Assessment methodology for urban excess heat recovery solutions

The work covered in this article focuses on presenting an assessment approach to support further consistent demonstration based on four representative case studies from the ongoing ReUseHeat project, which allow for different heat sources, markets and geographical areas across Europe. The full report is available on ScienceDirect.

Description of urban excess heat recovery case studies

The aim of this section is to briefly present a concept description for each case study as well as their main characteristics. This will facilitate the understanding of the evaluation framework in combination with the relevant particularities and/or restrictions of each case. The four addressed concepts are the following:

- Waste heat recovery from data centres. Brunswick (Germany) demo case.
- Waste heat recovery from sewage water. Nice (France) demo case.
- Waste heat recovery from cooling systems in tertiary buildings. Madrid (Spain) demo case.
- Waste heat recovery from underground railway stations. Bucharest (Romania) demo case.

Waste heat recovery from data centres

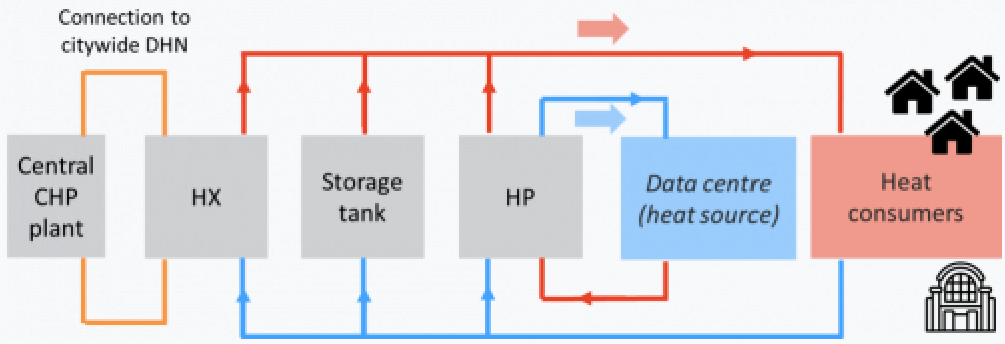

Fig. 1. Conceptual diagram of the heat recovery solution from a data centre in Brunswick. Image: CARTIF, IVL (link)(CC BY-NC-ND)

Data centres have rapidly emerged in response to the increasing demand of digital and cloud services. They are responsible for a relevant share of the total electricity consumption and involve important cooling demands. The need for rejecting heat from data centre indoor spaces provides a low-temperature excess heat source that can contribute to meet the heating demand of end users. Figure 1 shows the conceptual diagram of a case waste heat recovery from a data centre in Brunswick (Germany). A group of heat consumers (from residential and commercial sector) are connected to a local DHN. This local network is connected through a plate heat exchanger (HX) to the main citywide DHN based on central production in a CHP plant. A heat pump is used to capture excess heat from the data centre cooling facilities and upgrade it to the DH supply temperature level. The heat delivered by the data centre will be recovered through air-water HXs providing an outlet water temperature around 18-25 °C. In order to exploit all the heat recovered throughout a day, since the energy demand varies with respect to the heat generation, a thermal storage tank is included within the local DHN. The efficiency of the heat pump operation will be maximized with a simultaneous useful double effect: (i) data centre cooling supply at source level, and (ii) end-use heating supply at sink level.

Waste heat recovery from sewage water

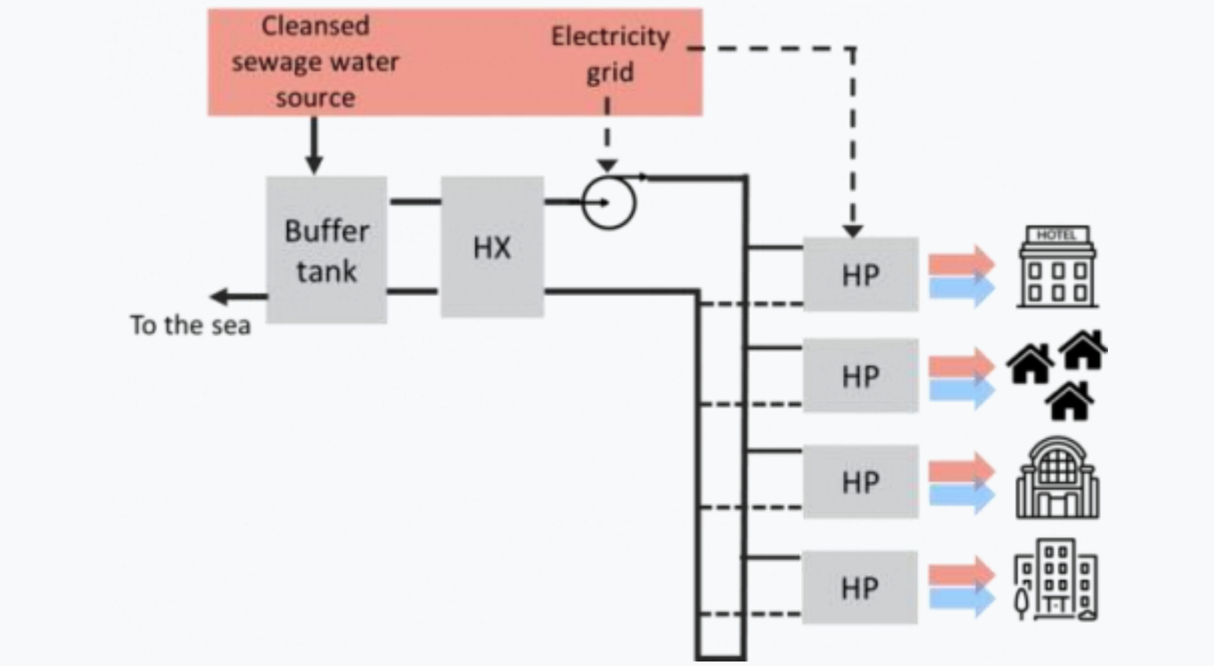

Fig. 2. Conceptual diagram of the heat recovery solution from sewage water in Nice. Image: CARTIF, IVL (link)(CC BY-NC-ND)

Water in urban sewage networks retains significant fraction of the thermal energy supplied to the buildings. This involves a relevant potential to provide sustainable heating and has made sewage water heat recovery applications become widespread in recent years. Figure 2 shows the conceptual diagram of a case waste heat recovery from sewage water in Nice (France). Once wastewater from the municipal network is cleansed in the WWTP and before being discharged to the sea according to the local environmental legislation, this water is passed through a buffer tank and partially pumped to a plate HX. Afterwards, a low-temperature DHN distributes the tempered water to each building substation, which hosts a reversible heat pump, a DHW tank and an electric boiler as back-up equipment. The estimated available temperature in the low temperature side of the HX varies depending on the season, being around 26 °C in summer and 12 °C in winter. Such moderate temperature levels are also based on a hybrid heating/cooling operation at network level with possible efficient load compensation among different buildings. In addition, they enable high-efficient operation of the end-use heat pumps, which otherwise will not be possible. Two different operating modes (at building level) should be considered:

- During the heating mode, end-use heat pumps will take the heat from the low-temperature network. Therefore, the return pipe of the LTDH network will be colder than the supply, thus extracting heat from the tank in the WWTP and cooling down the temperature of the outflow sent to the sea.
- During the cooling mode, the reverse situation will occur: end-use heat pumps will reject heat to the low-temperature network. Therefore, the return pipe of the LTDH network will be warmer than the supply, thus injecting heat to the tank in the WWTP and slightly increasing the temperature of the outflow sent to the sea.

Waste heat recovery from cooling systems in tertiary buildings

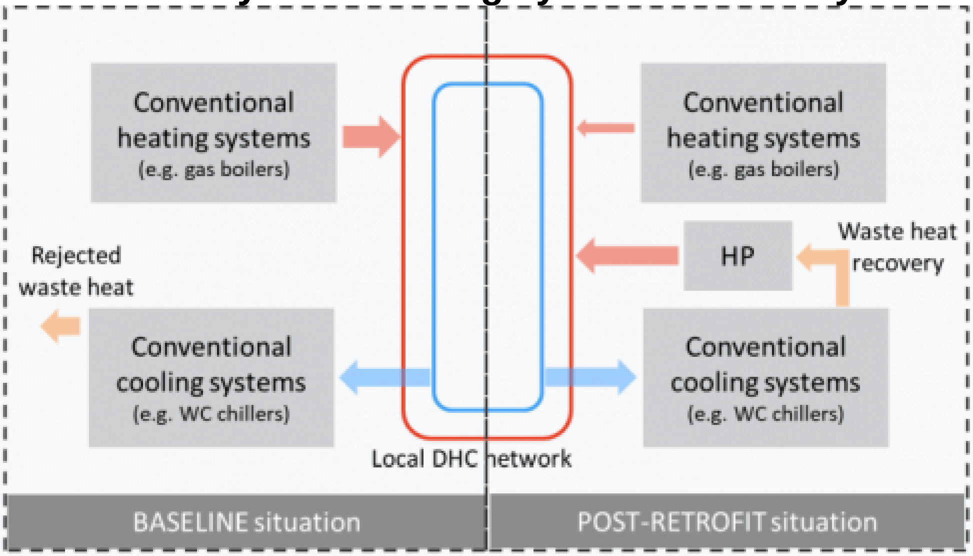

Fig. 3. Conceptual diagram of the heat recovery solution from a hospital's cooling system in Madrid. Image: CARTIF, IVL (link)(CC BY-NC-ND)

Tertiary buildings (offices, commercial buildings, hospitals, etc.) often present important cooling demands throughout the whole year, particularly in Southern countries. Heat removed from indoor spaces is normally rejected to the environment by conventional cooling systems, but it represents a low-temperature waste heat source of great potential to meet other surrounding heating demands.

Figure 3 shows the conceptual diagram of a case waste heat recovery from a hospital's cooling system in Madrid (Spain).

The hospital buildings are served by a local DHC network. In a baseline scenario, heat and cold production is performed by conventional equipment (gas boilers and water-cooled chillers individually connected to closed-loop cooling towers, respectively). The heat recovery intervention is based on a booster heat pump unit connected to the condensation circuit of the cooling generation plant. The heat rejected by the chillers is captured, thermally upgraded and injected to the heating supply. Particularly, the heat pump hot sink will be connected to the return pipe of the local DHN and used for preheating the water flowing into the district heating boilers. For the proper functioning of the facility, the targeted temperature available in the heat dissipation must be around 30 °C, aiming to reach 75 °C in the district heating flowing water. Electric energy is currently needed by the chillers and the cooling tower fans. By implementing the heat recovery solution, it is expected to get a decrease in the cooling towers consumption and an additional need in the heat pump and maybe in the target chiller (due to a slightly higher condensation temperature). In the end, the amount of primary energy used as well as some water additives is expected to be reduced after the heat recovery intervention.

Waste heat recovery from underground railway stations

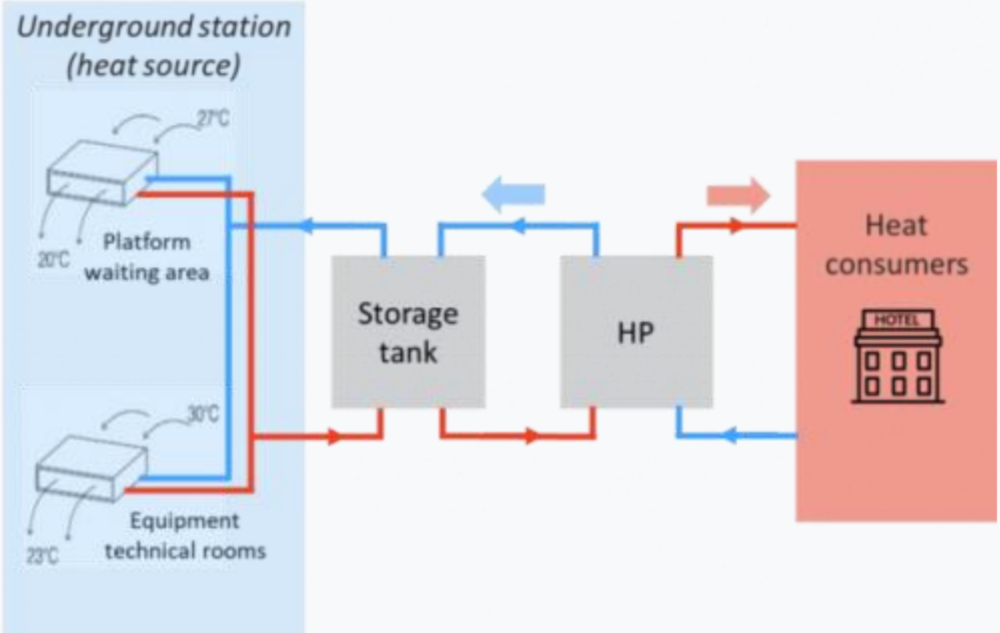

Fig. 4. Conceptual diagram of the heat recovery solution from an underground railway station in Bucharest. Image: CARTIF, IVL (link)(CC BY-NC-ND)

Underground railway transport systems in large cities comprise relevant excess heat sources at urban level. Train brakes energy use is ultimately rejected as heat into the tunnels and waiting platforms, which are also affected by heat gains from a great number of transport users. Additionally, technical rooms with electric equipment for traction, lighting, HVAC systems, etc. are particularly interesting hot spots. Figure 4 shows the conceptual diagram of a case waste heat recovery from an underground railway station in Bucharest (Romania).

The solution exploits that heat released in an underground station in order to supply a heating demand in a nearby area. A booster heat pump will be used for a temperature upgrade so that the heat recovery could be directly injected into the Bucharest citywide DHN or into a separate/private heat supply system. Some previous heat recovery experiences in underground transport systems reported in literature are based on HXs directly placed within existing ventilation shafts. Here, specifically, the heat capture is performed through a set of fan-coils distributed in two different spaces to be conditioned: the waiting platform and technical rooms. These fan coils, acting as cooling terminal units, provide heat up their water return pipes due to the heat dissipation. They are connected to a thermal storage tank and the heat pump, which provides upgraded energy to preheat the water flow supplied to the end consumers for space heating and/or DHW provision. Beside the subsequent reduction of the energy consumption for heating purposes at the demand side facilities, there will be benefits linked to thermal comfort gains within the underground spaces and, above all, benefits for the transport system operator and owner of the underground infrastructure. These will be associated to the reduction of the electricity use for HVAC systems at the underground facilities.

General evaluation methodology

Based on the preconditions of the case studies described above, the definition of the evaluation framework is provided next. This approach relies on existing methodologies and definitions that are commonly used in similar energy-efficient retrofitting interventions, aiming to adapt to the particular cases of urban excess heat recovery, as well as extend the scope of the evaluation to account for other dimensions of its potential impact. A twofold objective is addressed:

- Savings verification, which must be based on proper measurements and a consistent methodology for data-processing comparing baseline and post-retrofit scenarios. This will define the M&V plan.
- Extended assessment of impacts and performance, since there will be many other relevant variables, parameters, etc. besides what can be strictly defined as 'savings'.

Both aspects are treated from four different perspectives, namely: energetic, environmental, economic and social; and they will be condensed into a set of KPIs and auxiliary measurements.

Savings Measurement and Verification (M&V)

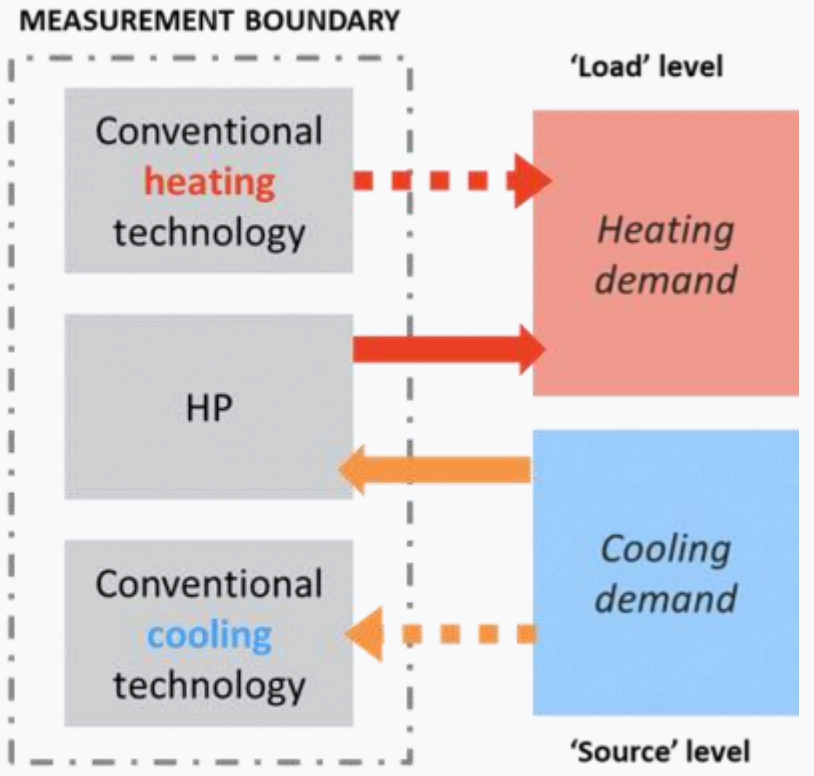

Fig. 5. Measurement boundary for energy savings evaluation. Image: CARTIF, IVL (link)(CC BY-NC-ND)

The present evaluation methodology takes the International Performance Measurement and Verification Protocol (IPMVP) [17] as the basis for the assessment of the targeted urban excess heat recovery solutions. Although this kind of technical interventions are not specifically addressed within the most commonly-used existing protocols, IPMVP has been considered as the most suitable one for this purpose, on account of its simplicity, adaptability and broader scope, including explicit consideration of economic aspects. The overall assessment methodology mainly relies on the comparison of the baseline and post-retrofit situations according to the definition of a measurement or evaluation boundary. Particular specifications apply depending on the availability of monitored data.

- Missing real data for the baseline scenario requires the development and calibration of a simulation model. The calibration will be based on values measured during the post-retrofit period. Then, the heat recovery is removed from the model, and simulations are performed to estimate the theoretical performance of the baseline scenario, considering typical reference energy systems and their performance curves/maps.
- If real data from both baseline and reporting periods are available, fair comparable reference conditions must be guaranteed. Energy use will be correlated to relevant independent variables (weather, use patterns, etc.) based on regression and/or detailed simulation models. These will be used to estimate the performance profile of the target systems under such comparable conditions.

Concerning the characterization of the measurement boundary for the targeted urban excess heat recovery solutions, it is a recurrent matter that such actions involve modifications in cooling systems, capturing the released low-temperature heat and upgrading it through a heat pump afterwards with the aim of reaching the targeted temperature for space heating and/or DHW supply. Then, they will have relevant impacts both at ‘source’ and ‘load’ levels. Considering this Figure 5 shows the proposed general definition of the measurement boundary.

Key Performance Indicators (KPIs)

An appropriate definition of indicators is recommended for a consistent evaluation of energy retrofitting projects. They allow both the assessment of the technical intervention at issue and potential similar implementation actions. This section tackles the definition of energetic and economic KPIs aiming to support the IPMVP approach. SCIS guidelines have also helped to select proper environmental and social indicators that complete a comprehensive assessment of the targeted solutions. Table 1 presents the proposed list of KPIs.

Energy indicators

Within the scope of non-conventional urban excess heat recovery interventions, energy is the main target dimension of the proposed evaluation methodology. EN stands for ENergy indicators in Table 1.

- Useful and final energy demands constitute the first step to enable the calculation of primary energy use and savings, which will then derive the main environmental and economic figures. Fixed conversion coefficients from European databases (e.g.) will be used in a first simplified approach for all demo cases. Further specific analyses based on variable coefficients depending on the season, on the differences in national energy mixes, etc. can be also addressed for more detailed evaluation.
- Energy savings will be quantified in terms of primary energy in order to allow a fair comparison. It should be noted that different energy sources (fuel and electricity) can used before and after the interventions.
- Energy efficiency quantification is based on the performance assessment of the heat pump (which is the central component of most of the solutions). Both heating and cooling HP performance are included, since useful effects will be obtained with both the HP source and sink heat flows.
- The relative importance of the energy supply coming from excess heat is of particular interest for this kind of solutions. Then, the degree the non-fossil energy supply is also considered.

Environmental indicators

Linked to the positive energy impact, environmental benefits can be derived. The main expectation of these heat recovery projects is to reduce the greenhouse gas (GHG) emissions associated to the energy use for heating and cooling. ENV stands for ENVironmental indicators in Table 1. Regarding this relation between energy and environmental savings, GHG savings (commonly expressed in terms of equivalent tCO2 avoided), must be calculated from primary energy savings according to contrasted values for the ‘emission factors’. To this purpose, [19] is proposed as a reference, so that a common contrasted approach for all the interventions can be followed.

Economic indicators

Economic benefits are also a direct consequence from energy savings. It can be easily stated that the less energy consumed, the less cost, either for the energy supplier or the end-user, depending on the level at which the savings are achieved. The economic assessment begins with the definition of a baseline which is established by the initial invoices, as well as the required investments for the energy retrofitting project. Then, the evaluation of the economic benefits is challenging because it requires taking into account a comparison with the costs associated to the energy consumed if the intervention or the project had not been implemented. In this sense, ‘cost savings’ and ‘cost avoidance’ should be differentiated in this context. The term ‘cost savings’ involves that the energy costs in the post-retrofit situation will be lower than those within the baseline period; however, it does not take into account changes in factors that determine energy use (e.g. changes in site activities, effects of independent variables such as production or weather, etc.), or price risks such as changes to energy contracts or tariff rates. Then, cost savings can be achieved due to influencing factors even if the target facilities are the same or even deteriorated in comparison to the baseline situation. On the other hand, the term ‘cost avoidance’ does include the effect of such influencing factors and accounts for the economic costs avoided in respect to a situation in which the energy intervention had not been undertaken. Thus, ‘cost avoidance’ is a more appropriate term according to the present evaluation approach and thus, it will be used from now on. Although the cost avoidance to be achieved by the excess heat recovery project is the main objective of the evaluation from an economic perspective, a breakdown of this concept is of great relevance for a proper analysis of the investments. Additionally, other aspects should be considered when addressing the economic feasibility of similar actions (e.g. return of the investment). EC stands for EConomic indicators in Table 1.

Social indicators

The last dimension of the evaluation approach refers to social aspects. In the context of energy efficiency projects this social dimension is of much more importance when there is a direct involvement of the end user or a direct impact on the price that he/she pays for a given service (normally the energy supply). In this regard, urban excess heat recovery concepts tackled here does not imply such a direct and evident techno-economic impact on the end users, changes related to comfort conditions or in the energy price they pay for the energy supply. On the contrary, positive impacts are more focused on the excess heat owners and the operator of the heat recovery facilities, who will contribute to improve energy efficiency (in global terms) and will benefit from a business model linked to the provision of energy as a service. Therefore, the evaluation of social impact, being understood as the impact on the everyday people perception of the services that they receive, on the end-user satisfaction, etc., is considered as a secondary aspect of the proposed assessment methodology, with the exception of cases oriented to increase the end-users interaction, similar to the above-introduced heat recovery from sewage water system case, where it is foreseen to develop a dashboard aiming at stimulating user participation.

Social evaluation scope and suggested indicators

Despite of the previous arguments, it is intended to provide some social insight focused on those people directly interacting with the heat source and/or the heat recovery facility itself. The proposed KPIs include definitions to quantify the relevance of urban excess heat recovery projects and increase social awareness to energy efficiency and environmentally clean initiatives, as well as to evaluate people perception of the quality of the services that they receive (e.g. thermal comfort, secure supply, reliable service, etc.). S stands for Social indicators in Table 1.

Social evaluation procedures

Social evaluation is proposed to be based on the following procedures:

- Survey method: This is the main procedure for the evaluation of the social acceptance since it provides the subjective perspective of the owners. It is based on a question/answer process. The selection of relevant surveys and the definition of the related questionnaires should be addressed during evaluation.
- Analysis of participation in social media and software platforms on behalf of end-users or interested stakeholders.
- Measurements: Social acceptance should be completed with an objective point of view. Data from the monitoring system will be used for assessing real parameters, such as comfort conditions or energy consumption. Comparison of both survey and measurements will provide a better knowledge of the real situation.

Table 1. Definition of Key Performance Indicators (KPIs).

Name	Category	Units	Description
EN01	Energy	kWh/yr; %	Primary energy savings
EN02	Energy	kWh/yr	Useful energy demand: heating
EN03	Energy	kWh/yr	Useful energy demand: cooling
EN04	Energy	kWh/yr	Final energy demand: fuel
EN05	Energy	kWh/yr	Final energy demand: electricity
EN06	Energy	%	Degree of Primary energy supply based on RES/excess heat recovery
EN07	Energy	-	Seasonal COP of the HP (cooling performance)
EN08	Energy	-	Seasonal COP of the HP (heating performance)
EN09	Energy	-	“Total heating and cooling useful energy” to “Electric consumption” ratio
ENV01	Environmental	tCO2/yr; %	GHG emissions reduction
ENV02	Environmental	tCO2/yr	Total GHG emissions
EC01	Economic	€	Cost avoidance
EC02	Economic	€	Total costs (along the facility lifetime)
EC03	Economic	€; €/kW	Capital expenditure (CAPEX)
EC04	Economic	€; €/yr	Operating expenditure (OPEX)
EC05	Economic	€/yr	Energy costs: fuel
EC06	Economic	€/yr	Energy costs: electricity
EC07	Economic	€/yr	Maintenance costs
EC08	Economic	€/yr	Financing costs
EC09	Economic	yr	Payback time
EC10	Economic	%	Return of Investment (RoI)
EC11	Economic	%	Internal Rate of Return (IRR)
EC12	Economic	€	Net Present Value (NPV)
EC13	Economic	n. of jobs	Job creation
S01	Social	n; %	People that are positive about the project
S02	Social	n (Likert scale)	Degree of people satisfaction
S03	Social	PPD; PMV	Average comfort perception

Table 1. Definition of Key Performance Indicators (KPIs).			
Name	**Category**	**Units**	**Description**
S04	Social	Tweets, web visits	Presence in social media

As a general remark, it should be noted that absolute units have been only considered so far within the KPI lists. However, providing many of these indicators in specific terms (i.e. as ratios in respect to a given characteristic parameter of the demo case) is considered of great importance within the proposed assessment methodology. For this reason, relevant characteristic features for each specific heat recovery solution should be identified, contributing to enable future comparison studies on similar projects as well as replicability analyses.

Monitoring requirements

A general guidance to set the basis on the variables to be measured is provided since design and technical details must be given in each specific case. Table 2 presents a list of the main variables that will be required for the evaluation of the intervention both within the 'after' and 'before' scenarios. These parameters must be in line with the conceptual diagrams presented previously for the measurement boundary.

Table 2. Main variables to be measured.		
Variable	**Use/Contribution to**	**Data source**
Fuel consumption	Final energy consumption of conventional heating system	Smart meters, Energy bills
Electricity consumption	Final energy consumption of conventional HVAC equipment (e.g. boilers, chillers, cooling tower fans, water pumps)	Smart meters, Energy bills
	Final energy consumption of the HP during post-retrofit period	
	Power of the HP contributing to COP calculation	
Fluid energy flow	End-use (useful) thermal energy demand as dependent variable of energy models	Smart meters
	Input/ouput thermal energy flows in the HP contributing to COP calculation	
Fluid temperature	Indirect measurement for fluid energy flow determination	Smart meters
	Surveillance and control systems	
Fluid mass flow rate	Indirect measurement for fluid energy flow determination	Smart meters
	Water consumption	
	Surveillance and control systems	
Air temperature	Excess heat source temperature characterization	Smart meters
	Thermal comfort conditions	
	Surveillance and control systems	

In addition, the assessment methodology must determine a reference requirement in terms of the monitoring sampling rate for the aforementioned variables. This will enable to check the system behavior as well as meet the data resolution required for control and surveillance purposes. Hence, a 15-minute period is considered as the reference sampling rate requirement for those variables registered by smart sensors/meters. However, exceptions to this rule could be accounted for within the detailed specifications and also regarding such variables coming from other data sources (e.g. energy bills for baseline characterization).