



CLIMATE RESILIENT STRATEGIES BY  
ARCHETYPE-BASED URBAN ENERGY MODELLING

# Atlas of the typical urban context configuration: KPIs under future urban climate

DELIVERABLE 3.3

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## 1. INTRODUCTION

### 1.1 Purpose

Global climate change leads to increased ambient temperatures, causing buildings to overheat and demand more energy while worsening indoor environmental quality. Urban Heat Island (*UHI*) effects, caused by local warming in urban areas, further exacerbate these challenges. Existing Urban Building Energy Modelling (*UBEM*) struggles to address *UHI* due to limited data on microscale climatic conditions and detailed mapping of urban areas. The CRiStAll project aims to address these gaps by creating detailed climatic datasets and exploring different urban configurations at the microscale.

Under the CRiStAll project, three interconnected research lines are developed. These include:

- A. building an urban climate model that incorporates the impacts of the Urban Heat Island (*UHI*) at the microscale, as well as the short-, mid-, and long-term (future weather data) consequences of climate change,
- B. putting the archetype-based Urban Building Energy Model (*UBEM*) into practice using typical urban environment configurations (urban blocks), and
- C. evaluating the impact of climate resilience and *UHI* reducing methods in urban locations.

The Task 3.3 of the CRiStAll project (“*KPI assessment of the typical urban context configurations*”) concerned the simulation of the urban models defined in Task 3.2 with current and future weather files inclusive of *UHI* (as defined in Task 2.3). After an analysis of the literature, the most meaningful metrics and key performance indicators (*KPIs*) descriptive of building energy performance, as well as indoor and outdoor thermal comfort conditions, were identified, calculated, and discussed in order to describe the severity of *UHI* phenomena in the selected urban districts, using thresholds and classes to indicate the level of severity of *UHI*.

The present deliverable, D3.3 – “*Atlas of the typical urban context configuration: KPIs under future urban climate*”, reports the results regarding the selected *KPIs*, including also maps of the selected districts where appropriate, which can be exploited to identify critical zones and propose measures of intervention. The D3.3 represents the final stage of the WP3, with the achievement of milestone M2 regarding the *UBEM* modelling and performance simulation of Italian typical urban archetypes and the characterization of their energy performance and thermal comfort indicators in both current and future climate conditions accounting for *UHI* phenomena.

### 1.2 Deliverable structure

This deliverable is structured into four main sections, aimed at presenting the results for the representative urban blocks across three distinct Italian climatic zones.

- **Section 1** introduces the document, outlining its objective (1.1), deliverable structure (1.2), and partner contributions to Task 3.3 development (1.3).
- **Section 2** describes the mathematical formulation of the selected *KPIs*, covering energy performance indicators (2.1), indoor thermal comfort metrics (2.2), and climate variables (2.3). Subsection 2.4 summarises the assumption adopted for the calculation of the selected *KPIs*.

- **Section 3** presents the results for Urban Blocks A in the municipalities of Turin (3.1), Rome (3.2), and Bari (3.3), under current, mid-term, and long-term climate scenarios. A discussion section is presented in 3.4.
- **Section 4** is dedicated to general remarks and conclusions.

### 1.3 Contribution of partners

POLITO automated the calculation of the *KPIs* and carried out the simulations, in collaboration with unibz, for the case studies presented in T3.2 “Implementation of UBE tool with the urban context configurations”. unibz defined the structure of the present deliverable and both unibz and POLITO contributed to its drafting. All the partners reviewed and finalised the deliverable.

## 2. GENERAL DESCRIPTION OF THE RESULTS

According to the literature review, [Table 1](#) presents a set of relevant metrics for assessing the severity of the *UHI* in terms of building energy performance and indoor/outdoor overheating stresses. The *KPIs* are calculated from the outputs of the selected *UBEM* tool, i.e., CitySim.

The following sections (2.1, 2.2, and 2.3) provide the mathematical definitions of the evaluated *KPIs*, accompanied by the corresponding references (technical standards or scientific publications).

Table 1 – List of Key Performance Indicators in different fields

| Quantity                                                      | Symbol        | Unit                            |
|---------------------------------------------------------------|---------------|---------------------------------|
| <b>Energy Performance</b>                                     |               |                                 |
| Energy need for space heating per unit conditioned floor area | $EP_{H;nd}$   | $\text{kWh}\cdot\text{m}^{-2}$  |
| Energy need for space cooling per unit conditioned floor area | $EP_{C;nd}$   | $\text{kWh}\cdot\text{m}^{-2}$  |
| Peak heating load per unit conditioned floor area             | $\phi_{H;ld}$ | $\text{W}\cdot\text{m}^{-2}$    |
| Peak cooling load per unit conditioned floor area             | $\phi_{C;ld}$ | $\text{W}\cdot\text{m}^{-2}$    |
| <b>Indoor Thermal Comfort</b>                                 |               |                                 |
| Weighted Warm Hours of Discomfort                             | $WHD_w$       | h                               |
| Indoor Overheating Degree                                     | $IOD$         | $^{\circ}\text{C}$              |
| Overheating Escalation Factor                                 | $\alpha_{OD}$ | –                               |
| <b>Climate</b>                                                |               |                                 |
| Ambient Warmness Degree                                       | $AWD$         | $^{\circ}\text{C}$              |
| Heating Degree Days                                           | $HDD$         | $^{\circ}\text{C}\cdot\text{d}$ |
| Cooling Degree Days                                           | $CDD$         | $^{\circ}\text{C}\cdot\text{d}$ |
| Urban Heat Island Intensity                                   | $UHII$        | $^{\circ}\text{C}$              |

### 2.1 Energy Performance

The annual thermal energy need for space heating/cooling ( $EP_{H/C;nd}$ ) is calculated according to Eq. (1).

$$EP_{H/C;nd} = \sum_{h=1}^n EP_{H/C;nd;h} \quad (1)$$

where

$EP_{H/C;nd}$  = thermal energy need for space heating/cooling,  $\text{kWh}\cdot\text{m}^{-2}$

- $h$  = time step counter, –  
 $n$  = total number of time steps, –  
 $EP_{H/C;nd;h}$  = hourly thermal energy need for space heating/cooling, kWh·m<sup>-2</sup>

The peak heating load per unit conditioned floor area is calculated according to Eq. (2).

$$\phi_{H;ld} = \max(0; \phi_{H;ld;h}) \quad (2)$$

where

- $\phi_{H;ld}$  = peak heating load per unit conditioned floor area, W·m<sup>-2</sup>  
 $\phi_{H;ld;h}$  = hourly heating load per unit conditioned floor area, W·m<sup>-2</sup>

The peak cooling load per unit conditioned floor area is calculated according to Eq. (3).

$$\phi_{C;ld} = \min(0; \phi_{C;ld;h}) \quad (3)$$

where

- $\phi_{C;ld}$  = peak cooling load per unit conditioned floor area, W·m<sup>-2</sup>  
 $\phi_{C;ld;h}$  = hourly cooling load per unit conditioned floor area, W·m<sup>-2</sup>

## 2.2 Indoor Thermal Comfort

The summation of the product of the weighting factor ( $wf$ ), and the time  $t$ , represents the Weighted Warm Hours of Discomfort ( $WHD_w$ ), calculated using Eq. (4), for a characteristic period of the year.

$$WHD_w = \sum wf \cdot t \quad \text{for } \theta_0 > \theta_{0;limit;upper} \quad (4)$$

where

- $WHD_w$  = Weighted Warm Hours of Discomfort, h  
 $wf$  = weighting factor, –  
 $t$  = time, h  
 $\theta_0$  = indoor operative temperature, °C  
 $\theta_{0;limit;upper}$  = upper limit of operative temperature, °C

The weighting factor ( $wf$ ), for  $\theta_0 - \theta_{0;limit;upper} > 0$ , is calculated according to UNI EN ISO 7730 (2006), by means of Eq. (5):

$$wf = 1 + \frac{\theta_0 - \theta_{0;limit;upper}}{\theta_{0;limit;upper} - \theta_c} \quad (5)$$

where

- $wf$  = weighting factor, –  
 $\theta_0$  = indoor operative temperature, °C  
 $\theta_{0;limit;upper}$  = upper limit of operative temperature, °C  
 $\theta_c$  = optimal operative temperature, °C

The upper limit of operative temperature ( $\theta_{0;\text{limit};\text{upper}}$ ), optimal operative temperature ( $\theta_c$ ), and outdoor running mean temperature ( $\theta_{\text{rm}}$ ) are calculated according to UNI EN 16798-1 (2019).

The upper limit of operative temperature ( $\theta_{0;\text{limit};\text{upper}}$ ) is calculated by means of Eq. (6):

$$\theta_{0;\text{limit};\text{upper}} = 0.33 \cdot \theta_{\text{rm}} + 18.8 + 3 \quad (6)$$

where

$$\begin{aligned} \theta_{0;\text{limit};\text{upper}} &= \text{upper limit of operative temperature, } ^\circ\text{C} \\ \theta_{\text{rm}} &= \text{running mean outdoor temperature, } ^\circ\text{C} \end{aligned}$$

The optimal operative temperature ( $\theta_c$ ) is calculated by means of Eq. (7):

$$\theta_c = 0.33 \cdot \theta_{\text{rm}} + 18.8 \quad (7)$$

where

$$\begin{aligned} \theta_c &= \text{optimal operative temperature, } ^\circ\text{C} \\ \theta_{\text{rm}} &= \text{running mean outdoor temperature, } ^\circ\text{C} \end{aligned}$$

The outdoor running mean temperature ( $\theta_{\text{rm}}$ ) is calculated by means of Eq. (8):

$$\theta_{\text{rm}} = \left( \theta_{\text{ed}-1} + 0.8 \cdot \theta_{\text{ed}-2} + 0.6 \cdot \theta_{\text{ed}-3} + 0.5 \cdot \theta_{\text{ed}-4} + 0.4 \cdot \theta_{\text{ed}-5} + 0.3 \cdot \theta_{\text{ed}-6} + 0.2 \cdot \theta_{\text{ed}-7} \right) / 3.8 \quad (8)$$

where

$$\begin{aligned} \theta_{\text{rm}} &= \text{running mean outdoor temperature, } ^\circ\text{C} \\ \theta_{\text{ed}-1} &= \text{daily mean outdoor air temperature for previous day, } ^\circ\text{C} \\ \theta_{\text{ed}-i} &= \text{daily mean outdoor air temperature for the } i\text{-th previous day, } ^\circ\text{C} \end{aligned}$$

The Indoor Overheating Degree ( $IOD$ ), calculated according to Eq. (9) (Hamdy *et al.*, 2017), quantifies the indoor overheating risk taking into account severity and frequency of high indoor temperatures.

$$IOD = \frac{\sum_{z=1}^Z \sum_{i=1}^{N_{occ}(z)} \left[ (\theta_{0;i;z} - \theta_{\text{comf};i;z})^+ t_{i,z} \right]}{\sum_{z=1}^Z \sum_{i=1}^{N_{occ}(z)} t_{i,z}} \quad (9)$$

where

$$\begin{aligned} IOD &= \text{Indoor Overheating Degree, } ^\circ\text{C} \\ z &= \text{building zone counter, } - \\ Z &= \text{number of building zones, } - \\ i &= \text{occupied hour counter, } - \\ N_{occ} &= \text{total number of occupied hours, } - \\ \theta_{0;z;i} &= \text{indoor operative temperature of time step } i \text{ and zone } z, ^\circ\text{C} \end{aligned}$$

$\theta_{\text{comf};z;i}$  = static or adaptive thermal comfort limit of time step  $i$  and zone  $z$ , °C  
 $t_{i,z}$  = time, h

### 2.3 Climate

The Ambient Warmness Degree ( $AWD$ ), calculated according to Eq. (10) (Hamdy *et al.*, 2017), indicates the severity and frequency of high outdoor temperatures according to a predefined base temperature.

$$AWD = \frac{\sum_{i=1}^N (\theta_{e;i} - \theta_b)^+ t_i}{\sum_{i=1}^N t_i} \quad (10)$$

where

$AWD$  = Ambient Warmness Degree, °C  
 $i$  = time step counter, –  
 $N$  = total number of time steps, –  
 $\theta_{e;i}$  = external air temperature of time step  $i$ , °C  
 $\theta_b$  = external base temperature, °C  
 $t_i$  = time, h

The Overheating Escalation Factor ( $\alpha_{IOD}$ ), calculated according to Eq. (11) (Hamdy *et al.*, 2017), is used to estimate the sensitivity of buildings to overheating.

$$\alpha_{IOD} = \frac{IOD}{AWD} \quad (11)$$

where

$\alpha_{IOD}$  = Overheating Escalation Factor, –  
 $IOD$  = Indoor Overheating Degree, °C  
 $AWD$  = Ambient Warmness Degree, °C

The Heating Degree Days ( $HDD$ ) are calculated according to UNI 10349-3 (2016) and Eq. (12).

$$HDD = \frac{\sum_{h=1}^n (\theta_{b;H} - \theta_{e;h})^+}{24} \quad (12)$$

where

$HDD$  = Heating Degree Days, °C·d  
 $h$  = time step, h  
 $n$  = total number of time steps, h  
 $\theta_{b;H}$  = heating base temperature, °C  
 $\theta_{e;h}$  = external air temperature of time step  $h$ , °C

The Cooling Degree Days ( $CDD$ ) are calculated according to UNI 10349-3 (2016) and Eq. (13).

$$CDD = \frac{\sum_{h=1}^n (\theta_{e,h} - \theta_{b,c})^+}{24} \quad (13)$$

where

|                |                                                  |
|----------------|--------------------------------------------------|
| $CDD$          | = Cooling Degree Days, °C·d                      |
| $h$            | = time step, h                                   |
| $n$            | = total number of time steps, h                  |
| $\theta_{e,h}$ | = external air temperature of time step $h$ , °C |
| $\theta_{b,c}$ | = cooling base temperature, °C                   |

The Urban Heat Island Intensity ( $UHII_m$ ), calculated according to Eq. (14), represents the monthly difference in external air temperature between the urban weather station (UWS) and the rural weather station (RWS).

$$UHII_m = \bar{\theta}_{e,UWS;h;m} - \bar{\theta}_{e,RWS;h;m} \quad (14)$$

where

|                            |                                                                                            |
|----------------------------|--------------------------------------------------------------------------------------------|
| $UHII_m$                   | = Urban Heat Island Intensity, °C                                                          |
| $\bar{\theta}_{e,UWS;h;m}$ | = monthly average of external air temperature at urban weather station UWS, month $m$ , °C |
| $\bar{\theta}_{e,RWS;h;m}$ | = monthly average of external air temperature at rural weather station RWS, month $m$ , °C |

## 2.4 Application

The Urban Building Energy Modelling present limitations in assessing indoor thermal comfort, mainly due to constraints in zoning different thermal spaces. In the case studies of the municipalities of Turin, Rome, and Bari, each building is represented by a single thermal zone. This assumption affects the hourly calculation of indoor temperatures, as only one hourly temperature profile is available per building.

Furthermore, CitySim does not provide internal operative temperature as an output, but only indoor air temperature. For this reason—considering the single-zone modelling assumption and in order to avoid additional uncertainty in the assessment of indoor overheating—the calculation of Indoor Overheating Degree ( $IOD$ ) and Overheating Escalation Factor ( $\alpha_{IOD}$ ) was not performed.

**Table 2** summarises the assumption adopted for the calculation of the selected *KPIs* and, where applicable, the reasons why certain indicators were not evaluated. All metrics will be calculated for the case studies presented in D3.2 “*Atlas of the typical urban context configuration: model features*”, under current, mid-term, and long-term climate scenarios, with comparison between *UWS* with the *RWS*, where relevant. However, in this deliverable the results for the urban block A in Turin, Rome, and Bari will be presented and discussed.

Table 2 – Calculated KPIs with related assumptions

| Symbol                        | Unit                            | Calculated | Calculation assumptions/notes                                                                                                                                                                                                                                                                                                                                                                                                                 |
|-------------------------------|---------------------------------|------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Energy Performance</b>     |                                 |            |                                                                                                                                                                                                                                                                                                                                                                                                                                               |
| $EP_{H;nd}$                   | $\text{kWh}\cdot\text{m}^{-2}$  | x          | <ul style="list-style-type: none"> <li>Single-zone building</li> <li>Calculation performed for the whole year, <math>n = 8760</math></li> </ul>                                                                                                                                                                                                                                                                                               |
| $EP_{C;nd}$                   | $\text{kWh}\cdot\text{m}^{-2}$  | x          | <ul style="list-style-type: none"> <li>Single-zone building</li> <li>Calculation performed for the whole year, <math>n = 8760</math></li> </ul>                                                                                                                                                                                                                                                                                               |
| $\phi_{H;ld}$                 | $\text{W}\cdot\text{m}^{-2}$    | x          | <ul style="list-style-type: none"> <li>Single-zone building</li> <li>Calculation performed for the whole year</li> </ul>                                                                                                                                                                                                                                                                                                                      |
| $\phi_{C;ld}$                 | $\text{W}\cdot\text{m}^{-2}$    | x          | <ul style="list-style-type: none"> <li>Single-zone building</li> <li>Calculation performed for the whole year</li> </ul>                                                                                                                                                                                                                                                                                                                      |
| <b>Indoor Thermal Comfort</b> |                                 |            |                                                                                                                                                                                                                                                                                                                                                                                                                                               |
| $WHD_w$                       | h                               | x          | <ul style="list-style-type: none"> <li>Single-zone building</li> <li><math>\theta_0</math> assumed equal to indoor air temperature</li> <li>If <math>\theta_{rm} &gt; 30\text{ }^{\circ}\text{C}</math>, <math>\theta_{rm}</math> is set to <math>30\text{ }^{\circ}\text{C}</math> for the calculation of <math>\theta_{0;limit;upper}</math> and <math>\theta_c</math></li> <li>Calculation performed for June, July, and August</li> </ul> |
| $IOD$                         | $^{\circ}\text{C}$              |            | <ul style="list-style-type: none"> <li>Unavailability of <math>\theta_0</math></li> </ul>                                                                                                                                                                                                                                                                                                                                                     |
| $\alpha_{IOD}$                | –                               |            | <ul style="list-style-type: none"> <li><math>\alpha_{IOD}</math> function of <math>IOD</math></li> </ul>                                                                                                                                                                                                                                                                                                                                      |
| <b>Climate</b>                |                                 |            |                                                                                                                                                                                                                                                                                                                                                                                                                                               |
| $AWD_{18}$                    | $^{\circ}\text{C}$              | x          | <ul style="list-style-type: none"> <li><math>\theta_b = 18\text{ }^{\circ}\text{C}</math></li> <li>Calculation performed for June, July, and August</li> </ul>                                                                                                                                                                                                                                                                                |
| $HDD_{18}$                    | $^{\circ}\text{C}\cdot\text{d}$ | x          | <ul style="list-style-type: none"> <li><math>\theta_{b;H} = 18\text{ }^{\circ}\text{C}</math></li> <li>Calculation period: from 15<sup>th</sup> October to 14<sup>th</sup> April (4368 hours)</li> </ul>                                                                                                                                                                                                                                      |
| $CDD_{18}$                    | $^{\circ}\text{C}\cdot\text{d}$ | x          | <ul style="list-style-type: none"> <li><math>\theta_{b;C} = 18\text{ }^{\circ}\text{C}</math></li> <li>Calculation period: from 15<sup>th</sup> April to 14<sup>th</sup> October (4392 hours)</li> </ul>                                                                                                                                                                                                                                      |
| $UHI$                         | $^{\circ}\text{C}$              | x          |                                                                                                                                                                                                                                                                                                                                                                                                                                               |

### 3. RESULTS OF UBEM SIMULATIONS WITH CURRENT AND FUTURE CLIMATE CONDITIONS

In this section the results on building energy performance and indoor/outdoor overheating are presented for urban block A in the municipalities of Turin (section 3.1), Rome (section 3.2), and Bari (section 3.3), under current, mid-term, and long-term climate scenarios, both with and without *UHI* effect.

At the beginning of subsection, an illustration of the urban block with the building IDs is provided. The results are then categorised into three fields: energy performance, indoor overheating, and

temperature-derived climatic *KPIs*. For each case study, the same type of comparison graphs described below is reported.

The energy performance subsection presents two histogram graphs showing, for each building in the assessed urban block, the thermal energy need for space heating ( $EP_{H;nd}$ ) and cooling ( $EP_{C;nd}$ ), respectively, under the three climate scenarios, using *UWS* data. In addition, the overall building stock  $EP_{H/C;nd}$ , calculated as a net floor area-weighted average of the buildings in the three representative urban blocks, is reported. A similar representation is also provided for peak heating ( $\phi_{H;ld}$ ) and cooling ( $\phi_{C;ld}$ ) loads. The calculation period of both thermal energy need for space heating/cooling and peak heating/cooling load is the whole year.

The indoor thermal comfort subsection presents the Weighted Warm Hours of Discomfort ( $WHD_w$ ) for the most vulnerable building in each assessed urban blocks, i.e., the building with the highest  $WHD_w$  value, under the three climate scenarios, using *UWS* data. A second graph shows the temporal distribution of the daily cumulative  $WHD_w$  values for the most vulnerable building during the calculation period (June–August) under the long-term climate scenario with *UWS* data.

The climate subsection presents outdoor temperature-based *KPIs* ( $AWD_{18}$ ,  $HDD_{18}$ ,  $CDD_{18}$ , and  $UHI$ ), derived from both from *RWS* and *UWS* data. Specifically, the first graph compares the Ambient Warmness Degree ( $AWD_{18}$ ) under current, mid-term, and long-term climate scenarios with and without UHI effect. The calculation period of  $AWD_{18}$  is June–August. The same histogram representation across the three scenarios is provided for Heating Degree Days ( $HDD_{18}$ ) and Cooling Degree Days ( $CDD_{18}$ ). The calculation period of  $HDD_{18}$  and  $CDD_{18}$  is defined by UNI 10349-3:2016. Finally, a table reports the monthly temperature difference ( $UHI$ ), under the three climate scenarios.

The thermophysical characteristics of the building archetypes are available in D3.2 “*Atlas of the typical urban context configuration: model features*”.

### 3.1 Turin

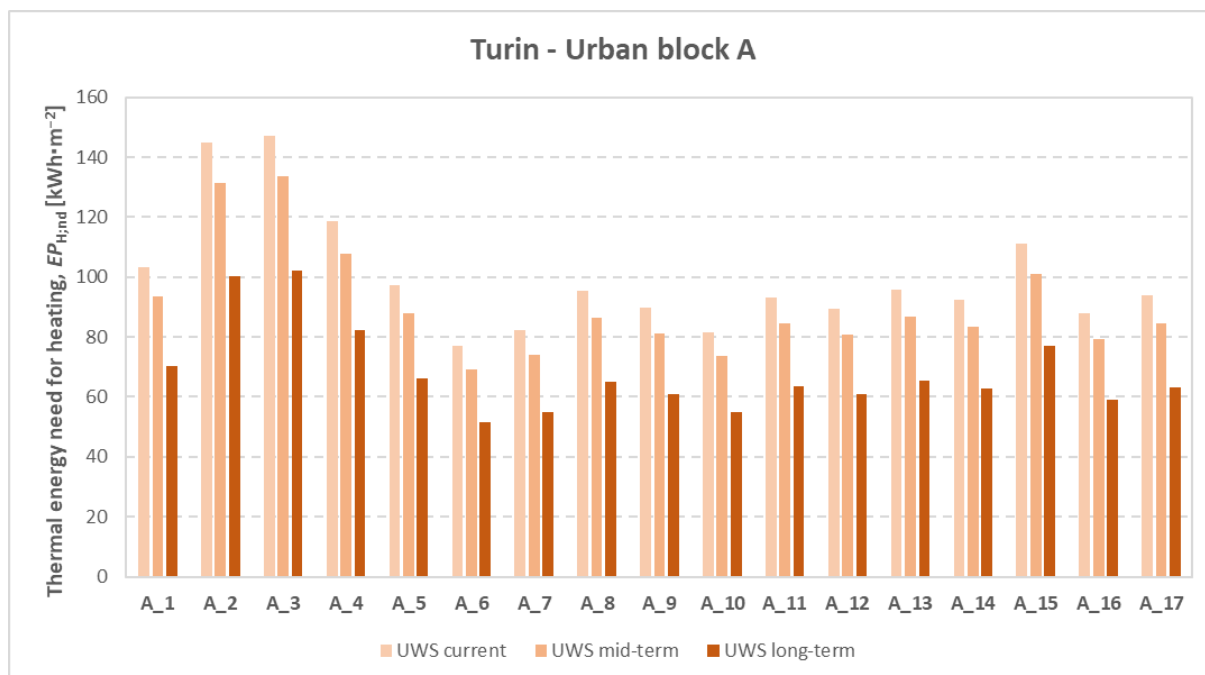
Figure 1 shows the geometrical representation and building IDs of Urban Block A in the municipality of Turin.



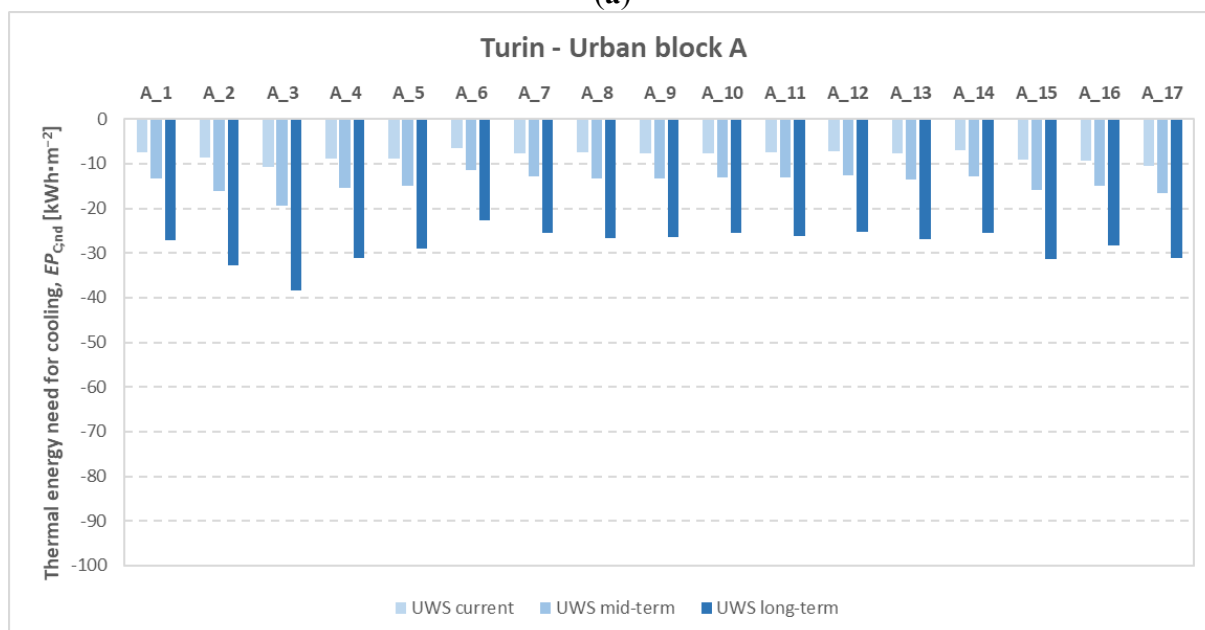
Figure 1: Urban block A (Turin) visualised in CitySim Pro

#### 3.1.1 Energy Performance

Figure 2 shows the thermal energy need for space heating ( $EP_{H,nd}$ ) and cooling ( $EP_{C,nd}$ ) of the assessed buildings in Urban Block A, under current, mid-term, and long-term climate scenarios.



(a)



(b)

Figure 2: Thermal energy need for space heating (a) and cooling (b) using UWS data for the current, mid-, and long-term periods for Urban Block A (Turin)

Figure 3 presents the overall building stock  $EP_{H/C;nd}$ , calculated as a net floor area-weighted average of the buildings in the three representative urban blocks, under current, mid-term, and long-term climate scenarios.

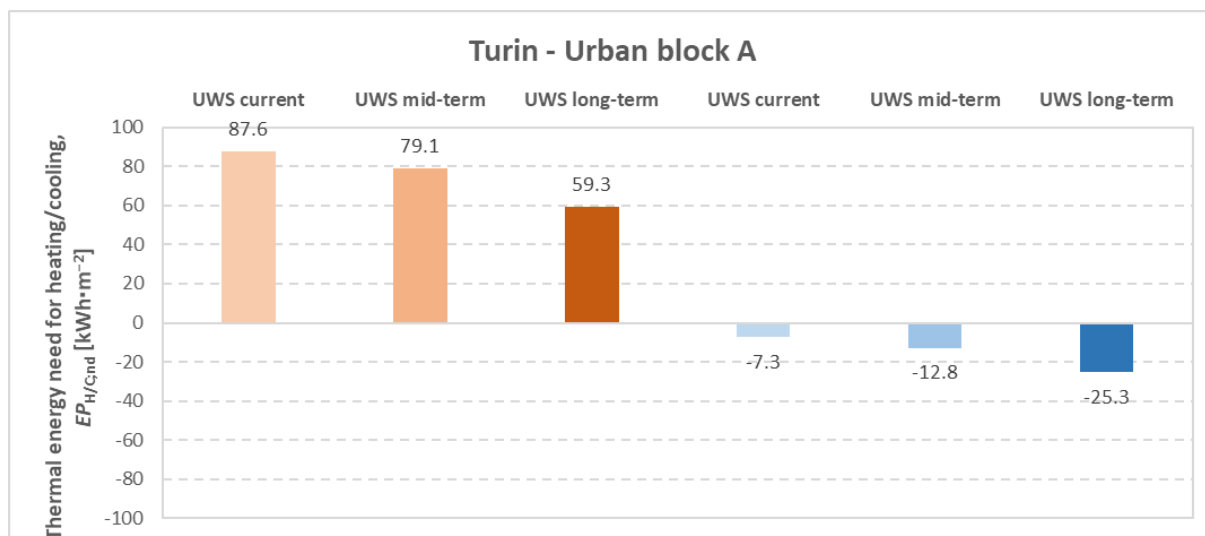


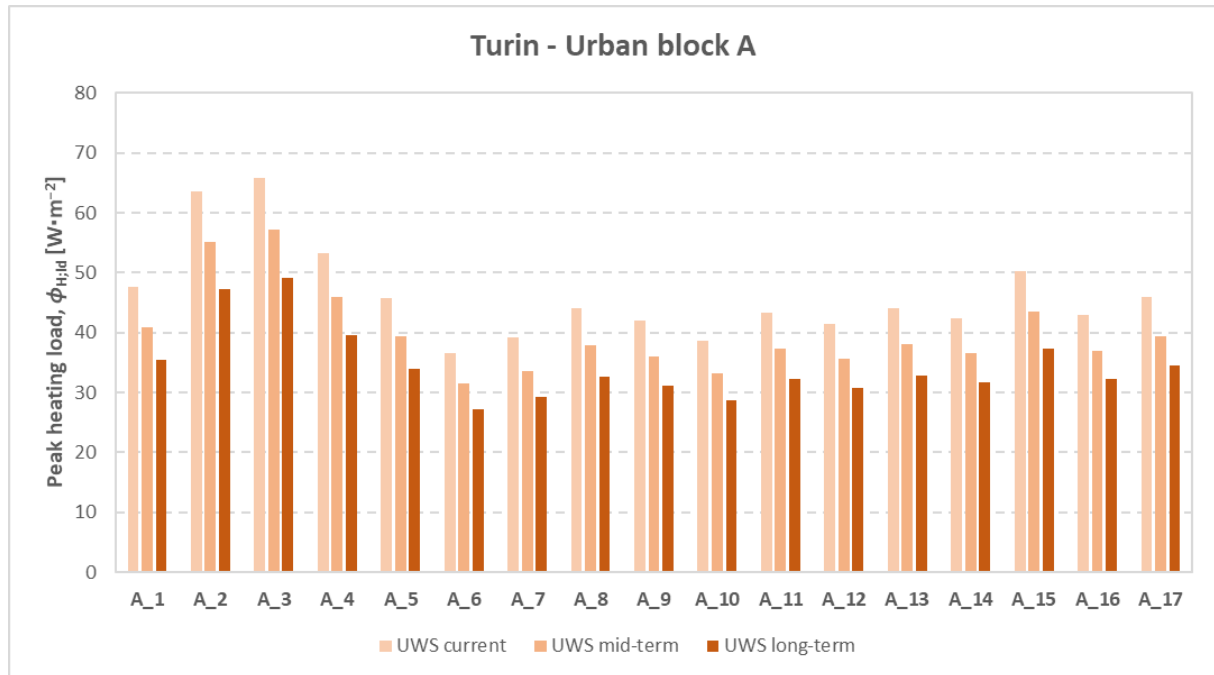
Figure 3: Thermal energy need for space heating and cooling, calculated as a net floor area-weighted average of the buildings, using UWS data for the current, mid-, and long-term periods for Urban Block A (Turin)

Table 3 summarises the reduction in  $EP_{H;nd}$  and the increase in  $EP_{C;nd}$  due to climate change under mid- and long-term climate scenarios, compared to current conditions. The block energy needs are reported both as absolute variations in kWh/m² and percentage changes.

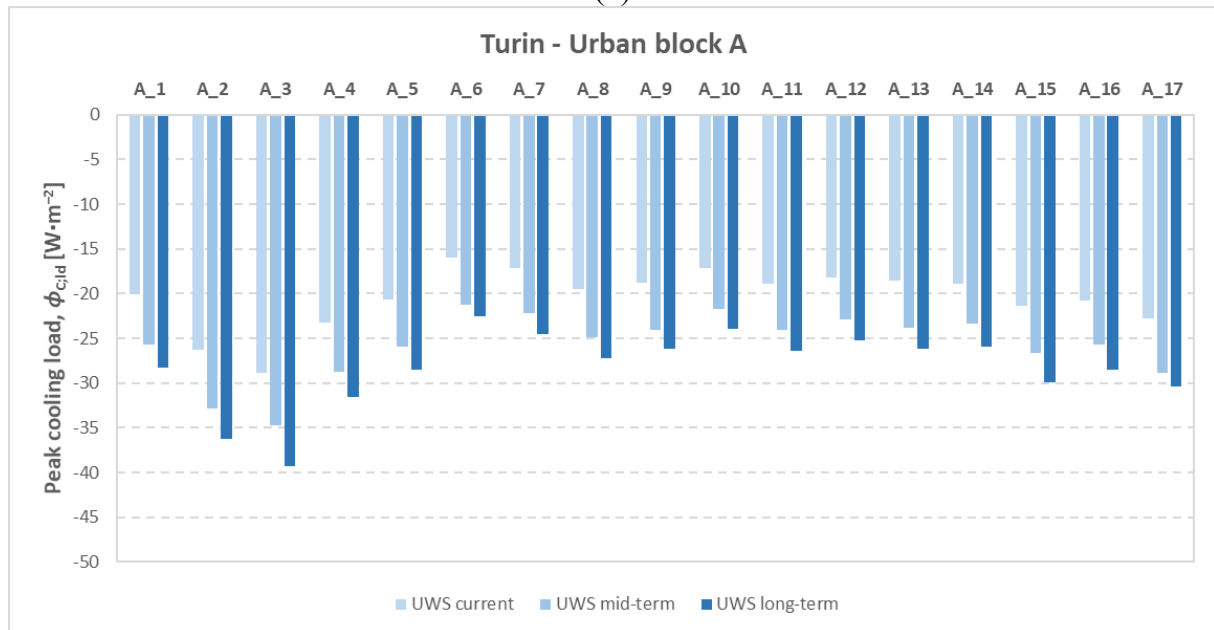
Table 3 – Overall variation in urban block  $EP_{H/C;nd}$  relative to the current scenario for Urban Block A (Turin)

| Urban Block A       | $\Delta EP_{H;nd}$<br>[kWh/m²] | $\Delta EP_{C;nd}$<br>[kWh/m²] | $\Delta EP_{H;nd}$<br>[%] | $\Delta EP_{C;nd}$<br>[%] |
|---------------------|--------------------------------|--------------------------------|---------------------------|---------------------------|
| Mid-term - current  | – 8.6                          | + 5.4                          | – 9.8 %                   | + 74.3 %                  |
| Long-term - current | – 28.4                         | + 18.0                         | – 32.4 %                  | + 245.1 %                 |

Figure 4 illustrates the heating ( $\phi_{H;ld}$ ) and cooling ( $\phi_{C;ld}$ ) peak loads of the thermally simulated buildings in Urban Block A, under current, mid-term, and long-term climate scenarios.



(a)

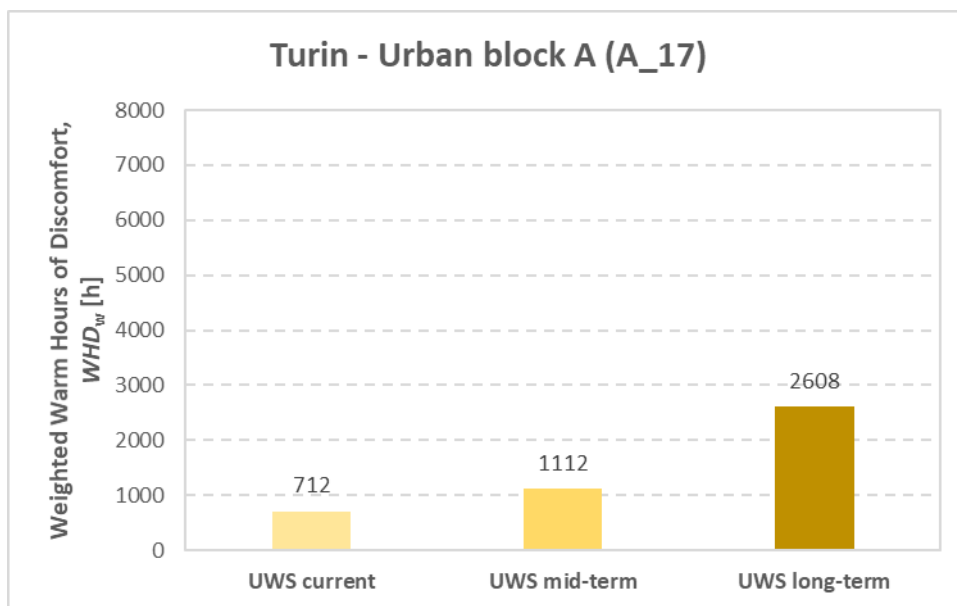


(b)

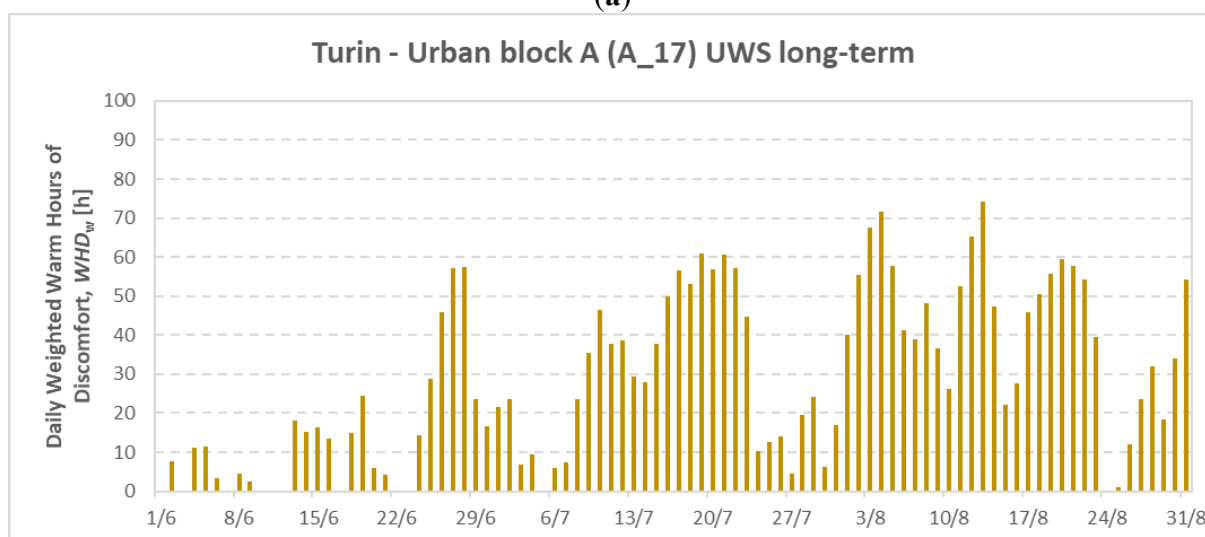
Figure 4: Peak heating (a) and cooling (b) loads using UWS data for the current, mid-, and long-term periods for Urban Block A (Turin)

### 3.1.2 Indoor Thermal Comfort

Figure 5a shows the Weighted Warm Hours of Discomfort ( $WHD_w$ ) for the most vulnerable apartment block (A\_17) in Urban Block A, under current, mid-term, and long-term climate scenarios, based on UWS data. Figure 5b presents the temporal distribution of daily cumulative  $WHD_w$  for A\_17 over the considered calculation period (June–August) under long-term climate scenario, using UWS data.



(a)

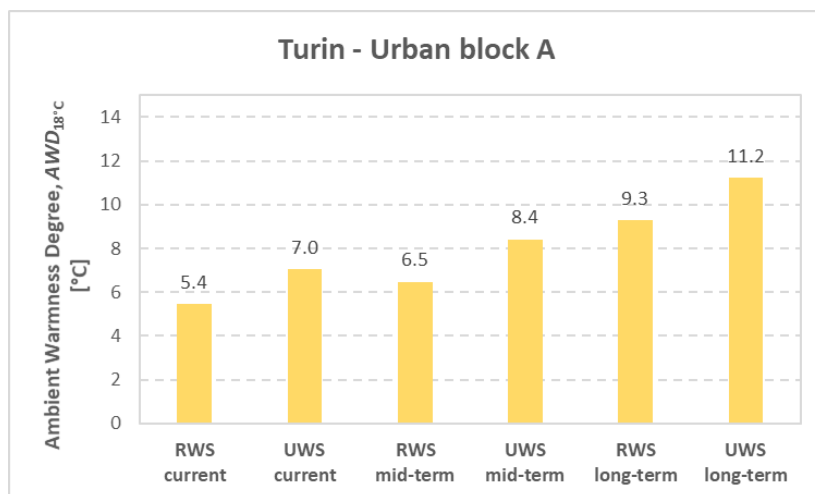


(b)

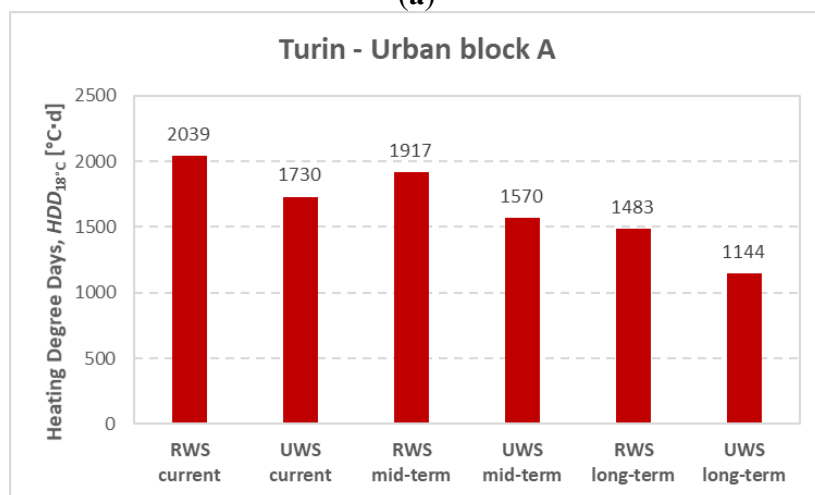
Figure 5: Weighted Warm Hours of Discomfort (WHDw) for the most vulnerable apartment block (A\_17), based on UWS data for the current, mid-, and long-term periods in Urban Block A (Turin) (a); daily daily cumulative temporal distribution of WHDw for the long-term period, based on UWS data (b)

### 3.1.3 Climate

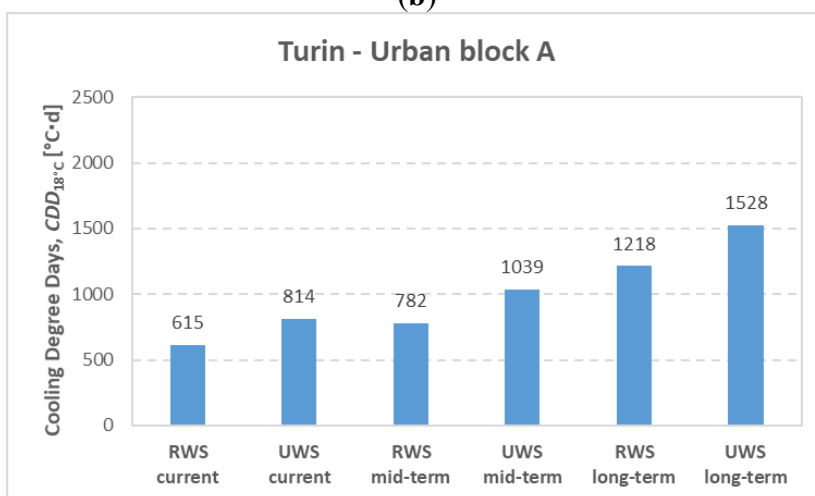
Figure 6a, Figure 6b, Figure 6c show the Ambient Warmness Degree ( $AWD_{18}$ ), Heating Degree Days ( $HDD_{18}$ ), and Cooling Degree Days ( $CDD_{18}$ ), respectively, for Urban Block A under current, mid-term, and long-term climate scenarios, using both *RWS* and *UWS* data.



(a)



(b)



(c)

Figure 6: Ambient Warmness Degree (a), Heating Degree Days (b), and Cooling Degree Days (c) based on RWS and UWS data for the current, mid-, and long-term periods in Urban Block A (Turin)

Table 4 reports the absolute and percentage variations in  $AWD_{18}$ ,  $HDD_{18}$ , and  $CDD_{18}$ , based on UWS data and relative to the current scenario.

Table 4 – Variation in  $AWD_{18}$ ,  $HDD_{18}$ , and  $CDD_{18}$  based on UWS data, relative to the current scenario for Urban Block A (Turin)

| Urban Block A       | $\Delta AWD_{18}$<br>[°C] | $\Delta HDD_{18}$<br>[°C·d] | $\Delta CDD_{18}$<br>[°C·d] | $\Delta AWD_{18}$<br>[%] | $\Delta HDD_{18}$<br>[%] | $\Delta CDD_{18}$<br>[%] |
|---------------------|---------------------------|-----------------------------|-----------------------------|--------------------------|--------------------------|--------------------------|
| Mid-term - current  | + 1.4                     | – 160                       | + 225                       | + 19.7 %                 | – 9.2 %                  | + 27.6 %                 |
| Long-term - current | + 4.2                     | – 586                       | + 714                       | + 59.7 %                 | – 33.9 %                 | + 87.7 %                 |

Table 5 summarises the monthly Urban Heat Island Intensity ( $UHII$ ) under current, mid-term, and long-term climate scenarios.

Table 5 –  $UHII$  for current, mid-, and long-term climate conditions for Urban Block A (Turin)

| Month | Current        | Mid-term       | Long-term      |
|-------|----------------|----------------|----------------|
|       | $UHII$<br>[°C] | $UHII$<br>[°C] | $UHII$<br>[°C] |
| Jan   | 1.5            | 2.2            | 2.2            |
| Feb   | 1.7            | 1.8            | 2.3            |
| Mar   | 1.8            | 1.7            | 1.7            |
| Apr   | 1.6            | 2.0            | 1.5            |
| May   | 1.5            | 1.5            | 1.8            |
| Jun   | 1.8            | 1.7            | 2.0            |
| Jul   | 1.6            | 2.2            | 2.1            |
| Aug   | 2.0            | 2.3            | 1.8            |
| Sep   | 2.2            | 2.1            | 2.0            |
| Oct   | 2.2            | 2.0            | 1.9            |
| Nov   | 2.2            | 2.0            | 1.8            |
| Dec   | 1.2            | 1.9            | 2.0            |

### 3.2 Rome

Figure 7 shows the geometrical representation and building IDs of Urban Block A in the municipality of Rome.

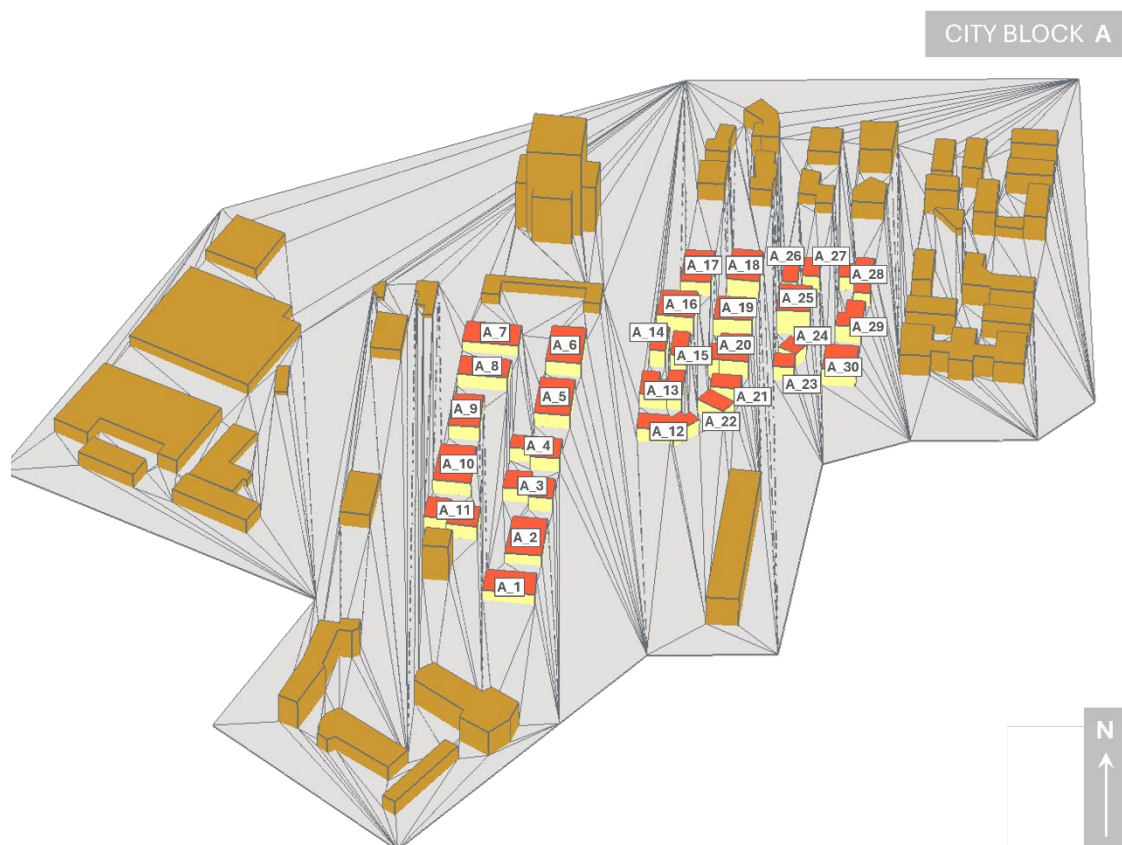
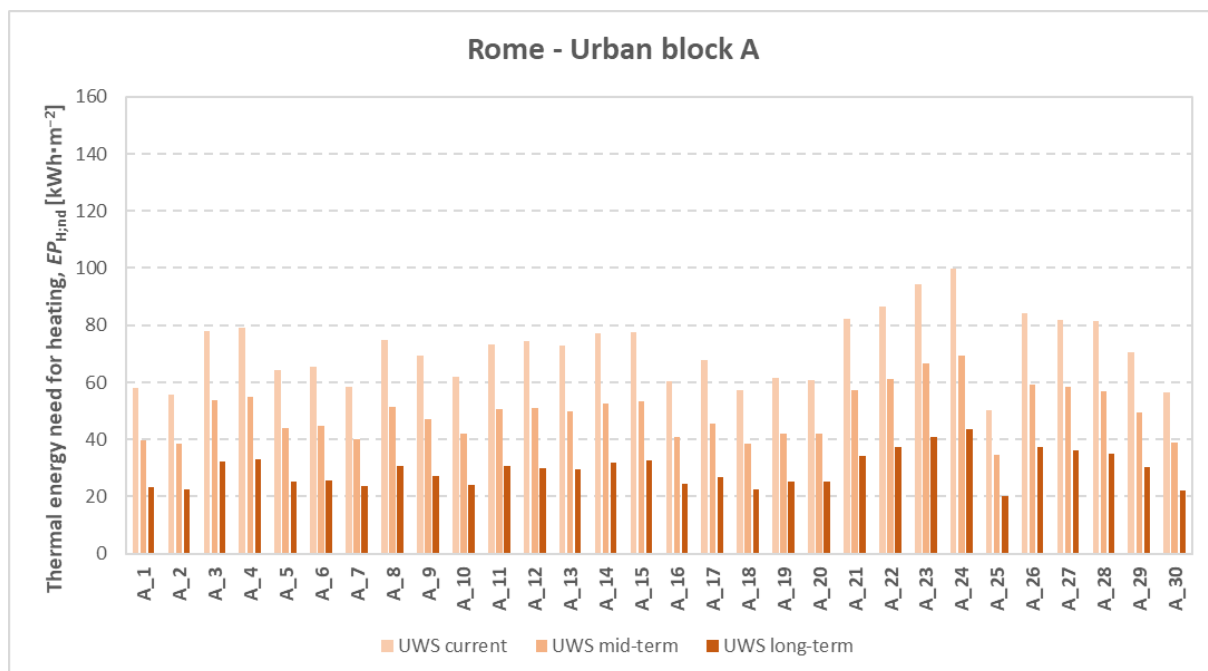


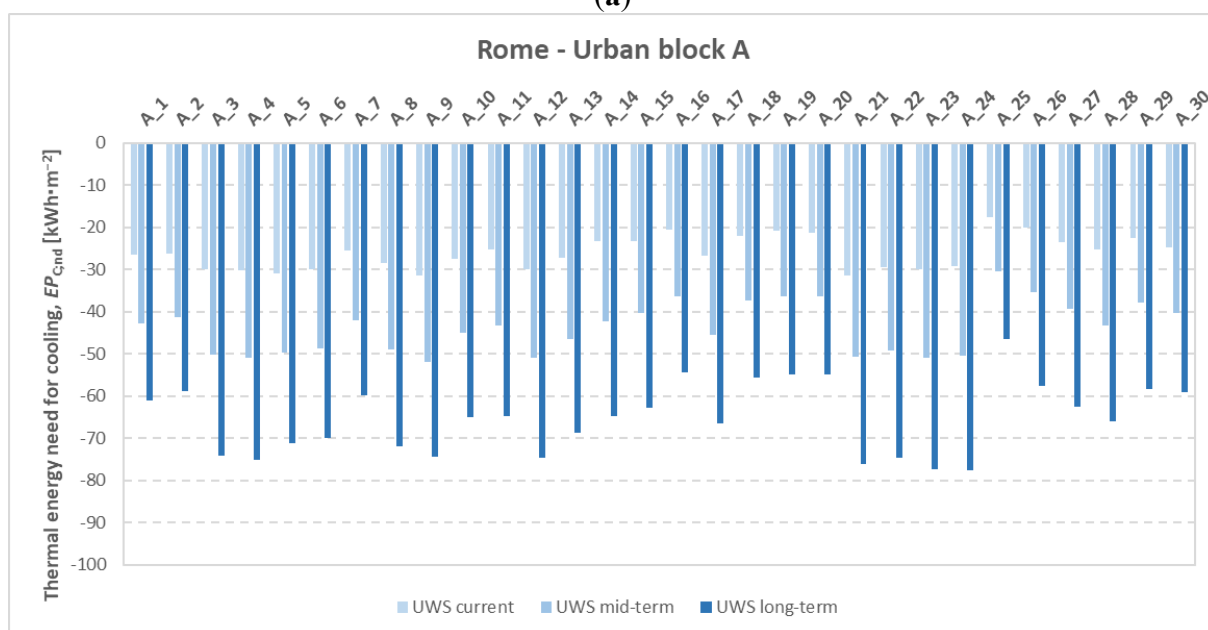
Figure 7: Urban block A (Rome, EUR district) visualised in CitySim Pro

#### 3.2.1 Energy Performance

Figure 8 shows the thermal energy need for space heating ( $EP_{H;nd}$ ) and cooling ( $EP_{C;nd}$ ) of the assessed buildings in Urban Block A, under current, mid-term, and long-term climate scenarios.



(a)



(b)

Figure 8: Thermal energy need for space heating (a) and cooling (b) using UWS data for the current, mid-, and long-term periods for Urban Block A (Rome)

Figure 9 presents the overall building stock  $EP_{H/C,nd}$ , calculated as a net floor area-weighted average of the buildings in the three representative urban blocks, under current, mid-term, and long-term climate scenarios.

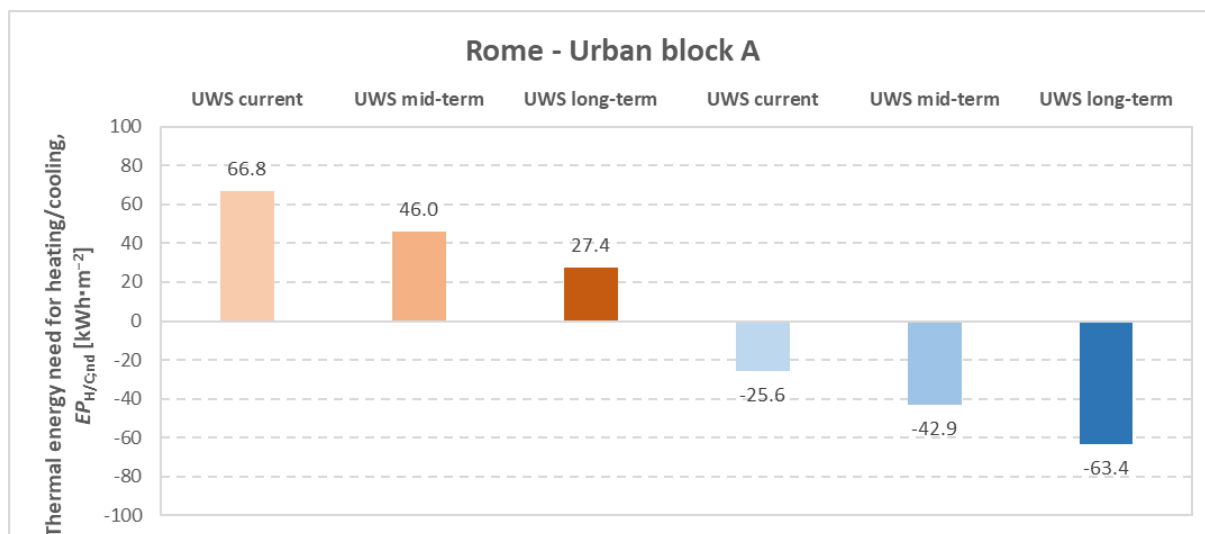


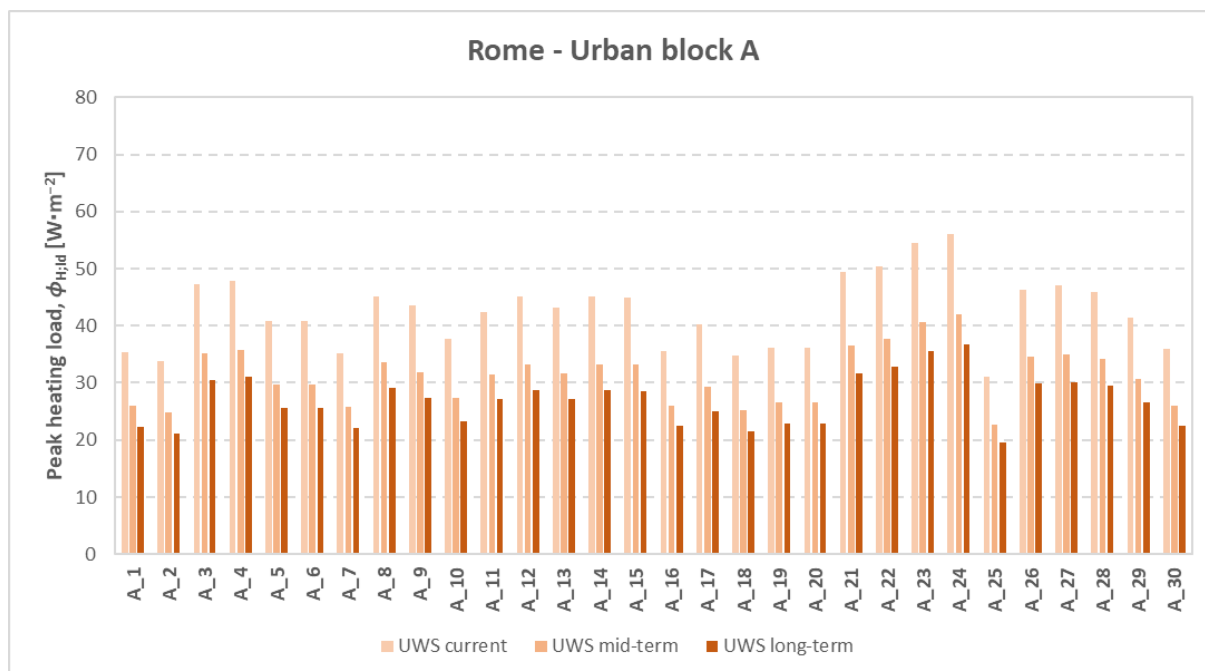
Figure 9: Thermal energy need for space heating and cooling, calculated as a net floor area-weighted average of the buildings, using UWS data for the current, mid-, and long-term periods for Urban Block A (Rome)

Table 6 summarises the reduction in  $EP_{H;nd}$  and the increase in  $EP_{C;nd}$  due to climate change under mid- and long-term climate scenarios, compared to current conditions. The block energy needs are reported both as absolute variations in kWh/m<sup>2</sup> and percentage changes.

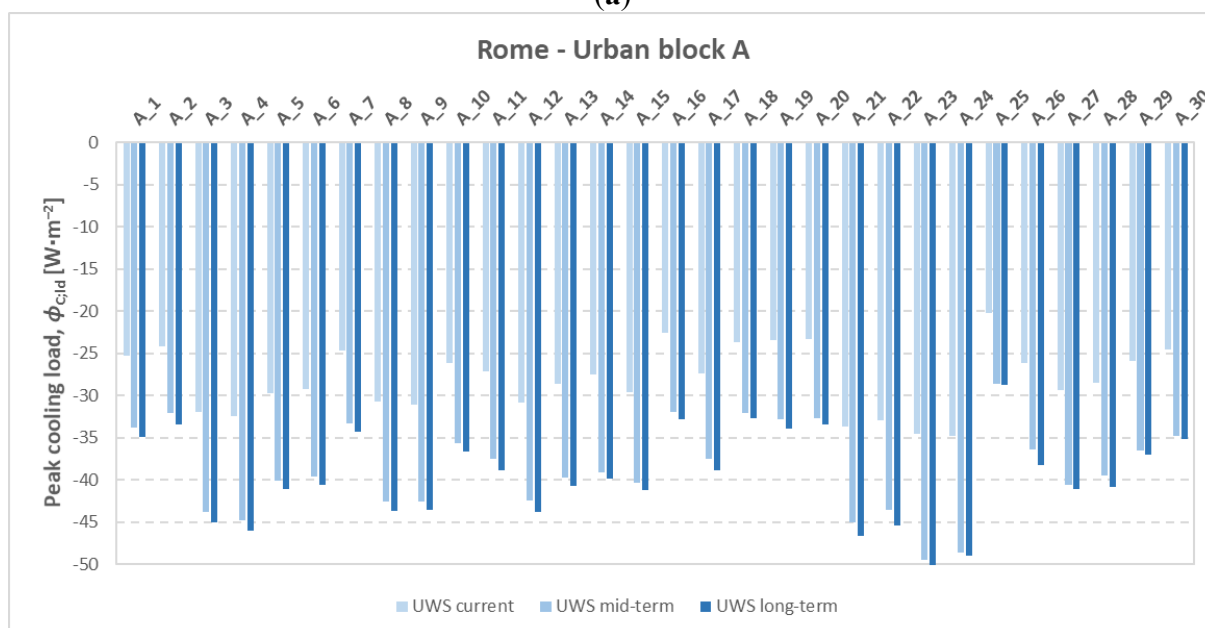
Table 6 – Overall variation in urban block  $EP_{H/C;nd}$  relative to the current scenario for Urban Block A (Rome)

| Urban Block A       | $\Delta EP_{H;nd}$<br>[kWh/m <sup>2</sup> ] | $\Delta EP_{C;nd}$<br>[kWh/m <sup>2</sup> ] | $\Delta EP_{H;nd}$<br>[%] | $\Delta EP_{C;nd}$<br>[%] |
|---------------------|---------------------------------------------|---------------------------------------------|---------------------------|---------------------------|
| Mid-term - current  | – 20.9                                      | + 17.3                                      | – 31.2 %                  | + 67.6 %                  |
| Long-term - current | – 39.5                                      | + 37.8                                      | – 59.1 %                  | + 147.9 %                 |

Figure 10 illustrates the heating ( $\phi_{H;ld}$ ) and cooling ( $\phi_{C;ld}$ ) peak loads of the thermally simulated buildings in Urban Block A, under current, mid-term, and long-term climate scenarios.



(a)

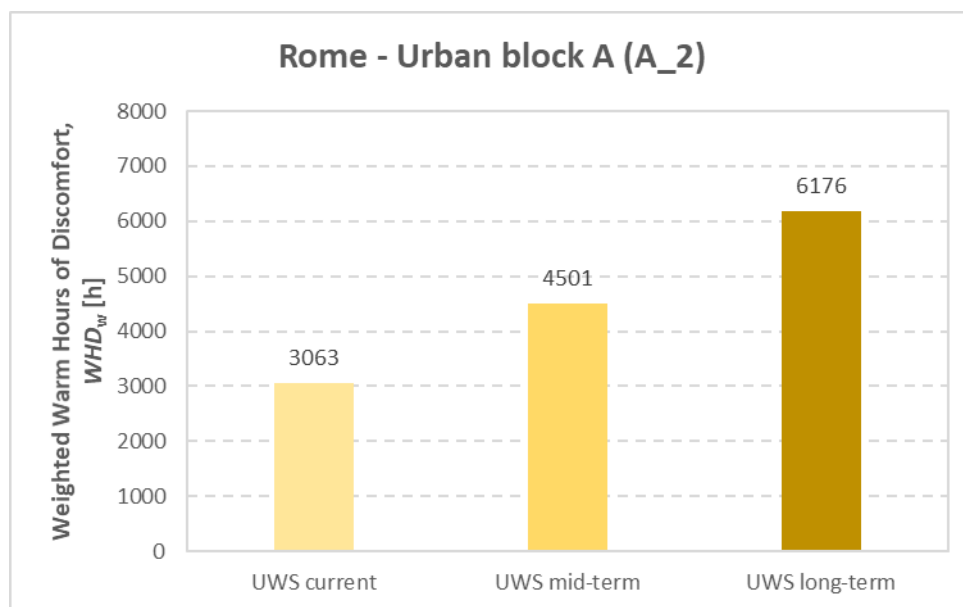


(b)

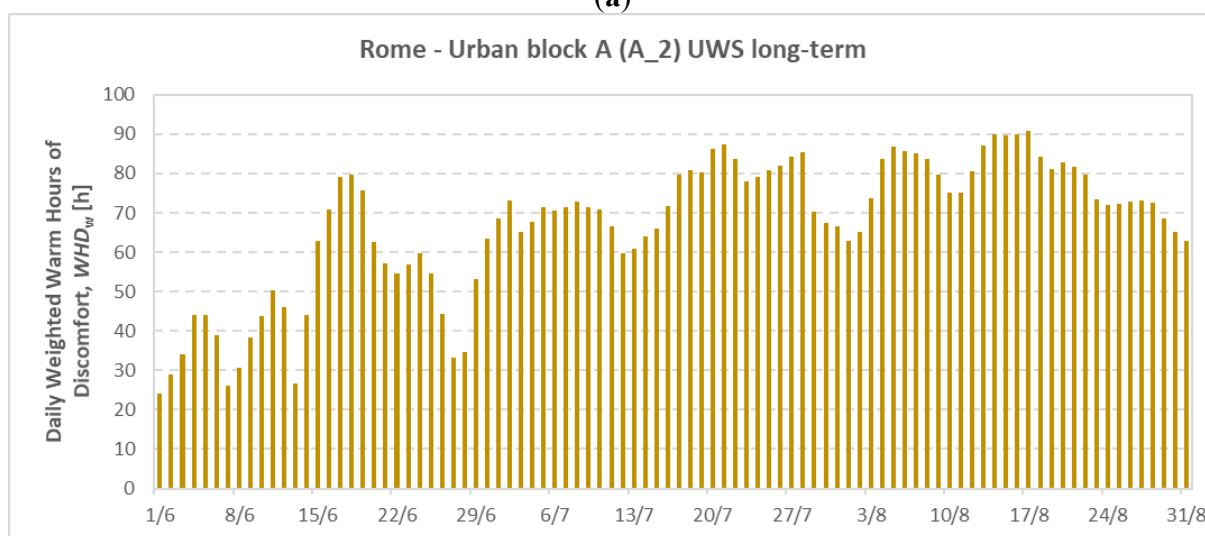
Figure 10: Peak heating (a) and cooling (b) loads using UWS data for the current, mid-, and long-term periods for Urban Block A (Rome)

### 3.2.2 Indoor Thermal Comfort

Figure 11a shows the Weighted Warm Hours of Discomfort ( $WHD_w$ ) for the most vulnerable apartment block (A\_2) in Urban Block A, under current, mid-term, and long-term climate scenarios, based on UWS data. Figure 11b presents the temporal distribution of the daily cumulative  $WHD_w$  for A\_2 over the considered calculation period (June–August) under long-term climate scenario, using UWS data.



(a)

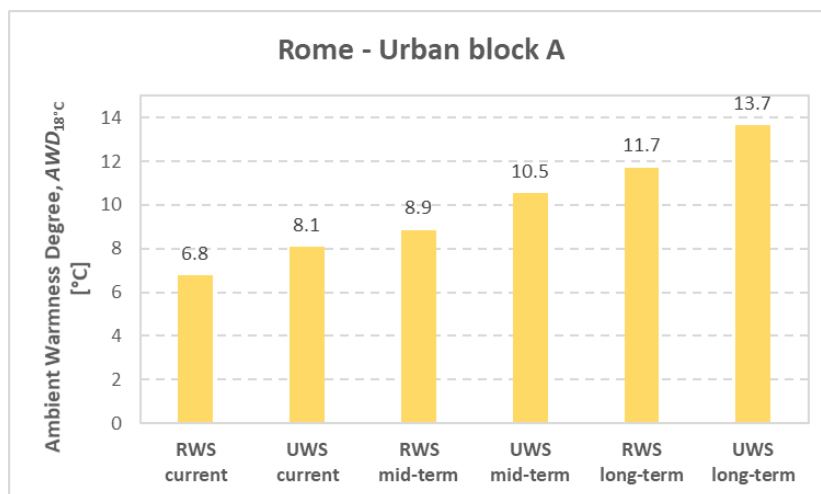


(b)

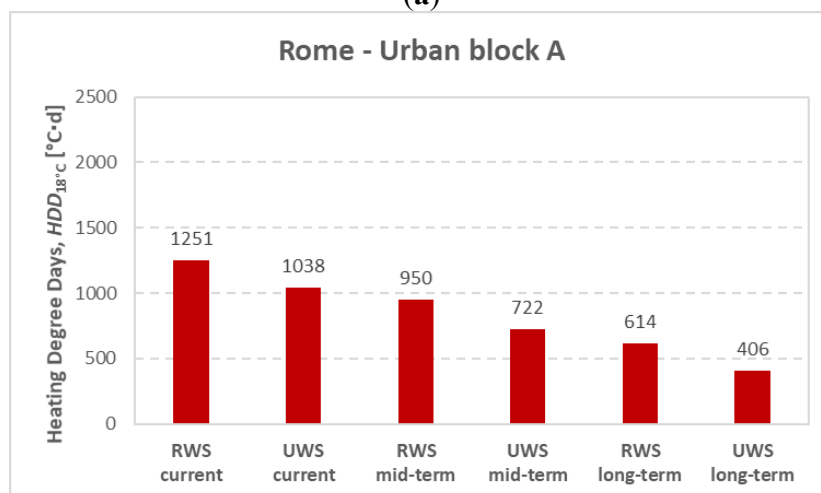
Figure 11: Weighted Warm Hours of Discomfort (WHD<sub>w</sub>) for the most vulnerable apartment block (A\_2), based on UWS data for the current, mid-, and long-term periods in Urban Block A (Rome) (a); daily daily cumulative temporal distribution of WHD<sub>w</sub> for the long-term period, based on UWS data (b)

### 3.2.3 Climate

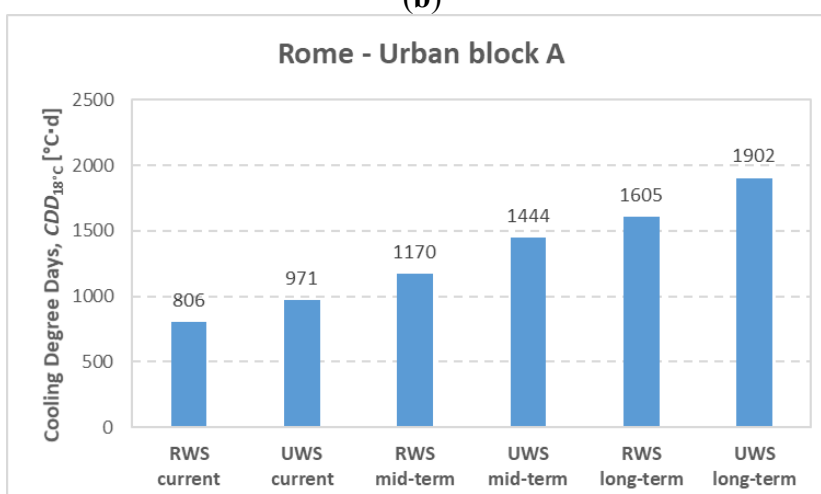
Figure 12a, Figure 12b, Figure 12c show the Ambient Warmness Degree ( $AWD_{18}$ ), Heating Degree Days ( $HDD_{18}$ ), and Cooling Degree Days ( $CDD_{18}$ ), respectively, for Urban Block A under current, mid-term, and long-term climate scenarios, using both *RWS* and *UWS* data.



(a)



(b)



(c)

Figure 12: Ambient Warmness Degree (a), Heating Degree Days (b), and Cooling Degree Days (c) based on RWS and UWS data for the current, mid-, and long-term periods in Urban Block A (Rome)

Table 7 reports the absolute and percentage variations in  $AWD_{18}$ ,  $HDD_{18}$ , and  $CDD_{18}$ , based on UWS data and relative to the current scenario.

Table 7 – Variation in  $AWD_{18}$ ,  $HDD_{18}$ , and  $CDD_{18}$  based on UWS data, relative to the current scenario for Urban Block A (Rome)

| Urban Block A       | $\Delta AWD_{18}$<br>[°C] | $\Delta HDD_{18}$<br>[°C·d] | $\Delta CDD_{18}$<br>[°C·d] | $\Delta AWD_{18}$<br>[%] | $\Delta HDD_{18}$<br>[%] | $\Delta CDD_{18}$<br>[%] |
|---------------------|---------------------------|-----------------------------|-----------------------------|--------------------------|--------------------------|--------------------------|
| Mid-term - current  | + 2.5                     | – 316                       | + 473                       | + 30.8 %                 | – 30.4 %                 | + 48.7 %                 |
| Long-term - current | + 5.6                     | – 632                       | + 931                       | + 69.4 %                 | – 60.9 %                 | + 95.9 %                 |

Table 8 summarises the monthly Urban Heat Island Intensity ( $UHII$ ) under current, mid-term, and long-term climate scenarios.

Table 8 –  $UHII$  for current, mid-, and long-term climate conditions for Urban Block A (Rome)

| Month | Current        | Mid-term       | Long-term      |
|-------|----------------|----------------|----------------|
|       | $UHII$<br>[°C] | $UHII$<br>[°C] | $UHII$<br>[°C] |
| Jan   | 0.9            | 1.1            | 1.1            |
| Feb   | 1.3            | 1.1            | 1.1            |
| Mar   | 1.4            | 1.6            | 1.7            |
| Apr   | 1.1            | 1.7            | 1.8            |
| May   | 1.2            | 1.6            | 1.5            |
| Jun   | 1.2            | 1.7            | 1.7            |
| Jul   | 1.3            | 1.6            | 1.9            |
| Aug   | 1.5            | 1.8            | 2.2            |
| Sep   | 1.2            | 1.9            | 2.2            |
| Oct   | 1.4            | 1.9            | 1.4            |
| Nov   | 0.9            | 1.8            | 1.4            |
| Dec   | 1.1            | 1.0            | 1.1            |

### 3.3 Bari

Figure 13 shows the geometrical representation and building IDs of Urban Block A in the municipality of Bari.

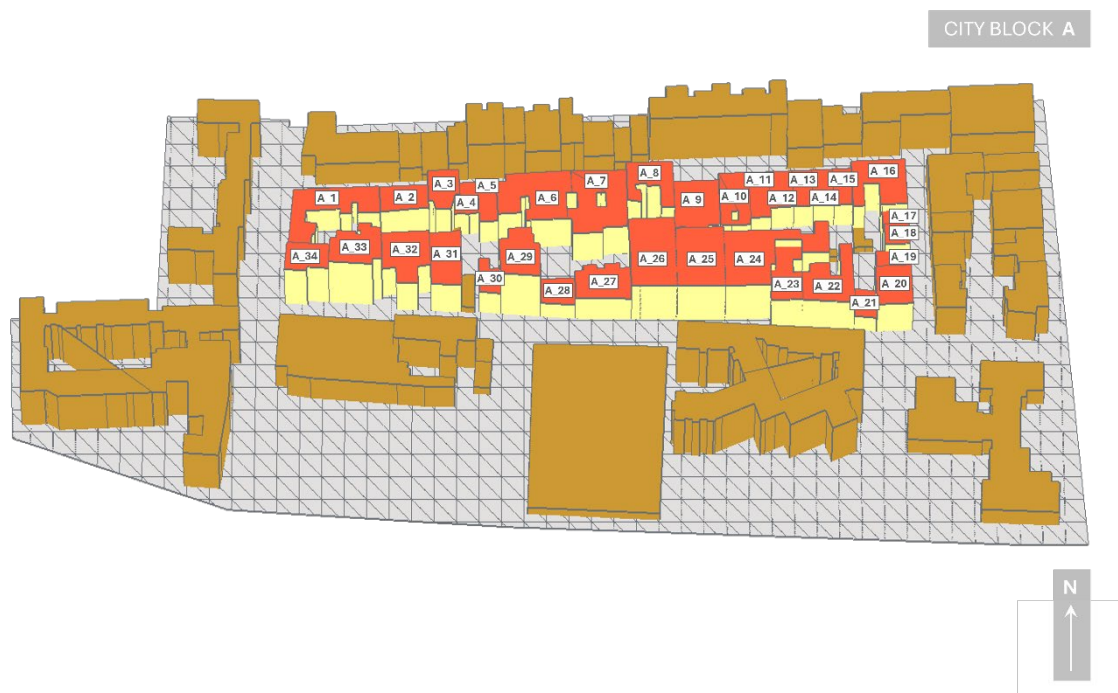
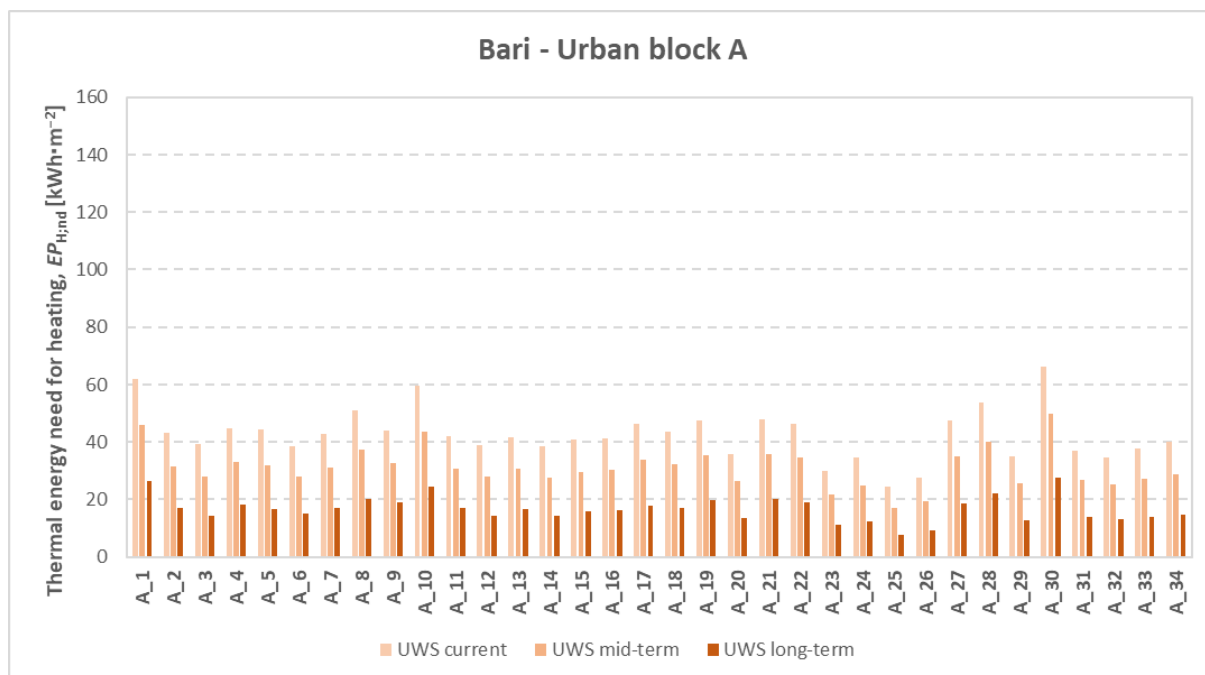


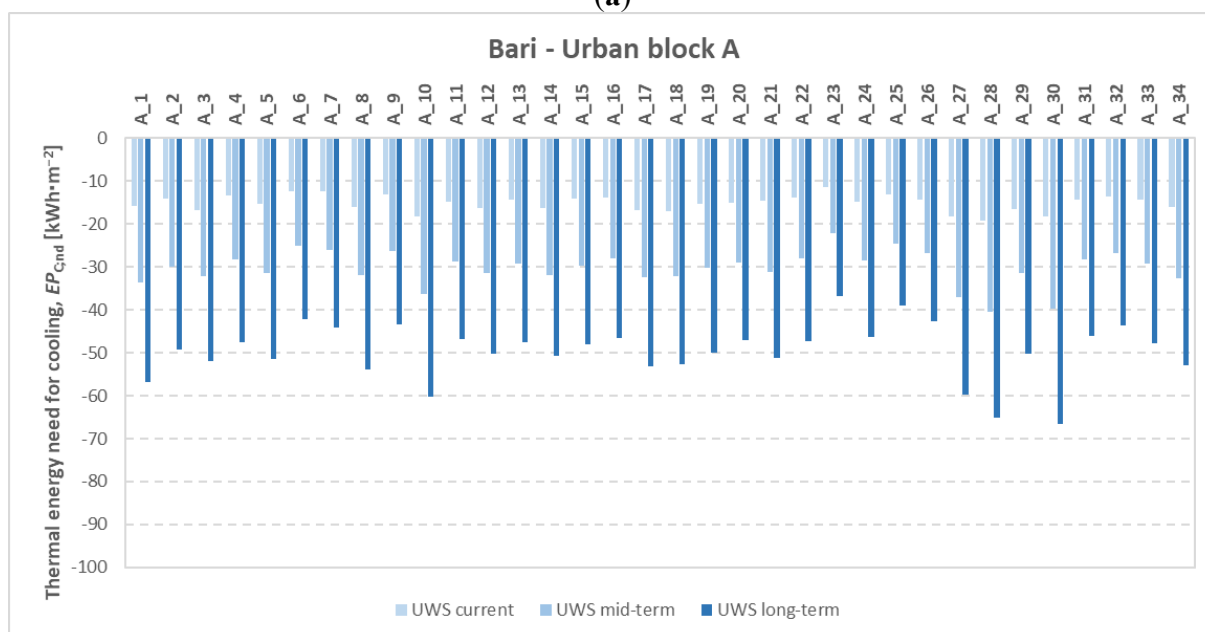
Figure 13: Urban block A (Bari) visualised in CitySim Pro

#### 3.3.1 Energy Performance

Figure 14 shows the thermal energy need for space heating ( $EP_{H;nd}$ ) and cooling ( $EP_{C;nd}$ ) of the assessed buildings in Urban Block A, under current, mid-term, and long-term climate scenarios.



(a)



(b)

Figure 14: Thermal energy need for space heating (a) and cooling (b) using UWS data for the current, mid-, and long-term periods for Urban Block A (Bari)

Figure 15 presents the overall building stock  $EP_{H/C,nd}$ , calculated as a net floor area-weighted average of the buildings in the three representative urban blocks, under current, mid-term, and long-term climate scenarios.

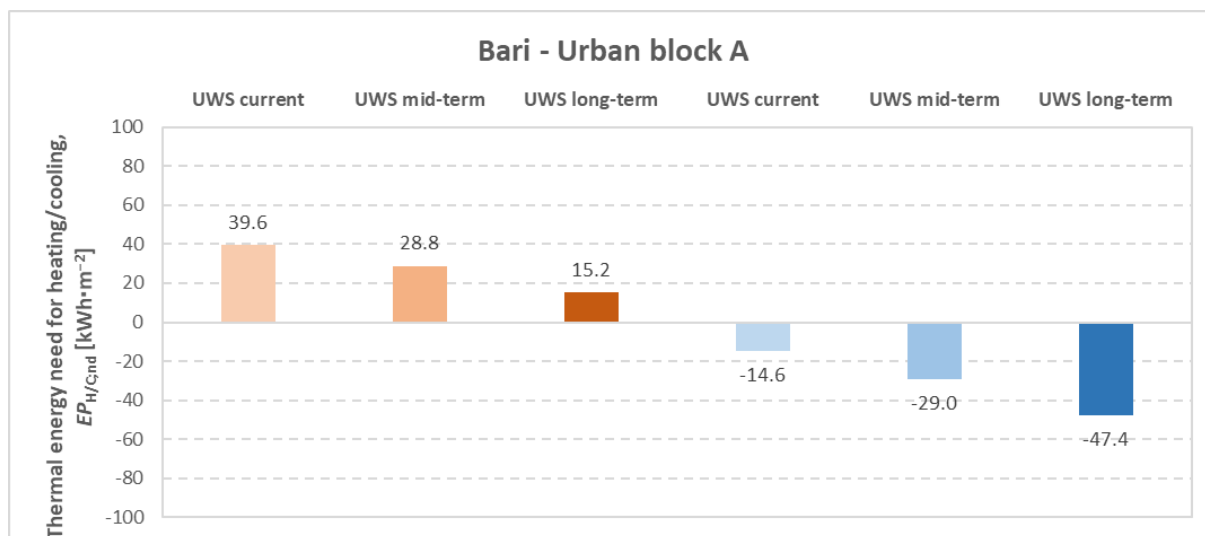


Figure 15: Thermal energy need for space heating and cooling, calculated as a net floor area-weighted average of the buildings, using UWS data for the current, mid-, and long-term periods for Urban Block A (Bari)

Table 9 summarises the reduction in  $EP_{H,nd}$  and the increase in  $EP_{C,nd}$  due to climate change under mid- and long-term climate scenarios, compared to current conditions. The block energy needs are reported both as absolute variations in kWh/m<sup>2</sup> and percentage changes.

Table 9 – Overall variation in urban block  $EP_{H/C,nd}$  relative to the current scenario for Urban Block A (Bari)

| Urban Block A       | $\Delta EP_{H,nd}$<br>[kWh/m <sup>2</sup> ] | $\Delta EP_{C,nd}$<br>[kWh/m <sup>2</sup> ] | $\Delta EP_{H,nd}$<br>[%] | $\Delta EP_{C,nd}$<br>[%] |
|---------------------|---------------------------------------------|---------------------------------------------|---------------------------|---------------------------|
| Mid-term - current  | – 10.8                                      | + 14.4                                      | – 27.2 %                  | + 98.3 %                  |
| Long-term - current | – 24.4                                      | + 32.8                                      | – 61.7%                   | + 224.4 %                 |

Figure 16 illustrates the heating ( $\phi_{H,ld}$ ) and cooling ( $\phi_{C,ld}$ ) peak loads of the thermally simulated buildings in Urban Block A, under current, mid-term, and long-term climate scenarios.

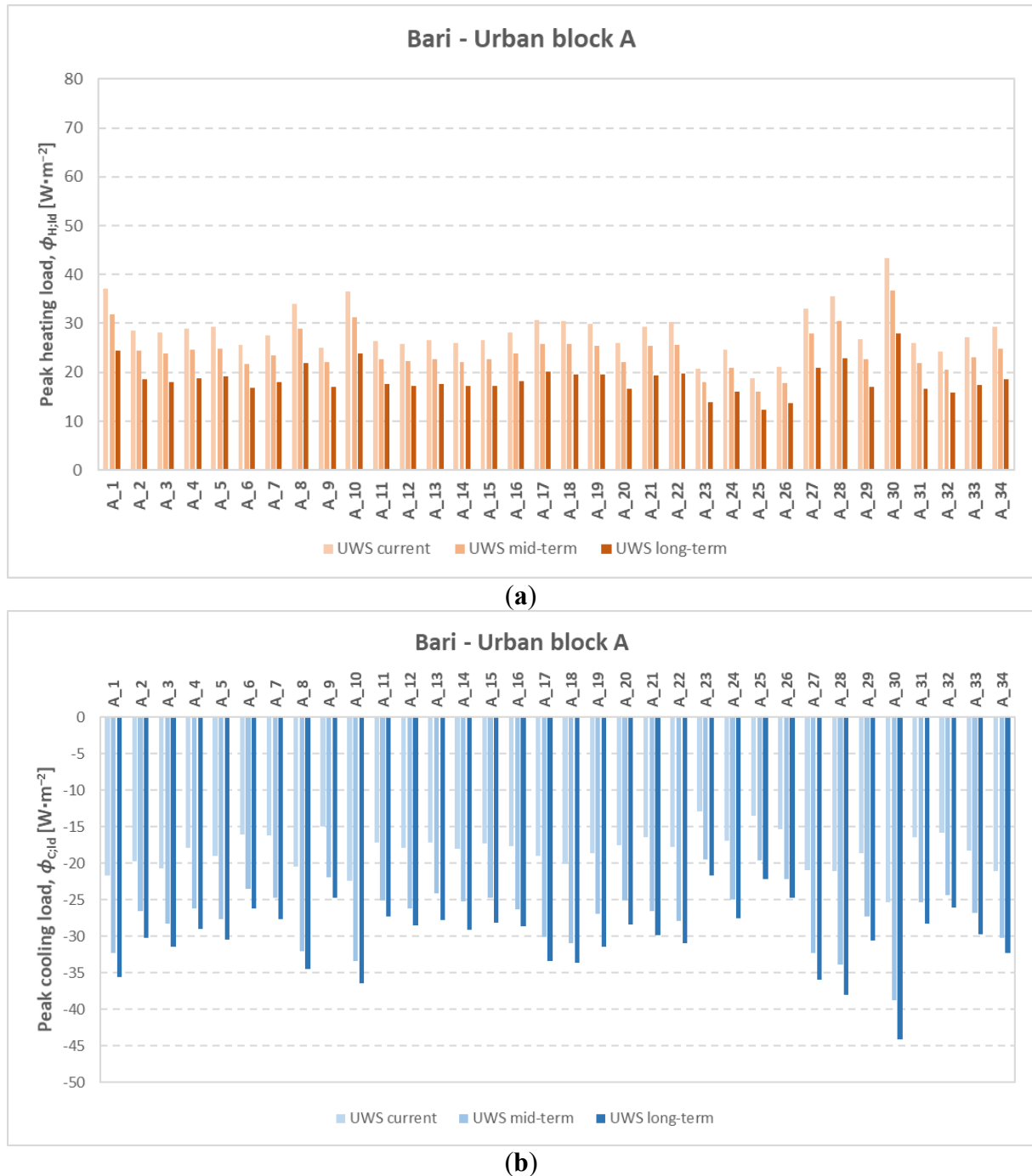
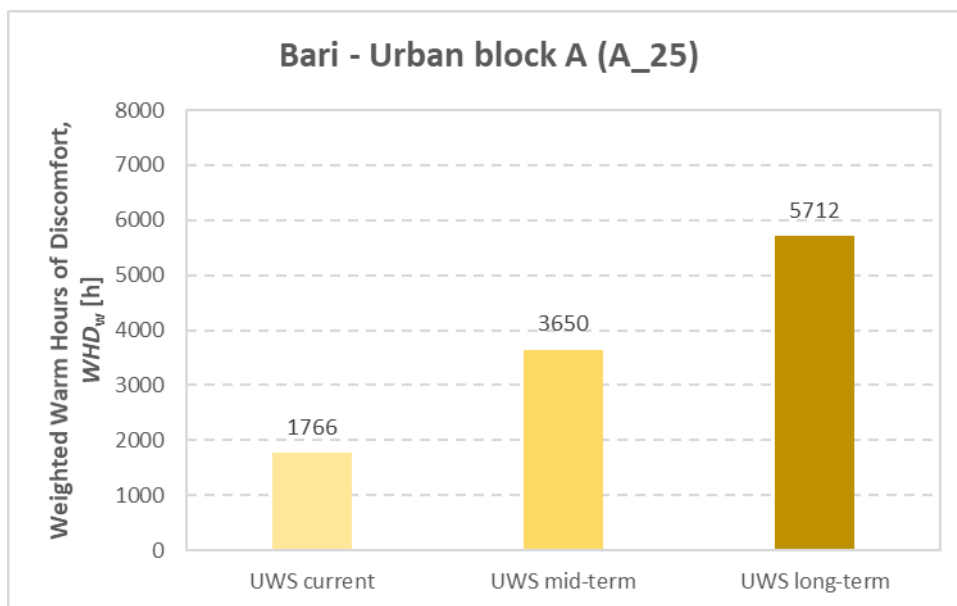


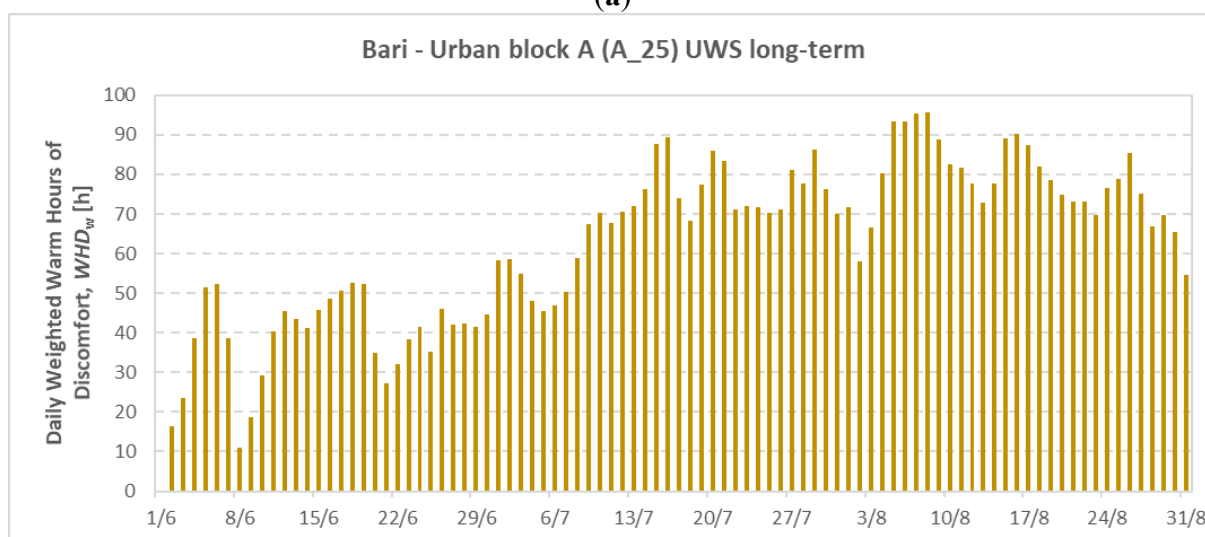
Figure 16: Peak heating (a) and cooling (b) loads using UWS data for the current, mid-, and long-term periods for Urban Block A (Bari)

### 3.3.2 Indoor Thermal Comfort

Figure 17a shows the Weighted Warm Hours of Discomfort ( $WHD_w$ ) for the most vulnerable apartment block (A\_25) in Urban Block A, under current, mid-term, and long-term climate scenarios, based on UWS data. Figure 17b presents the temporal distribution of the daily cumulative  $WHD_w$  for A\_25 over the considered calculation period (June–August) under long-term climate scenario, using UWS data.



(a)

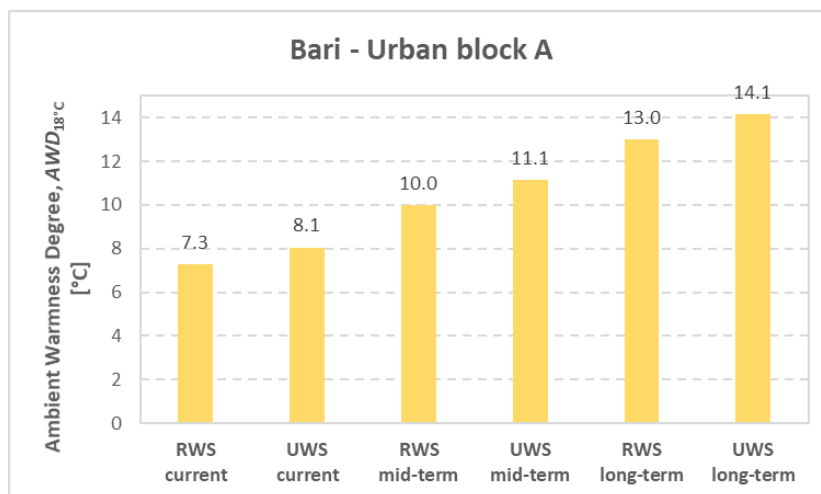


(b)

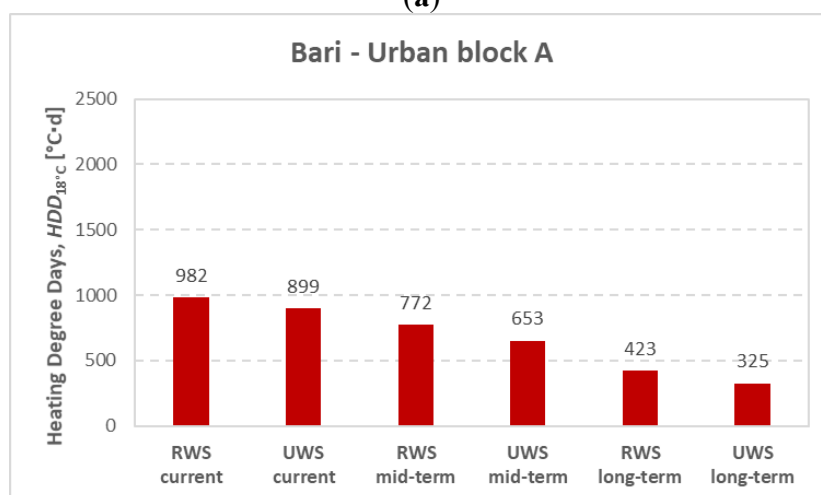
Figure 17: Weighted Warm Hours of Discomfort (WHD<sub>w</sub>) for the most vulnerable apartment block (A\_25), based on UWS data for the current, mid-, and long-term periods in Urban Block A (Bari) (a); daily cumulative temporal distribution of WHD<sub>w</sub> for the long-term period, based on UWS data (b)

### 3.3.3 Climate

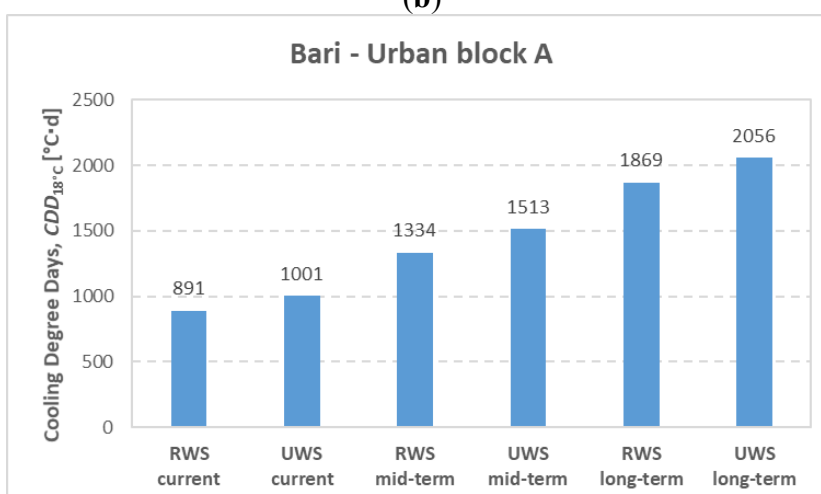
Figure 18a, Figure 18b, Figure 18c show the Ambient Warmness Degree ( $AWD_{18}$ ), Heating Degree Days ( $HDD_{18}$ ), and Cooling Degree Days ( $CDD_{18}$ ), respectively, for Urban Block A under current, mid-term, and long-term climate scenarios, using both *RWS* and *UWS* data.



(a)



(b)



(c)

Figure 18: Ambient Warmness Degree (a), Heating Degree Days (b), and Cooling Degree Days (c) based on RWS and UWS data for the current, mid-, and long-term periods in Urban Block A (Bari)

Table 10 reports the absolute and percentage variations in  $AWD_{18}$ ,  $HDD_{18}$ , and  $CDD_{18}$ , based on UWS data and relative to the current scenario.

Table 10 – Variation in  $AWD_{18}$ ,  $HDD_{18}$ , and  $CDD_{18}$  based on UWS data, relative to the current scenario for Urban Block A (Bari)

| Urban Block A       | $\Delta AWD_{18}$<br>[°C] | $\Delta HDD_{18}$<br>[°C·d] | $\Delta CDD_{18}$<br>[°C·d] | $\Delta AWD_{18}$<br>[%] | $\Delta HDD_{18}$<br>[%] | $\Delta CDD_{18}$<br>[%] |
|---------------------|---------------------------|-----------------------------|-----------------------------|--------------------------|--------------------------|--------------------------|
| Mid-term - current  | + 3.1                     | – 246                       | + 512                       | + 38.3 %                 | – 27.4 %                 | + 51.1 %                 |
| Long-term - current | + 6.1                     | – 574                       | + 1055                      | + 75.6 %                 | – 63.8 %                 | + 105.4 %                |

Table 11 summarises the monthly Urban Heat Island Intensity ( $UHII$ ) under current, mid-term, and long-term climate scenarios.

Table 11 –  $UHII$  for current, mid-, and long-term climate conditions for Urban Block A (Bari)

| Month | Current        | Mid-term       | Long-term      |
|-------|----------------|----------------|----------------|
|       | $UHII$<br>[°C] | $UHII$<br>[°C] | $UHII$<br>[°C] |
| Jan   | 0.4            | 0.5            | 0.5            |
| Feb   | 0.5            | 0.6            | 0.5            |
| Mar   | 0.6            | 0.9            | 0.9            |
| Apr   | 0.5            | 0.9            | 0.7            |
| May   | 0.5            | 0.8            | 0.8            |
| Jun   | 0.6            | 1.2            | 1.1            |
| Jul   | 0.9            | 1.1            | 1.1            |
| Aug   | 0.9            | 1.1            | 1.2            |
| Sep   | 0.7            | 1.2            | 1.3            |
| Oct   | 0.7            | 1.1            | 1.0            |
| Nov   | 0.6            | 0.8            | 0.8            |
| Dec   | 0.4            | 0.7            | 0.6            |

### 3.4 Discussion

In sections 3.1, 3.2, and 3.3, the results concerning building stock energy performance, indoor thermal comfort, and outdoor overheating risks are presented for urban blocks A in the municipalities of Turin, Rome, and Bari, respectively. The *KPIs* were calculated using from CitySim outputs. The building and urban block performances were evaluated under current, mid-term, and long-term climate scenarios, using both rural weather station (*RWS*) and urban weather station (*UWS*) data. *UWS* data were generated by correcting *RWS* data with the Urban Weather Generator (*UWG*) tool. The properties of the building archetypes are reported in D3.1 “*Typical urban context configurations using archetypes*”, while the geometrical and thermal characteristics of the buildings within the assessed urban blocks are detailed in D3.2 “*Atlas of the typical urban context configuration: model features*”.

Due to differences in urban morphology, building orientation, and archetypes, direct comparisons of energy and thermal comfort outcomes across cities are not possible. However, the trends within each municipality can be identified and discussed. As expected, the projected temperature rise due to climate change leads to a general reduction in heating-related indicators ( $EP_{H;nd}$ ,  $\phi_{H;ld}$ ,  $HDD_{18}$ , etc.) and an increase in cooling-related indicators ( $EP_{C;nd}$ ,  $\phi_{C;ld}$ ,  $CDD_{18}$ , etc.), a trend clearly confirmed by the results.

The fluctuations in building energy need ( $EP_{H/C;nd}$ ), which are strongly influenced by variations in external air temperature, are more pronounced than those in peak heating/cooling loads ( $\phi_{H/C;ld}$ ). The latter depend not only on air temperature but also on solar irradiance and building inertia. In Turin, urban block space heating thermal energy need shows a moderate reduction of about  $-9.8\%$  in the mid-term and  $-32.4\%$  in the long-term, while cooling needs rise sharply by  $+74.3\%$  and  $+245.1\%$  (Table 3). In Rome, the decrease in space heating need is even more pronounced, reaching  $-31.2\%$  in the mid-term and  $-59.1\%$  in the long-term, accompanied by a substantial increase in cooling requirements of  $+67.6\%$  and  $+147.9\%$  (Table 6). Bari follows the same pattern (Table 9), with heating needs dropping by  $-27.2\%$  and  $-61.7\%$ , while cooling almost doubles in the mid-term ( $+98.3\%$ ) and more than doubles in the long-term ( $+224.4\%$ ). Overall, the results reveal a consistent pattern: climate change markedly reduces space heating need while strongly amplifies cooling requirements, with effects that intensify toward the long-term.

From the indoor thermal comfort perspectives, the results clearly indicate that the Weighted Warm Hours of Discomfort ( $WHD_w$ ) increase consistently from the current scenario to the mid-term and further to the long-term period. This highlights the strong impact of climate change on indoor overheating and thermal discomfort in urban residential buildings. In all cases, the long-term scenario shows a substantial escalation of  $WHD_w$ , in some instances more than doubling compared to the current period. This emphasises that occupants will be increasingly exposed to overheating risks in the future unless mitigation measures are implemented. The daily cumulative temporal distributions for the long-term period show that discomfort is not evenly distributed across the summer months. Instead, it tends to concentrate in specific heatwave events, during which  $WHD_w$  rises sharply and repeatedly. These peaks are evident throughout July and August, with some clusters also occurring in late June. Such temporal patterns underline the importance of considering not only the seasonal averages but also the frequency and intensity of extreme hot days, which drive the majority of discomfort.

The climate-related *KPIs* are directly dependant on outdoor temperature. According to Italian legislation and  $HDD$  values, Bari belongs to climatic zone C, Rome to zone D, and Turin to zone E. The calculated  $HDD_{18}$  and  $CDD_{18}$  align with this classification. In long-term scenarios,  $HDD_{18}$  decreases by around  $-60\%$  in Rome and Bari (Table 7 and Table 10) and by  $-33.9\%$  in Turin (Table 4). Conversely,  $CDD_{18}$  increases steadily, ranging from  $+87.7\%$  and  $+105.4\%$  (Table 4, Table 7, and Table 10), with Bari showing the highest growth (Table 10). The  $\Delta AWD_{18}$ , calculated over a different period than  $CDD_{18}$ , follows the same upward trend, with increases up to  $+75.6\%$  in the long-term (Table 4, Table 7, and Table 10).

Regarding the Urban Heat Island Intensity ( $UHII$ ), Turin already experiences the highest  $UHII$  values under current conditions, ranging between  $1.2\text{ }^{\circ}\text{C}$  and  $2.2\text{ }^{\circ}\text{C}$  (Table 5), with pronounced peaks in autumn (September–November). In future scenarios,  $UHII$  remains consistently high. Rome starts from intermediate values ( $0.9\text{--}1.5\text{ }^{\circ}\text{C}$  under current conditions) (Table 8) but shows a clear tendency to intensify in mid- and long-term scenarios, particularly during summer and autumn, when  $UHII$  may reach up to  $2.2\text{ }^{\circ}\text{C}$ , approaching the levels observed in Turin. Bari, by contrast, shows the lowest  $UHII$  values (Table 11), generally below  $1\text{ }^{\circ}\text{C}$  at present, with modest increases in summer and early autumn in the mid-term scenario (up to  $1.2\text{--}1.3\text{ }^{\circ}\text{C}$ ).

## 4 GENERAL REMARKS AND CONCLUSIONS

Climate change and Urban Heat Island (*UHI*) effects increase urban temperatures, impacting building energy demand and indoor comfort. The CRiStAll project develops detailed urban climate models and archetype-based Urban Building Energy Models (*UBEM*) to assess selected key performance indicators (*KPIs*) for typical urban contexts under future climate scenarios, focusing on energy performance and thermal comfort in Italian cities.

- **Project overview, selected *KPIs* and methodology:** CRiStAll integrates urban climate modeling within *UBEM* to simulate microscale *UHI* effects and future climate impacts, aiming to evaluate energy performance and thermal comfort in archetypal urban blocks. Calculated *KPIs* presented in the Deliverable D3.3 include energy needs for heating and cooling, peak loads, Weighted Warm Hours of Discomfort (*WHD<sub>w</sub>*), and climate indicators such as Ambient Warmness Degree (*AWD*), Heating and Cooling Degree Days (*HDD*, *CDD*), and Urban Heat Island Intensity (*UHII*). Calculations are based on CitySim outputs.
- **Simulation assumptions:** Buildings are modeled as single thermal zones, and certain indoor comfort metrics (Indoor Overheating Degree and Overheating Escalation Factor) were not calculated due to data limitations. *KPIs* were computed for current, mid-term, and long-term climate scenarios using urban and rural weather station data corrected by the Urban Weather Generator tool.
- **Results:**
  - **Turin.** Heating energy needs decrease by up to – 32.4 % in the long-term, while cooling needs increase by + 245.1 %. Peak heating loads decline moderately, and peak cooling loads rise significantly under future climate scenarios. *WHD<sub>w</sub>* increases substantially over time, indicating rising indoor overheating risks, with discomfort concentrated during heatwave periods in summer months. Ambient Warmness Degree and Cooling Degree Days increase markedly, while Heating Degree Days decrease. *UHII* ranges from 1.2 °C to 2.2 °C currently, with peaks in autumn and consistent values projected for future scenarios.
  - **Rome and Bari:** Rome shows larger reductions in heating needs (up to – 59.1 %) and increases in cooling demand (up to + 147.9 %), with *UHII* rising to 2.2 °C in summer/autumn. Bari exhibits heating reductions up to – 61.7 % and cooling increases over + 224 %, with lower *UHII* values generally below 1 °C but increasing modestly in summer.
- **Overall findings:** Climate change is projected to significantly reduce space heating need and increase cooling requirements across Italian urban contexts, intensifying indoor overheating risks. *UHI* effects remain significant, especially in Turin and Rome, underscoring the need for targeted mitigation strategies in urban energy planning.

## NOMENCLATURE

### Symbols

|            |                                                          |
|------------|----------------------------------------------------------|
| <i>AWD</i> | Ambient Warmness Degree [ $^{\circ}\text{C}$ ]           |
| <i>CDD</i> | Cooling Degree Days [ $^{\circ}\text{C}\cdot\text{d}$ ]  |
| <i>EP</i>  | Energy Performance indicator [ $\text{kWh}/\text{m}^2$ ] |
| <i>HDD</i> | Heating Degree Days [ $^{\circ}\text{C}\cdot\text{d}$ ]  |
| <i>IOD</i> | Indoor Overheating Degree [ $^{\circ}\text{C}$ ]         |
| <i>t</i>   | time [h]                                                 |
| <i>UHI</i> | Urban Heat Island Intensity [ $^{\circ}\text{C}$ ]       |
| <i>WDH</i> | Weighted Hours of Discomfort [h]                         |
| <i>wf</i>  | weighting factor [–]                                     |
| $\alpha$   | Overheating Escalation Factor [–]                        |
| $\theta$   | temperature [ $^{\circ}\text{C}$ ]                       |
| $\phi$     | areic heat load [ $\text{W}/\text{m}^2$ ]                |

### Subscripts

|    |              |
|----|--------------|
| b  | base         |
| C  | cooling      |
| e  | external     |
| H  | heating      |
| ld | load         |
| nd | need         |
| rm | running mean |
| w  | warm         |

### Acronyms

|      |                                      |
|------|--------------------------------------|
| UBEM | Urban Building Energy Model/Modeling |
| UHI  | Urban Heat Island                    |
| RWS  | Rural Weather Station                |
| UWS  | Urban Weather Station                |

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