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Recov'Heat: An estimation tool of urban waste heat recovery potential in sustainable cities

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Abstract. Waste heat recovery is considered as an efficient way to increase carbon-free green energy utilization and to reduce greenhouse gas emission. Especially in urban area, several sources such as sewage water, industrial process, waste incinerator plants, etc., are still rarely explored. Their integration into a district heating system providing heating and/or domestic hot water could be beneficial for both energy companies and local governments. EFFICACITY, a French research institute focused on urban energy transition, has developed an estimation tool for different waste heat sources potentially explored in a sustainable city. This article presents the development method of such a decision making tool which, by giving both energetic and economic analysis, helps local communities and energy service companies to make preliminary studies in heat recovery projects.

1. INTRODUCTION

According to studies of CEREMA [1], a French Centre for Studies and Expertise on Risks, Environment, Mobility, Urban and Country Planning, urban area account for 52 % of total energy consumption in France and equivalent emission of carbon dioxide gas. Thermal energy consumption in the building sector, including mainly space heating and domestic hot water supply, is the major player. Researches are developed in order to promote renewable energy and waste heat recovery in the building sector [2, 3].For this, different French national and European projects are under investigation [4]. Currently, only a few district heating systems integrating waste heat recovery has been realized in France and in general those projects require consequently long preliminary studies. The latter has become a major obstacle for decision makers to do efforts in the sustainable city development.

An estimation tool covering major waste heat sources and their characteristics may help decision makers understand quickly the benefits of a heat recovery project. What else, this tool should include main information on the heat demand side. An annual estimation of diverse techno-economic indicators such as annual coverage rate, installation capacity, etc., should help decide whether a detailed study is necessary. In the institute EFFICACITY, such a tool named Recov'Heat has been developed using only a few input data concerning the waste sources and demands. The program is based on simplified algorithm using a monthly time step. This article firstly presents the methodology of the development and then some estimation results regarding several potential energy recovery

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projects. In terms of indicators, monthly or annual coverage rates, recovered energy are used. At the end, a model validation is conducted by comparing estimated results with real installations.

2. SOURCES OF WASTE HEAT: PRESENTATION AND CLASSIFICATION

Waste heat can be found in various processes or localizations in a city: sewage water, waste incinerator factory, industrial laundry, etc. These sources can be very different in terms of temperature level, carrying fluid, and their distances with regard to a district heating network, etc.

2.1. Sources of heat

In this study, five main waste heats are studied: sewage water, datacenter, waste incinerator factory, industrial laundry and glass factory. These sources are considered sufficiently powerful for a recovery project in a central heating network (compared with small-scale individual recoveries).

2.1.1. Waste heat in sewage water

Domestic sewage water is generally at a higher temperature level than the air environment. Its temperature can vary according to the heat recovery location, since sewage water flows from a building to district sewage network, before going to a central water treatment plant. In each of these three steps, waste energy recovery is possible. For this source, only a small number of waste heat recovery projects are developed in different countries at large scales [5].

The main characteristics of sewage waste heat are temperature and flowrate. Both of the two parameters are time dependent, either in seasonal level, or within 24 hours. What else, the geolocation should also be considered since the two parameters can be different among cities. In France, the statistical lowest and highest temperatures of sewage water in a normal year are respectively 10 °C and 30 °C. Thus for such a low temperature source, a heat pump system is necessary so that the minimum temperature of demand at 40 °C in the end-users is respected.

As far as concerning the flowrate, it depends on the number of inhabitants connected to district heating system as well as the point of heat recovery. The higher the connection density, the greater the flowrate and more interesting for a district heating network with heat recovery integration.

2.1.2. Waste energy recovery in datacenter

Datacenters shelter various information and data equipment such as computers, servers, storage arrays, networking and telecommunications. It’s important to control a temperature of the room where these technologies are used and the maximum temperature is 27°C [6]. Thus, a cooling system is used to regulate the ambient temperature during operation. Waste energy recovery comes from the air conditioning processes. These buildings have increasing electricity consumption which is almost 100% converted to waste thermal energy. According to a study done in 2012 [7], 2% of world electricity consumption is dedicated to datacenters so as the waste energy quantity.

If a datacenter is cooled by a mechanical compression refrigeration system, the heat recovery is generally done at the condenser side. For example, a water cooled condenser heat exchanger can prepare hot water at a temperature generally higher than 30°C. This source can be considered as a low-grade waste source since a heat pump is required to upgrade the temperature according to the heating network or heat demands.

2.1.3. Waste incinerator factory

In France, a total estimation of 11 TWh per year of thermal and electric energy are produced in waste incinerator factory [8]. Required by energy regulations, the incinerator heat recovery has been implemented since several years. However waste heat is still present in many cases due to at least three reasons: i) no thermal energy demand during warm and intermediate season, ii) the incinerator factory is situated too far away from the demand to construct a central heating network, and iii) hot smoke and incineration residues are not always treated. For the last, from 30% to 70% of losses at 180°C can be recovered by using a gas-liquid heat exchanger.

2.1.4. Industrial sources (glass factory, industrial laundry)

The process of glassware manufacturing requires a high consumption of energy for the melting and the post-treatments. To do this, the furnace is constantly maintained at 1500 °C. The energy used for this, is finally completely dissipated in the workshop. With cooling water or air, the energy is potentially recoverable. Currently in Europe, glass factories have an average production of 700 tons of different glassware per day [9]. An estimation of available waste heat can be done according to this value.

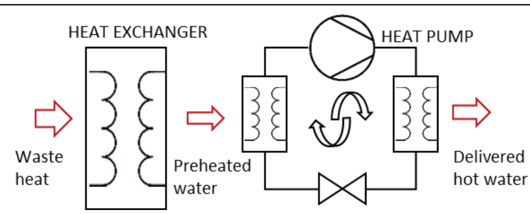
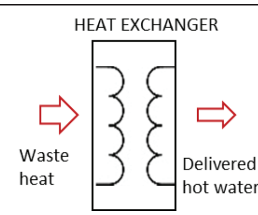
Industrial laundries, including that in public hospitals and private professional laundry providers, produce a huge quantity of waste heat through their washing, drying and ironing equipment. Tons of laundry can be processed every day and the main heat carrier is hot water. What else, according to European regulations [10], when the effluent water temperature is higher than 30 °C, it must be cooled before injecting to the sewage water network.

Estimation of the waste energy quantity is based on approximately 8 liters of water and 3 kWhth per kg of laundry. In this study, its temperature is supposed to be 25 °C and it constitutes a low source waste energy with daily and seasonal variations.

2.2. Sources characteristics and categorization

The use of heating and domestic hot water (DHW) requires a minimal production temperature to operate. There are three different scales of temperature for thermal energy production: low, medium and high temperatures. Temperature generally lower than 45 °C space heating only works with new buildings with adapted heating transmitters. Medium temperature working at around 65 °C could cover heat and DHW needs and temperature as high as 100 °C can cover both recent and old building heat needs and its main advantage the easy adaptation into an existing district heating system. Table 1 displays recovery characteristics of heat sources.

TABLE 1. Recovery characteristics of heat sources

Sources	Sewage water	Datacenter	Laundry factory	Incinerator	Glass factory
Calorie carrier	liquid	air	liquid	steam	steam
Variations	seasonal	weak	weak	seasonal	weak
Sources temperatures	10°C - 25°C	20°C - 27°C	15°C – 30°C	90°C – 180°C	90°C – 140°C
Recovery equipment	Heat exchanger + heat pump			heat exchanger	
Schematic					

3. WASTE HEAT RECOVERY

The process of recovering waste heat is about the whole chain, from the source to end users. With the objective of developing a working system, it is necessary to broach the recovery technologies and equipment.

3.1. Recovery equipment

In buildings, thermal energy consumptions lie in space heating and DHW. Heating has to be distributed at a minimum of 40°C (it corresponds to new low temperature transmitters) and DHW at 60°C minimum. To reach these temperature standards, some waste heat sources like wastewater or water from laundry factories need to be upgraded by a heat pump. For the high temperature waste sources, heat exchangers are used to recover energy. A simplified characterization of heat pump can be expressed by the Carnot efficiency and the type of refrigerant. The refrigerant is represented by a coefficient R_c, and a value of 0.55 is used in this study. The effective Coefficient of Performance (COP) is given by Eq.1:

$$COP_{eff} = R_c \frac{T_c}{T_c - T_f} \tag{1}$$

Concerning heat exchangers, they are either associated with a heat pump or used independently. For the sewage energy recovery, their dimensioning parameters are chosen so that: i) The maximal value of the temperature difference between inlet and outlet of sewage water is 2°C; and ii) To start the heat recovery process, the minimal inlet temperature of sewage water must be equal to 12°C. These values are imposed by the waste water treatment regulation to maintain a high purification efficiency. The sewage water treatment process degrades below this limit in water treatment plant.

For incinerator and glass factory, the energy recovery through heat exchanger is based on a percentage of production by recovery location.

3.2. District heating

A district heating network provides heating and/or DHW at the scale of a city or a district. Heat is produced by one or several production plants; then it is distributed in the form of water or steam with underground pipes until connected buildings. Substations are used to for each individual building energy system. After the substation, the working fluid, most commonly water, goes back to production plants where it would be heated again in a closed loop. A substation is composed of heat exchangers, pumps and regulation system.

These urban heating systems have several advantages like economic and reliable distribution [11]. Especially, they are robust tools for local authorities to contribute to energy transition [9, 12]. Waste heat sources, which be integrated in these district heating systems have a key part in the actual energy context [12, 13], to reach 50% of renewable energy in the mix of a new district heating project.

4. THE TOOL RECOV'HEAT

Recov'Heat has been developed with the goal to have an easy-to-use estimation of waste heat sources potential. It supplies the quantity of heat recoverable month by month by a chosen source and evaluates it according to user-defined energy needs of a district.

4.1. Model introduction

As the input interface of Recov'Heat user should select the waste heat source and entre its characteristics. Table 2 presents the studied sources, demands and the corresponding data in the input to run the simulation.

TABLE 2. Input data for each source studied

Sources	Inputs
Sewage water	Number of inhabitants connected to the wastewater collector
Datacenter	Size, type of datacenter, energetic density
Laundry factory	Laundry quantity washed by day, days of activity
Glass factory	Quantity of produced glass and kind of glass produced
Incinerator plant	Quantity of waste incinerated
Demands	**Inputs**
Building heating	Surface
DHW	Surface, Number of inhabitants

For example, recoverable heat from a sewage collector can be estimated by the number of inhabitants connected. It enables to have the flow estimation. The global model calculates a monthly and yearly balance. Recov'Heat compares this estimation to energy consumption of a district. The user describes the district with the size and the type of buildings (houses, offices, school…) and the tool proposes global energy consumption. The tool also details the conditions to recover and reuse energy sources, mainly analyzing temperature compatibility between the source and needs.

4.2. Methodology

"**FIGURE 1,**" presents the methods used to develop the tool. Initial data come from the state of art of each source [9]. The user adds necessary elements according to Table 2.

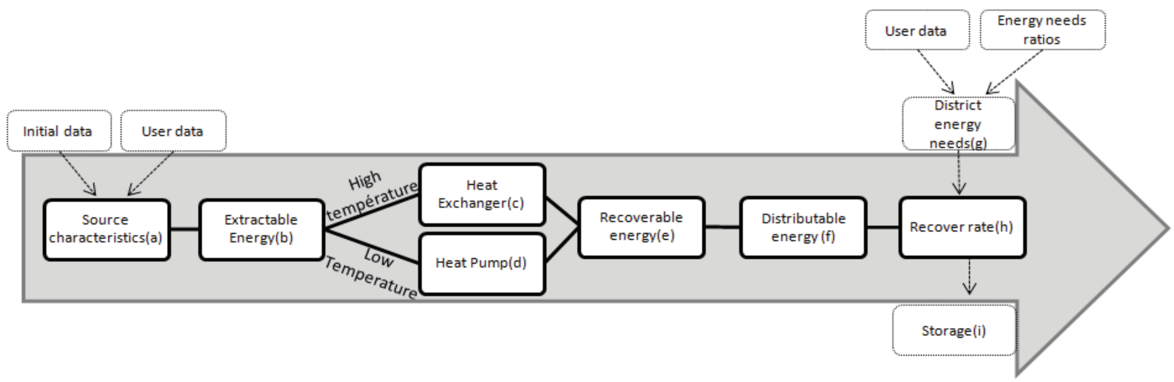


FIGURE 1. Diagram of the model used in Recov'Heat which

The first step (a) enables to have necessary characteristics of a selected source. Extractable energy (b), in MWh, corresponds to the maximum monthly energy dissipated by each source. It is a physical and theoretical potential and constitutes the first level of waste heat source estimation [10]. Calculation methods are different for various sources but it starts from calorific value of concerned elements (water, incinerated waste…) or from the dissipated energy of a process (datacenter, glassware manufacturer).

According to the temperature level (high or low, in c and d) of a selected waste energy source, either heat exchanger or heat pump will be used for the recovery. After this step, the recoverable energy (step e) is obtained which represents the remaining energy after valorization by adapted technology. Then the distributable energy (step f) corresponds to the subtraction of distribution losses to the distributable energy. Losses are calculated with the distance between the selected source and the district designed by the user. Heat loss ratios are used and they vary with the heat source temperature.

When distributable energy is obtained, it is compared with the energy consumption of the district designated by user inputs. Energy consumption including heating and DHW is calculated for a year and with a monthly time step. Depending of the types of building designated as users, energy consumption ratios (in Wh/m²/month) are multiplied by the building surface (step g). The hypothesis taken is 70 m² for a house, with an average composition of 3 inhabitants per family. This result gives estimation about the number of people benefitting from the selected waste source. In current version of Recov'Heat, we consider that all buildings are low consumption ones built under the latest French building thermal regulation RT2012 [14].

This method, estimating a quantity of recoverable waste heat and comparing it to energy needs, enables to have an idea of its interest in terms of coverage rate. Nevertheless, the monthly results simulated are not in enough to assure that the energy from the waste source and the needs are concordant, i.e. the problem of intermittence. The quantity of waste heat could not be sufficient to answer to daily heating peak. That is why the last steps of the model consist in calculating both a monthly coverage rate for heating and DHW separately and a global one (step h). This rate gives a more precise indication about the simultaneity between potential and needs thanks to heating and DHW simultaneity coefficients (also called concordance coefficients) since their annual consumption curves are independent and complementary. The heating simultaneity coefficient is between 0 and 1, defined by the relation from the number of hours when production and consumption are synchronized with the total number of hours in a month. Heating consumption is high in winter so the simultaneity coefficient is getting close to 1 whereas it is 0 in summer. This coefficient varies depending on the types of buildings (offices, housing…) since DHW consumption still presents in summer and it is generally indispensable in family buildings. If the designed district has mixed buildings, the coefficient is generally high. So, the simultaneity coefficient is getting close to 1 for mixed building. The number of hours when production and consumption are synchronized with the total number of hours in a month increases because the probability of consumption grows up for mixed building.

For the DHW supply, the hypothesis is to consider that the consumption peak of DHW corresponds to daily consumption of DHW. The time of the peak depends on the number of housing in the designed district. More there are housing, longer is the peak time. The hypothesis on this method is that the peak time is evolving as a logarithmic curve until 50 000 housing. Beyond this number, the daily peak is limited at 9h. Finally, the simultaneity coefficient is equal to this peak time divided by 24, the number of hour in a day.

With these simultaneity coefficients, coverage rates ($\mathrm{Cr_H}$ and $\mathrm{Cr_{DHW}}$) are obtained by the following equations:

$$Cr_H = \delta_H \left[\frac{Q_{distr}}{Q_{needs}}\right]_H \tag{2}$$

$$Cr_{DHW} = \delta_{DHW} \left[\frac{Q_{distr}}{Q_{needs}}\right]_{DHW} \tag{3}$$

Where $\mathrm{\delta_H}$ and $\mathrm{\delta_{DHW}}$ are the simultaneity coefficients of heating and DHW, $\mathrm{Q_{distr}}$ the distributable energy (step f), $\mathrm{Q_{needs_H}}$ and $\mathrm{Q_{needs_{DHW}}}$ are heating and DHW energy demands.

The global coverage rate of a waste heat source is obtained by weighting the heating and DHW coverage rate with their needs every month and the annual coverage rate is deduced.

If the distributable energy is higher than demands, a surplus energy quantity can be stored (step i). Under current version, only the storable energy is calculated for information without being discharged upon demand. Another module integrating different types of thermal energy storage is under investigation and will be integrated in the next version.

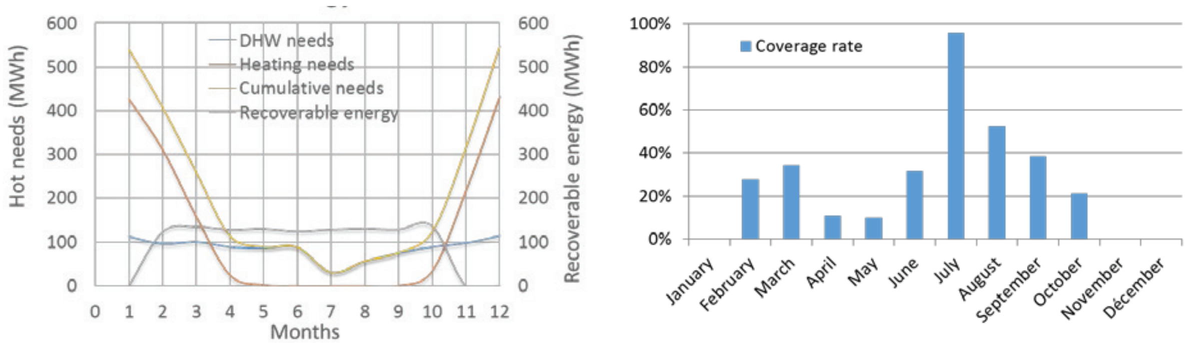
4.3. Tool application

This part is a study of two districts with the same consumptions for different types of sources of production. In Table 3, the results show that the coverage rate of the glass factory is better than that of sewage water.

TABLE 3. Sources characteristics of sewage water and glass factory heat recovery cases

	Sources	**Sewage water**		**Glass factory**	
Sources parameters	Quantity of produced glass	-		8 000	
	Number of inhabitants connected to the sewage water system	7 500		-	
	Distance source – district heating system (m)	500		500	
	Temperature (°C)	10 - 25		90 – 140	
Parameters of demands	Total area (m²)	68 000		68 000	
	Heat usage	Heating	Heating + DHW	Heating	Heating + DHW
	Temperature of use (°C)	40 – 45	55 – 65	40 – 45	55 – 65
Results/ estimate	Recoverable energy (MWh/year)	1 018	1 170	7 166	7 166
	Coverage rate (%)	40	26	100	100

The heat pump is used only for the sewage water recovery because it's a low source of temperature. The results of simulation are presented in "**FIGURE 2**".



a) Recoverable energy and needs b) Coverage rate

Annual results

Input : 7500 inhabitants connected to the sewage water system

Output : 1170 MWh/year

Annual Coverage rate : 27 %

Annual average COP : 3

c) Main results from a waste heat recovery estimation

FIGURE 2. Estimation with Recov'Heat tool for a sewage water energy recovery case

4.4. Model validation

To validate the model, Recov'Heat simulation results were compared with available data collected in existing projects. Waste incinerators and sewage water heat recovery are almost exclusively the only sources doing heat recovery. It is possible to obtain the quantity of waste incinerated by each incinerator in France and their annual heat recovery (data between 2008 and 2012) [15]. Four French incinerators of different sizes are selected and compared with estimated results by Recov'Heat tool.

TABLE 4. Model validation – source: waste incinerator

Inputs		Results		Difference	
Incinerator	**Waste quantity** *(Ton/year)*	**Recov'Heat** *(MWh/year)* (incinerator+smoke)	**Real data** *(MWh/year)* (incinerator)	**Absolute** *(MWh/year)*	**Relative** *(%)*
Sarcelles	150 000	215 406	201 737	13 669	7 %
Thiverval-Grignon	240 000	344 649	119 000	225 649	189 %
Villejust	90 000	129 726	92 070	112 180	41 %
Massy	85 000	150 630	113 786	36 844	32 %

Table 4 gives the comparison between Recov'Heat estimation and some running incineration heat recovery projects in the region of Île-de-France. The difference between Recov'Heat method and real data vary from 7 % to 189 %. It can be concluded that the Recov'Heat method overestimates the recoverable waste heat quantity, and it can be explained by several reasons. Firstly, the Recov'Heat algorithm estimates the heat extracted by the incinerator oven and also extracted by the smoke treatment. Nowadays, incinerators only recover heat from the oven. Besides, the recoverable energy is calculated in a year, 8760 h and does not consider the necessity of stopping the activity few days a year for maintenance. The heat of combustion (J/kg) of waste has also an impact. It determines the amount of energy per kilogram of treated waste. It is supposed as a constant in the model but it may vary depending on different seasonal composition of wastes and their water content ratios.

There are also cases where an incinerator plant is not in an urban zone and thermal needs around the plant are less important than resource. This is the case of the incinerator situated in Thiverval-Grignon.

Similar study has been done with three other projects recovering energy from sewage water and a datacenter. Results and shown in Table 5.

Table 5. Model validation for sewage water and datacenter

Inputs	Results		Difference	
Source and case	**Recov'Heat** *(MWh/year)*	**Real data** *(MWh/year)*	**Absolute** *(MWh/year)*	**Relative** *(%)*
Sewage water : eco-district Sainte Geneviève	2 123	1 417	706	49,8 %
Sewage water : eco-district Cap-Azur	1 832	1 000	832	83,2 %
Datacenter : Val d'Europe	29 527	26 000	3 527	13,6 %

Similar to the incinerators results, potential estimations are superior to the actual cases. The relative difference looks high but amounts of recovered energy have the same order of magnitude. The estimation is a maximal technical potential without considering any urban or economic constraint. For example, the eco-district Cap-Azur has 1000 MWh/year of thermal needs and it is all supplied by the sewage water heat recovery. Estimated quantity indicates that it can possibly bring more energy if there were higher local demands.

5. CONCLUSIONS AND FURTHER STUDIES

Waste heat recovery in urban area is studied in this study with the aim of developing a decision making tool based on simple but realistic parameters. Recov'Heat is developed in this study based on which different cases of waste heat recovery are estimated and compared to real installations.

The results of this study, Recov'Heat, offers a decision support tool in the choice of source of waste heat recover. Based on our comparisons, Recov'Heat provides generally overestimated heat recovery values which are still in the same scale of magnitude with the real cases. With its monthly time step, the time variation of both production and consumptions are taken into consideration without doing a dynamic simulation. The idea of a simple-to-use estimation tool provides decision makers critical information such as waste energy coverage rate, annual consumption, etc., which are useful to judge the interest of heat recovery before a substantial pre-study.

The tool can be assessed free of charge at http://tools.efficacity.com.

Limitations of current version of Recov'Heat include: i) monthly scale, ii) energy estimation without consider temperature level for several sources such as datacenter, and iii) without storage.

Future works for design Recov'Heat 2 will be focused on a modification of month scale to hour scale. With this scale, a storage system will be integrated. In order to study several sources at once precisely, economic data and geographic information are also integrated. The integration of a thermal energy storage module is also under development.

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