Minimizing the inconsistencies of urban building energy simulations through strong microclimate coupling

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Georgios – Evrystheas Kyriakodis[1]*, University of La Rochelle / CSTB (France)*
Emmanuel Bozonnet, University of La Rochelle (France)
Peter Riederer, CSTB (France)

ABSTRACT

The impact of microclimate conditions on energy demand is investigated through various coupling schemes between a zonal microclimatic tool and an urban building energy simulation software for a canyon settlement. Additionally, the impact of split air condition units on ambient air temperatures is examined for an annual period. The numerical calculations for a mild oceanic climate confirm the necessity of integrating the microclimate conditions in building energy performance simulations. Air conditioning units, have a significant impact on air temperature both for cooling and heating period. Furthermore, discrepancies emerging from online and offline coupling schemes are highlighted.

Introduction

The increased urbanization of the past decades combined with energy harvesting constructions and huge alterations in land use constitute the base of the local climate change, known as urban heat island (UHI) effect. It deals with the development of higher air temperatures in city centers compare to the rural environment. UHI is experimentally documented for hundreds of cities around the world (Santamouris 2015). Local characteristics and their respective heat sources contribute to the amplitude of the effect (Santamouris et al. 2015). In parallel, energy demand for cooling is the fastest growing end-use in buildings. According to IEA's Tracking Clean Energy Progress 10 air conditioners will be sold every second over the next 30 years.

To this end, particular attention has been paid to the feedback of AC systems on outdoor air temperatures. De Munck (De Munck et al. 2013) demonstrate a coupling scheme between a meso-meteorological model and a single layer-module to account for the built environment, in order to estimate Paris air temperature increase due to air conditioning units. The 6 days' simulation period was chosen for anticyclonic conditions of the 2003's heatwave. The outcomes revealed a maximum of 2°C for the future doubling of air conditioning waste heat released to air. Similarly, Salamanca et al. (2011) integrated a meso-scale with a multilayer urban canopy and a simplified building energy model for the city of Houston (nested area of 110km). The results obtained from a 2-day simulation period, found an increase in night temperatures of up to 2°C. Concerning district scale, a coupled "ping-pong" scheme was developed from Hsieh et al. (2007) based on a BES and a computational fluid dynamics (CFD) code. In this study only five simulation hours where realized during a hot night in Taipei city in Taiwan, although the authors indicated that the maximum measured heat island intensity was depicted at 2pm with a value of 4.9°C. He estimated that the maximum air temperature increase was found to be 1.89°C for a fixed COP value of a window type AC unit. Finally, Wen and Lian (Wen and Lian 2009) developed a

[1] Corresponding Author: gkyria01@univ-lr.fr, gkuriakodis@phys.uoa.gr

mathematical nested urban box model, to correlate the atmospheric stability with the possible air temperature increase due to the fluxes of the AC units injected in the lower level of the atmosphere. In their method building parameterizations were not taken into account. They estimated that air temperature increase could reach 2.56°C and 0.2°C under inversion and normal conditions respectively. These studies could give an estimation about the amplitude of the UHI combined with systems feedback in air temperatures, however they are either temporally limited (from hours to days) either the representation of buildings as cells of coverage ratio do not allow to correlate individual building thermal footprint with the local ambient environment.

The dependency of rising energy demand and local climatic phenomena is demonstrated in various studies. Considerable attention has been concentrated to cooling dominated period, since the phenomenon is much more intense during it. To this end, various numerical approaches and studies arise with the scope of estimating the potential energy loss capture due to the local phenomena. Usually, a Building Energy Simulation (BES) model coupled with a microclimate code is preferred. Martin (Martin et al. 2017), performed a one-way coupling of a lumped thermal parameter model with a BES. The outcomes of this study showed that the divergence between estimates of the cooling demand varies whether detailed and simplified BEMs are run under isolated or non-isolated conditions. Gobakis (Gobakis and Kolokotsa 2017) followed a similar coupling approach between a BES and a microclimate model to study the impact of different convective heat transfer coefficients to a building settlement in the University campus of Chania. In their study showed that cooling demand could vary up to 25%. Another effort to minimize the uncertainties of building energy simulation has been conducted by Allegrini (Allegrini, Dorer, and Carmeliet 2012). In their approach, they examined the variations on energy demand between a stand-alone building and buildings integrated in a street canyon by coupling a 2D CFD code and a BES tool for a moderate climate in Basel, Switzerland. He showed that space cooling demand is higher while space heating demand lower for the street-canyon configuration. He suggested that neglecting UHI effect leads to an important underestimation of the cooling demand. This type of approaches seem capable to serve the concept of Net zero energy buildings (NZEB) however, they are also temporally limited due to the time expensive microclimate simulations (CFD), and also spatially restrained, as they account just for the building scale. Moreover, the offline coupling schemes, could give a general estimation about the actual environmental conditions but crucial information is lost. Considering a district, the site-specific air temperature could significantly vary.

In order to extend the boundaries of the simulation domain, a novel series of coupled models have emerged. Mauree (Mauree et al. 2017), applied a one-way coupling scheme between an UBEM and a 1D meteorological model to study the impact on energy demand when urban climate is taken into account for the EPFL campus. They demonstrated that the wind speed and air temperature deviations compared to a typical dataset, could lead to a reduction of the simulating heating demand error by a factor of 2.

In this framework, we propose a new methodology of a coupling scheme between an UBEM and a coupled microclimate model aiming in a twofold study: minimizing the inconsistencies of the UBEM model by considering local microclimate phenomena and testing the impact of energy systems to microclimate and vice versa. The developed coupled model allows to take into account a variety of phenomena, such as detailed radiative and convective transfers for the buildings and the outdoor environment, building thermal transfers, and a diversity of detailed representation of energy systems.

In the present study, three coupling schemes are tested for a street canyon settlement. Annual simulation results of energy loads are examined, while the feedback of air conditioning systems to ambient air is also evaluated. Furthermore, the discrepancies between online and offline coupling schemes are estimated.

Methodology

Overview

Considering the existing challenges in energy assessment simulations, a strong coupling scheme (Kyriakodis, 2019) is implemented to enhance the meteorological boundary conditions of the urban building energy model. The proposed combination could offer also the possibility to address the objective of systems feedback to air temperatures, subtracting them from the sensible heat ejected from the buildings. Thus, a research developed tool, (1) EnviBatE (Gros, Bozonnet, and Inard 2014), representing a coupled scheme between a simplified BES tool, a solar radiation model and an urban airflow simulation code and a dynamic simulation platform based on the bottom-up approach for district and territory energy assessment, (2) Dimosim (Riederer et al. 2015) have been selected to fulfill the assessment. EnviBatE initially aim to assess building energy demand, including microclimate interactions on buildings. It was further used to study the impact of cool materials in various rehabilitation projects. Dimosim developed with the aim to simulate any possible combination of systems, models and buildings at any scale, at a high execution time and in a modular and flexible way in order to respond to any demand and type of project. Both tools are developed in object-oriented programming language, Python.

Workflow

Import layouts. The geometrical data of Dimosim are characterized by an open structure to enable multiple data sources like databases, standardized information models, or self-defined file formats. More in detail, the structural geometrical file corresponds to a cityGML or json file format. The data are obtained by 2D or 3D vector databases. EnviBatE uses a design software of 3D modeling to process the geometrical layouts. A module capable to transform data between the referenced formats, has been implemented in the coupled model. It allows to index the studied elements (building, surfaces) while in parallel, ensures that the building footprints are identically imported to both tools.

Meshes generation. The generation of various different meshes is a necessary action in order to perform the microclimate simulations. Each of them corresponds to a different calculation domain. At the end, all of them are integrated in a unique final zonal mesh that accounts for buildings, outdoor surfaces and outdoor air cells. More in detail, EnviBatE tool, is using a fine triangulated mesh (**Figure 1**b) for the calculation of solar radiation, a hexahedral structure grid for the airflow calculation (**Figure 1**a) and an unstructured zonal outdoor mesh (**Figure 1**c). Indexation and generation of the meshes are automatically performed by the core code of the tool. In the actual case study, we choose a characteristic length of the outdoor cells equal to the length of each thermal zone. This option ensures that the heat injected from buildings and the respective system flux is equally diffused in the adjacent air volumes.

Solar calculation. Solar radiation is pre-processed for both tools. In this case study, we choose to integrate in the coupled model the solar radiation calculation module of EnviBatE. It corresponds to Solene (Groleau, Fragnaud, and Rosant 2003) radiation model and it is based in the radiosity method. This option allows to evaluate the: 1) direct solar irradiance, 2) sky luminance, 3) solar reflections and longwave interchanges in the urban environment. The spatial resolution of the solar mesh corresponds to maximum 2m, discretizing each building surface to at least 44 sub-surfaces (**Figure 1**b). At the end, the incident radiation corresponds to the sum of its respective triangles. Sky vault generation is required and it is also discretized to 256 patches.

In order to perform fast calculations in a detailed meshed geometry, the calculation is performed in a daily basis with standard conditions of a clear sky. Thus, solar irradiance from the meteorological file was used to weight it as a function of real conditions. For the diffuse component, daily average Perez coefficients were used.

Airflow calculation. For the airflow calculation, the three components (u, v, w) of air velocity are required for each outdoor cell. They are provided to the model by the use of the urban airflow model QUIC (Pardyjak and Brown 2003). This model is based on empirical laws and a zonal approach developed by Rockle (1990) to provide airflows consistent with the continuity equation. This approach was selected in order to avoid time consuming CFD calculations, as our purpose is to compute the coupled effects of buildings and microclimate over an annual period. The computational domain of this case study consists of 86 x 86 x 24 computational cells, discretized to 1(dx) x 1(dy) x 3(dz) m for each axis respectively (**Figure 1**a).

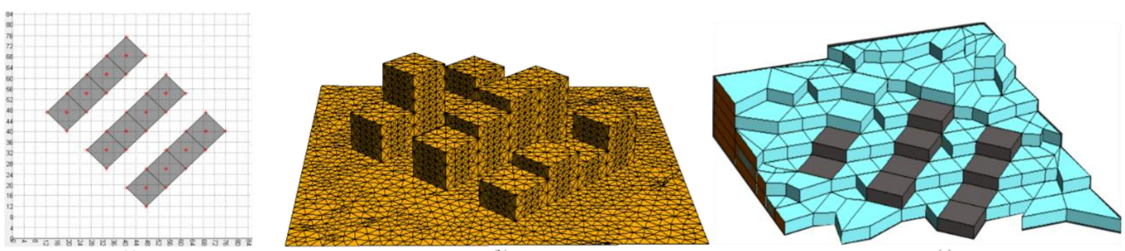

Figure 1. The fine airflow grid (a), triangulated solar mesh (b) and the integrated zonal mesh (c).

Building models. Both models perform building energy simulations for energy consumption (heating, cooling, ventilation and lighting) in buildings. Notably, the building model of EnviBatE is established with the Weighting Factors method (Rousseau 1978). The surface temperature, calculation is strongly coupled to the respective outdoor air temperature, allowing to take into account convective exchanges. Ventilation and occupancy schedules are also included in the model, according to French national regulations or user defined data. In parallel, the building model of Dimosim, corresponds to RC structure taking into consideration the necessary features to perform the thermal calculations. Windows, wall/roof and floor external envelopes, thermal bridges and internal mass, ventilation/infiltration and internal gains from occupants and appliances are included to perform the thermal model computation. In the current version of Dimosim, heat exchange between zones is neglected and only thermal inertia is considered. This is currently being updated and multizone calculations could be achieved in a future version of the tool.

Case study Implementation

The case study is based in an urban canyon settlement composed of 16 buildings of various heights randomly selected. The orientation of the domain is 45° (from N counter clockwise). Each thermal zone is 3m height and the floor surface is 100m². Window to wall ratio is assumed to be 0.2. The thermal transmittance is 0.34, 0.78 and 2.5 [W/m²K] and the solar reflectance is 0.3, 0.2

and 0.08 for zone envelopes and floors, roofs and windows respectively. Interior insulation of polystyrene has been added, as it is the most common application in French building stock. Constant infiltration rate of 0.7 [ACH] is selected. The set point temperatures are forced to be 28 and 19 [°C] for the cooling and heating season. The selection is established to represent buildings constructed after 2000s. Indeed, the thermal characteristics are strongly affecting the performance of the buildings and thus their respective impact to the microclimate. For comparison purposes, we followed this general application.

The urban geometry has a maximum aspect ratio of 1.8 [H/W] formation, depicting a discontinuous row of mid-rise high density urban canyon, following the urban typologies classification of (Stewart and Oke, 2012). The outdoor space is formed by concrete pavements presenting a thermal transmittance of 3.2 [W/m²K] and 0.5 albedo. This morphology is representative of many European cities.

Split air conditioning units amount to the energy system providing the necessary loads. This type of systems are commonly used and preferred as an instant and low-cost solution for individual usage. The efficiency is set to 1 and the mode is reversible to account both for heating and cooling period. The fuel type is set to electricity. In this case study, we assume that in every thermal zone a local AC unit is operating. The meteorological file corresponds to typical meteorological year data (TMY2) and it is interpolated with CCWorldWeatherGen (Jentsch et al., 2013) to 2030 according to the A1B future scenario of forcing agents given in the IPCC Special Report.

Coupling Procedures

Coupling surface temperature (Cpl_Ts). In the microclimate model, surface temperature is strongly coupled with the outdoor air temperature. Thus, we can assume that the impact of microclimate (present wind speed and air temperature conditions) is embedded in the calculation. We choose, as a first step, to impose this parameter combined with the pre-calculated shortwave solar radiation to all building surfaces of the UBEM (Figure 2). Simultaneously, the estimated heat flux of the AC unit is injected to the adjacent outdoor air cell. The concurrent exchange is established through a co-simulation platform based on sockets for every time step of the annual simulation.

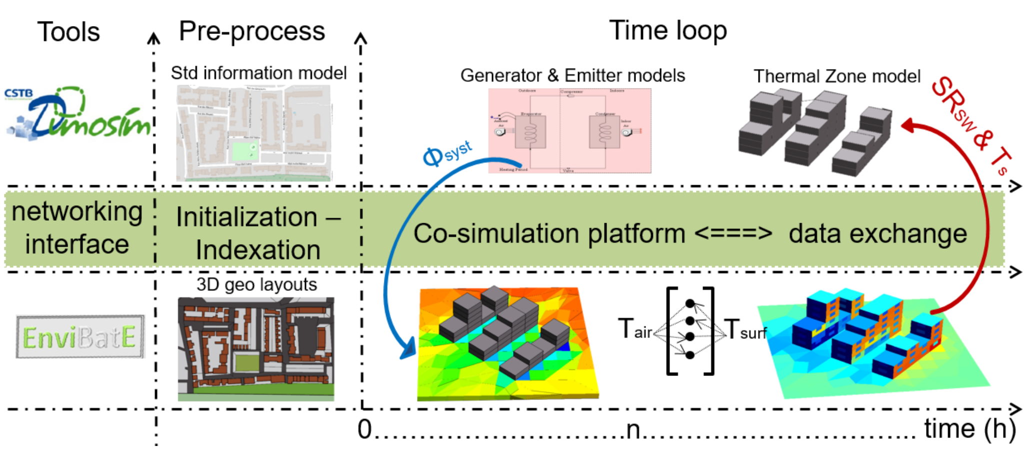

Figure 2. The initial coupling scheme (CPL_Ts) where the surface temperature is provided to the UBEM.

Coupling air temperature (Cpl_Inter). A second coupling scheme (Figure 3) is established following the same exchange approach. At this step, we choose to "integrate" the zonal model to the UBEM. In order to perform the concurrent exchange, we set the calculated outdoor air temperature of the microclimate model as a boundary condition to the UBEM. In parallel, building and system thermal fluxes are injected to the zonal cells. Notably, the building model is simulated only once (UBEM calculation) reducing the execution time in half. Solar radiation has remained intact.

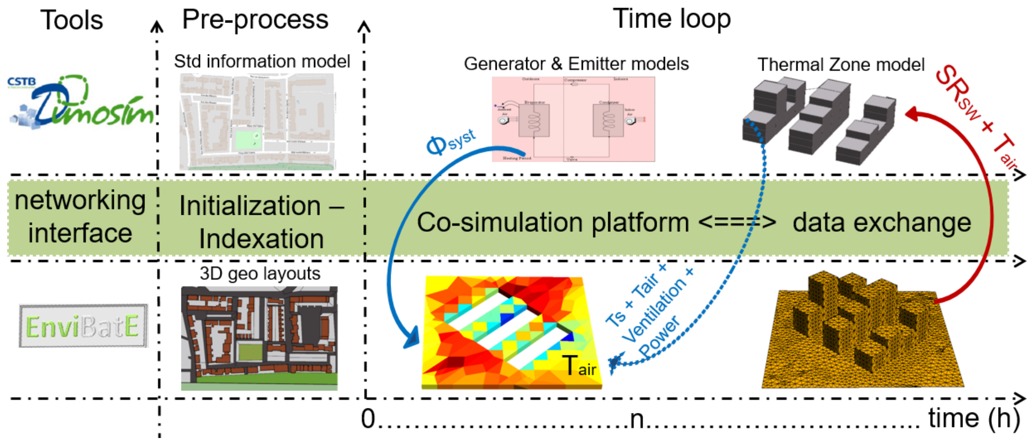

Figure 3: The integrated coupling scheme (CPL_Integ) where the air temperature is used as boundary to the UBEM.

Offline coupling of air temperature. The last years the most commonly used methodology to account microclimate in BES has increasingly become the one-way coupling of specific climate parameters. Based on the simulation results of the last coupling scheme two modified annual meteorological files were generated and imported to the UBEM as boundary conditions. We scope to evaluate the discrepancies between these two coupling approaches. Thus, the average air temperature of the entire district is considered in the first offline scenario (EB_int) while the average air temperature of the canyon cells forms the second (EB_int_can). Solar radiation still remains intact. Annual simulations of the UBEM (standalone) were performed with the modified boundary conditions.

Results

Impact on Energy loads

In order to estimate the impact of microclimate to building energy demand, a comparison between the standalone (UBEM) and the coupled model (Cpl_Inter) has been realised. Cooling loads and the respective relative difference between the two scenarios is plotted for each building (Figure 4). The average increase of the cooling loads is 20%, while the peak is reaching 35% (B_5). In terms of absolute values the maximum increase is reaching 0.5MWh. The 2-storey buildings are mainly affected and exhibit the maximum differences, prooving the capability of the coupled model to account the SUHI and the CUHI effects. Moreover, the coupled model can efficiently capture the feedback caused by the ejected system fluxes. During the cooling period, the flux injected to the ambient environment (evaporator) is warmer than the respective air. This is causing a further increase on energy loads for cooling, presenting a maximum difference of 2.1%.

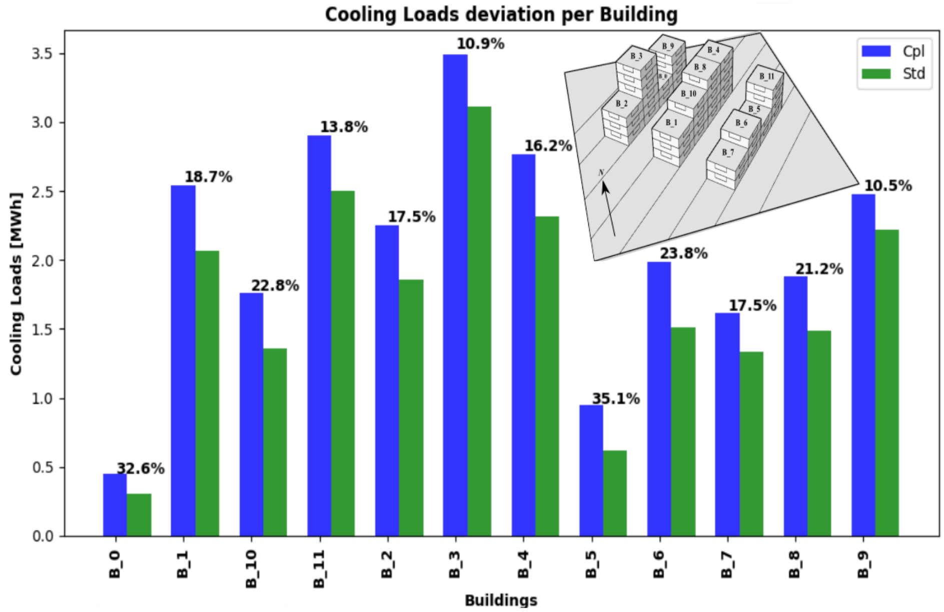

Figure 4. Cooling loads comparison between standalone and coupled simulations.

Heating loads are also presenting the same trend especially when system fluxes are taken into account. In general, the increase is less intense but still significant. The average increase of heating loads is 7%, while the peak is way much smoother, reaching 7.8% (B_5). Systems feedback is captured and presents a further slight increase of heating loads with a maximum value of 1.2%.

A straight comparison between the standalone (UBEM) and the coupled model (Cpl_Ts) is not possible to be conducted, mainly due to the fact that the surface temperature parameter is not converging between the two models. Although, the maximum absolute difference of the surface temperature between the two models is 1,2^{o}C, it is sufficient to underestimate the effect of local climate conditions to the ambient environment.

The average increase of the cooling loads is 20%, while the peak is reaching 35%. The 2-storey buildings are mainly affected due to the interference with the outdoor space. Generally for the entire cooling period the difference between S3 and S4 is almost neglectible reaching maximum the value of 0.02%. Further studies (hourly load differences, different climatic zones, etc.) have to be examined in order to correlate more accurately the temperature increase with the increase of cooling loads. Refering to bilbiography this is in aggreement with (Santamouris, 2015) for a mild climate.

Impact on Air Temperature

The impact of systems flux to ambient air is captured on both coupling procedures. During the summer period, the air temperature of the canyon derived from the coupled simulations is increasing and most of the canyon cells present a 0.2 - 0.5^{o}C increase of air temperature. At the same time the average air temperature of the canyon is slightly higher compared to the standalone simulation. The absolute difference varies from 0.1 ^{o}C to 1.4 ^{o}C (Figure 1Figure 5a). The same trend is observed also for the heating period. The range of difference is higher, since the heating loads and the respective ejected flux of a heating dominated city (La Rochelle) are higher. The maximum air difference is observed inside the canyon with an absolute value of 1.94 (Figure 5b).

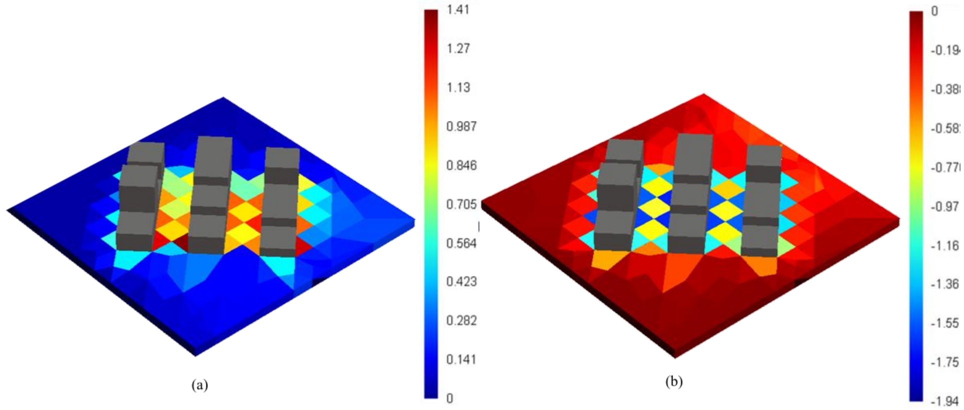

Figure 5: Maximum absolute difference of the air temperature distribution in the canyon during cooling (a) and heating (b) periods when system fluxes are injected.

Coupling Schemes Comparison (Online Vs Offline)

In this section we present the discrepancies between the online coupling scheme (Cpl_Inter) and the commonly used approach of offline coupling. As shown in Figure 6. Online Vs offline comparative results. the average relative difference on cooling loads between online and offline coupling scenarios is reaching 8%. The maximum difference is approximately 22%. Moreover, the cooling loads of two buildings (B_3 and B_9) are overestimated in the offline coupling scenario, while in the rest of them, we can observe an underestimation.

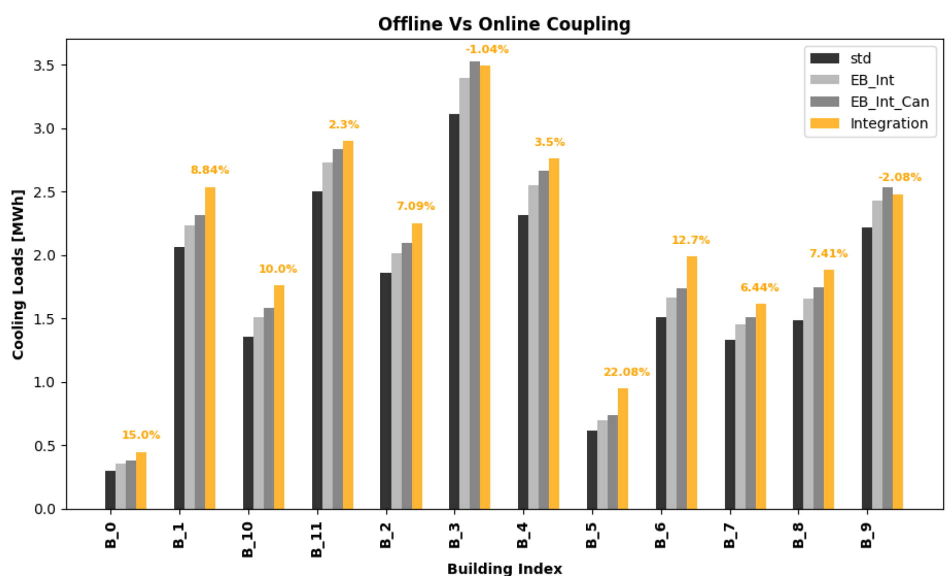

Figure 6. Online Vs offline comparative results.

Discussion & future perspectives

A monitoring campaign for a district in La Rochelle (smart meters and local meteorological stations) is actually ongoing. The onsite measurements could allow validating the new developed model. Comparative analysis for different climate zones, building thermal characteristics and system types is also ongoing.

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