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How to deal with technical and economic constraints to recover waste heat in France?

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Abstract:

The aim of this paper is to give an overview of waste heat potentials in France (from manufacturing industry, datacenters, refineries, water treatment plants and waste incineration plants), and to analyse opportunities as well as technical and economic constraints for waste heat recovery. The study confirms a high theoretical potential for waste heat recovery (118 TWh). 60 TWh are at a temperature under 100 °C, 45 TWh between 100 and 200 °C and the rest above. The main source of waste heat is related to driers, condensers of cooling production units, furnaces and boilers. We can define and locate waste heat sources in France and compare them to heat demand. Moreover, a strong politic will in terms of energy transition allows for the emergence of organisations and infrastructures to recover waste heat implementing territorial symbiosis. This free waste heat is not systematically recovered and reused because of technical (fouling and corrosion of heat exchangers, difficulties to store heat) and economic constraints (financial security for the quality, quantity and regularity of supply, cost of a backup solution in case of failure, long investment payback). We present three existing business models, allowing to secure heat supply and increase confidence between involved partners.

Keywords:

Circular economy, Datacenter, Economic constraints, Energy transition, Heat availability, Heat recovery, Industry, Savings potential, Sugar plant, Warm effluents, Waste heat, Waste incineration plant

1. Introduction

Nowadays, reducing the environmental impacts of human activities is a priority. We are particularly targeting greenhouse gases emissions to mitigate climate change. The French energy transition policy [\[1\]](#) (Loi de transition énergétique pour la croissance verte) sets an objective of reducing greenhouse gases emissions by 40% between 1990 and 2030. To achieve this goal, this law also promotes carbon-free or less-carbon intensive energy sources. The ambition is to raise the renewable energy part to 32% of the final energy consumption, 38% of the final heat consumption, 15% of the final fuel consumption and 10% of the final gas consumption.

To reduce efficiently greenhouse gases emissions, renewable energy usage must be coupled to energy consumption reduction. One of the key drivers of energy efficiency is waste heat recovery. Waste heat refers to heat that is released into the environment after it has served its primary purpose. Today, a strong political will in terms of energy transition allows for the emergence of organisations and infrastructures to recover waste heat implementing territorial symbiosis, in a circular economy logic. In France, tax reduction on district heating network, subsidies like “Fond Chaleur” (managed by the French environmental agency ADEME) and the increasing number of calls for projects are relevant examples of financial and regulatory incentives.

Several studies [\[2-7\]](#) present estimations of the waste heat theoretical potential in France. Technologies to recover this free heat, such as heat pumps, heat exchangers and Organic Ranking Cycle, have been studied by many publications [\[8-10\]](#). Finally, a lot of methods and models have been proposed to optimise energy systems and size of both equipment and heating networks [\[11-14\]](#). Despite scientific knowledge of technologies, analysis and optimisation methods, exploiting waste heat recovery potential faces technical and economic constraints. For instance, fouling and corrosion of heat exchangers limit opportunities to transfer heat to users. On the other hand, adequacy between heat characteristics and users’ needs has to be taken into account. Quality, quantity and regularity of

supply can change within the day or the year. Solutions to secure industrial or urban energy needs obviously represent an extra-cost. Other economic constraints have been mentioned in [\[15, 16\]](#). The aim of this paper is to give an overview of waste heat potentials in France (from manufacturing industry, refineries, datacenters, waste water treatment plants and waste incineration plants) and to analyse opportunities as well as technical and economic constraints for waste heat recovery. We consider three existing business models, allowing to secure heat supply and increase confidence between involved partners who share heat through a heating network.

2. Waste heat potential in France

2.1. Method to evaluate the potential

2.1.1. Data: waste heat sources identification

The method to evaluate waste heat potential in France combines an energy consumption database with a thermal equipment stock characterisation database. The expertise on industrial sectors and processes from EDF completes databases analysis. The CEREN (Centre d'Etudes et de Recherches Economiques sur l'Energie) conducts studies [\[17\]](#) on the energy consumption of the French industry. Data is structured by industrial sectors (steel, food, chemical...), by energy types (electricity, natural gas, fuel...) and by energy uses (furnaces, boilers, dryers ...).

The database regarding industry is built from about thousand investigations on the largest industrial sites. It is then completed with over six thousands annual phone surveys on the small and medium-sized enterprises. About seventy specific questionnaires have been filled to evaluate the energy contained in the fumes of the furnaces and sixty others to evaluate energy contained in the steam of dryers.

Data regarding refineries come from seven phone interviews over a total of eight existing plants. The questionnaires are used to evaluate the energy contained in the combustion gases from boilers and the combustion gases from furnaces.

To study datacenters, we used a list of 150 datacenters hosters, ADEME studies (Ile-de-France and Provence-Alpes-Cote-d'Azur) and several bibliographical sources.

Data regarding municipal waste incineration plants (MWIPs) is collected from a database named SINOE (by ADEME), which details the consumption of the 126 French MWIPs. Ten phone interviews were carried out to assess the energy content in combustion gases from incineration furnaces.

Data Regarding Wastewater Treatment Plants (WWTPs) come from a base of 60 WWTPs that incinerate dried sludge, according to the water supply agency (Ministère de l'Environnement de l'Energie et de la Mer). Six phone interviews were carried out on WWTPs that have an incinerator and 3 phone interviews on WWTPs that have driers.

2.1.2. Waste heat origin characterisation

Waste heat is characterised by its energy value. Energy value can be divided by type of warm effluent, temperature, heat availability and business sector. Energy data are analysed regarding these parameters.

Warm effluents studied in this paper are:

- combustion gases from furnaces (without blast furnaces),
- combustion gases from boilers,
- steam from dryers,
- cooling fluids from air compressors,
- cooling fluids from refrigeration compressors,
- cooling fluids from refrigeration condensers,
- cooling fluids from heat exchangers in desuperheaters of the refrigeration groups,

- hot water from clean-in-place (CIP effluents)
- sensible heat from some specific products

Effluents from some processes (concentrators, cooling fluids network, energy contained into the products etc.) are not included because data is not available.

2.1.3. Industrial sites, refineries, datacenters, waste incineration plants and water treatment plants characterisation

In this study, industries are classified into 140 sectors, based on the French classification of economic activities (250 sectors). The French system (NAF rev. 2, 2008) is used to present statistical information about economic activities. This classification level is accurate enough and very adapted to study energy consumption by business sector. Different products and thus different manufacturing processes can be distinguished. This study proposes a global overview using the aggregated classification shown below:

- Food products and beverages,
- Pulp, paper and edition,
- Basic chemicals,
- Other non-metallic mineral products,
- Capital goods (equipment goods),
- Iron and steel,
- Fabricated metal products,
- Fine chemical products,
- Textile,
- Net balance.

We also study: refineries, datacenters, Municipal Waste Incineration Plants (MWIPs) and Wastewater Treatment Plants (WWTPs).

For all business sectors, heat availability is defined as the frequency of equipment's operations, which is assumed similar to the frequency of the factory's operations:

- 1 shift of 8 hours per day
- 2 shifts of 8 hours per day
- 3 shifts of 8 hours per day with a pause on the weekends
- Continuous operating.

2.2. Total energy consumption and waste heat recovery potential by sector

Total energy consumption in the French industry is estimated at 432 TWh in 2013¹ and the business sectors repartition is presented in Fig. 1. Other tertiary sectors consumption is given in the Table 1.

Global waste heat in the industry is estimated around 103 TWh in 2013¹ (25 % of total energy consumption) [19]. Energy uses and waste heat origins in the industry have already been analysed and detailed in 2009 [2]. We can compare both studies and see the evolution between 2009 [20] and 2013 (Fig. 2).

¹ The study was done in 2016 with data consumption from 2013.

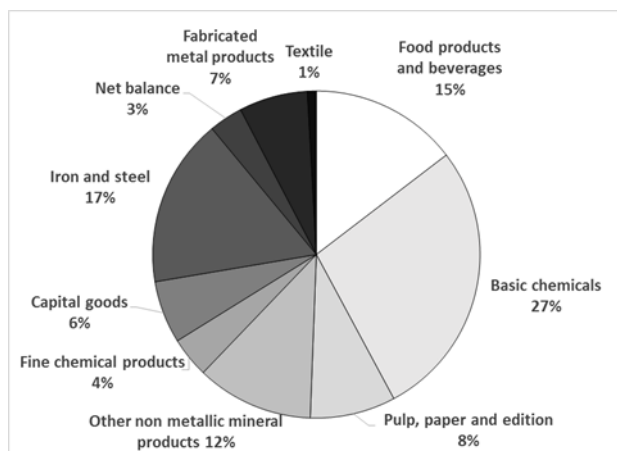


Fig. 1. Global energy consumption by industrial sectors

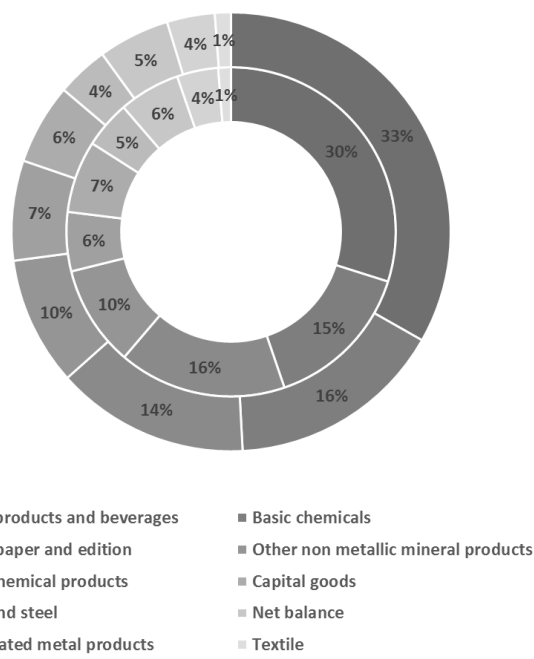


Fig. 2. Comparison of the waste heat in the industry between two studies: 2009 (internal ring) and 2013 (external ring)

Table 1. Energy consumption and waste heat values

Others tertiary sectors	Consumption (TWh)	Waste heat (TWh)
Municipal Waste Incineration Plants (MWIPs)	-	4.4
Datacenters	6-7*	3.6
Refineries	38*	3.4
Wastewater Treatment Plants (WWTPs)	2,4*	0.4

(*) internal EDF values

Based on the same scope, the total waste heat potential calculated decreased from 109 TWh² to 103¹ TWh between 2009 and 2013. Over the same period, total energy consumption increased slightly from 423 TWh to 432 TWh. Consequently, waste heat decline has not been caused by energy consumption evolution.

In 2014, exhaust gas losses, dryers and sensible heat from hot products of steel, cement and paper industries were particularly focused on. Furnaces have a high energy consumption in the steel and cement industries. Dryers have a high energy consumption in the paper industry. In 2016, the method was further reinforced in the chemical, glass, tile and brick industries.

Sensible heat in some industrial products (steel, cement, glass and tiles and bricks) which are cooled during the process has been evaluated. Temperatures of the products from tiles and bricks are very low and waste heat is considered to be negligible. Sensible heat from the other products is evaluated at 3 TWh. Total waste heat of the industry is estimated at 106 TWh.

Waste heat availability is an important point if we want to recover it. 68 % of waste heat in industry is always available (non-stop operating factories). 20 % is available 24 hours a day with a pause on the weekends and 9 %, 16 hours a day (2 shifts of 8 hours). There are significant differences between industrial sectors. For example, around 25% of capital goods industry runs non-stop, 35 % in operation 24 hours a day with a pause on the weekends and 29 % in operation 16 hours a day, whereas

² The study was done in 2012 with data consumption from 2009.

pulp, paper and edition industry runs non-stop at 92%, 24 hours a day with a pause on the weekends at 5% and 16 hours a day at only 2%.

Waste heat potentials for refineries, datacenters, waste incineration plants and water treatment plants are given in the Table 1.

French MWIPs handle 14.3 million tons of domestic waste, which represents a consumption of 36.4 TWh for 2013. Their total waste heat is estimated at 4.4 TWh at low (less than 80°C) and medium (between 80 °C and 250 °C) temperature. Waste heat comes from combustion gases from incineration furnaces. It can be recovered implementing a heat exchanger between the furnace and the chimney. Availability of the heat in the MWIPs raises 100 % in non-stop operating factories.

French datacenters consume 7 TWh of electricity, mainly for servers electricity supply and cooling. Total waste heat is estimated at 3.6 TWh, half of the consumption. This heat comes mainly from refrigeration units (cooling fluids from refrigeration compressors, cooling fluids from refrigeration condensers, cooling fluids from heat exchangers in desuperheaters of the refrigeration groups), at a low temperature (less than 80 °C). In datacenters, the heat is available at all times.

French refineries consume 37 TWh of oil and 2 TWh of electricity, including 1.3 TWh of self-generated electricity. Energy is mainly used to heat products. Their total waste heat is estimated at 3.4 TWh. This heat mainly comes from the process (combustion gases from the boilers and combustion gases from furnaces, steam from dryers) at medium and high temperature (mostly between 150 and 350 °C). In refineries, the heat is available at all times.

French waste water treatment plants (WWTPs) consume 2.4 TWh of electricity. Total waste heat is estimated at 0.4 TWh. This heat doesn't come from the consumed energy, but mainly from dry sludge incineration. It is generated by sewage sludge driers (between 40 and 150 °C) and by the fumes of incinerating furnaces (between 100 and 300 °C). In WWTPs, the heat is available at all times.

2.3. Waste heat vs. heat needs potential by sector and by temperature range

Quantities of waste heat and heat needs by sector are broken down to their corresponding temperature level (Fig. 3). Waste heat should be compared with heat needs in the same industrial sector then with others. Reference [5] describes the method to evaluate the waste heat recovery potential across the industrial sectors. The key idea is to segment waste heat potential into three types. The first type concerns waste heat that can be avoided increasing production system efficiency. The second type is waste heat that can be reused on-site to substitute local heat demand. The third type is waste heat that can be reused off-site to supply heating and cooling grids, or to produce electricity.

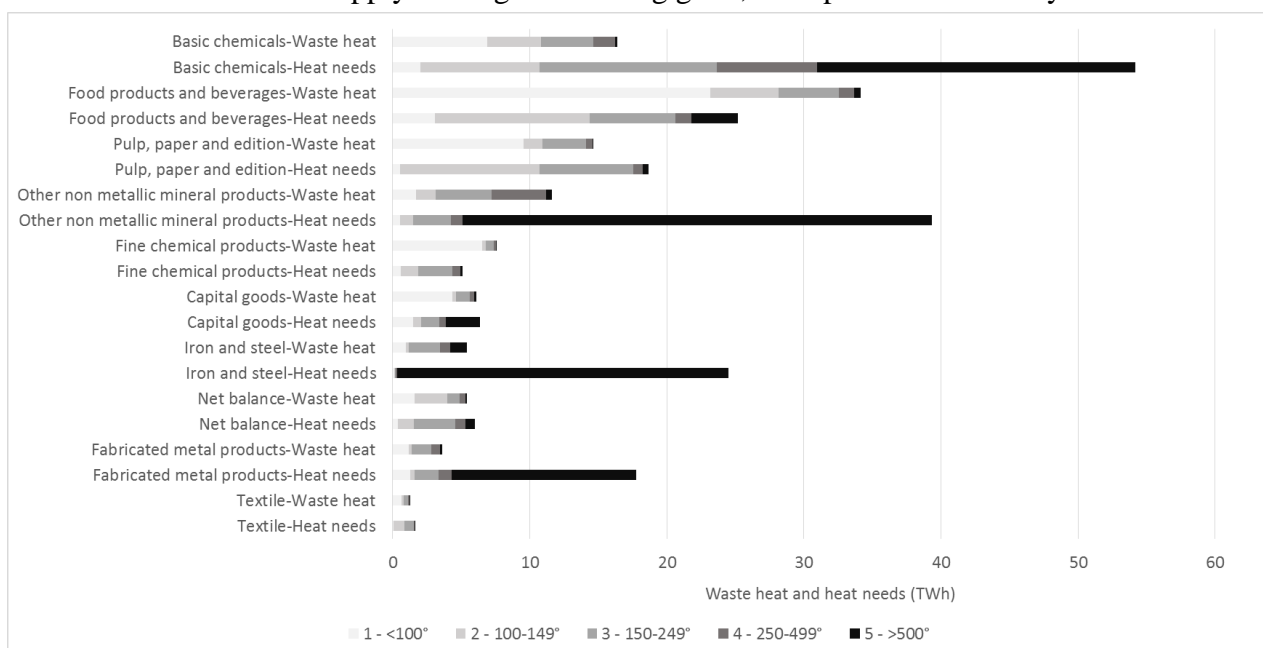


Fig. 3. Waste heat vs heat needs potential by sector, by temperature for the industry

Avoiding or reusing this waste heat inside the process is the most economical solution. This solution is currently implemented in industry and meets with technical and economic success. Waste heat can be directly recovered with a heat exchanger and indirectly recovered when temperature level is increased with a heat pump [9, 11]. This solution is interesting for industrial sectors using low temperature processes, like food, paper and a part of the chemical industry.

Nevertheless, many sectors have a high temperature process and can't reuse waste heat on-site. These sectors are: iron and steel, fabricated metal products and non-metallic metal products industries. They can hardly recover their waste heat and need support to find technical and economical solutions to be able to share it locally with the surrounding industries. Waste heat potential from food products, beverage and fine chemical products industries is higher than their heat needs. This can be explained by their use of refrigeration compressors, which produce 4 or 5 units of waste heat³ per electrical energy unit consumption.

2.4. Waste potential by administrative region

Waste heat potential can be quantified by French administrative region, as shown on Fig. 4. Potential is not evenly distributed on the regions because some of them are heavily industrialized like in Hauts de France (18 TWh), Grand Est (18 TWh) and Auvergne Rhone Alpes (15 TWh), whereas others like Centre (5 TWh), Bourgogne Franche Comté (5 TWh) and Occitanie (5 TWh) are less industrialised.

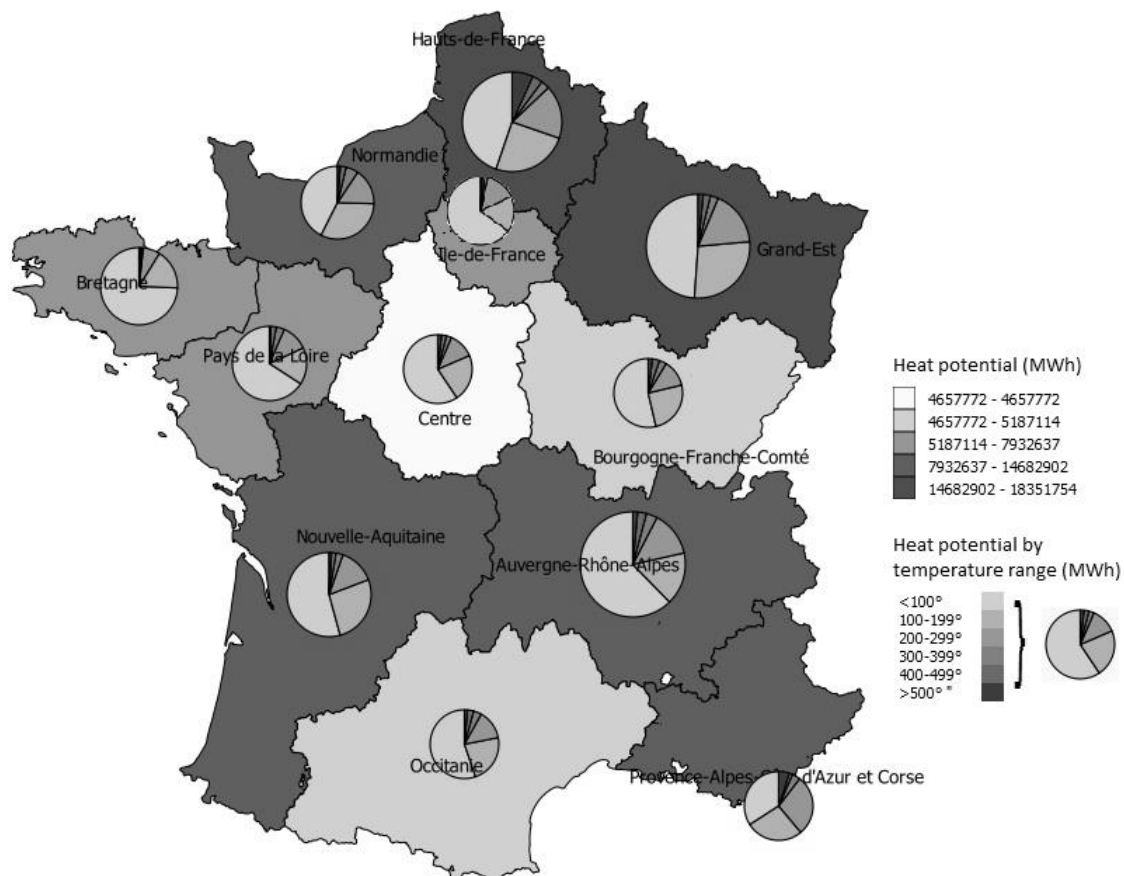


Fig. 4. Waste heat potential by region and temperature (MWh)

³ The energy performance coefficient of a refrigeration compressor (COP) is equal to the ratio between the quantity of cold produced and the electrical energy consumed by the compressor. In the same time, the quantity of heat produced equal COP plus one. Classic value of COP is around 3.

Distribution of temperature depends on which industry sectors are implanted in the concerned region. In Haut de France (13 % of waste heat above 300 °C) and Provence Alpes Cote d'Azur (10 % of waste heat above 300 °C), large iron and steel industry factories with high temperature process (blast furnaces from Dunkerque and Fos-sur-mer) are implanted. In Bretagne (74 % of waste heat under 100 °C), Pays de la Loire (66 % of waste heat above 100 °C) and Auvergne Rhône Alpes (62 % of waste heat above 100 °C), food products and beverages factories generate low temperature heat from cooling production, essential for food production and preservation.

In the first part of this paper, we presented a detailed analysis of theoretical waste heat potential recovery and the method to estimate it. To exploit this potential, it is crucial to be aware of technical and economic constraints. The following part intends to highlight some of them through case studies.

3. Integration of technical and economic constraints into waste heat recovery projects: 3 case studies

To develop a circular economy, symbiosis between local actors allow to save resources (such as fossil energy) and avoid energy or resources waste. Waste heat recovery projects have to benefit all partners involved to succeed. Every stakeholder wants to increase its performance. To ensure this assumption, any feasibility study needs to take into account everyone's characteristics. One of the main issues to share heat between local actors is concomitance between heat production and its use. Heating network that allows heat exchange addresses every partners' needs. The more heat suppliers and heat users are connected to the network, the more sustainable it becomes.

Among business sectors presented in part 2 of this paper, we selected three sectors with different operating rhythms within the year. We focused on their waste heat potential and identified advantages and constraints they have to recover and share waste heat with local users.

In this part, Figs 5, 9 and 11 are presented to illustrate waste heat production and heat needs variability. They are voluntarily shown without scale considering that the purpose is to give general tendencies.

3.1. Municipal waste incineration plants and urban heating needs symbiosis

According to the law [20], municipal waste incineration plants (MWIPs) have to valorise heat produced by waste incineration up to 65% efficiency for installations built after 2008 and up to 60% for the others. In Paris, 3 MWIPs contribute to supply an urban heating network (managed by CPCU, Compagnie Parisienne de Chauffage Urbain): Syctom Saint Ouen (146 MWth 210t steam/h), Syctom Ivry-sur-Seine (146 MW th, 220 t steam/h) and Syctom Isséane Issy-les-Moulineaux (105 MW th, 180 t steam/h). The CPCU urban heating network is 490 km long and provides heat to 17 cities, including Paris. Urban heat needs vary as the seasons change (Fig. 5). Consequently, a solution to adapt heat supplied to the urban heating network has to be found to ensure concomitance between heat production and heat demand.

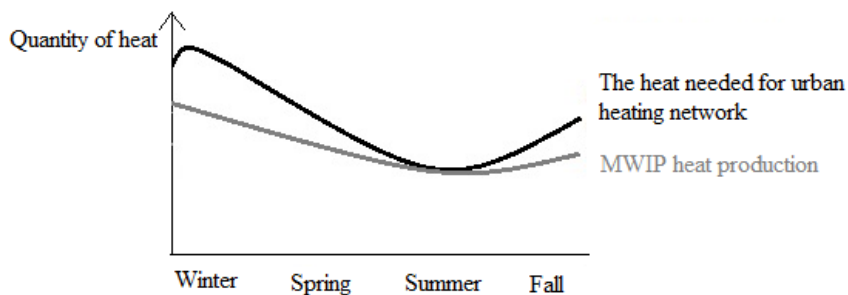


Fig. 5. Annual MWIPs heat production and urban heating network needs

Energy storage is particularly focused on addressing this specific problem in [21, 22]. However, it still faces economic, technological and scientific issues. Heat storage solutions (individual hot water tanks for example) can provide several hours of flexibility but they are limited by volume requirement.

On the specific matter of waste heat recovery, another solution can be implemented: modulate cogeneration [23]. The Parisian municipal waste incineration plants use it to adapt heat supply to urban heating network demand and produce electricity. The ratio between electric production and heat production varies during the day and the year, in compliance with residential heat consumption. Cogeneration use is restricted to heat effluent with a temperature higher than 500°C, which corresponds to a total potential of waste heat of 2.8 TWh in France [19].

When urban heating network demand is higher than MWIPs heat production capacity, other heat supply solutions (gas combustion equipment) are used. In the summertime, these complementary solutions can be stopped to realize maintenance works since the three MWIPs are able to provide for urban heating network needs. The presence of several sources of heat supply is a strength for CPCU, which optimises costs and annual functioning.

In addition to heat used with cogeneration, waste heat sources are targeted in MWIPs [24, 25]. As explained in part 2, theoretical waste heat potential from MWIPs raises 4.4 TWh. It comes from combustion gases from furnaces.

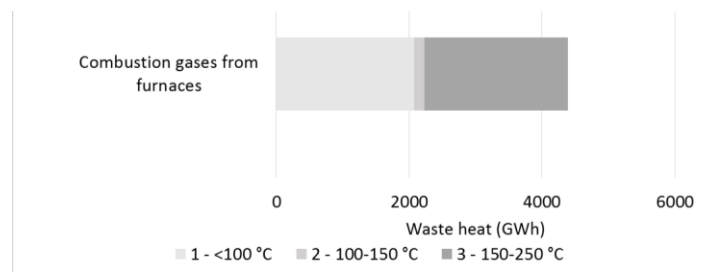


Fig. 6. Waste heat from MWIPs by type of warm effluent and by temperature

MWIPs are equipped with either a wet or a dry process system to treat combustion gases before releasing them. The wet process system produces gases at a temperature of 60°C (half of the potential, Fig. 6) and with a pH around 1.6. The very acidic pH requires either to adapt material (for instance plastic heat exchanger would answer to the corrosion matter) or to increase pH. Both solutions generate an important extra-cost. In this case, current technical feasibility doesn't match with economic reality. On the other hand, with dry processing, gases temperature is around 150°C but actual equipment (chimneys made of steel are very sensitive to chemical corrosion) and configuration inhibit waste heat recovery. The interest of this potential is also limited by the transition cost. Today, some of the existing MWIPs use air coolers to reduce water temperature before releasing it into the river. It is an opportunity to recover low temperature (50°C) waste heat, if local users are involved. Finally, most of the existing MWIPs design results with a lack of space to add any equipment, such as heat exchangers. This constraint on the infrastructure itself limits waste heat recovery in many existing industrial sites.

For MWIPs, corrosion risks and lack of space considerably reduce theoretical waste heat recovery potential of existing sites. However, regulation on their efficiency implies that MWIPs are already efficiently using the heat generated. If technical and economic constraints identified earlier were addressed, MWIPs would have the capacity and knowledge to recover their waste heat and provide it to local users.

3.2. Sugar plants and wheat starch processing plant symbiosis

Sugar production is highly seasonal: in France beets are harvested between September and December and sugar extraction has to be done around the same time to avoid sugar concentration loss. Consequently, waste heat from the sugar refinery is available only about 3 months a year. In France, the waste heat generated by sugar plants is estimated at 2.1 TWh [19]. Most of this potential comes

from combustion gases from boilers and has a temperature of 150 to 250°C (Fig. 7). To exploit it, an essential condition is obviously to find a heat user close to the sugar plant. It is important to note that waste heat potential from sugar plants is not easily exploitable because of their well-balanced energy system [26]. Indeed, sugar plants are almost autonomous in energy factories because they combine heat and power generation (cogeneration) and reuse steam several times in the production process.

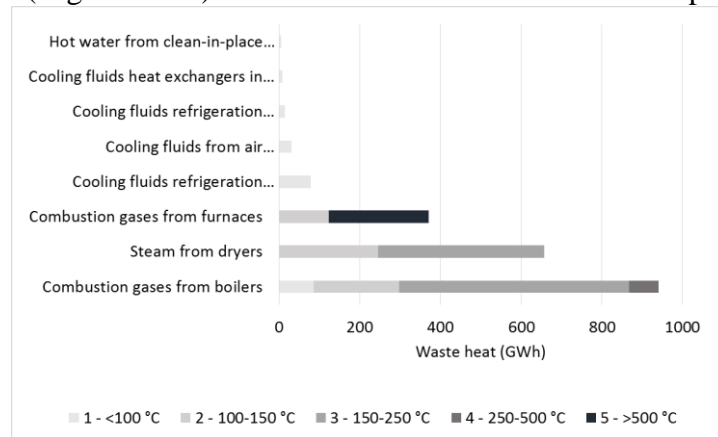


Fig. 7. Waste heat from sugar industry by type of warm effluent and by temperature

In the European Institute of biorefinery, based in Pomacle Bazancourt (France), the sugar beet refinery (Cristal Union) recovers heat from its process to supply the wheat starch processing plant (Chamtor) [27]. In Pomacle Bazancourt, the solution is to recover waste heat from sugar refinery only during these 3 or 4 months of production, as shown on Fig. 8. During the rest of the year, the wheat starch processing plant use its own boiler to produce heat.

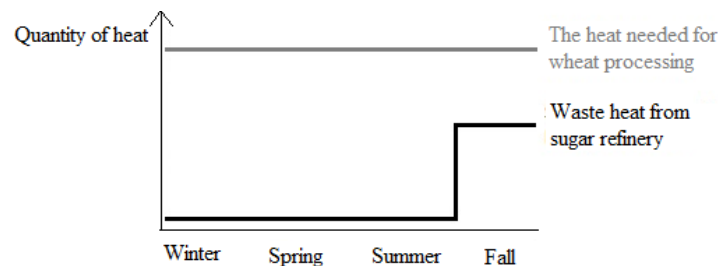


Fig. 8. Annual variation of sugar refinery heat production and wheat processing heat needs

Dependence towards a partner can be an inhibiting factor to waste heat use. To hedge against supply failure, having a back-up solution is essential. The backup solution can consist in an auxiliary boiler, which will be always available to secure heat supply, as we presented for Parisian MWIPs and the CPCU heating network. Then, the cost of its maintenance must be taken into account when project profitability is calculated. On the opposite side, when waste heat production variation is seasonally anticipated, waste heat can become the backup solution. As it is used as a seasonal and complementary heat supply, the symbiosis between the two local actors in Pomacle Bazancourt is a success.

3.3. Datacenter, swimming pool and offices symbiosis

Waste heat from datacenters is often targeted [28]. We earlier estimated a potential for heat recovering of 3.6 TWh from French datacenters. It mainly concerns cooling fluids refrigeration condensers (Fig. 9), with low-grade temperature.

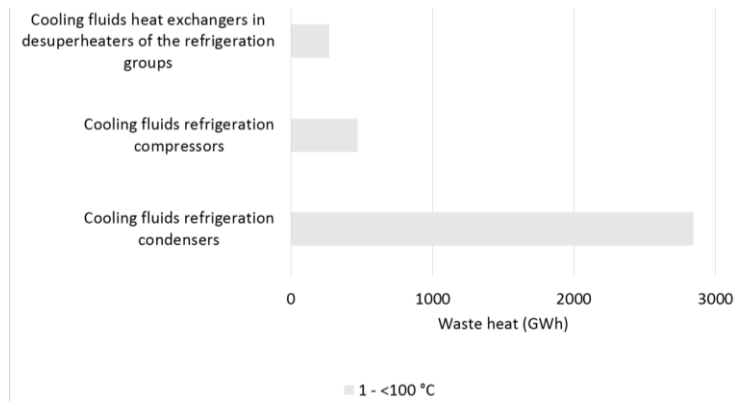


Fig. 9. Waste heat from datacenters by type of warm effluent and by temperature

Cooling represents almost one-third of datacenter energy use because it is essential to keep IT equipment rooms at a temperature lower than 27°C (ASHRAE recommendations). Datacenters would be an ideal candidate for heat recovery in term of regularity according to their constant operating rhythm during the year (Fig. 10). Yet, most of existing datacenters have not been designed for recovering heat and it is difficult to adapt them.

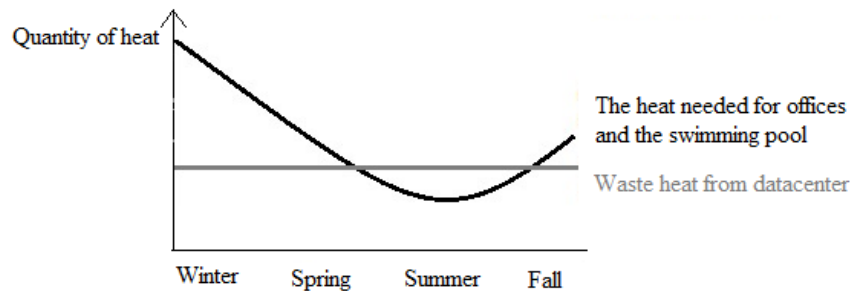


Fig. 10. Annual variations of datacenter waste heat production and urban heat needs

In the east of Paris, a 4 kilometres heating network is supplied by waste heat which is recovered from a 10 000 square meter datacenter [29]. Heat exchangers (2,4MW th) and heat pumps have been implemented to recover and raise effluent temperature. A back-up boiler secures heat supply in case of failure. A swimming pool and offices, representing a total of 6 000 square meters, are now connected to the heating network. Heat price is set at 80 €/MWh, which is superior to classic gas boilers. According to the network operator (Dalkia), system capacity is able to supply up to 600 000 square meters [29]. This example demonstrates the technical feasibility of recovering waste heat from datacenters. Nevertheless, economic development of the area is slower than expected and the potential cannot currently be exploited at its maximum.

To replicate this symbiosis with a datacenter, the first issue is to find a local heat need. Indeed, many datacenters are located far away from potential heat users. Consequently, the theoretical potential is difficult to exploit. To replicate the quoted case, future project developers should take into account current heat demand of users to reasonably size the system. Finally, it is primordial to formalize performance commitments, as explained in the following section.

3.4. Formal contract to insure matching between heat supply and users' needs

Through three case studies, we highlighted the importance of checking adequacy between heat supplier and users' need during the feasibility study. Quality, quantity and regularity of heat supply have to suit user's requirements. Besides, to comply with project profitability, a minimum duration commitment is required by investors. For the datacenter example detailed in part 3.3, a commitment of 25 years has been taken by partners [29]. It can also involve penalties in case of breach of contract.

Return on investment time, which implies a minimum duration commitment, may discourage most industrial actors, which have in general a 3 years visibility on their activities.

Consequently, to ensure sustainability of this complex system, all these parameters should constitute commitments in a formal contract. To secure supply but also durability of equipment, the partner at fault exposes itself to financial penalties if contractual performance level is not reached. Juridical implications must not be set aside, as we can note when a failure occurs. Purpose of the contract is to formalise and support the organisation between all stakeholders involved into heat symbiosis.

4. Conclusion

Waste heat is equivalent to one-third of French industry energy consumption. Recovering this free heat is thus a major stake for energy efficiency and industry competitiveness. The presented data show a large heterogeneity between business sectors, effluents types and geographical implantation of industrial sites. Despite the highlighted potential, few examples exist today. Indeed, to recover waste heat, it is primordial to consider :

- Technical constraints such as the design of existing sites, corrosion and fouling of materials
- Concomitance between heat production and heat demand on short-term (daily variation), mid-term (seasonal variation) and even long-term (project sustainability and profitability) : quality, quantity and regularity requirements
- Complex system organization, defined through precise feasibility study

A balance contract between stakeholders (industrials, municipalities, investors, ...) should formalise the complex organization, set to run the thermodynamic system. Finally, human factor is an essential key of success during the project lifetime.

Today, several symbiosis based on waste heat recovery can be used as references to identify good practices and help the achievement of new successful projects in terms of technical, economic and environmental performance.

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