UNIVERSITA' DEGLI STUDI DI PADOVA

**Dipartimento di Ingegneria Industriale DII**

Dipartimento di **Ingegneria Industriale**

Corso di Laurea Magistrale in Energy Engineering

# *Development and assessment of the Unterhaching district energy model using EUReCA and Urban Heat Pro*

RELATORE

**Prof. Dr. Michele de Carli**
**Università degli Studi di Padova**

CANDIDATO

**Marco Vanzetto**
**Matricola 2054146**

CORRELATORE

**Prof. Dr. Thomas Hamacher**
**Technische Universität München**

**M.Sc. Leonhard Odersky**
**Technische Universität München**

**Dr. Enrico Prataviera**
**Università degli Studi di Padova**

**Dr. Sara Bordignon**
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# Abstract

This thesis focuses on the development and assessment of the building energy model of the Unterhaching district using EUReCA and UrbanHeatPro. These models have been developed by the Department of Industrial Engineering at the University of Padua and by the Renewable and Sustainable Energy Systems group at the Technical University of Munich (TUM), respectively. The main purpose is to analyse the differences between the two tools and how they calculate heating and cooling energy demands by simulating the behavior of an entire city, specifically Unterhaching.

To carry out this comparison, two main simulations are presented: the first simulation considers consumption using standard input data for UrbanHeatPro and EUReCA, as they areusually set for each tool (this simulation is referred to as "simulation with no adaptation of input data"); the second simulation ("simulation with adaptation of input data") involves tweaking the input data of the two piece of software in order to make them as similar as possible. The latter simulation aims at understanding whether differences in the results are due to different building energy model used.

This thesis is then concluded with an optimization. The analysis involves evaluating two different technologies for building heating and cooling production, i.e., heat pumps and boiler and electric chillers, while minimizing energy usage and investment costs.

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# Introduction

The increase of the temperature compared to pre-industrial levels is an increasingly pressing issue that requires immediate and strong intervention. This problem affects all countries worldwide, making it crucial for global measures to be implemented. As highlighted in the published report *IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels"* temperature is steadily rising [1]. In particular, human-induced warming reached approximately 1°C above pre-industrial levels in 2017, increasing at 0.2°C per decade. This increase of the temperature is attributed to various factors and undoubtedly the $CO_2$ emissions contribute significantly to this phenomenon. Regarding to that, the figure Figure 0.1 illustrates the $CO_2$ emissions across different sectors: it's clear that the buildings' filed carry significant weight, making it of paramount importance to evaluate and implement energy efficiency measures within this sector.

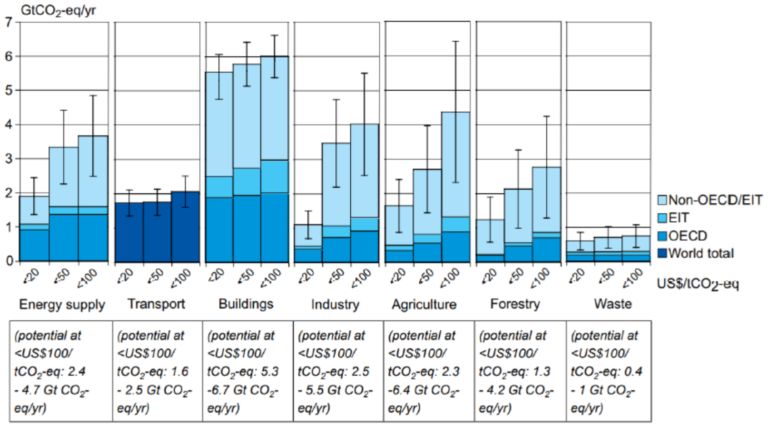


*Figure 0.1: Global potential of mitigation from IPCC [2]*

The increase in temperature has significant consequences in the field of both residential and non-residential buildings, such as the rising demand for air conditioning. In fact, air conditioning systems have witnessed a 55% increase in Germany, from 127,000 to 227,000 units between 2012-2021 (data sourced from *Statista, Demand for air conditioners in Germany from 2012 to 2021*). Similarly, in Italy, there has been a 60% increase in the same period (data sourced from *Statista, Demand for air conditioners in Italy from 2012 to 2021*) [3].

This number will increase during the next years with the consequently increase of the cooling demand: for this reason, it's important to evaluate which is the cooling demand required by single town and to evaluate which is the role and the impact on the consumption of the refurbishment.

Regarding the calculation of the heating and cooling demand, the buildings are considered as a dynamic system: it means that the system evolves over time. The goal is to define a principle that links old and new values of the variables of the system; for this reason, different modelling approaches are used depending on the level of detail needed. Different models can be distinguished from the simplest to the most complex:

- Steady-state models
- Quasi-steady-state models
- Simplified dynamic models
- Detailed dynamic models

### Steady-state models

The steady-state model is used for determining the design heating capacity of a heating system: this approach is adopted in the standard BS EN 12831 [4]. The assumption is that the heat flows depends by the transmission heat losses ($q_T$) and the ventilation heat losses ($q_V$):

$$q = q_T + q_V \tag{1.}$$

The ventilation heat losses depend on the ventilation heat transfer coefficient $H_V$ and by the temperature difference between indoor and outdoor.

The transmission heat losses depend on two different contributions: direct and indirect losses. The direct losses are the one that are exchanged between indoor and outdoor through the thermal bridge, the roof and the external wall exposed to the wind, while the direct losses are the one that are exchanged between indoor and outdoor through unheated spaces and through the ground.

In that way, knowing the heat losses due to transmission and ventilation, the heat flows can be evaluated.

### Quasi steady – state models

In these models the dynamic effects are taken into account introducing correlation factors. As reported in the standard BS EN ISO 13790 [5], an utilization factor for the internal and solar heat gain is used for the heating: in fact, it considers that only a part of the internal heat gains is used to decrease the energy need for the heating, while the rest leads to an undesired increase of the internal temperature above the set-point temperature: in other words, the gain utilization factor is a measure of the amount of the overheating.

So, the monthly or seasonal energy need for heating is calculated according to:

$$Q_{H,nd} = Q_{H,ht} - \eta_{Hgn} \cdot Q_{H,gn} \qquad 2.$$

Where $Q_{H,ht}$ is given by the sum of the ventilation and transmission heat losses, while $Q_{H,ng}$ is given by the sum of the solar radiation and the internal loads: so, it's the total heat load. $\eta_{Hgn}$ is the gain utilization factor.

For the cooling two different approaches can be considered:

- Loss utilization factor:
  it considers that only a part of the transmission and ventilation heat transfer is used to decrease the energy need for the cooling. Even if the set-point temperature is not always reached, the transmission and ventilation heat transfer are calculated referring to the set-point temperature for the cooling.
  So, the monthly or seasonal energy need for cooling is calculated according to:
  $$Q_{C,nd} = Q_{C,gn} - \eta_{C,ls} \cdot Q_{C,ht} \qquad 3.$$
  Where $Q_{C,ht}$ is the total heat transfer for cooling by transmission and ventilation, $Q_{C,gn}$ is the total solar and internal heat gains for the cooling and $\eta_{C,ls}$ is the loss utilization factor.
- Gain utilization factor (as for the heating):
  It takes in account that only part of the internal and solar heat gains is compensated by thermal heat transfer by transmission and ventilation, assuming a certain maximum internal temperature. The other part leads to cool needs to avoid an undesired increase of the internal temperature above the set-point.

**Dynamic models**

About the dynamic models, they are defined by the simplified and the detailed ones. In the simplified dynamic models the behaviour of the building is represented by a series of resistances and of capacitances. The number of the resistances and of the capacitances represent the order of the model.

In particular, a model with five resistances and one capacitance (5R1C) is proposed [5]. That model permits to have a time-step lower than one hour and to predict the annual energy needs for space heating with good accuracy. It has also a good load profile in heating season but, on contrary, it fails predicting the peak load after long shut down periods.

About detailed dynamic models, they can be implemented in software for building simulations as TRNSYS, EnergyPlus and so on. It can be used different methods in order to describe these models, such as the transfer function method, finite element methods, finite difference methods and so on.

However, in order to evaluate the energy required for heating and for cooling, the thermal balance of a room must be evaluated. In fact, a building is considered as a series of rooms in which the thermal balance is calculated. Let's start considering the balance on a generic room surface (that is in contact with the external environment) with uniform air temperature and with uniform external air temperature. In Figure 0.2 are reported the heat flows on a generic surface.

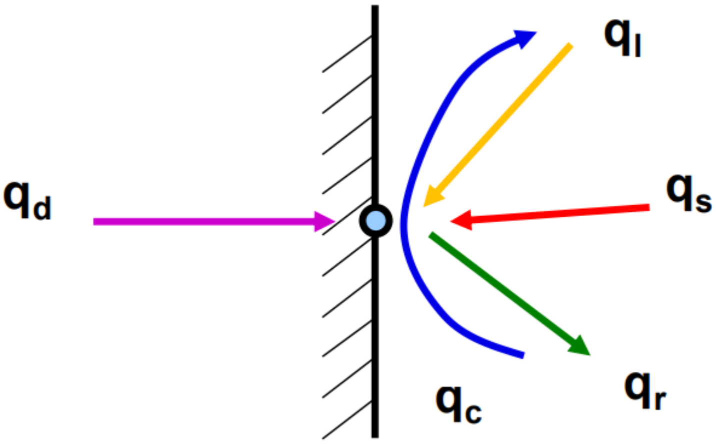


*Figure 0.2: Heat flows on a generic surface*

The heat flows that contribute to the balance are the conduction heat flow, convective heat flow, the infrared radiation heat flow, the high frequency radiant heat flow due to solar radiation and the radiant heat flow due to lighting or other internal gains.

So, considering the generic surface, the total heat flow is:

$$q_{d,i} + q_{c,i} + q_{r,i} + q_{s,i} + q_{l,i} = 0 \quad 4.$$

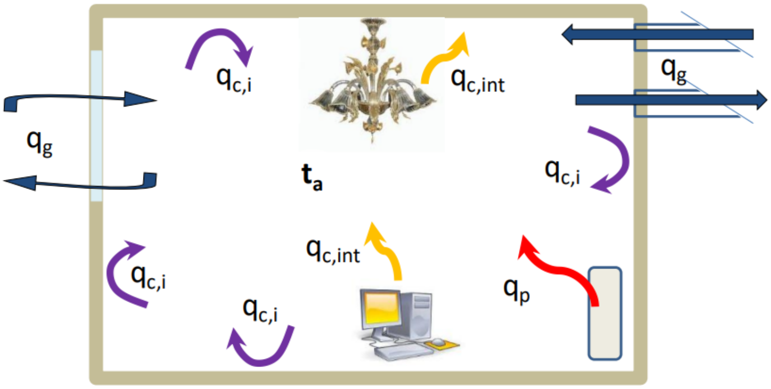


*Figure 0.3: Thermal balance of a room*

In particular, in Figure 0.3, $q_{c,i}$, $q_{c,int}$, $q_{c,p}$, $q_g$ and $q_p$ are respectively the convective heat exchange with internal surfaces of the building envelope, the convective heat exchange with internal heat sources as lights and appliances, the convective heat exchange with HVAC system, the convective heat exchange due to ventilation and infiltration and the convective heat power of the internal plants. So, the thermal balance of the air can be written as:

$$\sum_{i=1}^{n} q_{c,i} + q_{c,int} + q_g + q_p = \frac{M_a \cdot c_V \cdot [T_a - T_{a-\Delta\tau}]}{\Delta\tau} \qquad 5.$$

In the equation (5), the ratio on the right side represents the internal energy variation with respect to the time where $T_a$ and $T_{a-\Delta\tau}$ are the temperature of the whole air mass $M_a$ respectively at the current timestep and at the previous timestep.

So, the equation (4) must be applied for each surface of the room, while the equation (5) must be applied only once. Therefore, if the building has n surfaces, n equation of (4) are set and just one equation (5) is defined: it brings to a system with $n+1$ equations but with $n+2$ variables: it means that a new equation has to be introduced in order to solve the system and, depending on the goal, the internal air temperature ($T_a$) of the room can be set, or the heat flow required by the plant ($q_p$) can be defined.

If the internal air temperature is fixed, the variable that must be found is the heat required by the plant: as consequence, the heating and cooling demand can be evaluated. On other hand, if the heat flow required by the plant is fixed, the goal is to find the value of the internal temperature of the room.

### Urban Building Energy Models

So, since the different types of models are explained for the calculation of the heating and cooling, it’s possible to enter in the field of the Urban Building Energy Modelling (UBEM) in order to define the behaviour of the tools (EUReCA and UrbanHeatPro) and to evaluate energy scenarios to better manage and design cities.

According to [6], “Urban Building Energy Model is born as a research field to study urban and city-level energy system, it aims at developing methods and tools to collect, manage and forecast energy data at city-scale”.

Two different approaches can be used: top-down or bottom-up approach as reported in Figure 0.4. According to [7], the “top-down models determine the effect on the energy consumption due to ongoing long-term changes or transition within residential sector”; while “the bottom-up approach encompasses all models which use input data from a hierarchal level less than that of the sector as a whole”. In other words, the top-down models start from urban energy model, but they are not able to consider the energy demand of each individual building explicitly. On the other hand, the bottom-up models define the behaviour of the city starting by the knowledge of statistical data and engineering methods: as consequence, the end-use and the consumption per each building can be evaluated. Note that only engineering methods are able to simulate the consequences of important changes (for instance massive refurbishments) thanks to their high level of detail [8].

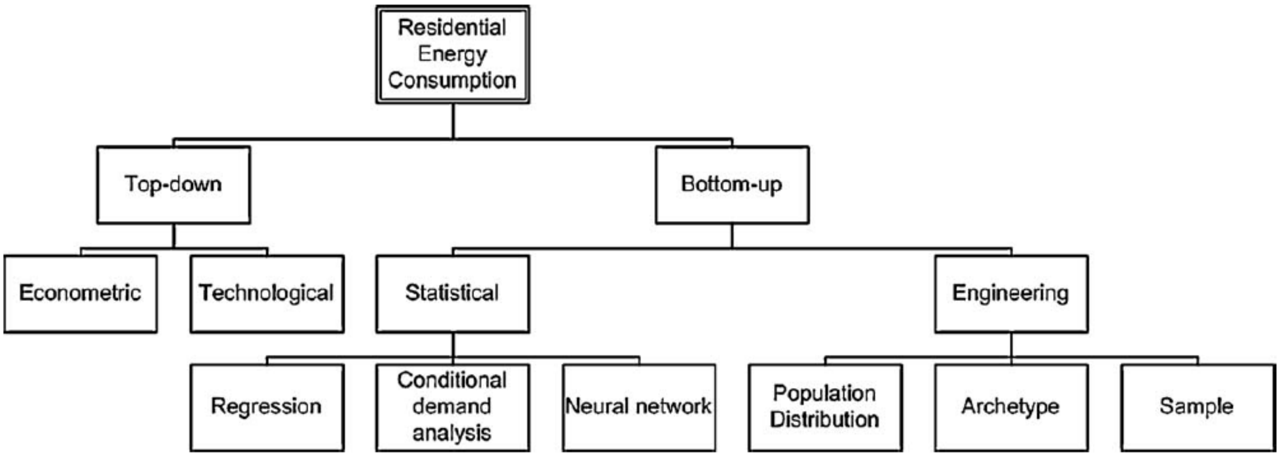


*Figure 0.4: Top-down and bottom-up modelling techniques [7]*

According to [9], three different approaches can be considered:

- White-box approach
- Gray-box approach

- Black-box approach

The white-box approaches are based on a very detailed physical description of the building and for this reason they can be implemented in simulation software like EnergyPlus: the thermal behaviour of the building can be obtained in an accurate way.

Black-box approaches are based on the analysis of measured time series and statistical data. They don’t require any previous knowledge of the physical description of the building (so the computational power required is lower). On the other hand, they are not able to evaluate non-linear effects and they have good performances and solutions just for a limited range of values.

Grey-box approaches represent intermediate models between the two previously described. The main concept of the grey-box models is to define the building through capacities (C) and resistances (R): for this reason, they are referred to as RC-lumped models. The number of resistances and capacities used defines the order of the RC-model, in particular:

- UrbanHeatPro is 1R1C model;
- EUReCA is 5R1C model.

Up to now, the different kind of models that can be used for the evaluation of heating and cooling demand have been shown: in particular, both EUReCA and UrbanHeatPro are a stand-alone Python-based Urban Building Energy Model tool for the bottom-up simulation of large districts and city, predicting the dynamic behaviour of the building.

In this thesis, both for UrbanHeatPro and EUReCA, the set-point temperature of the room is fixed in order to evaluate the heating and cooling demand: in fact, the goal is to compare the different behaviour of the two software and to obtain the real consumption of Unterhaching, a city close to Munich. Once the district heating and the district cooling are obtained, an optimization is proposed through the software urbs: in this part, the goal is to evaluate which is the best technology, considering a ground source heat pump and a condensing boiler with a compression chiller, to satisfy the energy demand simulated with the previously mentioned software.

# 1. Models description: UrbanHeatPro, EUReCA, urbs

In the following chapter the general aspects of three different software tools that are used for this thesis will be presented. In particular, the first two software, UrbanHeatPro and EUReCA (developed respectively by researchers from the *Technische Universität München (*TUM*)* and from *Università degli Studi di Padova*), simulate the building's energy demand of an entire city, while urbs (a software developed by researchers from the *Technische Universität München (*TUM*)*) is an optimization tool, that aims at the minimization of the cost of supplying energy with different technologies.

## 1.1 UrbanHeatPro – General aspects

UrbanHeatPro is a Python-based bottom-up for the evaluation of heating, domestic hot water and cooling demand of a district: it allows to evaluate the total actual consumption of the building and to perform simulation with different levels of refurbishment. The tool is developed through the grey-box approach, representing the building with one resistance (R) and one capacity (C), as represented in Figure 1. 1 ($R_{eq}$ represents the equivalent heat transfer coefficient, while $C_{eq}$ represents the equivalent thermal mass). The resistance (R) depends on the heat losses $H_T$ between internal environment at temperature T(t) and external environment at temperature $T_0$(T). $H_T$ has a positive sign only if the heat is entering inside the building.

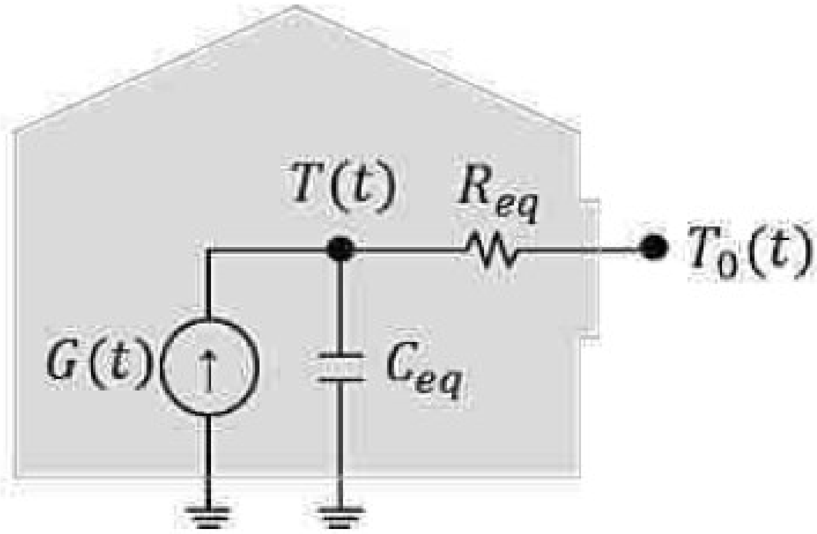


*Figure 1. 1: Single zone building model (1R1C)*

*Calculation of the heat balance of the building*

According to [10], the building is considered as an accumulator with a uniform temperature T(t) and an equivalent heat capacity $C_{eq}$.

G(t), instead, represents the sum of all gains:

- solar gains $G_s$
- internal gains $G_i$
- external heat input $P_{in}$

The solar gains $G_s$ are calculated, for the simulation with UrbanHeatPro, as the contribution of two different factors [11]:

$$G_{s,tr} = A \cdot F_F \cdot F_V \cdot g_{tot} \cdot I_{s,max} \tag{6.}$$

$$G_{s,op} = R_{se} \cdot U \cdot A \cdot (\alpha \cdot I_{s,max} - F_f \cdot h_r \cdot \Delta T_{er}) \tag{7.}$$

Where:

- $G_{s,tr}$ and $G_{s,op}$ are respectively the solar heat gains through transparent component and the solar heat gains through opaque components;
- $I_{s,max}$ is the maximum hourly solar irradiance and it's expressed in W/m$^2$;
- $A$ is the area of the transparent component in (16) and of the opaque component in (17);
- $U$ is the thermal transmittance while $R_{se}$ is the thermal resistance: they give information on the insulation of the building;
- $F_F$ is the reduction factor due to frame portion: it indicates the ratio of the transparent area to the total area;
- $F_V$ is the dirt depreciation factor;
- $g_{tot}$ is the total energy transmittance: it includes sun shading and the glazing's material properties;
- $R_{se}$ is the thermal resistance,
- $\alpha$ is the absorption coefficient,
- $F_f$ is the radiation-effective form factor: it's equal to 1 for angles up to 45° of inclination and it's equal to 0.5 for angles higher than 45° of inclination;
- $h_r$ is the external radiative heat transfer coefficient;
- $T_{er}$ is the difference between the external air temperature and sky temperature.

Up to this point, the evaluation of the heat balance of the building can be determined as follows:

$$\frac{dQ}{dt} = \frac{1}{C_{eq}}[H_T(T,t) + G(t)] \qquad 8.$$

By including the heat gain and heat loss mechanisms, the previous equation becomes:

$$\frac{dT}{dt} = \frac{1}{R_{eq} \cdot C_{eq}} \cdot [T_0(t) - T(t)] + \frac{1}{C_{eq}} \cdot \left[P_{in(t)} + G_i(t) + G_s(t)\right] \; for\ heating \qquad 9.$$

$$\frac{dT}{dt} = \frac{1}{R_{eq} \cdot C_{eq}} \cdot [T_0(t) - T(t)] + \frac{1}{C_{eq}} \cdot \left[-P_{in(t)} + G_i(t) + G_s(t)\right] \; for\ cooling \qquad 10.$$

Where:

$$R_{eq} = R_t + R_v \qquad 11.$$

$$R_t = \frac{1}{\sum_i U_i \cdot A_i} \qquad 12.$$

$$C_{eq} = \sum_i m_i \cdot c_i \qquad 13.$$

in which, $R_v$ represents the ventilation losses, $R_t$ represents the transmission losses and $U$, $A$, $m$ and $c$ represent the thermal transmittance coefficient, the area, the mass and the specific heat capacity of the building element $i$ respectively. The building is considered as a cube, that is delimited by 4 different building elements: external walls, windows, roof and floor.

The differences between equation (9) and (10) is due to the fact that when the external temperature of the air becomes higher than the temperature of the building, the ventilation and transmission losses (they were losses for the heating) become gains (so, ventilation and transmission gains for the cooling). Since the temperature difference expresses this phenomenon, nothing changes on the relation (20), but their contribution is now different. The internal gains remain constant because they are seen as a heat source. The only difference regards the power (that is now negative) because the system has to cool down the building.

The heat flow due to transmission losses through a building that has an external air temperature higher than the internal one, is evaluated as:

$$Q_T = \sum H_T(T_a - T_i) \cdot t \qquad 14.$$

Where $H_T$ is the heat transfer coefficient due to transmission between the building and the external environment, $T_a$ is the external ambient temperature, $T_i$ is the internal building temperature and t is the duration of the calculation.

For the evaluation of the $H_T$, the U-values and the Area must be specified as reported in the paragraph *2.1 UrbanHeatPro – Input data,* and the typical values per category of building are taken by the online webtool TABULA (Typology Approach for Building Stock Energy Assessment) calculation method, published in 2013 by the IWU (Institut Wohnen und Umwelt). TABULA is a webtool that gives general information about the typical data of each building classified on the basis of the year of construction and on the typology (if single family house, multi-family house, terrace house and apartment block). TABULA has information on all the example buildings for all the European states (including also UK). [12].

The calculation method for ventilation losses and solar gains were adapted from the TABULA calculation method.

***Method of power calculation for heating and for cooling demand demand***

Firstly, the energy for the space heating (or for the space cooling) is calculated as the amount of energy required in order to maintain the set-point temperature of the building. Note that, as specified in the previous paragraph, the ambient temperature of the building must to be set as input. The calculation of the power can be evaluated as:

$$P_{in}(t_n) = \begin{Bmatrix} C_{eq} \cdot [T_{set} - T_i(t_{n-1})] - (Q_T + Q_V) \cdot [T_a(t_{n-1}) - T_i(t_{n-1})] + \\ +[Q_s(t_{n-1}) + Q_i(t_{n-1})] \end{Bmatrix} \cdot a(t_n) \qquad 15.$$

$T_{set}$ is the set-point temperature at which we want to maintain the internal temperature of the building.

$T_{set}$ must be maintained only if the building is occupied: for this reason, there is a strict connection between the occupancy of the building and its heating and cooling. Moreover, a set-back temperature is fixed for the occupancy of the building during the night. Therefore, to calculate the energy needs for cooling and heating, a time-dependent occupancy profile must be taken into account: this is the role of the parameter $a(t_n)$ that considers the occupancy of the building. Note that during the absence of occupancy (holidays) there is no room control of the temperature of the building. Another role of $a(t_n)$ is to introduce a heating event if the temperature is lower than the lowest permitted one. In fact, per each category of building (residential or non-residential), it's defined also a *dt* that represents the range around the set-point temperature in which the heating system switches on or switches off: for instance, if $T_{set} = 18\ °C$ with $dt = 2\ °C$, it means that the heating system starts to work when the temperature becomes lower that 16 °C and it stops when the temperature becomes higher than 20 °C.

Therefore:

- if the temperature at time step $(t_{n-1})$ is higher than the set-point temperature $(t_{set})$, the power at time $(t_n)$ is equal to zero: it means that the space heating demand is null;
- if the temperature at time step $(t_{n-1})$ is lower than the set-point temperature $(t_{set})$, the power at time $(t_n)$ calculated until the temperature $T_i(t_n)$ is equal to the set-point temperature $(t_{set})$: it means that the space heating demand is required.

In the end, the total power for the space heating demand per each time step (the simulation is performed considering 1 time-step per hour) is calculated as:

$$P_{in,total-heating} = \sum P_{in-heating} \cdot (t_n) \qquad 16.$$

About the cooling load calculation, the logic is the same, but in the opposite direction: in fact, the thermal behaviour of the building is the same both for cooling and for heating. It means that if the outside temperature increases, the internal temperature of the building increases too. So, if we set a set-point temperature, a cooling system must be present in order to keep the temperature controlled in the building: so, as for the heating, the space cooling energy demand is equal to the demand of cooling to maintain the internal temperature of the building under-control (close to the set-point temperature).

The cooling load can be calculated as:

$$P_{in}(t_n) = \begin{Bmatrix} C_{eq} \cdot [T_i(t_{n-1}) - T_{set}] - (Q_T + Q_V) \cdot [T_a(t_{n-1}) - T_i(t_{n-1})] + \\ +[Q_s(t_{n-1}) + Q_i(t_{n-1})] \end{Bmatrix} \cdot a(t_n) \qquad 17.$$

The $T_{set}$ must be maintained only if the building is occupied: for this reason there is a strict connection between the occupancy of the building and its cooling energy demand $a(t_n)$ that considers the occupancy of the building. Note that during the absence of occupancy (holidays) there is no room control of the building temperature.

Another role of $a(t_n)$ is to introduce a cooling event if the temperature is higher than the highest permitted one. In fact, per each category of building (residential or non-residential), it's defined also a $dt$ that represents the range around the set-point temperature in which the cooling system switches on or switches off: for instance, if $T_{set} = 24\ °C$ with $dt = 2\ °C$ it means that the cooling system starts to work when the temperature becomes higher that 26 °C and it stops when the temperature becomes lower than 22 °C.

Summarizing:

- if the temperature at time step $(t_{n-1})$ is lower than the set-point temperature $(t_{set})$, the power at time $(t_n)$ is equal to zero: it means that the space cooling demand is null;
- if the temperature at time step $(t_{n-1})$ is higher than the set-point temperature $(t_{set})$, the power at time $(t_n)$ calculated until the temperature $T_i(t_n)$ is equal to the set-point temperature $(t_{set})$: it means that the space cooling demand is required.

In the end, the total power for the space heating demand per each time step (the simulation is performed considering 1 time-step per hour) is calculated as:

$$P_{in,total-cooling} = \sum P_{in-cooling} \cdot (t_n) \qquad 18.$$

About the calculation of the domestic hot water, UrbanHeatPro based the calculation on various input parameters, including the average daily consumption of hot water, the capacity of the hot water tank, the probabilities of hot water consumption, the simulation time frame and other relevant information as the seasonal variation, which accounts for the changes in hot water demand across different seasons. Additionally, the model considers the active hours of the building, representing the time periods when occupants are present and likely to use hot water. The probabilities of hot water consumption for different load categories, such as showers, baths, medium loads, and small loads, are also incorporated.

The simulation calculates the flows, durations, and volumes of hot water consumed in each time interval, taking into account the probabilities and specific load variables. For example, the model generates events of hot water consumption, such as showers or baths, based on random numbers and probability distributions. These events are then used to calculate the corresponding hot water flows and durations, creating a realistic representation of hot water consumption over time. The state of hot water tank is also tracked during the simulation. As hot water is consumed, the tank's volume decreases, and when it reaches a certain limit, the tank is refilled to maintain the supply of hot water.

## 1.2 EUReCA – General aspects

EUReCA (Energy Urban Resistance Capacitance Approach) is a python-based urban building energy modelling tool for the hourly calculation of district heating and cooling energy demand.

The building element component, as for UrbanHeatPro, is modelled through a single thermal zone. Moreover, the building is schematized with five resistances and one capacity (5R1C) according to [5]. By [6] the Figure 1. 2 (a) represents the physical scheme of the model while Figure 1. 2(b) represents the equivalent electrical network.

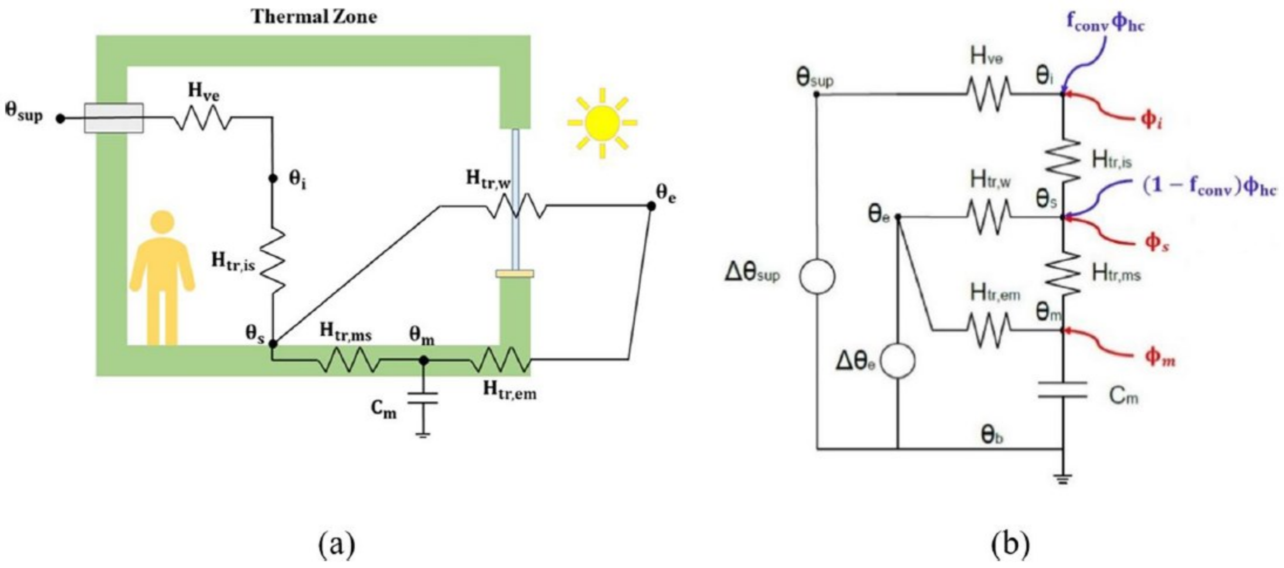


*Figure 1. 2: 5R1C model. (a) Physical scheme. (b) Equivalent electrical network*

As reported in the previous imagine, there are five different nodes:

- node *i*: refers to internal air
- node *s:* refers to all surface
- node *m*: refers to all structures
- node *sup:* refers to the supply air
- node *e*: refers to the external air

Moreover, five different heat transfer coefficients are present:

- $H_{ve}$ is the ventilation heat transfer coefficient that considers both the contribution of the ventilation and infiltration. It depends on the density $\rho_a$, the specific air heat $c_a$ and on the k-th external air flow rate $\sum\dot{V}$

$$H_{ve} = \rho_a c_a \sum \dot{V} \tag{19.}$$

- $H_{tr,w}$ is the glazed surfaces transmission coefficient, given by the product between the thermal transmittance of the window $U_w$ and the area $A_w$:

$$H_{tr,w} = \sum U_w \cdot A_w \tag{20.}$$

- $H_{tr,ms}$ is the coupling conductance between node *m* and *s*, given by the heat transfer coefficient between node *m* and *s* ($h_{ms}$)and by the effective mass area ($A_m$) which depends on the heat capacity:

$$H_{tr,ms} = h_{ms} \cdot A_m \tag{21.}$$

- $H_{tr,is}$ is the copuling conductance between node *i* and *s (*$h_{is}$), given by the product between the coupling heat transfer coefficient and the total area of the building ($A_{tot}$):

$$H_{tr,is} = h_{is} \cdot A_{tot} \tag{22.}$$

- $H_{tr,op}$ is the opaque structure heat transfer coefficient and $H_{tr,em}$ is the coupling conductance between node *m* and *e*: they compose $H_{tr,ms}$.

The thermal capacitance is calculated according to [13]. So, a system for the calculation of the heat flux can be set in order to calculate the heating or cooling energy demand:

$$H_{ve}(\theta_{sup} - \theta_i) + H_{tr,is}(\theta_s - \theta_i) + \phi_i + f_{conv}\phi_{hc} = 0 \tag{23.}$$

$$H_{tr,w}(\theta_e - \theta_s) + H_{tr,is}(\theta_i - \theta_s) + H_{tr,ms}(\theta_m - \theta_s) + \phi_s + (1 - f_{conv})\phi_{hc} = 0 \tag{24.}$$

$$H_e(\theta_e - \theta_m^{\tau}) + H_{tr,ms}(\theta_s - \theta_m^{\tau}) + \phi_m + \frac{C_m}{\Delta\tau}(\theta_m^{\tau-\Delta\tau} - \theta_m^{\tau}) = 0 \tag{25.}$$

Where $\theta_{sup}$ is the supply temperature, $\theta_i$ is the air temperature of the thermal zone, $\theta_s$ is the surface temperature, $\theta_m^{\tau}$ and $\theta_m^{\tau-\Delta\tau}$ are the thermal capacitance temperatures for the current and previous simulation time step, $f_{conv}$ is a parameter that was used to model different radiative and convective contributions.

These equations derive from the energy balance in the previous chapter, whereas here they are applied to the 5R1C model: as previously stated, the simulation is performed hour after hour by fixing the internal temperature of the building and obtaining as a result the heat flow rate that must be produced in order to maintain the set-point temperature.

Considering the solar contribution, solar heat gains are crucial for the thermal balance of an environment and they can significantly impact the heating and cooling load, especially with low-efficiency glazing. To assess these gains, the RC model considers the transmission, absorption, and reflection coefficients of glazing components. To simplify its application across numerous buildings, a model has been developed that utilizes U and $SHGC_n$ values to define angular profiles for reflection, transmission, and SHGC.

The procedure calculates the thermal resistance of the equivalent layer and the transmission, absorption, and reflection coefficients for normal incidence. The angles of solar radiation incidence are calculated using solar declination, the equation of time, and the hour angle, combined with window characteristics. Finally, solar heat gains through opaque surfaces and glazing are evaluated using the parameters obtained from the RC model.

Finally, the standard BS EN ISO 13790 [5] defines that the total solar heat gains can be calculated as:

$$\phi_{sol} = \sum(F_{sh}A_{sol}I_{sol} - F_r R_{se} U A h_r \Delta T_{er}) \qquad 26.$$

Where $F_{sh}$ is the shading coefficient for external obstacles, $I_{sol}$ is the total solar irradiance, $F_r$ is the view factor between the surface and the sky, $R_{se}$ is the outside film resistance, $U$ is the thermal transmittance, $A$ is the area (given by the contribution of the transparent and opaque component), $h_r$ is the radiative heat transfer coefficient and $\Delta T_{er}$ is the temperature difference between external temperature and sky apparent temperature.

$A_{sol}$ is given by the contribution of the effective collecting area through glazed elements (depending on the shading coefficient for ventilation blinds, window area, frame portion of the window area and the solar heat gain coefficient) and the effective collecting area through opaque components (depending on the absorption coefficient, thermal transmittance, outside film resistance and the frame area).

Moreover, the latent load calculation is not included in ISO 13790 standard, and neither the mechanical ventilation is considered. This may have little significance when considering industrial buildings (since residential buildings typically do not have mechanical ventilation systems). Therefore, even though not defined in ISO 13790, they have been implemented in order to create a model that simulates the reality as close as possible. Regarding mechanical ventilation, an Air Handling Unit (AHU) has been constructed using equations that take into account the common components of an AHU: sensible and latent heat recovery, air mixer, dehumidification, adiabatic saturator and post-heater coil.

The domestic hot water demand is calculated according to the standard UNI/TS 11300 [14]: it's the national standardization organization in Italy; it aims to define, develop and public technical standards in various sectors. In particular, the domestic hot water demand is calculated as follows:

$$Q_{DHW} = \rho \cdot c \cdot (\theta_{required} - \theta_{aqueduct}) \cdot V_{day} \tag{27.}$$

Where $V_{day}$ depends on the area of the building (as reported in

Table 1. 1) according to the next relationship:

$$V_{day} = a \cdot A_f + b \tag{28.}$$

*Table 1. 1: values of the parameter a and b in function of the area of the building for the calculation of the domestic hot water demand*

| | $A_f \leq 35$ | $35 < A_f \leq 50$ | $50 < A_f \leq 200$ | $A_f > 200$ |
|---|---|---|---|---|
| a[l/(m$^2$ day)] | 0 | 2.667 | 1.067 | 0 |
| b[l/(day)] | 50 | -43.33 | 36.67 | 250 |

### 1.3 urbs – General aspects

urbs is a linear programming optimization model for multi-tasking energy systems, their sizing, development and utilization. It finds the lowest cost energy system to meet the given demand time series for possible multiple commodities.

In particular, an energy system optimisation framework takes as input the time series information and essential parameters of an energy system then, as output, it gives back the optimal expansion and dispatch planning, the total costs and the CO2 emissions. urbs works with MIMO ("multiple input multiple output") processes developed by the form of Renewable and Sustainable Energy Systems group [15].

In Figure 1. 3 it is reported the basic structure of urbs model:

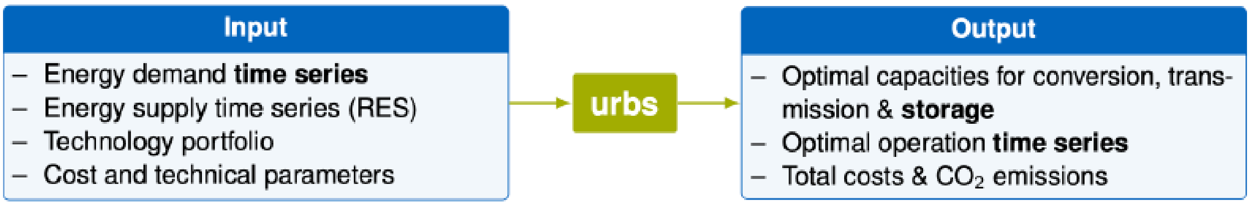


*Figure 1. 3: Input/Output flow chart of model urbs [16]*

Since urbs is a linear optimization model with many objects (e.g. variables, parameters), it's reasonable to use sets to define the group of objects. With the use of sets, many facilitations are achieved, such as understanding the main concepts of the model. Many objects are represented by various sets; therefore, sets can be easily used to check whether or not an object possesses a certain characteristic. Additionally, sets are useful to define a hierarchy of objects. In particular, urbs consists of 10 elementary sets. However, this work only models the energy system for a single year. Therefore, the relevant sets are the following seven:

- Timesteps: each time step represents another point in time.
- Sites: locations in the energy system. In this case: loads in distribution networks.
- Commodities: assets that can be generated, stored, transmitted, or consumed.
- Commodity Types:
  a) Stock: buyable at any time for a given price. Supply can be limited per timestep or for a whole year. Examples are: coal, gas, uranium, or biomass.
  b) SupIm: supply intermittent stands for fluctuating resources like solar radiation and wind energy, which are available according to a timeseries of values that could be derived from weather data.

c) Demand: these commodities have a timeseries for the requirement associated and must be provided by output from other processes or from storage. Usually, there is only one demand commodity called electricity (abbreviated to Elec), but multiple demands can be specified (e.g. electricity, space heating, process heat, space cooling).

d) Env: the special commodity CO2 is of this type and represents the amount (in tons) of greenhouse gas emissions from processes. Its total amount can be limited to investigate the effect of policies on the model.

e) Buy/Sell: commodities of these two types can be traded with an external market. Similar to Stock commodities, they can be limited per hour or per year. Unlike Stock commodities, the price at which they can be traded is not fixed but follows a user-defined time series.

- Processes: the action of changing one or more forms of commodities, to others.
- Storages: store energy to generate a commodity at a later time.
- Transmissions: transport commodities between sites.

The structure of the energy system has to be translated into the urbs' structure as an urbs' input file in order to conduct the modelling and optimisation process. An urbs' input file is an Excel workbook with multiple sheets. It contains information from urbs' sets. The overall CO2 and cost limits are defined in the Global sheet. The energy system structure and techno-economic parameters of power plants, storage systems, transmission lines, etc., are stored from Site sheet to Storage sheet. The time series of energy demand, energy supply, process efficiency, etc., are stored from Demand sheet to TimeVarEff sheet. All the sheets are reported in Figure 1. 4.

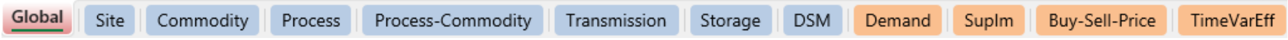


*Figure 1. 4: urbs input file structure*

In the urbs model two important parameters are distinguished:

- Technical parameters
- Economic parameters

***Technical parameters***

They are classified in:

- Time step duration [h]: defines the duration of the simulation;
- Demand for commodity [kW]: it defines the demand per timestep of each commodity;
- Intermittent supply capacity factor [kW]: provides the normalised production for each intermittent commodity;
- Maximum annual stock supply limit [kW]: it defines how much of a stock commodity may be used per time step per year;
- Maximum stock supply limit per timestep [kW]: it defines how much of a stock commodity may be used per time step per timestep;
- Maximum environmental output per time step [kg/h]: it defines the limit that an environmental commodity may produce per timestep;
- Maximum annual environment output [kg]: it defines the limit that an environmental commodity may produce per year;
- Maximum global annual $CO_2$ emission limit [kg]: it defines the limit for greenhouse gas commodity in order to limit the annual generation of the $CO_2$;
- Process capacity [kW]: defines the different value of capacity that is already installed, that should be installed and the maximum and minimum value of capacity that can be installed;
- Storage efficiency and storage initial and final storage content [-]
- Storage capacity [kWh] and power [kW]: it defines the capacity of the storage and its power
- Transmission capacity [kW]: it concerns the power related to the connection between two different locations;

***Economic parameters***

The economic parameters are classified in:

- Stock commodity fuel costs [€/kWh]
- Annualised process capacity investment [€/kWh y]
- Process capacity fixed costs [€/kWh y]
- Annualised storage power investment [€/kW y]
- Annual storage power fixed costs [€/kW y]
- Storage power variable costs [€/kWh]
- Annualised storage size investment [€/kWh y]
- Annual storage size fixed costs [€/kWh y]

- Storage usage variable costs [€/kWh]
- Annualised transmission capacity investment [€/kW y]
- Annual transmission capacity fixed costs [€/kW y]
- Transmission usage variable costs [€/kWh]

Costs are categorized in annualized investment costs in [€/kW], annual fixed costs in [€/kW], total variable costs in [€/kWh] per year, accumulated fuel costs over one year in [€/kWh] and the annual penalties for environmental pollution in [€/tCO$_2$]. In absolute value, the total cost is evaluated as:

$$c = c_{inv} + c_{fix} + c_{var} + c_{fuel} + c_{env} \tag{29.}$$

To understand the total cost of the plant over the years, it is essential to consider its operational lifespan. To this end, a depreciation factor is defined in years [y], indicating the estimated useful life of the plant and the period for which operating and maintenance costs must be evaluated. Additionally, the WACC (Weighted Average Cost of Capital) is incorporated, which is a financial indicator specifically designed to consider the total cost of the plant throughout its entire operational period. It takes into account both the financing composition (such as the cost of debt and equity capital) and the plant's utilization period (represented by the depreciation factor). The WACC enables the calculation of the required rate of return to finance the plant, considering both capital costs and the estimated lifespan of the plant. This analysis provides an overall view of the operating and maintenance costs throughout the entire lifecycle of the plant.

# 2. Case study description and input dataset definition

In this chapter, the setup of the case study simulation between the two pieces of software previously reported is highlighted. The first two sections describe the input and the output data that characterize UrbanHeatPro and EUReCA, while, the last section describes the assumption carried out to adapt the two software and compare them.

In this way, the number of the buildings is lower and the simulations require less time. For this purpose, we selected the city of Unterhaching, a city with just over 25,000 inhabitants that is located in the south of the Bavarian state capital (Munich).

However, due to the relatively high number of buildings, only a small percentage of them is considered for the comparison of the two tools (EUReCA and UrbanheatPro). Specifically, 185 buildings are considered, and they are divided as follows:

- 112 residential buildings (60.54 %);
- 39 commercial buildings (21.08 %);
- 27 public buildings (6.85 %);
- 7 industrial buildings (3.78 %).

## 2.1 UrbanHeatPro – Input data

In order to perform the simulation, the definition of some input must be done. In fact, UrbanHeatPro generates a synthetic city starting from the input data: the synthetic city contains all the information about the buildings (i.e. the envelope, the set-point temperature, the hour of operation of the plants, the level of refurbishment and so on); these information are assigned by random effects. After the building of this synthetic city, the space cooling and the space heating is calculated as shown in the previous paragraph.

The synthetic city is built from the initialization, passing through the building characterization and the occupancy distribution. A general scheme is reported in Figure 2. 1.

We can observe that the synthetic city is generated from aggregated building stock statics through a Monte-Carlo sampling scheme. The building data and its footprint are geographically allocated using a geographical information (GIS)-base probabilistic approach. [10]

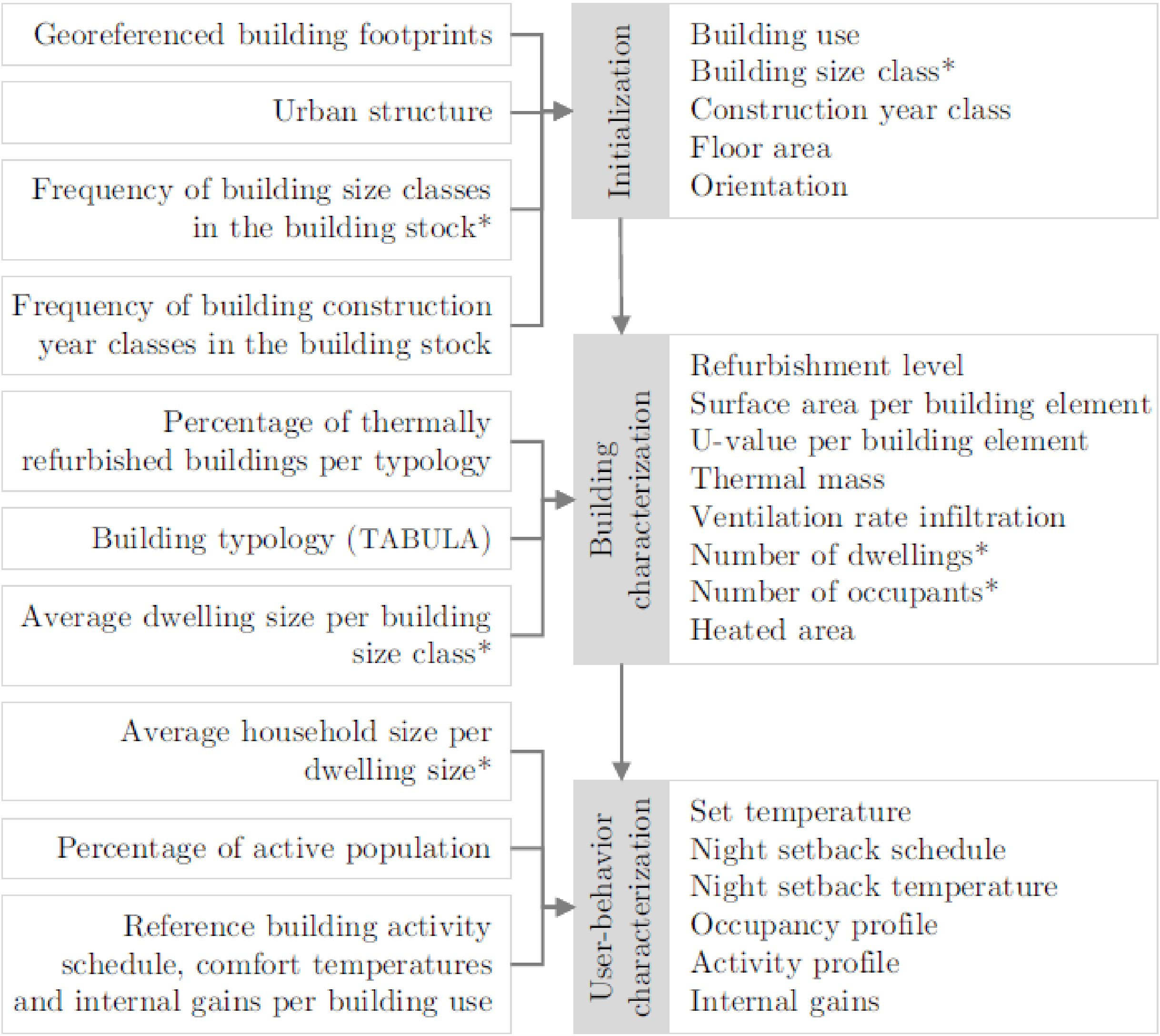


*Figure 2. 1 workflow for the creation of a synthetic building stock. Input data on the left. Output building and occupant related parameters on the right.*
**only for residential buildings.*

In particular, the building data are available in OpenStreetMap [17]. The data that UrbanHeatPro needs at the beginning are:

- the location of the building, obtained though it's coordinates: longitude and latitude;
- the footprint area;
- the final use: it can be residential, commercial, industrial or public. They are be defined as integer:
  - 0 for commercial buildings.
  - 1 for industrial buildings.
  - 2 for public buildings.

    - 3 for residential buildings.
- the number of free walls: it means the number of external walls of the buildings that are wind exposed;
- the distance to the heat source.

According to TABULA [12] the construction years are defined as follow (the integer number is used for the simulation):

*Table 2. 1: Construction year defined according to TABULA*

| Integer | Range of year |
|---|---|
| 0 | <1859 |
| 1 | 1860 – 1918 |
| 2 | 1919 – 1948 |
| 3 | 1949 – 1957 |
| 4 | 1958 – 1968 |
| 5 | 1969 – 1978 |
| 6 | 1979 – 1983 |
| 7 | 1984 – 1994 |
| 8 | 1995 - 2001 |
| 9 | 2002 – 2009 |
| 10 | >2009 |

Moreover, another differentiation is made for residential buildings, that are distinguished per each year in four different categories:

- Single-Family House (SFH)
- Multi-Family House (MFH)
- Terrace House (TH)
- Apartment Block (AB)

The commercial, industrial, public and industrial buildings are classified as non-residential (integer equal to -1).

OpenStreetMap gives only information about the final use of the building and nothing about the single size class (if it’s a SFH, TH and so on) and about the construction year class. For this reason, the Monte Carlo sampling scheme was used in order to obtain a synthetic city that can be as similar as possible to an actual urban area.

About the U-values of the buildings, all the data are taken by TABULA [12]. In particular, TABULA gives only the total U-vales of the single wall, roof, ground and window, but it doesn’t give any information about the stratigraphy and the materials. All the values are reported in Appendix A.

From TABULA it can be possible to obtain information regarding the surface area per building element, the average value of floors number, the infiltration flow rate and the window orientation ratio per each building, as reported in Appendix A. The window orientation ratio represents which is percentage of wall area covered by transparent component.

About the infiltration flow rate, two different contributions are considered:

- the first one is related to the air change rate due to the natural opening of the windows, doors and so on. It’s set as a constant value (equal to 0.4 vol/h) both for the residential and non-residential buildings;
- the second infiltration is related to the properly infiltration of the air through the windows, door and so on. It’s set equal to 0.2 vol/h for all the residential and non-residential buildings except to the residential one that are built after 2002 in which the infiltration flow rate is set equal to 0.1 vol/h.

Moreover, TABULA proposes two different levels of refurbishment to which correspond two different scenarios: the first one is the scenario correlated to a usual refurbishment, while the second is associated to an advanced refurbishment. The different refurbishment required different insulation of the building with the consequence variation of the U-values and the air flow rate.

Concerning cooling and heating, a mean temperature is reported with a delta temperature around the mean value: it means that the set-point temperature can be different per each building and can vary inside the range around the mean temperature. All the values are reported in the Table 2. 2 for the heating and in Table 2. 3 for the cooling.

*Table 2. 2: Range of the set-point temperature for heating per category of building*

| | $T_{set}$ | dt | Range |
|---|---|---|---|
| Residential | 20 °C | 2 °C | 18 °C – 22 °C |
| Commercial | 18 °C | 2 °C | 16 °C – 20 °C |
| Public | 18 °C | 2 °C | 16 °C – 20 °C |
| Industrial | 17 °C | 2 °C | 15 °C – 19 °C |

*Table 2. 3: Range of the set-point temperatures for cooling per category of building*

| | $T_{set}$ | dt | Range |
|---|---|---|---|
| Residential | 23 °C | 2 °C | 21 °C – 25 °C |
| Commercial | 23 °C | 2 °C | 21 °C – 25 °C |
| Public | 23 °C | 2 °C | 21 °C – 25 °C |
| Industrial | 21 °C | 6 °C | 15 °C – 27 °C |

About the system, the heating and the cooling systems are switched on/off depending on a probability as reported in Table 2. 4.

The monthly heating/cooling probability denotes the likelihood with which each building determines whether to activate the heating/cooling system within a given month. Consequently, during winter, all buildings have their heating/cooling systems turned on, whereas during summer, only a portion of the total number of buildings activates the heating. The monthly heating/cooling probability can be considered analogous to the plant's operational availability.

*Table 2. 4: Monthly space cooling and heating probability per month*

| Month | Probability of using space heating | Probability of using space cooling |
|---|---|---|
| January | 100 % | 0 % |
| February | 100 % | 0 % |
| March | 90 % | 50 % |
| April | 80 % | 80 % |
| May | 50 % | 100 % |
| June | 15 % | 100 % |
| July | 10 % | 100 % |
| August | 15 % | 100 % |
| September | 50 % | 80 % |
| October | 80 % | 50 % |
| November | 90 % | 0 % |
| December | 100 % | 0 % |

Up to now, all the data referred to the building typology have been defined.

However, there are different data that vary depending on the city evaluated. For this reason, we will call them “regional input data”; these include:

- the active hours Table 2. 5: they represent the time during which the building is occupied, plus a dt value that represents the number of hours by which the start and the end time can vary. Different active hours are defined per each use (residential, commercial, industrial and public);

*Table 2. 5: hours in which the building can be occupy in UrbanHeatPro*

| Building type | Start [h] | End [h] | dt [h] | Range [dt] |
|---|---|---|---|---|
| Residential | 0 | 23 | 0 | 0 – 23 |
| Commercial | 8 | 18 | 2 | 6 – 20 |
| Public | 8 | 16 | 2 | 6 – 14 |
| Industrial | 8 | 18 | 2 | 6 – 20 |

- average dwelling size: it’s used for the definition of the number of the dwellings from the German Census 2011; [18]
- building stock: it represents the percentage-based distribution of each building. The data are taken by German Census 2011 [18] and are referred to Germany and not to the single region. So, they are reported in Table 2. 6;

*Table 2. 6: Building stock of residential and non-residential buildings from Germany Census 2011*

| Residential Building Stock | | | | |
|---|---|---|---|---|
| | SFH | TH | MFH | AB |
| <1859 | 0.00% | 0.00% | 0.00% | 0.00% |
| 1860-1918 | 1.09% | 0.21% | 0.18% | 0.00% |
| 1919-1948 | 5.36% | 1.21% | 0.47% | 0.00% |
| 1949-1957 | 9.05% | 2.56% | 2.06% | 1.09% |
| 1958-1968 | 9.05% | 2.59% | 2.06% | 1.09% |
| 1969-1978 | 9.05% | 2.59% | 2.06% | 1.09% |
| 1979-1983 | 9.90% | 2.80% | 2.56% | 0.41% |
| 1984-1994 | 5.48% | 1.66% | 3.83% | 1.03% |
| 1995-2001 | 2.74% | 1.04% | 2.27% | 0.09% |
| 2002-2009 | 5.99% | 2.79% | 4.27% | 0.27% |
| >2009 | 5.99% | 2.79% | 4.27% | 0.27% |
| Total | 63.70% | 20.24% | 24.05% | 5.33% |
| Non-Residential Building Stock | | | | |
| <1918 | 1919-1976 | 1977-1983 | 1984-1994 | >1995 |
| 5.00% | 45.00% | 16.70% | 16.70% | 16.70% |

- current refurbishment and max refurbishment: they represent the two different levels of refurbishment (the max one corresponds to the advanced refurbishment). This input defines which is the number of buildings (in percentage) per each year and per each category that has a wall, window, roof or floor renewed;
- house hold size: it's represented the probability that a specific number of people occupies a building with a certain area. The data are taken by German Census 2011 [18] and are referred to Germany and not to the single region. So, they are reported in
- Table 2. 7.

*Table 2. 7: House hold size from German Census 2011 [18]*

| N° people | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| <40 | 85.90% | 9.50% | 2.70% | 1.80% | 0.00% | 0.00% |
| 40 - 59 | 71.60% | 23.30% | 3.70% | 1.10% | 0.30% | 0.00% |
| 60 - 79 | 42.80% | 37.90% | 12.50% | 5.30% | 1.20% | 0.30% |
| 80 - 99 | 30.00% | 40.00% | 20.00% | 10.00% | 0.00% | 0.00% |
| 100 - 119 | 18.80% | 38.90% | 19.60% | 17.90% | 3.10% | 1.60% |
| 120 - 139 | 16.60% | 35.90% | 21.40% | 21.60% | 3.70% | 0.70% |
| 140 - 159 | 20.20% | 25.00% | 20.20% | 24.80% | 6.80% | 3.10% |
| 160 - 179 | 16.20% | 29.70% | 20.50% | 21.10% | 10.80% | 1.60% |
| 180 - 199 | 7.50% | 33.30% | 29.00% | 22.60% | 4.30% | 3.20% |
| >200 | 18.50% | 16.00% | 18.50% | 31.90% | 12.60% | 2.50% |

- solar radiation, considering the Global horizontal radiation, the diffuse horizontal radiation and the extra-terrestrial solar radiation
- the ambient temperature of the external air per each hour along the year
- All the previous data referred to Unterhaching, a city located closed to Munich, that is used for the simulation in that thesis.

All the input data are collected in csv files, implemented in the python code.

## 2.2 UrbanHeatPro – Output data

The output of the tool are several csv files. The energy per building file lists the total calculated space heating and hot water demand of each building created together with the output parameters shown in Figure 2. 1. In addition, each created building can be individually monitored in the set time sequence with its dynamic parameters such as building temperature, outside temperature, solar and internal gains, and space heating/hot water demand. The same is done for the whole city to understand the correlation between the ambient temperature, the gains, and the building´s thermal response.

About the heated area of each building this is obtained from the relation described in the previous paragraph. Based on the number of floors and the footprint area (obtained from OpenStreetMap) the storey area can be calculated according to the German standard VDI 3807-1 [19]. Moreover, the heated area is lower than the storey area due to the presence of the correction factor that is calculated according the standard [20]:

- for the residential building the correction factor is set equal to 0.84;
- for the non-residential building the correction factor is set equal to random value between 0.75 and 0.85.

Thus, the heated area is easily calculated as:

$$A_{heated} = A_{footprint} \cdot N_{floors} \cdot corr_{factor} \qquad 30.$$

The occupancy varies hour by hour and it’s calculated considering the number of occupants in a residential building based on the size of the dwellings and statistics on household size. It determines the dwelling size category and generates a cumulative distribution of household size. For each dwelling in the building, a random number is generated and used to determine the corresponding household size. This method provides an estimation of the number of occupants for the residential building based on dwelling sizes and the distribution of household size.

For the non-residential buildings the occupancy is based on the recommended area per person for different types of buildings.

Depending on the building's use (commercial, industrial, or public), a random value for the area per person is chosen.

The number of occupants is then calculated by dividing the heated area of the building by the area per person and multiplying by a specified capacity percentage. The set-point temperature is obtained randomly with a temperature within the range dT, as reported in Table 2. 2 and Table 2. 3.

Similarly, in a random way it is obtained the start and the end of the building's active hours. The values differ based on the building types as in Table 2. 5. The active hours define the hours in which the building is occupied, and it influences the heating and cooling demand (it will be highlighted in the next chapter).

## 2.3 EUReCA – Input data

In this paragraph it's discussed which are the data that EUReCA required for the simulation and how they were set: in fact, the first goal is to define which are the differences between the two different software, and for this reason, the input data that are already collected for the UrbanHeatPro simulation can be set in the EUReCA's input data.

There are four principal input files:

- GeoJSON file;
- EnergyPlus Weather (*.epw*) file;
- Materials and construction file;
- Schedules file.

About the GeoJSON files, EUReCA [21], can handle both three-dimensional CityJSON models and two-dimensional GeoJSON models derived from Shapefile. In the case of CityJSON, the surface and vertex data are extracted from buildings to calculate the area, orientation, and surface types. In the GeoJSON model, buildings are created by combining contour vertices and the specified height from the input, generating corresponding extruded surfaces. This workflow enables the import and manipulation of surfaces and vertices in both scenarios.

The GeoJSON has been built through a GIS (geographic information system) project. The software used is QGIS: it's a free desktop app GIS open source that gives the possibility to visualize, organize, analyse and represent geographical data published in July 2002. The georeferenced description of the district has been built with the following attributes:

- Building id: increase integer number from 1;
- Name: increasing integer number from 1;
- Number of floors: data from UrbanHeatPro;
- Height: given by the product of the number of floors and the average height of one floor: 3m
- End use: data from UrbanHeatPro. It defines if the building has a residential, commercial, public or industrial final use;
- Envelope: data from UrbanHeatPro. It defines which is the age of the building (as reported in the input data of UrbanHeatPro), and per each year it is given also the category of the building (it means a SFH, TH, MFH or AB for the residential building. For the non-residential buildings, they are just categorized as NR).

For some attributes the input data are taken by UrbanHeatPro and not by OpenStreetMap. This is due to the fact that the data from the shape file used for the definition of the synthetic city in UrbanHeatPro, were not consistent with the reality: for instance, the shapefile provides information such as the building's use (residential, commercial, industrial, or public). Upon evaluating a sample of buildings, it has been observed that the designated use of these buildings does not align with the reality. For example, buildings marked as "Residential" are actually shopping centres (and therefore should be classified as "Commercial"). This verification was conducted using Google Maps Street View.

On the other hand, when examining the input data of UrbanHeatPro (including the defined end-use), the data remain unaltered and correspond accurately to the reality. As a result, the synthetic city created with UrbanHeatPro was imported into QGIS. This means that the output of UrbanHeatPro serves as the input for EUReCA. It considers, for instance, how the year of construction and the building category are assigned randomly.

Nevertheless, having the output of UrbanHeatPro as the input is not a problem at present. The ultimate objective, after all, is to compare the energy demand for heating and cooling. Hence, the goal is to obtain a city that resembles closely the real scenario.

Data by UrbanHeatPro represent the buildings as circle while EUReCA needs multi-polygons for the definition of the city: for this reason, a new layer must be created in which the properties of the input file of UrbanHeatPro are given to the buildings of the shape file (that it’s defined by multi-polygons). In this way the GeoJSON file can be written with the attributes and exported for EUReCA.

The EnergyPlus Weather file (*.epw*) [22] is a file format used to represent climatic data that is utilized by the EnergyPlus energy simulation software. EnergyPlus is a building energy simulation program that is employed to assess the energy performance of buildings based on climatic conditions. An .epw file contains a wide range of meteorological data, including temperature, humidity, solar radiation, wind speed, and various other climatic parameters. These data are recorded at specific time intervals, typically every hour, and cover a period of at least one year. The .epw file represents the average climatic conditions for a particular location or geographical area, and it is used by EnergyPlus to simulate the energy behavior of buildings in relation to the local climate.

In order to adapt the weather file to the external conditions fixed in UrbanHeatPro, the .epw file was modified: in particular, the values of the dry-bulb temperature, of the global horizontal radiation and of the diffuse horizontal radiation from the input regional data of UbranHeatPro are inserted in EUReCA.

The materials and construction files are present in an excel sheet. As for UrbanHeatPro, TABULA webtool was used to obtain the thermal transmittance per each wall of each category of buildings (the values are reported in Appendix A). However, differently from UrbanHeatPro, EUReCA requires also the weight class and the thermal transmittance of the internal ceiling and internal wall. The weight class is related to the materials that compose the wall and since TABULA doesn't give any information about that, it's defined as follow: if the structure is made by bricks or concrete, the class is set as "heavy", otherwise it is set as "light". The difference gives different values of density: in fact, in order to evaluate the heating or cooling demand, the density must to be considered in the calculation (this is not evaluated in UrbanHeatPro).

There are no information available in TABULA regarding the stratigraphy of the internal ceiling and internal wall. Consequently, various reference stratigraphies have been considered across different time periods. From these stratigraphies, a reference U-Value was derived and incorporated into the input Excel sheet. The typical stratigraphies and the total thermal transmittance per each period, are reported in Table 2. 8

*Table 2. 8: Internal wall and internal ceiling properties*

| Name | type | Stratigraphy | U-value [W/(m2 K)] | Weight Class |
|---|---|---|---|---|
| Internal Ceiling <1948 | IntCeiling | Floor<br>Screed<br>Infill<br>Joists<br>Bearing beams | 3 | Light |
| Internal ceiling 1949-1977 | IntCeiling | Floor<br>Waterproofing layer<br>Infill<br>Bearing beams | 2.5 | Light |
| Internal Ceiling 1978-1994 | IntCeiling | Floor<br>Waterproofing layer<br>Thermal insulation<br>Infill<br>Bearing beams | 1.5 | Heavy |
| Internal Ceiling >1995 | IntCeiling | Floor<br>Waterproofing layer<br>Thermal insulation<br>Infill<br>Bearing beams | 0.5 | Heavy |
| Internal Wall <1948 | IntWall | Internal plaster<br>Materials of construction<br>External plaster | 3 | Light |
| Internal Wall 1978-1977 | IntWall | Internal plaster | 2.5 | Light |

| | | | | |
|---|---|---|---|---|
| | | Insulating material<br>Materials of construction<br>External plaster | | |
| Internal Wall 1978-1944 | IntWall | Internal plaster<br>Insulating material<br>Materials of construction<br>Hollow bricks<br>External Plaster | 1.5 | Heavy |
| Internal Wall >1995 | IntWall | Internal plaster<br>Insulating material<br>Materials of construction<br>Hollow bricks<br>External Plaster | 0.4 | Heavy |

About the windows, UrbanHeatPro uses as input only the U-values defined in TABULA. For EUReCA, as described in the previous section where the solar heat gain contribution was introduced, the values of the solar heat gain coefficient (SHGC), the visible transmittance, the frame factor and the internal and external shading coefficient must be evaluated. The shading coefficient is set equal to 1 both for internal and external shading; about the frame factor it is set equal to 0.1 per each kind of windows. About the SHGC and the visible transmittance, average values were considered from Table 2. 9:

*Table 2. 9: Typical Values of the overall thermal performance of a glass*

| Description | U-value [W/(m$^2$ k)] | $\tau_v$ [%] | g-value [%] |
|---|---|---|---|
| Single clear glass (4mm) | 6.0 | 91 | 89 |
| 4-12-4 mm (Air) | 3.0 | 80 | 68 |
| 4-12-4 mm (Argon and low-emissivity) | 1.5 | 77 | 58 |
| 4-12-4-12-4 mm (Air) | 2.0 | 72 | 59 |
| 4-12-4-12-4 mm (Air and low-emissivity) | 1.2 | 77 | 55 |
| 4-12-4-12-4 mm (Argon and low-emissivity) | 0.5 | 70 | 45 |
| 4-12-4 mm (Air, medium reflective and low-emissivity) | 1.6 | 29 | 30 |
| 4-12-4 mm (Argon, medium reflective and low-emissivity) | 1.6 | 9 | 18 |

The schedules are defined per each archetype and per each hour:

- Occupancy in [W/m$^2$];
- Appliances in [W/m$^2$];
- Lighting in [W/m$^2$];
- Infiltration flow rate in [vol/h];
- Heating and cooling setpoint in [°C];
- No Dehumidification;
- Dehumidification = 60 %;
- Ventilation flow rate in [m$^3$/(s m$^2$)];
- Ventilation Supply temperature heating mode = 22 °C;
- Ventilation Supply specific humidity heating mode = 0.0105 $kg_v/kg_{da}$;
- Ventilation Supply temperature cooling mode 23 °C;
- Ventilation Supply specific humidity cooling mode = 0.0105 $kg_v/kg_{da}$;
- Domestic hot water, calculated according to the standard [23].

***Occupancy***

The occupancy is defined differently for the residential, commercial, public and industrial building. Regarding the residential building, the calculation is performed according to the below procedure.

The probability of the number of people residing in an apartment within a specific area can be derived from the 2011 Germany census (see

Table 2. 7). For each dwelling size, the number of people was determined based on a weighted average as follows:

$$n_{people} = \frac{\sum k_j \cdot p_j}{\sum p_j} \tag{31.}$$

Here, $k_j$ represents the number of people in a particular area (ranging from 1 to 6), and $p_j$ represents the respective probability. Then, for each size category, the number of people was divided by the square meter in order to obtain the number of people per square meter. By taking the average of all values and multiplying it by 120 W, the value in W/m$^2$ was obtained (equal to 2.7 W/m$^2$). However, up to now, only the nominal value is set according to the standard BS ISO 18523 [24].

The time spent for sleeping, going-out, watching television, eating, bathing and so forth, is based on the existing survey carried out by a public broadcasting organization.

The nominal value of occupancy of the commercial, public and industrial buildings, it's set considering the occupancy density, defined as follows:

- 10 $m^2$/px in a commercial building (considering the average between the occupancy density of a restaurant between 8 – 12 $m^2$/px and a restaurant between 6 – 8 $m^2$/px);
- 20 $m^2$/px in a public building;
- 40 $m^2$/px in an industrial building (considering the average between manufacturing facilities – with a typical value between 10 – 20 $m^2$/px – and warehouses and storage facilities – with a typical value between 50 – 100 $m^2$/px).

Considering that the body emits 120 W, the value in W/$m^2$ can be easily determined.

The schedule for commercial and public buildings – like offices, hotels, schools and education places, lecture halls, restaurants, wholesale centres and hospital – are defined according to the standard BS EN 15232 [25]: in particular, starting from the standard we can obtain the normalized level of occupancy in function of time (in hours).

However, the standard BS EN 15232 [25] doesn't take into consideration the archetype defined by us: for this reason, some assumptions are done:

- as for commercial buildings, the schedule of offices, hotels, restaurants and wholesale centres were considered. Since the schedule for each building type is different (due to the different usage patterns of each building category), the most common commercial building categories in Germany were taken as the reference.
  Specifically, by using statistics [3], it is possible to obtain the percentage of offices, hotels, restaurants, and wholesale centres compared to the total. As shown in Table 2. 10, it is evident that the percentage of offices is significantly higher than the others. Consequently, the schedule is set by following the offices behaviour (Figure 2. 2). However, fractional values have been slightly increased (up to a maximum of 0.1) to account for the influence of hotels, restaurants, and wholesale centres.

*Table 2. 10: share of commercial buildings from Statista.com*

| Offices | Hotels | Restaurants | Wholesale centres |
|---|---|---|---|
| 77.8 % | 2.74 % | 14.6 % | 4.89 % |

Furthermore, occupancy in commercial buildings is active during the weekdays, including

Saturdays. However, Sundays are set to zero in accordance with the Arbeitszeitgesetz [26], a law that regulates working hours in Germany.

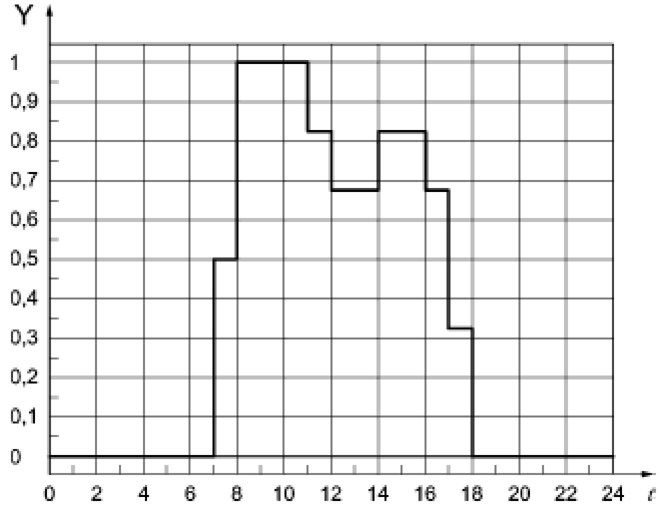


*Figure 2. 2: User profile for an office building according to BS EN 15232, where Y is the normalized level of occupancy and t the time in hours*

- For public buildings, the same approach used for commercial buildings is applied. However, in this case, schools, libraries, and hospitals are taken as references.
  Through statistical analysis [3], it is possible to obtain the percentage of schools, libraries, and hospitals compared to the total. As shown in Table 2. 11, it is evident that the percentage of schools is significantly higher compared to the other categories.

*Table 2. 11: share of public buildings from Statista.com*

| Schools | Libraries | Hospitals |
|---|---|---|
| 72.08 % | 23.04 % | 4.89 % |

Therefore, the schedules are configured based on the behaviour of schools as the primary reference (Figure 2. 3). However, the fractional values have been slightly increased (up to a maximum of 0.1) to account for the influence of libraries and hospitals.

Furthermore, the occupancy of public buildings is active exclusively during weekdays, while no occupancy is maintained during the weekends.

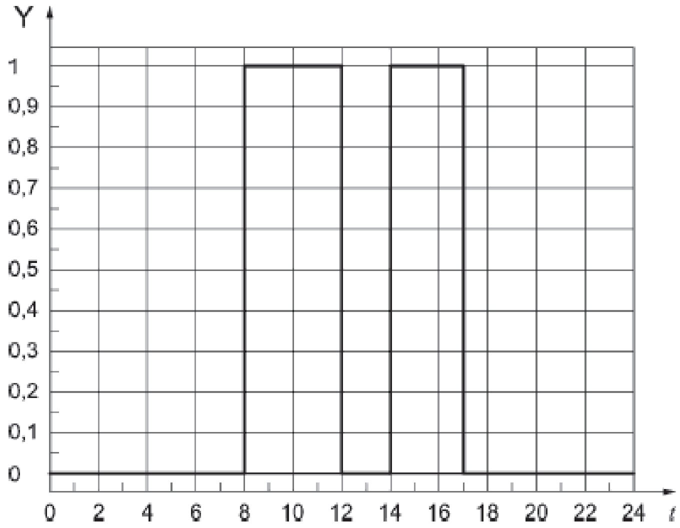


*Figure 2. 3: User profile for an office building according to BS EN 15232, where Y is the normalized level of occupancy and t the time in hours*

As for the schedule of industrial buildings, there are no specific regulatory standards, similar to the other building categories. This lack of standardization can be attributed to the complexity of setting schedules for industrial buildings, as factors such as occupancy and building characteristics vary significantly depending on the type of industrial activity. The maximum occupancy has been considered during the daytime hours, from 9 a.m. to 5 p.m. During the nighttime hours, occupancy remains active but at a significantly lower level (approximately -10% compared to the daytime occupancy) to compensate for business activities operating during night hours.

Throughout the week, the occupancy remains active. However, during the weekends the occupancy is set to zero. This decision is driven by the difficulty of determining which types of industries remain open on weekends; therefore, keeping occupancy active could cause excessive skewing of the data. Moreover, according to Germany's Federal Statistical Office, a survey conducted in 2018 revealed that 30% of manufacturing industries operate seven days a week. As a result, zero occupancy was chosen to be considered during weekends.

The absence of specific regulatory guidelines for industrial buildings emphasizes the importance of considering the unique characteristics and requirements of each type of industry when determining their schedule. This approach ensures that each schedule is tailored to the specific needs and dynamics of each industrial activity, facilitating effective management of buildings and resources.

### *Electrical appliances and lighting*

As for the schedule of electrical appliances and lighting for residential buildings, the nominal values in W/m2 are determined according to the guidelines set by the German Federal Ministry for Economic Affairs and Energy. It defines the average emissions for appliances to be 10 W/m2 and for lighting to be 2.5 W/m2. In terms of schedule, high emissions are considered during breakfast, lunch, and dinner hours, as defined in the schedule's occupancy for residential buildings provided in the normative. During nighttime hours, however, emissions remain significantly low, due to the fact that some appliances, such as refrigerators and freezers, continue to operate but their impact, compared to total emissions, remains relatively low.

These considerations were applied to the weekly schedule. However, on weekends, both Saturdays and Sundays, the schedules are generally increased during daylight hours due to the increased occupancy of the building, as indicated by the occupancy schedule for residential buildings provided in [24].

As regards the commercial and public buildings, the standard BS EN 15232 *[25]* defines both the schedule and the nominal value of emission per square meter, as reported in

Table 2. *12* and Table 2. 13. However, as far as occupancy is concerned, through Statista *[3]* it is possible to obtain the percentage of offices, hotels, restaurants and wholesale centers to total commercial buildings and the percentage of school halls and hospitals to total public buildings. As shown in Table 2. 10 and Table 2. 11, it is evident that the percentage of offices (for commercial buildings) and of schools (for the public ones) is significantly higher than the others. As a result, the schedules are set following the behaviour of offices and schools for the two different categories. In addition, the fractional values have been slightly increased (to a maximum of 0.1) to account for the influence of hotels, restaurants and wholesale centres.

*Table 2. 12: Nominal power per unit of area for light and for electrical appliances for the commercial buildings.*

| | | Offices | Hotels | Restaurants | Wholesale centres |
|---|---|---|---|---|---|
| Light | Power [W/m2] | 13 | 10 | 10 | 15 |
| Operation | from [h] | 7.00 | 18.00 | 10.00 | 10.00 |
| | to [h] | 18.00 | 8.00 | 23.00 | 23.00 |
| Appliances | Power [W/m2] | 10 | 4 | 2 | 3.5 |

*Table 2. 13: Nominal power per unit of area for light and for electrical appliances for the public buildings*

| | | Schools | Lecture Halls | Hospitals |
|---|---|---|---|---|
| Light | Power [W/m2] | 13 | 25 | 15 |
| Operation | from [h] | 7.00 | 7.00 | 10.00 |
| | to [h] | 18.00 | 20.00 | 23.00 |
| Gain | Person [m2/px] | 3.3 | 1 | 0.7 |
| | equipment [W/m2] | 4 | 4 | 4 |

The nominal power is set considering the weighted average of various types of commercial buildings, thus obtaining:

- Light nominal power = 12.58 W/m$^2$;
- Appliances nominal power = 8.35 W/m$^2$;

Like commercial buildings, nominal values are obtained for public buildings:

- Light nominal power = 15.86 W/m$^2$;
- Appliances nominal power = 4 W/m$^2$.

Weekday and weekend scheduling is set with the same criteria as occupancy: this means that the scheduling of commercial buildings is on from Monday to Saturday (off on Sunday according to [26]), while for public buildings the scheduling of electrical appliances and lighting is on from Monday to Friday.

As for the industrial building, there are no references to emissions from electrical appliances and lights. However, on the website of the German Energy Saving Ordinance (EnEV), the minimum requirement for general lighting in an industrial building is set at 100 lux; in order to obtain the consumption in W/m$^2$ we can consider the average value of the luminous efficiency of a typical lamp (about 10 lumens/W). Thus, considering an area of 1 m$^2$, the nominal value of power is equal to 10 W/m$^2$. However, in order to be safer, this value was increased to 15 W/m$^2$ to account for some error in the calculation due to approximation. For electrical appliances, the nominal value of the power is set equal to 5 W/m$^2$.

Schedules follow occupancy behaviour: this means that if occupancy scheduling is high, the schedules of electrical appliances and lights are also high (and vice versa).

### *Infiltration and ventilation*

As for infiltration, EUReCA requires the amount of air that passes through components such as doors, windows and so forth. The value is measured in vol/h; since it is known by UtbanHeatPro's input data, we use the values reported in Table A. 3 in Appendix A.

As for mechanical ventilation, UrbanHeatPro has not any information as it's not implemented. So, some reference values can be taken by the standard BS ISO 18523 [24], that defines the mechanical ventilation's value for non-residential buildings. In particular:

- Offices, conference rooms, and classrooms: 0.001 to 0.0015 $m^3/(s\ m^2)$;
- Retail stores and supermarkets: 0.0012 to 0.002 $m^3/(s\ m^2)$;
- Restaurants and bars: 0.002 to 0.005 $m^3/(s\ m^2)$;
- Libraries, student rooms, universities: 0.0015 to 0.0019 $m^3/(s\ m^2)$;
- Industrial and manufacturing spaces: 0.0005 to 0.0015 $m^3/(s\ m^2)$;
- For commercial buildings an average value equal to 0.00130 $m^3/(s\ m^2)$ is considered;
- For public buildings an average value equal to 0.00172 $m^3/(s\ m^2)$ is considered;
- For industrial buildings an average value equal to 0.0.0009 $m^3/(s\ m^2)$ is considered;
- For residential buildings any value was fixed since, usually, the residential buildings don't have it.

### *Heating and cooling set point temperature*

The heating and cooling set-point temperature has been fixed considering the values used by UrbanHeatPro (reported in Table 2. 2 and Table 2. 3) without the variation of temperature dt.

However, the value of the set-point temperature for cooling in industrial buildings in UrbanHeatPro (21 °C), seemed very low compared to reality: indedd, a range of $\pm$ 6 °C is considered in UrbanHeatPro, which means that the cooling temperature (randomly assigned) can vary between 15 and 27 °C to take into account even enterprises that require a very low ambient temperature to work (i.e., industries working in the field of food freezing).

In EUReCA there is no random set-point temperature assigned to each building, but it's defined at the beginning and is the same for all buildings in the same category: for this reason, 21 °C for cooling in industrial buildings could be underestimated, so a temperature equal to 26 °C was set.

The values are reported in

Table 2. 14:

*Table 2. 14: set-point temperature for Heating and Cooling in EUReCA*

| | Set temperature Heating [°C] | Set temperature Cooling [°C] |
|---|---|---|
| Residential | 20 | 23 |
| Commercial | 18 | 23 |
| Public | 18 | 23 |
| Industrial | 17 | 26 |

The schedules are fixed, as with UrbanHeatPro, and they take into account building occupancy. Specifically, when occupancy is high, heating and cooling are on and vice versa. More or less, we can say that:

- heating is on between 8.00am and 6.00pm for commercial, public and industrial buildings;
- cooling is on between 11.00am and 5.00pm for commercial, public and industrial buildings: the cooling is off during the morning because, usually, the external temperature is not that high and varies a lot between day and night. An example is shown in Figure 2. 4, where it's evident that the temperature in July 2022 (the hottest month of the year) exceeds 30 °C only a few times (and also reaches very low temperature at night). As reported in Figure 2. 4, if we consider a normal day, we can observe that there is no need for the cooling system before 11.00 am.

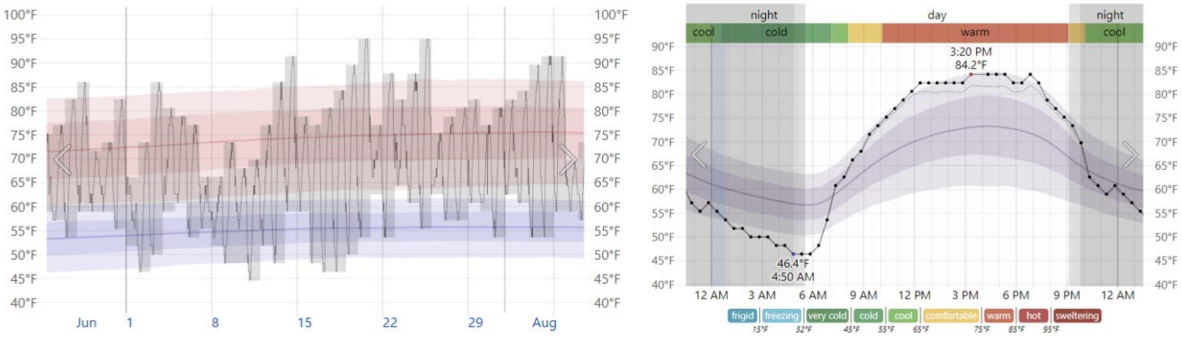


*Figure 2. 4: on the left it is reported the temperature variation in July 2022 in °F, while on the right it is reported the temperature variation in °F on the 18th of July 2022*

- heating is on all the day in the residential buildings, but a setback temperature has been included that considers the lowest heating set point (19 °C) during night hours to ensure good thermal comfort.
- cooling is on between 2.00pm and 9.00pm for the same reasons previously described; observe that cooling during lunchtime is maintained because, usually, occupancy is not that high.

Moreover, it’s also very important to define the seasonality of the plants. In particular:

- the heating system is active from the 1st of October until the 30th of April;
- the cooling system is active from the 1st of June until the 30th of August.

## 2.4 EUReCA – Output data

The output of the tool consists on a csv file per each building, which contains some important consumption information such as sensible and latent heat, pre-heating and post-heating load (the sum of the three components gives the total amount of space heating and cooling during the year), heating gas, oil and electricity consumption, electric cooling consumption, domestic hot water demand, and other information on ambient temperature, operative temperature and average radiant temperature.

However, the heated area of the buildings is calculated as:

$$A_{heated} = A_{footprint} \cdot N_{floors} \qquad 32.$$

Differently from UrbanHeatPro case, the heated area doesn't consider any correction factor (a value lower than 1): the heated area simulated in EUReCA is higher than the one calculated in UrbanHeatPro.

The calculation of the heated area affects the results of domestic hot water demand: in EUReCA it depends on the area as reported in the chapter *1.2*.

## 2.5 EUReCA vs UrbanHeatPro – Adaption of the models

This section will discuss how the code is modified to obtain two solutions that are as similar as possible. The goal is to understand the divergences between the models and identify the factors that contribute to these dissimilarities.

The differences are related to:

- the definition of the model: UrbanHeatPro is 1R1C model, while EUReCA is 5R1C model;
- the first major difference on input data concerns heating and cooling set points, both in terms of their nominal values in °C and their scheduling. In the UrbanHeatPro model, fixed nominal values are determined along with a parameter "dt" that defines the range within which a random set point temperature is assigned. Furthermore, an additional "dt" is specified to establish the threshold values for activating or deactivating heating/cooling systems. Specifically, for heating, it starts when

  $$Tset < Tset - dt \text{ and stops when } Tset > Tset + dt;$$

  while for the cooling, it starts when

  $$Tset > Tset + dt \text{ and stops when } Tset < Tset - dt$$

  Regarding the schedule, heating and cooling are turned on when occupancy is active according to Table 2. 5; otherwise, they are turned off.

  In UrbanHeatPro, there is also a concept of "space heating/cooling probability" defined in Table 2. 4: this probability represents the likelihood with which in each building the heating/cooling system is activated within a given month. As a result, during winter, all buildings have their heating/cooling systems turned on, whereas during summer, only a portion of the total number of buildings activates the heating. This monthly heating/cooling probability can be considered analogous to the operational availability of the plant.

  On the other hand, in EUReCA, seasonal patterns are predefined, where all buildings can have heating active from 01/10 to 30/04 and cooling active from 01/06 to 31/08. The nominal set point temperature values are assigned by the user according to

  Table 2. 14, and the schedule follows the definition mentioned in the previous paragraph.

These differences in set point definitions and scheduling are critical aspects that distinguish heating and cooling strategies in the UHP and EUReCA models, respectively.

- The set-back temperature: in the case of EUReCA, it is assigned manually (e.g., set at 19°C during nighttime hours for residential buildings).

  On the other hand, for UrbanHeatPro, a probability of 0.5 is assigned, corresponding to the percentage of the number of buildings that have a specific set-back temperature (set at 21°C) between 11pm and 6am.
- Occupancy: the number of occupants per building is determined based on statistical data of people per building in UrbanHeatPro. Schedules are then defined by considering the active hours on Table 2. 5, representing the time periods when a building may be occupied or unoccupied. For residential buildings, an additional factor is considered: the percentage of population that is working - calculated as 0.583 based on a census conducted in 2011 [27] - to determine the hourly occupancy.

  For EUReCA, however, the occupancy calculation is handled as described at page (39)
- Internal loads: the standard BS EN ISO 18523 [24] for EUReCA serves as a reference, while UHP also employs random values, following the guidelines of the [28]. Specifically, UHP defines a heat gain per occupant in W/person (watts per person), sets at 80 W between 23:00 and 6:00, and varying between 125 and 230 W for the rest of the day. The internal gain, hour by hour, is then calculated as

  $$int_{gain} = random(125{,}230) \cdot occupancy \cdot 2 \qquad 33.$$

  during the daily hours; instead, during the night hours:

  $$int_{gain} = 80 \cdot occupancy \cdot 2 \qquad 34.$$
- Refurbishment: as explained on page (30), UrbanHeatPro defines for each archetype of building which is the probability that a wall, roof, window or floor has been renewed (in that way the U-value of the building will change a lot, increasing the thermal performance of the building). In EUReCA this is not considered.
- Mechanical ventilation: UrbanHeatPro doesn’t consider it, while in EUReCA it is implemented for public, commercial and industrial building considering the standard DIN 1946 [29].
- Domestic hot water (DHW) demand: in UrbanHeatPro is calculated based on various input parameters, including the average daily consumption of hot water, the capacity of the hot water tank, the probabilities of hot water consumption, the simulation time frame and other relevant information such as the seasonal variation, which accounts for the changes in hot

water demand across different seasons. Differently, in EUReCA, the DHW is calculated according to the standard UNI/TS 11300 [23].

- Area calculation: both UrbanHeatPro and EUReCA calculate the total area of the building as the product between the number of floors and the footprint area (obtained from OpenStreetMap) according to standard VDI 3807-1 [19]. However, UrbanHeatPro considers the value of the heated area, that is lower than the storey area due to the presence of the correction factor calculated according to VDI 3807-2 [20]:
    a) for residential building the correction factor is set equal to 0.84;
    b) for non-residential building the correction factor is set equal to random value between 0.75 and 0.85.

  Thus, the heated area in UrbanHeatPro is easily calculated as:

$$A_{heated,UHP} = A_{footprint} \cdot N_{floors} \cdot corr_{factor} \qquad 35.$$

  While, the storey area of EUReCA is determined as:

$$A_{storey,EUReCA} = A_{footprint} \cdot N_{floors} \qquad 36.$$

In the following table, all differences are summarized concisely and schematically to provide an overview:

*Table 2. 15: main differences in the definition of the model between EUReCA and UrbanHeatPro*

| | **EUReCA** | **UrbanHeatPro** |
|---|---|---|
| Heating set-point temperature | Hourly schedule: values set according to [<br>Table 2. 14] | Seasonal variation: values are randomly assigned within a range as in [Table 2. 2] |
| Cooling set-point temperature | Hourly schedule: values set according to [<br>Table 2. 14] | Seasonal variation: values are randomly assigned within a range as in [Table 2. 3] |
| Heating system work – hourly | If the temperature is lower than the heating set-point temperature | It starts when $T_{set} < T_{set}$ - dt and it stops when $T_{set} > T_{set}$ +dt |
| Cooling system work – hourly | If the temperature is higher than the cooling set-point temperature | It starts when $T_{set} > T_{set}$ + dt and it stops when $T_{set} < T_{set}$ - dt |
| Heating system active – season | Depends by the start and the end date, fixed by ourselves | Depends by the probability that defines the amount of buildings |

| | | |
|---|---|---|
| | | that maintain the heating active in each month |
| Cooling system active – season | Depends by the start and the end date, fixed by ourelves | Depends by the probability that defines the amount of buildings that maintain the cooling active in each month |
| Heating on and off - daily | Hourly definition as described at page (45) | Defined in function of the active-hours as reported in Table 2. 5 |
| Cooling on and off - daily | Hourly definition as described at page (45) | Defined in function of the active-hours as reported in Table 2. 5 |
| Occupancy – nominal value | Hourly definition according to [24] | Random calculation |
| Int gain – nominal value | Distinguish between lighting and electrical appliances: Hourly definition according to [24] | No differences between lighting and electrical appliances: values fixed by random function |
| Occupancy – schedule | Hourly definition according to [24] | Defined in function of the active-hours as reported in Table 2. 5 |
| Int gain – schedule | Hourly definition according to [24] | Defined in function of the active-hours as reported in Table 2. 5 |
| Refurbishment | Not implemented | Buildings have randomly assigned refurbishment level |
| DHW | Calculated according to [23] | Consider the occupancy, seasonal variation and load categories |
| Mechanical ventilation | Hourly definition considering the occupancy and standard [29] | Not implemented |
| Set-back temperature | Hourly fixed by our hands and apply for all the buildings of the single archetype | Fix equal to 21 °C and depends by a probability which corresponds to the amount of buildings that have $T_{set\text{-}back}$ active, |
| Area | $A_{EUReCA} = A_{footprint} \cdot N_{floors}$ | $A_{UHP} = A_{EUReCA} \cdot corr_{factor}$ |

All the input data are maintained as described in previous chapters, with some differences.

As stated before, since the main differences between the two models have been outlined, now we aim to modify the input data to achieve two models that are as similar as possible (at least in their assumptions, particularly by reducing the random effects of UrbanHeatPro and trying to "adapt" the EUReCA data to that of UHP – with the exception of mechanical ventilation). The objective is to assess whether the divergent solutions generated by the two models in Figure 3. 4 are primarily due to the variations in the definition of the input data or are influenced by other factors.

### *Mechanical Ventilation*

As it's reported in the next chapter in Figure 3. 4, consumptions of heating and cooling in EUReCA are strongly higher than the ones in UrbanHeatPro: it may be related to the fact that UrbanHeatPro doesn't take into account the contribution of mechanical ventilation (as described before), but only the infiltration due to the opening and closing of windows and doors and the natural infiltration through the building elements. For this reason, a new input is defined for the schedule, setting the mechanical ventilation equal to zero (in EUReCA) in the public, industrial and commercial buildings (in the residential ones it was already fixed since there is no mechanical ventilation in residential buildings).

### *Seasonality of heating and cooling system*

Another difference is related to the probability of the system's operation. In UrbanHeatPro model, this probability is defined as a variable ranging between zero and one, according to Table 2. 4. On the other hand, in EUReCA, the system's operating schedule is specified by indicating the start and end dates of the heating and cooling seasons as follows:

- Heating between 01/10 and 30/04;
- Cooling between 01/06 and 31/08.

To make the two models as similar as possible, the probability in UrbanHeatPro is set equal to one when the heating/cooling system is turned on (as defined by the EUReCA schedule), and it is set to zero when the system is turned off. As for heating, a probability equal to 0 is assigned from May to September (while it is 1 the rest of the months); for the cooling, a probability equal to 1 is assigned from June to August. This adjustment ensures that both models align in terms of when the heating or cooling systems are on, despite their different approaches in defining the system's probabilities.

***Set-point temperatures, hourly work of the plants and schedules***

As stated in Table 2. 2 and Table 2. 3 another random effect of the UrbanHeatPro software is the determination of set point temperatures. For both cooling and heating, the software assigns these set point temperatures to each building randomly, following the ranges specified in Table 2. 2 and Table 2. 3.

On the other hand, EUReCA defines a single, non-random set point temperature value per each hour, based solely on user's selection.

To enhance the similarity between the two input models, we initially set the "dt" parameter to zero. This ensures that each building category will only have one set point temperature value as shown in Table 2. 16 and Table 2. 17.

*Table 2. 16: Heating set-point temperature fix equal both for EUReCA and UrbanHeatPro*

| Heating | | | |
|---|---|---|---|
| | $T_{set}$ | dt | Range |
| Residential | 20 °C | 0 °C | 20 °C |
| Commercial | 18 °C | 0 °C | 18 °C |
| Public | 18 °C | 0 °C | 18 °C |
| Industrial | 17 °C | 0 °C | 17 °C |

*Table 2. 17: Cooling set-point temperature fix equal both for EUReCA and UrbanHeatPro*

| Cooling | | | |
|---|---|---|---|
| | $T_{set}$ | dt | Range |
| Residential | 23 °C | 2 °C | 21 °C – 25 °C |
| Commercial | 23 °C | 2 °C | 21 °C – 25 °C |
| Public | 23 °C | 2 °C | 21 °C – 25 °C |
| Industrial | 21 °C | 6 °C | 15 °C – 27 °C |

Regarding the scheduling, the "activity hours" provided in Table Table 2. 5 are used for both models. In UrbanHeatPro, these activity hours introduce time variations during which the HVAC systems can be activated, while in in EUReCA we specify manually these hours.

To achieve comparable results, a time variation equal to zero is set in UrbanHeatPro in order to obtain the hours in which the building is occupied without any random assignment (remember that in UrbanHeatPro the internal gains, heating, and cooling depends on the occupancy definition). The data are reported in Table 2. 18.

*Table 2. 18: Active hours modified in order to obtain similar input between EUReCA and UHP. The active hours are the hours in which the building is occupied, amd the internal gains, the heating and cooling are on*

| Active hours – modified for comparison | | | | |
|---|---|---|---|---|
| Building type | Start [h] | End [h] | dt [h] | Range [dt] |
| Residential | 0 | 23 | 0 | 0 – 23 |
| Commercial | 8 | 18 | 2 | 8 – 18 |
| Public | 8 | 16 | 2 | 8 – 16 |
| Industrial | 8 | 18 | 2 | 8 – 18 |

Subsequently, in EUReCA the set point temperature is set hour by hour according to Table 2. 18.

For shutting down the HVAC systems, the schedules are aligned with the new active hours defined in Table 2. 18. The occupancy, electrical appliances, lighting, heating and cooling plants are considered active during the hours reported in the previous table (while, the nominal value of occupancy, electrical appliances and lighting are defined according to the standard BS EN ISO 18523 *[24]*).

The weekdays and weekends were set to be the same from the beginning in both EUReCA and UrbanHeatPro models. Both models consider:

- an active schedule throughout the week for residential buildings;
- an active schedule from Monday to Saturday for commercial buildings;
- an active schedule from Monday to Friday for industrial and public buildings.

Additionally, as previously defined, heating and cooling systems in UrbanHeatPro are influenced by a parameter "dt" which defines the range within which heating and cooling can be activated. Up to now, “dt” is set equal to 2 °C and, as consequence, the HVAC system:

$$\text{starts when } T_{set} < T_{set} - 2 \text{ and stops when } T_{set} > T_{set} + 2 \text{ for the heating season}$$

while, for the cooling season:

it starts when $T_{set} > T_{set} + 2$ and stops when $T_{set} < T_{set} - 2$

EUReCA has a different behaviour: it takes into account that the heating starts only if the inside temperature of the building is lower than the set-point temperature defined in Table 2. 16, while the cooling starts only if the inside temperature of the building is higher than the set-point temperature defined in Table 2. 17. For this reason, in order to obtain a similar behaviour both in EUReCA and UrbanHeatPro, a "dt" equal to zero is fixed in UrbanHeatPro.

The set-back temperature must be changed because in EUReCA it depends by the user choice, while in UrbanHeatPro it depends by a probability that defines the percentage of the buildings that have a set-back temperature with a fix set-back temperature value. In order to obtain two similar input data, the probability is set equal to zero in UrbanHeatPro (it means that no building has a set-back temperature), while, in EUReCA, the set-point temperature in Table 2. 16 and in Table 2. 17 is maintained constant for all the active hours according to Table 2. 18 (so, none of the buildings have set-back temperature).

### ***Refurbishment level***

In UrbanHeatPro, a random level of refurbishment is assigned to each building. To ensure that there are corresponding U-values in both UrbanHeatPro and EUReCA models, the assigned random factor has been eliminated in order to avoid refurbishment differences.

# 3. Results – EUReCA vs UrbanHeatPro

In this chapter the results of the simulations are described and reported. In particular, it is highlighted the results of the simulations from UrbanHeatPro and EUReCA without any modification on the input as described in chapter *2.1* and 2.3 and the results of the simulations from the adapted model - considering the input as reported in the chapter *2.5*.

## 3.1 UrbanHeatPro and EUReCA results with no adaption of the input data

This section only presents the results obtained with EUReCA and UrbanHeatPro without any model adaptation. The simulations are carried out considering the city of Unterhaching as a reference.

### *UrbanHeatPro results*

By keeping all random factors active and using data on building location (latitude and longitude), its footprint area, end-use, number of free walls, and distance to the heat source, a synthetic city (called synthetic city 1) was constructed. The simulation then evaluates heating and cooling demands of each individual building (and hence their hourly and annual consumption for all 185 buildings). In particular, in Figure 3. 1 are reported the hourly energy consumption for space heating (considering also the domestic hot water production) and for space cooling.

The total demanded energy corresponds to:

- 11.62 GWh for heating, of which:
  - 10.91 GWh for space heating (which corresponds to the 93.95 %);
  - 0.70 GWh for the heating of domestic hot water (which corresponds to the 6.05%);
- 2.12 GWh for cooling.

Just to better distinguish the different periods in Figure 3. 1, consider that:

- the hour 3624 correspond to the 1st of June (start of the summer season);
- the hour 5832 corresponds to the 1st of September (end of the summer season).

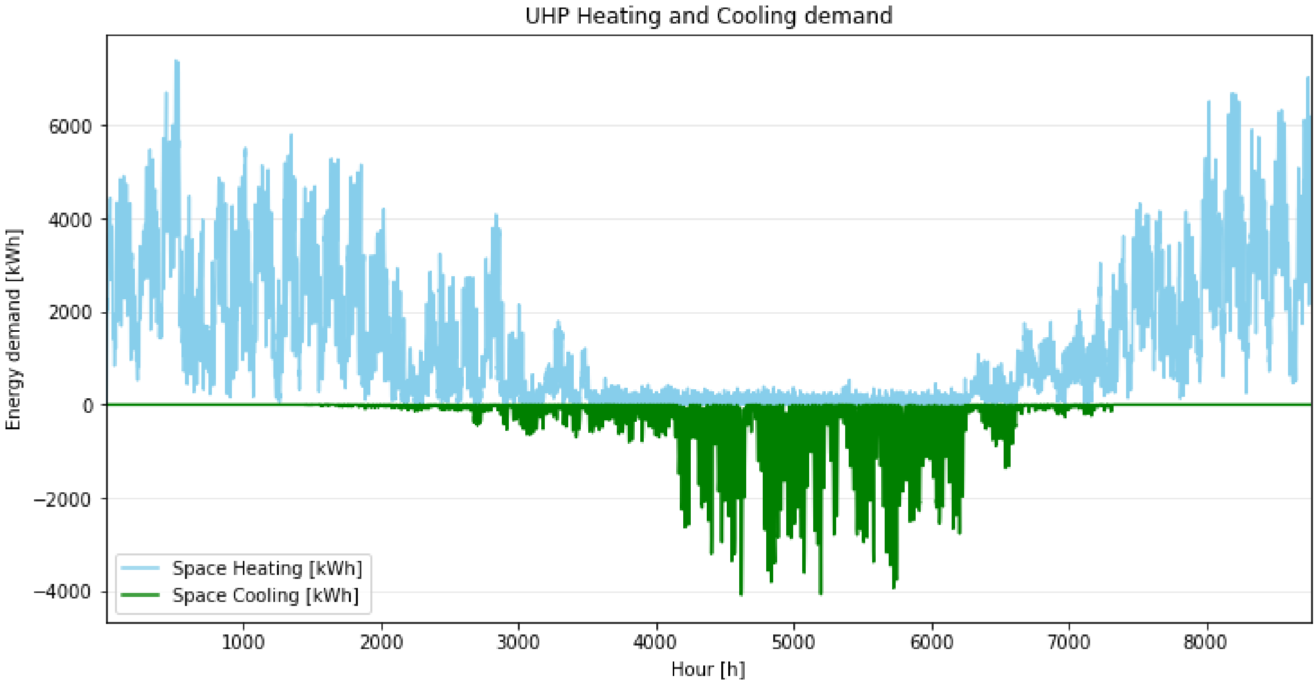


*Figure 3. 1: Hourly trend of heating and cooling demand simulated through UrbanHeatPro and using the synthetic city 1 as input*

The demand for space heating covers the 93.95 % of the total heating demand: it's related to the fact that usually the buildings in Germany maintain the heating system on from October to April. However, there are no guideline about the opening and the closing of the heating systems and they are defined according to Table 2. 4. As it's reported in Table 2. 4, the probability of using the space heating is high from October to May, after that period it decreases but it's not null. A similar trend is obtained in Figure 3. 1 in which it's shown a higher heating demand in the winter season with a consequent decrease during spring and autumn season. During the summer it's not equal to zero since UrbanHeatPro considers that a percentage of the buildings, according to Table 2. 4, maintain the heating on. Moreover, there is also the heating contribution of the domestic hot water (usually, during summer season, it represents the highest contribution).

About the trend of the cooling, the same observation can be done: the activity of the plants reflect the probability of using space cooling reported in Table 2. 4; it means that the plants can be active between March and October. A peak of demand during the last days of June and during July is shown: in fact, according to Figure 3. 1, the external temperature is high, the cooling demand increases. Moreover, the cooling demand, is quite lower than the amount of the heating demand due to the fact that the city of Unterhaching is located in an area where the climate is characterized by mild summers and relatively mild winters with precipitation evenly distributed throughout the year. Winters are not extremely harsh but can be cold. A trend of the external temperature is reported in Figure 3. 2.

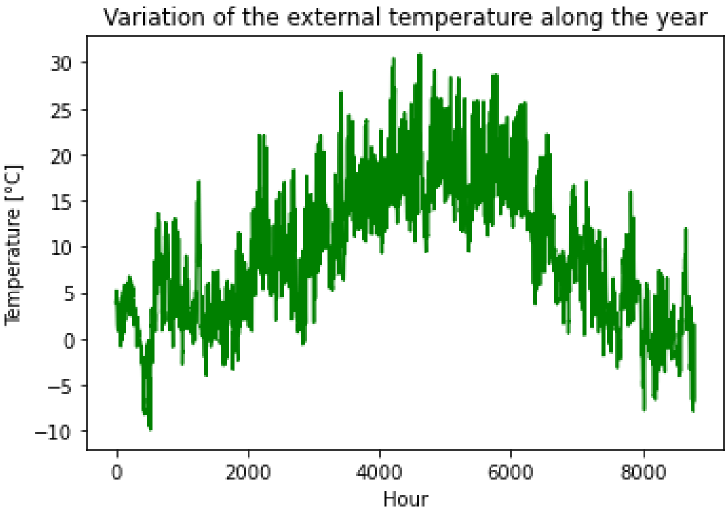


*Figure 3. 2: Hourly value of the external temperature of the air in Unterhaching*

### *EUReCA results*

From the synthetic city 1, constructed by UrbanHeatPro, and considering the input data reported in chapter *2.3*, the hourly space cooling demand and the hourly space heating demand Figure 3. 3 are calculated.

The total demanded energy corresponds to:

- 21.186 GWh for heating, of which:
  - 19.30 GWh for space heating (which corresponds to the 91.09 %);
  - 1.88 GWh for heating of the domestic hot water (which corresponds to the 8.91%);
- 4.09 GWh for cooling.

In order to better distinguish the different periods in Figure 3. 3 and according to the definition at page *45*:

- the heating system is active between October and May;
- the cooling system is active between June and August.

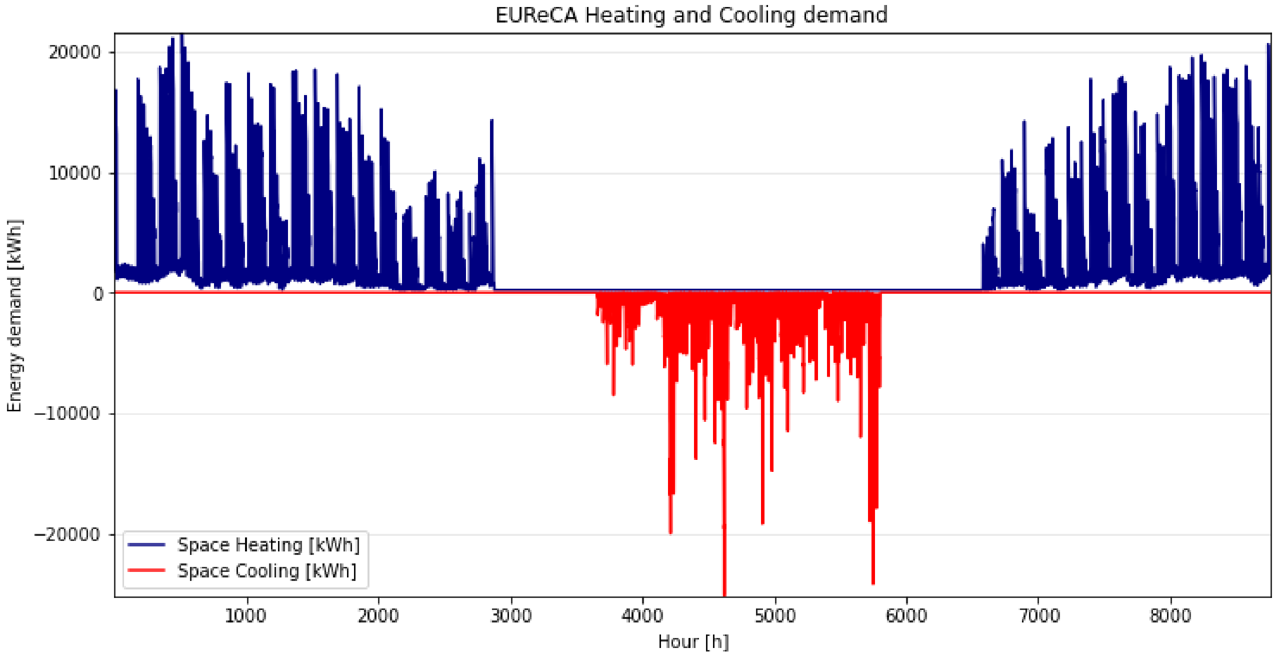


*Figure 3. 3: Hourly trend of heating and cooling demand simulated through EUReCA and using the synthetic city 1 as input*

The results (considering the annual values) seem to be consistent with the real behaviour of a city: in particular, a huge demand for the space heating, that covers the 93.95 % of the total heating demand.

During summer the heating demand is required only for the production of the domestic hot water (in fact in Figure 3. 3, a horizontal trend of the heating demand is required during the summer season).

Concerning the cooling demand, comparing the trend of the cooling demand reported in the negative y axis of Figure 3. 3 and the trend of the external temperature reported in Figure 3. 2, it’s clear that an increase in outside temperature corresponds to an increase in cooling demand.

### *UrbanHeatPro vs EUReCA – comparison of the results*

The differences in the results between UrbanHeatPro and EUReCA can be seen in the output values of the two simulations, where in EUReCA both the space heating and cooling demand are double thatt of UrbanHeatPro. The two trends are reported in  Figure 3. 4.

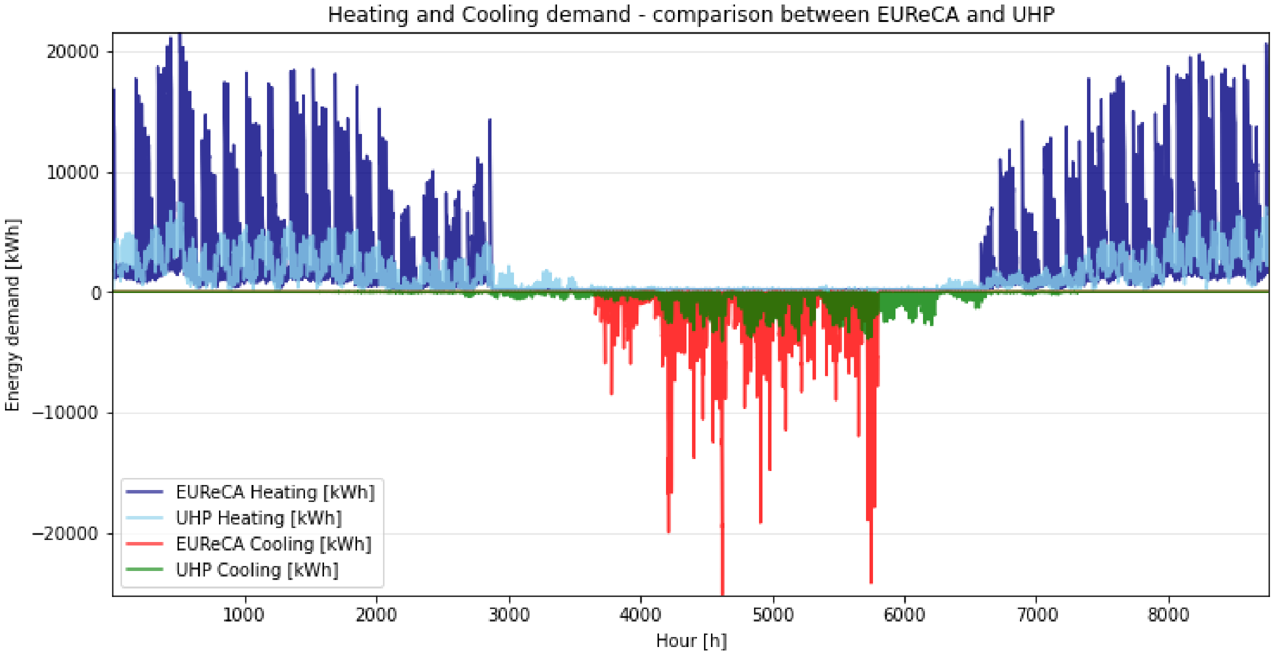


*Figure 3. 4: Comparison of the hourly trend of the heating and cooling demand simulated through EUReCA and UrbanHeatPro*

The next figures show the total heating and cooling consumption for each classification of building (residential, commercial, public and industrial) in order to understand which building category influences the results. Each figure reports:

- the average value of the demand (*mean*);
- the standard deviation (*std*);
- the minimum (*min*) and maximum (*max*) value of demand;
- values corresponding to three different percentiles (namely, 25%, 50%, and 75%). Each of these percentiles is associated with an energy demand expressed in kWh, indicating that the buildings corresponding to that percentile have a maximum demand of that amount in kWh. For instance, if a consumption of 150,000 kWh corresponds to the 25% column, it means that 25% of the evaluated buildings have an energy demand lower than 150,000 kWh.

According to Figure 3. 6, in the residential sector there is a similarity between the energy demand for heating and cooling. For heating, the differences can be attributed to two main factors: the random effects that characterise the UrbanHeatPro model, and the different calculation of hot water demand. However, it should be noted that this influence is rather marginal, reaching a maximum of 9% of the total demand for space heating, which refers to the energy demand of the city in residential buildings.

For cooling, on the other hand, it is noticeable that UrbanHeatPro tends to be slightly higher in the residential sector. This could be caused by the definition of schedules in EUReCA, as cooling only takes place in the afternoon hours as defined in *2.3*. However, at the urban level and for the residential sector, the EUReCA model simulates a similar demand to the one simulated by UrbanHeatPro.

Conversely, significant differences between the EUReCA and UrbanHeatPro models are observed within the commercial, public and industrial buildings, as both the heating and cooling demand simulated by EUReCA at urban level is at least twice the demand simulated by UrbanHeatPro model. In particular, Figure 3. 5 highlights the average energy consumption in MWh for each sector: it can be observed that the heating simulated by EUReCA is twice as much as that evaluated by UrbanHeatPro for commercial, public and industrial sectors, while for cooling it is twice as much for commercial buildings and seven times as much for public and industrial buildings.

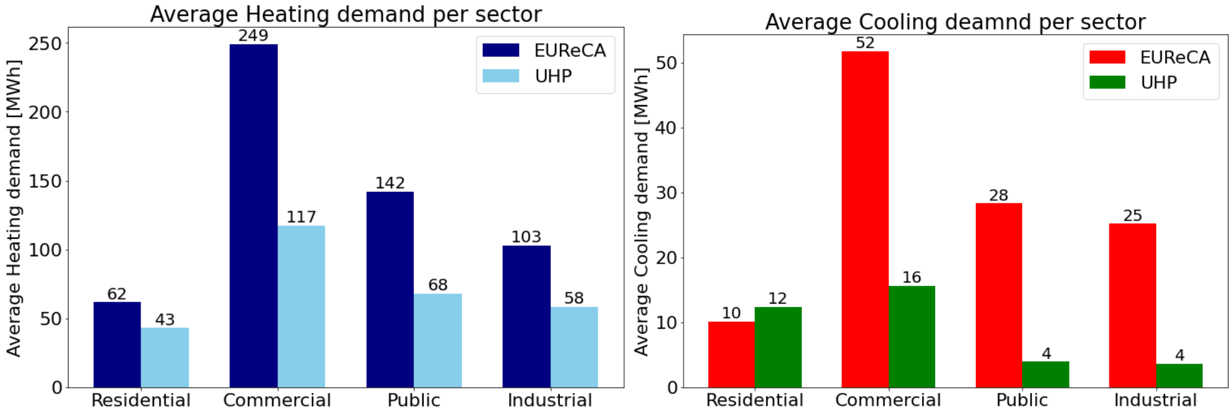


*Figure 3. 5: Average heating (left) and cooling (right) demand in MWh per sector – EUReCA vs UrbanHeatPro*

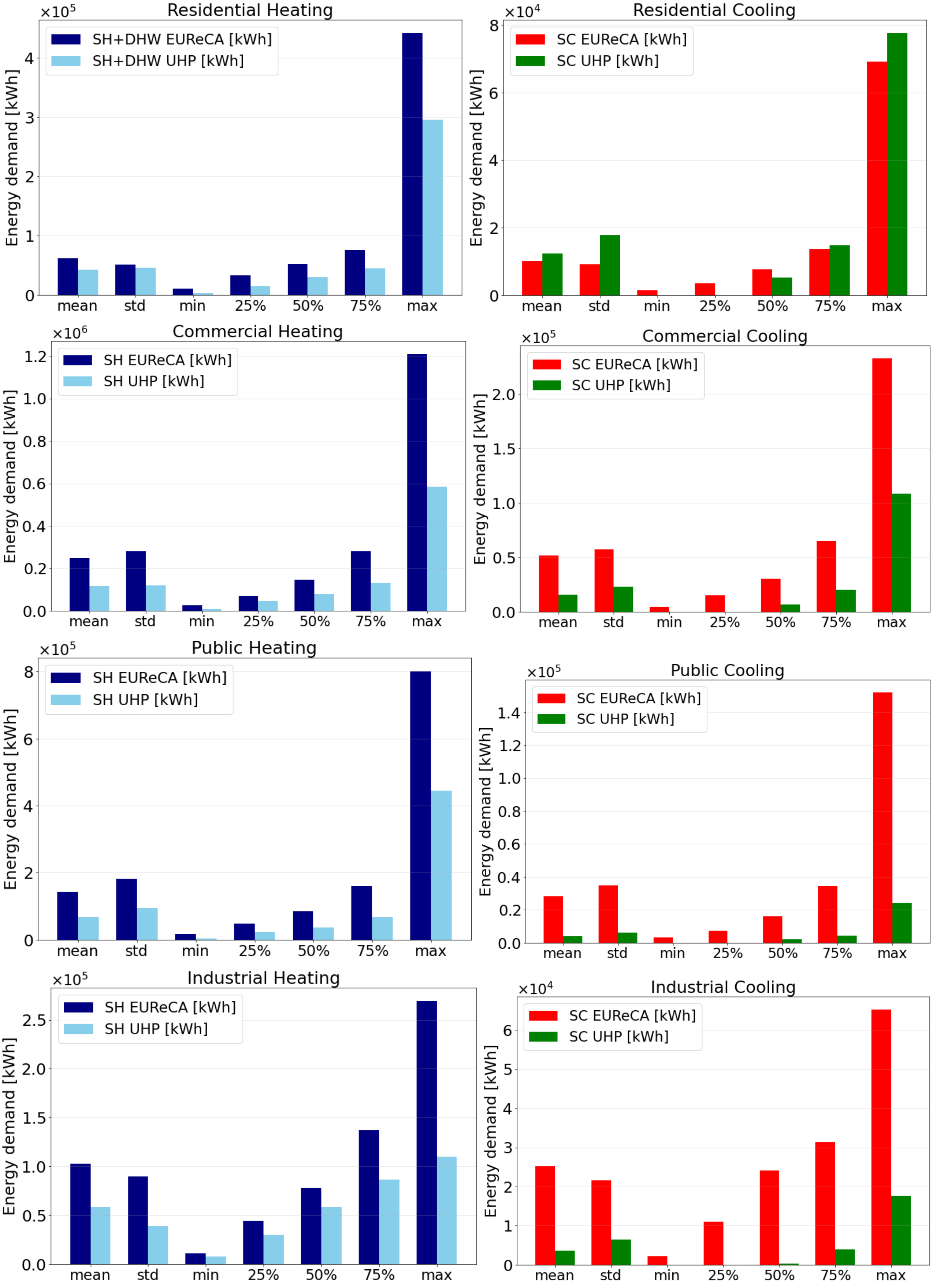


*Figure 3. 6: Statistics data regarding the consumption in kWh per each building category: residential (first row), commercial (second row), public (third row) and industrial (fourth row). The plots that are on the left represent the heating demand in kWh, while the ones that are on the right represent the cooling demand in kWh.*

The results in Figure 3. 5 and Figure 3. 6 show only the demand in kWh or MWh. In order to evaluate if the energy demand of the building is consistent with the reality, Figure 3. 7 reports also the data with the value in kWh/m$^2$ (it has been calculated as the average of the all values in kWh/m$^2$ of the entire district).

Nevertheless, when we are comparing the values in kWh/m$^2$ we have to take into account that the UrbanHeatPro's area is lower than that of EUReCA according to the standard [20]: this means that, for the same consumption of kWh, the value of kWh/m$^2$ tends to be lower in EUReCA with respect to UrbanHeatPro.

As we can see in the following figure, the energy required by EUReCA seems to present good results. In particular, the commercial, public, and industrial buildings (that had high consumption in Figure 3. 5), seem to have reasonable values considering the reality. On the contrary, with UrbanHeatPro they are quite low, especially in the cooling case.

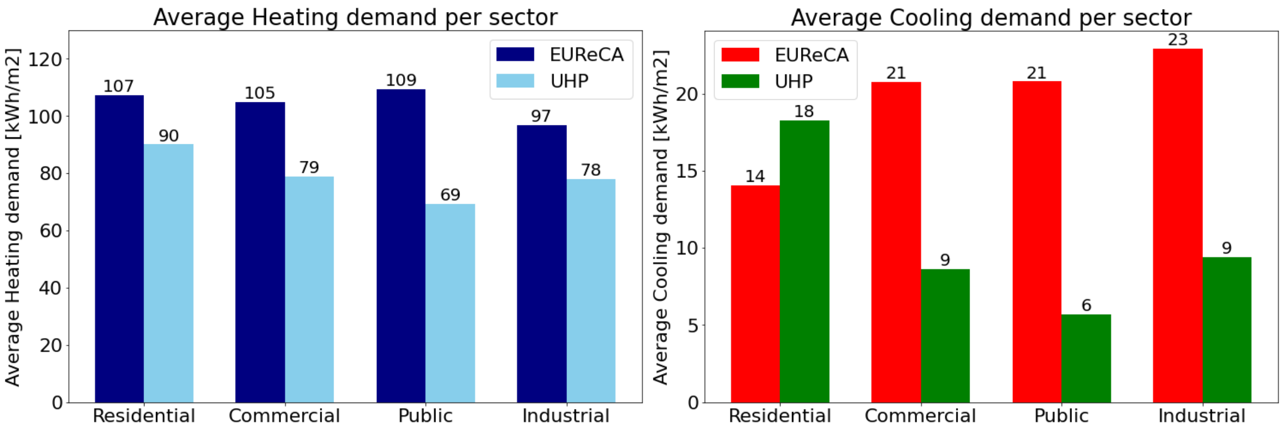


*Figure 3. 7: Average heating (left) and cooling (right) demand in kWh/m$^2$per sector – EUReCA vs UrbanHeatPro*

So far, the average consumption per sector was presented. However, the aim is to illustrate the differences between the two models and to clarify the factors responsible for these differences. To do this, the sectors that have the greatest impact on heating and cooling energy demand must be identified. In this way, a more comprehensive understanding of the origins of these discrepancies can be achieved by delving into the specifics of each sector.

The next table shows the contribution in GWh per each sector for heating and cooling, calculated by taking into account the two different models: EUReCA and UrbanHeatPro.

*Table 3. 1: Total amount of heating and cooling required by each sector - calculated considering as active the random effects*

| | Heating [GWh] | | Cooling [GWh] | |
|---|---|---|---|---|
| | EUReCA | UHP | EUReCA | UHP |
| Residential | 6.90 | 4.80 | 1.13 | 1.38 |
| Commercial | 9.72 | 4.57 | 2.01 | 0.61 |
| Public | 3.83 | 1.83 | 0.76 | 0.11 |
| Industrial | 0.72 | 0.41 | 0.18 | 0.02 |

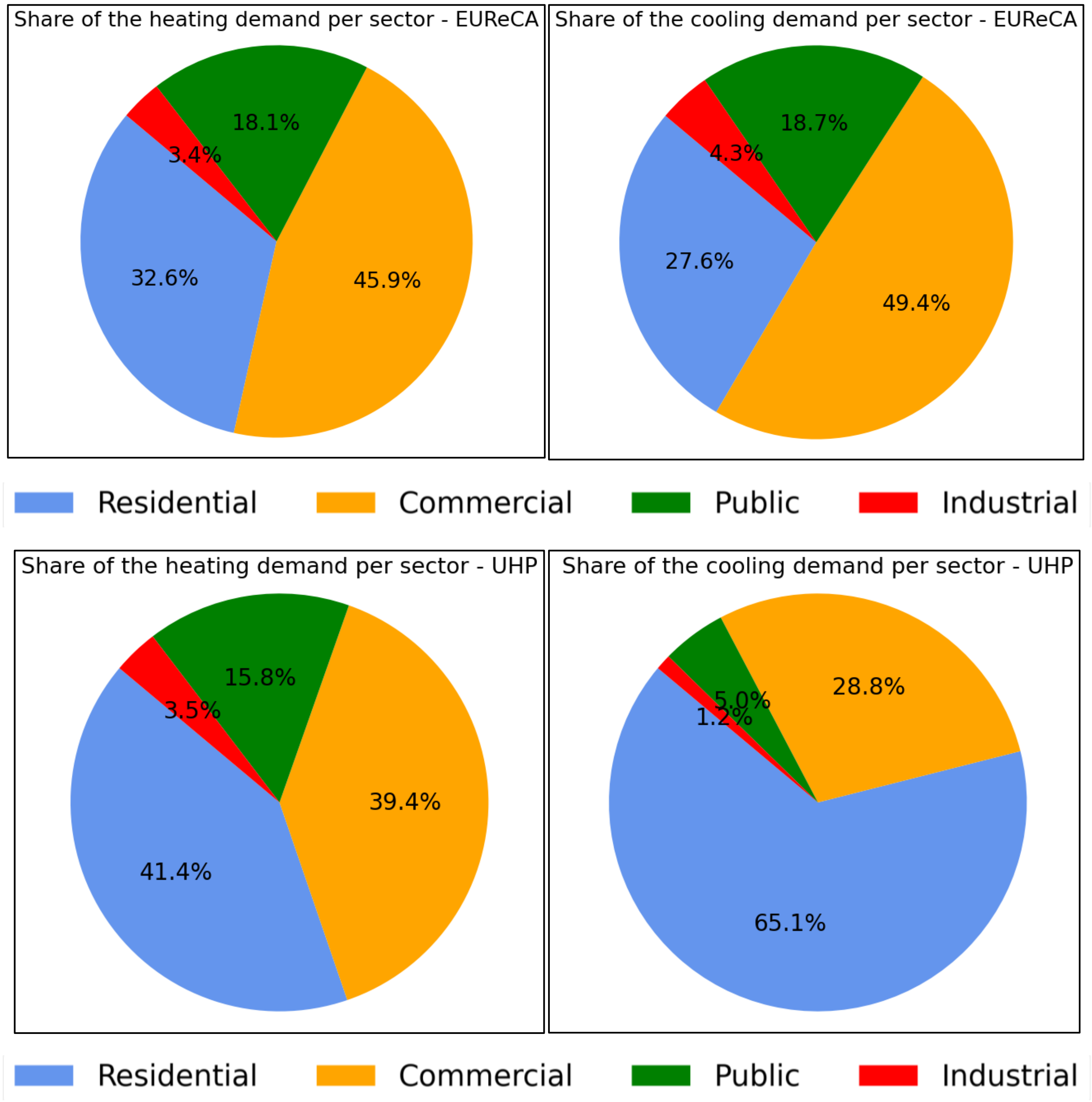


*Figure 3. 8: Share of heating and cooling demand per sector in the adapted models. On the first row are reported the EUReCA's data. In the second row are reported the UrbanHeatPro's data*

It's clear that there's a big difference between EUReCA and UrbanHeatPro for non-residential sector. Probably the main difference is related to the fact that UrbanHeatPro doesn't take mechanical ventilation into account: in fact, for residential buildings (where mechanical ventilation is not present in both models), the difference in energy requirements is not as great as in the case of non-residential buildings.

Furthermore, it is evident from Figure 3. 8 that the contribution of industrial sector can be considered negligible, as it has a limited impact on the overall results.

On the contrary, the commercial and residential sectors show a significant contribution. This is due to two main effects: for commercial buildings, the energy demand per individual building is high for both heating and cooling. Whereas, for residential sector, even if the individual building demand is lower, their total quantity – 61% of the buildings in the case study – has a significant impact on the city's overall demand.

In addition, Figure 3. 8 shows that the share of demand for heating is relatively similar for both EUReCA and UrbanHeatPro. For cooling, on the other hand, the shares are completely different; indeed, in UrbanHeatPro, the cooling required by the residential sector represents 65.1 % of the total, while in EUReCA it represents 27.6 % of the total. Once again, the significant difference in cooling demand is evident in the results.

In particular, according to Table 3. 1 the cooling demand in UrbanHeatPro is:

- 53 % lower than EUReCA’s demand for commercial buildings;
- 52 % lower than EUReCA’s demand for public buildings;
- 43 % lower than EUReCA’s demand for industrial buildings.

While the heating demand in UrbanHeatPro is:

- 70 % lower than EUReCA’s demand for commercial buildings;
- 86 % lower than EUReCA’s demand for public buildings;
- 89 % lower than EUReCA’s demand for industrial buildings.

This difference is given by the random effects: indeed, heating is required by each building while cooling is not required by each building. In particular, in the non-residential sector, 25 % of the buildings have no cooling consumption, as shown in Figure 3. 9. In this figure it is reported the cooling consumption per building per each sector, to show how the cooling demand of UrbanHeatPro differs from that of EUReCA. These kind of random effects alter only the non-residential sector; for this reason, we report only the comparison among the buildings in the commercial, public and industrial sector.

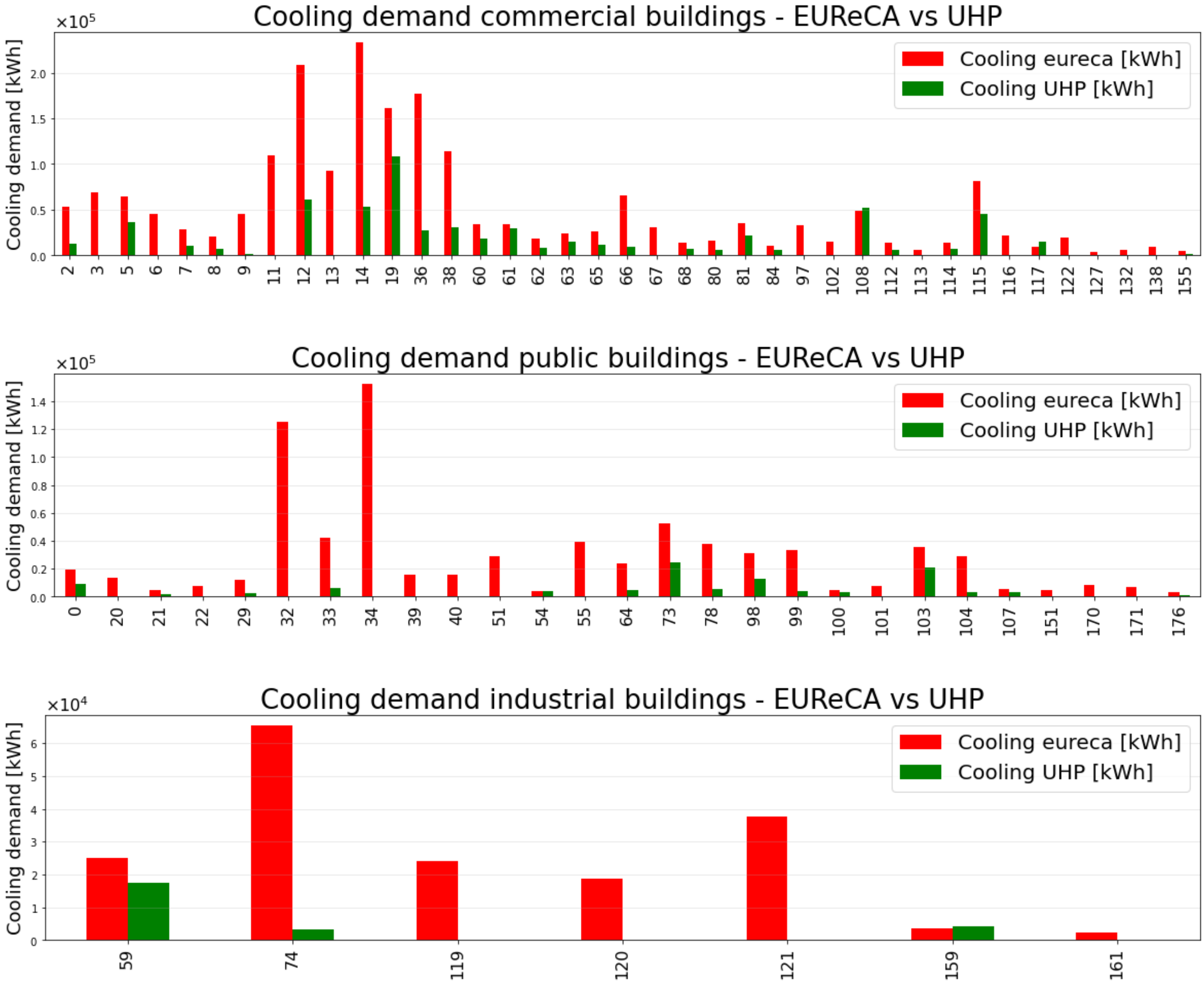


*Figure 3. 9: Cooling demand in the non-residential sector calculated with EUReCA vs Cooling demand in the non-residential sector calculated with UrbanHeatPro considering the random effects and the mechanical ventilation active.*

So far we have highlighted the most important differences in the results between the two different simulations, taking into account the random effects active in UrbanHeatPRo.

However, in order to evaluate which is the contribution of mechanical ventilation, a new simulation is performed with EUReCA, considering the same assumption of chapter *2.3*: the only difference is that the mechanical ventilation is set equal to zero. In fact, as reported in Table 3. 1, there is a great difference between commercial, public and industrial buildings (even if the latter doesn’t affect too much the results). The difference between the two models could be caused by the fact that UrbanHeatPro doesn’t take in account the mechanical ventilation.

### *UrbanHeatPro vs EUReCA – comparison of the results without mechanical ventilation*

In Table 3. 2 and Figure 3. 10 are reported the reductions of space heating and cooling after the removal of mechanical ventilation: the total energy simulated by the two different EUReCA simulations, the energy demand decreases significantly in the absence of mechanical ventilation: only the residential sector maintains the same level of consumption since it never has the mechanical ventilation active.

Furthermore, as heating and cooling decreases, we get a better solution in the end where the energy required by EUReCA without mechanical ventilation is more similar to the energy required by UrbanHeatPro. In fact, regarding heating consumption, UrbanHeatPro' demand is:

- 30 % lower than EUReCA's demand for residential buildings;
- 8 % lower than EUReCA's demand for commercial buildings;
- 25 % higher than EUReCA's demand for public buildings;
- 15 % lower than EUReCA's demand for industrial buildings.

While, for cooling consumption, the UrbanHeatPro's demand is:

- 22 % higher than EUReCA's demand for residential buildings;
- 50 % lower than EUReCA's demand for commercial buildings;
- 73 % lower than EUReCA's demand for public buildings;
- 85 % lower than EUReCA's demand for industrial buildings.

From the percentage, the heating demand calculated with EUReCA (with no mechanical ventilation) is quite similar to the heating demand of UrbanHeatPro (see the imagine on the top of Figure 3. 10 and the values reported in Table 3. 2).

On the other hand, the cooling demand is still very different: in particular, the energy demand of UrbanHeatPro is much lower than that of EUReCA in non-residential sector. The reasons are the ones already explained: some buildings in the commercial, public and industrial sector do not have an active cooling system throughout the season due to some random effects. The bottom part of Figure 3. 10 shows how the space cooling demand is lower in UrbanHeatPro simulation compared to the space cooling calculated with EUReCA (without mechanical ventilation).

*Table 3. 2: Total amount of heating and cooling required by each sector – considering the mechanical ventilation activated and deactivated in EUReCA.*

| | Heating [GWh] | | | Cooling [GWh] | | |
|---|---|---|---|---|---|---|
| | EUReCA MV ON | EUReCA MV OFF | UHP | EUReCA MV ON | EUReCA MV OFF | UHP |
| Residential | 6.90 | 6.90 | 1.80 | 1.13 | 1.13 | 0.38 |
| Commercial | 9.72 | 4.98 | 4.57 | 2.01 | 1.23 | 0.61 |
| Public | 3.83 | 1.46 | 1.83 | 0.76 | 0.40 | 0.11 |
| Industrial | 0.72 | 0.48 | 0.41 | 0.18 | 0.13 | 0.02 |

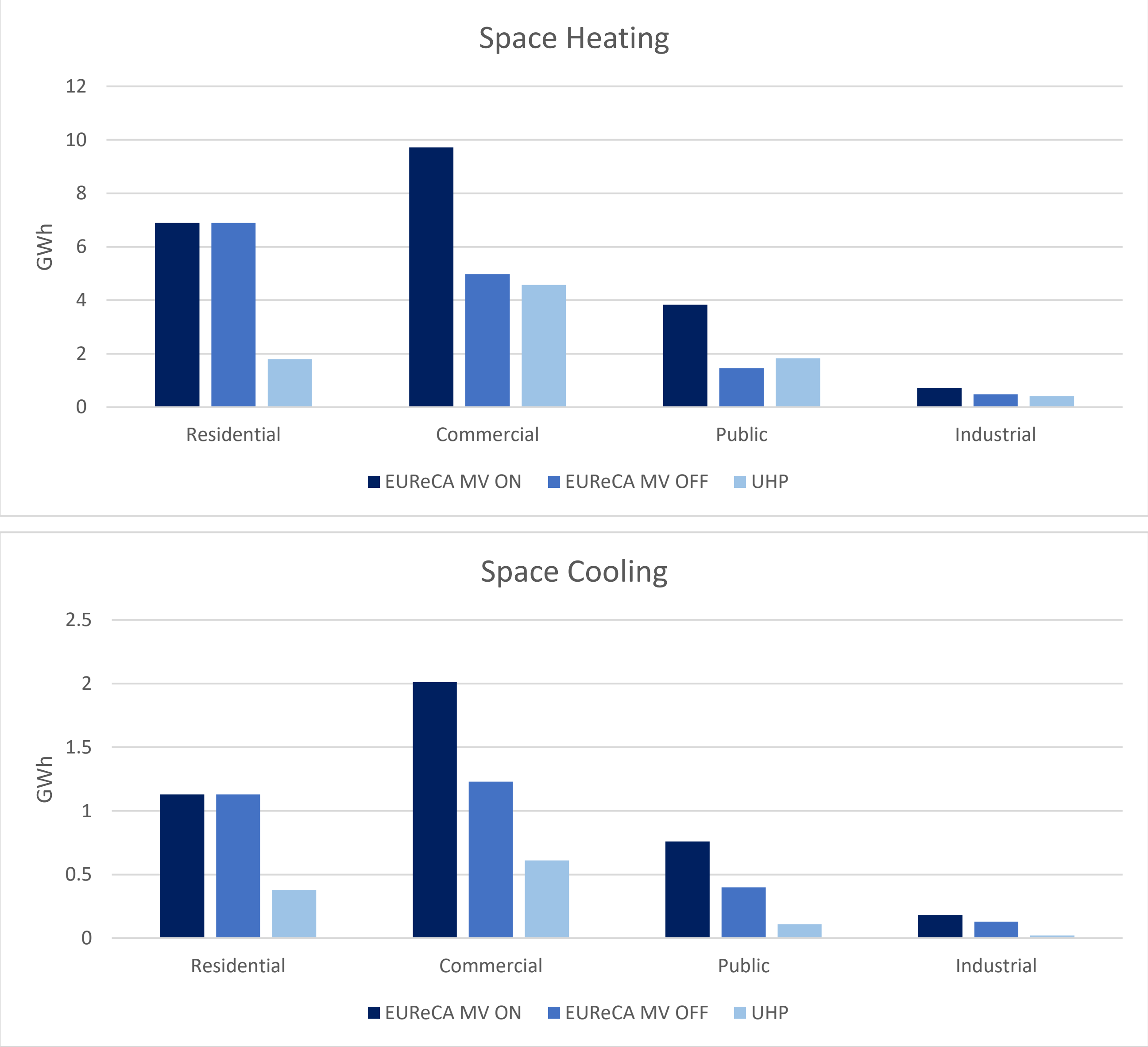


*Figure 3. 10: Comparison between space heating and space cooling demand calculated with: 1. EUReCA with mechanical ventilation active (EUReCA MV ON); 2. EUReCA with mechanical ventilation turned off (EUReCA MV OFF); 3. UrbanHeatPro with the random effects active (UHP).*

So, the mechanical ventilation has an important impact on the results and it cannot be neglect since it can vary a lot the demand in the non-residential buildings.

However, only the contribution of mechanical ventilation has been reported so far, but as described in the previous pages, also the random effects can lead to some distortion of the results. For this reason, it is crucial to go into detail and make a careful comparison between the two models, while reducing the influence of random variables and mechanical ventilation.

Therefore, adapted simulation phase is now presented, in which the extensive input data is used and the two models are standardised to the highest possible degree. The goal of this approach is to identify the underlying causes of the differences observed in the models.

## 3.2 UrbanHeatPro and EUReCA results with adaption of the input data

In this section, the input data are set as described in the chapter *2.5* both for EUReCA and UrbanHeatPro.

Since a new simulation is performed with new input data, a new synthetic city must be constructed (synthetic city 2): the number of the buildings and their share stay the same (112 residential, 39 commercial, 27 public and 7 industrial buildings), but their properties (like thermal transmittance, capacitance, hours of plants operation and so forth) are changed.

### *UrbanHeatPro results*

The simulation evaluates heating and cooling demands of individual buildings (and hence their hourly and annual consumption) for all 185 buildings. In Figure 3. 11 is reported the hourly energy consumption for space heating (considering also the domestic hot water production) and for space cooling.

The total energy demanded corresponds to:

- 14.74 GWh for heating, of which:
    - 13.74 GWh for space heating (which corresponds to 93.21 %);
    - 1.00 GWh for the heating of the domestic hot water (which corresponds to 6.79%);
- 2.21 GWh for cooling.

Just to better distinguish the different periods in Figure 3. 11, consider that:

- the hour 3624 corresponds to the 1st of June (start of the summer season);
- the hour 5832 corresponds to the 1st of September (end of the summer season).

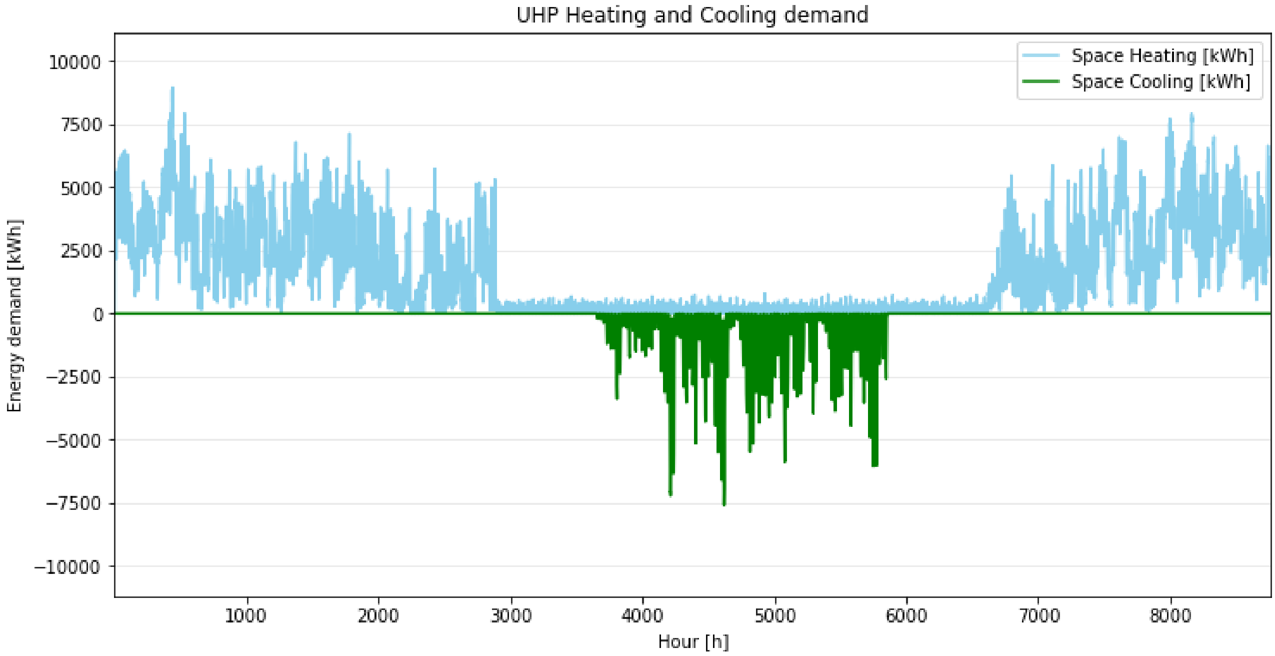


*Figure 3. 11: Hourly trend of heating and cooling demand simulated through UrbanHeatPro and using the synthetic city 2 as input*

### *EUReCA results*

Starting from the synthetic city 2, constructed by UrbanHeatPro, and considering the input data reported in chapter *2.5*, the hourly space cooling demand and the hourly space heating demand are calculated (they are reported in Figure 3. 12.

The total demanded energy corresponds to:

- 14.33 GWh for heating, of which:
  - 12.12 GWh for space heating (which corresponds to 84.56 %);
  - 2.21 GWh for the heating of the domestic hot water (which corresponds to 15.44%);
- 3.44 GWh for cooling.

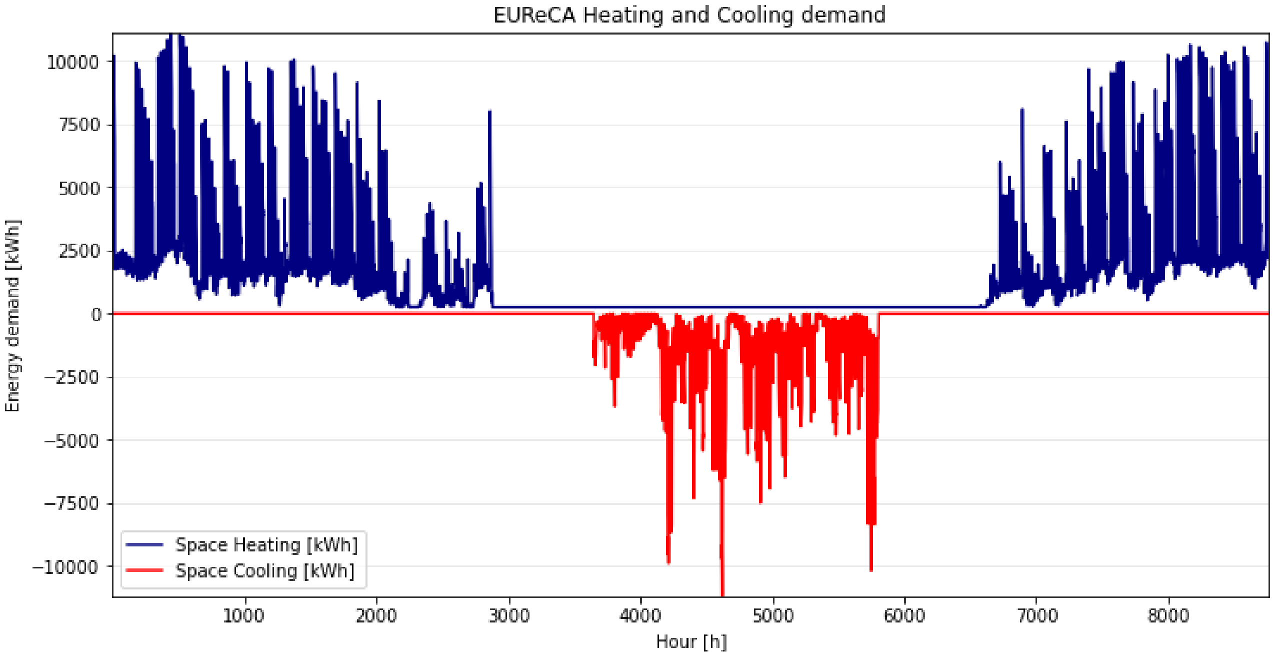


*Figure 3. 12: Hourly trend of heating and cooling demand simulated through EUReCA and using the synthetic city 2 as input*

### *UrbanHeatPro vs EUReCA – comparison of the results*

In Figure 3. 13, the trend of Figure 3. 11 and of Figure 3. 12 are reported. The heating is active in both models between the 1st of October and the 30th of April, while the cooling system works between the 1st of June to the 31th of August.

As for heating demand, the two models show similar overall trends, except for some differences highlighted by peaks. In particular, because of different definitions used in the two models, EUReCA simulates the energy demand needed to bring the building temperature from the current internal temperature to the setpoint temperature. Therefore, when heating and cooling systems are turned off during the night (as happens in non-residential buildings), the internal temperature tends to drop. Therefore, when the system is reactivated to reach the setpoint temperature (i.e., during the morning), the energy demand is very high because the temperature must change significantly in a short period of time (also because EUReCA does not take into account the thermal inertia of the building).

On the contrary, UrbanHeatPro takes into account the thermal inertia of buildings and assumes that the setpoint temperature of the building is reached gradually during its operating hours. This results in a more gradual decrease in energy demand during the night, as thermal inertia allows for a slower temperature change. The thermal inertia of buildings therefore has an impact on the difference between the two curves; UrbanHeatPro takes this into account, thus it reflects more realistically the thermal behaviour of buildings. This approach that takes into account the gradual accumulation and release of heat, contributes to the observed sinusoidal pattern during the night hours.

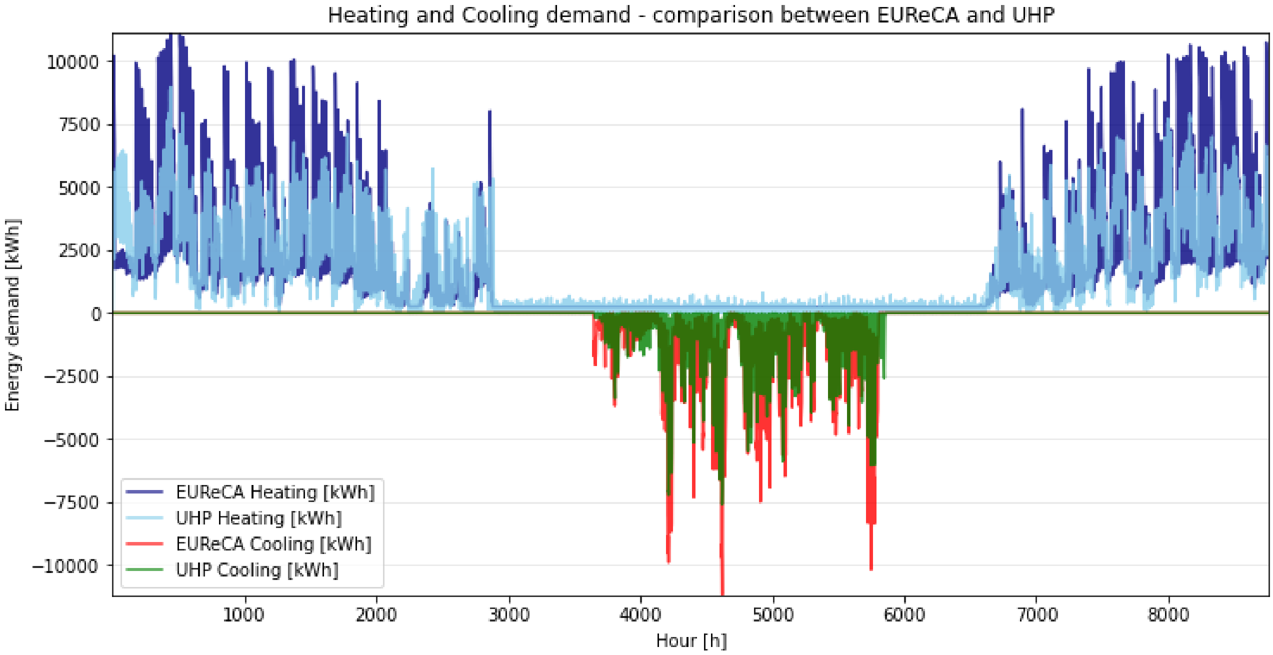


*Figure 3. 13: Comparison of the hourly trend of heating and cooling demand simulated through EUReCA and UrbanHeatPro of the adapted model*

Furthermore, as previously reported, the total heating is quite similar between the two cases: UrbanHeaetPro simulates 14.74 GWh as heating demand, while EUReCA simulates 14.33 GWh. The main difference regards the domestic hot water, but this aspect will be discussed later.

In order to understand which building category affects the results, in Figure 3. 14 are reported the statistical data on: the average value of the energy demanded, the standard deviation, the minimum and maximum value of energy demand and the value connected to the percentiles.

From Figure 3. 14, it's clear that heating demand is very similar in the two models. Whereas for cooling there is approximately a good correspondence only in residential sector; in non-residential sector instead, the cooling demand simulated by EUReCA seems to be strongly higher than the one simulated by UrbanHeatPro.

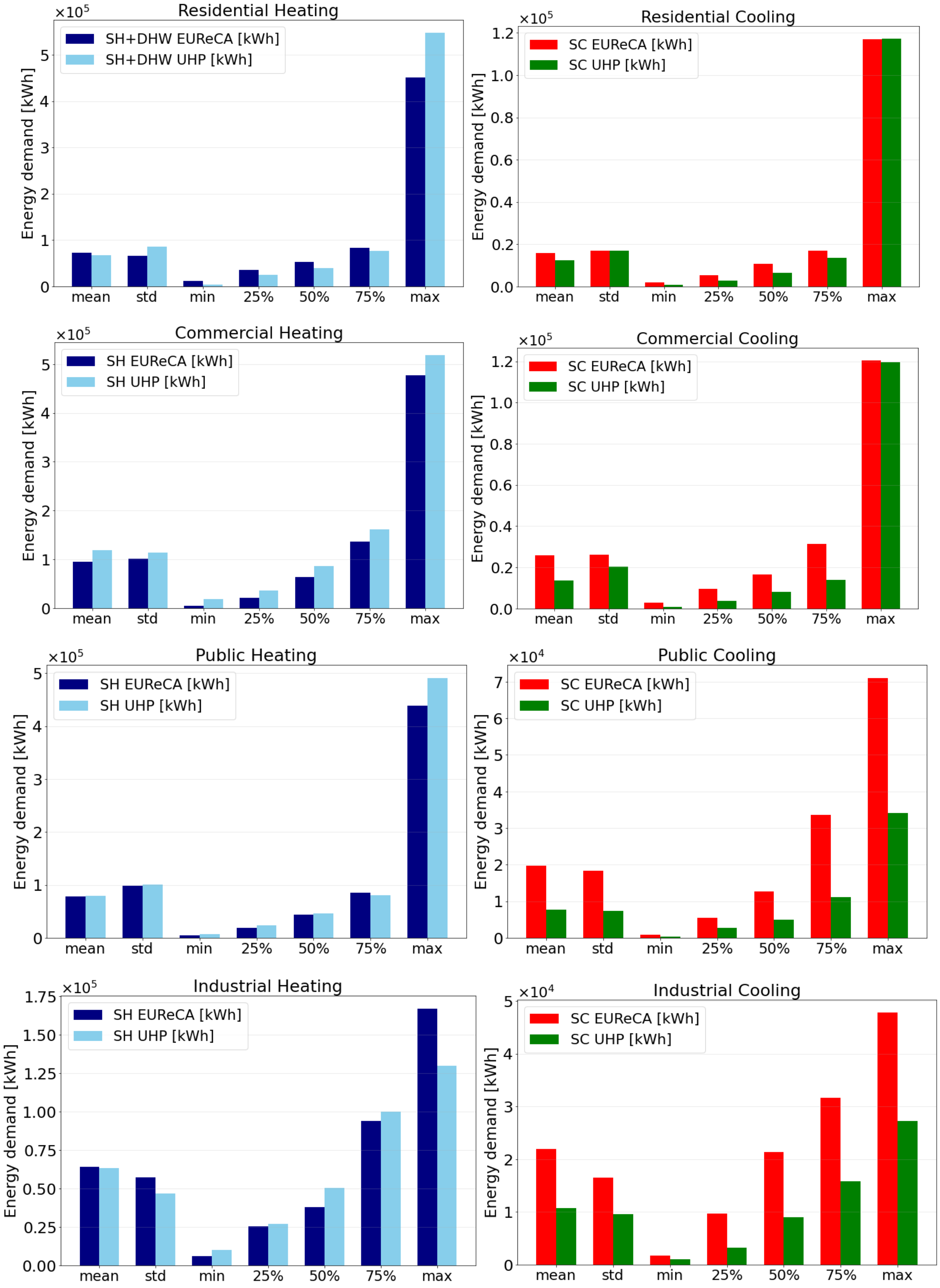


*Figure 3. 14: Statistics data of the adapted simulation regarding the consumption in kWh per each building category: residential (first row), commercial (second row), public (third row) and industrial (fourth row). The plots that are on the left represent the heating demand in kWh, while the ones that are on the right represent the cooling demand in kWh.*

In Figure 3. 14, the mean demand per each sector is reported, which gives a first information about the goodness of the results. However, the goal is to evaluate which is the total energy demanded per sector in order to obtain the contribution of each individual sector in the city energy demand. In particular, in Table 3. 3 the total energy demand in GWh is reported, while, in Figure 3. 15 are reported the shares of consumption per each sector.

*Table 3. 3: Total amount of heating and cooling required by each sector - adapted model*

| | Heating [GWh] | | Cooling [GWh] | |
|---|---|---|---|---|
| | EUReCA | UHP | EUReCA | UHP |
| Residential | 8.06 | 7.55 | 1.76 | 1.40 |
| Commercial | 3.70 | 4.64 | 1.01 | 0.53 |
| Public | 2.14 | 2.12 | 0.54 | 0.21 |
| Industrial | 0.45 | 0.44 | 0.15 | 0.08 |

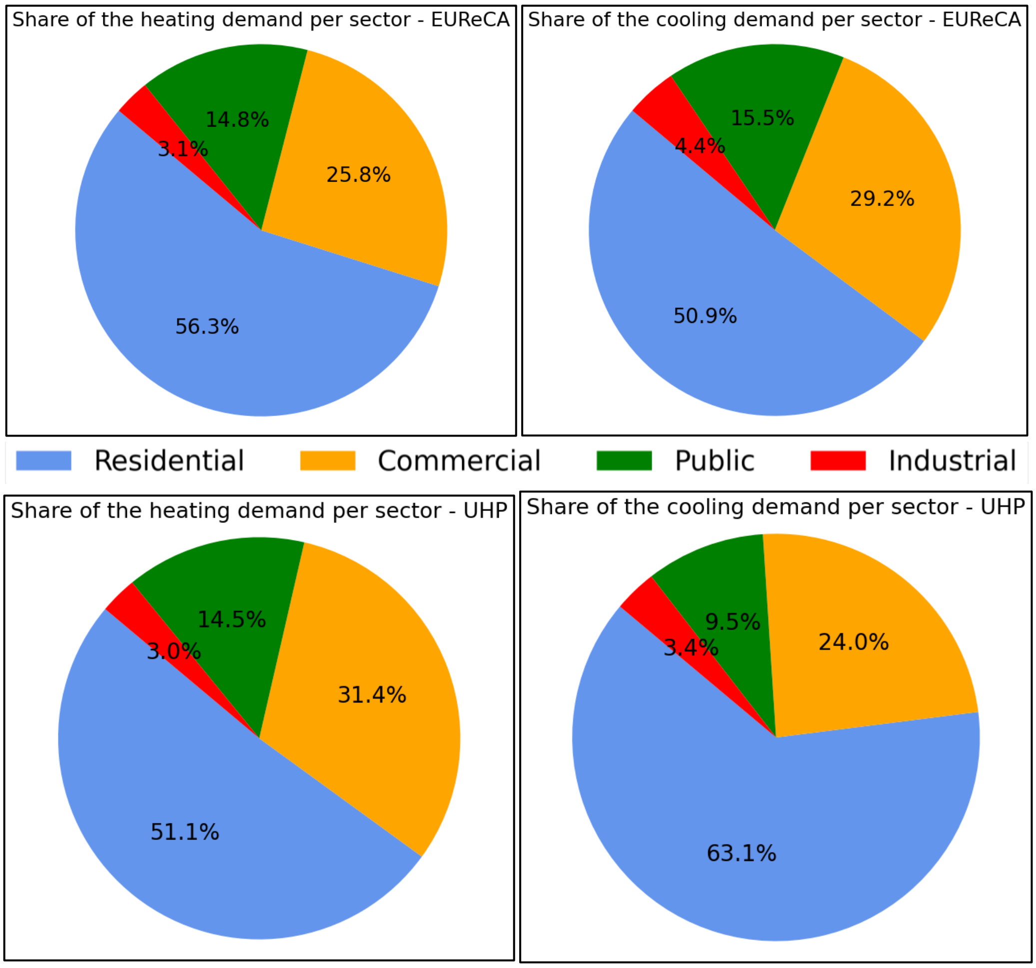


*Figure 3. 15: Share of heating and cooling demand per sector in the adapted models. On the first row are reported the EUReCA's data. In the second row are reported the UrbanHeatPro's data.*

As evident from both the graph and the Table 3. 3, the residential sector stands out as having the most significant urban impact in terms of heating and cooling demand for buildings. It should be noted that among the different building categories there is a notable similarity in heating demand, with the exception of the commercial sector which shows a slightly higher value.

As for cooling demand, substantial differences emerge among non-residential building categories: commercial, public, and industrial. On the contrary, in residential sector there are approximately similar values between the two calculation methodologies. Nevertheless, it is interesting to understand why, even excluding random factors, significant differences on energy demand related to cooling persist in non-residential buildings.

Furthermore, concerning residential sector, there is a higher consumption in EUReCA compared to UrbanHeatPro. This rise can likely be attributed to a greater amount of domestic hot water in EUReCA (2.21 GWh) compared to UrbanHeatPro's calculation (1 GWh). In order to understand whether this difference is due to domestic hot water production, in Figure 3. 16 it is reported the energy required per each building along the year. It should be considered that the residential sector is made up of four different types of buildings:

1. Single family house (SFH);
2. Multi family house (MFH);
3. Terrace house (TH);
4. Apartment block (AB).

The domestic hot water demand is strongly lower than the space heating demand. The domestic hot water can have an important role when the area of the building increases: in fact exists a proportionality between the area of the building and the domestic hot production in the case of EUReCA, as described in the chapter *2.5*. It plays an important role in the buildings with a large surface (especially in the MFH, TH and AB), because it's expected a higher production of the domestic hot water demand..

From Figure 3. 16, it’s clear that in SFH and in AB the total energy demanded (space heating demand plus domestic hot water demand) simulated by EUReCA is very similar to the one simulated by UrbanHeatPro. Whereas for MFH and TH there is a more evident difference between the energy demand calculated by the two different models: in particular, EUReCA seems to require a higher heating demand.

The disparity among the energy demand is related to the disparity in domestic hot water. In fact, as reported in Figure 3. 17, it’s clear that the difference between the total demand calculated with the two different model is very close to the difference between the domestic hot water required by the buildings in EUReCA and that requested by the buildings of UrbanHeatPro. So, the different methodology used for the calculation of domestic hot water demand can bring to some discrepancies on total heating demand in residential sector.

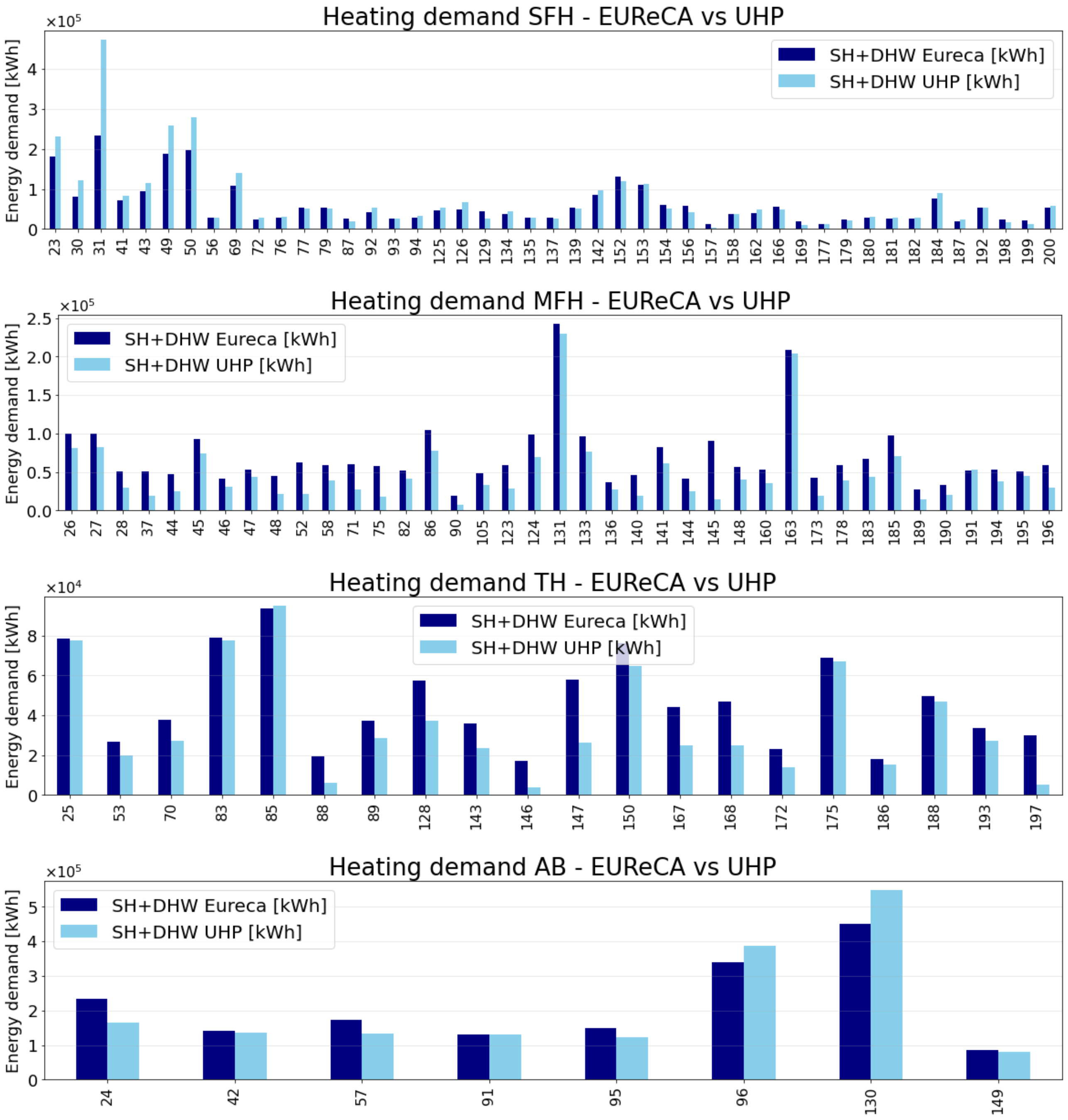


*Figure 3. 16: Heating consumption per building category – residential sector*

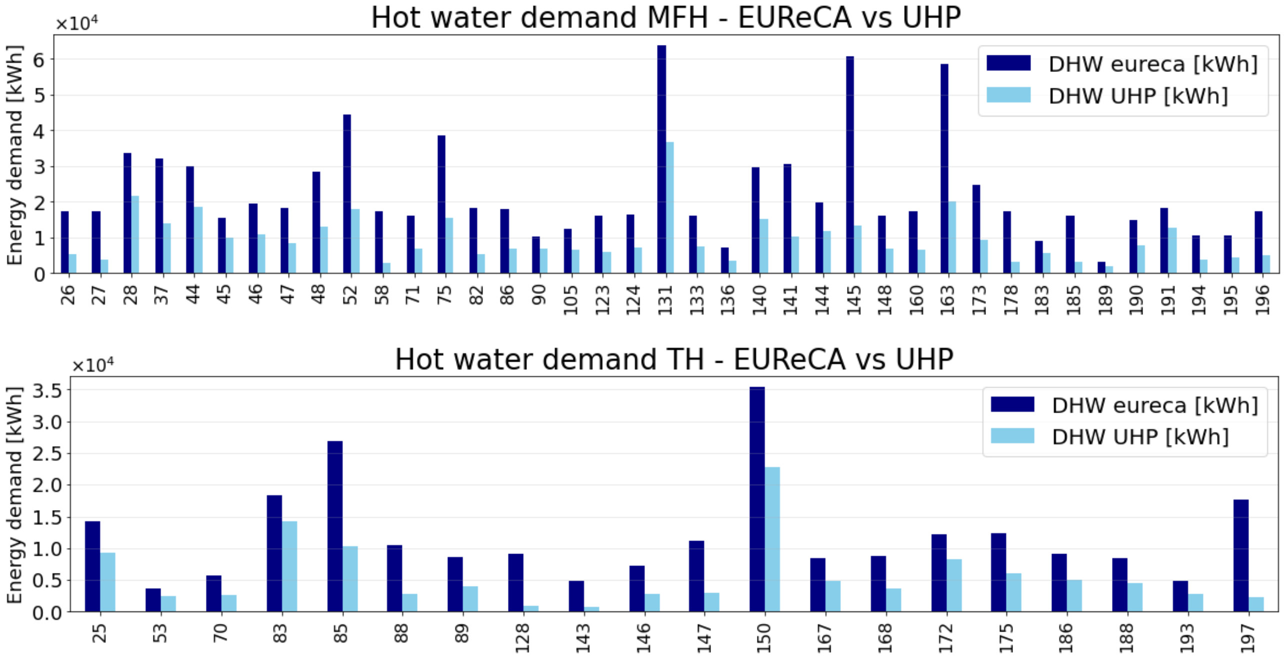


*Figure 3. 17: Domestic hot water production per building in MFH's category and TH category*

Considering the cooling system, it's crucial to consider that UrbanHeatPro is still in its early developmental stages, and it functions as a "reverse heating process". Up to now, its implementation has been mainly sized for residential sector: for this reason, it should yield more realistic results compared to the commercial, public, and industrial sectors.

Looking at the detailed results, the total simulated energy consumption for the whole city does not show significant differences (1.76 GWh for EUReCA compared to 1.40 GWh for UrbanHeatPro), in line with what is shown in Figure 3. 18. However, the true differentiation lies in the examination of individual buildings: it becomes evident that buildings classified under the TH category demonstrate higher energy consumption for cooling in UrbanHeatPro simulation compared to that of EUReCA. For the SFH, MFH, and AB buildings, on the other hand, energy consumption tends to be generally similar (with minimal variations noted in the case of single-family homes, "SFH").

Possible reasons for these discrepancies could be attributed to the current fledgling nature of UrbanHeatPro cooling system, which has not undergone meticulous optimization yet, especially with respect to cooling itself. Furthermore, the assumptions and premises employed to outline the cooling process might be too cautious and not entirely aligned with the reality, considering their original development primarily focused on heating process. Figure 3. 16 confirms once again that energy consumption for heating is roughly in line (EUReCA simulates a demand 6% higher than UrbanHeatPro). However, when it comes to cooling, there's an increase in simulated consumption in

EUReCA compared to that observed in UrbanHeatPro (approximately 20% more), as reported in Figure 3. 18.

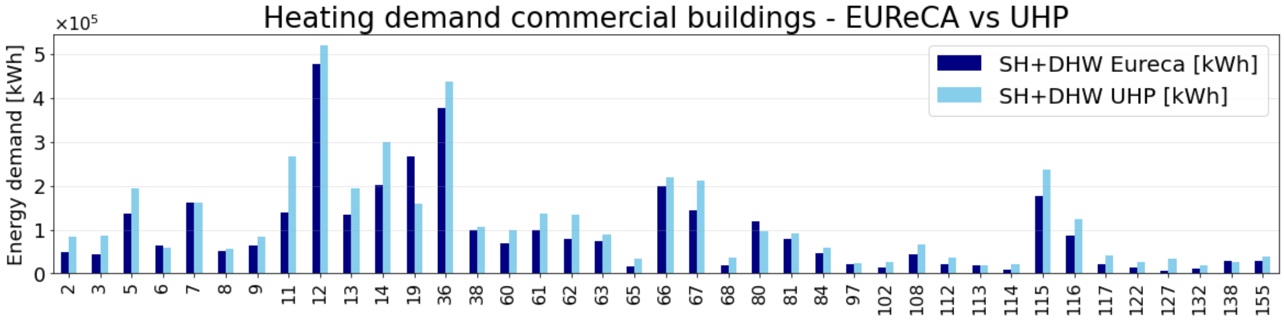
*Figure 3. 18: Cooling consumption per building category – residential sector*

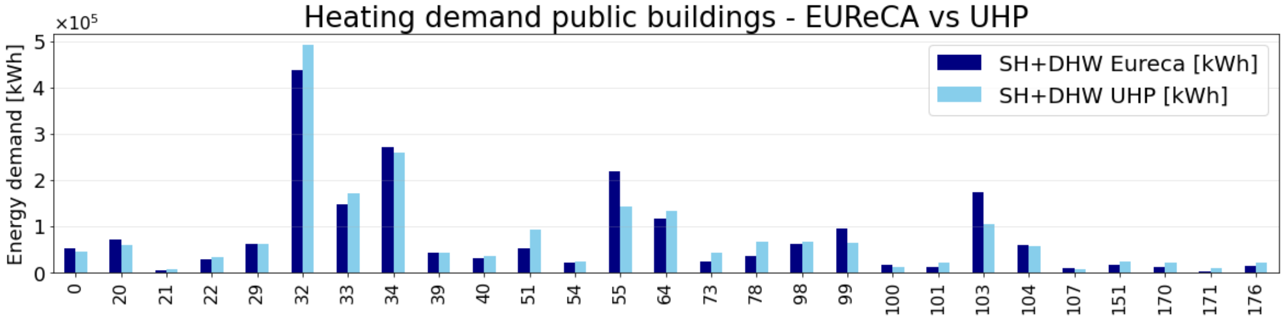
This discrepancy takes on significant proportions when moving into the non-residential context. Looking into the details of Table 3. 3, it's clear that EUReCA's results indicate considerably higher energy consumption compared to that derived from UrbanHeatPro:

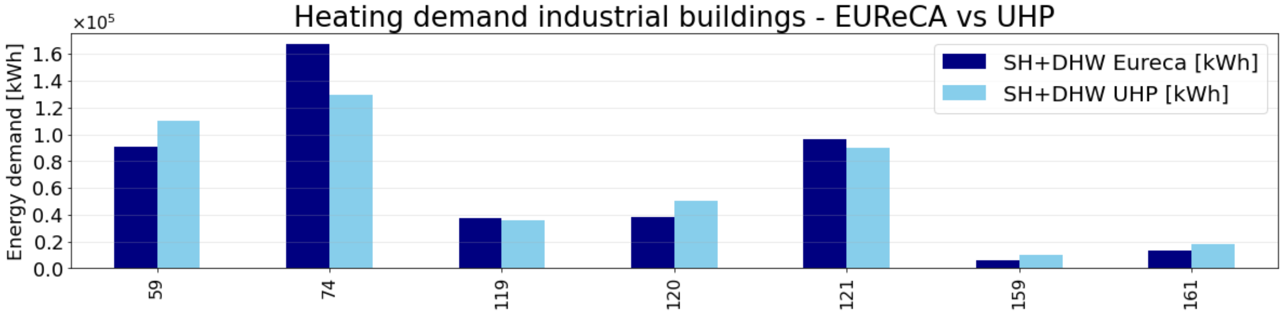
- In the commercial sector, EUReCA's energy usage exceeds that of UrbanHeatPro by 47.5%.

- In the public sector, there's a 39.8% increase in energy consumption of EUReCA compared to UrbanHeatPro.
- In the industrial sector, EUReCA's simulated energy consumption is 46.7% higher than UrbanHeatPro.

These differences reflect the relatively new implementation of UrbanHeatPro cooling system, which, so far, has been sized exclusively for residential sector. The assumptions formulated for residential sector might be wrong when applied to the commercial, public, and industrial sectors. The images on the right of Figure 3. 19 clearly illustrate that the demand for cooling in non-residential buildings (with a few exceptions in the commercial sector) consistently exceeds that simulated by EUReCA. Conversely, as shown in the same Figure 3. 19, the heating demand seems to remain more stable.







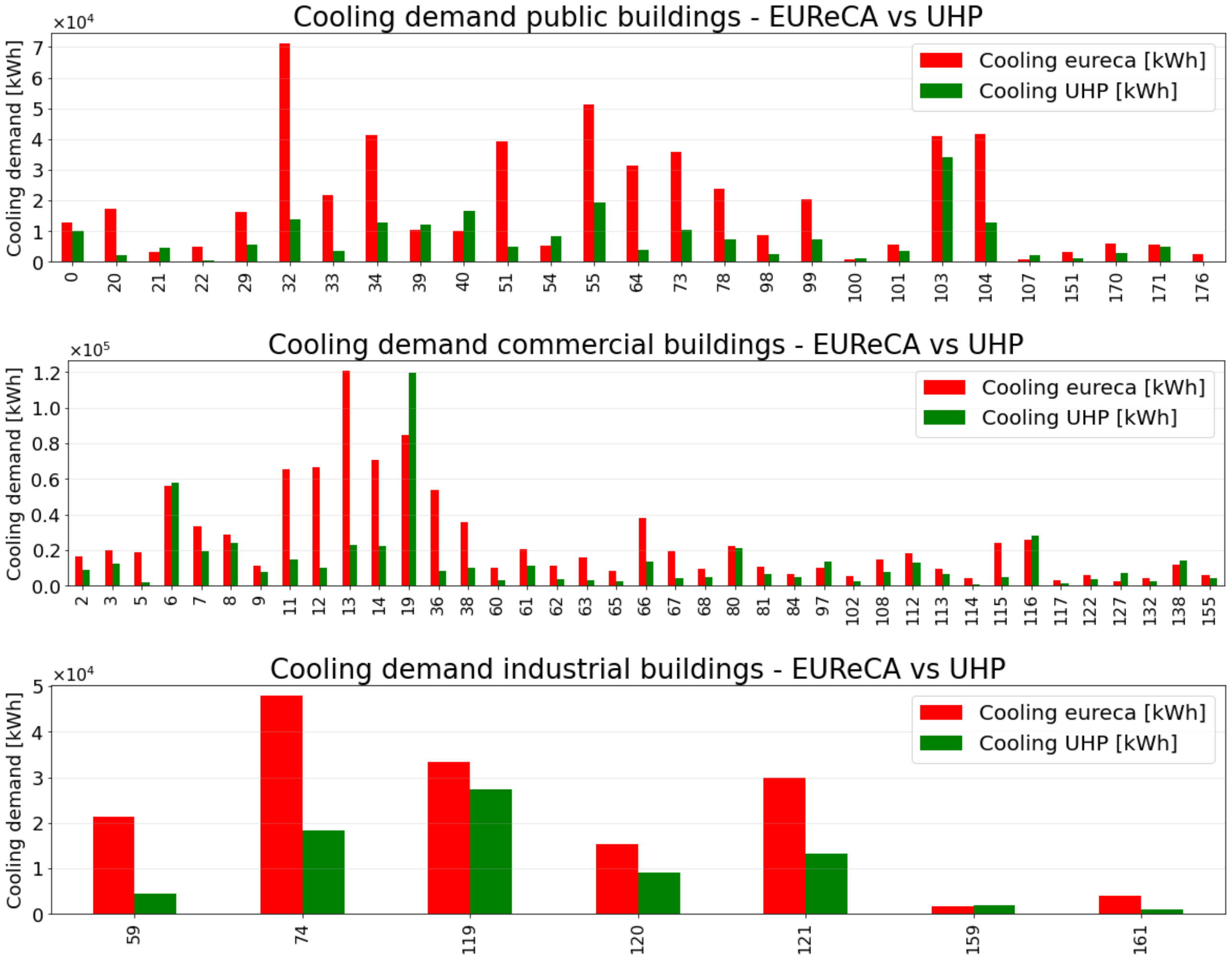


*Figure 3. 19: Heating and cooling consumption per each building – non-residential sector.*

Additional factors that significantly influence energy consumption are the internal gains, the solar gains and the building occupancy.

As for building occupancy and internal loads, UrbanHeatPro is based on random variables defined in function of the probability assigned, both in terms of their nominal values and their temporal scheduling. On the contrary, in EUReCA these inputs are predetermined by us. Therefore, a different definition of these contributions can result in significantly different demands for both cooling and heating (although in this case they have a minor impact). Specifically, if internal loads and occupancy are higher, the internal temperature of the building is higher, leading to an increased need for cooling to lower the building's temperature from its internal level to the set-point value.

The contribution of solar radiation depends largely on the window area of the building: EUReCA considers 12% of the total perimeter wall area as windows, while UrbanHeatPro considers not only a portion of the building area, but also a specific probability for each envelope. This probability reflects the likelihood of the window area facing different directions (north, south, east and west). This means that the windows are not evenly distributed on all sides of the building, but there are more windows on some sides than others. This aspect can significantly influence the amount of solar radiation entering through the windows. In particular, the window area defined in UrbanHeatPro tends to be generally smaller than the one in EUReCA: this results in a reduction in cooling demand (as the larger it is the window area, the greater it is the contribution of solar radiation). As the solar radiation increases, the internal temperature of the building also increases, resulting in a higher energy demand to cool the indoor environment from the indoor temperature until the setpoint. Additionally, it should be noted that UrbanHeatPro has a probability-based distribution of the window area of the building: this can further increase or decrease the cooling demand. For example, if the window area facing south is smaller, the cooling demand will also be lower.

To conclude, these combined factors contribute significantly to the observed differences in energy consumption between UrbanHeatPro and EUReCA.

### *Zoom on the heating and cooling demand of few buildings*

After the examination of the 'annual' energy consumption of individual buildings and the understanding of the contribution of each sector at the city level, the goal now is to deepen the analysis by focusing on specific buildings. In particular, it must be selected one representative building for each sector and assess the number of hours during which heating and cooling systems are operational: the kilowatt-hour (kWh) demand curves over time are reported, dividing the analysis into two reference periods:

- a winter period ranging from February 1st to February 21st.
- a summer period ranging from July 5th to July 18th.

Thanks to this approach, a more detailed and specific understanding of energy consumption dynamics during different seasonal periods is sought. This will allow to evaluate the coherence of the annual consumption results depicted in Figure 3. 16, Figure 3. 18 and Figure 3. 19 with the previous observations.

Among the buildings under study, we have specifically selected the following representative ones for each sector:

- residential: Building 31, constructed between 1984 and 1994, categorized as SFH (Single-Family House);

- commercial: Building 5, constructed between 1919 and 1976, categorized as NR (Non-Residential);
- public: Building 55, constructed before 1918, classified as NR (Non-Residential);
- industrial: Building 74, constructed between 1919 and 1976, categorized as NR (Non-Residential).

The choice of these buildings is also motivated by the fact that they show different heating and cooling needs. Hence, there is a particular interest in understanding potential variations in their energy requirements and identifying underlying causes for such differences.

Through this focused analysis and assessment of specific seasonal periods, the evaluation of the coherence between short-term observations and annual results are enabled, as well as the identification of any contributing factors to energy consumption variations across different sectors and buildings.

In

Table 3. 4 are reported the information about the buildings' properties (such as the area and the envelope), the heating and cooling demand calculated with EUReCA and UrbanHeatPro, and the number of hours in which the heating and cooling are active in the two different models.

At first, from

Table 3. 4, it apparent that the heating demand estimated by EUReCA is lower for residential and commercial buildings, but higher for public and industrial ones. As for cooling, on the other hand, EUReCA consistently shows a significantly greater demand compared to UrbanHeatPro.

Focusing specifically on residential building, it's clear that a higher heating demand from UrbanHeatPro also corresponds to a longer operating period for the heating system (specifically, EUReCA's heating system remains active for about 741 hours less than UrbanHeatPro's, roughly equivalent to 30 days). While acknowledging that EUReCA operating for a month less can impact the demand, it's important to stress that this alone isn't sufficient to justify UrbanHeatPro's double consumption. To address this issue, the graph reported on the left part of Figure 3. 20 is examined, where it's immediately evident that EUReCA heating demand is notably lower compared to UrbanHeatPro heating demand. This discrepancy in demand could be attributed to random factors tied to occupancy: UrbanHeatPro estimates the presence of 8 people within the building (considering an area of 3 426 m2). Conversely, EUReCA likely considers a higher occupancy rate, which results in a lower heating demand.

*Table 3. 4: Number of working hours of the plants – building 31 (residential), 5 (commercial), 55 (public) and 74 (industrial)*

| Cat. | Res | Com | Pub | Ind |
|---|---|---|---|---|
| bd | 31 | 5 | 55 | 74 |
| Envelope | 1984-1994 SFH | 1919-1976 NR | <1918 NR | 1919-1976 NR |
| Area EUReCA [m2] | 4078 | 1629 | 4061 | 3467 |
| Area UHP [m2] | 3426 | 1238 | 3330 | 2808 |
| Heating EUReCA [kWh] | 2.34E+05 | 1.37E+05 | 2.18E+05 | 1.67E+05 |
| Heating UHP [kWh] | 4.72E+05 | 1.93E+05 | 1.42E+05 | 1.30E+05 |
| Cooling EUReCA [kWh] | 6.34E+04 | 1.89E+04 | 5.13E+04 | 4.79E+04 |
| Cooling UHP [kWh] | 3.27E+04 | 2.06E+03 | 1.95E+04 | 1.83E+04 |
| ratio heating UHP/EUReCA | 202% | 141% | 65% | 78% |
| ratio cooling UHP/EUReCA | 52% | 11% | 38% | 38% |
| [h] heating EUReCA | 4148 | 1661 | 1422 | 1325 |
| [h] heating UHP | 4872 | 4814 | 3975 | 3956 |
| [h] Cooling EUReCA | 1965 | 952 | 770 | 1045 |
| [h] cooling UHP | 1183 | 249 | 929 | 1020 |

Regarding the cooling, we observe that EUReCA system operates for 782 more hours than UrbanHeatPro (approximately 32 days). At first, this contributes to EUReCA higher cooling demand. However, if occupancy (as well as contributions from internal loads and solar radiation) is lower in UrbanHeatPro, its cooling demand tends to increase. This is reflected in the internal temperature difference between UrbanHeatPro and EUReCA, where UrbanHeatPro generally maintains a lower temperature, resulting in a significant cooling demand to raise the set-point temperature (see Figure 3. 20).

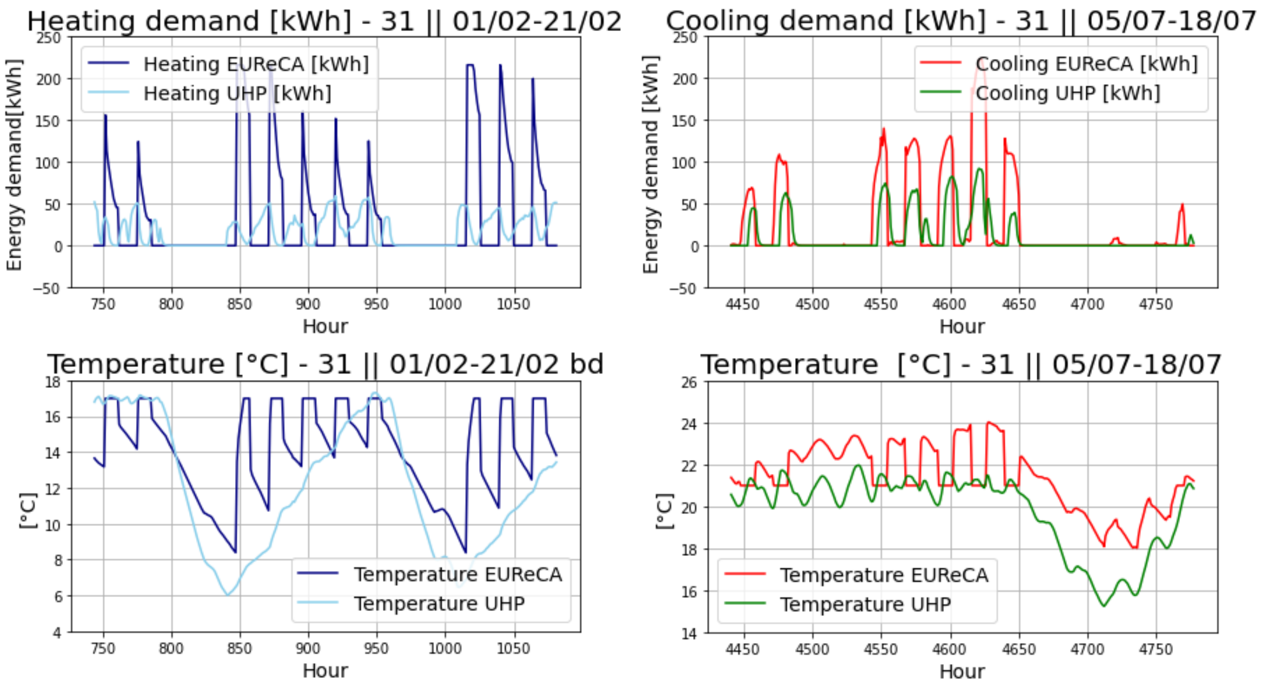


*Figure 3. 20: Trend of heating (left), of cooling (right) demand and of internal temperature simulated by EUReCA and UHP in the two reference periods – bd 31 (residential)*

It should be noted that the examined residential case represents one of the most complex buildings, as highlighted in Figure 3. 16 and Figure 3. 18, where both heating and cooling demand significantly differ. In contrast, other residential buildings exhibit relatively similar trends for heating simulations between EUReCA and UrbanHeatPro, while substantial differences persist in cooling demands, likely due to variations in schedules of internal gains, occupancy, and windows area.

In the residential sector, the differences between UrbanHeatPro and EUReCA results are due to the random variables typical of the UrbanHeatPro programme. In particular, different values for occupancy (as observed in particular in this building) can lead to significant distorsions.

The public, commercial, and industrial sectors can be considered as a single non-residential sector, where the observations are similar: for this reason, only the curves for industrial buildings are shown in Figure 3. 21, as the trends (and the observations) for the other non-residential buildings are similar. Examining Figure 3. 21, a significant difference in both hourly heating and cooling demands becomes apparent. Specifically, in all three cases, EUReCA shows higher peaks in heating demand compared to UrbanHeatPro. EUReCA generates a curve with sharp increases that reach much higher values in terms of kWh. This might stem from the fact that EUReCA calculates the energy required to immediately reach the set-point temperature starting from the internal ambient temperature: as highlighted by the graph in Figure 3. 21, across all sectors, the temperature rises rapidly. On the other hand, UrbanHeatPro tends to approach the set-point temperature more gradually, resulting in lower heating demand.

Furthermore, from the graphs, it is evident that the heating system of UrbanHeatPro is not turned off during the nighttime hours, but only slightly reduced, while EUReCA is active only during daytime hours. For instance:

- the heating system of UrbanHeatPro operates 3153 hours more than EUReCA (approximately 4 months more) in building 5 (commercial);
- the heating system of UrbanHeatPro is active 2553 hours more than EUReCA (approximately 3.5 months more) in building 55 (public);
- the heating system of UrbanHeatPro works 2631 hours more than EUReCA (approximately 3.5 months more) in building 74 (industrial).

As a consequence, although EUReCA presents higher peaks in energy demand (in terms of heating), UrbanHeatPro operates for a greater number of hours throughout the year (including nighttime hours). This balances out the annual energy demand peaks of EUReCA. Therefore, in non-residential sector, the total heating consumption appears to be similar between the two models as shown in Figure 3. 19, despite the different trends shown by the curves as in Figure 3. 21.

Regarding cooling, it's crucial to immediately note a significant discrepancy:

- the cooling system of EUReCA operates 703 more hours than UrbanHeatPro (approximately 29 days) in building 5 (commercial sector);
- the cooling system of EUReCA operates 159 fewer hours than UrbanHeatPro (approximately 29 days) in building 55 (public sector).
- the cooling system of EUReCA operates 25 more hours than UrbanHeatPro (approximately 1 day) in building 74 (industrial sector).

Consequently, the higher cooling demand can’t be attributed to the operational hours of the system, expect for the commercial sector.

Therefore, it's essential to comprehend the cause of the significant difference in cooling demand, which is considerably lower in UrbanHeatPro compared to EUReCA. As highlighted in the right part of Figure 3. 21, similarly to the heating case, EUReCA tends to exhibit higher peaks than UrbanHeatPro (which features a smoother curve). Moreover, these higher peaks stem from the fact that EUReCA needs to lower the internal temperature by a greater amount to reach the set point temperature. As it is evident from the temperature curves in Figure 3. 21, the internal temperature in UrbanHeatPro tends to be lower (by around 2 °C) compared to EUReCA. This discrepancy can be attributed to five main factors: internal gains, solar radiation, occupancy, external environmental conditions (especially outdoor air temperature) and the building envelope type. Since the last two factors have been set equally in both the UrbanHeatPro and EUReCA models, the differences must be determined by the first three factors.

Particularly, it should be remembered that in UrbanHeatPro, both occupancy and internal loads are defined randomly, while solar radiation depends on the probabilistic distribution of windows area on each wall. This can lead to a lesser thermal emission by the factors mentioned earlier in the UrbanHeatPro simulated model, resulting in lower internal temperatures. This justifies EUReCA's tendency to have a generally higher cooling demand compared to UrbanHeatPro.

Naturally, higher values of occupancy, internal loads, and solar radiation also influence heating demand, leading to a reduction. However, the contribution of these factors is lower during the summer season compared to the winter one.

Similarly to the residential case, buildings 5 (commercial), 55 (public), and 74 (industrial) have been considered as representative of "extreme" situations with substantial differences in cooling and heating.

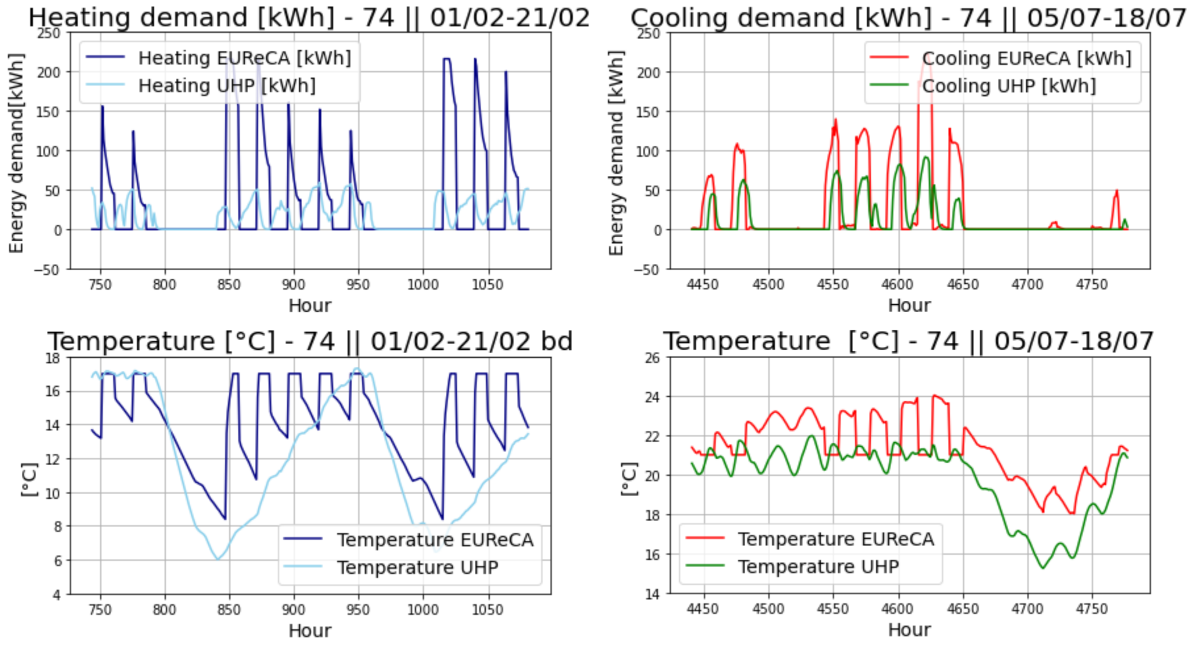


*Figure 3. 21: Trend of heating (left), of cooling (right) demand and of the internal temperature simulated by EUReCA and UHP in the two reference periods.*

## 3.3 Heating and cooling demand in 2022 and in 2050 with UHI

This section presents additional simulations to understand how heating and cooling demand changes when the urban heat island is considered, and how they change when a future scenario is considered, specifically in 2050.

In order to generate a future climate file (i.e., in 2050), the CCWeatherGen [30] tool is used: it enables to generate climate change weather files for the UK ready for use in building performance simulation programs. Considering the inclusion of the urban heat island, a python application is used: the Urban Weather Generator (uwg). It morphos rural EnergyPlus weather (*.epw*) files to reflect average conditions within the urban canyon using a range of properties as building geometry, building use, cooling system heat rejection to the outdoors, indoor heat leakage to the outdoors, urban materials, heat from traffic, vegetation coverage and atmospheric heat transfer from urban boundary and canopy layers.

The simulations are carried out with EUReCA considering the input of the unadapted model: the difference between the different simulations is that the *.epw* file changes as the temperature varies between different scenarios.

In particular, six different simulations are performed with different temperature trend:

- original, in which the *.epw* is obtained by EnergyPlus web site, considering the city of Munich;
- original with UHI, in which the *.epw* is based on the previous file and modified with the urban weather generator (uwg) to include the urban heat island;
- 2022, in which the *.epw* is based on the original one: in this file the temperature and the radiation are set equal to the one defined in the input data of UrbanHeatPro;
- 2022 with UHI, in which the *.epw* is based on the previous file and modified with the urban weather generator (uwg) to include the urban heat island;
- 2050, in which the *. epw* is based on the original one. The temperature is substituted with the one obtained with the CCWeatherGen tool considering 2050 as year.
- 2050 with UHI, in which the *.epw* is based on the previous file and modified with the urban weather generator (uwg) to include the urban heat island.

In several scenarios an increase in cooling demand is expected due to rising outdoor temperatures compared to the baseline case. This increase is evident in the 2022 and 2050 scenarios compared to the original case. Furthermore, a further increase in cooling demand is expected with the introduction of an urban heat island.

To illustrate this phenomenon, the temperature trends in the six different cases were examined over two reference weeks, as reported in Figure 3. 22:

- in the winter scenario, the period from 1st to 14th December was considered;
- in the summer scenario, the period from 5th to 18th July was analysed.

It was observed that temperatures in 2022 and in 2050 tend to be consistently higher than in the baseline case. In addition, when the urban heat island effect is introduced, temperatures in 2022 and in 2050 continue to increase both in summer and winter. This trend applies throughout the year.

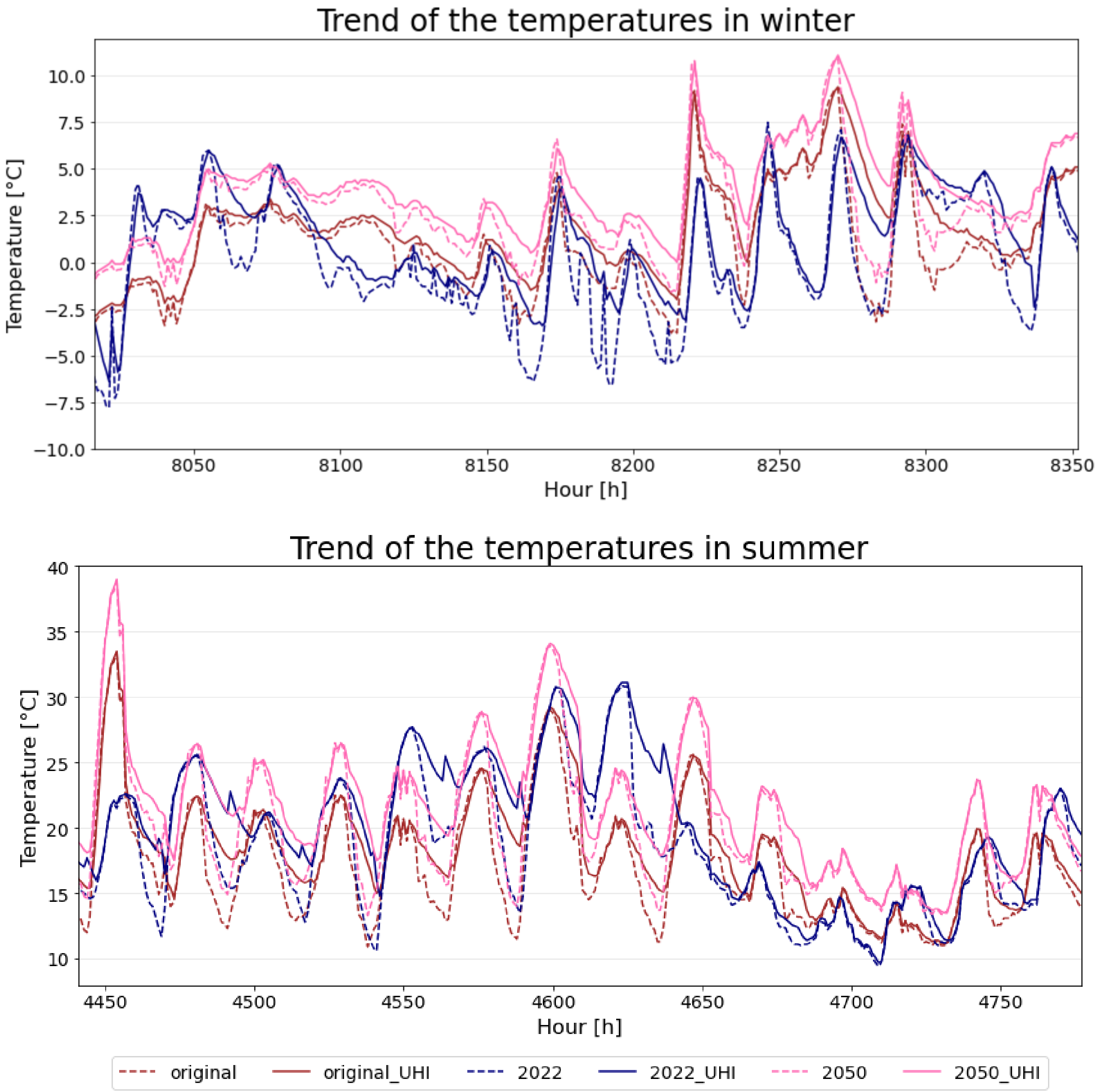


*Figure 3. 22: Temperature trend in different years and with the influence of the urban heat island*

In summary, an increase in temperature over the years is expected, and a further increase in temperature is expected due to the influence of the urban heat island. This phenomenon is clearly shown in Figure 3. 22 and reflects the effect of rising outdoor temperatures and the introduction of the urban heat island.

The increase in external air temperature has two main effects on heating and cooling requirements of buildings:

1. there is a reduction in heating demand as the outdoor temperature increases, as it is directly related to the difference between the desired indoor temperature and the outdoor temperature;
2. an increase in cooling demand is observed with increasing outdoor temperatures, as it is proportional to the difference between the desired indoor temperature and the outdoor temperature.

*Table 3. 5: Total heating and cooling in GWh of the entire city in the different scenarios*

| | Original | Original_UHI | 2022 | 2022_UHI | 2050 | 2050_UHI |
|---|---|---|---|---|---|---|
| Heating [GWh] | 25.70 | 24.28 | 21.19 | 20.09 | 21.77 | 20.49 |
| Cooling [GWh] | 2.72 | 3.31 | 4.09 | 4.71 | 4.88 | 5.65 |

In Table 3. 5 are reported the total heating and cooling demand of the entire city in the different scenarios. Examining the changes in different scenarios:

- compared to the baseline case, heating demand is about 20% lower in both 2022 and 2050. This means that the higher the outdoor temperature, the lower the heating demand. However, a direct comparison between the 2022 and 2050 temperatures cannot be made. This is because the 2022 temperature data was not derived from the original *.epw* file, as is the case for the 2050 temperature data. The 2022 data, in fact, was derived from meteorological information used by the TUM research group while the 2050 temperature data is generated by a model, which has uncertainties and the potential for error;
- cooling demand, on the other hand, increases by 50% in 2022 and by 80% in 2050 compared to the baseline case. This increase is due to rising summer temperatures, in line with the trend in external temperatures reported in Figure 3. 22.

The introduction of the urban heat island, instead, affects the results as follows:

- in all three scenarios (original, 2022 and 2050) there is a tendency for heating demand to decrease by about 6%, which contributes to maintaining higher temperatures.
- Cooling demand increases by about 15% in the three scenarios, leading to higher temperatures in summer.

It is important to note that heating systems are active from 1st October to 30th April, while cooling systems are active from 1st June to 31th August. However, due to rising external temperatures, it may be necessary to consider the appropriateness of these periods, especially for cooling demand in the 2050 simulation. It may be necessary to adjust the activity times to match the real needs of the users: this means that the cooling demand obtained from the simulation may be underestimated.

*Moreover, in*

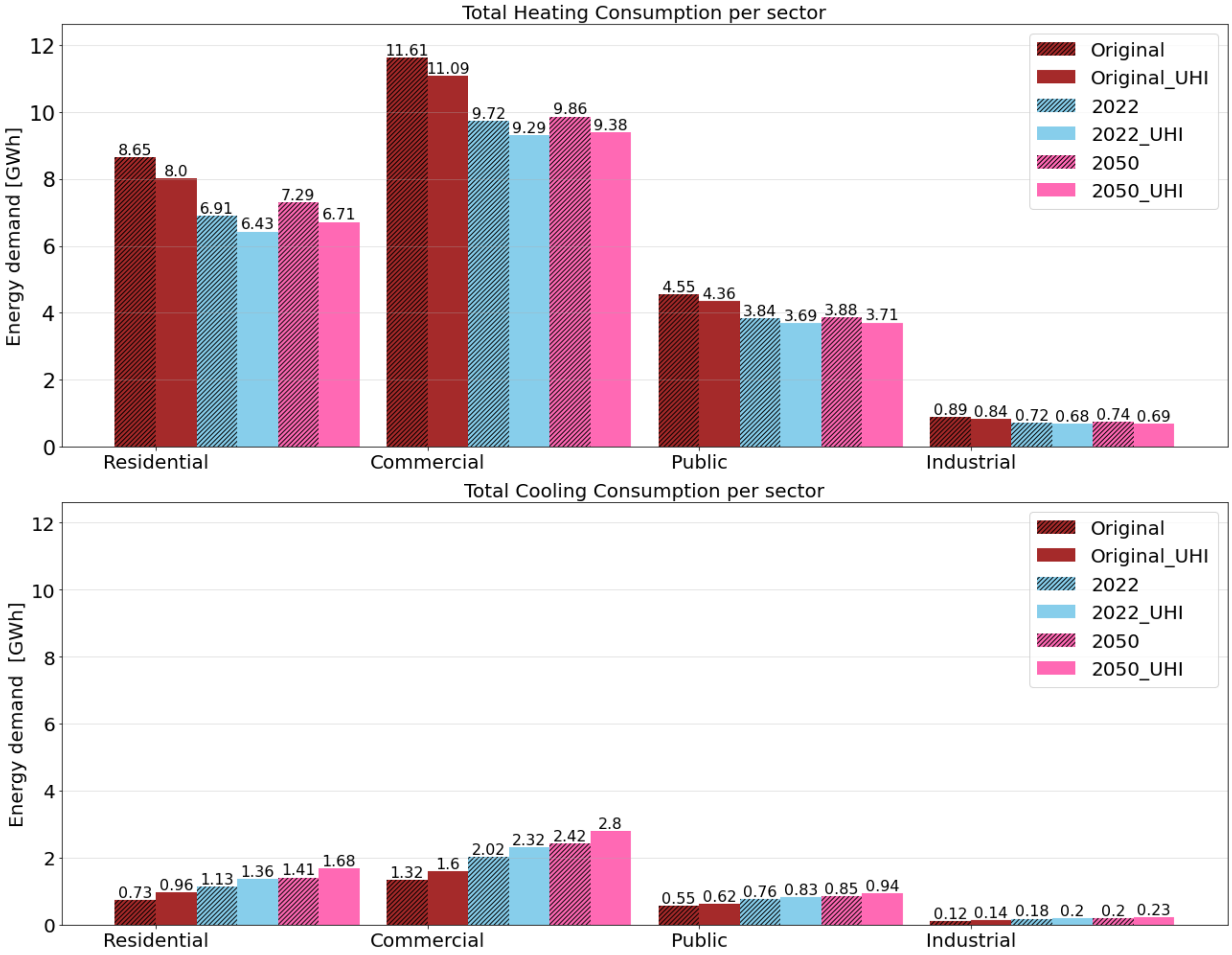


Figure 3. 23 it's reported the total heating and cooling demand per each sector in the different scenarios. Looking at the bars, it is clear that the heating demand in each sector is always decreasing with respect to the baseline: on the other hand, the cooling demand in each sector is increasing with respect to the baseline.

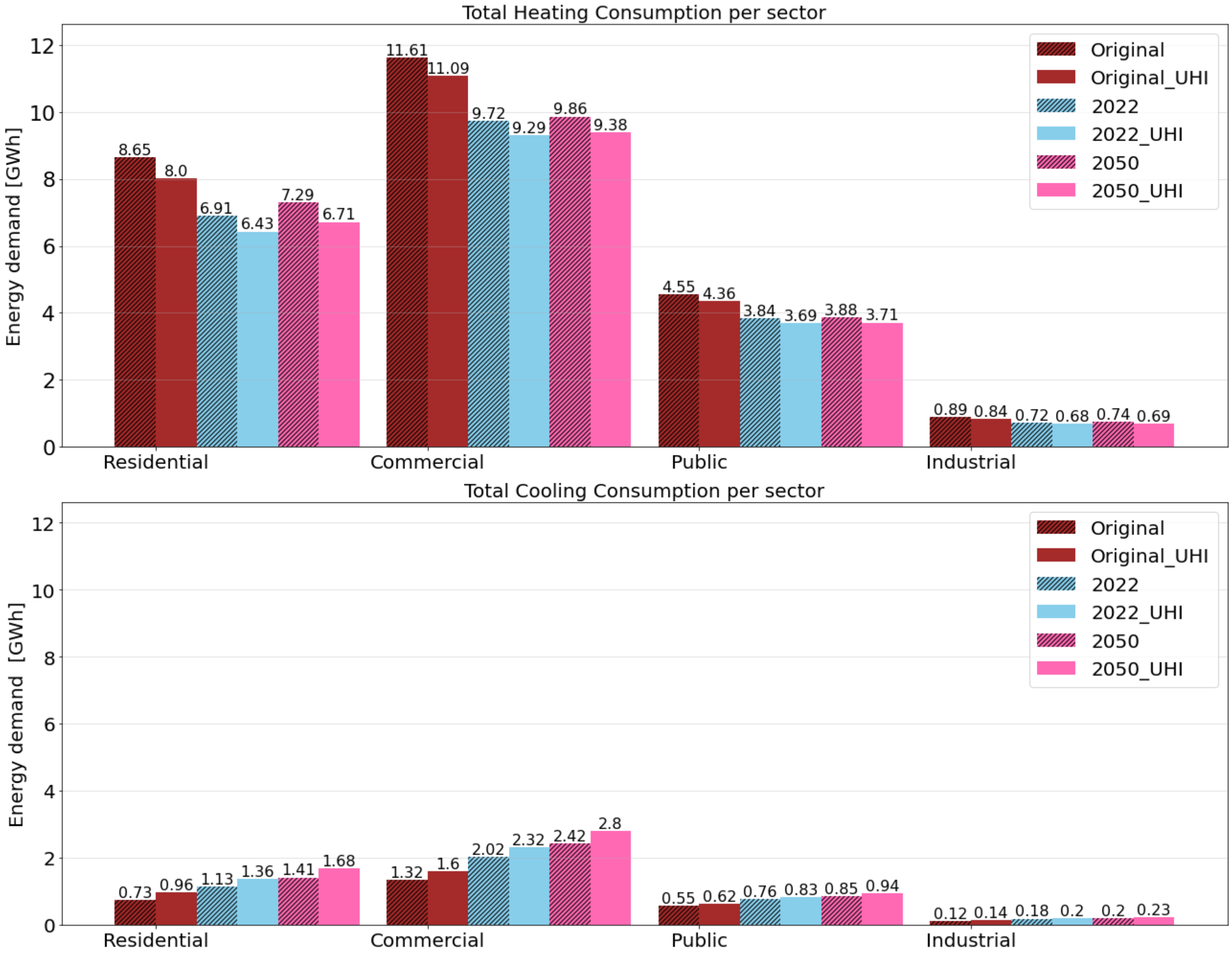


*Figure 3. 23: Energy demand per sector in the different scenarios*

# 4. Optimization

So far, EUReCA and UrbanHeatPro models have been defined and utilized separately, obtaining specific results from each model. Then, the two models were adapted to understand their differences. Finally, the final results for heating and cooling energy consumption have been compared.

Now, the objective is to proceed with the optimization process: the goal is to evaluate which is the most advantageous technology for providing heating and cooling using Urbs software and comparing how Urbs optimizes the system when heating and cooling demands are calculated with different software. In particular, four different scenarios are considered:

1. Optimization considering heating and cooling demand from UrbanHeatPro with the adapted data, as described in the section *2.1*
2. Optimization considering heating and cooling demand from EUReCA with the adapted data, as described in the paragraph *2.3*
3. Optimization considering heating and cooling demand from UrbanHeatPro with the included random factors, as described in the section *2.1*
4. Optimization considering the heating and cooling demand from EUReCA without the adaption of the data, as described in the section *2.3*

## 4.1 urbs modelling

The goal of this optimization approach is to define which is the best solution (from an economical point of view) for the production of heating and cooling required by a city (Unterhaching in our case) and to understand how the optimization changes with different demand curves.

In this dissertation, two different processes are implemented, both for heating and cooling. In particular:

- condensing boiler for the production of heating and domestic hot water with a compression chiller for the production of cooling;
- ground source heat pump for the production of heating and cooling.

The compression chiller is the most common technology for air conditioning worldwide [31]. It's composed by four components: compressor, condenser, throttle valve and evaporator. These parts are connected in a closed circuit, and a fluid refrigerant serves as energy carrier (see Figure 4. 1).

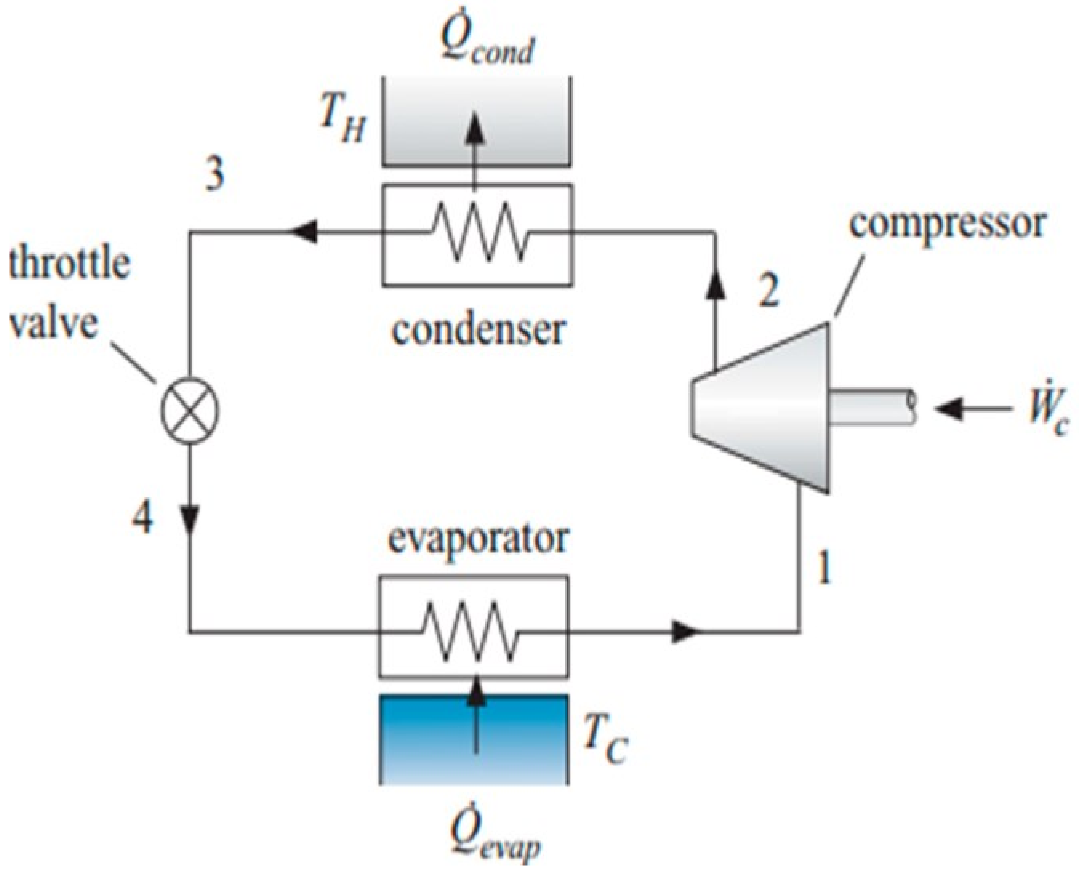


*Figure 4. 1: schematic diagram of vapor compression cycle from [32]*

The whole system can be split into two parts: a high-pressure side and a low-pressure side.
The compressor delivers the refrigerant vapor mechanically from the low-pressure side and compresses it to the high-pressure side by using electricity. In this process, the compressor absorbs the electrical work $W_c$ and releases part of it as heat into the circulating refrigerant. The electrical work that must be done is equal to the electric power multiplied by the time needed for that. Reaching the condenser, which has a large surface and a heat-conducting material, the refrigerant liquefies by releasing the energy $Q_{cond}$. The refrigerant liquid flows through the expansion valve back to the low-pressure side.

Once expanded, parts of the liquid evaporate, thus extracting the heat $Q_{evap}$ from the environment and leading to a cooling of the medium. The temperature drops to the dew point of the refrigerant, and the liquid evaporates completely. The steam that has absorbed the heat $Q_{evap}$ returns back to the compressor, and the cycle begins again. The output of the system can be reduced by reducing the amount of refrigerant supplied to the evaporator. Less energy is then required to compress the steam to the high-pressure side. The efficiency of compression chillers can be determined for ideal conditions (Carnot) solely through the temperatures during evaporation and condensation.

$$\eta_{carnot} = \frac{T_u}{T_c - T_u} \qquad 37.$$

Compression chillers generally release their heat output usually into the environment ($T_0$=$T_{amb}$), which means that the efficiency is often related to the outside temperature. Additionally, the required temperature level $T_c$ on the user side plays an important role.

The energy efficiency ratio (EER) is defined as the ratio between the absorbed heat (which is the cooling load) and the electrical input power $W_c$.

$$EER = \frac{\dot{Q}_{evap}}{\dot{W}_c} \qquad 38.$$

About the condensing boiler, in 2005, European Union Directive [33] mandated EU member states to require manufacturers of boilers to sell exclusively condensing models, in compliance with community and international energy-saving regulations, in line with the spirit of the 1997 Kyoto Protocol.

A condensing boiler differs from a traditional boiler due to the presence of condensation. When the water steam contained in the exhaust gases condenses, it releases a significant amount of thermal energy transferred to the heating system's water. This condensation process releases additional latent heat, making condensing boilers more efficient than traditional boilers. Because part of the exhaust gas temperature is used to preheat water, the exhaust gas temperature in condensing boilers is generally lower, resulting to lower NOx and CO emissions. A scheme of the condensing boiler process is shown in the next imagine.

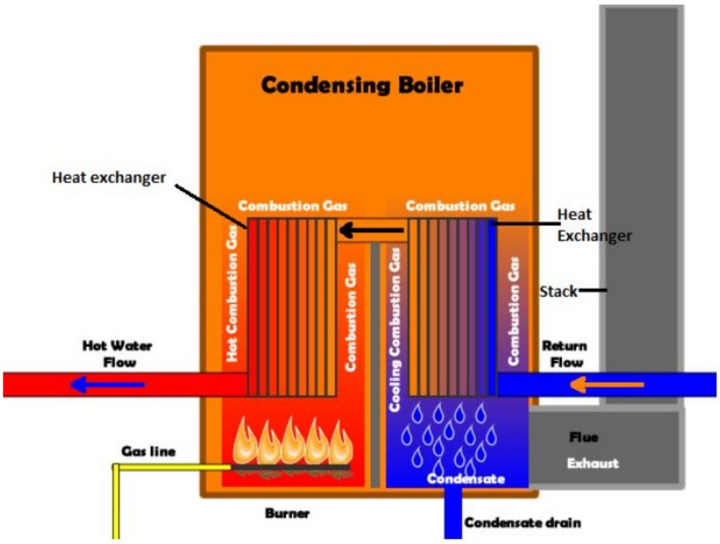


*Figure 4. 2: Scheme of condensing boiler from [34]*

About the geothermal heat pump, it's a heating and cooling system that uses a type of heat pump to transfer heat (or taking heat) from the ground. ). The ground is used because about half of the solar radiation received by the earth is absorbed by the soil surface and, as a result, the temperature of the soil varies with depth: in particular, there is a strong variation in temperature near the ground, while, if the depth increases, the temperature variation decreases (as shown in Figure 4. 3)

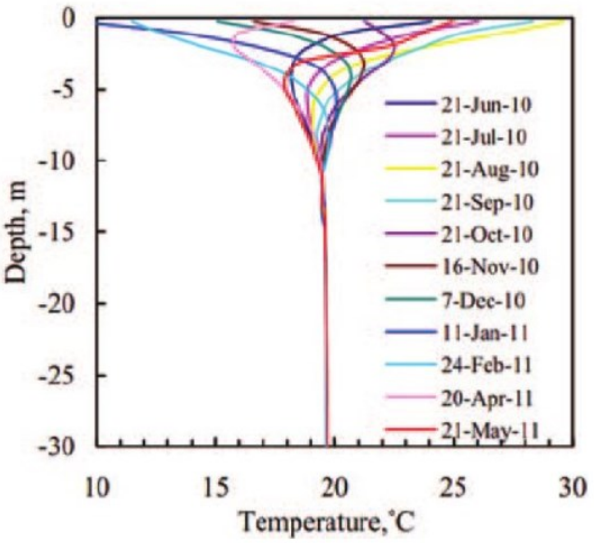


*Figure 4. 3: variation of the temperature of the ground in function of the depth according to [35]*

The GSHP uses some electricity to run the heat pump, but the energy supplied by GSHP for space heating is at least three times more than that fed into GSHP, so it produce fewer greenhouse gases than conventional heating systems [36]. A ground source heat pump requires the presence of a heat pump, which is the central unit of the building heating and cooling system and is usually used in two main variants: liquid-water heat pump and liquid-air heat pump. Ground source heat pumps use a heat exchange in contact with the ground to extract or dissipate heat, and because the ground temperature is more constant than the external air temperature, performance is better (a general scheme is reported in Figure 4. 4).

Some advantages of ground source heat pumps will now be highlighted:

- Significant energy savings by having ambient temperatures close to comfort temperatures in any season;
- Virtually constant temperatures throughout the year (thus, it means constant efficiencies);
- They are present everywhere and continuously;
- Significantly reduce electrical peaks;
- Long components life due to excellent working conditions;

- Possible thermal storage;
- Possibility of free cooling.

The main disadvantages relate to the costs, which are high: for this reason, the technology is mature but poorly applied.

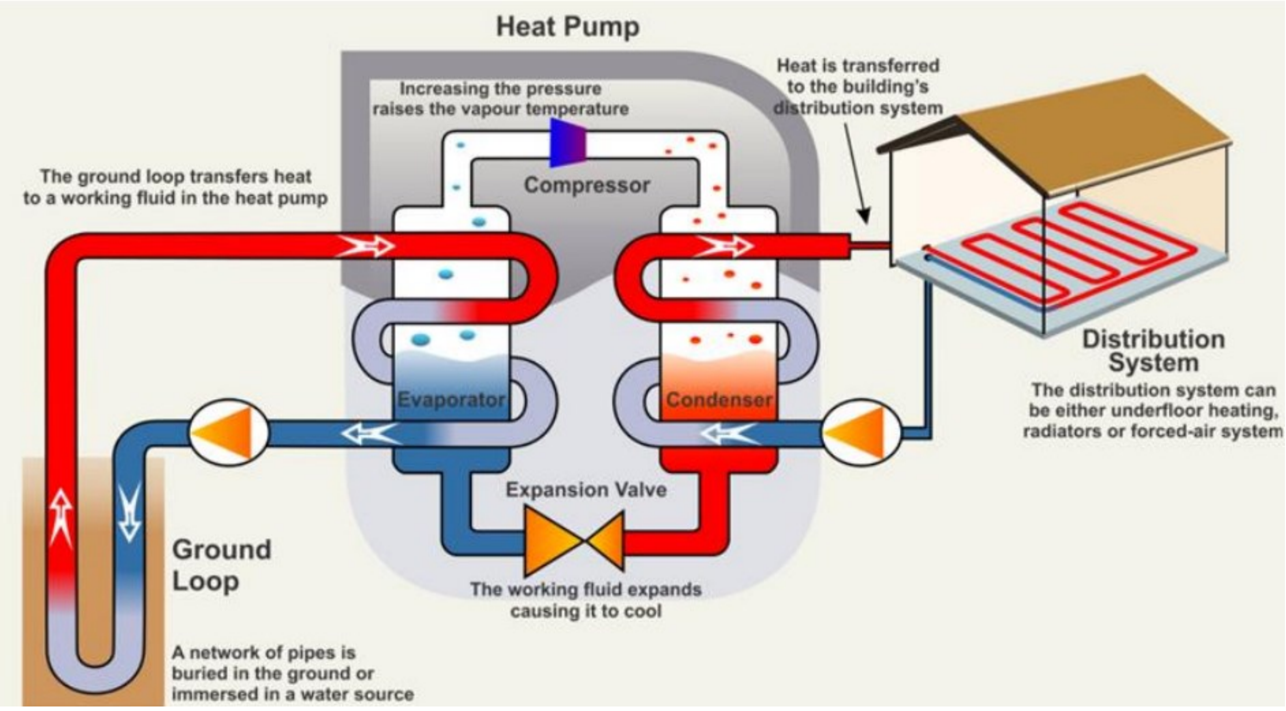


*Figure 4. 4: Operating scheme of a ground source heat pump*

So far, we have highlighted which systems produce energy for heating and cooling. Now we want to evaluate how these systems are implemented on an urban scale to meet the demand simulated by the two software: EUReCA and UrbanHeatPro.

The ground source heat pump system can be considered for implementation on an urban scale. As mentioned above, this system consumes a large amount of electricity, so it may be cost-effective to install a photovoltaic system to reduce the operating costs of the geothermal pump. In addition, since the pump also operates at night, to meet the energy demand a battery connected to the photovoltaic system can help reduce the costs: in fact, during the day, when solar efficiency is high, the amount of excess energy produced by the photovoltaic system can be stored and reused during the night hours.

As for the second system, a condensing boiler is implemented for heating production and a compression chiller for cooling production. Similar to the case of the geothermal pump, it may be convenient to install a solar thermal system to use the free energy of the sun to heat water by reducing the amount of energy consumed by the condensing boiler. In addition, a domestic hot water storage tank can be provided to store heated water during the day, when solar thermal panels have high efficiency and the heating of water by the solar thermal system is free.

For cooling, the compression chiller consumes electricity, so it is worth considering the installation of a photovoltaic system along with an external battery, as described above.

The urbs software is used to determine the most economical system for meeting the total energy demand for both cooling and heating production. This software requires the definition of commodities that represent the inputs and outputs for the processes, as well as the specification of the processes associated with these commodities. The scheme used in the simulations is the one reported in Figure 4. 5 in which:

- the vertical lines represent the commodities,
- the blocks represent the processes, of which:
  a) the red ones refer to the processes involved in the production of heating through the use of the condensing boiler and solar thermal system;
  b) the orange ones refer to the processes involved in the production of cooling through the use of the compression chiller;
  c) the green blocks refer to the GSHP source for heating production;
  d) the light blue blocks refer to the GSHP source for cooling production.

As described in chapter (*1.3 urbs – General aspects*) there are different kinds of commodity:

- *Demand* commodity composed by:
  a) *Heat* commodity, in which the values per timestep of heating demand simulated by EUReCA or UrbanHeatPro are entered,
  b) *Cool* commodity, in which the values per timestep of cooling demand simulated by EUReCA or UrbanHeatPro are entered,
  c) *Total Demand* commodity, in which the values per timestep of heating + cooling demand simulated by EUReCA or UrbanHeatPro are entered,
  d) *Elec* demand, in which the values per timestep of the electricity consumed by the entire city are inserted.
- *Buy* commodity composed by:
  a) *Gas*, in which per each timestep the hourly price of gas for the household is fixed,
  b) *Elec buy*, in which per each timestep the hourly price of electricity for the household is fixed.

- *Sell* commodity, in which per each tempested the hourly price of the electricity by household is fixed
- *Environment* commodity composed only by $CO_2$ commodity
- *Supply intermittent* commodity composed only by *Solar* commodity and it represents the capacity factor time-series of the solar panels
- *Stock* commodity composed by:
    a) Virtual GSHP
    b) Virtual Boiler_ST
    c) Virtual Heating
    d) Dummy GSHP
    e) Dummy Boiler+ST+CC

  The commodities are considered *virtual commodities* and are associated with zero cost. They are essentially an intermediate step in the simulation process, as they do not physically exist in a real-world context, but they are crucial to achieving the desired results. The basic idea of these virtual commodities is that they should be generated exclusively through the processes to which they are connected, taking into account the efficiency of each process. Furthermore, according to Kirchhoff's current law, once generated, these virtual commodities must be consumed immediately.

In the specific case of the GSHP, a "virtual demand" called "Virtual GSHP" has been introduced to define two distinct processes (heating and cooling). No direct costs are associated with these processes (as the costs are attributed to the GSHP), but different efficiencies are associated with them to distinguish between the COP and the EER.

Moreover, as it is now defined, urbs minimises the costs, giving as output the power that must be installed for each technology in order to satisfy the demand. However, urbs doesn't consider that, for example, if a certain demand is supplied by the system composed by boiler and compression chiller, it cannot be supplied at the same time also by the GSHP: if this is the case, it means that, in extreme cases, it is possible that the two systems are present at the same time in the same building. In fact, this is what happens with urbs, because it returns as output the optimal power to be installed, taking into account that in each time period and for all buildings, the energy demand can be satisfied simultaneously by both the geothermal system and the boiler (in the winter season) and by the GSHP and the compression chiller (in the summer season).

To solve this problem, it is necessary to implement the proportional operation: often many individual consumers are gathered at a single site. If the demand of these consumers is satisfied by a set of decentralized units, it’s important that the different technology options for these decentralized units each satisfy a fixed fraction of the demand at each time step. This means that the different technology options are proportional to each other and to demand. This is exactly what happens in our case: we want to ensure that heating demand is met by a percentage of the share between GSHP and Boiler+ST that remains constant throughout the year: thus, theoretically, in a single building there will be either only GSHP or only Boiler+ST. Similarly, we want the cooling demand to be met proportionally by GSHP and compression chiller.

To ensure proportional operation, processes that satisfy the same commodity proportionally must be coupled. They are coupled:

- The *Boiler+ST* process with the *Heating+Tank_Heating* process to satisfy the heating demand
- The *Cooling* process with the *CC* process to satisfy the cooling demand

For this reason, the Virtual Heating and Virtual Boiler_ST commodities have been introduced. This allows the two systems to be allocated proportionally, taking into account the boiler, the solar thermal system and the thermal storage, and on the other hand the GSHP for heat production (i.e. the "Heat" commodity).

An additional proportional operation has been introduced to ensure that the proportion of heating demand met by the processes 'Boiler+ST' and 'Heating+Tank_Heating' is the same as the proportion of cooling demand met by the processes 'CC' and 'Cooling' respectively. To achieve this, dummy commodities are defined to proportionally relate the two associated processes to the production of the commodity "Total Demand". This means that by making the processes 'Pro_dummy_GSHP' and 'Pro_dummy_Boiler+CC' proportional, the heating and cooling demand are proportionally met by the following two types of installations in both winter and summer seasons:

- condensing boiler for the production of heating and domestic hot water, paired with a compression chiller for cooling production;
- ground source heat pump for the production of heating and cooling.

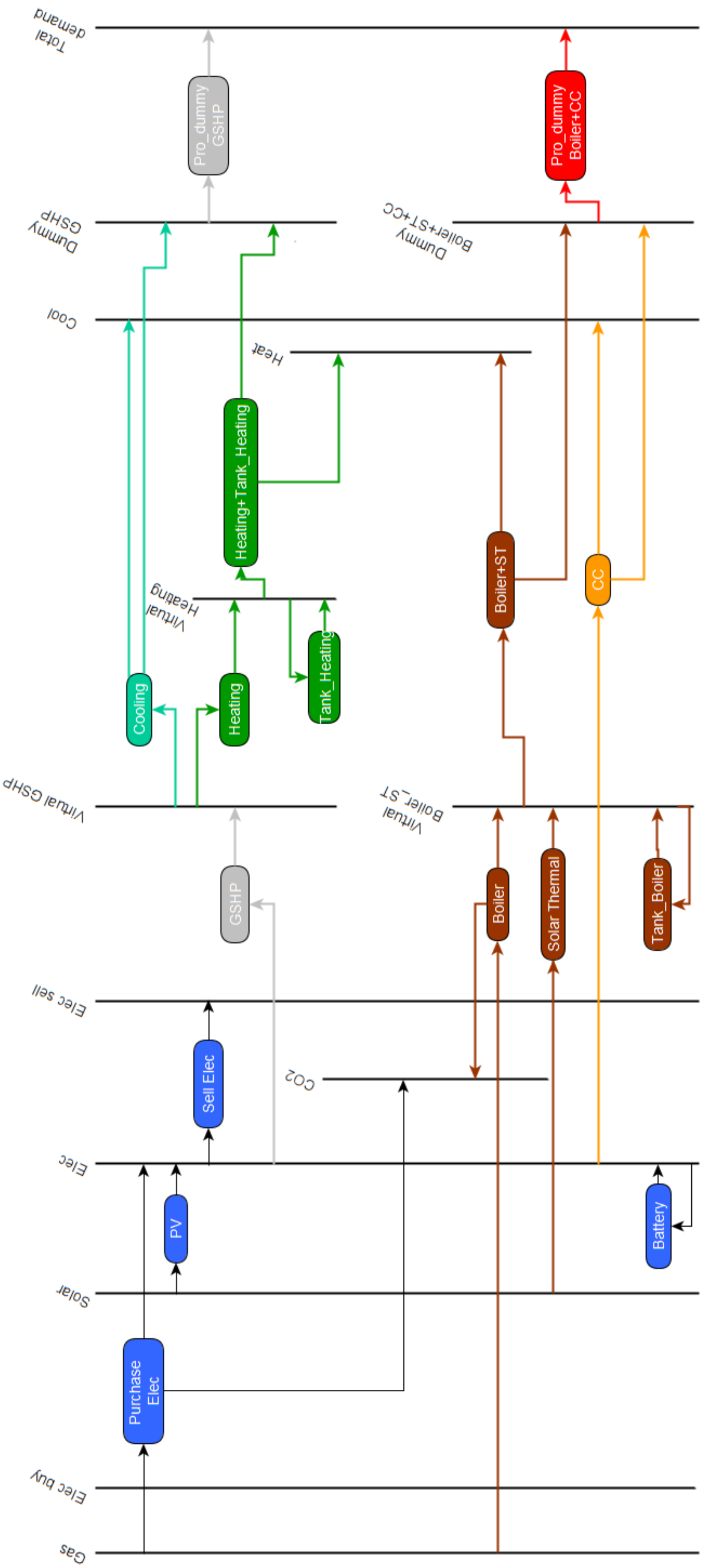


*Figure 4. 5: Process-commodity scheme implemented in urbs*

## 4.2 urbs input data and assumptions

Affecting the urbs' simulation are prices due to investments and operations, gas and electricity prices, efficiencies of installed plants (the processes) and electric and thermal demand. Therefore, it's very important to set all these parameters accurately in order to obtain a result that is in line with reality.

The prices information for GSHP, the storage of domestic hot water and the compression chiller, have been taken from a database in accordance with KEA Klimaschutz - und Energieagentur Baden-Württemberg GmbH [37] while the prices for the photovoltaic system, the batteries connected to it, the solar thermal system and the condensing boiler, have been received from quotations of private companies in the industry.

For all components, investment costs are expressed in €/MW, while operating costs are expressed in €/MWh. It is important to note that these values may vary depending on whether they are applied to the residential or non-residential sector. However, since the dissertation focuses on providing heating and cooling for the entire urban district, we have considered the residential sector as the reference sector, as it has the highest consumption for both heating and cooling, as highlighted in Figure 3. 8 and Figure 3. 15.

### *Electricity and Gas prices*

As for energy purchase prices, however, they were set according to the price list published by the main German supplier SWM:

- gas purchase is set equal to 20.89 c€/kWh, so 208.9 €/MWh;
- electricity purchase, on the other hand, is set equal to 51.9 c€/kWh, so 510.9 €/MWh.

These prices, as mentioned, refer to the domestic users and are held constant per each timestep: this means that the cost of energy (both gas and electricity) does not vary throughout the year.

***Heating, Cooling and Electricity demand***

About heating and cooling demand, they were taken as follows:

- in the first scenario, heating and cooling demand are as simulated by UrbanHeatPro in the adapted model, as described in the chapter *3.2*. In particular, as reported in Figure 3. 12 and in Table 3. 3, the results of the simulation yield:
  - a) 14.74 GWh for heating
  - b) 2.21 GWh for cooling
- In the second scenario, heating and cooling demand are as simulated by EUReCA in the adapted model as described in the chapter*3.2*. In particular, as reported in Figure 3. 12 and in Table 3. 3, the results of the simulation yield:
  - c) 14.33 GWh for heating
  - d) 3.44 GWh for cooling
- In the third scenario, heating and cooling demand are as simulated by UrbanHeatPro considering the random effects active as described in the chapter*3.2*. In particular, as reported in Figure 3. 1 and in Table 3. 1, the results of the simulation yield:
  - e) 11.62 GWh for heating
  - f) 2.12 GWh for cooling
- in the fourth scenario, heating and cooling demand are as simulated by EUReCA considering the random effects active as described in the chapter *3.2*. In particular, as reported in Figure 3. 3 and in Table 3. 1, the results of the simulation yield:
  - g) 21.19 GWh for heating:
  - h) 4.09 GWh for cooling.

In each scenario, the commodity *Total Demand* is simply calculated as the sum of heating and cooling demand per each timestep.

As for electricity demand, it was calculated from the trend of the standard load profile (SLP), a load profile used to prevent and balance the load profile of a market location without recording power (electricity or gas) measurements (see Figure 4. 6). The curve we need is called “Lastprofil Haushalt H0”: it provides information about the energy profile consumed by a household (haushalt) in a reference residential building; in particular, the curve returns us the value, per each timestep, of the electricity consumed per household. So, since the goal is to obtain the electricity required by the entire district of Unterhaching the curve of the "hours in function of the electricity consumed per household" reported in Figure 4. 6 should be converted into the curve of the "hours in function of the electricity consumed".

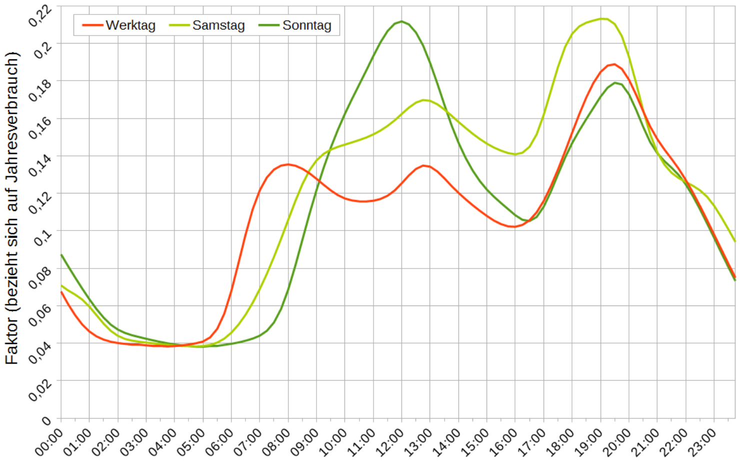


*Figure 4. 6: standard load profile H0 according to VDEW.*

Depending on whether the results were obtained from the EUReCA simulation or the UrbanHeatPro simulation, the calculation method is different.

In the case of UrbanHeatPro, the number of occupants per building is given. Also, knowing that there are on average 3 occupants per household, the electricity demand curve can be obtained by applying the following calculation for each time step:

$$elec_i = \frac{x_i \cdot occ}{3} \qquad With\ i\ \in [1,8760] \qquad 39.$$

Where $x_i$ is the value at hour i from the Lastprofil Haushalt H0 curve, occ is the sum of the occupants of all buildings of Unterhaching simulated by UrbanHeatPro.

the case of EUReCA, however, the previous calculation cannot be implemented because the number of occupants is not calculated by the model. However, in EUReCA, the value in W/m$^2$ related to occupancy is defined: thus, knowing the power emitted by the single body (120 W/px), the emission per square meter (2.7 W/m$^2$ for the residential sector) and the sum of the area of the buildings of the entire city, the number of occupants can be estimated as follows:

$$occ = \frac{2.7 \cdot \sum_{i=1}^{n} Area_i}{120} \qquad with\ i = id\ of\ the\ building \qquad 40.$$

Once the number of occupants is obtained, the previous equation can be implemented to obtain the electricity required by the users by considering a scenario in which the heating and cooling demand is that of EUReCA.

### ***Solar efficiency***

To define solar efficiency, we need to consider the standard [38] which describes what the efficiency of the solar thermal collector is considering the steady-state condition:

$$\eta = \eta_0 - \frac{a_1(T_m - T_a)}{I} - \frac{a_2(T_m - T_a)^2}{I} \tag{41.}$$

Where:

- $\eta_0$ is the efficiency at null reduced temperature $T_m = T_a$,
- $a_1[\frac{W}{m^2 \cdot K}]$ is the heat loss linear coefficient,
- $a_2[\frac{W}{m^2 \cdot K^2}]$ is the heat loss quadratic coefficient,
- $T_m[°C]$ is the mean fluid temperature in the collector calculated as $T_m = \frac{T_{fi}+T_{fu}}{2}$, where $T_{fi}$ and $T_{fu}$ are respectively the inlet and outlet temperature of the fluid,
- $T_a[°C]$ is the external air temperature,
- $I\left[\frac{W}{m^2}\right]$ is the solar global irradiance in the collector.

The inlet and outlet temperature of the fluid are fixed equal to 15 °C and 45 °C, while the values of $\eta_0$, $a_1$ and $a_2$ are taken by the technical sheet, and the value of the solar irradiance is taken by *[39]*, an API (application programming interface) that gives users the possibility to use solar radiation information in different places around the world.

By implementing the previous relation per each hour of the year, the solar efficiency can be obtained: in particular, it varies from 0.4 during the winter season to 0.85 during the summer: this is related to the fact that the irradiance during the winter is lower than during the summer and that the temperature difference $T_m - T_a$ during the winter is higher because the external ambient temperature is higher.

### *Efficiency of the GSHP and of the compression chiller*

Regarding the efficiency of GSHP, a distinction must be made between the coefficient of performance (COP) and the energy efficiency ratio (EER). The COP considers the efficiency of transferring energy from a lower-temperature source to a higher-temperature source: in fact, it refers to the heating season. EER, on the other hand, represents the efficiency of removing heat from a space to decrease its temperature. Because the GSHP operates under two different conditions (heating and cooling), it is necessary to consider two different COPs and EERs.

COP is the same as that used to evaluate the integration of groundwater heat pumps in energy system optimization models *[40]*, a topic developed by the Technical University of Munich.

On the other hand, in EER a fixed value equal to 3.5 is used for each timestep along the year: it's related to the fact that we can consider the cooling used by the GSHP as free due to the presence of the ground that allows for a natural source of refrigerant (without compressor activation).

Regarding the compression chiller, a compressor was chosen through the use of software provided by companies like Frascold, Copeland or Bitzer. We used R290 (propane) as the refrigerant fluid: it is characterized by high flammability, but is a typical refrigerant used in these applications and, if handled and manipulated correctly, can be used safely. Moreover, this refrigerant has a very low Global Warming Potential (around 3) and zero Ozone Depletion Potential.

To choose the compressor, the temperature range in the heat exchangers (both in the condenser and the evaporator) is required to determine the condensing and evaporating temperatures. Initially, temperature ranges within the room (i.e., indoor temperatures) were considered. The refrigerant fluid (in red) evaporates and absorbs heat from the secondary fluid, which lowers its temperature (in our case, the indoor air of the apartment). Considering the heat exchange, it is necessary to maintain a certain temperature difference, so the inlet and outlet temperatures of the secondary fluid are set. Thus, the indoor air temperature is set at 26°C when it enters the system and exits at a lower temperature (specifically, 18°C). This is what happens on the indoor side of the apartment. To set the evaporation temperature, we need to consider the required superheating temperature (approximately 10 K). The temperature curves should not intersect, and since the minimum temperature of the secondary fluid is 18°C, we can set the maximum superheat temperature to 13°C and, therefore, the Evaporation Temperature to 13°C-10K = 5°C. For the condenser, it has been done something similar. The outside air temperatures has been chosen and consequently the condensation temperature.

Considering that the outside air temperature is 30°C and it comes out at 35°C, the condensing temperature is set at 40°C (taking into account the need for a subcooling of approximately 3°C).

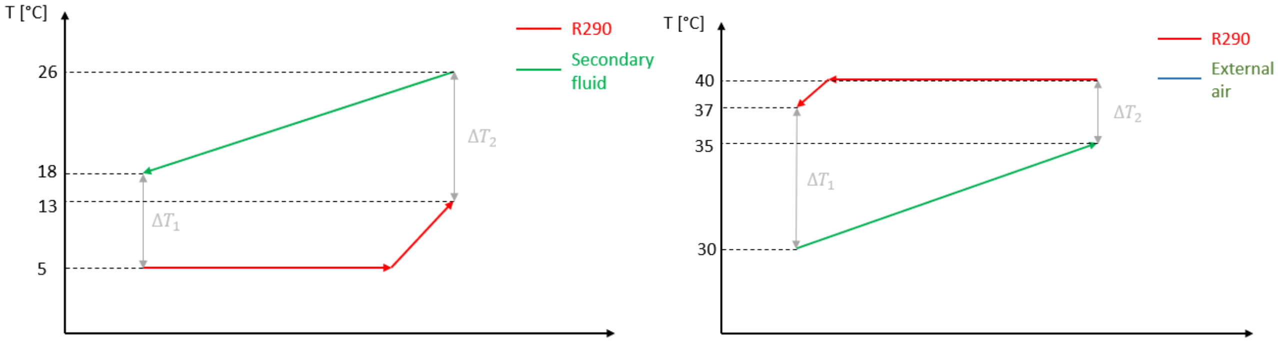


*Figure 4. 7: Temperature of the refrigerant fluid in the evaporator (left) and in the condenser (right)*

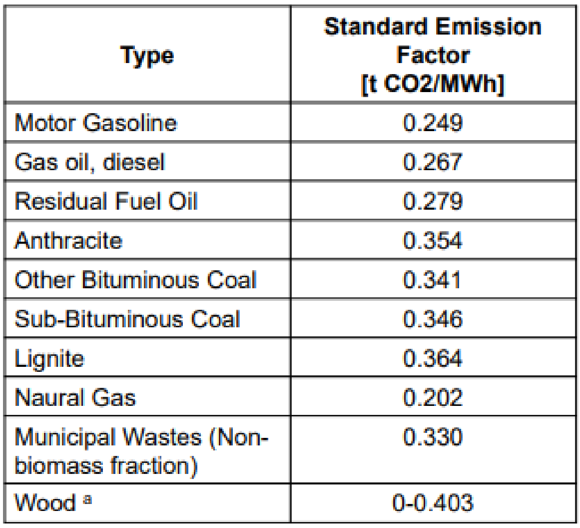
Using the Copeland software and implementing the previous data, a compressor was suggested, and from the polynomial curves (obtained from the Copeland software), the values of the power required to operate the compressor can be derived.

Using a matlab script, a cycle is run in which the external temperature is set as defined by the data held by TUM and a EER value is obtained as a function of the variation of external temperature (since $Q_{cooling}$ depends on temperatures)

$$EER = \frac{Q_{cooling}}{P_{compressor}} \tag{42.}$$

### *CO2 emissions*

From the IPCC 2006, the standard $CO_2$ emission factors for the most common fuel types (EU) can be obtained, as reported in Figure 4. 8:



| Type | Standard Emission Factor [t CO2/MWh] |
|---|---|
| Motor Gasoline | 0.249 |
| Gas oil, diesel | 0.267 |
| Residual Fuel Oil | 0.279 |
| Anthracite | 0.354 |
| Other Bituminous Coal | 0.341 |
| Sub-Bituminous Coal | 0.346 |
| Lignite | 0.364 |
| Naural Gas | 0.202 |
| Municipal Wastes (Non-biomass fraction) | 0.330 |
| Wood [a] | 0-0.403 |

*Figure 4. 8: Standard $CO_2$ emission factors for the most common fuel types (EU)*

In the following models, there are only two systems that contribute to $CO_2$ emissions in accordance to Figure 4. 5:

- Boiler, with a factor equal to 0.202 $tCO_2/MWh$
- Electricity purchased, with a factor equal to 0.301 $tCO_2/MWh$

## 4.3 Urbs results

As a first step, we want to evaluate what happens if we re-scale the COP value of GSHP: if it increases, the convenience to use the GSHP increases as well. This analysis is done just to highlight which is the importance of parameters definition in the optimization model: it's also very important taking into account that any variation in the input data can strongly influence the final results.

To do so, we consider as heating and cooling demand inputs the values obtained from the EUReCA simulation considering the adaption of input data as described in *2.5*. In particular:

- If $COP_{NEW} < COP_{TUM} \cdot 1.4$ only the boiler and compression chiller are used to produce heating and cooling respectively;
- If $COP_{TUM} \cdot 1.4 < COP_{NEW} < COP_{TUM} \cdot 1.7$ both the boiler and GSHP work to meet the heating demand, while both the compression chiller and GSHP work to meet the cooling demand;
- If $COP_{NEW} = COP_{TUM} \cdot 1.8$ only the GSHP works to provide heating and cooling demand.
- So, three different scenarios with three different COP values for GSHP are performed:

1. $COP_{NEW} = COP_{TUM}$
2. $COP_{NEW} = 1.5 \cdot COP_{TUM}$
3. $COP_{NEW} = 1.8 \cdot COP_{TUM}$

Figure 4. 9 shows the area of the technology that needs be installed to meet the demand with the three different COPs. It can be seen that in the three different scenarios the power of the GSHP increases while the amount of boiler decreases: this is because the COP of GSHP is more efficient and allows us to reduce costs. Moreover, it's clear that the amount of PV increases because the electricity demand increases due to the higher amount of the GSHP: furthermore, since the size of the PV system is larger, a larger amount of electricity sold is present. We also expect a greater amount of "purchase" process because the electricity demand required by GSHP is higher.

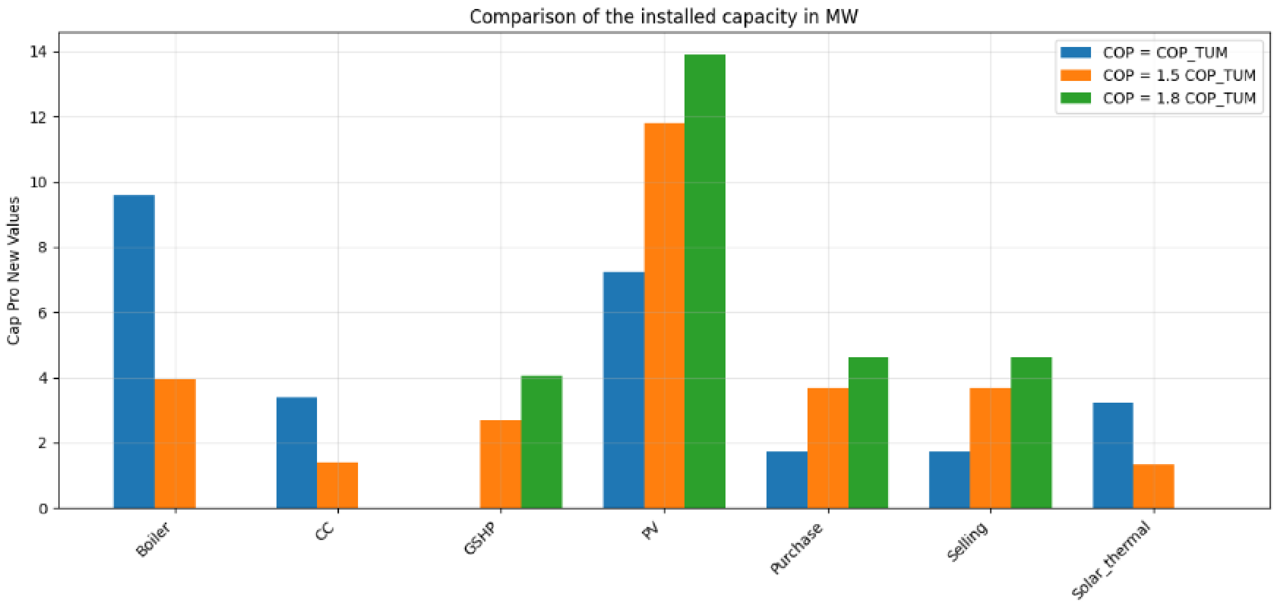


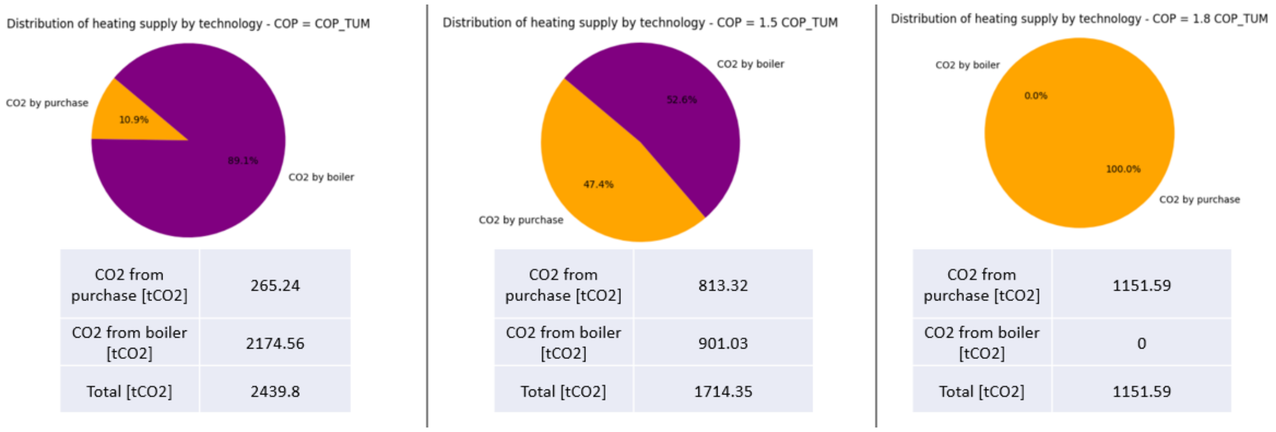
*Figure 4. 9: Comparison of the capacity that must installed to satisfy heating, cooling and electricity demand in the scenarios with different COP*

Costs are reported in Table 4. 1; since all the parameters remain the same expect for the COP of the GSHP, a lower cost is expected when the COP increases. In particular, in the third scenario, the costs decrease due to the higher value of the COP and that also the revenue increases (revenues dependsonly by the electricity sold to the grid due to the overproduction of the photovoltaic system: the revenue increases since the power of the photovoltaic system increases to satisfy the electricity required by the GSHP).

*Table 4. 1: Share of the costs in the three different scenarios with different COPs*

| | Scenario 1 | Scenario 2 | Scenario 3 |
|---|---|---|---|
| Investment | 2,485,282 € | 2,651,701 € | 2,546,683 € |
| Fixed | 604,255 € | 905,706 € | 1,028,673 € |
| Variable | 328,614 € | 404,522 € | 412,654 € |
| Purchase | 2,729,876 € | 2,347,910 € | 1,992,031 € |
| Total costs | 6,148,027 € | 6,309,839 € | 5,980,041 € |
| Revenues | -202,090 € | -445,904 € | -560,622 € |

Moreover, as the amount of GSHP increases in the three different scenarios with a consequent decrease in the boiler, it was also expected that less $CO_2$ would be emitted from the boiler. Thus, emissions related to the “purchase” process increase, as shown in Figure 4. 10 even though the total amount of $tCO_2$ decrease: this is because the boiler has a large impact on emissions, and this result is something we expected.



| | |
|---|---|
| CO2 from purchase [tCO2] | 265.24 |
| CO2 from boiler [tCO2] | 2174.56 |
| Total [tCO2] | 2439.8 |

| | |
|---|---|
| CO2 from purchase [tCO2] | 813.32 |
| CO2 from boiler [tCO2] | 901.03 |
| Total [tCO2] | 1714.35 |

| | |
|---|---|
| CO2 from purchase [tCO2] | 1151.59 |
| CO2 from boiler [tCO2] | 0 |
| Total [tCO2] | 1151.59 |

*Figure 4. 10: $CO_2$ emissions in the three different scenarios with different COPs*

From the above observation, it can be seen that just changing the COP (same value but different multiplier) can strongly influence the results. Moreover, a similar observation can be made by changing any input data: however, this is not the goal of this dissertation because we want to highlight how changing the heating and cooling demand simulated by the two different models (EUReCA and UrbanHeatPro) will get different results.

However, the goal is to examine how the urbs optimizes the system in four different scenarios as described at the begging of this chapter. Moreover, it is coupled the scenarios in the following way:

- in the first comparison (scenario 1 and 2), heating and cooling demands (calculated both by UrbanHeatPro and EUReCA) are implemented using the adapted models, as reported in *3.2*. This approach will allow us to analyse how heating and cooling demand curves may influence the results obtained by urbs.
- in the second comparison (scenario 3 and 4), on the other hand, heating and cooling demands (calculated both by UrbanHeatPro and EUReCA) are implemented using non-adapted models (keeping random factors active), as described in *3.1*. This allow to compare the optimization performed by urbs in two simulations that theoretically represent the actual building demand.

### *Urbs results from the first comparison*

In this section, the scenario 1 (heating and cooling demand from UrbanHeatPro of the adapted model) and the scenario 2 (heating and cooling demand from EUReCA of the adapted model) are compared: the goal is to evaluate how much the differences in the two software affects the optimization; moreover, we can note from Table 3. 3 that the heating demand simulated by EUReCA and UrbanHeatPro are quite similar (14.33 GWh against 14.74 GWh), while the cooling calculated by EUReCA (3.44 GWh) is higher than the one calculated by UrbanHeatPro (2.21 GWh). In Figure 4. 11 are reported the heating and cooling' trends of the two different scenarios.

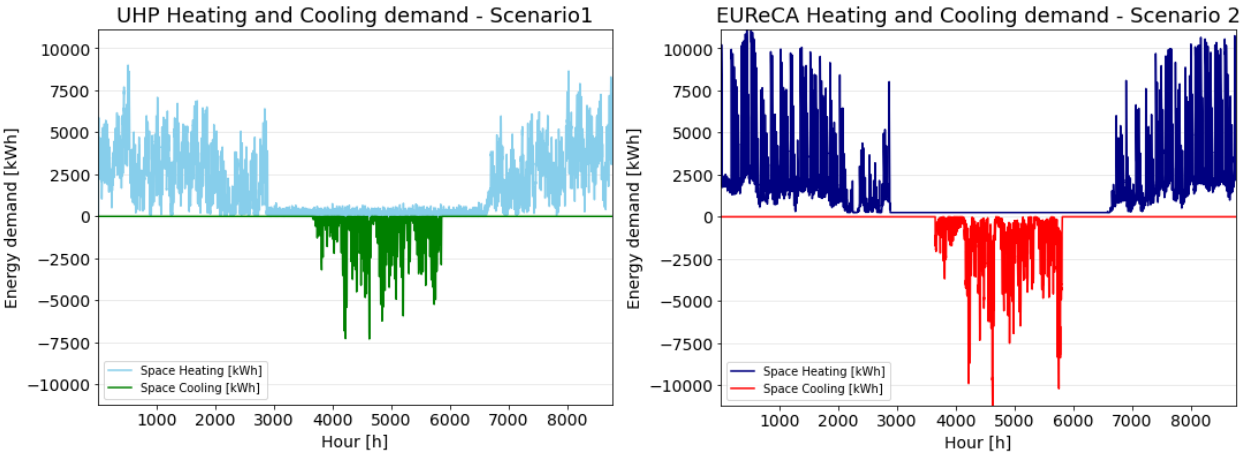


*Figure 4. 11: Hourly heating and cooling demand in the Scenario 1 (left) and 2 (right) – first comparison*

Heating and cooling seasons are equal in the two models because we are considering the adapted models.

However, as described in the observations of the chapter *3.2*, even if the total amount of the heating required by the entire city along the year is very similar both in the EUReCA and UrbaHeatPro, their hour values are strongly different: in fact, as shown in Figure 3. 21, EUReCA deactivate the plants during the night hours in the non-residential buildings, differently by UrbanHeatPro: it means that, in EUReCA, there is a pick of the heating and of the electricity demand during the day because it is required to heat up the buildings of a higher quantity since the temperature difference (between the internal one and the set-point one) in EUReCA is higher.

Moreover, the cooling energy demand simulated by UrbanHeatPro is strongly lower than the one of EUReCA.

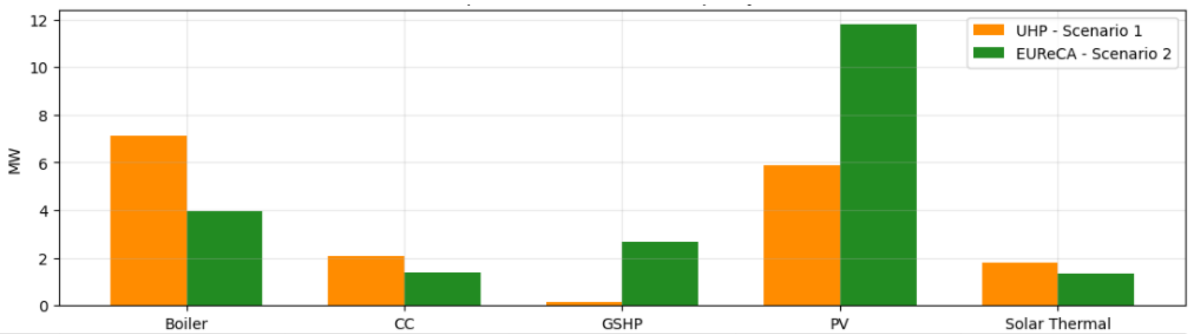
So, as consequence, the share of the GSHP in the EUReCA's scenario (Scenario 2) is higher: in fact, a significant energy demand needs to be satisfied during daylight hours. During this period, photovoltaic solar panels are much more efficient, allowing the energy they generate to be used to satisfy the electricity demand required by the GSHP for heating and cooling.

Furthermore, regarding the cooling, it is essential to consider that, as previously described, the GSHP operates under free-cooling conditions. Consequently, if energy demand increases, a corresponding increase in installed capacity to satisfy such demand, given the low operating costs of GSHP. This behaviour is also illustrated in the Figure 4. 11, which shows the hourly vdemand for electricity, heating, and cooling demand in Scenario 1 (UrbanHeatPro) and Scenario 2 (EUReCA), and it is evident that the amount of energy covered by GSHP is significantly higher in Scenario 2 compared to Scenario 1.

Moreover, in Table 4. 2, the amount of energy supplied by each technology in the two different scenarios is shown and it's highlighted that in scenario 2 the use of GSHP for heating and cooling production is strongly higher (58.6 % in the EUReCA's scenario versus 4.6 in UrbanHeatPro's scenario) than in scenario 1. This is also consistent with the installed capacity in MW that Urbs simulates to meet the demand: from Figure 4. 12 it can be seen that the amount of installed capacity of GHSP is strongly lower in Scenario 1. Due to the low amount of GSHP, there is a lower demand for electricity (since most of the heating demand is satisfied by the boiler, thus by gas) which has, as a consequence, a lower electricity need of the photovoltaic system: in fact, as reported in Figure 4. 12, the installed capacity of the photovoltaic system in the scenario 1 (UHP) is approximately 50 % lower than the installed capacity in the scenario 2 (EUReCA). Moreover, since the production of the heating by solar thermal is higher in the scenario 1, its installed capacity is higher, as reported in Figure 4. 12.

*Table 4. 2: Amount of energy (heating and cooling) supplied per technology in scenarios 1 (UHP) and 2 (EUReCA)*

| Adapted model | | | |
|---|---|---|---|
| | Technology | Scenario 1 (UHP) | Scenario 2 (EUReCA) |
| Heating [MWh] | Boiler | 12715 (86.2 %) | 4866 (33.9 %) |
| | Solar Thermal | 1360 (9.2 %) | 1074 (7.5 %) |
| | GSHP | 675 (4.6 %) | 8403 (58.6 %) |
| Total Heating [MWh] | | 14750 | 14343 |
| Cooling [MWh] | CC | 2113 (95.4 %) | 1429 (41.4 %) |
| | GSHP | 101 (4.6 %) | 2020 (58.6 %) |
| Total Cooling [MWh] | | 2214 | 3449 |



| | Boiler | CC | GSHP | PV | Solar Thermal |
|---|---|---|---|---|---|
| UHP [MW] | 7.12 | 2.09 | 0.17 | 5.9 | 1.81 |
| EUReCA [MW] | 3.97 | 1.4 | 2.69 | 11.81 | 1.33 |

*Figure 4. 12: Installed capacity per technology in scenarios 1 (UHP) and 2 (EUReCA)*

Now, the goal is to investigate what is happening along the year for electricity, heating and cooling energy demand; in addition, it's interesting to enter into the details of the summer and winter periods using two reference weeks as follows:

- the first two weeks of December for the winter period as reported in Figure 4. 14
- the first two weeks of July for the summer period as reported in Figure 4. 15

A closer examination is conducted within these selected time periods, focusing solely on the electricity demand, heating, and cooling. This detailed analysis aims at providing a better understanding of the situation during these seasons versus the annual period shown in Figure 4. 13.

As for Figure 4. 13 on electricity demands, an immediately different both in the electricity produced (positive y-axis) and electricity consumed (negative y axis): in the EUReCA scenario, the total electricity required is higher, reaching approximately a peak of 7.5 MWh, while in the UrbanHeatPro scenario the peak of the total electricity required is closed to 4.5 MWh. It's related to two different aspects:

- the electricity demand of EUReCA is 5394 MWh, whereas the electricity demand of UrbanHeatPro is 4454 MWh (both calculated as described at page 106)
- the amount of the GSHP increases according to Figure 4. 12 and so does the amount of electricity required (controlla se vuoi dire questo): in EUReCA scenario the GSHP requires 4350 MWh of electricity during the year, while in UrbanHeatPro scenario it requires 344 MWh of electricity during the year.

Therefore, the second aspect (the electricity required by the GSHP) affects a lot the electricity demand. The share GSHP depends on the demand for heating and cooling and on the energy produced by the photovoltaic system. However, since the efficiency of the photovoltaics is the same in both scenarios, the share of GSHP depends only on the demand for heating and cooling. As previously described, these two demands exhibit very different trends: EUReCA has a stepped curve, while UrbanHeatPro has a gradual curve.

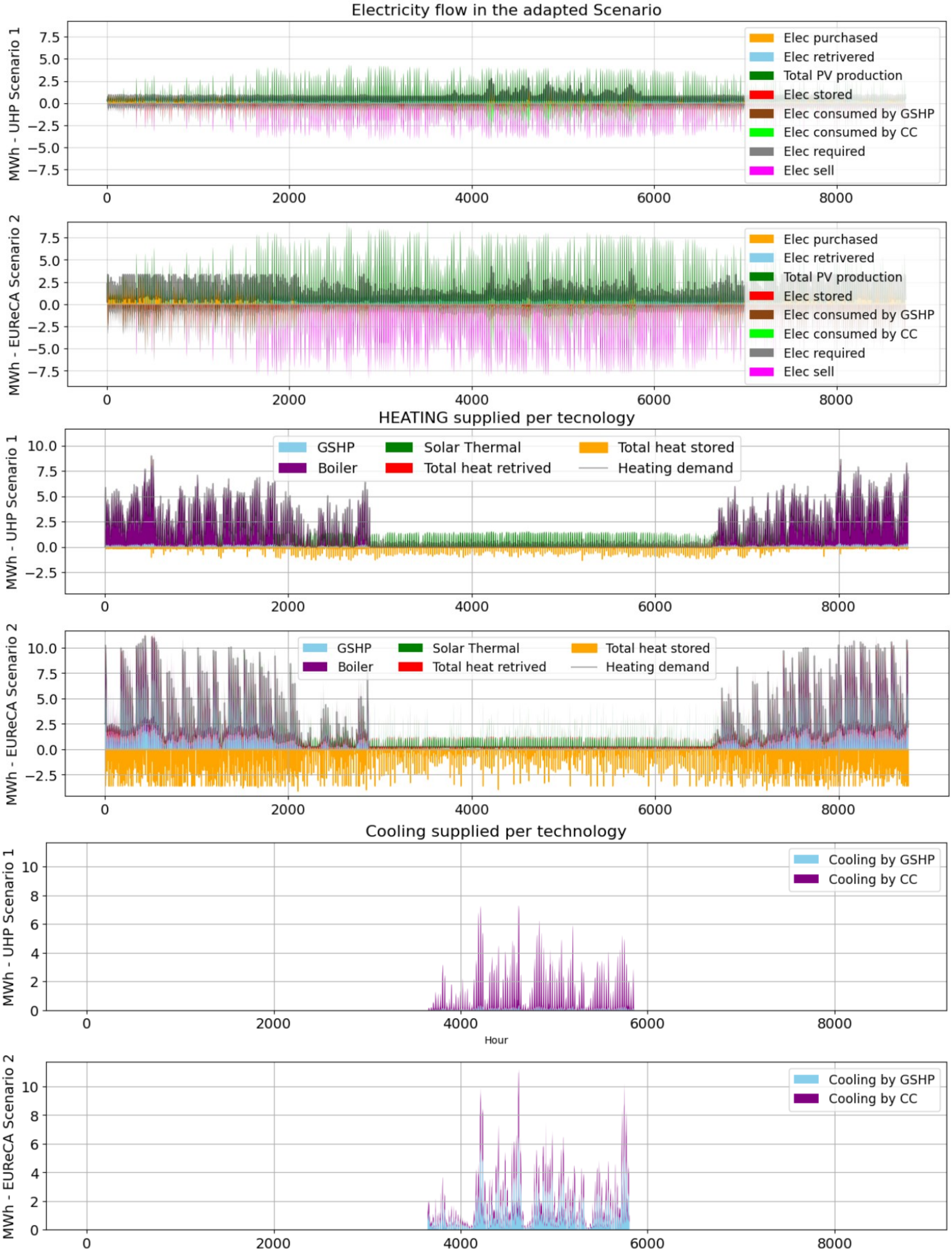


*Figure 4. 13: Hourly electricity, heating and cooling supplied per technology – Scenario 1 (UHP ) and 2 (EUReCA)*

In Figure 4. 14 are shown the two different curves during the heating season (the cooling is not reported since it's null during this period).

Firstly, we have to note that EUReCA heating demand has the peaks in the demand corresponding to the peaks of electricity produced by the photovoltaic system (during the daylight hours). On the contrary, during the nighttime hours the heating demand of EUReCA tends to decrease due to the fact that non-residential buildings turn off the heating system (only the residential sector contributes to the heating demand); on the other hand, we can see that UrbanHeatPro curve is more gradual and the heating system is not completely closed during the nighthours; as a consequence, we need to heat up the buildings during the hours in which there isn't any electricity production by the photovoltaic system.

From the graph of electricity flows in the adapted scenario during the heating season Figure 4. 14, the electricity puchased from the grid increases in the EUReCA's scenario due to the fact that the amount of the electricty stored is consumed in few hours; it's related to the fact that the electricity demand is strongly higher because also during the nigthtime hours the GSHP continue to work requiring a higher amount of electricity.

Figure 4. 15 reports a zoom of the fisrt two weeks of July and shows the electricity, heating and cooling demand during this period. About the electricity demand, both system, more or less, are self sufficient since the main part of the demand is covered by the photovoltaic system or by the batteries: during summer, in fact, the efficiency of the solar panels increases a lot due to the higher solar radiation and also due to the fact that the daylight time increases.

About the heating required during the cooling season, it's not affecting the results since it's negligible with respect to the heating produced during the winter season: this is due to the fact that during the summer season there is only the heating demand for the domestic hot water production. As described in the chapter *2.5,* the domestic hot water demand is calculated in two different ways and, as reported in Figure 4. 15, EUReCA maintains a fixed and constant value, while UrbanHeatPro has a fluctuating value (that becomes null during the night hours). Thus, the heating demand is completely covered by the batteries during the night hours and with the help of the solar thermal plant (for the boiler) and the photovoltaic system (for the GSHP) during the day. For this reason, the heating demand is not affecting the results of the electricity required, while the cooling demand has a crucial impact.

About the cooling required during the cooling season, it's covered primarly by the compression chiller in the first scenario and by both system in the second scenario.

In scenario 2, a substantial MW capacity of photovoltaic panels has been installed to satisfy the electricity demand during winter for powering GSHP systems. Of course, excess electricity generated, which is considerable during the summer months, is sent to the grid, resulting in economic gains. As depicted in the figure, the quantity of electricity sold in scenario 2 (EUReCA) is significantly greater than scenario 1 (UrbanHeatPro): specifically, 5728 MWh in EUReCA versus 2086 MWh in UrbanHeatPro (approximatly 64 % lower).

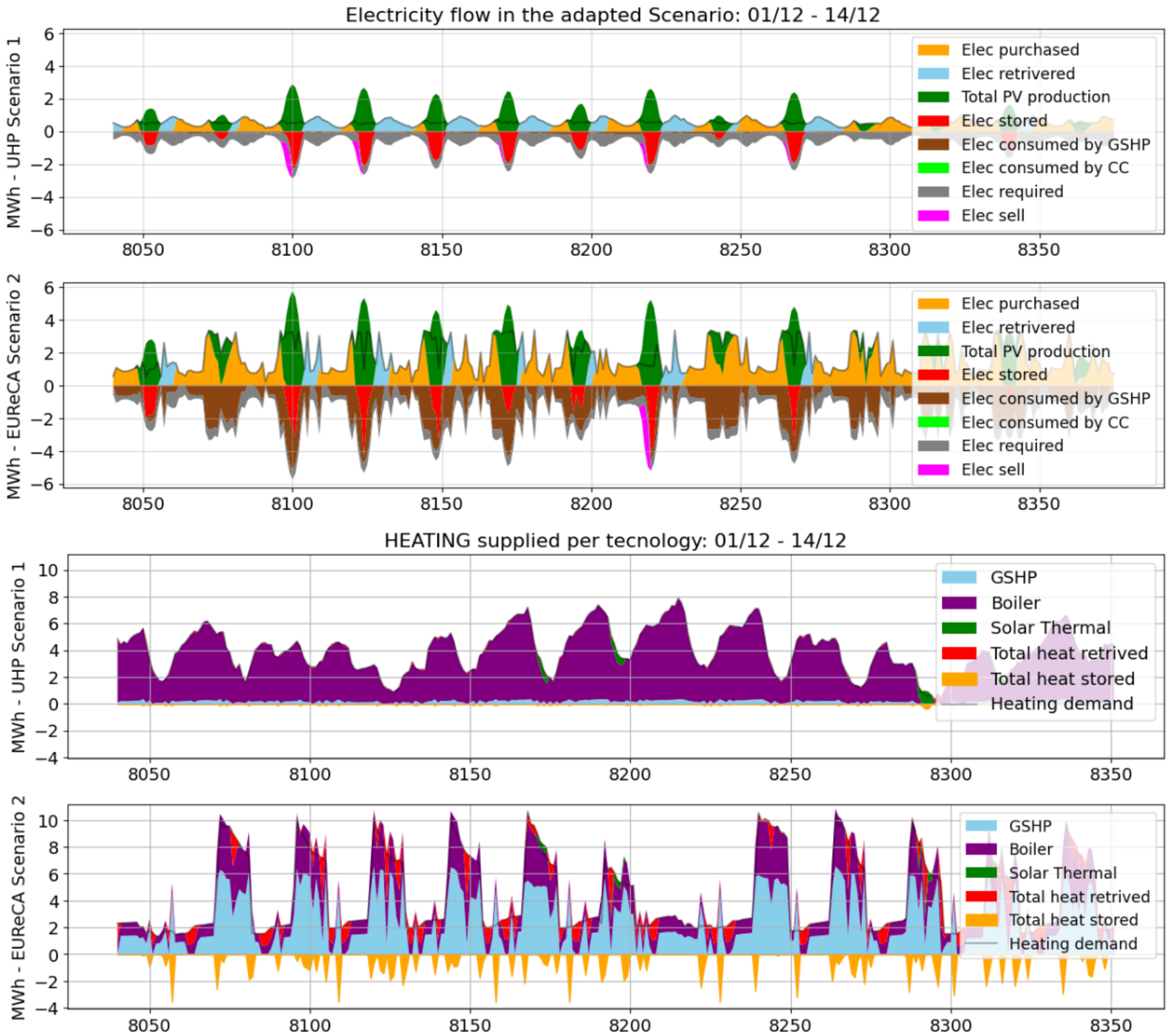
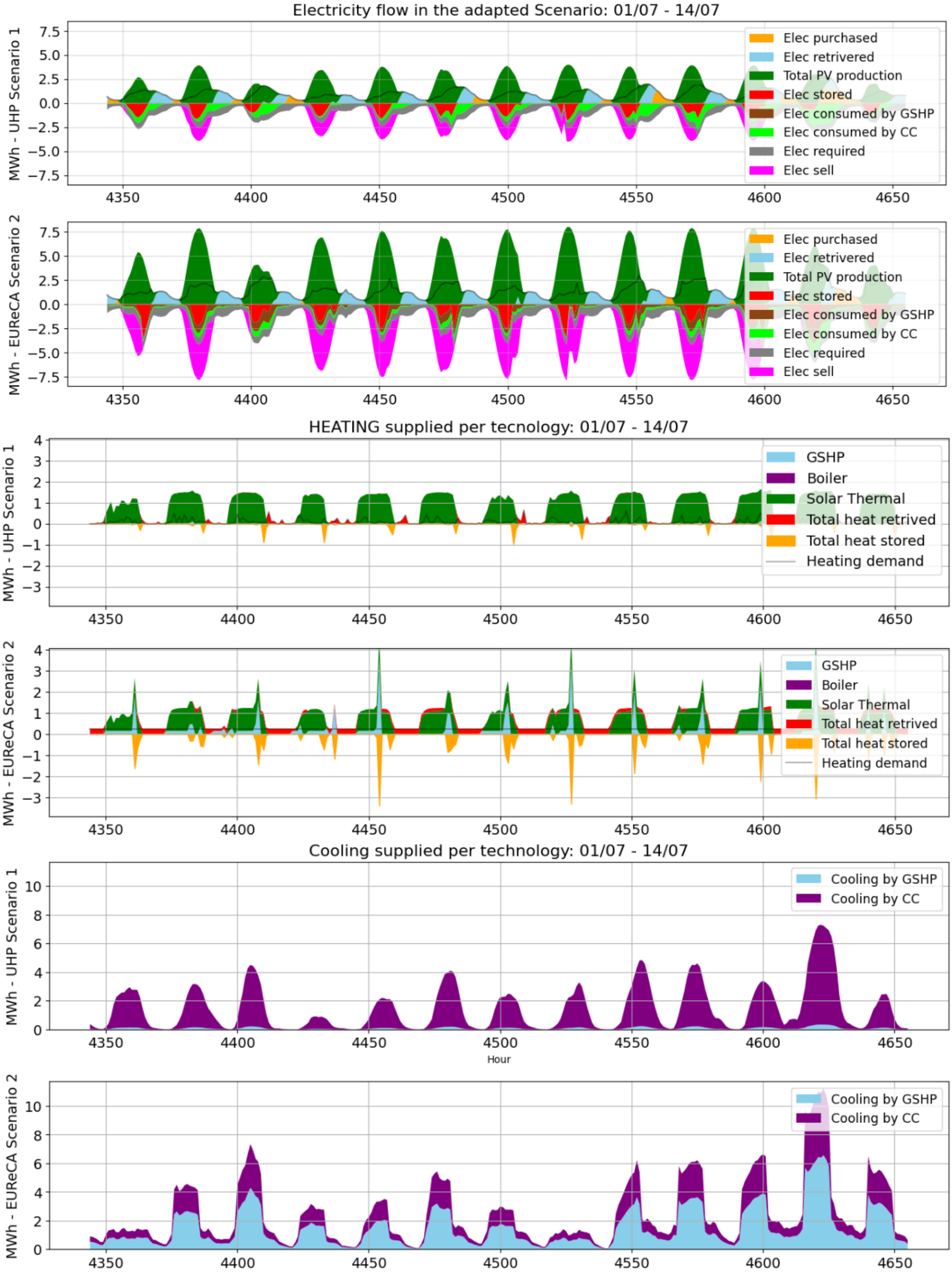


*Figure 4. 14: Hourly electricity and heating supplied per technology during the first two weeks of December. Scenario 1 (UHP ) and 2 (EUReCA)*


Electricity flow in the adapted Scenario: 01/07 - 14/07

HEATING supplied per tecnology: 01/07 - 14/07

Cooling supplied per technology: 01/07 - 14/07

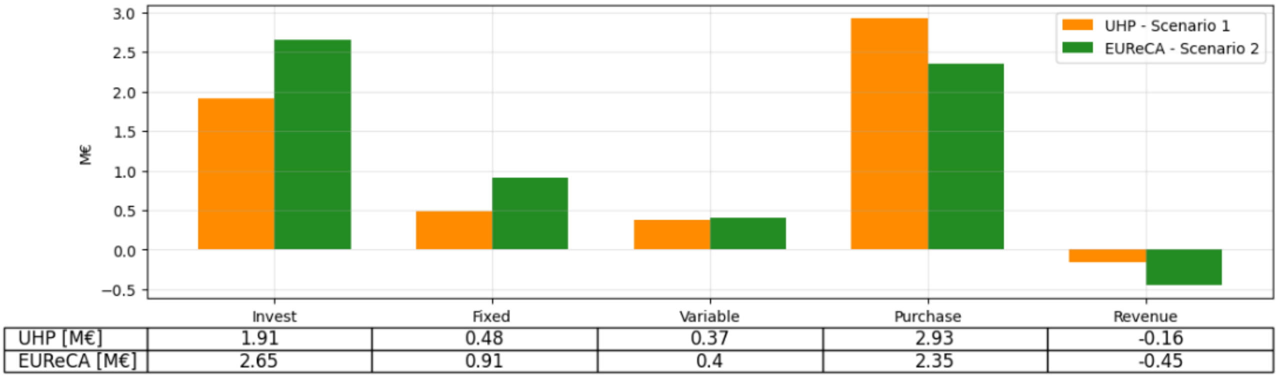
*Figure 4. 15: Hourly electricity and heating supplied per technology during the first two weeks of July. Scenario 1 (UHP ) and 2 (EUReCA)*

As for costs, urbs also simulates the annual costs to satisfy the demand. It can be seen that the investment costs in scenario 1 account for 33.5 % of the total cost, while in scenario 2 they account for 42.0 %: it should be considered that in scenario 2 the total demand is higher than in scenario 1 and that the investment costs for GSHP are quite higher: in fact, the advantage of GSHP is obtained with prolonged use of GSHP.

Moreover, as shown in Figure 4. 16, the costs of purchased gas and electricity (column "Purchase") are lower in scenario 2: the share of GSHP is higher and, consequently, the amount of gas required is lower (because only the boiler requires gas). Additionally, the energy demand that was previously produced by the boiler (using gas) is now satisfied by the GSHP (using electricity). However, since the GSHP is more efficient than the boiler, this results in lower electricity and gas purchase costs.

Fixed and variable costs depend on operational and maintenance (O&M) costs and are set in €/MW and in €/MWh respectively. Therefore, since both total installed capacity and energy demand are higher in scenario 2, fixed and variable costs are higher in scenario 2.

As for revenues, for the same reason explained before, urbs return a higher profit for scenario 2.



| | Invest | Fixed | Variable | Purchase | Revenue |
|---|---|---|---|---|---|
| UHP [M€] | 1.91 | 0.48 | 0.37 | 2.93 | -0.16 |
| EUReCA [M€] | 2.65 | 0.91 | 0.4 | 2.35 | -0.45 |

*Figure 4. 16: Annual costs in M€ per scenario – adapted models*

Furthermore, urbs returns the total CO2 emissions of the boiler and electricity purchased from the grid. In particular:

*Table 4. 3: Emissions of $CO_2$ in the scenarios 1 (UHP) and 2 (EUReCA)*

| | [$tCO_2$] | | [$tCO_2$/GWh] | |
|---|---|---|---|---|
| | Scenario 1 | Scenario 2 | Scenario 1 | Scenario 2 |
| Boiler | 2355 (89.7 %) | 901 (52.6 %) | 139 (89.7 %) | 51 (52.6 %) |
| Purchase | 270 (10.3 %) | 813 (47.4 %) | 16 (10.3 %) | 46 (47.4 %) |
| Total emission | 2625 (100 %) | 1714 (100 %) | 155 (100 %) | 97 (100 %) |

From Table 4. 3 it can be seen that the total amount of emissions in scenario 2 is 35 % lower than in scenario 1. This is due to the fact that the total boiler emissions decrease by 62 % with the larger share of GSHP. On the other hand, emissions from the purchasing process increase significantly, but to a lesser extent than the decrease in boiler emissions.

It is evident that in scenario 2, although energy demand is higher, emissions remain lower. This can be attributed to the presence of GSHP, which effectively reduces emissions. Consequently, using EUReCA's cooling and heating demands as inputs results in lower CO2 emissions, as Urbs favors the use of GSHP to satisfy heating and cooling requirements.

### *urbs results from the second comparison*

In this part, scenario 3 (heating and cooling demand from UrbanHeatPro of the unadapted model) and scenario 4 (heating and cooling demand from EUReCA of the unadapted model) are compared: the aim is to evaluate how the different heating and cooling demand affects the results of the optimization.

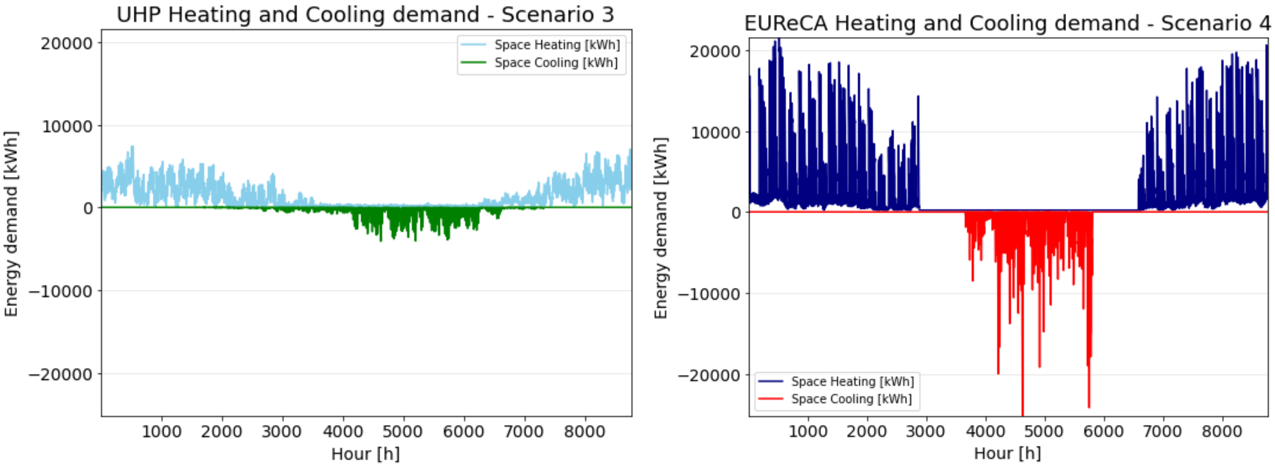
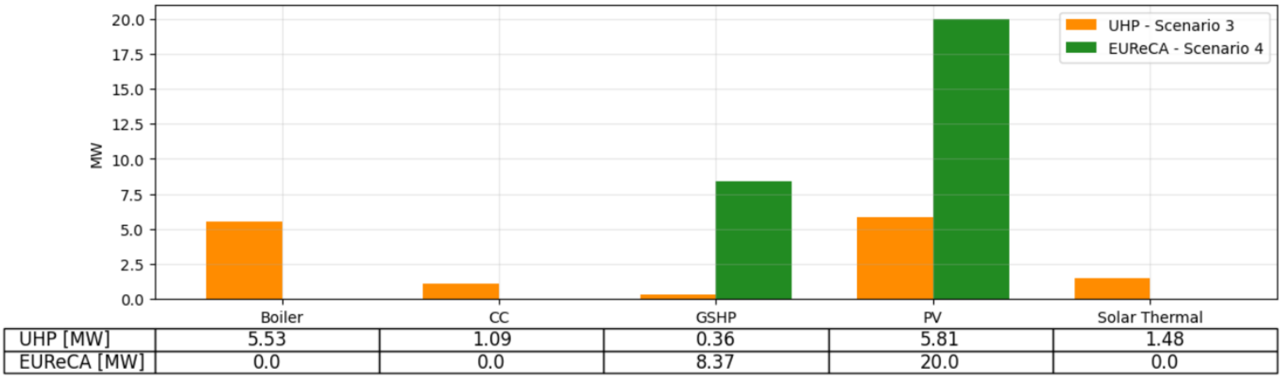


*Figure 4. 17: Hourly heating and cooling demand in the Scenario 3 (left) and 4 (right) – second comparison*

In contrast to scenarios 1 and 2, heating and cooling have a different trend and a completely different annual value: in fact, the total demand in scenario 4 is 25.28 GWh versus the total demand in scenario 3 of 13.74 GWh.

First of all, from Figure 4. 18, it's clear that the absence of the boiler (same for the compression chiller and of the solar thermal panels) in scenario 4 (EUReCA): ): this means that - in this scenario - the entire heating and cooling demand is supplied by GSHP. In scenario 1, on the other hand, both systems work to meet the energy demand and, as shown in Table 4. 4, GSHP provides 11.8 % of heating and cooling demand.



| | Boiler | CC | GSHP | PV | Solar Thermal |
|---|---|---|---|---|---|
| UHP [MW] | 5.53 | 1.09 | 0.36 | 5.81 | 1.48 |
| EUReCA [MW] | 0.0 | 0.0 | 8.37 | 20.0 | 0.0 |

*Figure 4. 18: Installed capacity per technology in scenarios 3 (UHP) and 4 (EUReCA)*

The next table shows the amount of energy provided by each technology in the two different scenarios and shows that in scenario 3 the use of GSHP for heating and cooling production is significantly higher (100 % in EUReCA scenario versus 11.8 % in UrbanHeatPro scenario) than in scenario 1.

*Table 4. 4: Amount of energy (heating and cooling) supplied per technology in scenarios 3 (UHP) and 4 (EUReCA)*

| Unadapted model | | | |
|---|---|---|---|
| | Technology | Scenario 3 (UHP) | Scenario 4 (EUReCA) |
| Heating [MWh] | Boiler | 9068 (78.1 %) | 0 (0 %) |
| | Solar Thermal | 1172 (10.1 %) | 0 (0 %) |
| | GSHP | 1370 (11.8 %) | 21195 (100 %) |
| Total Heating [MWh] | | 14750 | 21195 |
| Cooling [MWh] | CC | 1874 (88.2 %) | 0 (0 %) |
| | GSHP | 251 (11.8 %) | 4093 (100 %) |
| Total Cooling [MWh] | | 2125 | 4093 |

Similar observations made for the previous case can be done here. However, in scenarios 3 and 4, we have to consider that there are a few more elements that may affect the results: first, the UrbanHeatPro scenario has active heating and cooling demand during the summer and winter season, respectively. Since the COP is higher during summer, it may be more convenient to install more GSHP than in scenario 1 (in which the share of GSHP was 4.6 %).

Figure 4. 19 shows the electricity, heating and cooling demand per each hour of the year. It can be seen that all the demands simulated by EUReCA are strongly higher in all three demands.

Moreover, although the electricity demand is not so different (5394 MWh for EUReCA versus 4199 MWh for UrbanHeatPro), the electricity demand is strongly different due to the present of GSHP: in scenario 4 only GSHP works to provide heating and cooling demand and therefore the electricity consumed also increases. Moreover, since the heating and cooling demand of EUReCA is roughly double than that of UrbanHeatPro, additional electricity is required to run GSHP.

Figure 4. 19 shows all the plots of hourly electricity and heating and cooling; the same observations can be made as those made for  Figure 4. 13.

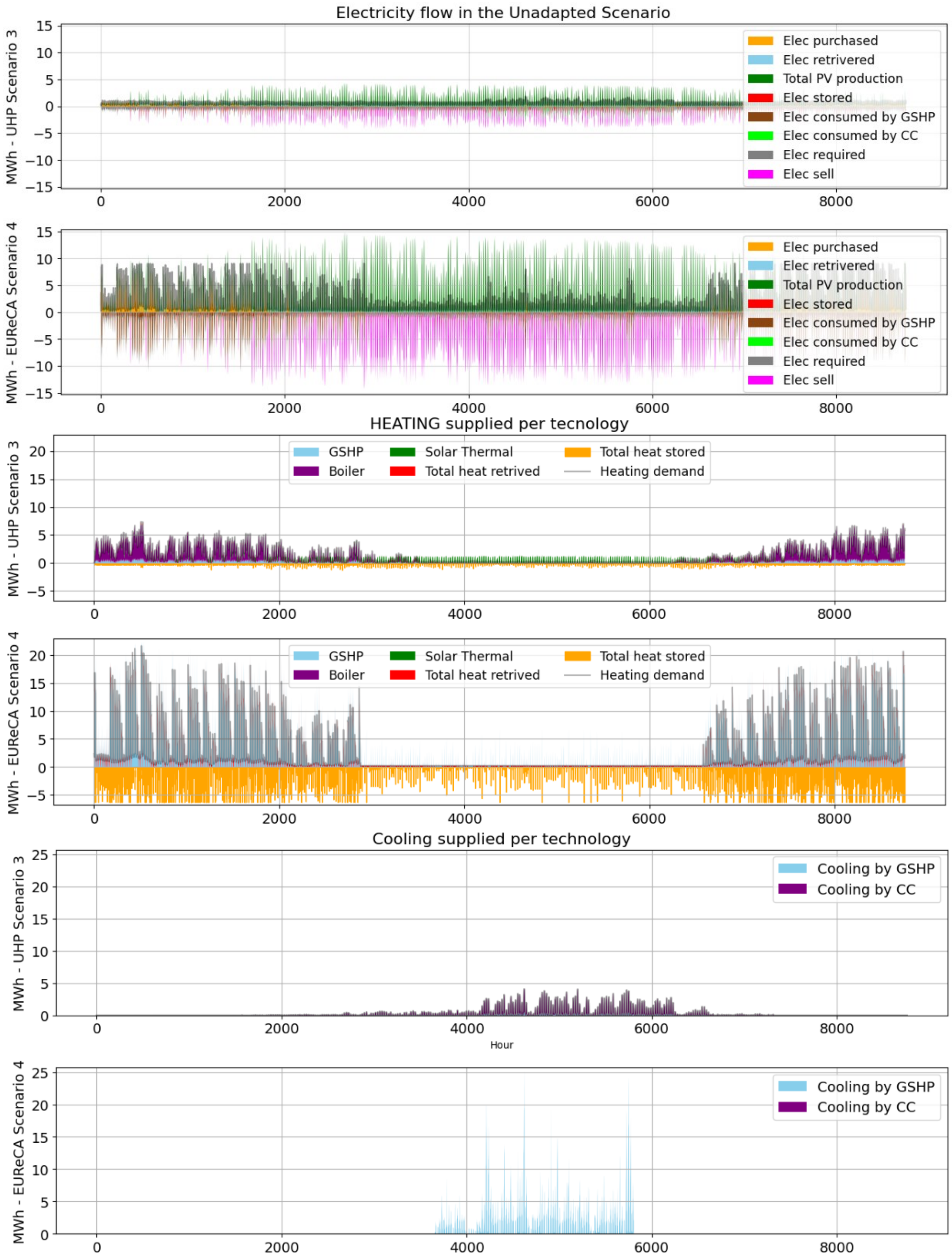


*Figure 4. 19: Hourly electricity, heating and cooling supplied per technology – Scenario 3 (UHP ) and 4 (EUReCA*

As it was done before in Figure 4. 14 and in Figure 4. 15, we now want to investigate in detail what is happening; for this purpose, summer and winter reference periods are chosen:

- the first two weeks of December for the winter period Figure 4. 20
- the first two weeks of July for the summer period Figure 4. 21

Within these selected time intervals, a more in-depth examination is conducted, focusing exclusively on electricity, heating and cooling demand. This detailed analysis aims to provide a better understanding of the situation during these seasons, in contrast to the annual period shown in Figure 4. 19.

We should note that EUReCA's heating demand peaks at the peak of electricity produced by the photovoltaic system (during daylight hours). During nighttime hours, however, EUReCA's heating demand tends to decrease because non-residential buildings turn off the heating system (only the residential sector contributes to the heating demand). Moreover, for the residential sector, a set-back temperature is set during the nighttime hours, and this allows for a lower heating energy demand during the nighttime hours in scenario 4 (EUReCA) than in scenario 2 (EUReCA – adapted).

On the other hand, we can see that UrbanHeatPro curve is more gradual and the heating system is not completely shut down during the nighttime hours and, as a result, it is necessary to heat the buildings during these hours when there is no electricity production by the photovoltaic system. The gradual trend of the curve is related to the fact that different buildings activate the heating system at different hours.

As for the cooling season, the Figure 4. 21 shows a zoom of the fisrt two weeks of July on the demand for electricity, heating and cooling during this period. Regarding the heating demanded during the cooling season, we can observe that it does not affect the results much since it's negligible compared to the heating produced during the winter season and also compared to the values of the cooling energy demanded. As for the cooling required during the cooling season, in fact, we can observe that it is mainly covered by the compression chiller in the first scenario and only by GSHP in the second scenario.

Additionally, in scenario 4, a substantial MW capacity of photovoltaic panels is installed to meet the electricity demand during the winter to power GSHP systems (see Figure 4. 18). Of course, the excess electricity generated, which is considerable during the summer months, is sent to the grid, resulting in economic gains. Specifically, in scenario 4 (EUReCA) 11802 MWh is sold to the grid, while in scenario 3 only 2023 MWh is sold to the grid: this means that the revenues are strongly higher in scenario 4 than in scenario 3.

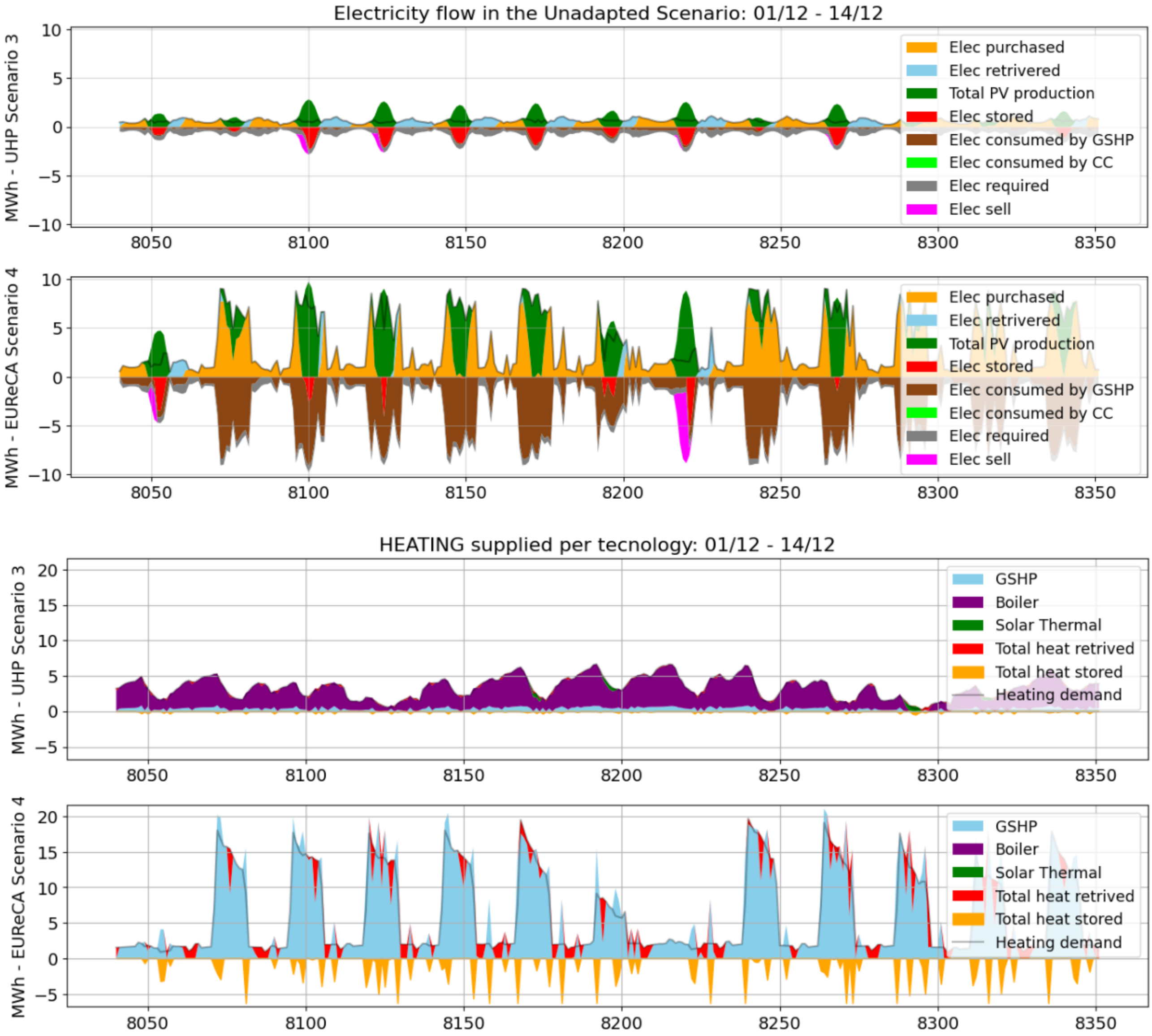


*Figure 4. 20: Hourly electricity and heating supplied per technology during the first two weeks of December. Scenario 3 (UHP ) and 4 (EUReCA)*

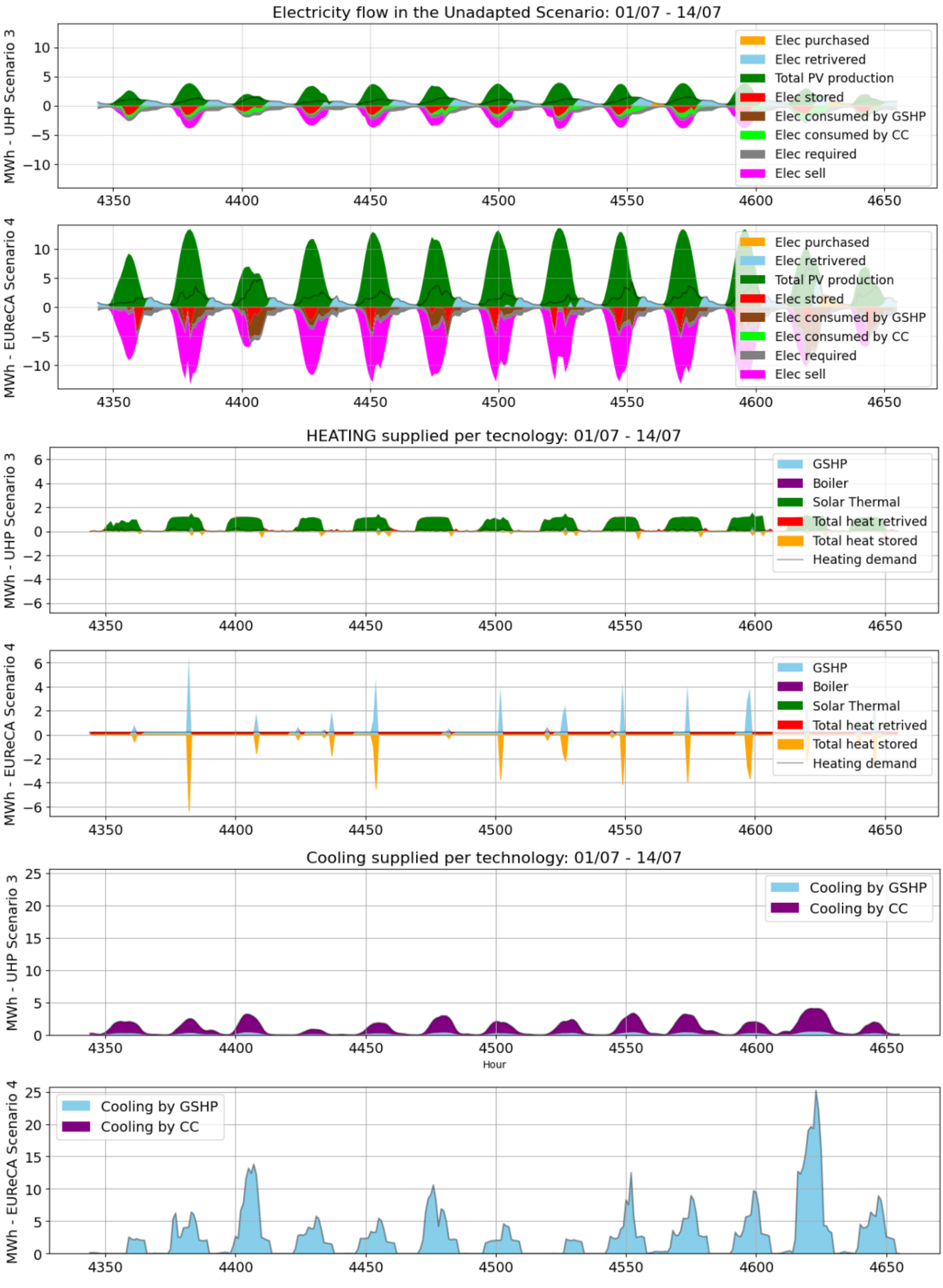


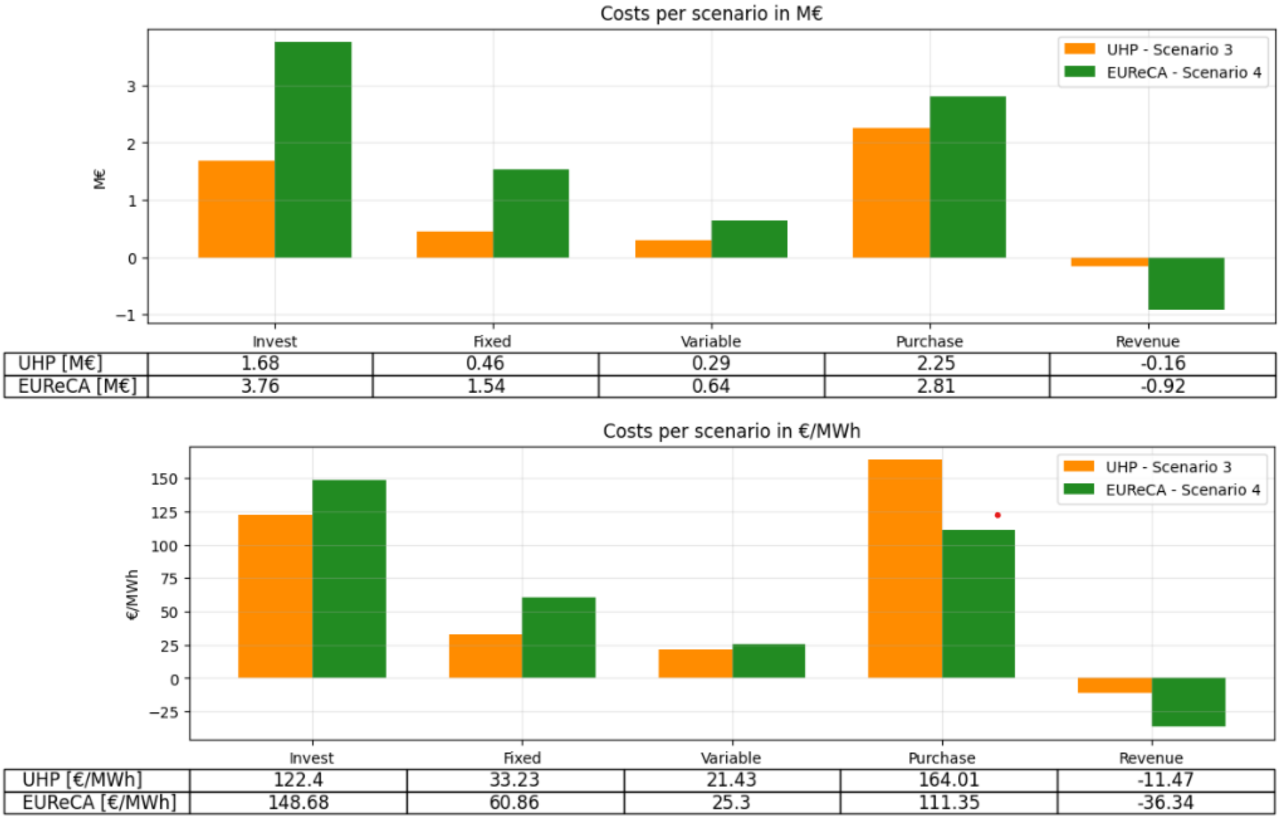
*Figure 4. 21: Hourly electricity, heating and cooling supplied per technology during the first two weeks of July. Scenario 3 (UHP ) and 4 (EUReCA)*

In Figure 4. 22 are reported the annual costs. In particular, the investment costs in scenario 3 represent the 35.9 % of the total cost, while in scenario 4 they represent the 42.9 %: here the total demand is higher than in scenario 3 and the investment costs for the GSHP are higher.

Figure 4. 22 shows both M€ and M€/MWh costs (obtained by dividing the previous value by the total demand of UrbanHeatPro in scenario 3 and EUReCA in scenario 4): in this way we can compare the annual costs considering also the fact that EUReCA has twice the energy demand.

In scenario 4 the amount of gas required is zero (because only the boiler requires gas) and the amount of electricity required decreases because the efficiency of GSHP is better than that of condensing boilers: this means that the purchasing process has less impact in scenario 4 (32.2 %) than in scenario 3 (48.1 %).

As for revenues, it should be considerd that in scenario 4, a significant MW capacity of photovoltaic panels has been installed and, as a result, more electricity is produced and sent to the grid, resulting in economic gains.



| | Invest | Fixed | Variable | Purchase | Revenue |
|---|---|---|---|---|---|
| UHP [M€] | 1.68 | 0.46 | 0.29 | 2.25 | -0.16 |
| EUReCA [M€] | 3.76 | 1.54 | 0.64 | 2.81 | -0.92 |

| | Invest | Fixed | Variable | Purchase | Revenue |
|---|---|---|---|---|---|
| UHP [€/MWh] | 122.4 | 33.23 | 21.43 | 164.01 | -11.47 |
| EUReCA [€/MWh] | 148.68 | 60.86 | 25.3 | 111.35 | -36.34 |

*Figure 4. 22: Annual costs in M€ and in M€/MWh per scenario – unadapted models*

Furthermore, urbs returns the total emissions of $CO_2$ emissions of the boiler and electricity purchased from the grid. In particular:

*Table 4. 5: Emissions of $CO_2$ in the scenarios 3 (UHP) and 4 (EUReCA)*

| | [$tCO_2$] | | [$tCO_2$/GWh] | |
|---|---|---|---|---|
| | Scenario 3 | Scenario 4 | Scenario 3 | Scenario 4 |
| Boiler | 1679 (85.4 %) | 0 (0 %) | 122 (85.4 %) | 0 (0 %) |
| Purchased | 288 (14.6 %) | 1627 (100 %) | 21 (14.6 %) | 64 (100 %) |
| Total emissions | 1967 (100 %) | 1627 (100 %) | 143 (100 %) | 64 (100 %) |

From

Table 4. 5 it can be seen that the total amount of the emissions in scenario 4 is 56% lower than in scenario 3. This is due to the fact that the total boiler emissions decrease by 100% with the higher share of GSHP. On the other hand, the emissions from the purchasing process increase significantly, but less than the decrease in boiler emissions.

It is clear that in scenario 4, even if the energy demand is higher, the emissions remain lower (see the [$tCO_2$/GWh] column in [

Table 4. 5]). This can be attributed to the presence of GSHP, which effectively reduces emissions. C Consequently, by using EUReCA's cooling and heating demands as inputs, we obtain lower CO2 emissions, as Urbs favors the use of GSHP to meet heating and cooling requirements.

# Conclusion

In conclusion, the detailed analysis of the EUReCA and UrbanHeatPro models has brought to light several noteworthy considerations that warrant further investigation:

- Level of Data Detail: it is evident that EUReCA requires a significantly higher level of detail compared to UrbanHeatPro, especially in defining key parameters such as occupancy and internal loads. The reliance of UrbanHeatPro on random data enhances its scalability, allowing efficient simulations of cities with a large number of buildings. In contrast, EUReCA, due to its need for more in-depth information, requires a longer simulation time, reducing its scalability compared to UrbanHeatPro.
- Impact of Mechanical Ventilation: a crucial aspect that emerges is the significant influence of mechanical ventilation on results, both for heating and cooling. The absence of this component in UrbanHeatPro necessitates immediate implementation to improve the accuracy of simulations compared to the real behavior of buildings.
- Differences in Definitions: the diversity in definitions of internal loads and occupancy levels between the two models can lead to disparities in results. The risk of underestimating internal loads for non-commercial buildings in UrbanHeatPro is particularly noteworthy. A revision of the random ranges assigned for residential and non-residential loads could contribute to greater consistency with EUReCA data.
- Optimization through urbs: the analysis of optimization using URBS reveals divergent hourly curves for EUReCA and UrbanHeatPro. While EUReCA suggests the effectiveness of geothermal heat pump use in reducing emissions, UrbanHeatPro leans towards more traditional systems, generating a higher level of emissions for the same amount of energy produced. Model harmonization is therefore essential before comparing optimal strategies.

For the future, a number of strategic steps are proposed to improve the effectiveness and applicability of the models: the integration of mechanical ventilation into the UrbanHeatPro model is considered crucial to achieve a more accurate simulation of heating and cooling demand. Immediate implementation of this component is recommended to address existing gaps in the model's representation of real-world building behaviour.

It is also suggested that an expansion of the conditioning component within UrbanHeatPro is advocated. Currently limited to the residential sector, this modelling aspect should be extended to a wider range of building types. A comprehensive approach is considered essential to avoid distortions in consumption, especially when benchmarked against the EUReCA model. This extension should contribute to a more nuanced understanding of energy use in different building categories.

Consistency in the optimization processes is also crucial. Harmonization of models has been identified as a prerequisite to facilitate meaningful and accurate comparison during the optimization phase. Alignment of methodologies and parameters is proposed to ensure that results derived from UrbanHeatPro are directly comparable to those from EUReCA, allowing for a more informed decision-making process.

Beyond harmonization, exploration of specific contexts is proposed to identify when results generated by UrbanHeatPro are more applicable than those from EUReCA. This analysis is expected to provide valuable insights into the strengths and limitations of each model in different scenarios, guiding their optimal use.

In essence, these strategic steps are aimed at refining the accuracy of the models, tailoring them to their specific applications and addressing observed divergences in the simulations. The ultimate goal is to provide more reliable and applicable results, thereby promoting advances in building energy design and optimization practices.

# Bibliography

[1] M. R. Allen, O. P. Bude and W. Solecki, “Global Warming of 1.5 °C-Chapter 1,” IPCC, 2022.

[2] IPCC, “Climate Change 2007: Mitigation of Climate,” 2007.

[3] Statista, “Statista.com,” 2007. [Online]. Available: https://www-statista-com.eaccess.tum.edu/.

[4] BS EN 12831, “Energy performance of buildings - Method for calculation of the design heat load,” BSI Standard Publication, 2017.

[5] BS EN ISO 13790, “Energy performance of buildings - calculation of energy use for space heating and cooling,” BSI standard Publication, 2008.

[6] A. Zarrella, E. Prataviera, P. Romano, L. Carnieletto and J. Vivian, “Analysis and application of a lumped-capacitance model for urban building,” *Sustainable Cities and Society,* 2020.

[7] L. Swan and I. Ugursal, “Modeling of end-use energy consumption in the residential sector: A review,” *Renewable and Sustainable Energy Reviews,* 2009.

[8] L. Frayssinet, L. Merlier, F. Kuznik, J.-L. Hubert, M. Milliez and J.-J. Roux, “Modeling the heating and cooling energy demand of urban buildings at city,” *Renewable and Sustainable Energy Reviews,* 2017.

[9] H. Harb, N. Boyanov, L. Hernandez, R. Streblow and D. Muller, “Development and validation of grey-box models for forecasting thethermal response of occupied buildings,” *Energy and Buildings,* 2016.

[10] A. Molar-Cruz and T. Hamacher, “A GIS-based gray-box approach for the estimation of the heat demand at the urban scale,” Technical University of Munich - Chair of Renewable and Sustainable Energy Systems, Munich, Germany, 2019.

[11] DIN V 18599-2, “Energy efficiency of buildings - Calculation of the net, final and primary energy demand for heating, cooling, ventilation, domestic hot water and lighting - Part 2: Net energy demand for heating and cooling of building zones,” Deutsches Institut für Normung, Berlin, 2018.

[12] IWU, “Typology Approach for Building Stock Energy Assessment - Calculation Method,” Institut Wohnen und Umwelt GmbH (IWU), https://episcope.eu/building-typology/country/de/, Darmstadt, 2013.

[13] BS EN ISO 13786, “Thermal performance of building components - Dynamic thermal characteristics - Calculation method,” BSI Standards Publication, 2017.

[14] UNI/TS 11300-2, “Prestazioni energetiche degli edifici - Parte 2: Determinazione del fabbisogno di energia primaria e dei rendimenti per la climatizzazione invernale, per la produzione di acqua calda sanitaria, per la ventilazione e per l'illuminazione in edifici,” UNI - Ente Italiano di Normazione, 2019.

[15] J. Dorfner, “urbs,” 18 july 2023. [Online]. Available: https://urbs.readthedocs.io/en/latest/#.

[16] J. F. F. C. Dorfner, “Open Source Modelling and Optimisation,” PhD thesis, Munich, 2015.

[17] OpenStreetMap, “OpenStreetMap.org,” 2004. [Online]. Available: https://www.openstreetmap.org/#map=6/48.676/13.436.

[18] Bayerisches Landesamt für Statistik, “Census database of the census 2011 from Federal Statistical Offices,” https://ergebnisse.zensus2011.de/?locale=en#, 2018.

[19] VDI 3807-1, “DE: Verbrauchskennwerte für Gebäude - Grundlagen; EN: Characteristic consumption values for buildings - Fundamentals,” VDI Verein Deutscher Ingenieure e.V., 2013.

[20] VDI 3807 - 2 , “DE: Verbrauchskennwerte für Gebäude - Verbrauchskennwerte für Heizenergie, Strom und Wasser; EN: Characteristic consumption values for buildings - Characteristic heating-energy, electrical-energy and water consumption values,” VDI Verein Deutscher Ingenieure e.V., 2014.

[21] E. Prataviera, P. Romano, L. Carnieletto , F. Pirotti, J. Vivian and A. Zarrella, “EUReCA: An open-source urban building energy modelling tool for the efficeint evaluation of cities energy demand,” *Renewable Energy,* 2021.

[22] EnergyPlus, “Funded by the U.S. Department of Energy’s (DOE) Building Technologies Office (BTO),and managed by the National Renewable Energy Laboratory (NREL).,” 2001. [Online]. Available: https://energyplus.net/weather-location/europe_wmo_region_6/DEU/DEU_Munich.108660_IWEC.

[23] UNI/TS 11300-2, “Prestazioni energetiche degli edifici - Parte 2: Determinazione del fabbisogno di energia primaria e dei rendimenti per la climatizzazione invernale, per la produzione di acqua calda sanitaria, per la ventilazione e per l'illuminazione in edifici non resi,” BSOL, 2019.

[24] BS ISO 18523, “Energy performance of buildings — Schedule and condition of the building, zone and space usage for energy calculation,” BSI Standard Pubblication, 2018.

[25] BS EN 15232, “Energy Performance of Buildings,” BSI Standard Pubblciation, 2017.

[26] Bundesministeriums der Justiz und des Bundesamtes für, “Arbeitszeitgesetz,” Bundesministeriums der Justiz und des Bundesamtes für, Berlin, 1994.

[27] Zensus datenbank, “Zensus datenbank,” 2011. [Online]. Available: from https://ergebnisse.zensus2011.de/#StaticContent:091840148148,BEG_1_6_1,m,table.

[28] VDI 2078, “DE: Berechnung der thermischen Lasten und Raumtemperaturen (Auslegung Kühllast und Jahressimulation); EN: Calculation of thermal loads and room temperatures (design cooling load and annual simulation),” VDI Verein Deutscher Ingenieure e.V., 2015.

[29] DIN 1946, “DE: Raumlufttechnik - Teil 6: Lüftung von Wohnungen - Allgemeine Anforderungen, Anforderungen an die Auslegung, Ausführung, Inbetriebnahme und Übergabe sowie Instandhaltung,” Deutsches Institut für Normung., Berlin, 2019.

[30] B. A. a. J. P. Jentsch M.F., “Climate change future proofing of buildings – Generation and assessment of building simulation weather files.,” Energy and Buildings, 2008.

[31] International Energy Agency, “The Future of Cooling: Opportunities for energyefficient air conditioning,” https://www.iea.org/reports/the-future-of-cooling, 2018.

[32] M. R. F. R. A. H. Z. N. M. S. Tauseef Aized, “Energy and Exergy Analysis of Vapor Compression Refrigeration System with Low-GWP Refrigerants,” Energies, 2022.

[33] Directive 2005/32/EC, “Directive 2005/32/EC of the European Parliament and of the Council,” *Official Journal of the European Union,* 2005.

[34] S. B. Harish Satyavada, “A Novel Modelling Approach for Condensing Boilers Based on Hybrid Dynamical Systems,” Machines, 2016.

[35] A. B. M. A. K. M. R. A. Md. Akhter Jamil, “Underground Soil and Thermal Conductivity Materials Based Heat Reduction for Energy Efficient Building in Tropical Environment,” *Indoor and Built Environment,* 2015.

[36] ,. K. P. Sivasakthivel.T, “Potential Reduction in CO2 Emission and Saving in Electricity by Ground Source Heat Pump System for Space Heating Applications - A Study on Northern Part of India,” *Procedia Engineering,* 2012.

[37] D. M. Peters, T. Steidle, H. Hebisch, J. Skok, A. Berg, D. Graef and F. Anders, “TECHNIKKATALOG KOMMUNALE WÄRMEPLANUNG Version 1.0,” KEA Klimaschutz- und Energieagentur Baden-Württemberg GmbH, https://www.kea-bw.de/waermewende/wissensportal/technikkatalog, 2022.

[38] BS EN 9806, “Solar energy - Solar thermal collectors - Test methods,” BSI Standards Publication, 2017.

[39] Solcast, “SOLCAST a DNV company,” 2015. [Online]. Available: https://toolkit.solcast.com.au/historic/async/653c8ee2-b2e9-4248-81b1-800a133e8093/download.

[40] L. O. T. H. Smajil Halilovic, “Integration of groundwater heat pumps into energy system optimization models,” *Energy,* 2022.

[41] BS EN ISO 6946, “Building components and building elements - Thermal resistance and thermal transmittance - Calculation methods,” BSI Standard Pubblication, 2017.

[42] BS EN ISO 10077-1, “Thermal performance of windows, doors and,” BSI Standard Pubblication, 2017.

[43] BS EN ISO 14683, “Thermal bridges in building construction - Linear thermal transmittance - Simplified methods and default values,” BSI Standard Pubblication, 2017.

[44] BS EN ISO 10211, “Thermal bridges in building construction - Heat flows and surface temperatures - Detailed calculations,” BSI Standard Pubblication, 2017.

# Appendix A: tables of input data

*Table A. 1: U-Values from TABULA for residential buildings*

| U-value residential building (No refurbishment) | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ROOF | | | | WALL | | | | FLOOR | | | | WINDOW | | | | DOOR | | | | THERMAL BRIDGE | | | |
| Constr | SFH | TH | MFH | AB | SFH | TH | MFH | AB | SFH | TH | MFH | AB | SFH | TH | MFH | AB | SFH | TH | MFH | AB | SFH | TH | MFH | AB |
| <1859 | 2.6 | 0 | 2.6 | 0 | 2 | 0 | 2 | 0 | 2.9 | 0 | 0.88 | 0 | 2.8 | 0 | 2.8 | 0 | 3 | 0 | 3 | 0 | 0.1 | 0 | 0.1 | 0 |
| 1860- | 1.3 | 0.77 | 1.3 | 1.3 | 1.7 | 1.7 | 2.2 | 1.7 | 0.88 | 0.88 | 0.88 | 0.88 | 2.8 | 2.7 | 2.7 | 2.8 | 3 | 3 | 3 | 3 | 0.1 | 0.1 | 0.1 | 0.1 |
| 1919- | 1.4 | 0.65 | 1.4 | 0.65 | 1.7 | 1.7 | 1.7 | 1.4 | 0.77 | 0.77 | 0.77 | 0.77 | 2.8 | 2.8 | 2 | 3 | 3 | 3 | 3 | 3 | 0.1 | 0.1 | 0.1 | 0.1 |
| 1949- | 1.4 | 0.65 | 1.08 | 1.08 | 1.4 | 1.2 | 1.2 | 1.2 | 0.78 | 1.29 | 1.33 | 1.29 | 2.8 | 2.8 | 3 | 3 | 3 | 3 | 3 | 3 | 0.1 | 0.1 | 0.1 | 0.1 |
| 1958- | 0.8 | 0.51 | 0.51 | 0.51 | 1.2 | 1.2 | 1.2 | 1.2 | 1.08 | 1.08 | 1.08 | 1.08 | 2.8 | 2.8 | 3 | 3 | 3 | 3 | 3 | 3 | 0.1 | 0.1 | 0.1 | 0.1 |
| 1969- | 0.5 | 0.51 | 0.51 | 0.51 | 1 | 1 | 1 | 1.1 | 0.77 | 0.77 | 0.77 | 0.77 | 2.8 | 2.8 | 3 | 3 | 3 | 3 | 4 | 4 | 0.1 | 0.1 | 0.1 | 0.1 |
| 1979- | 0.5 | 0.5 | 0.43 | 0 | 0.8 | 0.8 | 0.8 | 0 | 0.65 | 0.65 | 0.65 | 0 | 4.3 | 2.8 | 3 | 0 | 3 | 3 | 4 | 0 | 0.1 | 0.1 | 0.1 | 0 |
| 1984- | 0.4 | 0.4 | 0.36 | 0 | 0.5 | 0.6 | 0.6 | 0 | 0.51 | 0.51 | 0.51 | 0 | 3.2 | 2.8 | 3 | 0 | 3 | 3 | 4 | 0 | 0.1 | 0.1 | 0.1 | 0 |
| 1995- | 0.35 | 0.35 | 0.32 | 0 | 0.3 | 0.6 | 0.4 | 0 | 0.4 | 0.45 | 0.4 | 0 | 1.9 | 1.6 | 1.9 | 0 | 2 | 2 | 2 | 0 | 0.1 | 0.1 | 0.1 | 0 |
| 2002- | 0.25 | 0.2 | 0.2 | 0 | 0.3 | 0.3 | 0.25 | 0 | 0.28 | 0.28 | 0.32 | 0 | 1.4 | 1.3 | 1.4 | 0 | 2 | 2 | 2 | 0 | 0.05 | 0.05 | 0.05 | 0 |
| >2011 | 0.2 | 0.2 | 0.2 | 0 | 0.28 | 0.28 | 0.28 | 0 | 0.35 | 0.35 | 0.35 | 0 | 1.3 | 1.3 | 1.3 | 0 | 1.8 | 1.8 | 1.8 | 0 | 0.05 | 0.05 | 0.05 | 0 |

*Table A. 2: U-values from TABULA for non-residential buildings*

| U-Value non-residential builings (No refurbishment) | | | | |
|---|---|---|---|---|
| Construction | ROOF | WALL | FLOOR | WINDOW |
| <1918 | 1 | 2 | 1.2 | 2.9 |
| 1919-1976 | 1 | 1.5 | 1.2 | 2.9 |
| 1977-1983 | 0.45 | 1.2 | 0.85 | 2.9 |
| 1984-1994 | 0.3 | 0.85 | 0.4 | 1.9 |
| >1995 | 0.3 | 0.35 | 0.4 | 1.3 |

*Table A. 3: Air change flow rate from TABULA for residential and non-residential buildings. n_air refers to the air change rate due to the opening/closing of the windows, while n_use refers to the infiltration through the building elements*

| Air change flow rate residential buildings | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | n_air [vol/h] | | | | n_use [vol/h] | | | |
| Construction year | SFH | TH | MFH | AB | SFH | TH | MFH | AB |
| <1859 | 0.4 | 0 | 0.4 | 0 | 0.2 | 0 | 0.2 | 0 |
| 1860-1918 | 0.4 | 0.4 | 0.4 | 0.4 | 0.2 | 0.2 | 0.2 | 0.2 |
| 1919-1948 | 0.4 | 0.4 | 0.4 | 0.4 | 0.2 | 0.2 | 0.2 | 0.2 |
| 1949-1957 | 0.4 | 0.4 | 0.4 | 0.4 | 0.2 | 0.2 | 0.2 | 0.2 |
| 1958-1968 | 0.4 | 0.4 | 0.4 | 0.4 | 0.2 | 0.2 | 0.2 | 0.2 |
| 1969-1978 | 0.4 | 0.4 | 0.4 | 0.4 | 0.2 | 0.2 | 0.2 | 0.2 |
| 1979-1983 | 0.4 | 0.4 | 0.4 | 0 | 0.2 | 0.2 | 0.2 | 0 |
| 1984-1994 | 0.4 | 0.4 | 0.4 | 0 | 0.2 | 0.2 | 0.2 | 0 |
| 1995-2001 | 0.4 | 0.4 | 0.4 | 0 | 0.2 | 0.2 | 0.2 | 0 |
| 2002-2009 | 0.4 | 0.4 | 0.4 | 0 | 0.1 | 0.1 | 0.1 | 0 |
| >2011 | 0.4 | 0.4 | 0.4 | 0 | 0.1 | 0.1 | 0.1 | 0 |
| Air change flow rate non-residential buildings | | | | | | | | |
| Construction year | n_air [vol/h] | | | | n_use [vol/h] | | | |
| <1918 | 0.4 | | | | 0.2 | | | |
| 1919-1976 | | | | | | | | |
| 1977-1983 | | | | | | | | |
| 1984-1994 | | | | | | | | |
| >1995 | | | | | | | | |

*Table A. 4: Windows orientation ratio from TABULA*

| EAST | | | | | SOUTH | | | | | WEST | | | | | NORTH | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SFH | TH | MFH | AB | Non-residenti | SFH | TH | MFH | AB | Non-residenti | SFH | TH | MFH | AB | Non-residenti | SFH | TH | MFH | AB | Non-residenti |
| 21% | 0% | 26% | 45% | 34% | 41% | 57% | 32% | 5% | 16% | 23% | 0% | 26% | 45% | 34% | 15% | 43% | 16% | 5% | 16% |

*Table A. 5: Number of floors, groud floor area and reference floor area from TABULA.*

| | NUMBER OF FLOORS (TABULA) | | | | GFA (TABULA) | | | | REFERENCE FLOOR AREA (TABULA) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Construction | SFH | TH | MFH | AB | SFH | TH | MFH | AB | SFH | TH | MFH | AB |
| <1859 | 2.561404 | 0 | 3.895282 | 0 | 85.5 | 0 | 173.8 | 0 | 219 | 0 | 677 | 0 |
| 1860- | 1.813538 | 1.6 | 3.035019 | 5.064142 | 78.3 | 60 | 102.8 | 163.7 | 142 | 96 | 312 | 829 |
| 1919- | 2.091097 | 2.242063 | 2.429022 | 3.751264 | 144.9 | 50.4 | 158.5 | 395.6 | 303 | 113 | 385 | 1484 |
| 1949- | 1.389237 | 1.847291 | 1.780282 | 4.534653 | 79.9 | 81.2 | 355 | 353.5 | 111 | 150 | 632 | 1603 |
| 1958- | 1.044905 | 2.532468 | 3.222451 | 8.464721 | 115.8 | 46.2 | 971 | 459.2 | 121 | 117 | 3129 | 3887 |
| 1969- | 1.135916 | 1.740558 | 2.164282 | 6.151852 | 152.3 | 60.9 | 216.7 | 540 | 173 | 106 | 469 | 3322 |
| 1979- | 2.589928 | 1.479452 | 2.633911 | 0 | 83.4 | 73 | 248.3 | 0 | 216 | 108 | 654 | 0 |
| 1984- | 1.992032 | 2.28164 | 3.119487 | 0 | 75.3 | 56.1 | 249.4 | 0 | 150 | 128 | 778 | 0 |
| 1995- | 1.447212 | 2.870906 | 2.94325 | 0 | 84.3 | 51.9 | 283.7 | 0 | 122 | 149 | 835 | 0 |

| >2011 | 2002- |
|---|---|
| 1.7 | 1.842105 |
| 2.9 | 2.149929 |
| 4.07 | 3.535109 |
| 0 | 0 |
| 107.8 | 79.8 |
| 67.8 | 70.7 |
| 321.1 | 619.5 |
| 0 | 0 |
| 187 | 147 |
| 196 | 152 |
| 1305 | 2190 |
| 0 | 0 |