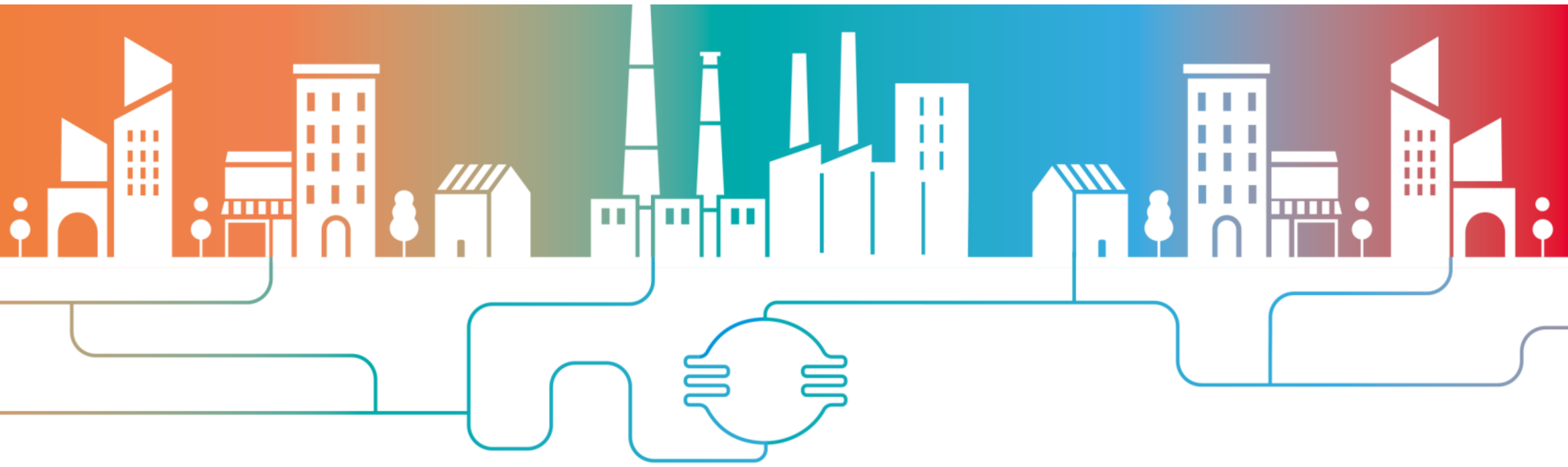
LIFE 4 HEAT
RECOVERY

Impact scenarios at the three demonstration networks – Action D1



Low temperature, urban waste heat into district heating and cooling networks

as a clean source of thermal energy

LIFE4HeatRecovery

Project Title: Low temperature, urban waste heat into district heating and cooling networks as a clean source of thermal energy

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1 Introduction

This report analyses the possible future scenarios for the demonstration cases of LIFE4HeatRecovery from a technical, environmental, and economic perspective.

LIFE4HeatRecovery is focused on low-temperature waste heat (WH) recovery into district heating and cooling (DHC) networks. The following three demonstration cases were implemented in the project:

- **Ospitaletto**, Italy: heat recovery from the cooling system of a **foundry** into a **cold network**, operated by Cogeme. The waste heat temperature is about 25 °C, while the network temperature is the same or lower (as it can be supplied also by aquifer wells at 15 °C). The installed substation can also deliver heat to the local heating system of the foundry (for space heating and sanitary hot water production), up to 60 °C using a heat pump (HP).
- **Heerlen**, the Netherlands: heat recovery from the cooling system of a **foundry** into a **cold network**. The network is a full neutral-temperature district heating and cooling network (NT-DHC) – often also defined as 5th generation DHC (5GDHC) – managed by Mijnwater, with supply temperatures of the order of 30 °C. The waste heat can be recovered up to a temperature of 42 °C, through a simple heat exchanger. The heat is then mainly reused at a nearby swimming pool, where a heat pump substation is installed.
- **Aalborg**, Denmark: heat recovery from a **data centre** of Aalborg University into a **medium-high temperature network**, operated by Aalborg Forsyning. The waste heat temperature can be in the range 40-60 °C (depending on the server operating conditions), thanks to a two-phase passive liquid cooling system developed by Heatflow. The network supply temperature is about 80 °C in winter and about 60 °C in summer. A heat-pump-based substation (with a configuration proposed by Eurac and a control implemented by Enisyst) is used to inject the recovered heat into the network, enabling direct heat exchange when the waste heat and the network temperatures match each other. The recovered heat is also used to heat the local building.

From the point of view of the network expansion, only the first two cases required a dedicated analysis, since the Aalborg network is already serving all the feasible city areas. For the Aalborg case, therefore, a focus on the WH penetration, as a replacement of fossil fuel sources of the district heating (DH) network, was carried out.

Multiple expansion phases were typically considered, with a long-term perspective until 2040-2050. The purpose of such large-scale roadmaps is not to provide a detailed scheduling of all the interventions, but rather to outline possible key steps. For Ospitaletto, three main development phases were considered, targeting a relatively short-term expansion (3 years after project end), a second similar step until 2030, and then a long-term result with the 2050 horizon. Similar phases were considered for Heerlen, though the company plan set a more ambitious “stabilization” target already for 2040. For the case of Aalborg only a single step was considered, as the expansion of the network itself is not required and a faster roll-out might occur.

2 Methodology

The demonstration cases of LIFE4HeatRecovery, while similar in terms of waste heat recovery concepts and solutions, are rather different in terms of city context. Therefore, in practice, different approaches have been used, as explained in the dedicated chapters. Nevertheless, having in mind the case of a small starting network going to expand in nearby areas with a large extension potential, a general techno-economic model was developed.

Within LIFE4HeatRecovery, the ideal context for the application of the devised model was given by the Ospitaletto case, where the current situation is given by a single small network surrounded by a relatively large disconnected area. In principle, also the Heerlen case provides a similar context, with a large expansion potential: however, in the latter case, the managing company Mijnwater developed a master plan based on a different approach, more focused on stakeholder interactions rather than pure techno-economic planning, also including initially separated subnetworks to be joined in later stages. Moreover, the Heerlen context is very peculiar due to the presence of and abandoned coal mine serving as a seasonal storage, which provides a crucial energy balancing solution. Finally, the case of Aalborg is not suitable for a network expansion analysis, as the network already extends to all reasonable city zones.

With the objective of applying the analysis to the Ospitaletto case, the techno-economic model was developed with a specific focus on neutral-temperature DHC networks (i.e., 5th generation networks). Apart from the calculation blocks devoted to heat pump substations at user sites, the methodology can anyway be easily generalized to conventional networks. Hence, in general, the techno-economic model presented below is expected to have a significant application potential, in many European cities. The more socio-economic approach presented in the Heerlen chapter can be seen as an important complement to the techno-economic one, possibly providing a “second-phase” analysis after developing an initial techno-economic draft.

2.1.1 Detailed aspects of the developed model

The model structure is presented in Figure 1. It includes (1) a “core” *annualized techno-economic model*, which evaluates energy balances and costs for a single operation year of the system, and (2) a surrounding iteration block carrying out a *multi-year optimized expansion* of the initial system. Details are provided in the next sections.

The entire methodology is meant to be simple and approximate. It preserves the detail level of a former single-year techno-economic tool developed in the FLEXYNETS project [1], that is comprised within this approach as the core annualized techno-economic model (with little adjustments). On the other hand, the approach complements this core model with several surrounding modules and an overall iteration block which calculates optimized expansion steps for the initial system in a multi-year framework. The methodology described here was published in Ref. [2] and is presented with even larger detail in the PhD thesis of one of the authors of this report [3].

The first part of the methodology outlines the possible areas where the network can expand, and the potential neutral-temperature sources (NTS) utilized. The spatial resolution used to analyze the NT-DHC network scenarios corresponds to the urban scale. A Functional Unit (FU) of 1 km^2 of residential areas was established. This choice was motivated by previous publications in which a reference area of this size has already been investigated. The required input data comes from the mapping tool Hotmaps. This tool uses a top-down statistical method to estimate the heating and cooling (H&C) demands of any European city zone with a spatial resolution from the hectare to the national level.

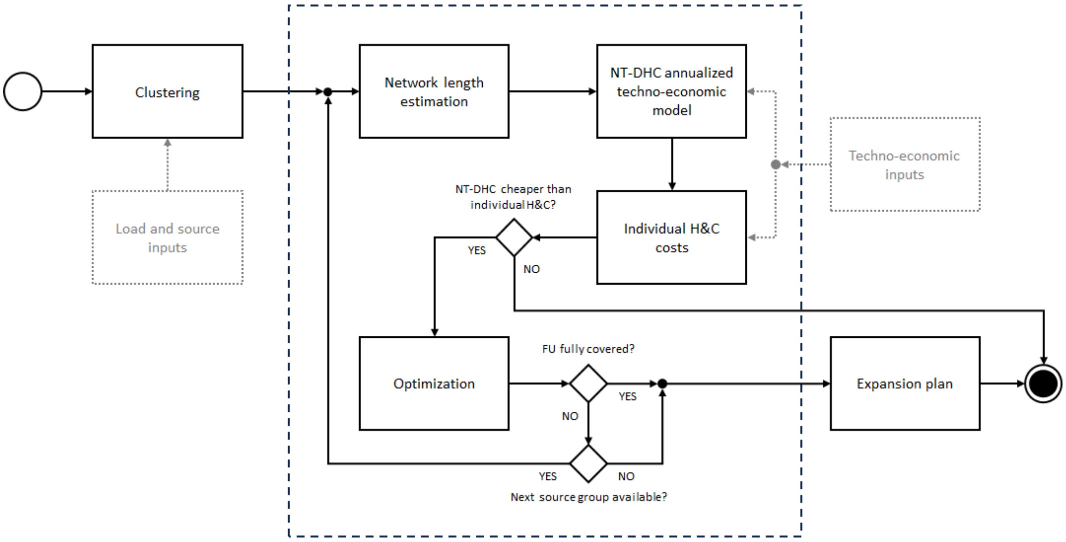


Figure 1. Model conceptual scheme. methodology. The blocks inside the dashed contour correspond to the iteration yielding different planning phases.

In the absence of information on how the built environment is organized, the model divides the FU into clusters with a peak thermal power not larger than the capacity of the available sources. Cluster analysis corresponds to an unsupervised machine learning task involving natural data grouping. For this work the Spectral Clustering method was used (see Ref. [2] for details). This method was applied to the case of Ospitaletto, selecting a FU of interest from the city center (see Figure 2).

In addition to the aggregation of residential areas into clusters, special buildings (commercial, public, schools, etc.) are also candidates to be connected to the network. The main distinction concerning residential buildings is that special buildings (SBs) exhibit different H&C profiles, both daily and seasonal.

Estimating the length of a network involves both distribution and service pipes installations. The first category corresponds to the main backbone to connect the sources with the potential loads (inter-distance). Through the geometrical centroid of a number of source points (latitude and longitude coordinates), a Virtual Source Point (VSP) can be identified and connected to any potential candidate through their respective centroid. The pipe diameter corresponds to the largest pipe size, facilitating the network flow in peak conditions. The second network length category incorporates all the service pipes within the cluster's area for the heat delivery to the buildings in the cluster (intra-distance). This length is estimated through the theoretical framework introduced by Persson [4]. The authors expressed the network length as a function of two parameters: the effective width, which is the ratio of the land area served by a network and its length, and the gross floor area of the buildings. These parameters are available in the open-source database from Hotmaps. Through the VSP, SBs are grouped similarly to sources, and the total network length required to connect them is the same as for clusters, except for the effective width approach.

The algorithm calculates the extension feasibility to each potential candidate (clusters and SBs). This iterative process involves the hourly calculation of the NT-DHC performance: it considers the energy balance between sources and loads, and accounts for both heating and cooling supply.

In addition to the network extension costs, the operational costs include electricity consumptions of the HPs, use of WH and other NTS, network pumping consumptions, etc. The techno-economic analysis (TEA) of the best extension scenarios will depend on a value function that considers the economic margin (revenues from the H&C sales minus implementation costs, including CO_2 emissions' taxes) and the maximum available capacity from NTS. Panel (b) of Figure 2 shows an example of the breakdown of expenses assessed in each extension scenario (in this process, the annualized techno-economic model shown in Figure 1 is called iteratively).

The model iteratively runs **three extension scenarios**. They are not related to a strict timing, as, from an economic point of view, all costs are annualized. Therefore, they can be interpreted as **construction phases**. In each extension scenario, the TEA of the NT-DHC solution is compared with the Business as Usual (BaU) cases. Benchmark technologies are reversible air-to-water HPs (A/W HPs) and individual gas boilers with split cooling units (individual H&C scenario). The feasibility of the system depends on the boundary conditions set by the model user, who will define the available and potential H&C sources, network operating conditions, energy prices, and other parameters.

An optimization algorithm selects the combination of extension choices that maximize the overall value of the portfolio after filtering out the choices that are more competitive compared to the BaU scenario. Investment allocation of potential extensions is a problem that can be framed as the 0-1 knapsack problem, which restricts the number of candidates that can be included to zero or one. Given a set of n candidates numbered from 1 to n, each with a weight w_i (here consisting in the peak load required by candidate/cluster i) and a value v_i (here consisting in the economic benefit of providing energy to candidate/cluster i) along with maximum sources capacity W, the constraint $\sum_i w_i \leq W$ must be respected. Dynamic programming is the technique used to solve this problem, which reduces the complexity and, therefore, the running time in comparison to a brute force approach ($O(nW)$ vs. $O(2^n)$). In this way, the model will prioritize the clusters or buildings that provide a higher value to the overall extension plan assuming a H&C service price equal to competing individual technologies. As for the other parts of the model, more detailed on the used equations and the actual model implementation can be found in Ref. [2].

The three resulting scenarios provided by the optimized iteration steps therefore correspond to optimal expansion phases of the system, in the sense that for each phase the most convenient clusters (starting from the initial network) are added to the system. Clusters where individual technologies provide better economic figures than DHC are simply left out. These expansion phases can be associated to the desired timing. **Each expansion phase is limited by the choice of heat sources for that phase**. Hence, the user has initially to provide **three source groups** to the model. In this way, the user can also indirectly “impose” the “size” of each expansion phase, e.g., keeping track of resulting investment costs and relating them to available funding, to develop investment plans.

Finally, it is worth emphasizing that, in order to assess the economic feasibility, a full life-cycle evaluation was done for all the system components. Source substations, network pipes, and user substations are all included in the cost analysis, properly annualizing investment costs according to the respective lifetimes and considering operation and maintenance and energy costs. In this way, a kind of cradle-to-grave analysis for the system can be provided.

(a)

(b)

Figure 2. (a) Spectral Clustering method applied to the case study. Inputs are latitude, longitude, and heat density of each city hectare. (b) Annual costs and revenues per candidate. The difference between the green line and the bars represents the net economic margin per year [€/y].

3 Ospitaletto case

3.1 Review of the current situation

3.1.1 Source mapping

Sources of different types (WH of twenty industrial sites, six supermarkets, and six parks), temperature level, estimated thermal capacity, and location were identified within the municipality's boundaries. The positions of the overall considered sources are shown in Figure 3. This is related to the large waste heat mapping carried out in Action C.6.4 of the project (see Deliverable "Report on the GIS tool for waste heat recovery opportunities individuation").

Many of these sources are small and not convenient to be included in a large-scale roadmap. A short-list of most promising sources was then selected. Priority was chosen in terms of size, temperature, and proximity to the network. Additional aquifer wells in park areas were considered mainly as auxiliary sources, continuing the approach already in place in Ospitaletto. As a result, three groups of sources presented in Table 1 were selected. It can be seen that a park areas was included in each group. Aquifer wells in park areas, while colder then other sources (and hence yielding worse COP for heat pumps), have the advantage of being always available, both in terms of hourly schedule and in terms of long-term duration. Including them in each expansion phase was considered an appropriate risk-mitigating measure for a system fully reliant on waste heat.

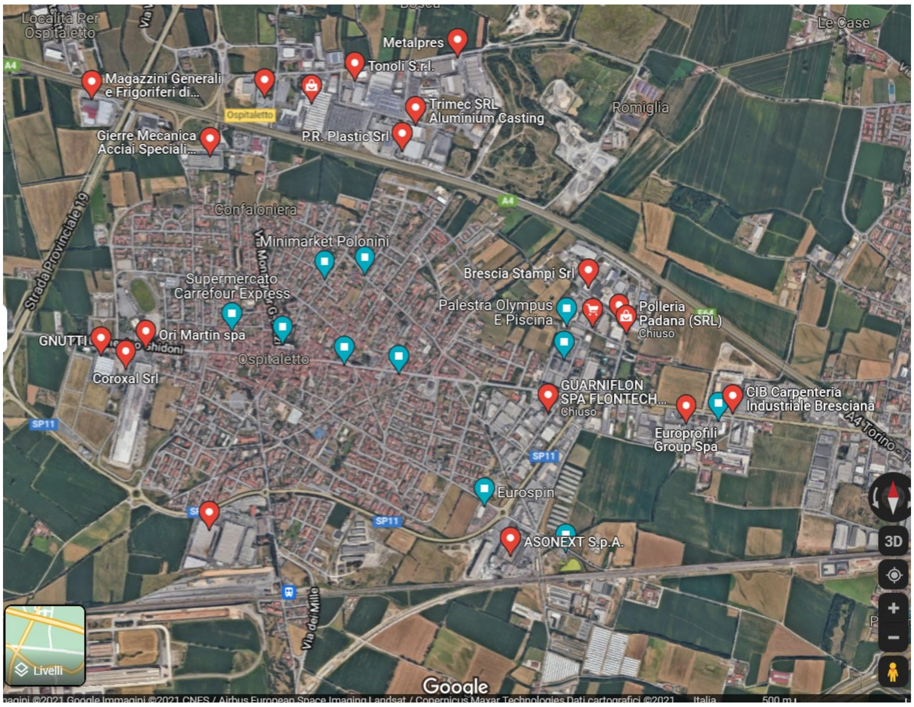


Figure 3. Neutral temperature sources survey in the Ospitaletto municipality. The red markers represent the location of industrial sites.

It is assumed that the sites with industrial waste heat have a higher exploitation priority since their operating schedule is typically stable and continuous. Moreover, their temperature level is superior to the ground sources and therefore beneficial towards the performance of the NT-DHC system.

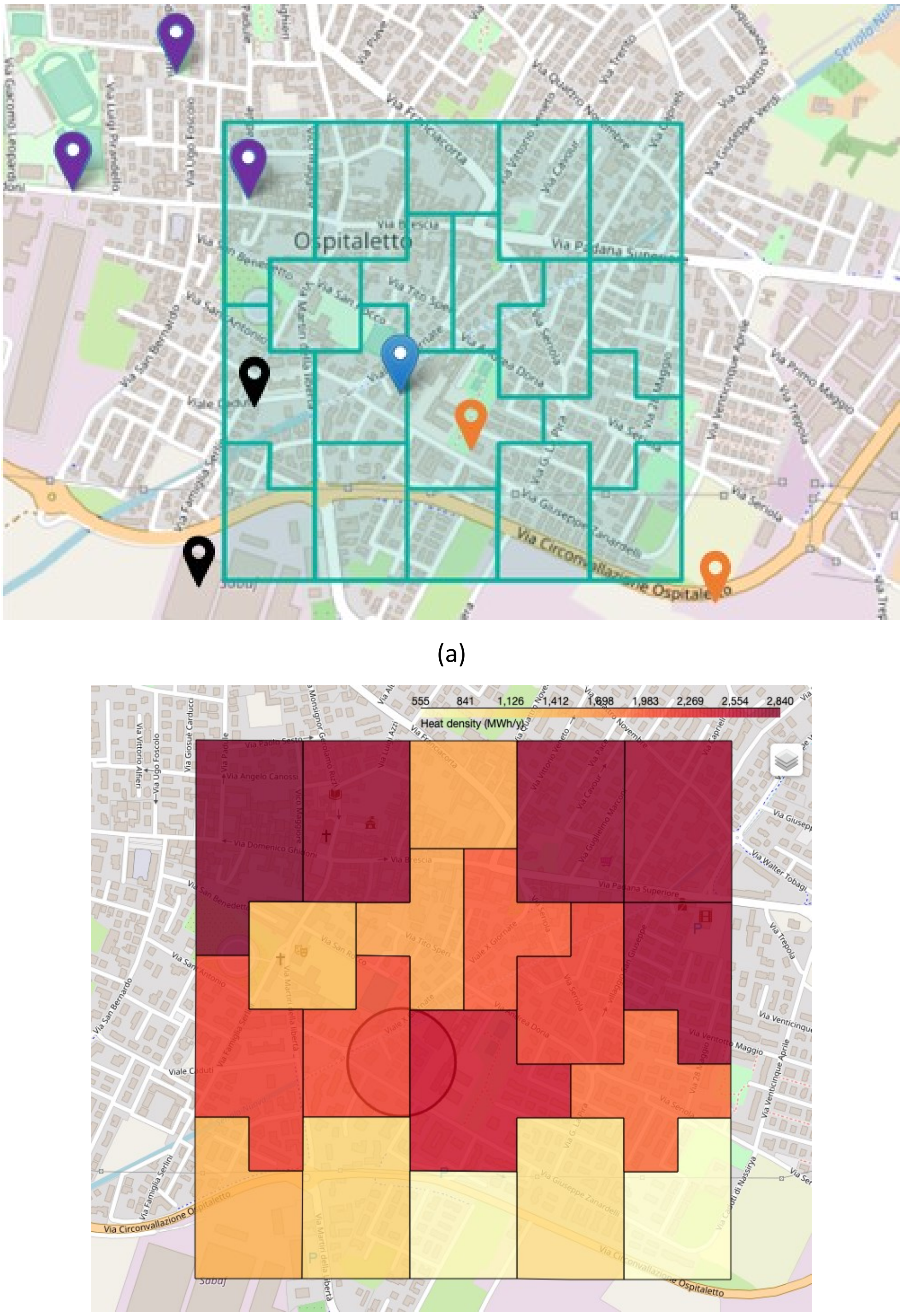
Table 1. Sources characteristics and grouping selection

Source	Category	Capacity [MW]	Temperature [°C]	Group
Baden Powell Park	Park	1.14	15	G1
Steel plant	Industry	1.58	22	G1
SABAF	Industry	6	25	G2
Piazza Mercato	Park	12.3	15	G2
Carrefour	Supermarket	0.1	18	G3
Ori Martin	Industry	15	25	G3
Manzoni Park	Park	3.15	15	G3

3.1.2 Loads

Heat density data of residential buildings at the hectare level is the smallest data unit retrievable from the online Hotmaps database. An arbitrary FU of 1 km^2 (thereby corresponding to 100 hectare-size cells) from the Ospitaletto municipality was selected, as presented in Figure 4. The total heat demand was found to be 35,726 MWh/y, with a peak demand of 17.28 MW.

The model iteratively applies the Spectral Clustering method to get a proper city zoning compatible with the size of available sources. Spectral Clustering requires the number of desired clusters as an input. In the model, this is initially an unknown parameter. At the same time, it is desirable that the maximum cluster size (intended as power load) does not exceed the size (intended as power capacity) of the smallest "relevant" source. Indeed, on the one hand it is not useful to waste computational time with clusters much smaller than sources sizes, as source sizes anyway determine the "precision" of the process. On the other hand, including clusters with sizes bigger than the source sizes would possibly prevent from finding properly energy balanced networks. Consequently, the model starts assuming a single big cluster to initialize the process, and then progressively increases the FU granularity (i.e., the number of clusters allowed for the Spectral Clustering method) until the capacity threshold is met. In practice, the algorithm provides an output when a configuration is found where the largest cluster does not exceed the sources' capacity limit and any configuration with more clusters would violate this constraint. The source capacity threshold can be specified by the user. Here, the threshold was set taking into consideration the capacity of industrial sources' only (including all three source groups). Indeed, these sources were assumed to be the pillars of the network operation, thanks to their relatively stable schedules. It can be observed in Table 1 that this limit comes from the smallest industrial waste heat plant available, with a peak capacity of 1.58 MW (found in the first group, G1). This choice yielded the cluster configuration shown in Figure 4. Other WH sources such as supermarkets are here considered as complementary sources, useful to meet the total load, but not for sizing. Finally, parks or other ground source sites are assumed to be auxiliary systems to meet the demand during weekends and other times when WH plants are unavailable (according to the logic used in the current Ospitaletto network), and again they are not used to size the threshold used to develop the expansion steps.



(a)

(b)

Figure 4. (a) Clusters and source groups' locations are symbolized in different colours. G1 in orange, G2 in black, and G3 in purple. The blue marker represents the centroid of SBs. (b) Heat density map of the clusters ranging from 555 to 2840 MWh/y.

3.2 Technical, economic, and environmental inputs

3.2.1 Energy prices

The energy prices vary considerably depending on the type of customer (residential or non-residential) and taxation. According to Eurostat data, the residential electricity price in Italy during the second semester of 2020 was 0.215 €/kWh (0.15 €/kWh corresponding to taxes and other costs). On the other hand, the non-residential electricity price was 0.15 and 0.175 €/kWh without and with taxes, respectively. Italy's average residential gas price has fluctuated between 0.060 to 0.080 €/kWh from 2018 to 2021, excluding taxes. The total gas price, including taxes and levies, varied from 0.07 to 0.095 €/kWh in the same period. In other LIFE4HeatRecovery deliverables and especially in deliverable "Report on the socio-economic impact produced at the 3 demonstration networks" of Action D.2.1 a broader sensitivity analysis on these values was carried out. While the prices mentioned above are smaller than current prices, these values can still be considered reasonable in the long term, where a general price decrease towards pre-2020 values is generally expected by energy consultants. This point is anyway addressed in later sections, where a sensitivity analysis is carried out.

Table 2 summarizes the assumptions used for a default simulation. The first assumption is that NT-DHC systems would benefit from no taxes on electricity. In contrast, the competing solutions of individual boilers are compared to the residential gas price, including taxes and levies, and split-units (for cooling) and A/W (air-water) HPs operate under residential electric pricing. Finally, H&C sales assume a maximum heat price equal to the competing solution price (gas boilers).

These assumptions are made since the network operator may benefit from a pricing scheme that residential users may not have access to. In the default scenario, it is expected that OPEX from the NT-DHC scenario (supported by a good SCOP/SEER) will provide an advantage over the OPEX of individual gas boilers and A/W HPs. Assumed H&C pricing aims at assessing feasibility by comparing at least the most common and current technologies. If it is possible to find feasible solutions at this energy pricing level, this does not limit other business cases that the energy analyst could consider.

Table 2. Energy prices selected for a reference scenario (€/kWh)

Variable	Value	Description
Gas	0.100	Residential price in Italy, including taxes.
Electricity, non-R	0.150	Non-residential price in Italy, excluding taxes, based on 2020 data.
Electricity, R	0.200	Residential price in Italy, including taxes.
Heating	0.100	Assumed equal to gas price.
Cooling	0.100	Network services are assumed to be equal for H&C.

3.2.2 Emission factors

In the default simulation, the selected electricity and natural gas values for the Italian case are presented in Table 3. The 2020 edition of emission factors in the electrical Italian grid and the main European countries from the Institute of Research and Environmental Protection (ISPRA for its Italian acronym) provides a more up-to-date value for the electricity emission factor. In this report, 0.281 tCO2/MWh corresponds to electricity consumption emissions for the reference year of 2018.

Table 3. Emission factors used in the default simulation (tCO2-eq/MWh)

Energy carrier	Value	Description
Electricity	0.281	2018 reference year (ISPRA,2020)
Natural gas	0.202	Standard method (IPCC-2006)

3.2.3 Techno-economic inputs

A series of technical inputs for a default simulation are presented in the following table, based on the current operating conditions of the network located in Ospitaletto. Detailed information about their application can be found in [3] (for the estimation of ground temperature and heat losses, for the application of DHW and SH temperature setpoints, for NT-DHC substations modelling, etc.).

Table 4. Techno-economic inputs used in the default simulation

Parameter	Value	Description
T_{DHW}	55	DHW temperature (°C)
$T_{max,i}$	55.66	Maximum indoor SH temperature delivered to the buildings (°C)
$T_{min,i}$	46.77	Minimum indoor SH temperature delivered to the buildings (°C)
z	1.3	Network pipes depth (m)
η_m	53	HPs compressor efficiency (%)
ΔT_{evap}	4	Supply-return network temperature difference
COP_{CF}	1	Correction factor applied to the COP formula
U_{CF}	1	Correction factor applied to the thermal losses' formula
i	3	Discount rate of the project (%)
$f_{disc,inv}$	1	Subsidy to the total NT-DHC investments (discount factor from 0-1)
f_{inc}	1	Incentive factor for the heat delivered through the NTDHC network (i.e., a factor of 1.2 would represent a 20% subsidy from a public entity).
c_{tax}	75	Carbon tax (€/tCO2).

3.3 Sensitivity analyses

Three factors will be analyzed to assess the competitiveness of the NT-DHC concept against conventional H&C solutions (individual gas boilers and split units or reversible A/W HPs): energy price conditions, electric grid environmental performance, and cooling penetration scenarios. Table 5 presents future scenarios that could occur in the energy markets. Gas is not explicitly addressed, as the considered default price is rather conservative (in the sense that lower prices are unlikely to occur and higher prices would only favour NT-DHC, which, as shown below, is already quite competitive under the default assumptions.). The renewability of the Italian grid and how does this impact the solution compared with individual solutions is analyzed through the cases presented in Table 6. Finally, a comparison with individual H&C solutions will be performed according to the cooling scenarios presented in Table 7.

Table 5. Energy prices scenarios. Favourable cases for the NT-DHC. The abbreviations "R" and "non-R" refer to residential and non-residential prices respectively.

Variable	Value	Description
Electricity, non-R	0.10 €/kWh (-33% of reference)	Subsidy to the NT-DHC energy cost component
Electricity, non-R	0.20 €/kWh (+33% of reference)	Electricity price increase for the non-residential sector
Electricity, R Electricity, non-R	0.30 €/kWh and 0.225 €/kWh (+50% of reference for both)	Electricity price increase (residential and non-residential)
Electricity, R	0.20 €/kWh	Residential customers' price remains stable or becomes cheaper

Table 6. Sensitivity analysis of electric grid renewability

Variable	Value	Description
Electricity emission factor	0.141(-50% of current factor)	Optimistic case. A high share of renewables in the Italian electric grid
	0.483(2005 Italian electricity factor)	Pessimistic case. A grid with a low share of renewables.

Global heating energy demand is projected to increase until 2030, then stabilize. However, it is predicted that cooling demand will overtake heating demand worldwide. Using 2020 as a baseline, cooling demand corresponds to 10.6% of potential building demand in the default simulation (i.e., not all buildings are endowed with cooling systems). However, future cooling scenarios with increased demand are worth being investigated. In 2030, assuming that cooling demand increases by 10% a year, this exponential growth translates into a cooling demand of 27.6% (compared to overall potential demand). This represents a net increase of 27.6%-10.6% = 17% (in terms of absolute percentages) with respect to the 2020 value, or an annual increase of roughly 1.7%. If the exponential growth stabilizes and then increases linearly with the same order of magnitude (17% every 10 years), cooling penetration would reach about 60% by 2050. The following table summarizes the future cooling scenarios that will be considered.

Table 7. Cooling scenarios. The "cooling factor" column represents the share of installed cooling with respect to the overall potential demand.

Case	Description	Cooling factor (%)
2020	Current cooling demand	0.106
2030	An exponential growth in the cooling demand of 10% per year	0.275
2050	A linear growth starting from 2030 with an approximate rate of 1.7%.	0.60

3.4 Default simulation

This approach provides a phasing schedule of sources and loads according to the expected thermal capacity to be utilized and the number of periods selected. In the default simulation, it is assumed that three groups of sources become available in the order shown in Table 1 and represented geographically in Figure 4a.

In Figure 5, it is shown that the model first estimates the NPV of each potential extension project. The clusters with a higher NPV appear in red on the heatmap, while the less economically attractive ones appear in yellow. The markers correspond to the locations of sources in group G1. The model then finds the optimal subset of clusters that, combined, adds the highest value to the portfolio, without exceeding the thermal capacity threshold (Figure 5b). For the **first iteration**, these are clusters 1 and 10 (see Figure 8 for the summary of all phases and for a map with the cluster numbering). Indeed, as can be seen in Figure 5, cluster 10 is the one with the highest NPV, while cluster 1, despite its marginal economic convenience, is chosen because it complements cluster 10 still remaining within the 1.6 MW capacity restriction.

In the **second iteration**, the model recalculates the NPV of the remaining candidates (clearly excluding the zones already selected in the previous scenario), considering that there are now 6 MW of WH capacity available (sources of group G2 are now included; see Table 1 for the source list). Panel (a) of Figure 6 shows both the NPV colour map for the considered clusters, as well as the markers representing the locations of new sources. The model selects the zones shown in Figure 8b, based on the best compromise between economic value and peak capacity.

In the **third iteration**, the model determines the NPV of the remaining loads, including the SBs (the position of the latter being shown as a green placeholder in Figure 7). As a result of the high thermal capacity in this step, all the *feasible* candidates can be served by the NT-DHC system (three clusters are left out as not feasible, see below). In general, the process ends if the algorithm cannot reach a better scenario than the BaU case or if the NT-DHC fully covers the FU or if no more sources are available.

Figure 8 presents the **transition pathway** for the NT-DHC system expansion based on default values. The three clusters 13, 14, and 17, located in the southern part of the FU, are not connected to the network (see Figure 7), as they cannot compete with individual solutions (i.e., their estimated levelized cost of energy exceeds the one of individual solutions, at least once the connection costs for the network backbone are included). See Figure 9 for a focus on the comparison of the costs of these clusters against individual solutions (reversible A/W HPs and the conventional combination of gas boilers for heating and split units for cooling).

The expansion process can be quantitatively summarized through a few key indicators for the three expansion phases:

- Cumulative installed WH power: 1.6, 7.6, 22.7 MW
- Cumulative WH recovery: 2.9, 11.5, 23 GWh/y
- Cumulative supplied heat: 4.0, 16.1, 32.2 GWh/y (92 % of FU demand)
- Cumulative investments: 1.4, 7.3, 13.3 M€
- CO2 emission reduction with respect to conventional individual H&C solutions: > 60 % (depending on evolution on electric grid emission factor and actual COP)

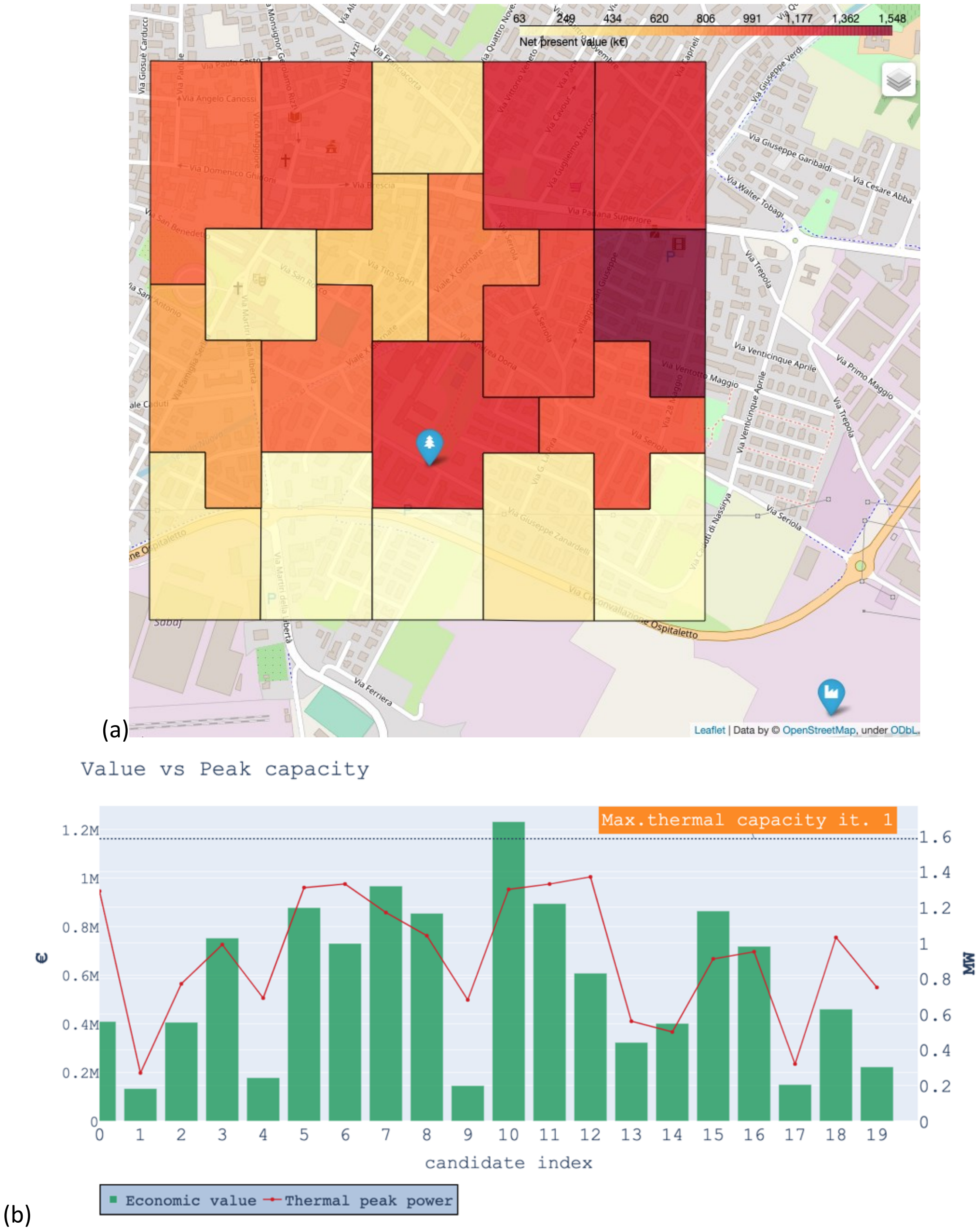


Figure 5. First network extension: (a) Colour map of the NPV for each cluster, with the 2 considered sources (group G1) marked with blue placeholders; (b) Economic value (NPV) and peak power for each cluster. The dotted line indicates the maximum capacity that can be exploited from the WH plants (1.6 MW in this scenario).

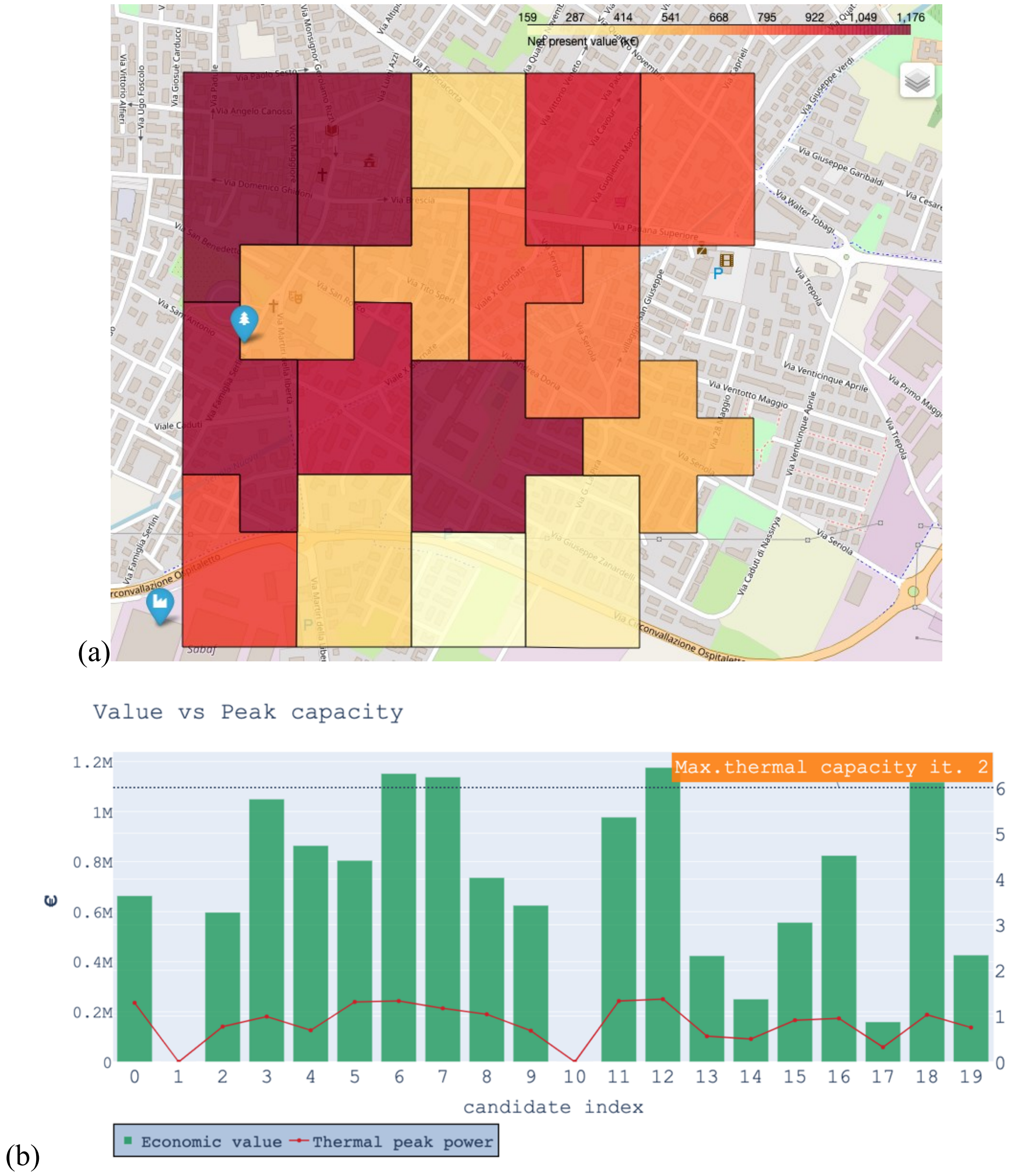


Figure 6. Second network extension: (a) Colour map of the NPV for each cluster in the, with the 2 new sources (group G2) marked by blue placeholders. (b) Economic value (NPV) and peak power for each cluster. The dotted line indicates the maximum capacity that can be exploited from the WH plants (6 MW in this scenario).

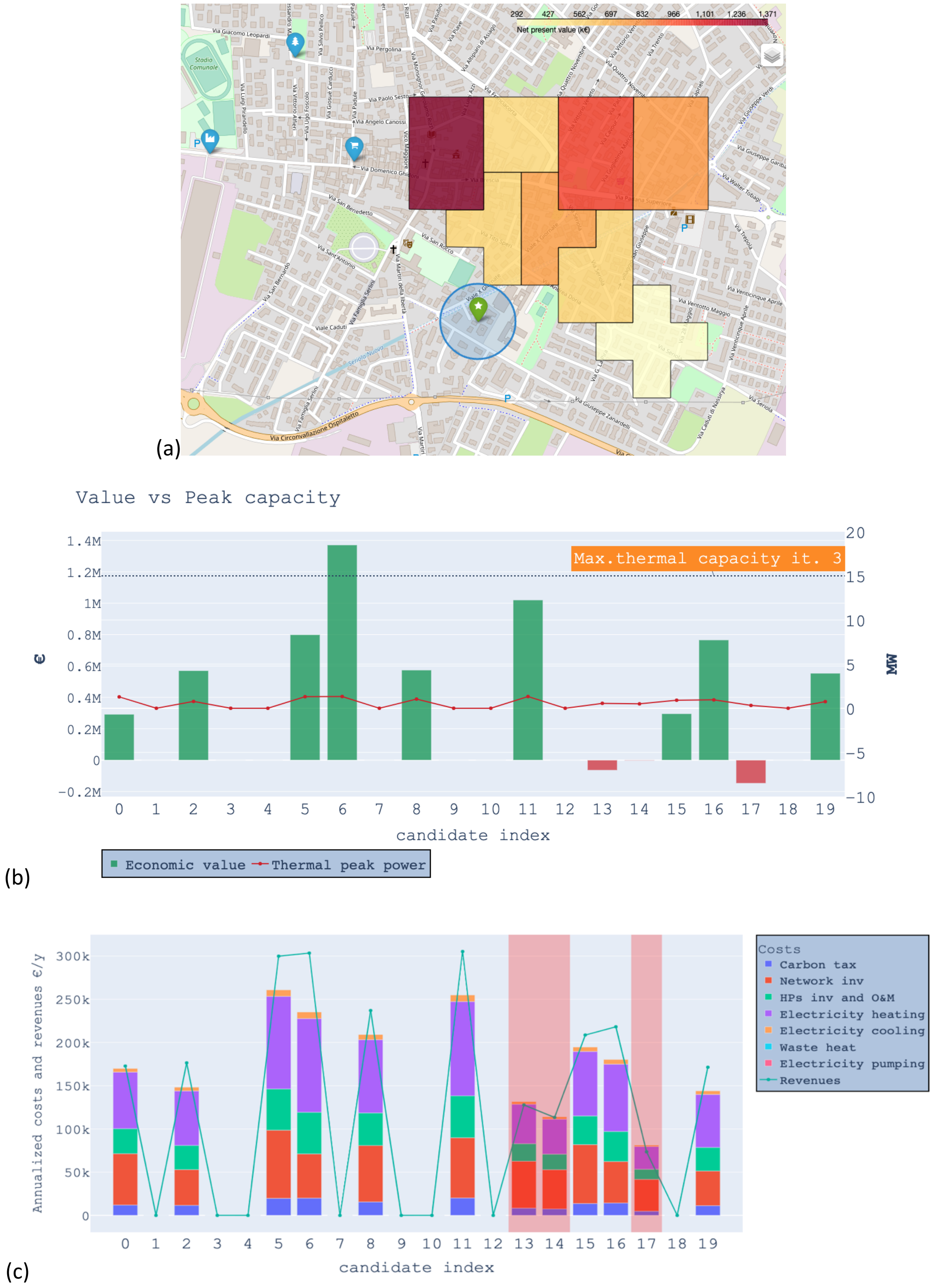
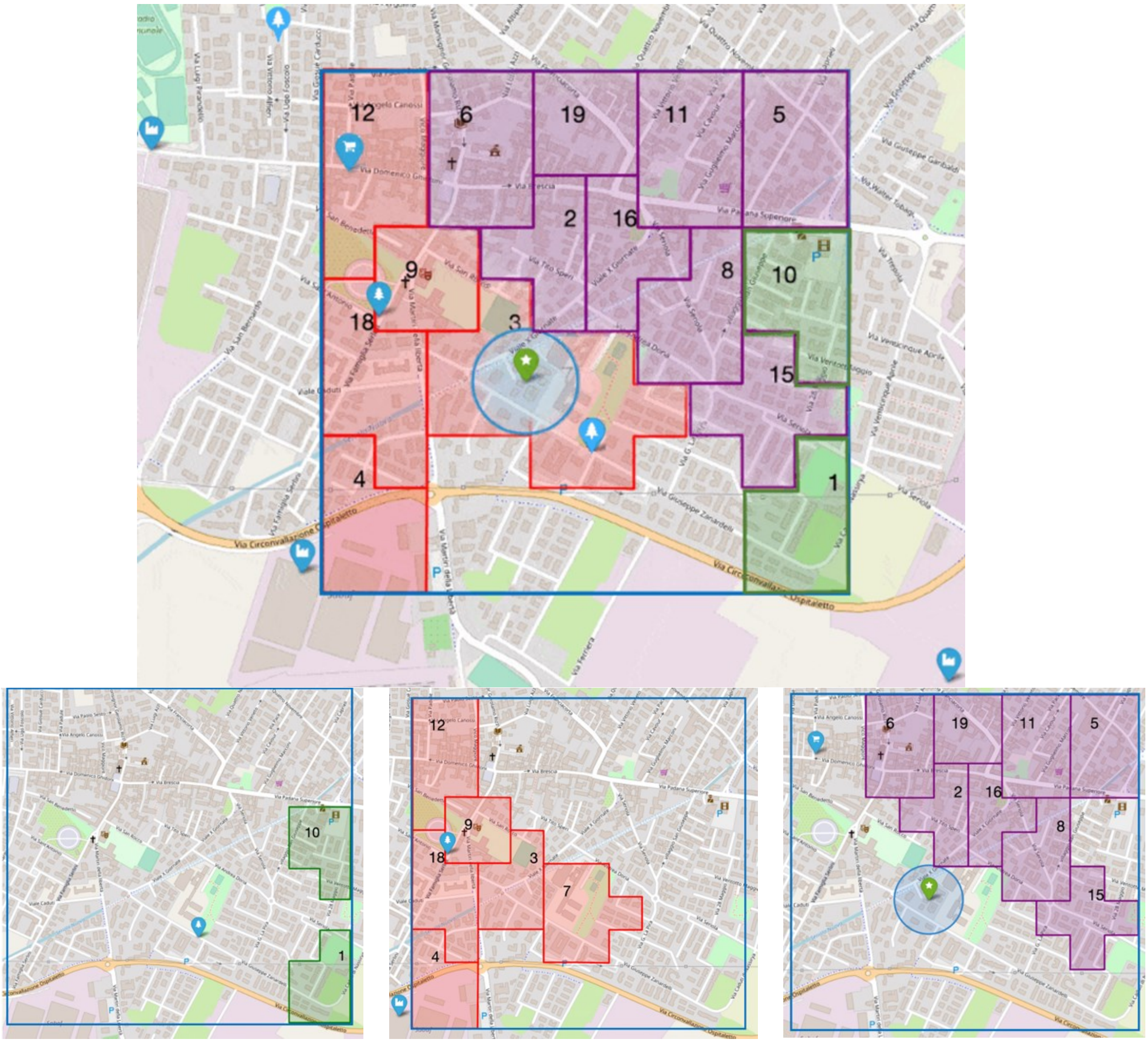
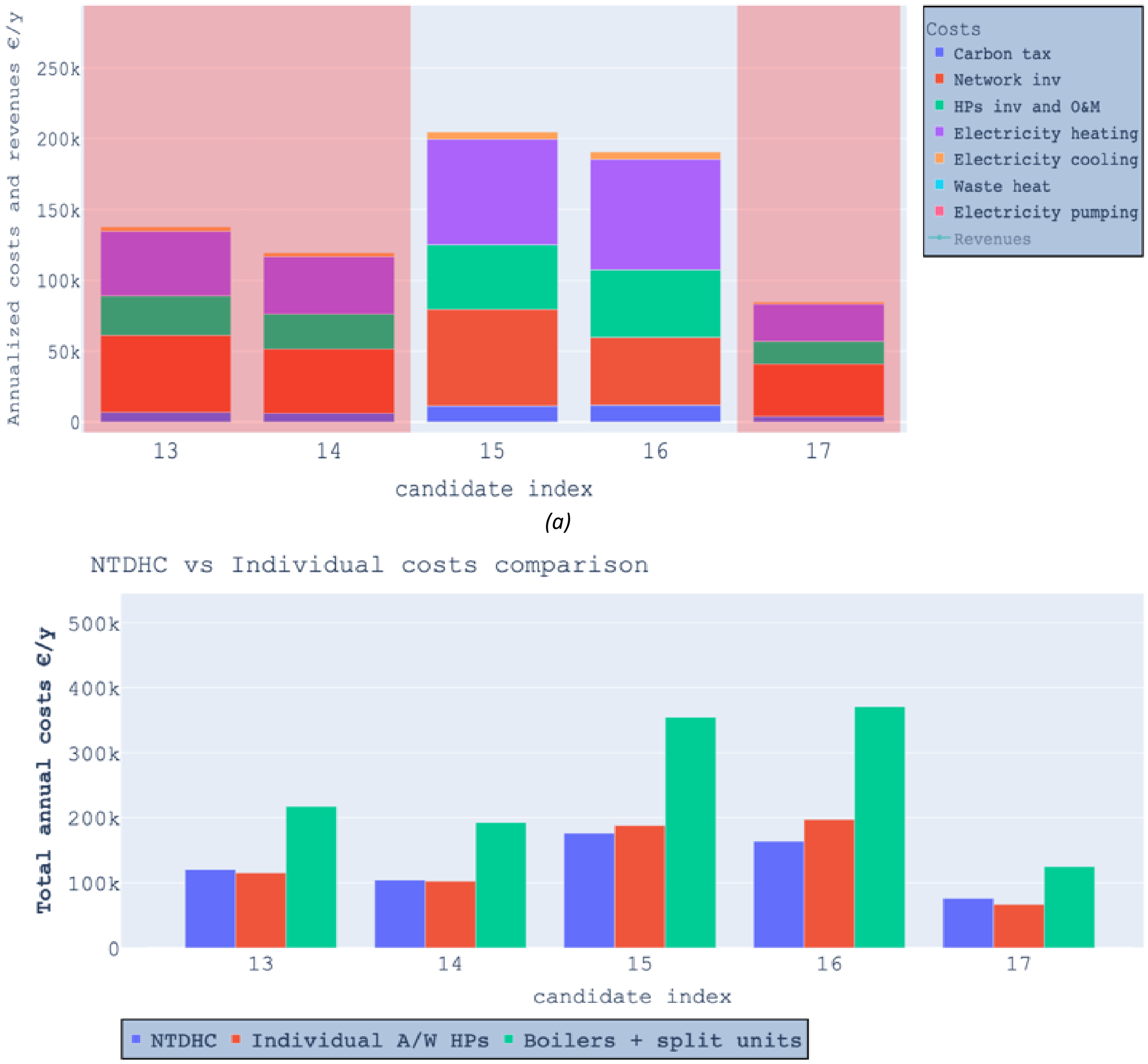


Figure 7. Third network extension: (a) Colour map of the NPV for each cluster in the, with the 3 new sources (group G3) marked by blue placeholders (the green placeholder marks special buildings). (b) Economic value (NPV) and peak power for each cluster (the dotted line marks the maximum WH of 15 MW in this round). (c) Clusters 13, 14, and 17 produce unfeasible scenarios, mainly because the revenues from the H&C sales are insufficient to cover the costs of the network to connect with the sources in group G3.



(a) (b) (c)

Figure 8. NT-DHC network extension tool applied to the case study. (a) The first optimal extension considers the available thermal power of 1.6 MW. (b) This second iteration assumes 6MW of waste heat is available. (c) The optimal extension when 15 MW of thermal heat becomes available at a later stage.



(a)

(b)

Figure 9. (a) Cost breakdown for NT-DHC. Red denotes an unfeasible scenario (higher costs than revenues). (b) Costs comparison among H&C alternatives. In Cluster 13, 14, and 17, A/W HPs are positioned as a superior solution over NT-DHC due to their lower cost.

It can be expected that, for the same available set of sources, the choice of their grouping can have an impact on the transition pathway. Here, the grouping was driven by the starting situation of the Ospitaletto network, where the source in the south-east of the functional unit is already connected (nearby cluster 1, see Figure 5). Nevertheless, in Ref. [3], this question was investigated by running the model including the largest source in the initial source group. Though the evolution was clearly different, a similar arrival configuration was obtained. In particular, clusters 13, 14, and 17 remained excluded from the final scenario, However, even cluster 1 was excluded. This can be explained with the fact that cluster 1 has a very low urban density and is hence not convenient, as such, for a network expansion. Adding the largest sources at the beginning, the network starts its development from the western zone of the functional unit. Moreover, the starting large sources are big enough to allow the network to expand to all valuable clusters without the need to add the source near cluster 1, located at the south-east of the functional unit. It would then not be convenient to add cluster 1 at the end, adding a significant extra cost for the network backbone only to connect a few users. As mentioned before, however, in the real case of Ospitaletto the expansion started just from cluster 1. This was motivated by the possibility for the network manager Cogeme to find an easier agreement with this source. It is hence related to negotiations and contractual aspects which are clearly outside the scope of the techno-economic model used here. This is one of the reasons why the model was developed to (partly) automatize the choice of connected areas, rather than to automatize the choice of sources, which anyway needs "manual" considerations. This might be even more relevant for NT-DHC networks than for conventional networks. Indeed, in contrast to traditional DH business models, this type of network involves a variety of stakeholders (industry, service sector infrastructure, supermarkets, shopping centers, etc.). This was a driving reason to introduce a significant flexibility in the developed tool when it comes to scheduling WH plants and grouping them geographically.

3.5 Energy price scenarios

Scenario "Electricity price increase for the non-residential sector" of Table 5. The sensitivity analysis of increasing the default electricity price for non-residential customers by 33% (0.2 €/kWh from 0.15 €/kWh) shows an increase in the number of non-feasible extension scenarios (up to 45% in the first iteration). As a result, the NT-DHC functional unit coverage is reduced from 92.38% to 81.65% under these conditions.

The maximum electricity price that still yields a feasible scenario for DHC is 0.35 €/kWh, based on an average SCOP of 4.68 for the highest performing HPs. If the SCOP of the HPs is reduced by 25%, the maximum acceptable electricity price drops to 0.265 €/kWh. This limiting situation (only one feasible cluster, i.e., cluster 4) arises when SABAF, the primary waste heat provider from the second group, is exploited to provide 1436 MWh/y of heat to a nearby area (covering only 3.85% of the total FU heat demand).

Scenario "Subsidy to the NT-DHC energy cost component" of Table 5. The best scenario for the NT-DHC solution occurs when lowering the non-residential electricity costs by 33%, i.e., the electricity for non-residential customers becomes 0.1 €/kWh. The system can cover up to 95.47% of the total FU demand, i.e., one more cluster is connected to the network with respect to the reference scenario, namely cluster 13. Because the network costs dominate in clusters 14 and 17, and the energy costs reduction is insufficient to justify the corresponding investment, the extension solutions generated by them are still unfeasible.

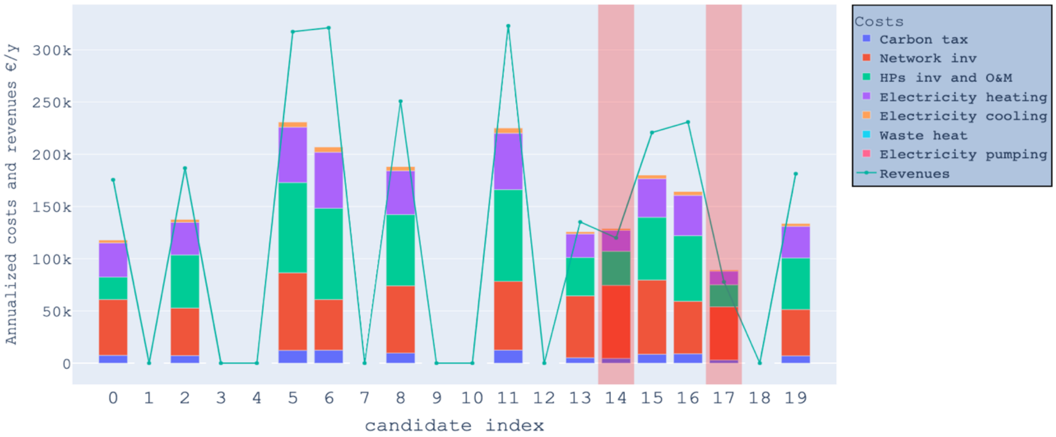
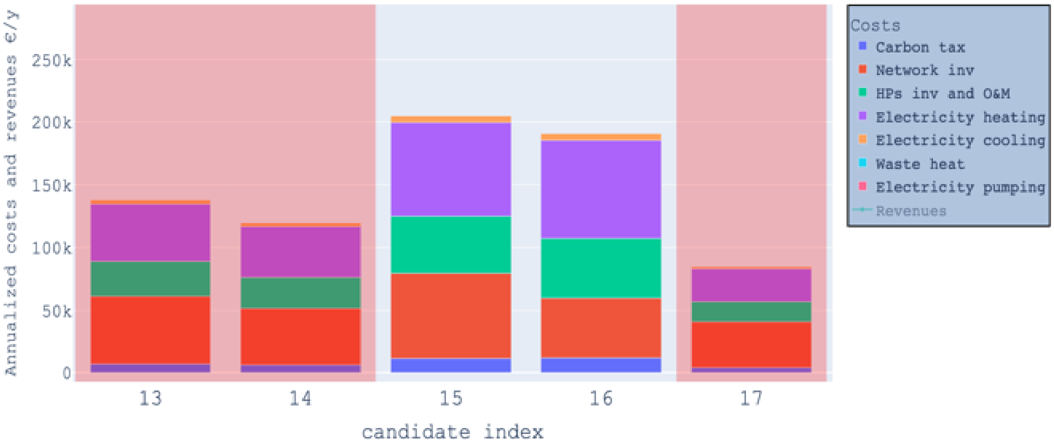


Figure 10. Annualized costs for the scenario with a 33%-lower non-residential electricity price: 95.47% of the FU is covered under this condition (i.e., one additional cluster is included with respect to the reference scenario).

Regarding the difference between decentralized HP technologies employing a network and individual A/W HP technologies, it is observed that the electricity costs are always higher for A/W HPs as compared to W/W HPs employed in the NT-DHC solution. Due to the favourable conditions of the source temperature during the heating season, the SCOP is indeed higher for the latter case. Moreover, it was assumed that the NT-DHC solution could benefit from a non-residential electricity price that is 25% lower compared to the residential electricity used by the A/W HPs. A/W HPs have higher installation and operation costs than W/W machines: even assuming the same investment cost data, a worse COP implies a larger installed capacity and higher electricity consumptions. In contrast, the network costs of the NT-DHC solution are a disadvantage, especially in areas where heat is low in density. Minor items such as carbon taxes and electricity for cooling do not significantly impact the overall difference.

Scenario "Electricity price increase (residential and non-residential)" of Table 5. If the electricity price goes up by 50% for all users (0.225 €/kWh for non-residential users and 0.30 €/kWh for residential users, respectively), the NT-DHC clearly faces significantly higher costs, as shown in Figure 11. Still, since in this scenario A/W HPs are affected by electricity cost increase in the same way, the competitiveness of the NT-DHC solution against the latter even increases (as the better operation of NT-DHC provides higher margin). Boilers become more competitive, though the overall H&C balance can remain in favour of NT-DHC if large cooling is introduced (see below), due to the high consumptions of split units.

Scenario "Residential customers' price remains stable or becomes cheaper" of Table 5. On the contrary, if the residential electricity price is lowered below 0.20 €/kWh, NT-DHC becomes less competitive against A/W HPs, as observed in Table 8. In this table, the winning NT-DHC scenarios are quantified in each of the three extension steps (S1, S2 and S3): the value "1" means that 100% of the scenarios find NT-DHC to be the best solution compared to the individual H&C solutions, and the value "0" means the opposite. Combined with Table 9, these results show that the electricity market affects the competitiveness of H&C solutions.



(b)

Figure 11. A 50% increase in electricity prices impacts adversely on the NT-DHC solution.

Table 8. Pricing conditions where the NT-DHC solution is more competitive than individual H&C scenarios. The colours represent the probability of a winning scenario based on the pricing conditions.

	Individual H&C									
	Electricity price [€/kWh]	0.150			0.20			0.30		
		S1	S2	S3	S1	S2	S3	S1	S2	S3
NT-DHC	0.10	0.90	0.83	0.75	1	1	0.83	1	1	1
	0.15	0.5	0.79	0.54	1	0.94	0.75	1	1	1
	0.225	0	0	0	0.45	0.79	0.54	1	0.95	0.77

Table 9. Percentage of the FU demand covered after three extensions under different electricity pricing scenarios

% FU demand vs. electricity pricing scenarios	**Individual H&C**			
NT-DHC	[€/kWh]	0.15	0.20	0.30
	0.10	92.38	95.47	95.47
	0.15	81.65	92.38	92.38
	0.225	0	81.65	85.83

Since the NT-DHC solution has network costs (and administrative costs, not explicitly included in the model) that individual solutions do not have, its competitiveness largely depends on favourable conditions leading to lower operating costs. In this regard, the W/W HPs in the network solution must perform at their highest level. The factors that may reduce the HPs' performance must be monitored: this includes systemic inefficiencies brought about by the HP's on/off cycles, thermal losses in substation pipes and buffers, and differences between datasheet and actual HP's performance.

This clearly depends on the network temperature. If H&C are both included, a compromise must be found (a higher temperature is convenient to boost the COP in heating mode, while a lower temperature is convenient to boost the EER in cooling mode). Figure 12 and Figure 13 illustrate how the temperature of the leading waste heat source, and therefore the network, impacts on the final costs and on the the HPs SCOP and SEER. In the NT-DHC context, the operation temperature is typically fixed by the available sources, but if a margin for tuning could be available, one could seek an optimal operation point depending on the amount of heating and cooling (possibly to be varied along the year).

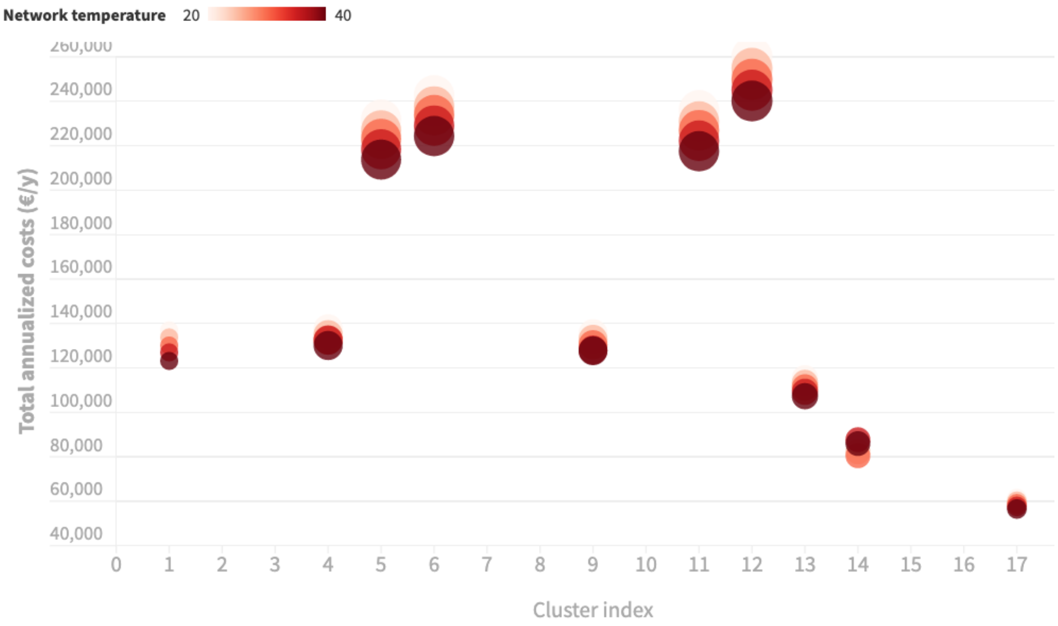
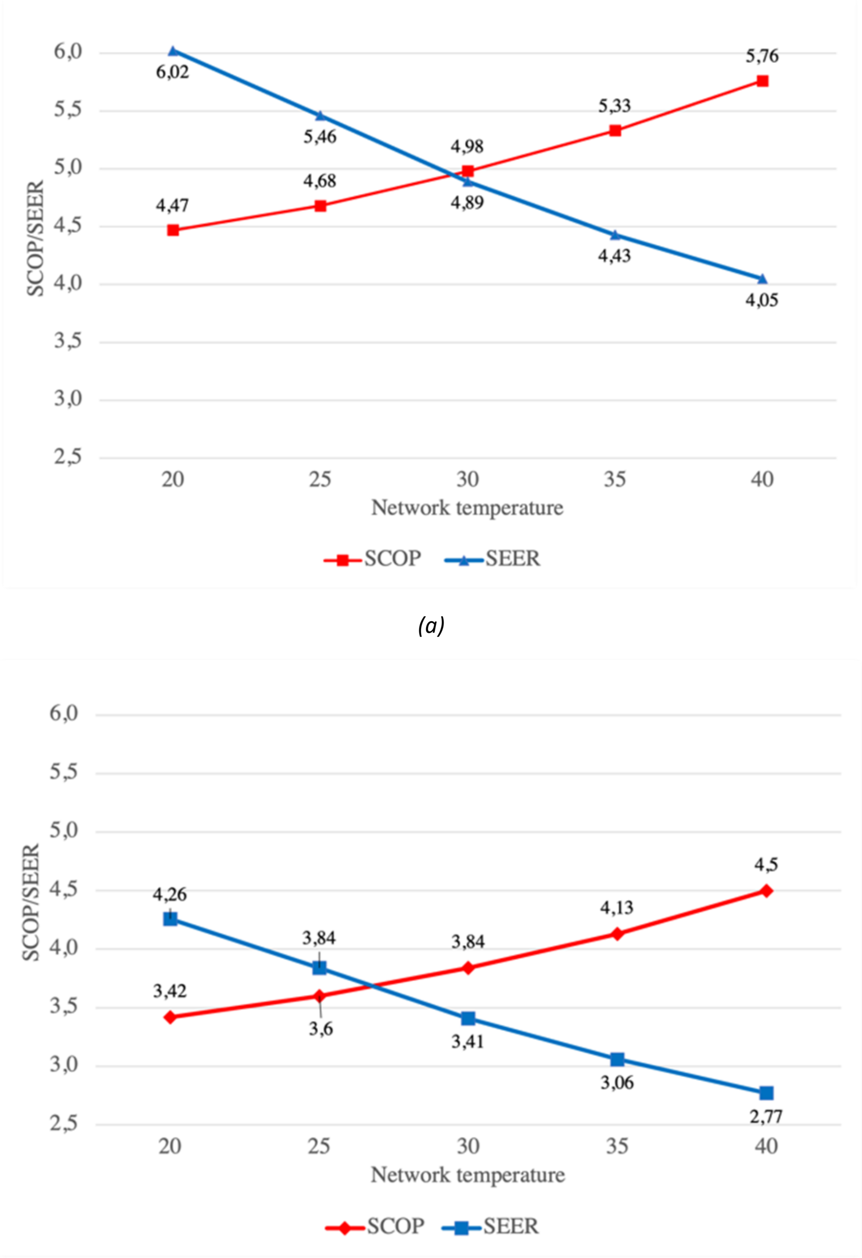


Figure 12. Impact in the total annualized costs based on different network operating temperatures. The size of the bubble represents the cluster peak power. Increasing the network temperature leads to maximum savings in larger clusters.



(a)

(b)

Figure 13. (a) Network temperature conditions and their impact on the theoretical network HPs performance (SCOP and SEER) used in the model. (b) Theoretical performance was reduced by 25%, accounting for possible operational inefficiencies independent from the source temperature.

3.6 Emission factors

A reduction in the renewable energy potential of electricity barely affects the techno-economic feasibility of the network extension. As a result, a scenario with a high share of renewables on the electricity grid (a reduction of 50% of the 2018 emissions) could save only 2 - 3% of the total costs. On the other hand, a grid based on emission levels from 2005 in Italy shows a maximum cost increase of 4.43%. Due to the electricity used by the HPs, the overall costs could have been even lower since these scenarios assume the network manager needs to pay a carbon tax of 75 €/tCO2 (relatively high taxation compared to the current European situation).

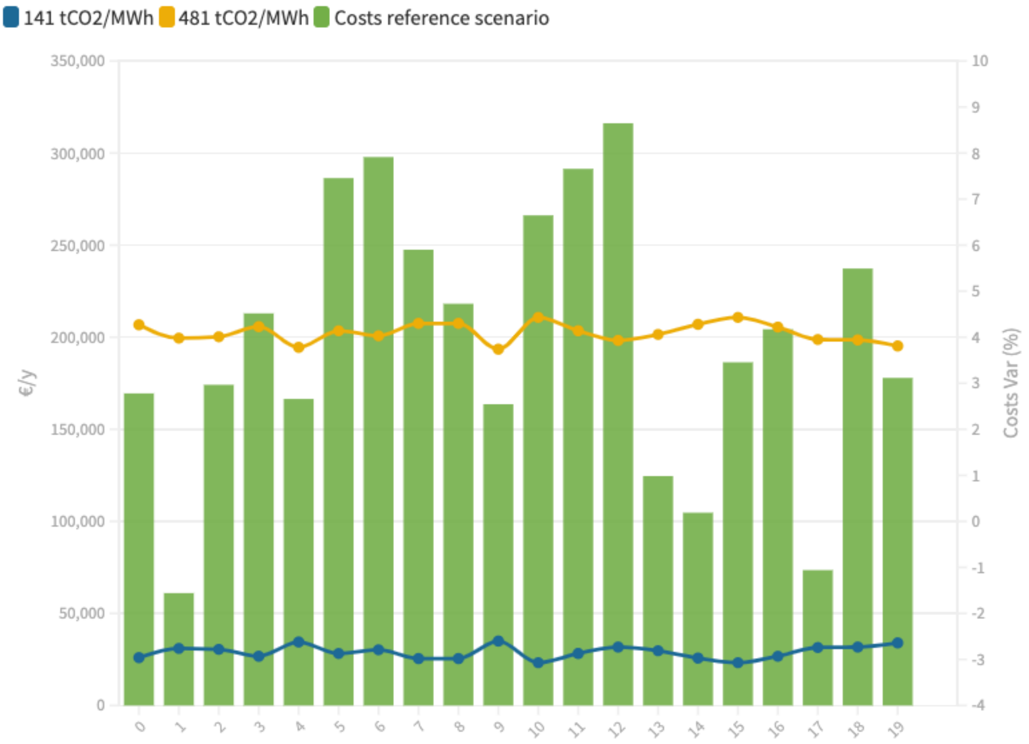


Figure 14. Total costs variation concerning the default emission factor. Results of the first extension scenario.

Table 10. Minimum and maximum costs variation in all extension scenarios.

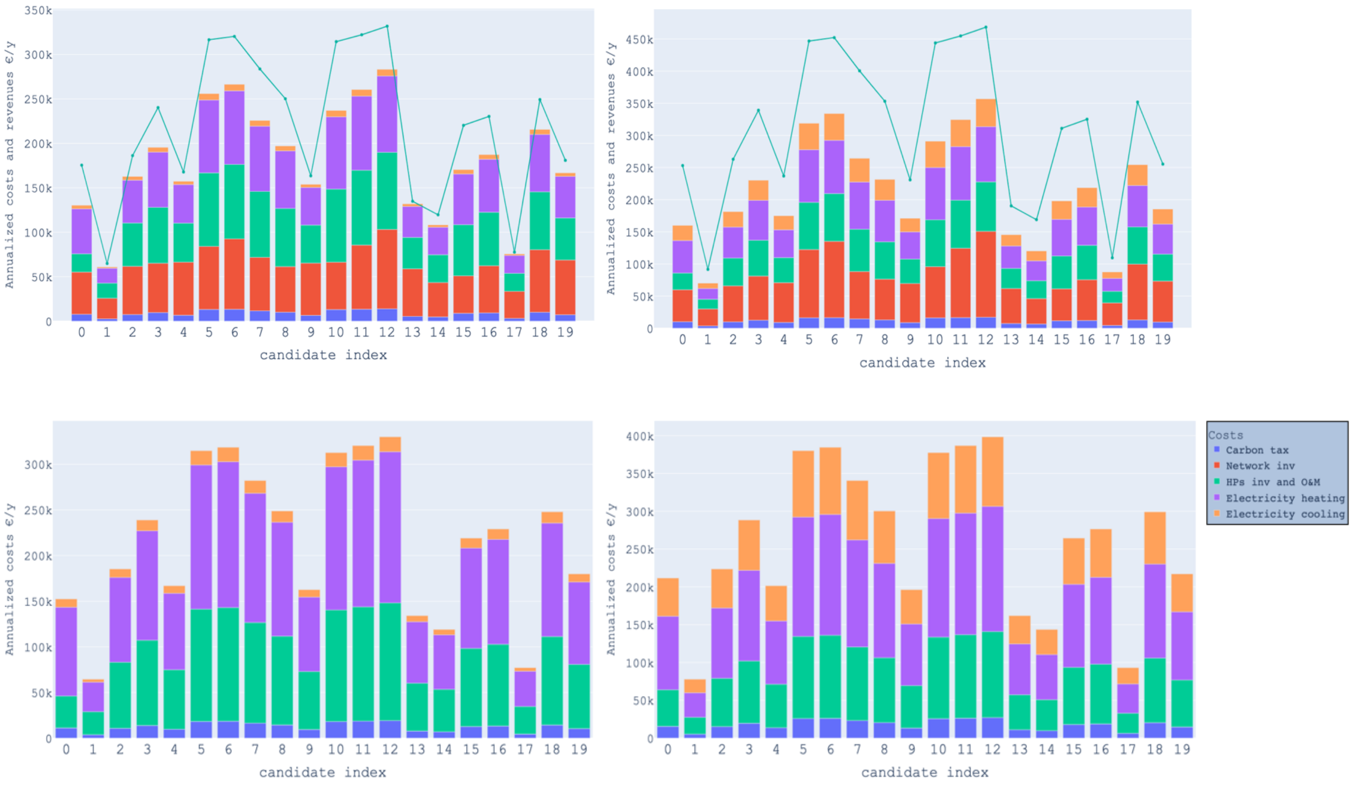
Extension scenario	Electricity emission factor			
	$0.141\ tCO_2/MWh$		$0.483\ tCO_2/MWh$	
	Min var (%)	Max var (%)	Min var (%)	Max var (%)
1	-3,07	-2,6	3,74	4,43
2	-3,20	-2,67	3,84	4,62
3	-3,06	-2,22	3,2	4,42

3.7 Cooling scenarios

In Figure 15, the NT-DHC system costs are compared with the A/W HPs solution in the first default network extension. The orange bars (electricity costs for cooling) for illustrate how the overall cost of both solutions increases as cooling penetration increases. In both the 2020 and 2050 scenarios, it is observed that the NT-DHC is less expensive than A/W HPs. Similarly, it is possible to see that the advantage of NT-DHC against individual solutions given by the combination of gas boilers and split units increase with higher cooling penetration.

Figure 16 shows that a slightly different transition pathway results from the cooling scenario of 2050 as compared to the transition pathway obtained in Figure 10. While the final covering of the city is the same, phase 2 and 3 are different in the two cases. In particular, due to the cumulative cooling sales under these cooling conditions, clusters 2 and 13 combined result in a more attractive investment option than cluster 12 alone in the second iteration.

It can be concluded that the NT-DHC solution in general benefits from a greater cooling penetration. Nevertheless, this factor alone does not justify investing in low heat density areas. Those areas are best suited to A/W HPs, as shown in the previous scenarios.



(a) (b)

Figure 15. Cooling scenarios. NT-DHC costs are shown at the top, while A/W HPs costs are shown at the bottom. (a) 2020 scenario (b) 2050 scenario

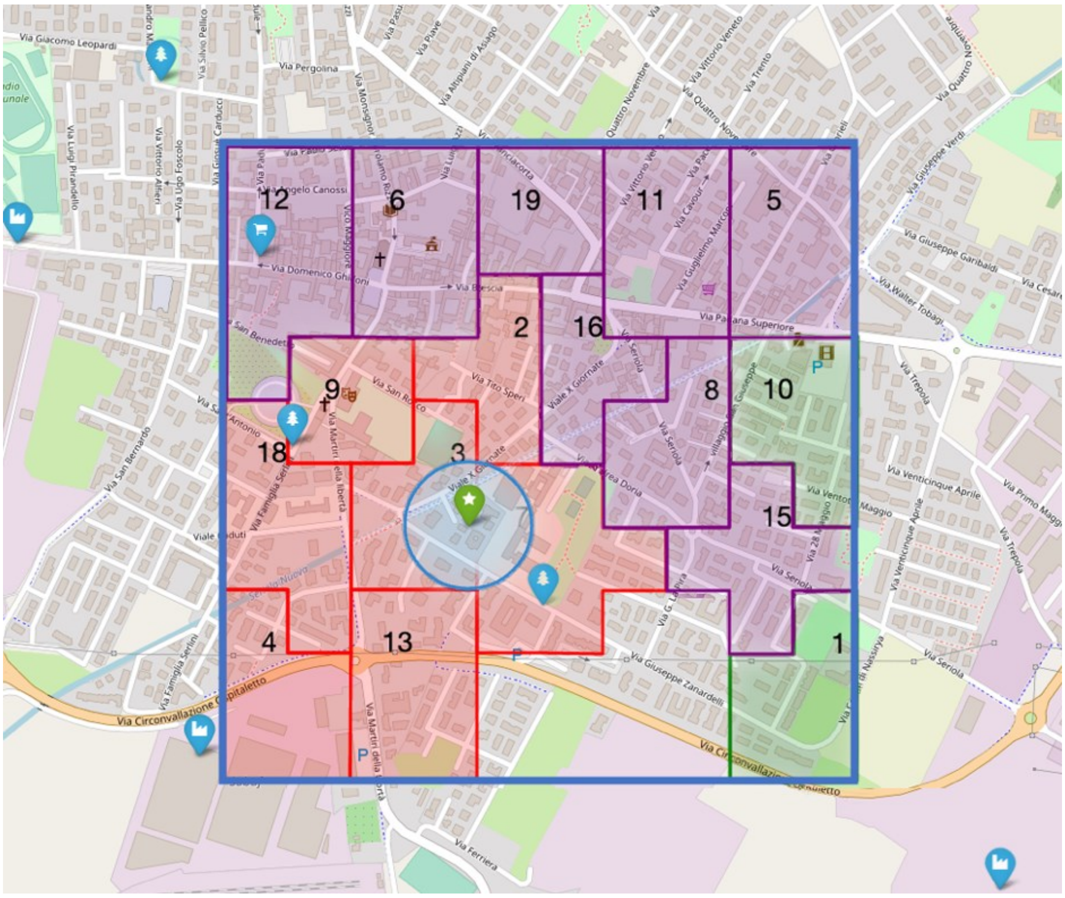


Figure 16. Final extension covering 95.47 % of the FU in the cooling scenario 2050.

4 Heerlen case

4.1 Review of the current situation

Heerlen is a city in the Netherlands, with around 85,000 inhabitants. It is part of Parkstad Limburg, a city-region agglomerate including other 7 municipalities (Heerlen, Kerkrade, Landgraaf, Brunssum, Simpelveld, Voerendaal and Beekdaelen), Heerlen being one of the largest ones. The entire Parkstad Limburg has a population of about 250,000 inhabitants. Nowadays, the different municipalities are basically touching each other, forming an almost continuous settlement. In turn, municipalities are sometimes further subdivided in different towns (with a main city with the same name of the corresponding municipality).

Within LIFE4HeatRecovery, this area has been analyzed from different perspectives. Besides being the location of one of the demonstration plants, located in cluster D of the Heerlen network, the Parkstad Limburg area was also considered for the identification of a “partner city” (see deliverable “Report on the pre-design studies at the Partner Cities networks”, Action C.6.3), considering first the Brunssum municipality and later also the town of Hoensbroek, which is part of the Heerlen municipality itself. Moreover, the development of the demonstration case started with the exploration of different options, first considering a detergent manufacturing company and finally identifying a foundry as the waste heat source (mainly coupled to a nearby swimming pool as a user to balance heat supply and consumption).

Due to this particular screening applied in other actions, it was not considered necessary to apply the same model developed for Ospitaletto to this case and some development scenarios were developed independently by Mijnwater (the company managing the Heerlen district heating network, beneficiary of the LIFE4HeatRecovery project).

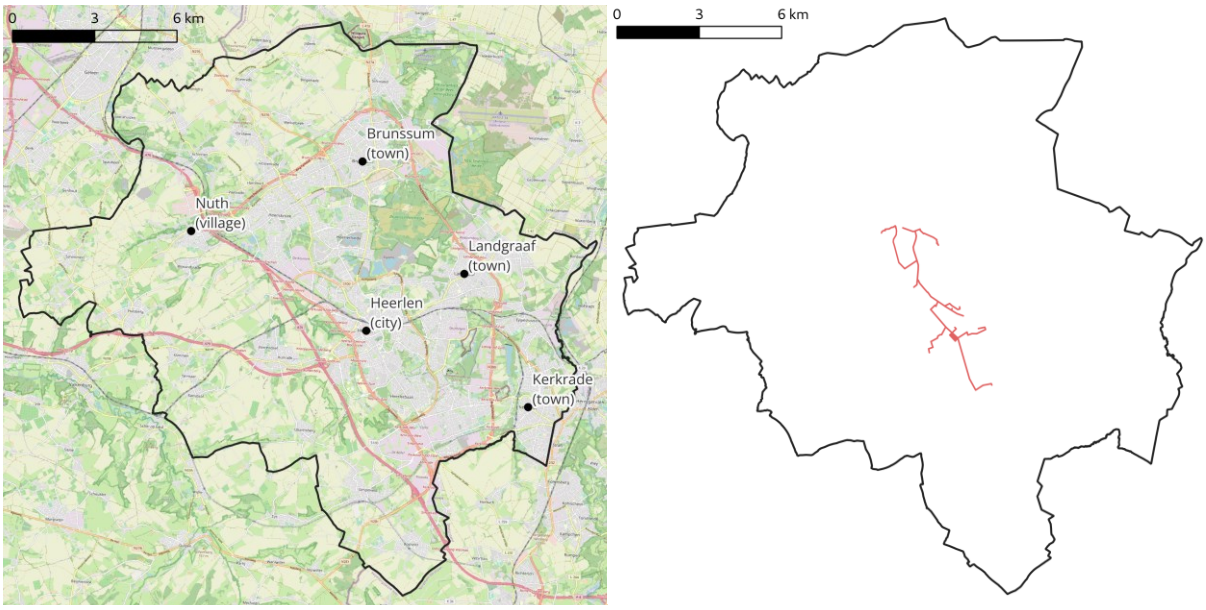
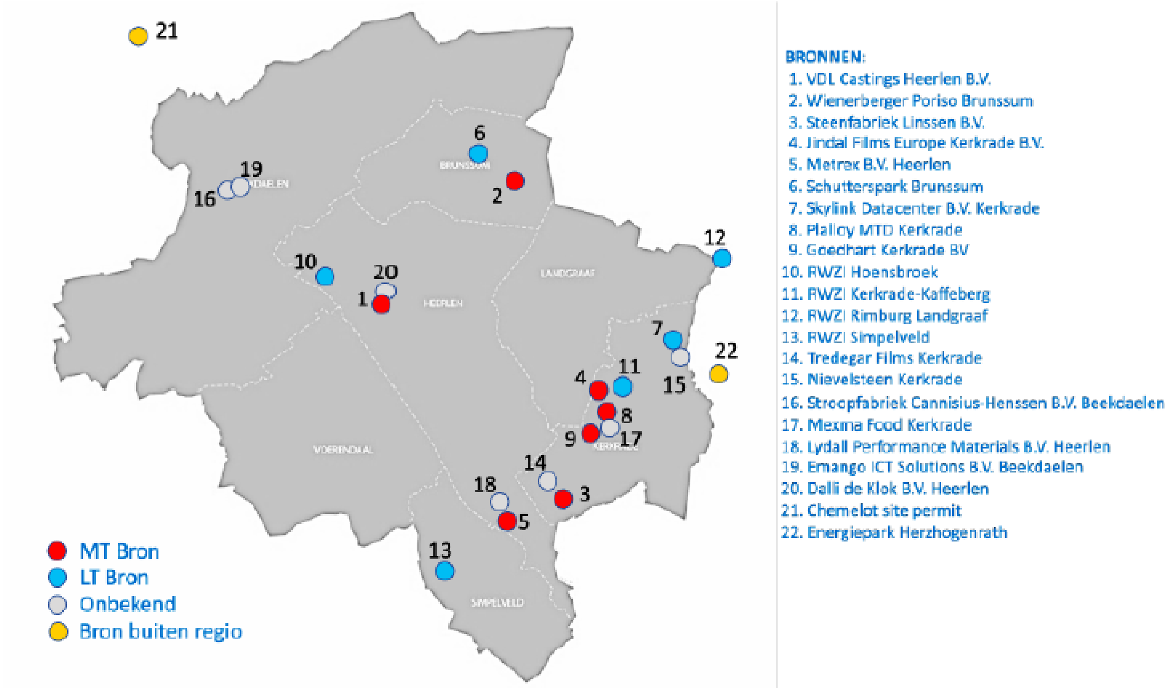


Figure 17. Map of the Parkstad Limburg area (left panel; Heerlen is roughly in the middle) and of the existing district heating infrastructure (right panel). It can be seen that a large expansion potential, in terms of non-connected buildings, is available.

4.1.1 Source mapping

Given the interest of Mijnwater for the entire Parkstad Limburg area, the waste heat mapping was extended to this boundary (see deliverable “Report on the GIS tool for waste heat recovery opportunities individuation”, Action C.6.4). The screening of **urban low-temperature waste heat** sources identified about 200 potential items (e.g., refrigeration from supermarkets and hospitals, as well as wastewater from laundries and swimming pools), for a total of **more than 250 GWh/y**. A large amount of this WH is generally difficult to exploit, being available in summer and being linked to small activities. In the case of Heerlen, however, the peculiarity given by the existence of an abandoned and now flooded coal mine, already connected to the network as a very large heat storage, offers the opportunity to have a seasonal balancing of the heat. More explicitly, the mine acts as a **seasonal thermal energy storage for the network**, so that even WH available in summer can be exploited.

Beside the aforementioned urban low-temperature WH, Mijnwater is constantly screening the industrial zones in the proximity of the network, where about 20 factories were identified as potential sources. The overall energetic potential cannot be reported here, as the industrial WH mapping methodology applied for Italy and Denmark was hindered by the Dutch regulation for chambers of commerce, which puts stricter limits on the sharing of company data. Nevertheless, the names and the locations of the identified activities can be shown, see in Figure 18, taken from Ref. [5].



Source: (Gemeente Heerlen, 2021).

Figure 18. The main available industrial waste heat sources [5]. The red sources are mid temperature sources, the blue sources are low-temperature sources, and the yellow sources are sources that are outside Parkstad Limburg.

4.1.2 Loads

Assuming that the 85,000 inhabitants of Heerlen are distributed in 35,000 apartments each with a floor area of 100 m^2, about 2.5 persons, and a specific consumption of 130 kWh/(m^2 y), one would get can an overall yearly consumption of about 455 GWh/y for the residential part. This is a conservative estimate which might be the arrival point of a series of efficiency measures applied to the building stock in future years. The current estimated residential energy consumption of the entire Heerlen municipality (including surrounding towns like Hoensbroek) is estimated to be about 2200 GWh/y [6].

The current number of customers of Mijnwater includes more than 400 dwellings and more than 250,000 m^2 of commercial buildings. It is hence clear that a large expansion potential exists.

4.2 Technical, economic, and environmental inputs

Mijnwater drafted and is continuously updating a general masterplan (see below) until 2040, which includes several strategic considerations at political, social, and regulatory level. Such roadmap is based on more general considerations with respect to the techno-economic analysis proposed for Ospitaletto. Therefore, a detailed analysis of the techno-economic and environmental parameters for the Heerlen case is not considered here, though specific tables with the parameter values estimated within LIFE4HeatRecovery are presented in the project deliverable of Action D.2.1, “Report on the socio-economic impact produced at the 3 demonstration networks”.

4.3 Scenarios

The approach described here below for Heerlen can be considered complementary to the type of analysis applied to Ospitaletto. As a whole, the combined methodologies presented in this deliverable can hence provide a broad perspective on the development of energy transitions scenarios.

Mijnwater worked on its masterplan with the objective to be in line with targets fixed by the national and local energy policies. From this point of view, Mijnwater always followed a development path [6]:

- The Mijnwater 1.0 system was developed in the 2005-2012 period, mainly with a centralized supply solution, based on the heat initially extracted from the warm water in the abandoned and flooded local coal mine. In winter, warm water at 28 °C was fed from the mine into the grid to deliver warmth, while in summer cool water at 16 °C from a shallower cool source was distributed. Booster heat pumps at customer substations provided the right temperature level to the user. In this phase, there was no simultaneous exchange between customers. This grid started by serving one large office building (national statistics bureau CBS) and a social housing project. However, there were signs that this setup was slowly exhausting the geothermal source, meaning that it could not be scaled up much further. Hence, a new design was made in 2012 by Mijnwater BV.
- The Mijnwater 2.0 system was started in 2013, becoming a fully functioning 5th Generation Heating and Cooling grid. With this step, the network became able to deliver both heating and cooling, allowing an energy exchange between all customers simultaneously, while the mine water system was used to store heat and cold. Customers could then become “prosumers”, i.e., both producers and consumers of heat. Bidirectionality of heat exchange became the standard. The network was structured as a backbone, connected to the mines for energy balancing, and a series of “cluster grids”, i.e., subnetworks serving specific areas and connected to the backbone through a large heat-exchanger in a “cluster installation”. In spring 2019 (about 1 year after the start of the LIFE4HeatRecovery project), the network included four cluster grids.
- The Mijnwater 3.0 system, still being implemented, pursues the last development step of the original design. Here, without affecting the required comfort levels for users, the objective is to optimize the exact timing of demand from buildings. As an example, large buildings could be heated more slowly by starting slightly earlier in time than requested by the thermostat, to avoid a morning peak from all large office buildings starting their working day at exactly the same time.

The purpose of this optimization is to reduce maximum peak demand on the grid infrastructure. Since the diameter of the existing piping infrastructure always forms a bottleneck in the system, this optimization of the controlling software will create space to reliably serve a substantially larger number of customers

The implementation of Mijnwater 3.0, expands the potential number of customers for the network.

The existing Mijnwater clusters are shown in Figure 19.

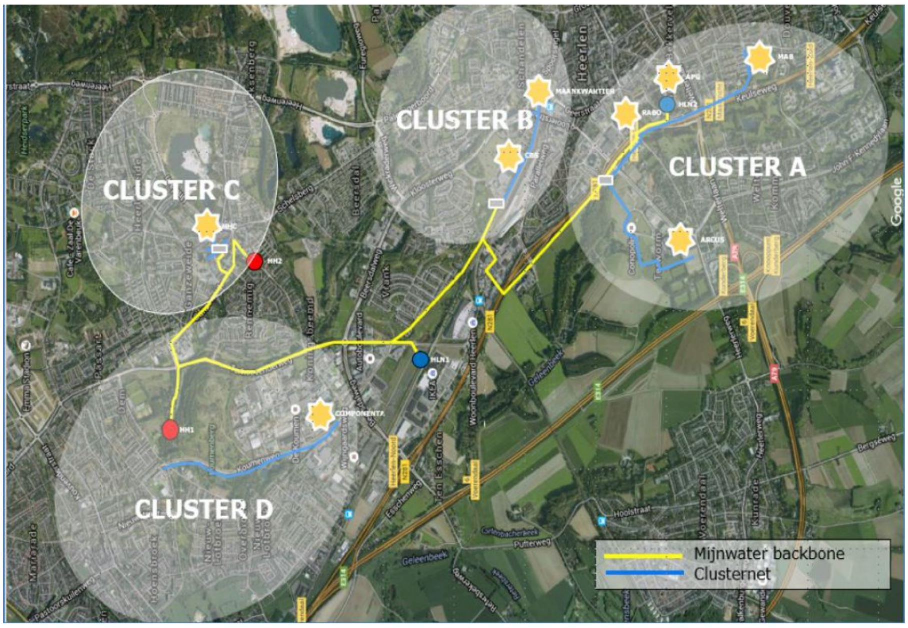


Figure 19. Heerlen network and related clusters.

In terms of general development targets, Mijnwater took into account the PALET (PArkstad Limburg Energy Transition) program developed by the Parkstad region in the past years.

In order to be able to significantly contribute to the decarbonization of the local area, Mijnwater followed a plan to build higher capacity with a more structured organization. In a first phase, the Mijnwater system was a sustainability project of the municipality of Heerlen. In 2012, together with the transition to the Mijnwater 2.0 system, Mijnwater was privatized becoming Mijnwater B.V., still with Heerlen municipality as 100 % shareholder. In 2018, the Limburgs Energie Fonds (LEF) has become the owner of the company (with the municipality of Heerlen still participating with a loan), and a new governance structure was introduced. This was crucial to scale-up the activities.

In parallel to this reorganization, Mijnwater started collaborating with local building associations, which own almost 50 % of the building stock in the Parkstad region. At the same time, attention to individual customers was kept high, due to their crucial role in terms of full system implementation and acceptance. Moreover, more interaction with large offices and enterprises was pursued, as they were found to represent a sector very interested in Mijnwater services.

At this stage, the **focus on waste heat** became crucial. Medium sized and large industries are high potentials for “mining” residual energy, but often more difficult to understand and connect to the grid, as interventions need to take place in their production processes. The challenge was found to be **seeking for win-win situations** that, on the one hand, bring benefits to the customer (i.e. by phasing out cooling towers or energy generators, achieving financial benefits, achieving sustainability goals and reducing CO2 emissions), and on the other hand create a sustainable business case for Mijnwater by delivering the required energy to the customer under simultaneous "mining" of usable residual energy. Once connected, these customers become prosumers.

In terms of system stakeholders, Mijnwater also explored possible synergies with other utilities, like drinking water companies, sewer-companies, water authorities. This can in principle lead to joint replacement programs, sharing costs for, e.g., excavation works in the streets and minimizing the inconvenience for local residents.

In terms of general planning, the following main **expansion scenario** is expected:

- In the 2024-2028 period, Mijnwater plans to gain a foothold in all municipalities with dense built environment: Heerlen, Brunssum, Kerkrade, Landgraaf. Also the municipalities to the South-West and North of Heerlen (Simpelveld, Voerendaal, Beekdalen) will be considered in this phase, even if they consist of smaller villages in a more open natural environment. Moreover and more in detail:
    - *Consolidation of the cluster D* of the Heerlen network, expanding the number of connected customers. The development of cluster D was started within the HeatNet NWE Interreg project for the piping system and was continued in the LIFE4HeatRecovery project with the connection of a foundry as a low-temperature waste heat source and of a swimming pool as a large user (see Figure 20).
    - Starting subnetworks in nearby municipalities, beginning with *Brunssum*. Here, it was identified a collaboration opportunity with Weller, a social housing corporation, in connection with a renovation plan involving about 550 apartments. As discussed in the deliverable "Report on the pre-design studies at the Partner Cities networks" (Action C.6.3), a large low-temperature heat source was identified in the nearby wastewater plant.
    - This phase is also expected to involve a focus on *optimizing the interaction with neighborhoods mostly comprising private homes* (as opposed to the current well-established experience with large offices and buildings). This might require forming a local representative council of homeowners, devising methods to ease the financing of the possibly necessary building refurbishments.
    - Other capacity-building objectives will include optimizing the cascading of heat exchange from high temperature waste heat. In connection to waste heat, MIjnwater is also prepared to face *possible setbacks*, like one industrial source of waste heat ending its delivery. The Mijnwater grid can handle this risk by exploiting more the mine geothermal resources for a limited period. Such an experience, including further optimization and learnt lessons, would further strengthen the robustness of the grid.
    - All these steps would contribute to leading more and more clusters to a "*safe asset*" status, with a stable income. This is considered a crucial progress for Green Bonds to become an important funding source for low interest investment in further expansion. Moreover, the scaling up of the systems would give increase standardization and mass production/procurement of components, possibly leading to economies of scale.
- In the 2030-2034 period, due to the long term maintenance required at timescales of 15 years, a larger fraction of owners of large buildings, building blocks, schools, shopping centres and building associations will become available for connection. This will enable a further scaling up. Moreover thanks to the expected penetration of renewable electricity, electric energy prices will probably

drop to more favorable levels for heat pump operation, enlarging the number of economically feasible cases for Mijnwater.

- In the <u>2035-2039 period</u>, a steady buildout is expected to continue. Large offices, shopping malls, and schools will nearly all be connected to the Mijnwater system, as well as a large fraction of homes owned by building associations. Standardization and mass production should start to make it affordable to connect even relatively small and isolated clusters of homes.
- The final target for <u>2040</u> for Mijnwater is to deliver sustainable heating to most of Parkstad region, with nearly fully decarbonized sources.

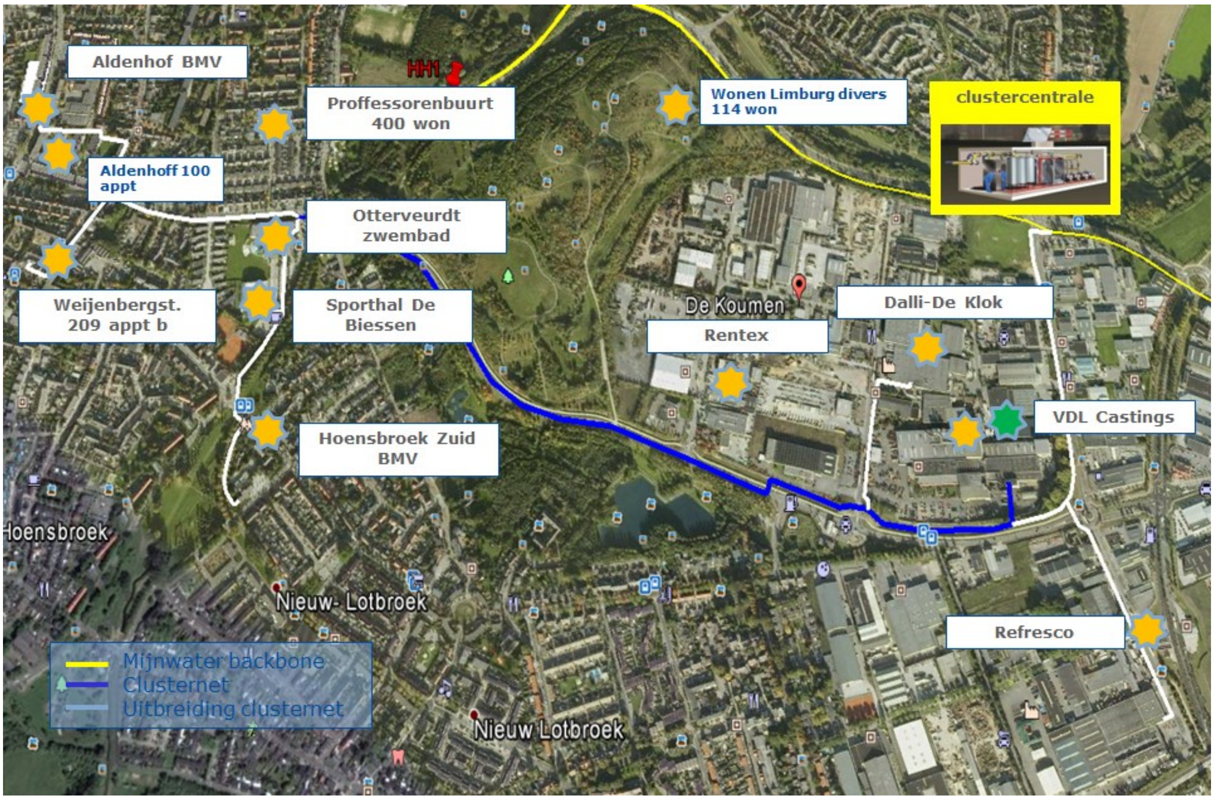


Figure 20. Some of the identified prosumers for cluster D. Some of them are already connected (VDL foundry and Otterveurdt swimming pool were connected as part of the LIFE4HeatRecovery project). Similar maps have been developed by Mijnwater for the other network clusters and the surrounding areas.

5 Aalborg case

5.1 Review of the current situation

Aalborg is a Danish city with an urban population of about 150,000 inhabitants (around 220,000 inhabitants including the entire municipality, which extends on a large territory). Most of the city is reached by a conventional district heating network (the supply temperature is controlled to reach about 80 °C in winter and about 60 °C in summer), largely supplied by waste heat (from a big cement factory) and combined heat and power plants (CHP), mainly burning coal.

Since the network has approximately already reached its maximum expansion potential, it was not considered of significant interest to apply the expansion model developed for Ospitaletto to this case. Indeed, non-connected clusters could be found only in very low-density zones, where individual heating technologies are expected to be a more convenient solution.

Nevertheless, this chapter quickly sketches a possible expansion scenario for low-temperature waste heat, as an alternative to fossil-fuelled plants. The identified sources are connected to the analysis carried out in Action C.6.4 for GIS mapping, integrated by some information on data centre expansion. A more detailed socio-economic scenario for the penetration of low-temperature waste heat is also reported in the deliverable of Action D.2.1, “Report on the socio-economic impact produced at the 3 demonstration networks”.

Figure 21. Map of Aalborg area (left panel) and of the existing district heating infrastructure (right panel). It can be seen that the connected area basically covers the entire urban area.

5.1.1 Source mapping

A general mapping of waste heat (for the entire municipality) was carried out in Action C.6.4. The overall potential urban waste heat (including all possible activities generating low-temperature waste heat, ranging from refrigeration in supermarkets and hospitals, to wastewater from laundries or swimming pools) of the municipality was estimated to be approximately 196 GWh/y. The potential non-exploited industrial waste heat was instead estimated to be in the range of 22-189 GWh/y, depending on the used method to analyze the different industrial sectors. On the one hand, these results involve a significant uncertainty (as evident from the large range identified for industrial waste heat), on the other hand they anyway suggest a very significant potential. The analysis also showed a rather distributed presence of waste heat sources. While this would require multiple connection projects (it is not possible to think in terms of a single large waste heat generation plant), the existing infrastructure (in terms, e.g., of pipe diameters) is expected to easily accommodate such distributed sources, which would act as local "load-reducing" nodes.

5.1.2 Loads

Ref. [7] reports some data on Aalborg loads, including suggestions and projections for their possible evolution. The paper reports a heat demand for the central district heating network of about 1.8 TWh/y (2.28 GWh/y of consumption), against an overall heat demand (including small decentralized networks and non-connected buildings) of about 2.15 TWh/y (2.7 TWh/y of consumption). One can then see that the central district heating network covers about 84 % of the overall demand. The paper also considers some load reduction possibilities, thanks to efficiency measures, possibly arriving to decrease the district heating consumptions down to about 1 TWh/y.

5.2 Technical, economic, and environmental inputs

Since it is not interesting to consider a network expansion for this case, the analysis of the techno-economic and environmental inputs is not discussed in detail here. On the other hand, parameters for energy prices, emission factors, and other techno-economic inputs for the Aalborg case are presented in the aforementioned project deliverable of Action D.2.1, "Report on the socio-economic impact produced at the 3 demonstration networks".

5.3 Scenarios

As mentioned above, the total unexploited amount of waste heat identified for Aalborg was estimated to be almost 400 GWh/y. Part of this WH can be out of phase with respect to demand (e.g., available in summer) and part can be difficult to exploit. Assuming an exploitation factor of 25 % (half of the waste heat discarded because of out-of-phase, and half of the remaining amount discarded because difficult to connect), this would yield about 100 GWh/y, i.e., about 10 % of the DH consumption (1 TWh/y) expected after the introduction of the efficiency measures considered by Ref. [7]. This is clearly a qualitative estimate, but it shows the order of magnitude of the potential impact of waste heat in this case. More quantitative results, including economic estimates about the penetration costs of low-temperature waste heat (as an alternative to part of the fossil sources currently used by Aalborg district heating), are reported in the work Action D.2.1, "Report on the socio-economic impact produced at the 3 demonstration networks".

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