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| --- | --- |
| **Deliverable Title** | Geospatial forecast of energy demand on multiple time scales (update of Section 6 and 7) |
| **Working Package** | WP8.4 Renewable Energy communities, smart districts and smart cities to enhance energy self-sufficiency and security in final uses |
| **Task** | T8.4.7 Urban building energy modelling and urban green infrastructures modelling for REC and PED |
| **Responsible Partner** | UNIPD |
| **Involved Partners** | POLITO |
| **Document date** | 25.03.2024 |

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| **Document Control** | | |
| Version | Status | Date |
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|  |  |  |
| 1 | Contributions from PoliTo | 25.07.2024 |

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**Nota**: abbiamo mantenuto la numerazione dei vecchi capitoli dell’ultima Deliverable, in modo tale che questi nuovi contributi siano più facilmente riconducibili al lavoro svolto in precedenza.

In particolare, la sezione 6 presenta gli avanzamenti riguardo il modello 5GDHC, mentre la sezione 7 è stata dedicata al calcolo dei fattori di conversione in energia primaria dinamici.

# Numerical approach to model generic fifth-generation district heating and cooling (5GDHC) networks: inputs, model preparation and preliminary applications

After focusing on the input processing, further development of the UBEM model focuses on the integrated simulation of district energy systems, in particular 5th Generation Heating and Cooling Networks.

## Overview of 5GDHC networks and model framework

Fifth-generation district heating and cooling (5GDHC) networks are nowadays a major urban design tool, capable of supporting and driving the sustainable and energy-efficient transition of entire neighborhoods. These networks represent a shift from traditional district heating methods by utilizing low-temperature heat sources and decentralized heat pumps at individual buildings. 5GDHC networks allow end-users to participate in thermal energy exchange, promoting energy efficiency, electrification and reducing carbon emissions. However, the decentralized and dynamic nature of 5GDHC networks necessitates advanced simulation tools for effective modeling, optimization, and performance evaluation, since the experimental validation of these systems is very complex and often requires high investment costs.

The model developed for simulating 5GDHC networks has the primary objective of simulating the energy flows dynamics within such systems. Key components of the model include:

* **Hourly dynamic simulation**, meaning that the model is able to solve energy and mass balance equations on an hourly basis throughout the year.
* **Modularity**, represented by the ability to add or remove users without altering the simulation logic.

The model, implemented in the MATLAB and Simulink development environment, requires specific input parameters and undergoes several steps, already discussed in previous deliverables and summarized below. Figure 1 summarizes the development phases of the model.

*A diagram of a grid level

Description automatically generated with medium confidence*

*Figure 1 – Model general framework*

#### Phase 1: Inputs definition

* **Weather/Location data**: Hourly outdoor air temperature and physical parameters of the ground.
* **Spatial distribution**: Relative distances between users for analyzing pressure and temperature losses.
* **Users’ thermal profiles**: Hourly energy demand profiles for heating, cooling, and domestic hot water (HCD), including potential waste energy contributions.

#### Phase 2: Model preparation

* **Ground modelling**, that accounts for ground heat losses between the network and the surrounding soil.
* **Grid configuration**, with the aim of evaluating the network's geometry and topology based on input distances.
* **WSHP (Water Source Heat Pump)** modelling, including the coupling between users and customized heat pumps based on peak power requirements and performance curves.

#### Phase 3: Simulation

* **Warmup period**: Initializing variables with a one-week warmup.
* **Hourly simulation**: Calculating energy flows, heat losses, electrical absorption, and network balancing energy.

#### Phase 4: Outputs

* **Global outputs**: Energy balance of the entire network, pumping energy, and general performance indicators.
* **Local outputs**: Performance and interaction trends at individual substations, including temperature profiles and WSHP performance trends.

## Recent developments on inputs definition and model preparation

Recent developments in the research and development of the 5GDHC model have focused on Phase 1 and Phase 2 of the general framework (Figure 1). In particular, two tools were developed to enable communication between the urban-scale energy simulation model (EUReCA) and the 5GDHC model. The first tool allows the results (output) of the EUReCA model to be organized in order to make them usable as input to the 5GDHC model, both from the point of view of thermal load profiles and climate variables. The second tool instead, starting from the geospatial coordinates of selected buildings, makes it possible to assume a simplified and ideal topology of the 5GDHC network. In the general view of the project, in fact, the two models will be able to interact through the exchange of functionalities and data.

The primary objective of these activities has been to create a robust and reliable interface system between different simulation tools involved in the project, implementing data exchange between initially independent simulation tools. This included integrating urban-scale simulation outputs to create efficient inputs to develop the 5GDHC network model. The key tasks outlined are:

1. **Data exchange**, processing urban-scale simulation outputs into 5GDHC model inputs 🡪Tool 1
2. **Grid preliminary configuration**, developing an ideal network topology 🡪Tool 2

The tools developed will interact with Phase 1 and 2 of the 5GDHC model framework, completing the tasks highlighted in Figure 2. The following sections describe the developed functions in detail.

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**Tool 1**

**Tool 2**

*Figure 2 – Model general framework (highlighted activities developed)*

## Interface code for data exchange (Tool 1)

A key step in developing the 5GDHC model was the creation of an interface code that facilitates the seamless integration of urban-scale simulation data with the 5GDHC model. This code performs the following functions:

* **Reading thermal loads** from urban-scale tool, including heating, cooling and domestic hot water load profiles of selected buildings.
* **Climate data reading**, ensuring that the same climate data used for the urban-scale simulation are implemented for subsequent use within the 5GDHC model. This consistency is vital for accurate and comparable results across different simulation stages.
* **Data parsing**, that prepares processed data as input data for the 5GDHC model.

The interface code is designed to read EUReCA data formats and organize them efficiently for use within the 5GDHC model, ensuring that the model had all external inputs available to work on the subsequent simulation of the scenario. The code, developed in the MATLAB environment, is made available on the project repository, together with an application of it to a case study to facilitate understanding (see following sections).

## Code for estimating network topology (Tool 2)

Developing an efficient network topology is crucial for the success of the 5GDHC system and represent a mandatory step to prepare 5GDHC network simulation. A specific code was developed in the MATLAB environment to estimate the optimal/ideal distribution of the network. This tool is able to work out an ideal path of a possible 5GDHC network, based on the geospatial coordinates associated with each building (latitude and longitude), respecting the basic topology that the model will be able to simulate. This topology is represented by a double side-by-side pipe for supply and return of the heat transfer fluid. Key features of this code include:

* **Geographical input processing**, reading geospatial coordinates associated with buildings.
* **Algorithm for shortest path**, implementing an algorithm to identify the shortest path connecting potential new users of the 5GDHC network. This ensures an ideal network layout, consistent with model topology.
* **Output generation**: producing a visual layout for the 5GDHC network, identifying relative distances between utilities and their order in the network.

The core of Tool 2 is the algorithm for finding the minimum linear path that the thermal network would have to cover in order to give all buildings (users) access to the thermal source. The following text box shows the commented MATLAB code implemented within the tool. Starting from an array of coordinates expressed as latitude/longitude pairs, the most efficient closed path to realize the network is searched for. The result, although ideal, represents a starting point for the subsequent design and modelling of the network.

%% Search for the minimum continuous linear path

% The coordinates variable represents the coordinates in latitude and longitude of the points to be considered

% Calculates the Euclidean distance between all points

n = size(coordinates, 1); % Number of points to consider

distances = zeros(n, n); % Array distance initialization

for i = 1:n

for j = 1:n

distances(i, j) = sqrt((coordinates(i, 1) - coordinates(j, 1))^2 + (coordinates(i, 2) - coordinates(j, 2))^2);

end

end

path = 1:n; % I initialize the path as a sequential path

% Calculate the total length of the initial path

total\_distance = sum(distances(sub2ind(size(distances), path, [path(2:end), path(1)])));

improved = true; % flag

while improved % Loop until there is no improvement

improved = false;

% Loops on all possible exchanges of two points in the path

for i = 1:n - 1

for j = i + 1:n

% Calculates path length after exchange

new\_path = path;

new\_path(i:j) = path(j:-1:i);

new\_distance = sum(distances(sub2ind(size(distances), new\_path, [new\_path(2:end), new\_path(1)])));

% If the length of the path after the exchange is shorter, make the exchange

if new\_distance < total\_distance

path = new\_path;

total\_distance = new\_distance;

improved = true;

end

end

end

end

In its current form, the output produced by the tool does not take into account roads and any obstacles in the area. However, its purpose is to provide a reliable and optimized estimate of the distances between buildings in a district, a fundamental parameter for estimating network pumping consumption and heat losses.

The MATLAB code of this tool has been made available on the project repository and a preliminary application to a case study is presented in the following section.

## Case study application: Padova historical centre

The developed interface tools were applied to a case study, represented by the historic centre of Padova. This district represents one of the case studies of the whole project and the urban-scale thermal energy simulation of the district had already been carried out in previous deliverables.

Within the historical centre of Padova, 38 buildings were selected. The neighbourhood is limited to “Via Cadorna” to the east, “Via Santa Maria in Vanzo” to the west, “Via Dimesse” to the north, and “Via Thaon di Revel” to the south. Based on 2011 census, it hosted 375 residents at time. There are different end uses for the buildings in this area, reported in Figure 3.

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*Figure 3 – End use distribution in the area*

By applying Tool 1 it was possible to read the outputs produced by EUReCA to identify building thermal loads and external climatic conditions. By reading and parsing the data, the variables needed for the 5GDHC model were created. Figure 4 gives an example representation of some of the values printed out by Tool 1, including cooling and heating thermal load and outdoor temperature.

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*Figure 4 – Thermal load and outdoor temperature from the case study selected*

On the other hand, the application of Tool 2 made it possible to move from the geo-spatial coordinates of the buildings to a preliminary proposal of a 5GDHC network, identifying an ideal route by minimizing the distances between users. Figure 5 represents the input (a) and output (b) of the application of Tool 2 to the case study of the historical centre of Padova.

  
*Figure 5 – Application of the minimum distance algorithm from geo-spatial data (a) to generate an ideal network (b) for the historical centre of Padova*

## Future developments and next steps

Following the development of the interface and topological estimation codes, these tools were integrated into the 5GDHC model. The integrated model was then subjected to initial testing phases, which included data validation, simulation runs and preliminary results analysis. The initial tests have shown promising results, demonstrating the potential of the developed tools to accurately model the 5GDHC network for the historic center of Padova.

The following steps are planned to further advance the development of the 5GDHC model:

1. **Detailed network design**, with the aim of refining the network topology based on initial simulation results and practical considerations. This step also necessitates that the input data from the urban-scale simulation was accurately read and processed by the 5GDHC model.
2. **Extended simulation testing**, in order to conduct more extensive testing to explore the model potential under various scenarios and conditions. This step will include a careful analysis of results in term of specific KPIs and optimization of input variables.
3. **Case studies extension**, to include tests on different scenarios consisting of urban neighborhood with different characteristics in terms of buildings use and climatic conditions.
4. **Stakeholder review**, and important process to engage with stakeholders to review the proposed network design and gather feedback for further refinement.

# UBEM outputs: focus on transient Primary Energy conversion Factors (PEF)

In the previous deliverable, the introduction of transient Primary Energy Factors (PEFs) in the context of Urban Building Energy Modeling (UBEM) was discussed. The use of PEF is necessary to convert final energy consumption into primary energy, which is a key indicator of a district's overall energy performance. The need for dynamic PEFs is driven by the complex energy interactions in modern buildings, especially those acting as prosumers within interconnected energy distribution networks.

In addition, the third recast of the European Performance of Buildings Directive (EPBD) proposes the utilization of dynamic PEFs for each energy vector when evaluating the energy performance of nearly Zero Emission Buildings (nZEBs). These buildings require a high degree of flexibility in energy demand, necessitating a precise match between energy supply and demand. Previous deliverable also provided the equations for calculating the non-renewable and renewable shares of PEFs, with detailed explanations of the variables involved. With this context, the use of standardized data and assumptions is essential for the accurate calculation of PEFs.

## Example of determination of dynamic primary energy factors: the Italian 2022 data

This section examines a specific case, useful for the purposes of the project, for the determination of dynamic primary energy conversion factors. Part of the contents of this section were presented during the 53rd International Conference AiCARR, 12-14 March 2024 in Milan and are now published in the conference proceedings.

Through the application of one of the methods proposed by the UNI EN 17423:2021 standard, the hourly trend of the primary energy factor for the electric carrier in Italy during the year 2022 was evaluated. As regards the physical boundary for the PEFs calculation, considering the data availability, the whole Italian territory should be retained since more refined and local data of energy import, export and production are not available at sufficiently lower time steps. The results were analyzed in order to obtain the relationship between its renewable and non-renewable shares and how such dynamic factor may be predicted for future time steps. The PEFs obtained were then applied to a case study of a residential building, evaluating the primary energy needs under different final energy conversion scenarios.

The hourly values for the Italian renewable and non-renewable PEFs were obtained for the entire year 2022, and then the total PEF were obtained (see Figure 6).

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*Figure 6 – Time plot of the electricity PEFs for 2022 in Italy and comparison with the static legislative values*

First, it can be observed that the average values are significantly lower than those envisaged by Italian legislation. In fact, the fp,ren,el takes on an average value of 0.34, significantly lower than the 0.47 required by the legislation. Similarly, the value of fp,nren,el has a value of 1.51 which is significantly lower than 1.95 envisaged by the Minimum Requirements Ministerial Decree of 2015. This leads to a value of the total average annual (2022) PEF for electricity of 1.85.

The main objective of this work is to compute PEFs values that can be dynamic and not static, to highlight how these are sometimes higher or lower than the values prescribed by the standard just mentioned. Analyzing the results obtained in Figure 1 that report the time evolution of the 2022 PEFs for electricity in Italy, it can be seen that they have a fairly high fluctuation, not only over the course of the year, but also within the same day.

This leaves room for the possibility of being able to carry out different analyzes from the results obtained in order to exploit the additional knowledge that arises. During the course of the year, there are very few results that exceed the limit of the legislative static total PEF. In fact, the calculated values relating to the total PEF that assume a result higher than 2.42 are only 3, equal to 0.03%.

In order to understand the daily variation, the following box-plot analysis was performed and reported in Figure 7. In the box plots of the renewable (left) and non-renewable (right) PEF, the average annual value assumed by the renewable PEF for each hour of the day, the values of the 1st and 3rd quartile and the two error bars to arrive at to the minimum and maximum values assumed during the 2022 year are reported. For the non-renewable PEFs, it can be observed how the trend of the box plots over the day creates a concavity with the peak at the minimum point identified at midday; this is due to the fact that in the central hours of the day the contribution of renewable sources is greater, mainly given by the large share produced through solar photovoltaic. From 6 pm until midnight the average value assumed by the non-renewable PEF is almost constant and then progressively increases its value up to the maximum that is reached at 6 am.

Similarly, what was observed for the non-renewable PEF is reflected in the renewable one: the curve has a convexity in the central hours of the day, with a maximum at midday. As regards the other hourly values reported, it can be observed how the same constancy of the values taken in the final hours of the day but how this is also present in the first hours of the day.

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*Figure 7 – Box plot of the electricity renewable and non-renewable PEFs for 2022 in Italy*

After having verified that there is a general correlation between the non-renewable PEF and the renewable one, it was decided to carry out a more detailed analysis by representing, through heatmaps created with the Rstudio software, the values of both PEFs for all the days of the year (Figures 8 and 9) trying to find days that could best express a correspondence between the two quantities (nren and ren) and may be studied in detail. The highest values assumed by the non-renewable PEF are found during the night hours and especially in the early hours of the morning (around 6 and 7 am) and to which correspond relatively low values of the renewable PEF. If we instead observe the maximum renewable PEF, they are reached during the central hours of the day, always due to the photovoltaic share reaching the maximum of its electrical producibility, highlighting the presence of days in which very high values of the renewable PEF are reached.

From the two graphs, this is quite evident for the days of 17 and 18 April, in which there are the highest values of the renewable PEF and the lowest values for the non-renewable PEF.

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*Figure 8 –* Heatmap of the electricity renewable PEFs for 2022

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*Figure 9 – Heatmap of the electricity non-renewable PEFs for 2022*

These two days correspond respectively to Easter and Easter Monday 2022. Therefore, from here on, by choosing as a reference the day of 18 April 2022 and the following working day, we will try to find a correspondence between the values assumed by the PEFs and the load profiles of the same days, made available by the data collected by Terna.

Looking at the trends of the renewable and non-renewable PEFs during April 18 and 19 in Figure 10, completely different values and trends can be seen. In fact, taking Easter Monday into consideration (April 18), we observe how the values assumed by the load are relatively low because the production of electricity from renewable sources is able to almost completely cover the energy demand during the central hours of the day, making it necessary to have a low participation of non-renewable sources in the electricity generation process considering the very low load (Figure 11). As regards the non-renewable energy there are very low values during the central part of the day, as a large production of energy from these sources is not necessary, making the corresponding PEF value low.

However, if we observe the day of April 19th, since the values assumed by the load are higher than those of the previous day, we have clearly different PEF values.

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*Figure 10 – Italian electricity loads of two subsequent days in April 2022*

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*Figure 11 – Italian electricity PEFs of two subsequent days in April 2022*

In fact, during daytime hours the energy required takes on higher values, meaning that the production of renewable sources is unable to reach the same percentage of coverage as on 18 April, making it necessary to produce a large amount of energy from non-renewable sources. Consequently, a more constant renewable PEF value is observed throughout the entire day but with lower values than those of the previous day; instead, the non-renewable PEF takes on higher values, as it is responsible for the need to produce the amount of energy to fill the gap between energy produced from renewable sources and the required load.

Applying the methodology proposed by the UNI EN 17423 standard, the renewable, non-renewable and total hourly PEFs of the electricity carrier for Italy in 2022 were determined. The results highlighted a discrepancy between the calculated values and the PEFs currently envisaged by Italian legislation, making clear the need for an urgent reevaluation of these values. In fact, analyzing the dynamic trend of the PEFs, an average value of 1.85 was reached, significantly lower than the value of 2.42 required by Italian legislation, it was observed that only a few values during the entire 2022 are greater than the regulatory value. Consequently, even the renewable and non-renewable fractions, which take on an average calculated value of 0.34 and 1.51, are decidedly lower than what is foreseen by the Minimum Requirements Ministerial Decree of 2015.

It can be deduced that priority should be given to updating the PEFs envisaged by the Minimum Requirements Ministerial Decree of 2015, to be replaced with new factors that are more truthful than those proposed by the legislation, as it is observed that the use of PEFs that are dated compared to those determined in the processed has a huge impact on primary energy consumption.

Then, it is clear that the concept of time-variation of PEFs cannot be neglected, as it allows the additional information deriving from this approach to further optimize and reduce the use of electricity, in accordance with what is described by the 3rd EPBD recast in case of district of buildings and highly interlinked energy networks. The hourly dynamic analysis of PEFs is crucial to understand the daily variability of the conversion factors and to be able to implement optimization strategies aimed at minimizing the primary energy requirement of district of buildings..