PED Energy Hub Design optimisation: the VUB tool to Support Stakeholder Decision-Making

CITIZENS4PED

Extended scope to WP3

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Authors **Reviewers**	A: Olivier Gilmont (VUB/Resolia) / Guangxuan Wang (VUB) / Florine Thiry (Resolia) / Yassine El Alali (VUB) R: Grégoire Wallenborn (ULB) / Julien Blondeau (VUB) / Alessandro Bonifazi (POLIBA) / Laura Grassini (POLIBA) / Vincenzo Basile (BARI)

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Peer reviewed by:

Partner	Reviewer
ULB	Grégoire Wallenborn
VUB	Julien Blondeau
POLIBA	Alessandro Bonifazi

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2. Acronyms table

Acronym	**Definition**
ASHP	Air Source Heat Pump
BAU	Business As Usual
CAPEX	Capital expenses
CHP	Combined Heat and Power
CNC	Carbon Neutrality Check
COP	Coefficient Of Performance
DHW	Domestic Hot Water
DHN	District Heating Network
GSHP	Ground Source Heat Pump
HP	Heat Pump
HT	High Temperature
IRR	Investment Return Rate
LCOH	Levelized Cost of Heat
LT	Low Temperature
MILP	Mixed-Integer Linear Programming
OPEX	Operational expenses
PV	Photovoltaic
SH	Space Heating
TAC	Total Annualised Cost
TES	Thermal Energy Storage
VUB	Vrije Universiteit Brussel

3. Executive summary

The Citizens4PED project aims to transform neighbourhoods into Positive Energy Districts (PEDs) by exploring the interplay between various techno-energetic options and socio-institutional dynamics, within the context of rapidly evolving regulatory and policy frameworks.

VUB and Resolia partners developed a Pareto optimisation tool to assist stakeholders in making informed decisions based on financial capabilities and carbon neutrality objectives. The tool was applied to real cases and living labs, allowing its evolution and adaptation for the PED context.

This task is an extension of the initial WP3 scope to include energy sufficiency investigations, which are essential for achieving PED objectives. The VUB optimisation tool was developed to support the design of energy hubs (heat production centres) and assess the impact of different techno-energetic choices. The tool's novelty lies in its application of Mixed Integer Linear Programming (MILP) for early-stage predesign of PEDs and the related multi-sourcing energy centers.

Simulation scenarios applied to Citizens4PED living labs show that collective decarbonisation is more cost-effective and less CO_2-emissive than individual solutions, and that energy sufficiency is essential to reduce costs and CO_2 emissions, although this impact is reduced in efficient & decarbonized contexts, while it is more significative in high-carbon ones. The virtual PED concept is essential for achieving PED objectives in dense urban areas.

The project also explored the challenges of integrating energy sufficiency into engineering tools and practices. Existing tools like Hysopt and nPro were found to be unable to generate adequate heat load curves, leading to the development of a custom energy sufficiency tool, which is presented at the end of this report.

4. Introduction

When aiming at transforming neighbourhoods into Positive Energy Districts, many techno-energetic options may flood on the stakeholders table, such as possible energy sources, energy distribution options or personal users preferences, often leading to high complexity in choosing the right option to start designing decarbonised energy production centres.

We developed this Pareto optimisation tool to help stakeholders choose amongst various techno-energetic possibilities, with a clear view on the impact of each choice that they are going to make, depending on their financial capabilities and the objectives they want to achieve.

4.1. Context in Citizens4PED project

At the end of 2023, after one year working on the Citizens4PED project, and in particular in WP3 about the district heating subject, we found that we needed to deepen the techno-energetic research more than it was initially planned with the Arteria tool. Indeed, the original focus of WP3 was on the optimisation of the operation of the energy systems selected for the PEDs, without addressing their **design**, which turned out to be an important first step to engage citizens implication and interest. As engagement of local stakeholders is one cornerstone of the Citizens4PED project, we decided to extend the WP3 objectives, as to make this research more thrilling and valuable.

At VUB, a tool was already under development to deliver multi-criteria Pareto fronts to design energy centres. The opportunity to apply it to real cases and living labs allowed for its evolution: the optimisation tool needed to be adapted for the PED context, including energy sufficiency that is fundamental to the Citizens4PED project and has been investigated by Resolia's partners, along with metrics to assess how close a techno-energetic proposition is to achieving PED objectives.

4.2. Tool development and sufficiency investigations

This document is divided into two main research sections.

The first section, § 5, details the entire process and presents the results obtained from the VUB optimisation tool. The complete study results are gathered in a scientific paper[1,] and in Guangxuan Wang's PhD thesis[2], synthetizing his work using Mixed Integer Linear Programming (MILP) for multi-objective optimisation of PED energy solutions.

The second section, §6, examines the integration of energy sufficiency into engineering processes, as incorporated within the VUB optimisation tool.

[1] *Pathways to Positive Energy Districts: A Comprehensive Techno-Economic and Environmental Analysis Using Multi-Objective Optimization*, G. Wang, O. Gilmont, J. Blondeau, *Energies* **2025**, *18*(5), 1134 https://doi.org/10.3390/en18051134

[2] *Optimal design of low carbon, multi-energy systems*, G. Wang, Dec 2024 https://researchportal.vub.be/en/publications/optimal-design-of-low-carbon-multi-energy-systems

5. VUB Pareto optimisation tool

The objective of this tool is to support stakeholders' decision-making when it comes to choosing the technologies to provide heat and electricity for consumers (building, district, city, etc.)

In the district heating vocabulary, we call "energy center" the place (building, basement, …) where the heat/cold is produced, before being distributed to the users, including the technologies used to produce the heat/cold.

Continuous discussions between the VUB tool developer and the Citizens4PED technical partners allowed to understand the needs and expectations of each part, and develop a tool that goes beyond its initial goals.

MILP is a well-established methodology in this field. However, the novelty of our work does not lie in the introduction of new methods, but in the innovative application of MILP to the early-stage planning of PEDs and multi-sourcing energy centres in general.

5.1. Data collection

The first step consists in collecting the input data needed to run the first simulations, per studied district, such as:

- General inputs (information of buildings in the district)
    - Building type (Office,school, residential,etc,.....),
    - Floor area,
    - Construction period (recent vs. older buildings),
    - …
- Energy demands (hourly heating, cooling & electricity demands during the reference year)
- Weather data (hourly weather data during the reference year)
- Technologies (energy conversion or storage technologies available in the district)
- Prices/costs of electricity, energy and potential taxes (CO_2, …)
- Model parameters
- Specific model parameters
    - Grid connection maximum capacity
    - CO_2 emission factor
    - …

Resolia has gathered this data for 2 of the 4 Living Labs in Brussels (Usquare & la Roue). The methodology and the hypotheses behind the data collection are explained in the two following paragraphs.

5.1.1. Usquare

For this living lab, we used the preliminary study carried out by MK engineering, which includes an estimate of the building's energy consumption. This report also includes the choice of design and the technical and financial data associated with this design.

From the "energy demand" point of view, Resolia used that report to establish annual consumption profiles. nPro software was used to generate hourly heat, cooling and electricity profiles based on Belgian weather data (see graph below).

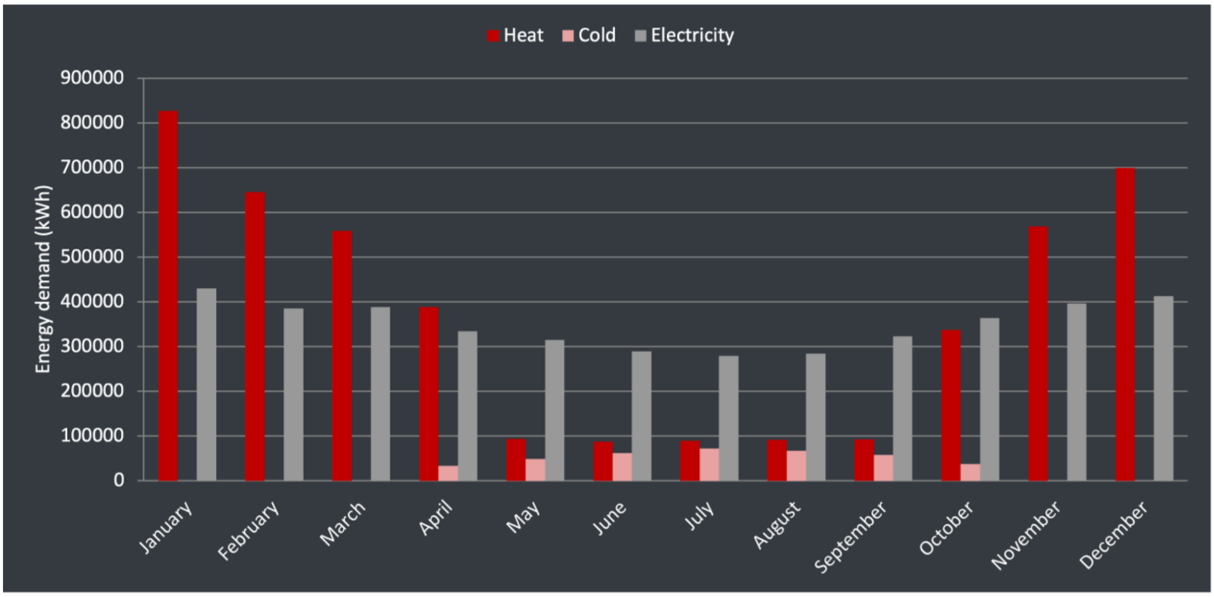


Figure 1: Monthly nPro generated heat, cooling and electricity curves

In terms of technology choices and prices, the values come from the preliminary study mentioned above and from internal Resolia data. However, as the Pareto tool is an optimisation tool, it requires a range of values rather than a fixed one. Therefore, the peak power values in the MK study are considered as a reference scenario around which the optimisation tool can oscillate (e.g. by doubling the number of geothermal probes).

Finally, the energy prices and emission factors were defined with Resolia and VUB.

5.1.2. La Roue

The methodology of this living lab is very similar to the previous one, except that the preliminary report was carried out by Resolia, which made access to data easier and more complete.

NPro was also used to derive consumption profiles from data provided by Sibelga (the operator of the electricity and gas distribution networks in the Brussels-Capital Region).

Finally, several scenarios were developed for the Resolia study (high & low temperature networks) and these were also used as input for the optimisation tool, which was again free to derive its optimised solutions from a previously studied scenario.

Building list Recalculate

Name	Usage type	Number	Floor area	Heat	Cold	Electricity
BB2459	Residential	1	6 504 m²	830 MWh	0 MWh	182 MWh
BB2353	Residential	1	13 040 m²	1 539 MWh	0 MWh	365 MWh
BB2429	Residential	1	6 731 m²	821 MWh	0 MWh	188 MWh
BB2446	Residential	1	2 681 m²	278 MWh	0 MWh	86 MWh
BB2385 (Quid Ecole)	Residential	1	16 050 m²	1 750 MWh	0 MWh	482 MWh
BB908 (Education-Scolaire)	School	1	41 154 m²	3 340 MWh	41,2 MWh	1 358 MWh
BB908 (Sport)	Gym	1	16 912 m²	1 002 MWh	0 MWh	676 MWh
BB908 (Resto)	Restaurant	1	19 577 m²	3 441 MWh	470 MWh	3 152 MWh
BB908 (Bureaux)	Office	1	6 324 m²	426 MWh	0 MWh	398 MWh
BB908 (Bâtiments Commerciaux)	Supermarket	1	1 528 m²	100 MWh	32,1 MWh	202 MWh
BB908 (Dépôt?)	Shopping center	1	1 348 m²	41,8 MWh	13,5 MWh	89 MWh
BB2372 (Res)	Residential	1	13 049 m²	1 532 MWh	0 MWh	365 MWh
BB2372 (Police)	Office	1	140 m²	10,8 MWh	0 MWh	11,9 MWh

Figure 2: example of data used to simulate La Roue district in nPro

5.2. Technological choices

Some technological choices regarding heat generation must be made before starting simulations, depending on the field reality, on political strategies or on stakeholders preferences, which limit the scope of technical options. In particular, the choice of discarding carbon-based technologies could be a logical choice when designing a PED or any other sustainable solution. It can also be included or studied in alternative scenarios, as a baseline to compare to.

Another technical aspect that influences a priori the possible technological choices is the heating temperature need at the consumer's side.

- A (modern) **low heating temperature** need (between 35°C & 55°C) is compatible with all renewable energy sources, and heat pump technologies in particular are well adapted.
    - In well-insulated houses, when the heating needs are low, **no adaptation** is needed to be connected to such a district heating.
    - In insufficiently isolated houses, when the heating needs are medium to high, **adaptation can be needed** to be able to be connected to such a district heating, such as changing the emitters (from traditional radiators to fan coils to improve heat diffusion). Still, for the highest heat needs, even adaptation may not be an option and connection to a low temperature DHN is simply not possible.
- A (traditional) **high heating temperature** need (over ~60°C) is not really compatible with heat pump technologies, as it will result in decreased COP's, discarding de facto their use. In these cases, a biomass boiler appears as a promising renewable alternative, although social acceptance can be more complicated to obtain (local exhaust emissions, biomass transport, …)

5.3. Literature review on PED definition

When we started the cross-work on the VUB optimisation tool with the other Citizens4PED partners, it appeared that a clarification was needed on both sides on how to evaluate a district being a PED objectively. Indeed, one goal is to integrate in the VUB optimisation tool an evaluation of "how far from a PED" each simulation and scenario is. Questions raised were such as:

- How to evaluate a PED energy balance?
- How to achieve the target: Demand response, storage, coupling, energy efficiency… ?
- Which actors benefit from the PED ?
- How to integrate mixed energy uses in PEDs (Elec vs Heat) ?
- Techno-economic trend to achieve PED (Sensitivity analysis)

A literature review has been performed with the aim of, amongst other, refining the evaluation of a PED. Here are the main sources that were used in the VUB optimisation tool development process:

- PED definition from "SET-Plan Action 3.2": *A PED is seen as a district with **annual net zero energy import**, and **net zero CO_2 emission** working towards an **annual local surplus production of renewable energy**.*

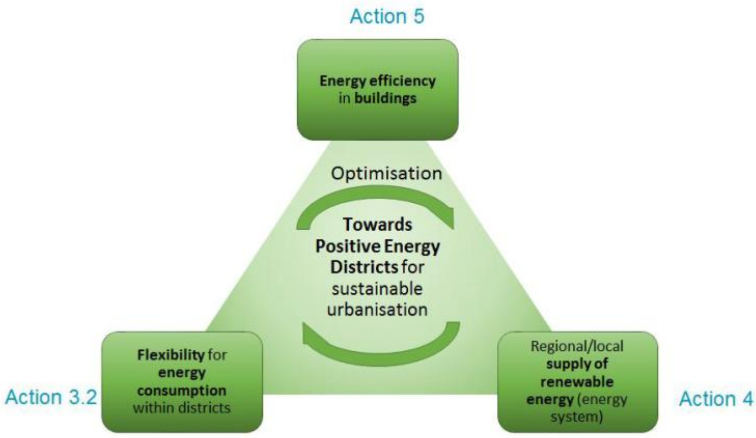


Figure 3: PED Definition form SET-Plan ACTION n°3.2 Implementation Plan, June 2018

- PED boundaries definition from "Positioning Positive Energy Districts in European Cities[3] " allows to enlarge the possibilities of reaching PED objectives by delocalizing some renewable energy sources with the PED Virtual concept. Briefly, these are the 3 possible PED boundaries:
  - **PED autonomous**: no energy import (100% self-sufficient), only local renewable energy surplus export.
  - **PED dynamic**: Bidirectional energy trading with other PEDs + energy import from external grid/heat network + local renewable energy surplus export.

[3] Lindholm, O.; Rehman, H.u.; Reda, F. Positioning Positive Energy Districts in European Cities. *Buildings* 2021, *11*, 19. https://doi.org/10.3390/buildings11010019

- **PED virtual**: same as dynamic + allows renewable energy generation & storage outside the geographical boundaries of the district.

NB: Energy means electricity and/or heat.

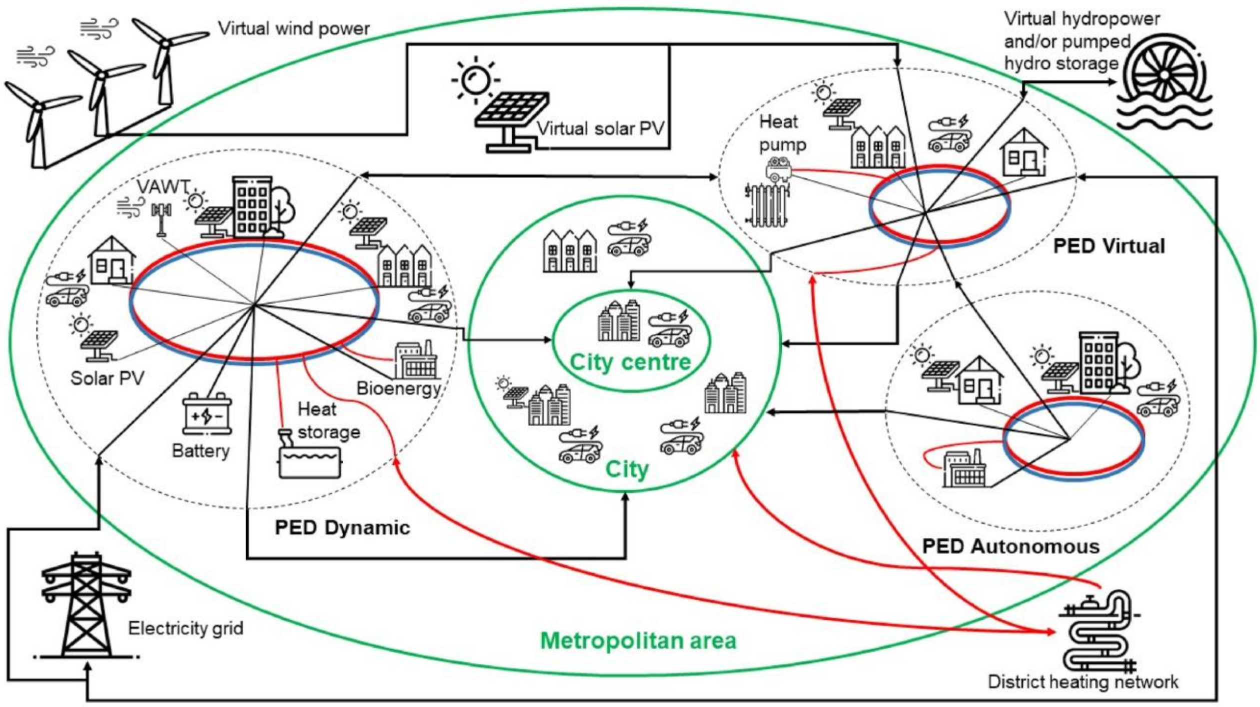
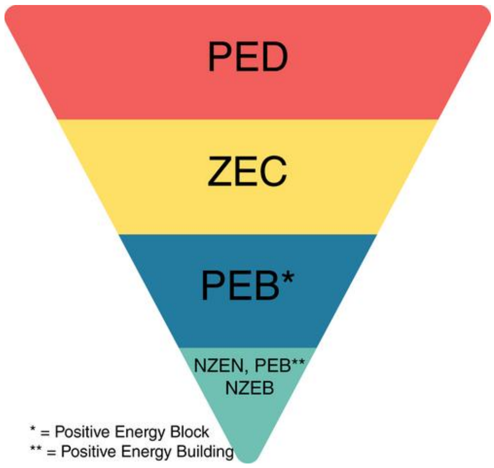


Figure 4: PED boundaries illustration[3]

- Hierarchy of sustainable housing concepts[4], and the place of PED regarding other existing concepts.
    - ZEC: Zero Energy Communities
    - NZEN: Net Zero Energy Neighbourhood
    - NZEB: Net Zero Energy Building



[4] Casamassima et al.,2022

5.4. Choice of metrics to evaluate PED objectives

Firstly, the "PED ratio" metric was proposed and tested in the optimisation tool to assess if the PED objective is reached. It is the ratio between imported and exported energy. When the balance is positive, it means the exported energy is > than the imported energy, meaning the PED objective is reached. On the contrary, PED objective is not reached when the PED ratio is negative.

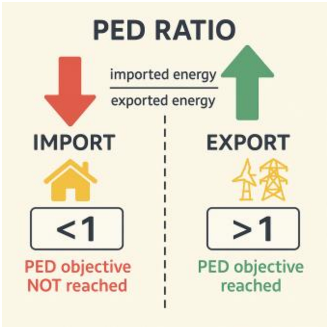


Figure 5: PED ratio illustration

The resulted graph is as follows, where the PED ratio is the blue line:

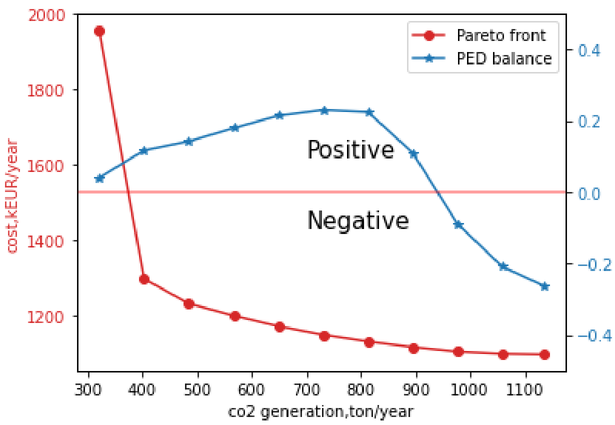


Figure 6: illustration of the PED ratio application to evaluate the Pareto front options regarding PED objectives

A drawback identified on this first metric is the fact that it needs the determination of the value of PEF_grid (Primary Energy Factor), which depends on the proportion of energy allocated to electricity production for the grid. However, calculating this value requires extensive work[5]. **Therefore, this metric to evaluate the results has not been selected for the next steps.**

Instead, in the latest paper by Marrasso et al. (2024)[6], the authors propose using the carbon equivalent emissions method. This method introduces a metric **called the Carbon Neutrality Check**

[5] PEF calculation factsheet in the MAKING-CITY project: MakingCity D4.2 Guidelines

[6] Marrasso et al. (2024) (DOI:10.1016/j.enbuild.2024.114435),

(CNC) and employs carbon intensity data specific to each country across different time horizons. These values can be easily obtained from internet (Nowtricity.com, for example).

$$CNC = \frac{CO_2^{in} - CO_2^{Cred}}{max(CO_2^{in}, CO_2^{Cred})}$$

CO_2^{in}: Carbon emissions imported in the district due to use of electricity from the grid.

CO_2^{Cred}: Carbon emissions credited to the district thanks to production of local renewable electricity, exported outside of the district.

We decided to apply this CNC method for this case study, as shown in the results presented further in this report.

5.5. Usquare (Brussels) case study

For the Usquare living lab, the study results have been gathered in a scientific paper[7] and Guangxuan's PhD thesis, synthetizing his work using MILP for multi-objective optimisation of PED energy solutions.

The main hypotheses and results are gathered here.

5.5.1. Hypotheses and simulation data

Usquare's particularity as a living lab in the citizens4PED project is the fact that its site is already undergoing through heavy transformations:

- building renovation (with and without isolation),
- erection of new buildings,
- implementation of a district heating network with geothermal energy (low temperature)
- mixed-use of the buildings (students housing, social housing, research and university offices, shared spaces, citizens supermarket…)

We thus started from the forecasted situation including the ongoing transformations as the base scenario for the Citizens4PED simulations to reach PED objectives, considering these transformations are already planned and will be implemented, independently from the present project conclusions.

The new heating system of Usquare is composed by:

- a low temperature (50°C/35°C) district heating network, mainly for the new buildings with low heating needs, supplied by the geothermal system, providing about 15% of Usquare heating needs. This network is also used for cooling the connected buildings during summer.

[7] Pathways to Positive Energy Districts: A Comprehensive Techno-Economic and Environmental Analysis Using Multi-objective Optimization, G. Wang, O. Gilmont, J. Blondeau

- a high temperature (70°C/50°C) district heating network for the other buildings (isolated and not isolated), supplied by gas boilers and gas CHP's, providing about 85% of Usquare heating needs.

The new PV installation of Usquare will have a power of 1176kWp, for an estimated annual production of 959MWh.

Here are the final energy demands[7]

Parameter	Peak load kW	Annual demand MWh
Electricity	1188	4201
Space heating (70/50 °C)	2097	2739
Space heating (50/40 °C)	406	569
DHW	328	1170
Cooling	266	379

Figure 7: Energy demand overview of the energy district for one year

Note: The Usquare district heating system's design may have been modified meanwhile, but these changes are not part of the present Citizens4PED study.

5.5.2. Simulations scenarios

BAU (Business As Usual): This scenario can be considered as the one existing before the Usquare renovation project started: gas boilers, no PV, HP for cooling. It is the classical carbonized way of doing things in the last decades.

BASE: This scenario reflects the current proposal under implementation at Usquare: a combination of PV, grid, and natural gas CHP for the electricity demand. Cooling demand is handled by passive cooling, high-temperature heat demand by CHP, BOI, and GSHP, and low-temperature heat demand by ASHP and GSHP.

AddPV: This scenario was built iteratively from the BASE scenario: First, PV capacity was set unlimited (considering the virtual PED theory). Then this PV capability was reduced by iteration and finally set to 5 times the PV capability of the BASE scenario, which is enough to meet carbon neutrality objectives.

Elect.: "Additionally to AddPV, this scenario assumes that all energy demands are met by electrical devices, with no carbon-based (natural gas, …) units allowed. Instead, high-temperature heat pumps, including a geothermal heat pump and an air-source heat pump, are utilized to fulfil high-temperature heat demands."

DSM: "In addition to Elect, this scenario incorporates demand response by shifting electricity demand with a dynamic Time-Of-Use (TOU) tariff."

Flex: In addition to DSM, "this scenario includes battery storage to utilise energy surplus properly."

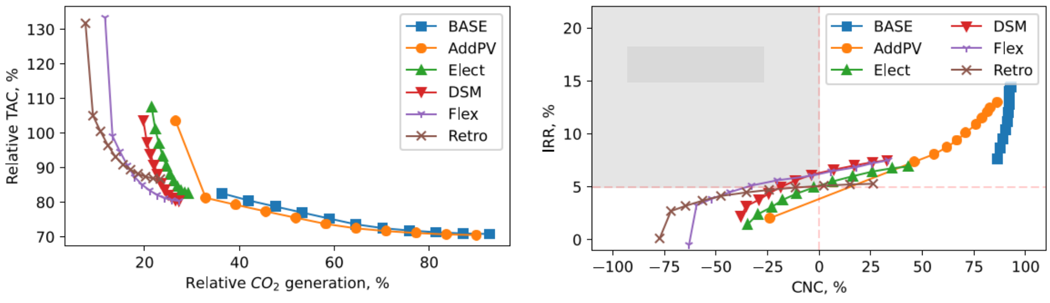
Retro: "In addition to the Flex scenario, this approach involves retrofitting the building envelopes of older structures."

5.5.3. Simulations results

The detailed final results are presented in a scientific paper[7] and in Guangxuan Wang's PhD thesis[2]. It is important to notice that the results presented in the publication and in this report are to be taken as case studies to illustrate the possibilities of the simulation tool: it is possible, on demand, to obtain a wide range of various additional results, graphs, scenarios etc., while adapting the hypotheses, or testing new ones. This has been communicated to the members of other WP of the project that are working with the citizens from the living labs, as to obtain the material they could need for discussions and citizens implication fostering.

The main optimisation results are presented as Pareto fronts: the optimisation tool will show the most interesting solutions inside the limits imposed by the case, with two possible adjustment variables (e.g. Carbon emissions VS TAC, CNC VS IRR,…).

Here is an example of the final results for the above-mentioned scenarios:



(a) Relative cost-emissions Pareto fronts (b) IRR-CNC Pareto fronts

Figure 4: Pareto frontiers for the selected scenarios visualizing as (a) total annual costs and carbon emissions, expressed relatively to the BAU scenario, in BAU scenario, TAC is 1701 k€/year with carbon emissions 1511 ton/year. (b) IRRs and CNC. The grey area shows the solutions can achieve PEDs and project profitability.

It is interesting to observe that the simulation shows that the BASE scenario is far from reaching the PED objectives, and that extra efforts are needed compared to the already planned improvements at Usquare to reach them:

- Multiplying by 5 the PV capability of the district allows to reach carbon neutrality, but it results in significantly higher expenses, leading to lower project profitability.
- Electrification is required to significantly reduce the carbon emissions and finally reach CNC objectives
- Energy sufficiency has not been included in these scenarios, and as for La Roue simulations presented in §5.6, it would help reach at lower cost and with lower carbon emissions the PED objectives.

5.6. La Roue (Brussels) case study

5.6.1. Scenario definitions and choice

For La Roue living lab, prior to the optimisation using the VUB tool, 4 DHN scenarios have been defined and proposed by Resolia to provide decarbonised heat solutions to the neighbourhood. The resulting scenarios sheets are available in appendix 1.

Briefly, 2 main DHN concepts are studied:

- a High Temperature (HT) DHN, which allows to heat the houses directly without modifications inside the buildings, but with more losses on the network.
- A Low Temperature (LT) DHN, which requires small modifications regarding the heat emitters and DHW generation in the buildings, but with reduced losses on the network

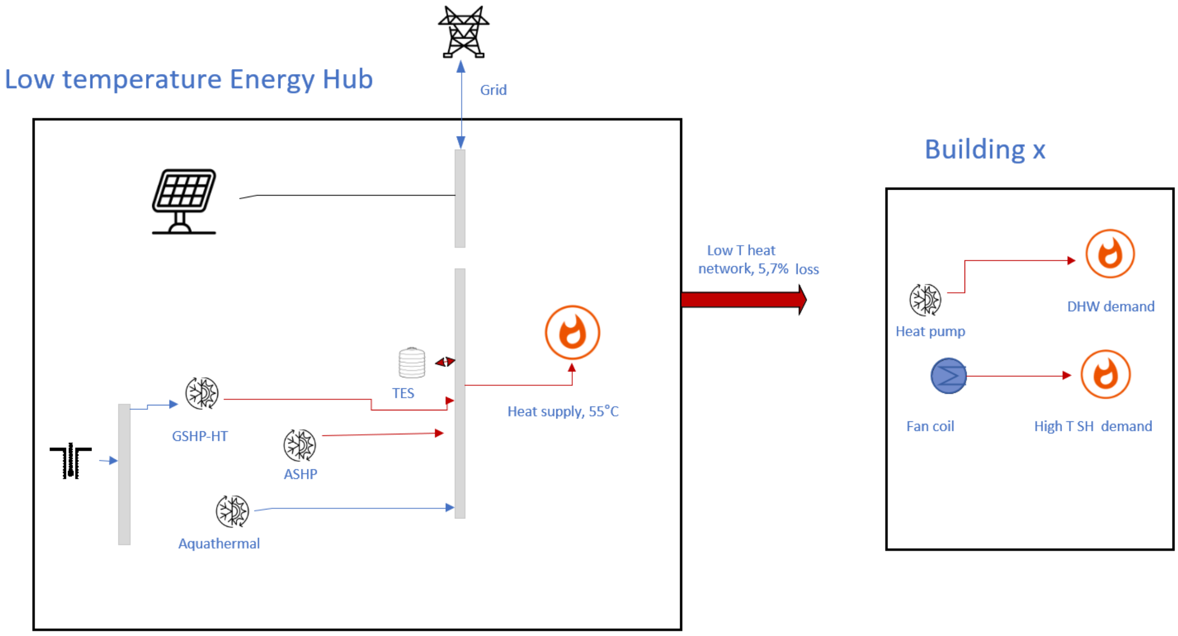
Each of these DHN concept is then investigated for two different scenarios:

- 100% of the district is connected to the network to fulfil its heating and DHW needs
- A part only of the district is connected, composed of its biggest consumers (which Resolia call the “structuring actors”) and the consumers located close to this network.

Note that selecting either the HT or LT network is a prerequisite for the VUB optimisation tool. This choice determines the technologies to be evaluated and the technical solutions to be included and compared during the optimisation process.

For the implementation in the VUB optimisation tool, **we choose to specifically work with the “Low Temperature on 100% of the district” scenario, called “LT Full”.** The other scenarios are still to be tested in the VUB optimisation tool for broader analysis and studies. The choice to start with the LT DHN is based on the preference to push electrification of the heating and autonomy with PV installations instead of relying on biomass boilers, which could have caused some discussions and drawbacks about the gas emissions, the biomass transport & logistics and about the biomass itself as a long-term renewable source.

Modelisation of the LT energy center and of the buildings demand is as follows:



5.6.2. Hypotheses and simulation data

The LT full scenario is composed of

- 1041 buildings
- A yearly heat demand of 34GWh
- A required heating power of 14.3 MW
- Renewable available sources
  - Geothermal energy
  - Aquathermal energy (from the canal)
  - Aerothermal energy
- A 55/35 DHN: water is distributed at 55°C in the district, and comes back to the energy center at 35°C.

Figure 8: Full scenario (100% of the district is connected) simulated in nPro online tool

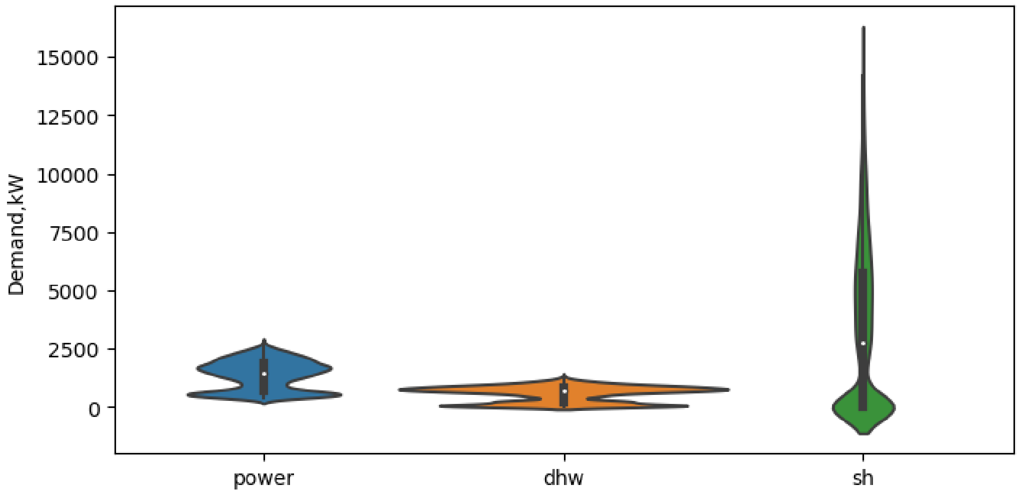


Figure 9: distribution of the total demand in La Roue district (Power = electrical needs; sh = space heating). The largest the figure, the highest the demand at that power.

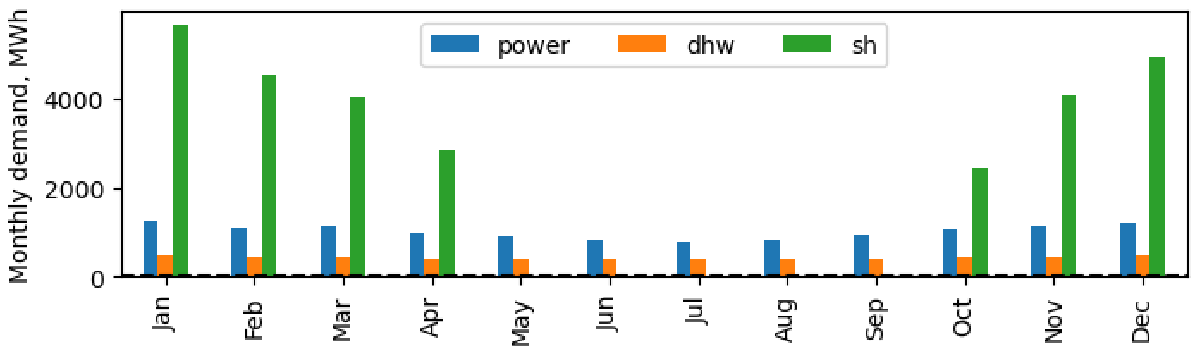


Figure 10: monthly distribution of the demand over one year

The techno-economic specific hypotheses used in the code, gathered from various sources during the citizens4PED project, are to be found in appendix 4. Note that it is a partial extract of the full code.

5.6.3. Simulations scenarios

Ref.: This scenario is the one existing before renovation project started: Gas boilers, no PV, individual HP for cooling. It is the “classical carbonized way of doing” of the last decades.

Individual: This scenario represents the situation where the heating is electrified individually (with individual heat pumps). This represents the “easy & fast way” to decarbonize heating, but we’ll see it is not the optimized way.

BASE (also called “_s0”): The Base scenario is a decarbonisation scenario including following technologies within the capabilities of the district:

- Photovoltaic (18 000 m²)
- heat pumps for geothermal, aquathermal, and aerothermal energy
- LT district heating (heat losses of 5,7%)
- Heating storage
- Grid connection

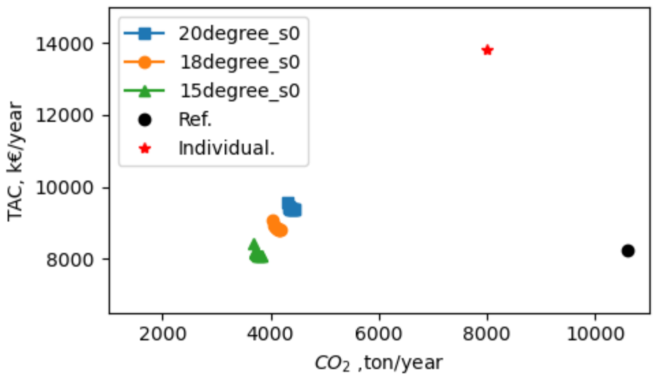
“_pv10”: This scenario extends the BASE scenario by permitting a photovoltaic (PV) capacity, according to the virtual PED theory, that is ten times greater than the PV capability of the BASE scenario.

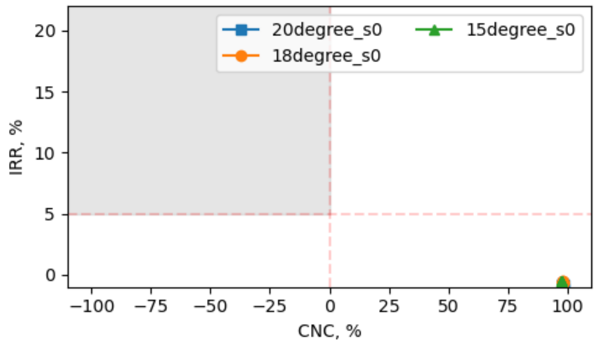
“_pv10_bat”: “Additionally to **“_pv10”**, this scenario considers electrical batteries.

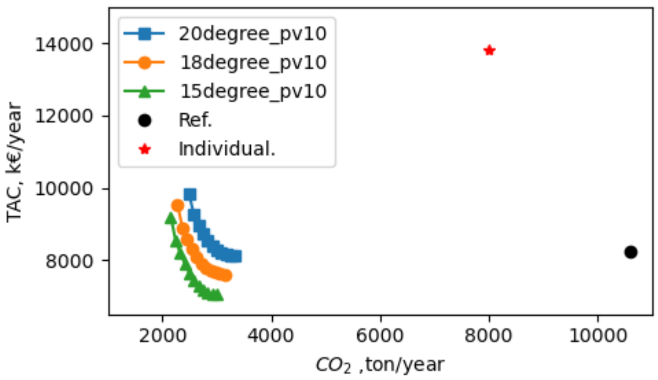
Energy Sufficiency scenarios: The scenarios described hereabove are tested for 3 in-house temperature situations: 20 degrees (BAU), 18 degrees and 15 degrees. Energy sufficiency concepts are explained in §6.

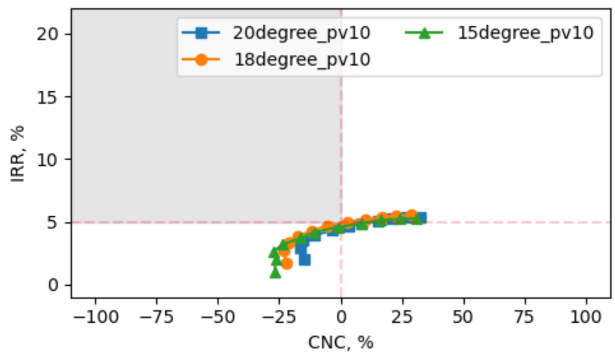
5.6.4. Simulations results

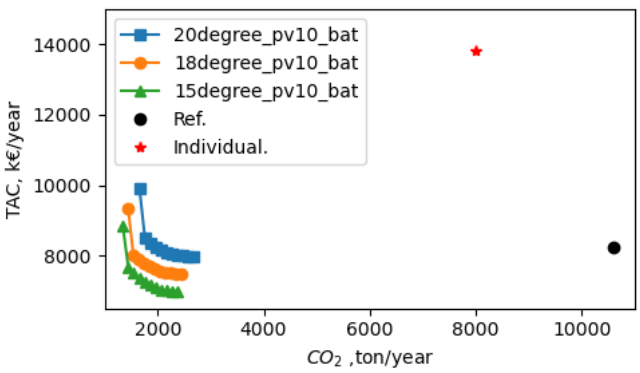
Here are the main results and achievements obtained. As for Usquare, the techno-energetic options are presented as Pareto fronts.

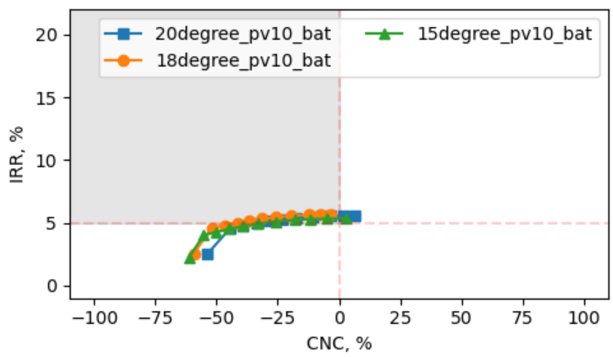












An important observation is that the collective DHN scenarios are always cheaper (on the long term) and less CO_2 emissive than the individual decarbonized scenarios.

Another observation is that reducing heating requirements (energy sufficiency scenarios) does not significantly lower costs or CO_2 emissions. This may be attributed to the fact that these sufficiency scenarios are integrated into decarbonized frameworks, where emissions have already been reduced compared to the reference scenario, and investment costs remain high, nearly independent of energy demands. It can be inferred that the impact of energy sufficiency might be more pronounced when applied to the reference scenario, in which emissions and costs are directly proportional to energy consumption.

Considering the PED objectives, it can be noted that La Roue is unlikely to become a PED based solely on its local capabilities (BASE scenario). Again, the "virtual PED" concept as presented in §5.3 is required to allow, in this case, 10 times more PV surface than possible in the district itself. In this scenario, CNC (see §5.4) reaches 0% or below in some configurations, which is the required condition to be considered a PED.

The results can be presented in various graphs and shapes, as shown here for example:

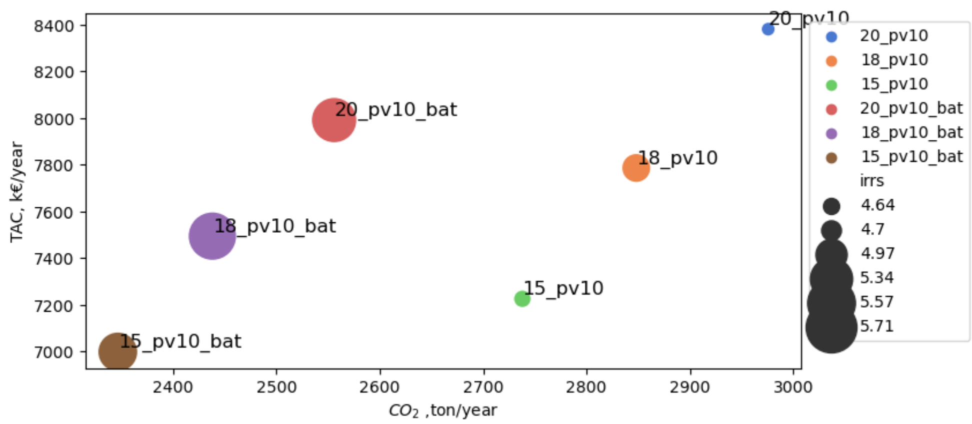


Figure 11: points where CNC=0. The size of the point shows the IRR

The following graph illustrates the possible technological breakdowns per scenario depending on the objective to achieve:

- **Costs**: optimize the costs
- **PEDs**: optimize the CNC
- **Emissions**: optimize the Emissions

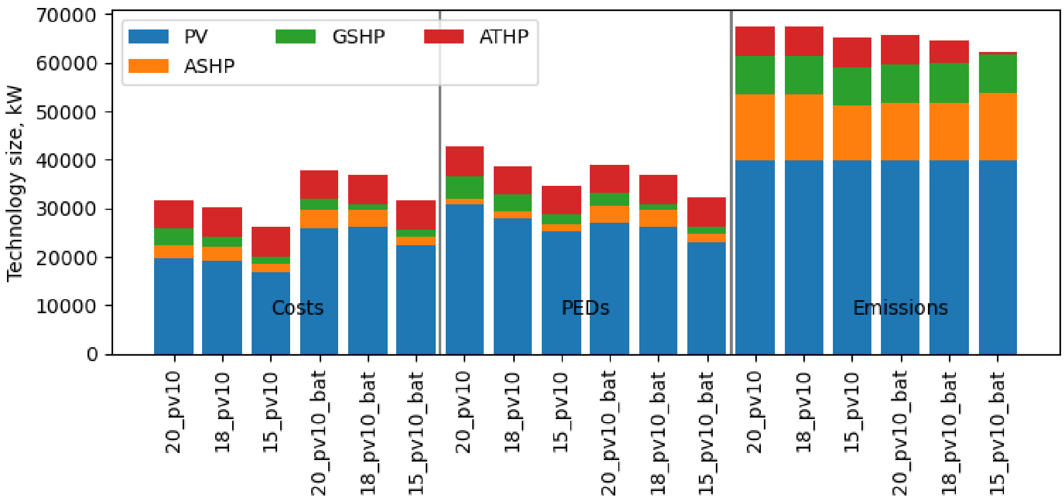


Figure 12: comparison of scenarios technological breakdowns depending on the objective to reach (costs, PEDs, Emissions)

5.7. San Paolo (Bari) case study

The third living lab that was studied using the VUB optimisation tool is the San Paolo district in Bari, Italy. This case study was focused on the comparison of decentralized energy production compared to centralized or community-based energy structures. For this case study two different optimisation methodologies were used. The first one is the same methodology as the one used for the other case studies, where the energy demands for all buildings are aggregated and then optimized at the energy centre within the constraints of each case. This aggregation substantially reduces the simulation time, but at the same time limits the usefulness of the comparative study performed for this living lab, as it reduces the case study to a comparison between more or less options for energy technologies.

To address this limitation, some experimentation was done with the model, including some fundamental changes. Instead of optimizing an aggregated demand with a defined set of devices, the model was adapted to optimize the demands of the individual structures that make up the district (buildings, dwellings etc.), with devices that can be defined individually and dynamically for each of these structures.

Note that this improvement of the VUB optimisation model was identified at the end of the Citizens4PED project, and is still under development.

5.7.1. Scenario definitions and choice

The different scenarios that were compared were the following:

1. **Per Dwelling**: An individualized energy scenario where each dwelling is responsible for its own energy. In this scenario the only option for heating is an air-source heat pump for both heating and cooling and electricity is only available from the grid.
2. **Per Building:** A per-building energy scenario, where each building can have energy systems installed which share energy across the different dwellings within that building. No energy is shared between buildings. A building can be fitted with air-source heat pumps, ground-source heat pumps, and solar panels.
3. **Centralized** (also called **Energy Hub**): A centralized energy hub scenario, with energy sharing for heating, cooling and electricity. To distribute the energy a low-temperature heating district is included. The system options here are air-source heat pumps, ground-source heat pumps, solar panels, thermal energy storage, wind energy and batteries.
4. **Renewable Energy Community**: A scenario where the electricity can be shared within the community, but heating is individualized. The possible technological solutions in this case are solar panels, wind energy, air-source heat pumps, batteries and gas boilers. To have some individualized energy types while others are shared was only possible using the second methodology, which is why this scenario was not included in the first simulations with aggregated demands.

Note that including partial and deep renovation options, applied to varying shares of the building stock, is a future research development to be implemented.

5.7.2. Hypotheses and simulation data

All of the values used in the simulations can be found in appendix 5 (*Bari data_sheet.xlsx)*.

The yearly demand data for residential buildings was partly taken from energy bills (for most non-residential buildings) and partly estimated by the Italian partners, based on data, assumptions and coefficients that had already been used as inputs for the energy planning scenarios included in Deliverable 3.4: this concerns space heating, space cooling, domestic hot water and electricity demands for 752 dwellings.

- For electricity, a demand of 300 kWh/year/person was provided, excluding heating, cooling and domestic hot water;
- For domestic hot water an assumption of 20.9 kWh/m²/year was provided;
- for cooling 37.5 kWh/m²/year;
- for space heating 68.96 kWh/m²/year was used for some buildings and 57.41 kWh/m²/year for others (based on the floor area).

Some additional demand data was also provided for 3 multipurpose buildings in the district (see here under).

The total yearly demands, that are used all along the following simulations, are:

- 6223 MWh for heating
- 2637 MWh for cooling
- 696 MWh for electricity

Name	Floor area	Heat	Cold	Electricity
Residential buildings	68,770 m²	5,759 MWh	2,579 MWh	607 MWh
Church (Chiesa S.G. Bosco)	2,229 m²	0 MWh	0 MWh	22.4 MWh
Casa Delle Culture + In.Con.Tra/Ala Azzurra	7,927 m²	297 MWh	43.6 MWh	32.9 MWh
CAPS	1,200 m²	167 MWh	14.4 MWh	33.7 MWh
Sum	**80,126 m²**	**6,223 MWh**	**2,637 MWh**	**696 MWh**

Figure 13: Demand data as entered in nPro for the San Paolo district in Bari, Italy

Figure 13 shows the demands as entered in nPro tool, for the following users:

- Parish (S.G. Bosco)
- Asylum Seeker Residence and Social Inclusion Facility (Casa delle Culture municipal centre)
- Homeless Support and Social Cooperative Service Centre (CAPS)
- Emergency and Welfare Support Centre (In.Con.Tra. and Ala Azzurra associations)

For the technological solutions, when no other local data was available, the investment and maintenance costs were assumed to be the same as in the LaRoue case. As economies of scale are an important factor in comparing centralized and decentralized systems – the same ratios were used to extrapolate the device costs for small, medium and large installations.

The ambient temperatures and power produced by the solar panels per kWp were obtained from the PVGIS simulation tool, and the wind speeds were obtained from MeteoStat. The total roof area available for solar panels was also provided and was equal to 31096 m².

The low temperature district heating network was modelled to operate at 50°C/30°C, and therefore booster heat pumps were added to reach 60°C for the DHW demand. Because radiators are still the most common heaters in San Paolo, an additional cost was added to convert these units to fan coils, allowing this reduction of the supply temperature. The design of this district heating network is shown in figure 11. The total pipe length was estimated at 3 km.

Figure 14: District heating network design for San Paolo, Bari

5.7.3. Simulations results with aggregated demands

As discussed for the 2 other living labs earlier in this document, the different optimal solutions for the trade-off between CO_2 emissions and total annual cost are presented in Pareto fronts. The first set of results that will be discussed for Bari case are the simulations performed on the aggregated demand, with different options and costs (due to economies of scale) for each scenario.

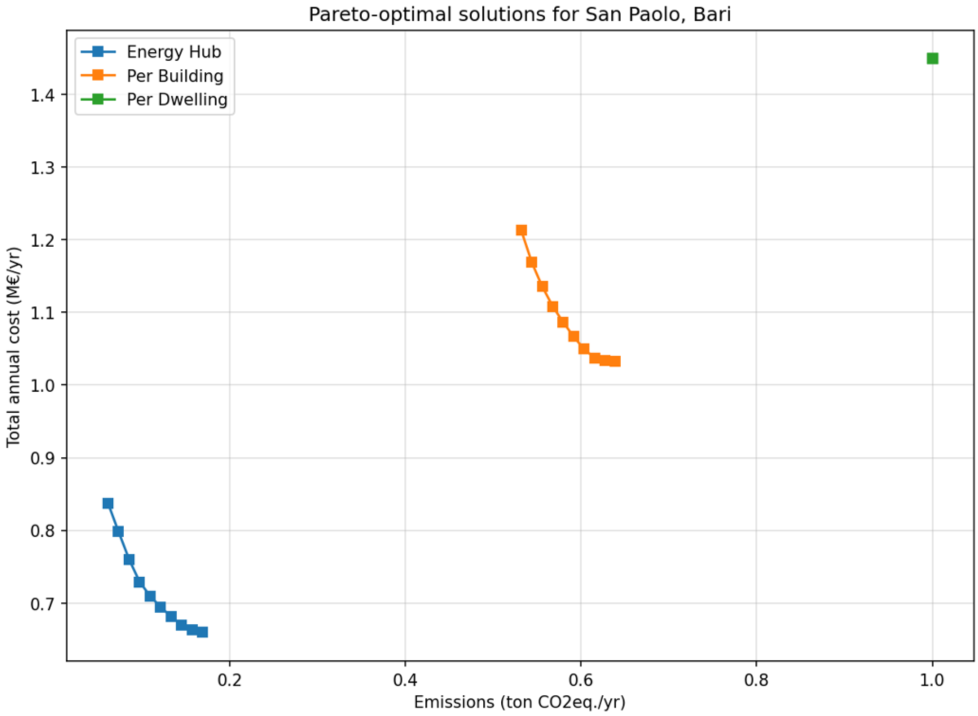


Figure 15: Pareto-fronts for the first three described scenarios (method 1)

The decentralized energy system per dwelling scenario has the highest cost and CO_2 emissions. This is not surprising, as the lack of economies of scale results in higher investment costs and the full dependency on the grid for electricity results in higher CO_2 emissions.

As the options for meeting the energy demands increase when centralizing the energy systems to building-scale – the emissions decrease due to the decreased dependency on the grid. The total annual cost also slightly decreases, but not as much. This is a result of economies of scale and added option of geothermal heating, which provides more efficient heating but also comes with a higher investment cost. As the economies of scale increase even more, and storage options are introduced in the centralized energy hub scenario, the emissions decrease even more, and the total annual cost is almost cut in half. This could be explained by the fact that the optimisation of both the heat and electricity storage results in the best possible use of the captured solar energy, further reducing the dependency on the grid and the required device capacity at any single time. The cost breakdowns of the per-dwelling, per-building and centralised scenarios for the different trade-off points are given in Figure 16. The costs of individualized scenario are only from the air-source heat pumps and the grid electricity needed to power them and meet the demand.

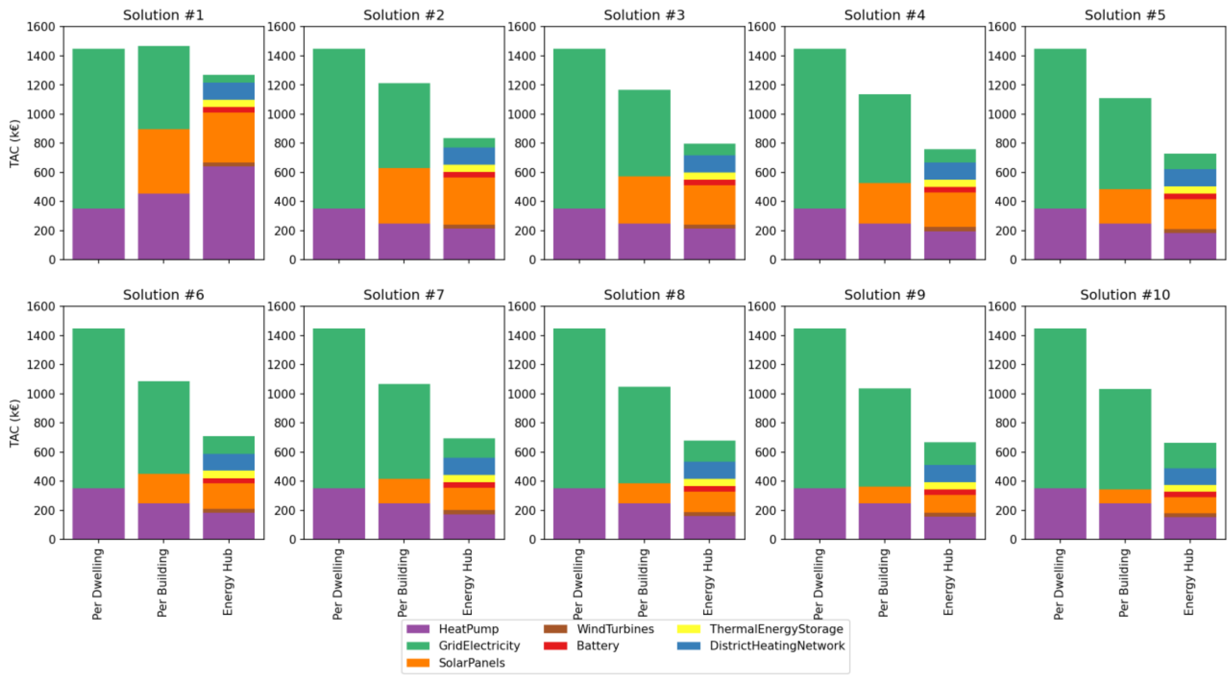


Figure 16: Cost breakdown for each scenario and all Pareto-optimal solutions (method 1)

5.7.4. Simulations results with separate optimisation

For the second methodology that was tested on Bari Living lab, all scenarios were simulated on the level of the building, except for the “Per Dwelling” scenario, which was optimized for each of the 752 dwellings. The optimal solutions are again visualized using Pareto-fronts.

It is clear that the advantage of centralisation within the community, both in terms of CO_2 and total annual cost, is still present in these results even with a fundamentally different optimisation logic. As this methodology was only recently developed at VUB (May-June 2025), it has not been validated yet and has been tested here for . The results however can serve as a useful confirmation of the previous results. The cost breakdown of each is shown in Figure 17.

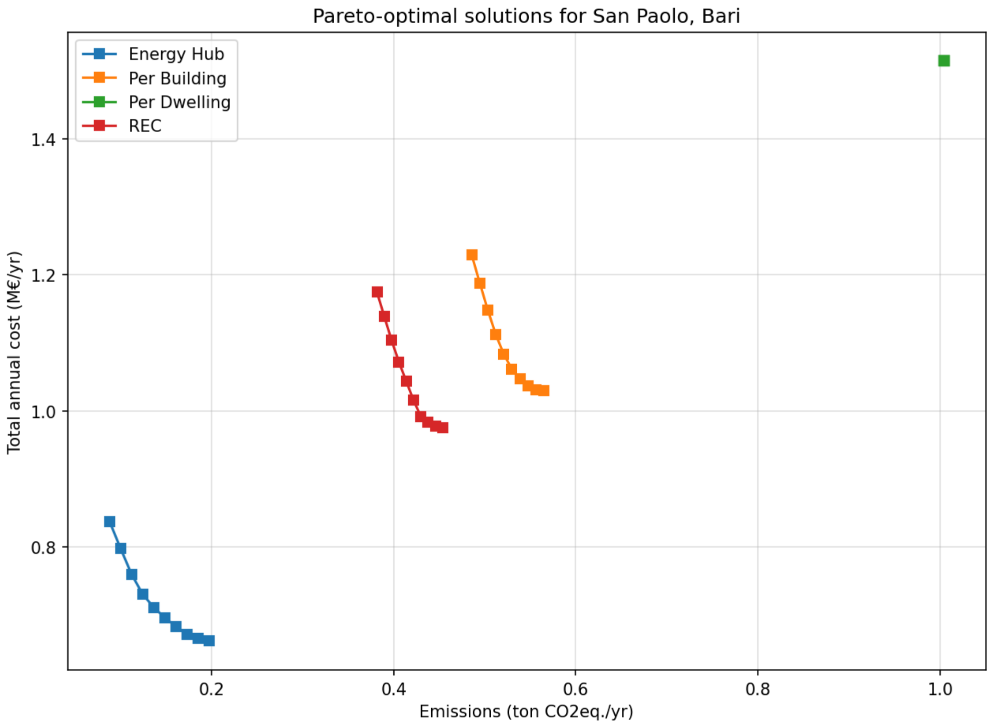


Figure 17: Pareto-fronts for all four described scenarios (method 2)

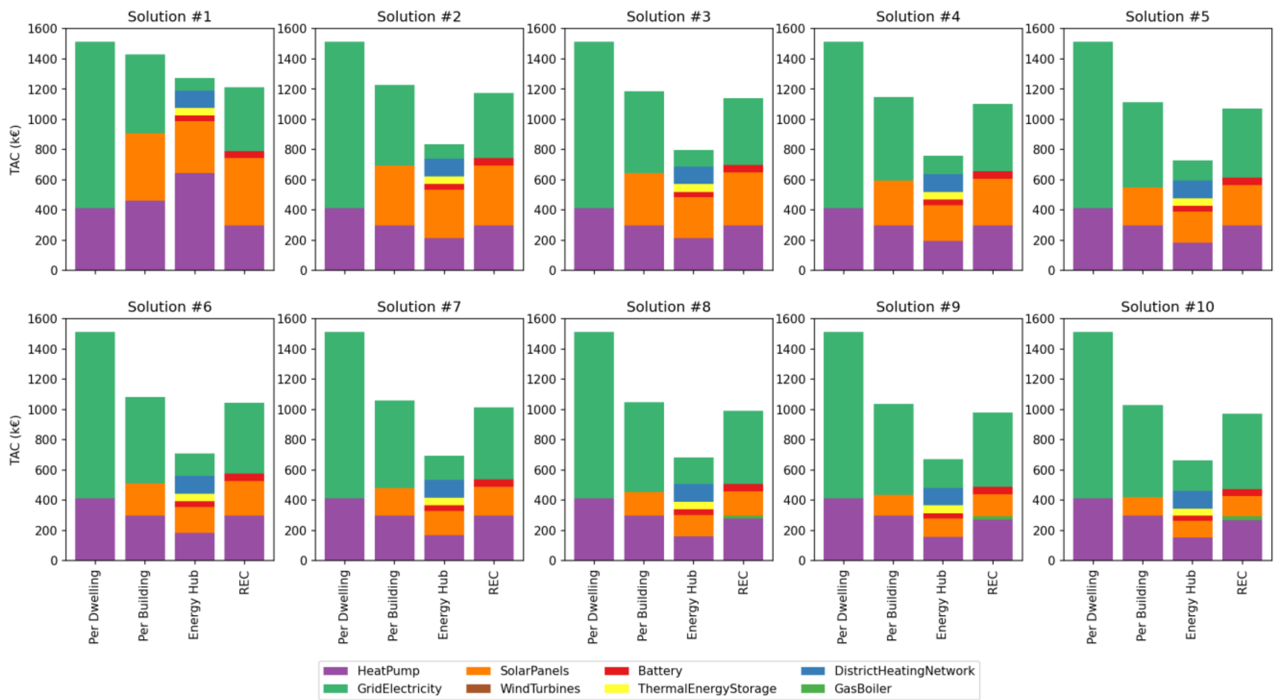


Figure 18: Cost breakdown for each scenario and all Pareto-optimal solutions (method 2)

The agreement between the two sets of simulations shows that the economies of scale on the investment costs have a significant effect on the economic viability of the multi-energy system.

We should also note that the performance of the per dwelling scenario is compromised by the exclusion of deep renovation. This is counterintuitive, as no expert would recommend the installation of heat pumps in poorly insulated buildings—particularly when PV self-consumption is not taken into account. Additionally, the omission of battery storage in the per building scenario is also likely to negatively impact its overall performance, and should be further investigated.

The dynamics and trade-offs between CAPEX and OPEX were also studied to evaluate the feasibility of the different options according to the financial and organisational capacity of actual local stakeholders in more detail.

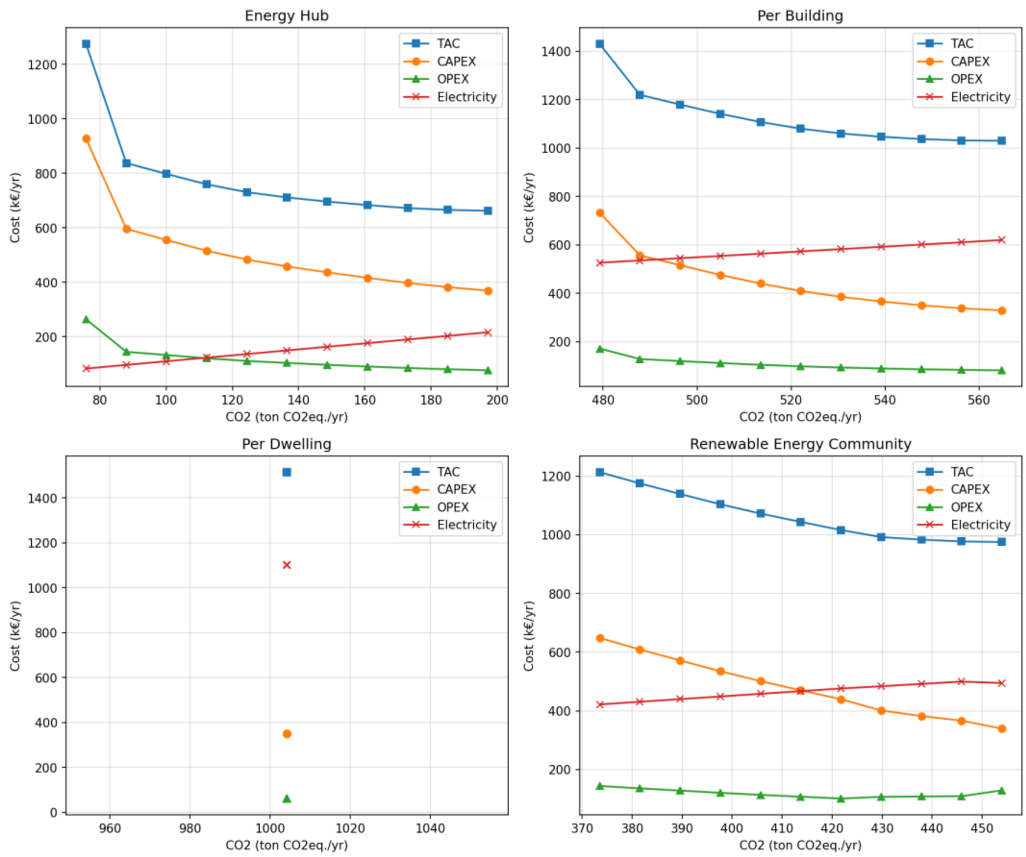


Figure 19: Breakdown of total annual cost for each scenario into CAPEX and OPEX

These results are very interesting and useful to allow an assessment of the potential improvements, should credit to cover the Capex or batteries (to decrease the electricity costs) be available.

These results show that the centralised solution (Energy hub) performs better in terms of CO_2 and total annual cost:

The lower investment costs under all scenarios are very similar, and it corresponds to similar emissions profiles, except for the centralised scenario that secures much lower emissions. On the other hand, the least emitting option under all other scenarios is still much more expensive than the cheapest option under the centralized scenario which, however, emits much less CO2.

6. Energy sufficiency?

In addition to the development of the Pareto optimisation tool itself, we explored the concept of energy sufficiency and the challenges it represents for an engineering company such as Resolia to include it in its district heating designs and simulations.

Energy sufficiency refers to the deliberate and structured reduction of energy consumption. In addition to a decrease, it influences, uses and pushes for a change in behaviour, both on an individual and collective level. It aims to reduce demand, and therefore reduce the strain on renewable sources.

For an individual, this may imply limiting the temperature in your house, for an employee, carpooling to work, for a public authority, developing bicycle paths in a municipality, or for a company, encouraging work from home when possible.[8]

When designing a district heating, demand is rarely questioned (or even never?): A base standardised demand curve is used to dimension the heating plant & the network, and it is implicitly considered that it has to be fulfilled 100% at all times. The "user need" is never taken as parameter nor questioned (e.g. 22°C has to be available at all times, all year long).

Still, an opportunity in the Citizens4PED project is to question this "user need" question, and study its influence with socio-economic parameters on the dimensioning of these district heating technologies.

In particular, we explored the following questions:

What is the influence on **CO_2 emissions** and on the **heating price** (LCOH[9]) when district heating users accept to have a heating system where:

- **Comfort temperature is defined to a lower value** than the standard 22°C (for ex. 20, 18, 16°C)
- Comfort temperature is not changed (still 22°C), but **during X days/year, the guaranteed temperature is lower** (for ex.: 10 days per year at 18°C)
- **Combination of the 2 first points:** Comfort temperature is defined to a lower value than the standard 22°C (for ex. 20, 18, 16°C) AND during X days/year, the guaranteed temperature is lower (for ex.: 10 days per year at 15°C)

Answering these questions will allow to include the users needs into modelling of PEDs, which is an inevitable step to reach PED objectives.

[8] https://www.engie.com/en/news/definition-energy-sufficency

[9] **LCOH (Levelized Cost of Heat)** is the average cost per unit of heat (e.g., €/MWh) produced by a system over its lifetime, including all capital, operation, and maintenance costs, divided by the total useful heat generated. It allows comparison of different heating technologies on an equal economic basis.

6.1. Are Engineers ready for energy sufficiency ?

First of all, it is important to mention that including sufficiency in their studies is not part of the daily work and culture of Engineers. It has been confirmed during various exchanges and discussions inside and outside the Citizens4PED project: Engineers do not want, at first sight, to launch a process of challenging their client's needs, but they are more often engaged in fulfilling their desires by finding and implementing innovative technological solutions. Proposing to challenge their in-house temperature is typically something that is never done by an Engineering company: "*I don't want to propose a system that today provides lower temperatures than yesterday*". After some discussion, however, they would agree that it could be done for the interest of research, and that the stakeholders would accept / be interested in these kind of "questioning the limits" questions.

6.2. Are Engineering tools ready for energy sufficiency ?

Amongst energy sufficiency, we'll discuss building heating solutions in particular, as it is the expertise of Resolia and the main optimisation objective of the VUB optimisation tool. It appeared that energy sufficiency is not a subject that is widely spread nor implemented in the engineering tools. For example, we found no tool able to generate heat load curves where the in-house temperature can be set manually. A default value is used (22°C), and often not even mentioned or showed, as it is not considered part of the discussion: it is taken for granted, as "non debatable".

When it comes to generate heat load curves with a different in-house temperature than the standard 22°C one, it appears one has to develop its own tools and methods because no existing tool allows to do it so far. Typically, we aimed to study the impact on a heating system design and operation when its users decide to heat their houses at 18°C or 15°C, instead of the default 20°C.

6.2.1. Hysopt software

We first took advantage of existing projects at Resolia to investigate the possibility to simulate these situations and generate the required load curves through the ***Hysopt*** software.

Hysopt main function is to optimise hydraulics and components of a HVAC system, and is not initially meant to generate load curves, which is a kind of "by-product". As a simulation tool, it evaluates the system's performance by providing key indicators such as energy consumption and comfort. Though, it is capable of generating load curves and it allows to parameterise almost everything in the district heating system, from the energy center to the users building and usages, including the in-house target temperature. It is thus a very powerful tool, that would allow us to generate reduced temperature load curves with our own parameters.

Unfortunately, Hysopt turned out to be unadapted to do so with the available resources on the project: the precision and complexity level to refine every part of the system is too high (see Figure 8 & Figure 9), and the models developed by Resolia and used as basis for this Citizens4PED research work were not initially designed to produce reduced temperature load curves, resulting in incoherent results in the simulations (negative heat flows at each start, peak load values incoherencies). Moreover, models were also limited to very specific situations (e.g. new build apartments with high level insulation), while investigating other situations would require a lot of adaptation work, making it a non-flexible tool at this point of the project (which is not in line with the Citizens4PED objectives of standardisation and dissemination).

Figure 20 shows how the load curve evolves and which savings in energy consumption are possible, going from 21°C in house to 15°C in house.

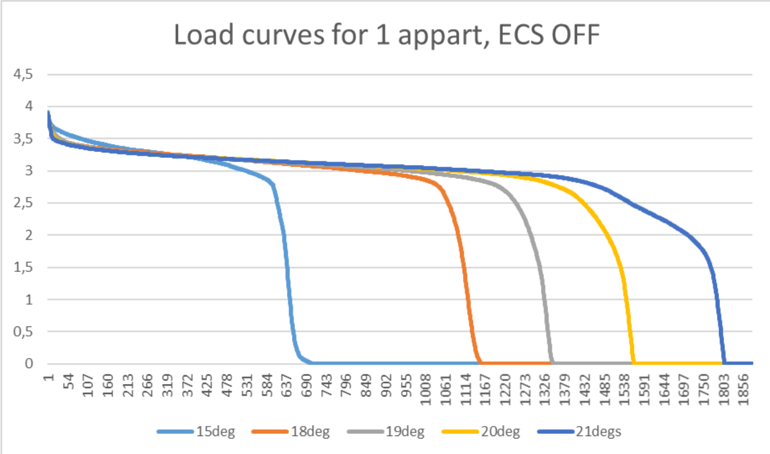


Figure 20: example of promising result obtained with hysopt for reduced temperature load curves, but with some incoherences and limited application scope

Several simulations and upgrade were tested, with very promising results such as the possibility to obtain the normalised level of comfort reached per apartment (see Figure 11), but finally we decided to investigate another way to achieve our goal of generating reduced temperature load curves.

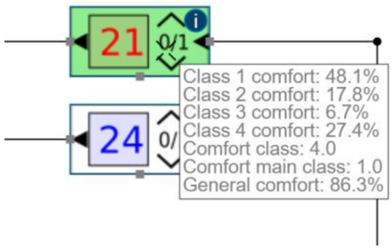


Figure 21: comfort classes generated by Hysopt

Comfort classes definition from hysopt[10] (see the source for full article and further explanations):

The difference between the configured setpoint and the actual temperature is monitored. The degree of temperature deviation is classified into four classes. In this case, the high setpoint is 20°C, which means the limits of all the classes are:

Class 1 = [19,21]
Class 2 = [18,19] and [21,22]

[10] https://hysopt.atlassian.net/wiki/spaces/HRM/pages/3089206518/Pareto+analysis+calculations

Class 3 = [17,18] and [22,23]
Class 4 = [-infinite,17] and [23,infinite]

The limit temperatures always deviate 1°C based on the setpoint. If the user changes the setpoint, the limits change as well.

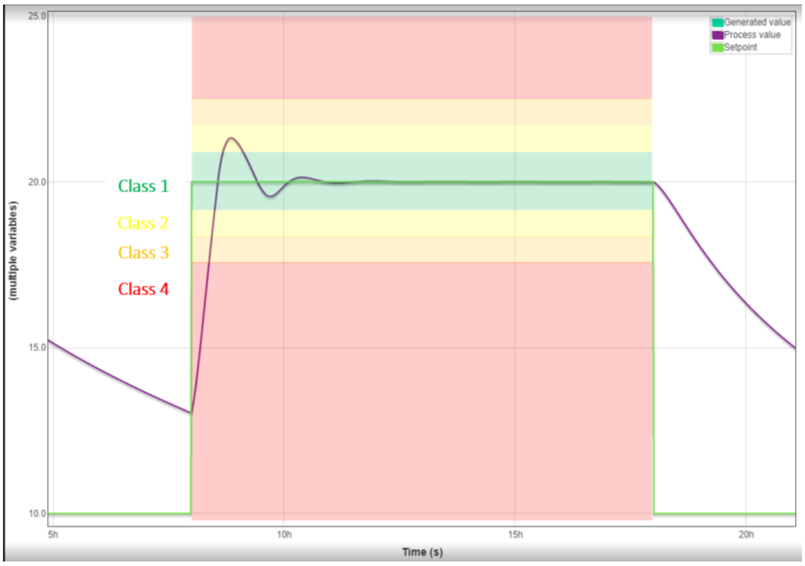


Figure 22: comfort classes definition from Hysopt

6.2.2. nPro Software (Version 2)

nPro offers a complete solution for the design, simulation and optimisation of complex energy systems, integrating advanced functionalities such as heat load curves generation, district heating demand simulation, integration of renewable energies, etc. Its intelligent algorithm makes it easy to optimise the sizing of generators and storage facilities, while its user-friendly interface makes the software intuitive to use. nPro is seen as a complete and reliable tool.

Still, despite all these advanced and multiple functionalities, nPro doesn't allow to define a desired in-house temperature when designing the heating system. Discussions with Marco Wirtz, founder and developer of nPro, allowed to understand that the standard temperature considered in the software is 20°C, and that it is a fixed value, not a parameter that is changeable by the software user.

This is a typical situation: even a tool as flexible and customisable as nPro doesn't consider it useful to leave the in-house temperature as a user choice, but considers it a fixed value not worth discussing.

nPro was useful to generate the base (20°C) load curves (see appendix 2) by introducing several information regarding the living lab situation, building types, … for the Citizens4PED living labs, which were then used as basis to generate reduced temperature load curves, as further explained in §6.3.

Note that version 3 of nPro was issued in October 2024 and has not been used for the Citizens4PED project; version 2 was used.

6.3. Own energy sufficiency tool development

Finally, as we were unable to satisfy our needs with an existing tool, we developed our own "energy sufficiency tool" to generate load curves at non usual in-house temperatures.

Starting from load curves generated by nPro, the idea is to adapt each heating value, based on the outside temperature and the new in-house temperature target. The DHW values are not impacted and does not change. This calculation is explained on Figure 23.

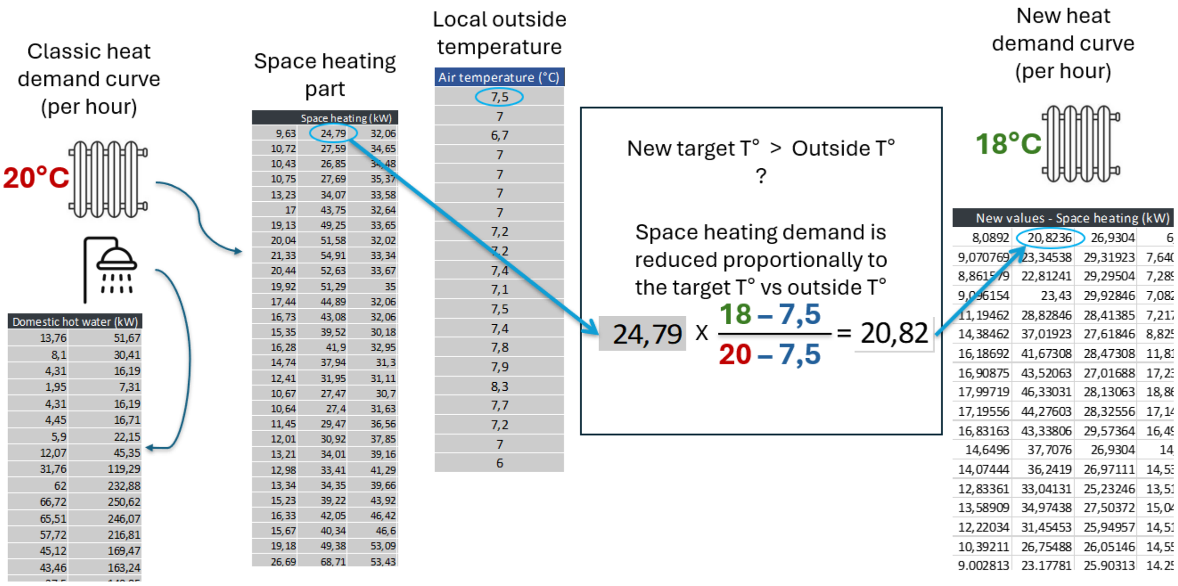


Figure 23: adapted demand curves to new in-house temperature target

This calculation method has been implemented in a "ready-to-use" Excel sheet (appendix 3) where the input data is:

- "classic" Hourly heating needs for a consumer (dwelling, building, district…) under the column "space heating (kW)"
- In-house temperature of these heating needs (G4)
- In-house temperature to be reached in the adapted demand curve (Q4)
- Hourly outside temperature (used as reference to calculate the classic heating needs) (column P)

The resulting new heat demand curve is in columns "*New values - Space heating (kW)*", and can be used as such for simulations in the VUB optimisation tool or Arteria, or other dimensioning or operation simulation softwares. They are showed in Figure 24 & Figure 25 as an example of application of this sufficiency tool for La Roue LT heating demand.

It is noteworthy that e7, a consortium partner, conducts similar hypotheses when designing a heating system. While their methodology yields comparable results, it starts from a different premise: they aim to anticipate future global warming by considering higher outside temperatures. This approach ensures that their system will not be oversized in the future, though it may operate at its capacity limit during the initial years of use.

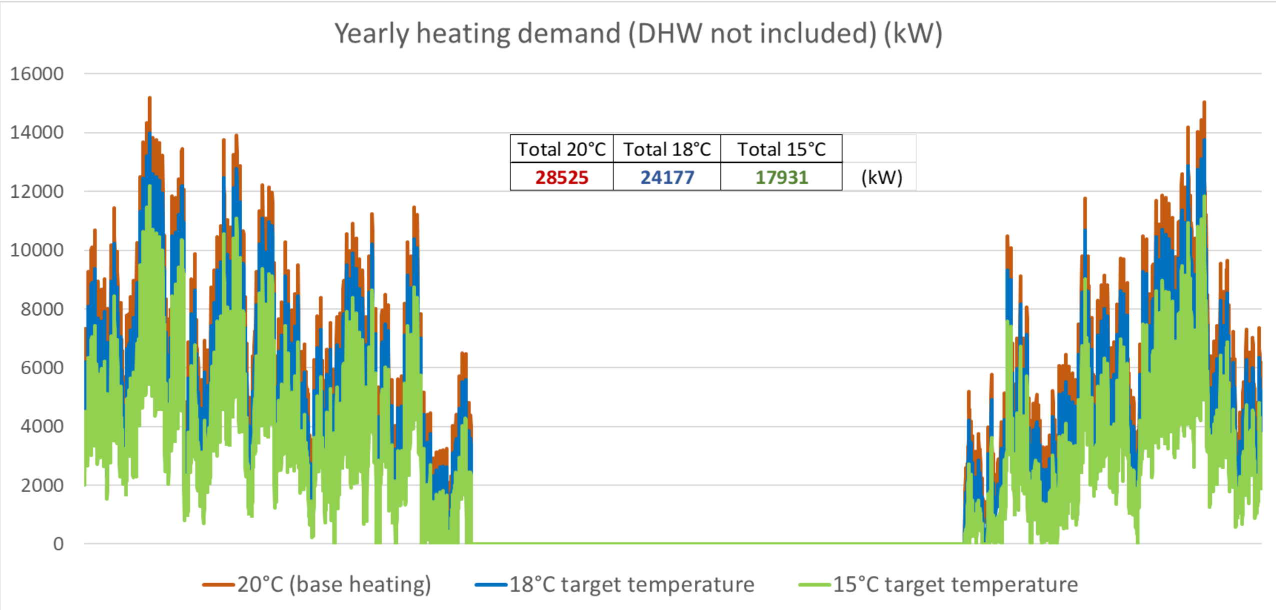


Figure 24: impact of sufficiency on heat demand curves

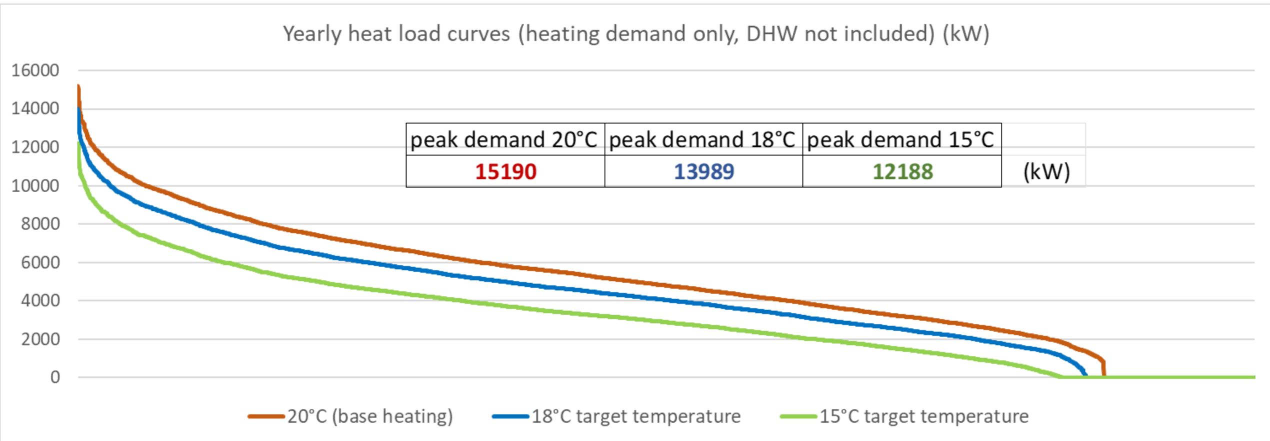


Figure 25: impact of sufficiency on heat load curves

7. Conclusion and recommendation

In conclusion, the Citizens4PED project has been an enabler for VUB and Resolia partners to develop an optimisation tool to support stakeholder decision-making in the design of PED Energy Centers. The Usquare, La Roue and San Paolo case studies have demonstrated the importance of energy sufficiency and the integration of renewable technologies to achieve PED objectives.

Simulation scenarios have shown that collective decarbonisation of heating networks is more cost-effective and less CO_2-emissive than individual solutions. Moreover, the concept of virtual PED seems indispensable to achieve PED objectives in dense urban areas. The results obtained offer promising perspectives for the implementation of sustainable and efficient energy solutions in neighbourhoods, while promoting the involvement of citizens and stakeholders.

8. References

Byrne, J.,Taminiau J., Kurdgelashvili L. and Kim N. K. A review of the solar city concept and methods to assess rooftop solar electric potential, with an illustrative application to the city of Seoul. Renewable and Sustainable Energy Reviews, 2015. https://doi.org/10.1016/j.rser.2014.08.023

All other references are in footnotes directly in this document.

9. Citizens4PED TEAM

Coordinator:

	Université Libre de Bruxelles (ULB)

Partners:

	e7 Energy Markt Analyse GmbH (e7)
	Brussels Institute for Thermal-fluid systems and clean Energy (BRITE) for Vrij Universiteit Brussel (VUB)
	Anderlecht Municipality – Division: Sustainable development (Anderlecht)
	Brussels Environment Division: Air Climat, Energy Sustainable Buildings (Bruxelles Environnement)

RESOLIA thermal networks engineering	Resolia Engineering bureau Sustainable & efficient thermal networks (Resolia)
ARTERIA TECHNOLOGIES	Arteria technologies engineering bureau (Arteria)
realitylab	Realitylab consultancy bureau (realitylab)
FH TECHNIKUM WIEN	FH Technikum Wien (FHTW) University of Applied Science Vienna
	Bari Municipality
Politecnico di Bari	Politecnico di Bari

CONTACT

Project Coordinator:

Université Libre de Bruxelles

Grégoire Wallenborn | gregoire.wallenborn@ulb.be

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