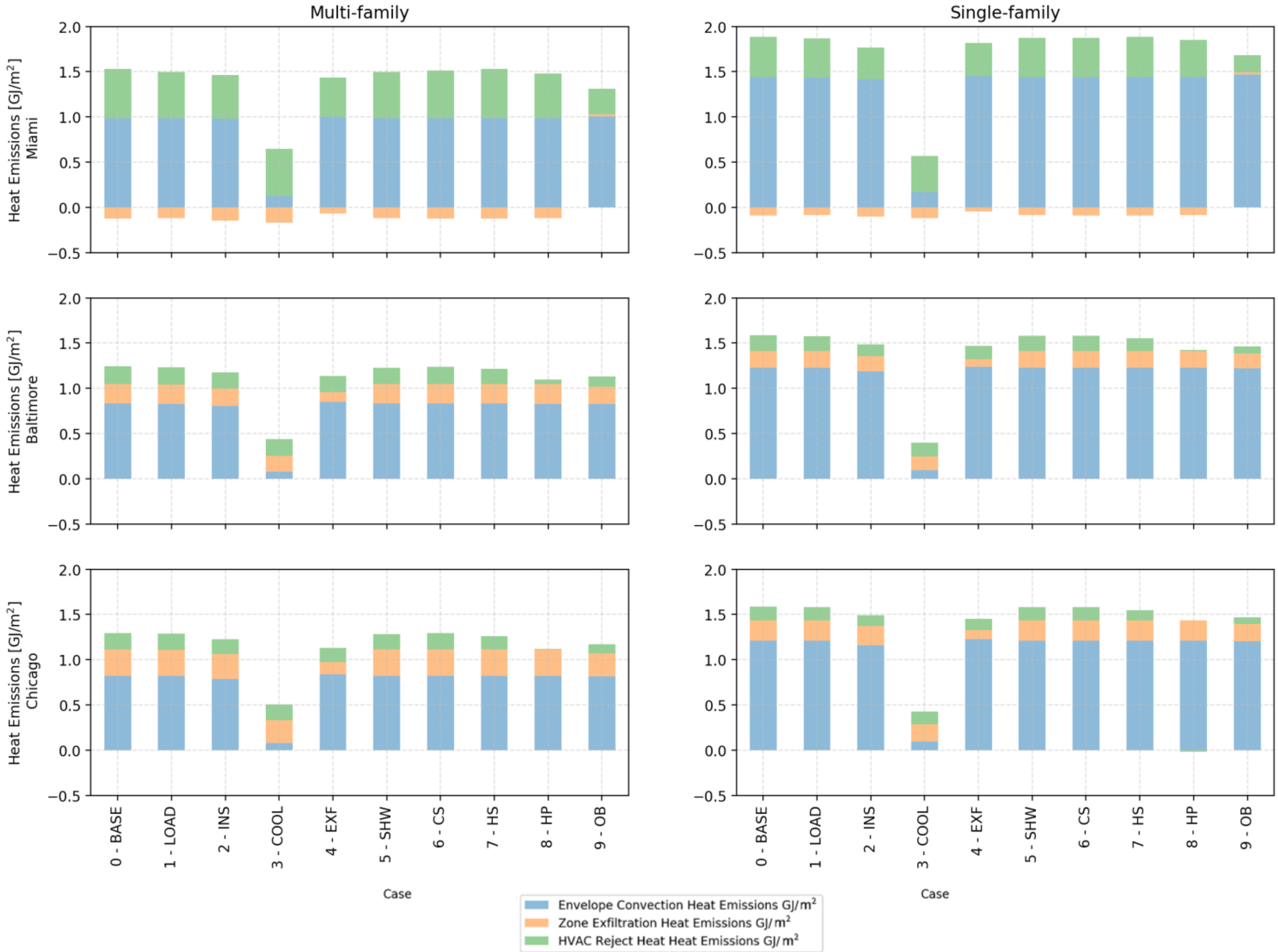


Figure 4: Annual heat emissions by components

To better understand sub-yearly dynamics of the heat emission, *Figure 5* and *Figure 6* show the monthly heat emission by component for Case 3 (cool coatings) and Case 8 (heat pump).

Figure 5 shows that the heat emission from the envelope increases with the increase of solar radiation. The result is that Miami has a higher heat emission from the envelope component respect to Baltimore and Chicago. Between Baltimore and Chicago, the differences are small and related to monthly values due to the very similar latitude of the two cities (39° and 41° respectively). This is evident also in the comparison between summer and winter months, with the highest share for the envelope component during July and August. This is registered for both Case 3 and Case 8, however, in Case 3, the monthly winter values are lower than zero (showing net heat absorption especially for Baltimore and Chicago cases). The negative value means that the surface temperature is lower than the outdoor one. This can happen during the winter months in which the sun directly heats the exterior envelope just for a few hours a day, and the solar altitude is lower, bringing to weaker solar radiation. The high-reflecting coating changes the heat balance of the envelope, it reduces the heat absorbed and transmitted by the construction and the resulting surface temperature is lower than in the base case. When then the outdoor temperature is higher than the surface, the heat emission has a negative value (i.e., there is a gain of heat from the outdoor air towards the building).

The zone exfiltration heat losses do not change greatly comparing Case 3 and Case 7 and remain very similar to the base case (*Figure 2*). This is because the Zone component heat emission is due to the difference in enthalpy between the internal and external air. The internal conditions are mostly maintained at the same level (the comfort of the occupants), and so the external climate, and thus the resulting heat emission. A trend is registered within months: the summer months have negative or low heat emission from the envelope, meaning that the enthalpy of the external air is higher than or equal to the one of the internal air. While the winter months register higher heat emissions for this component. Chicago registers higher heat emissions related to the zone component respect to Baltimore, since, on average, Baltimore has a warmer climate than Chicago. The trend between Baltimore and Chicago, for this component, makes it clear that the zone component is more correlated to the temperature of the air than to the solar radiation.

Lastly, the HVAC component is related to the use of heating and (especially) cooling systems throughout the year. For Case 3 (*Figure 5*) characterized by gas furnace as heating system, but also for the base case (*Figure 2*), the maximum values for heat emission by HVAC in all the models are registered in the summer months. Specifically, for Miami (a fully cooling-dominated climate), whereas the minimum values are registered for the winter months (i.e., January, February, and December). For Baltimore and Chicago, the minimum values are during the spring and autumn months (i.e., March, April, September, and October) and then a further increase for the winter months. The general trend is respected also for the heat pump (Case 8, *Figure 5*). The heat pump (Case 8, *Figure 5*) decreases the heat emission from the HVAC component during the winter in all models. It brings to negative values during the winter cold months in Baltimore and Chicago climates.

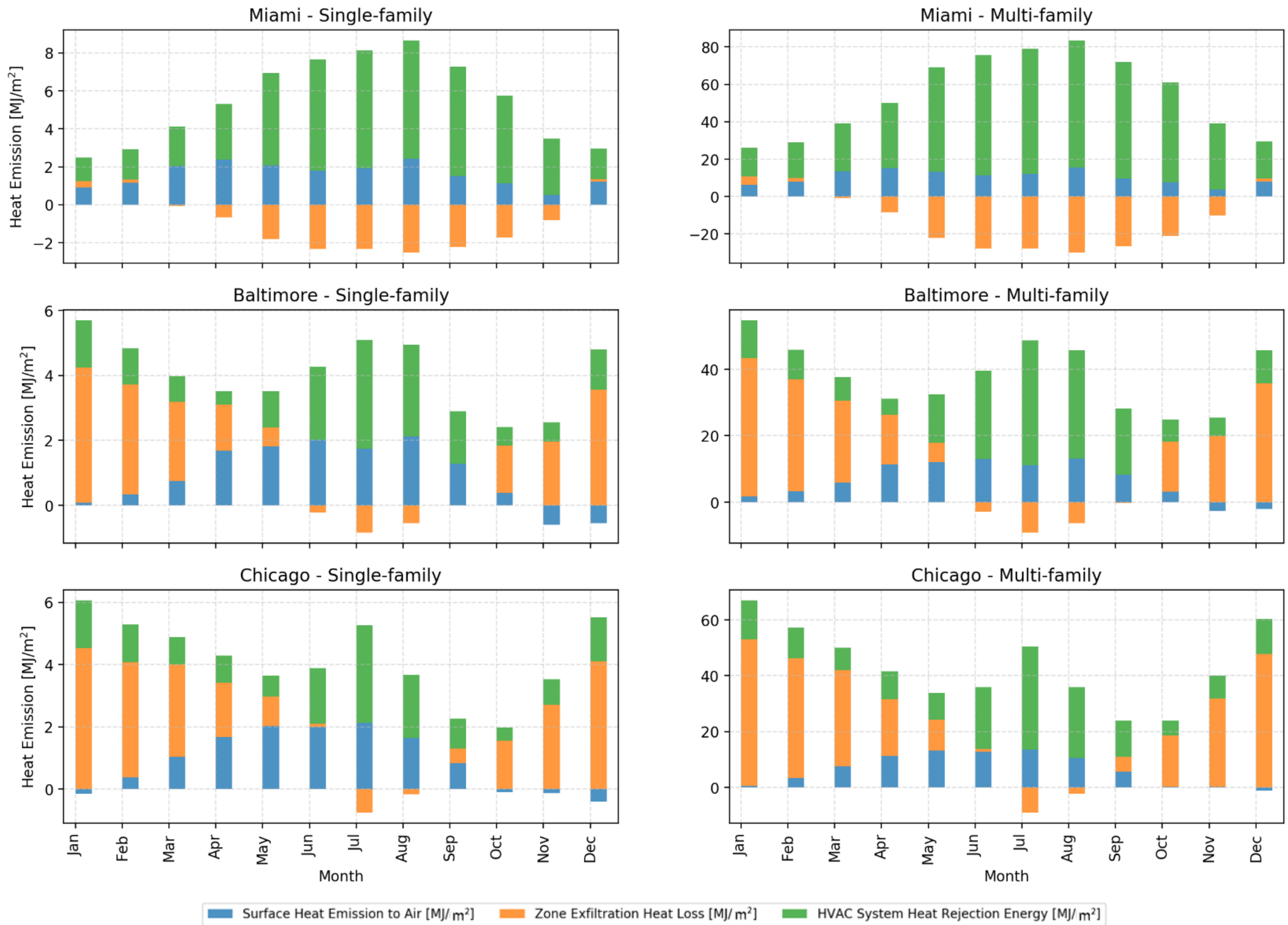


Figure 5: Monthly heat emission by component for Case 3

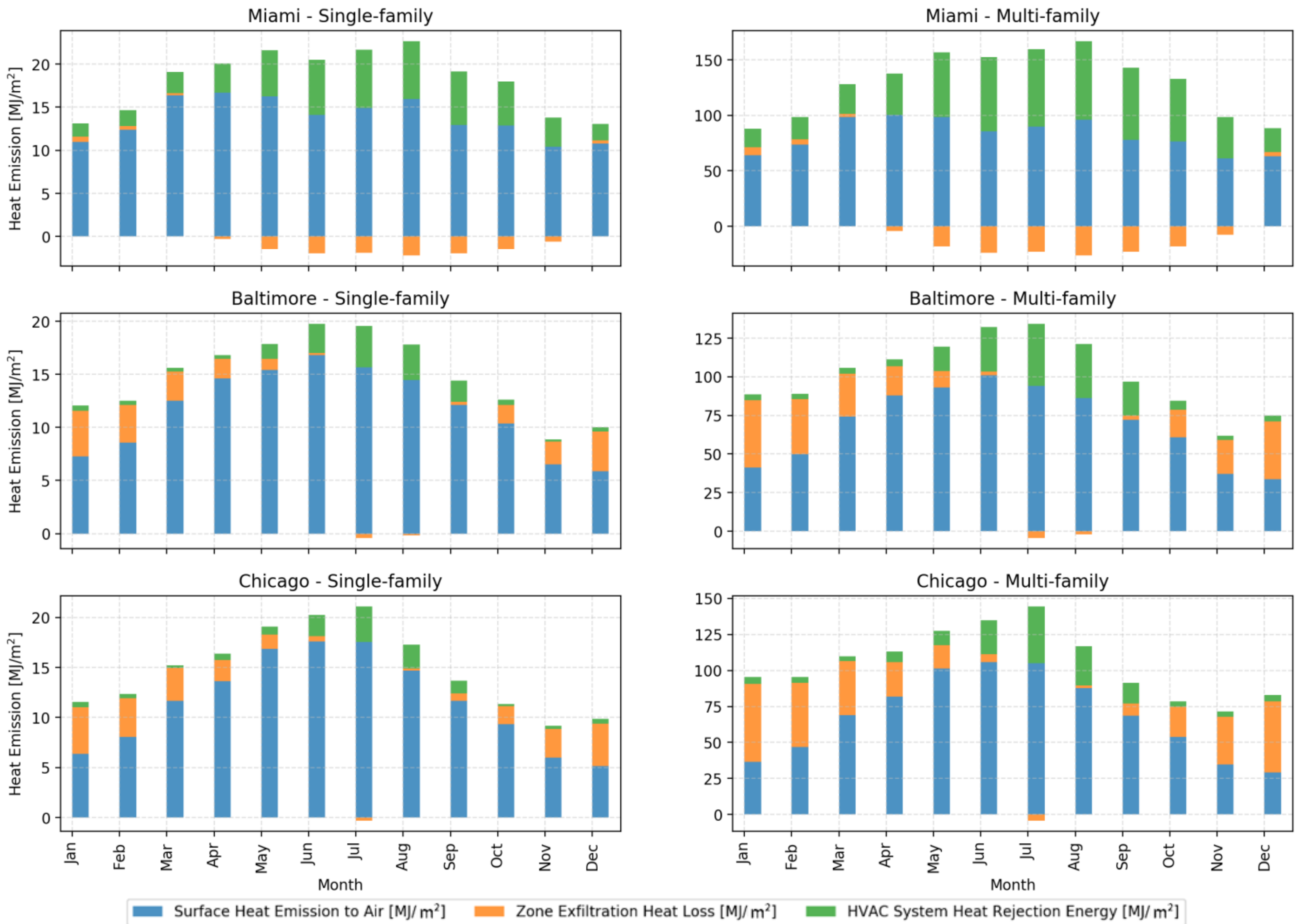


Figure 6: Monthly heat emission by component for Case 7

4. Discussion

4.1. Annual considerations

As a summary of the results, in *Figure 7*, the rank by impact (calculated as the ratio respect to the base case, resulting from *Figure 3*) on heat emission of different ECMs is plotted. In *Figure 7A*, all the cases are shown separately, while in *Figure 7B* the rank is grouped "as an average" by climate. The rank can be used to understand which ECMs are of priority in reducing heat emissions across different climates and different typologies of residential buildings (the lower the rank, the larger the impact on the reduction of heat emissions).

Case 1 (decrease of internal loads) has a small effect both on the energy and heat emission point of view. However, in the climate of Miami, its influence is larger, with 6th rank compared to 7th for Baltimore and Chicago (*Figure 7B*). This is because, in a cooling-dominated climate, the reduction of internal loads does not only decrease the direct electric load of the building due to the more efficient appliances and lighting but also, decreases the energy needed to cool the building. For the same reason, the effect on a cooler climate, such as the one of Baltimore and Chicago, is almost irrelevant due to the opposite effect of decreasing the internal loads in the different seasons (it brings to an increase of the heating energy needs and a decrease of cooling needs). Case 2, additional insulation on the external walls, has a significant impact from an energy point of view, and in terms of heat emissions (3rd, 4th, and 5th rank in *Figure 7A*). The climate of Miami has a large impact in terms of heat emissions, even if from an energy perspective it is the climate with a lower impact. Adding insulation for external walls is one of the ECM that can be considered effective also from a heat emission perspective.

Its effect is mainly related to the decrease in the HVAC component of the heat emission, due to the strong reduction in their use. Case 3, use of cool roof and cool walls, is the ECM with the largest impact on heat emissions. However, it has a positive effect on the site energy only for the cooling-intensive climate of Miami and a negative effect for Baltimore and Chicago. It sharply decreases the heat emission in all climates and thus it is always the 1st ECM in terms of rank. Even if, as specified in Section 3, its effects in an urban context should be studied more in detail, it is surely an ECM that should be exploited more also to mitigate UHI and urban overheating, as already underlined in the literature [12,47]. Case 4, a decrease of the exfiltration due to air leakage, shows a higher impact in the colder climates of Baltimore and Chicago (3rd and 4th rank respectively) than for Miami (5th rank). It does not show differences between SF and MF, because it is related to the difference between the ambient air conditions and the indoor ones (directly related to the comfort temperature setpoints). For cold climates, it is definitely an effective strategy to mitigate heat emission. Case 5, improvement of the water tank insulation, does not show a significant impact. It is slightly more relevant for the MF than SF models (2 ranks better in every climate). Case 6 and 7, the slight improvement of the efficiency of the cooling and heating system, show a small effect. Case 6 is more relevant for the Miami models (8th rank), while Case 7 is more relevant for Baltimore and Chicago models (6th rank). This ECM could have strong effects when the pre-ECM model has poorer efficiency systems than the used models. Case 8, installation of the heat pump and electric boiler, has a strong impact especially for Baltimore and Chicago climates in which the gas furnace is more used. It is an effective strategy with positive effects in all climates (4th rank for Miami and 2nd for Baltimore and Chicago). It has also a significant impact on the site energy (*Figure 3*), thus, it can help to reduce both energy consumptions and heat emissions. Finally, Case 9, has a decisive impact on the reduction of both site energy and heat emission (2nd, 3rd, and 4th rank respectively in the climates of Miami, Baltimore, and Chicago). This is due to the fact that occupants use setpoint levels more similar to the external environment, decreasing drastically the zone components heat emissions and the use of the systems (with the consequent decrease in the HVAC component). This ECM, even if in the residential sector is not easy to achieve, shows the potential to increase sensibility in occupants for an energy-aware use of their buildings, but also the effect on simulations on different methods to model occupants that should be accounted and done more realistically [48].

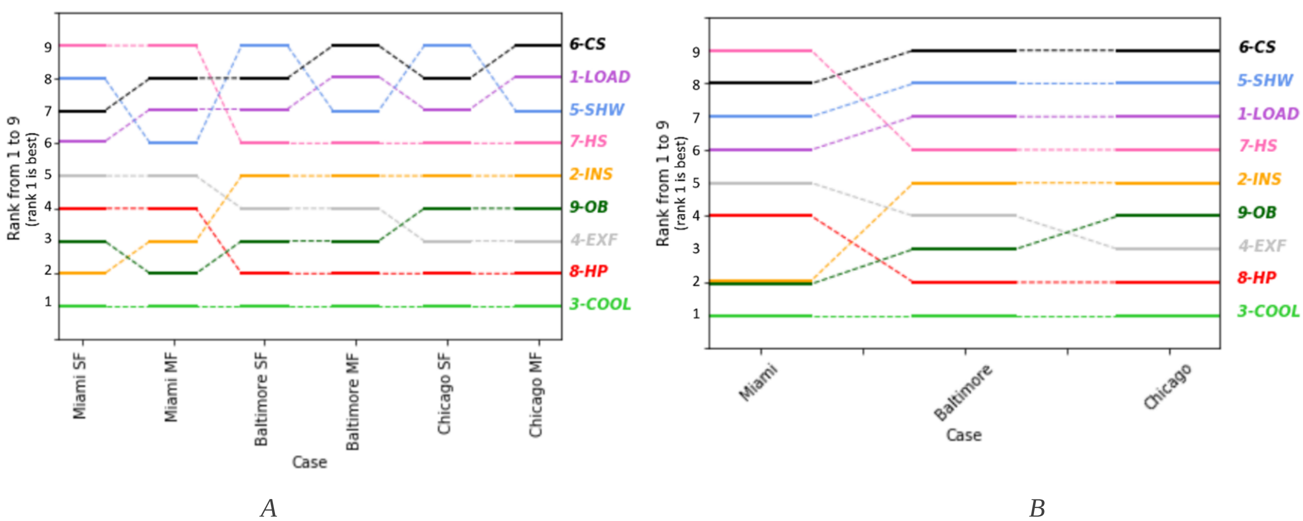
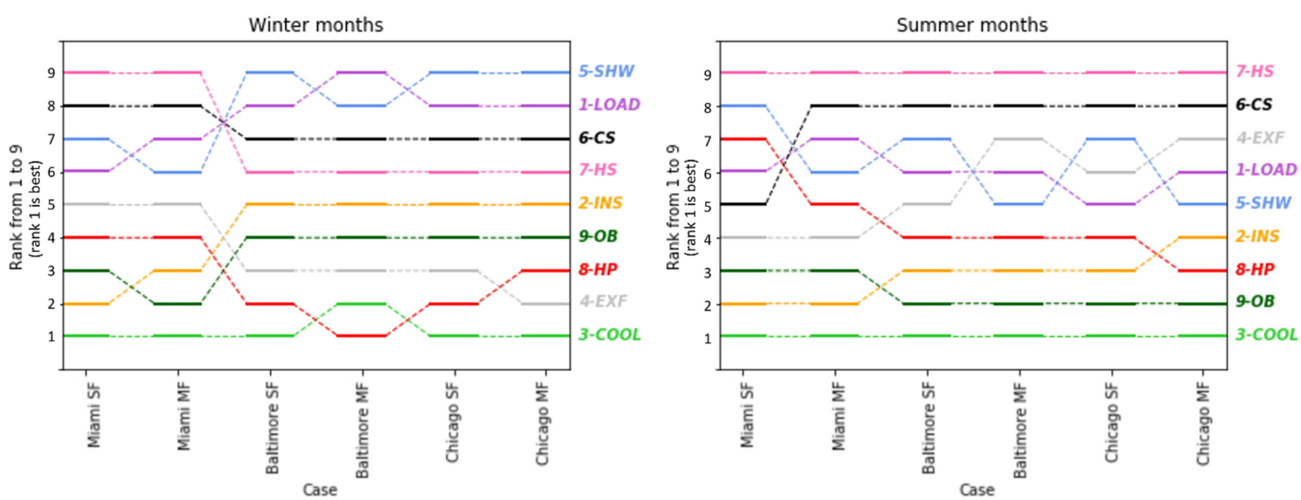


Figure 7: Rank from 1 to 9 of the ECMs based on their impact on the heat emission on annual results, (A) each case separately, (B) by climate

4.2. Seasonal considerations

Some ECMs show a clear difference when applied to the cooling-intensive climate of Miami with respect to the mild climates of Baltimore and Chicago. For this reason, some seasonal considerations are carried out (*Figure 8A* and *8B*), looking at the rank only for the winter period (i.e., January, February, and December) and the summer period (i.e., June, July, and August). In general, fewer differences are registered seasonally for the Miami models than in Baltimore and Chicago. This is due to the more constant conditions (especially temperature) that characterizes the climatic zone 1A respect to the 4A and 5A. Another general observation is that the ranks of the annual results (*Figure 7A* and *7B*) are more similar to the winter seasonal results than the summer ones (*Figure 8A*). This means that the "winter conditions" are more spread throughout the year, weighting more in the annual results.

Case 1, as already shown in *Figure 7*, has a larger impact on warmer conditions. Thus, its effect in the summer months is more relevant (on average, 6^{th} rank in summer and 8^{th} in winter). Overall, its effects are stronger for the MF models than SF ones. Case 2 shows a stronger impact in summer than winter, and also for Miami than for Baltimore and Chicago. It decreases greatly the HVAC component, due to the lower amount of energy needed to maintain the internal comfort conditions. Case 3 is the most impacting ECM reducing the envelope component of the heat emission drastically. It is the 1^{st} ECM in terms of rank both in winter and summer in all models except for the Baltimore MF case, in which Case 8 has larger effects. As suggested also from the annual results (*Figure 7*), Case 4 has greater effects in colder conditions, thus in winter more than in summer, and in Chicago and Baltimore climate more than Miami. In particular, for the winter Chicago climate, this ECM shows to be very effective (2^{nd} rank). Case 5 shows a good rank for the summer climates of Chicago and Baltimore, with better results than other ECMs like Case 4, 6, 7 and, in some cases, even Case 1 (internal load decrease). Case 6 and 7, also from the seasonal point of view, result in smaller effects than other ECMs. However, the heating system upgrade is more effective in the winter months (except for Miami that does not have a typical heating season) and vice versa for the summer. Particularly, for the SF Miami model, the cooling system upgrade is the 5^{th} ECM in terms of ranks. Case 8 is more effective during the winter months because it substitutes the gas furnace heating system. In particular, it looks effective for the Baltimore models. During summer it looks more effective for the Chicago models and far less for the Miami ones. Finally, Case 9, shows to be effective especially for the summer months and Chicago and Baltimore climate. Its rank is always quite low (from 4^{th} in the winter months and to 2^{nd} during the summer ones).



A

B

Figure 8: Rank from 1 to 9 of the ECMs based on their impact on the heat emission on annual results, (A) for the winter months (January, February, December), (B) for the summer months (June, July, August)

4.3. Combination of all ECMs

To define the potential of all ECMs combined, Case 10 is run. *Figure 9* shows the yearly results of Case 10. For the SF detached house, the final heat emission corresponds to 5.1%, 7.2%, 7.0% of the initial (base case) emissions for the weather of Miami, Baltimore, and Chicago respectively. For the MF building, the values are 19.0%, 14.0%, 13.3% with respect to the base case. For the Miami models, the Zone component is almost zero, while for the Baltimore and Chicago models the surface and HVAC components decreased drastically. While, for the SF models, the final site energy corresponds to 39.6%, 28.6%, 28.8% of the base case. The MF models showed a decrease of 43.2%, 36.1%, 34.2% respect to the base case. No gas use is registered, this is because the heat pump and the electric water heater are installed. With the implementation of electricity production on-site (e.g., photovoltaic and solar panels), also the site energy could greatly decrease. The combination of different ECMs, bring to strongly negative (heat absorption) values of some components that bring to almost null changes to total values.

Figure 10 plots monthly results of the different models for Case 10. For different months and type of building, some components result in negative values. In the SF Miami model, the HVAC component is always negative and for the summer months (from May to October) also the Zone component is negative, while the envelope component is always positive. On the other hand, for the MF building, the same range is registered for the envelope and zone components. However, the HVAC one is never negative, due to the higher cooling load absorbed by the heat pump. Baltimore and Chicago climates do not show a large difference comparing the SF and MF models. In both cases, negative results are registered for the colder months (January, February, March, October, November, and December) for the surface and HVAC components. However, these are the months less affected by UHI and heatwaves, thus, this negative effect is relatively less important. The Site Energy regards only electricity, because of the installation of the reversible electric heat pump and the electric water heater, and an average decrease of 64.9 % respect to the base case.

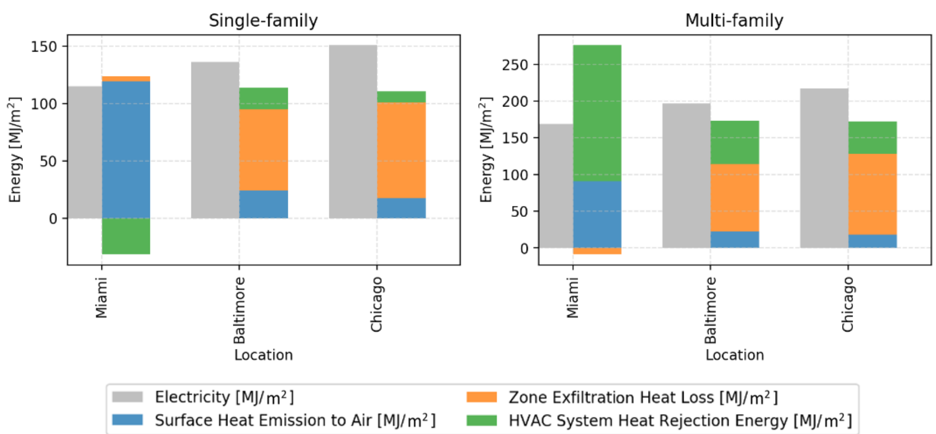


Figure 9: Yearly simulation results of Case 10 (a combination of all ECMs) regarding the site energy and the heat emission by component

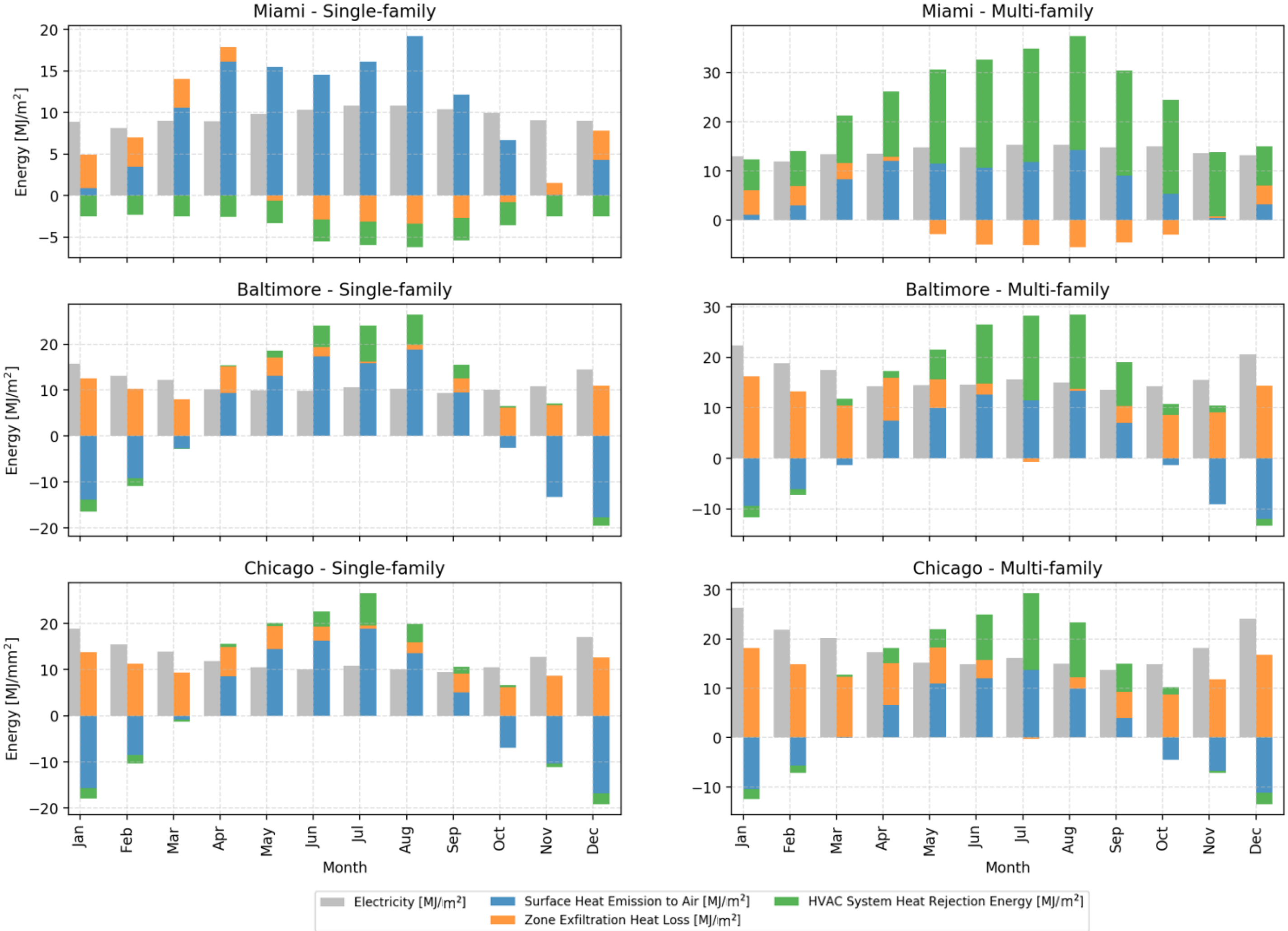


Figure 10: Monthly simulation result of Case 10 (a combination of all the ECMs) regarding the site energy and the heat emission by component

4.4. Diurnal considerations

To study more in detail the dynamics of the heat emission during a typical summer day, the hourly main weather variables and simulation results for the SF model in Miami on the hottest day (29th of July) regarding the heat emission by component for Case 3, Case 9 and Case 10 are plotted in *Figure 11*. The three cases are chosen to be, respectively, the case with the highest decrease of heat emission, the case with the highest decrease in energy consumptions, and the case with all the ECMs combined. *Figure 11A* reports, as a reference, the three main weather variables, dry bulb temperature, relative humidity and the total solar radiation on the horizontal plane. Case 3 (*Figure 11B*) shows a strong decrease in heat emissions from the envelope component during the daytime hours (on average -81% from 9 am to 5 pm) thanks to the application of high reflective coatings on the outer surfaces. During these hours a decrease for HVAC and zone components are also observed (i.e., respectively on average 8% and 59%), due to the decrease of the cooling load and different internal air condition. During the night hours, the heat emissions are equal to Case 0. Case 9 (*Figure 11C*) shows a net decrease in heat emission from the HVAC components (on average 52% from 9 am to 5 pm) while the Zone exfiltration component shows an increase of 114%. This is since the setpoint is increased (thus, the emission via exfiltration increases), the schedule of system operation (mainly from 5 pm to 9 am during the night) decreases the HVAC load, reducing the related heat loss component. The surface component does not show relevant differences with Case 0 (on average a decrease of 1% during the daytime hours). Finally, Case 10 (*Figure 10D*), shows a decrease in heat emissions from the surface and HVAC components (respectively on average 80% and 92% from 9 am to 5 pm), but a slightly increase in the Zone component (+ 88% during the day hours). The decrease in the Surface component is mainly due to the reflective coatings. While the heat emission related to the HVAC component decreases mainly due to all the strategies that are reducing the cooling load and thus the usage of the systems. In particular, for three hours of the day (from 10 am to 12 pm), the heat emission from the HVAC components is null. The slight increase in the Zone exfiltration means that the air exfiltration from inside has a higher enthalpy than Case 0, and this, as for case 9, is related to the new setpoints used.

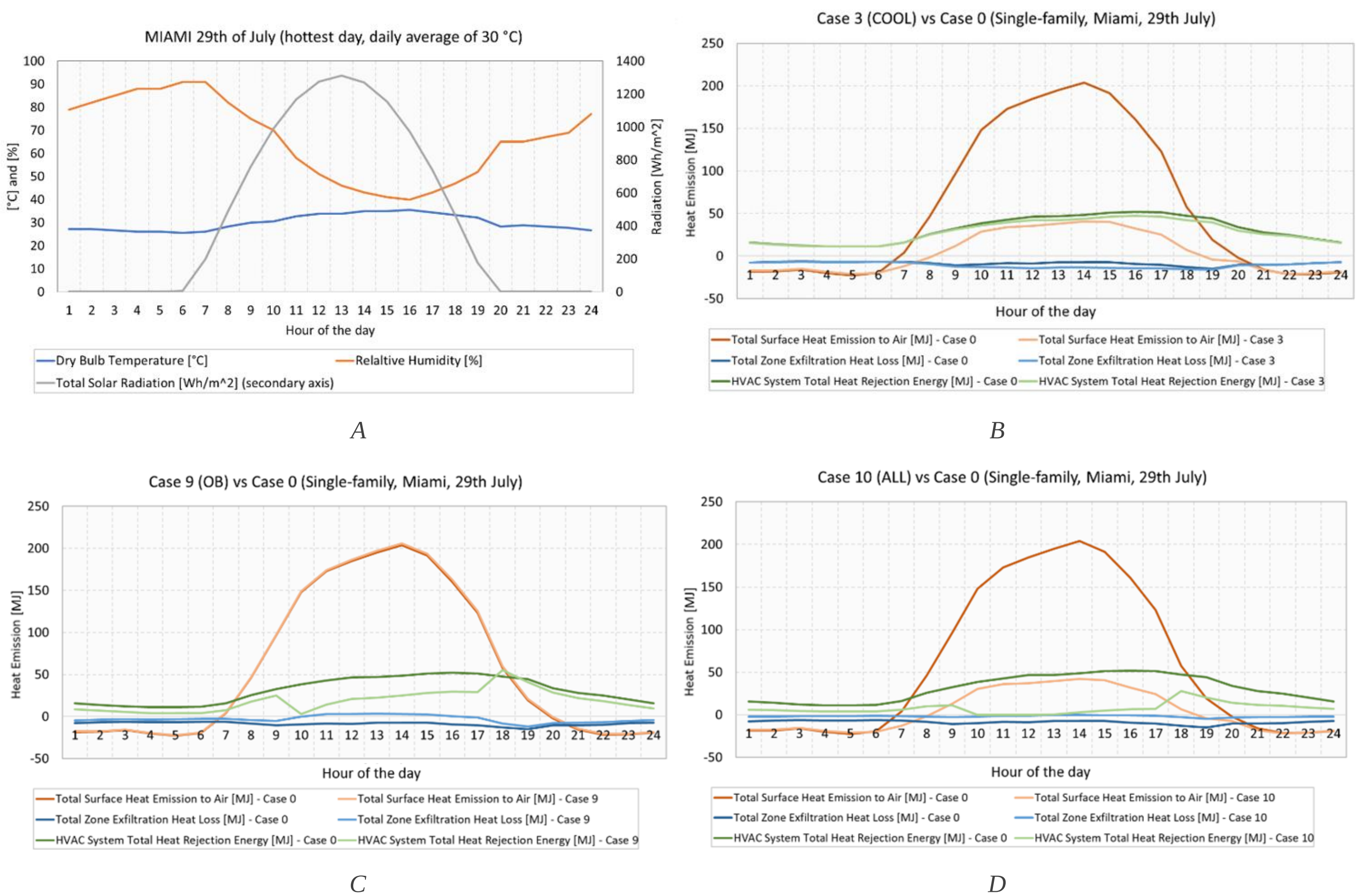


Figure 11: Diurnal hourly main weather variables (A) and simulation results for Single-family model in Miami in the hottest day (29th of July) regarding the heat emission by component for Case 3 (B), Case 9 (C) and Case 10 (D). In each of the B, C and D graphs there is comparison respect to the Case 0.

5. Conclusions and future outlook

This paper aimed to evaluate the impact of energy conservation measures (ECMs), that are traditionally used to reduce energy consumption in buildings, on the heat emissions from buildings to ambient air. Heat emissions from buildings to ambient air form a large part of the anthropogenic heat in the urban environment. This heat leads to urban overheating. Even if this topic is widely addressed in the scientific literature, the calculation method used to assess the heat emission from buildings is usually simplified, and, consequently, less understood.

In particular, this study used the recently developed engineering algorithms implemented in EnergyPlus, to calculate the heat emission from the three main components: envelope, zone, and systems. Hourly simulations are run for a single-family detached house and for a multi-family low-rise apartment building reference models. The simulations are run for three different climatic conditions: Miami, Baltimore, and Chicago. The final aim is to understand which are promising ECMs, able to also reduce heat emissions in different climates.

The results show that, in general, for a decrease in site energy use, a decrease in heat emission is registered. However, this study outlined that large differences and impacts are registered. The performance of the energy conservation technologies varies greatly among weathers, seasons, and, in some cases, among residential typologies. Particularly, some ECMs (i.e., the use of cool roofs and cool walls, the installation of heat pumps, the additional insulation, and, the energy-aware occupants) show a strong decrease in heat emissions, even if they are not always related with a proportional decrease in site energy. Among these three effective ECMs, the use of cool coatings is effective in both winter and summer. While the installation of reversible heat pumps is more effective in winter months and the increase of insulation and the energy-aware occupants more in the summer months. Other ECMs have smaller impacts on the heat emission but each has its peculiarities. For example, the decrease of exfiltration does not register differences between MF or SF models but it registers differences among climates (it is more effective in colder conditions). Whereas the decrease of internal loads has a relatively strong impact in cooling-intensive climates like Miami, especially in the summer months. Finally, when all the ECMs are combined, negative (heat absorption) results are registered and the final impact is larger on the heat emission (a reduction of 89%) than on the site energy (a reduction of 65%) from the base case results.). This effect could be exploited for the hottest months in which the outdoor environment is most affected by the UHI. The mix of strategies can bring to this “absorbing effect”, or, at least, to neutral impact respect to the urban environment. The different ECMs have different impacts on the hourly heat emissions during a hot summer day in Miami. For example, the cool coatings affect only the envelope component during the daytime hours, while the behaviour of occupant changes mainly the heat emissions from the zone and HVAC components. In general, all strategies differ largely from Case 0 during the daytime hours when urban overheating problem is more significant. This means that the ECMs usually used to decrease the energy consumption can be effective also to reduce the heat emissions if they are evaluated using the proposed approach.

The future outlook includes the study of the green roof technologies, several times listed among the most effective UHI mitigation measures [49]. In addition, the same study can be conducted for other building types (e.g., offices, schools, and hospitals) and for more climates or summer heatwaves. A limitation of the present study is the fact that the microclimate surrounding the building is not included in the simulation and that it is fundamental to set the buildings in an urban context to better understand how the implementation of cool roofs and cool walls acts in a more complex urban environment considering the inter-building effect due to solar shading and reflection as well as longwave thermal radiation. However, this study, exploiting the method integrated into EnergyPlus and so in BEM, is a first step of a more detailed and quantitative understanding of the mutual effects on the energy consumption and heat emission using building energy models. This methodology can be directly integrated into urban scale applications based on EnergyPlus (e.g., CityBES [50,51] or umi [52]). This will improve the knowledge and understanding of building technologies and human behaviours in terms of sustainable cities and urban environments. Finally, integration with the discussed heat emission model with an accurate UHI model that includes air temperatures, wind speeds and directions, urban geometry of streets, buildings, terrain and vegetation will be able to better understand the urban overheating phenomena dynamics and its consequences.

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