Assessment of the potential of heat recovery in food and drink industry by the use of TIMES model

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Abstract

In industry, around three-quarters of final energy uses are for thermal purposes (boilers, dryers, ovens, etc.). Unfortunately, it is estimated that one quarter of this energy is lost through heat losses in fumes and wastewater. However, the lowest temperature range of this heat could be (technically and economically) recovered through heat pumps systems. It is also possible to recover low temperature heat from other energy uses like air compressors or refrigeration systems. Heat pumps present great technical potentials by providing heat at higher temperatures, they can substitute part of the heat provided by traditional fossil combustible boilers. But their adoption will depend mainly on their economical competitiveness.

The purpose of our work is to highlight the opportunities of heat pumps in French food and drink industry and to examine the economical and technical conditions of market accessibility. We want to know what particular sub-sectors in food and drink industry are more promising for heat recovery. We also investigate what amount of energy recovery could be reached with innovative high temperature heat pumps.

For that, we use a prospective energy model, considering food and drink industry at a highly disaggregated level (4-digit level of NACE classification), with 11 energy uses, and 8 temperatures ranges per energy use. The modelling tool is TIMES model (family of best known MARKAL model). It is a mathematical model of an energy system of one or several regions that provides a technology-rich basis for estimating energy dynamics over a multi-period horizon.

This model was originally built for assessing energy consumption in industry, under different prospective scenarios. But it is also adequate to simulate competition between heat pumps and boilers using fossil combustibles, under different energy prices or heat pumps performances hypothesis.

Introduction

In French industry, around 75 % of the final energy use is for thermal purposes (boilers, furnaces, reactors, dryers etc …). The major part of that heat comes from the combustion of fossil fuels, generating large CO_2 emissions. It is estimated that an important part of this energy is lost through heat losses and waste water. However, the lowest temperature range of this heat could be (technically and economically) recovered through heat pumps systems. It is also possible to recover low temperature heat from other energy uses like air compressors or refrigeration systems. Heat pumps present great technical potentials by providing heat at higher temperatures, they can substitute part of the heat provided by traditional fossil combustible boilers. But their adoption will depend mainly on their economical competitiveness and technical performances.

Among French industry, many industrial sectors are suitable for heat recovery by heat pumps. We focused our work on food and drink industry for two reasons: the economical importance of this sector in France and the range of heat demand, with many end uses in the [60–140 °C] class, well adapted to the level of temperature reached by heat pumps.

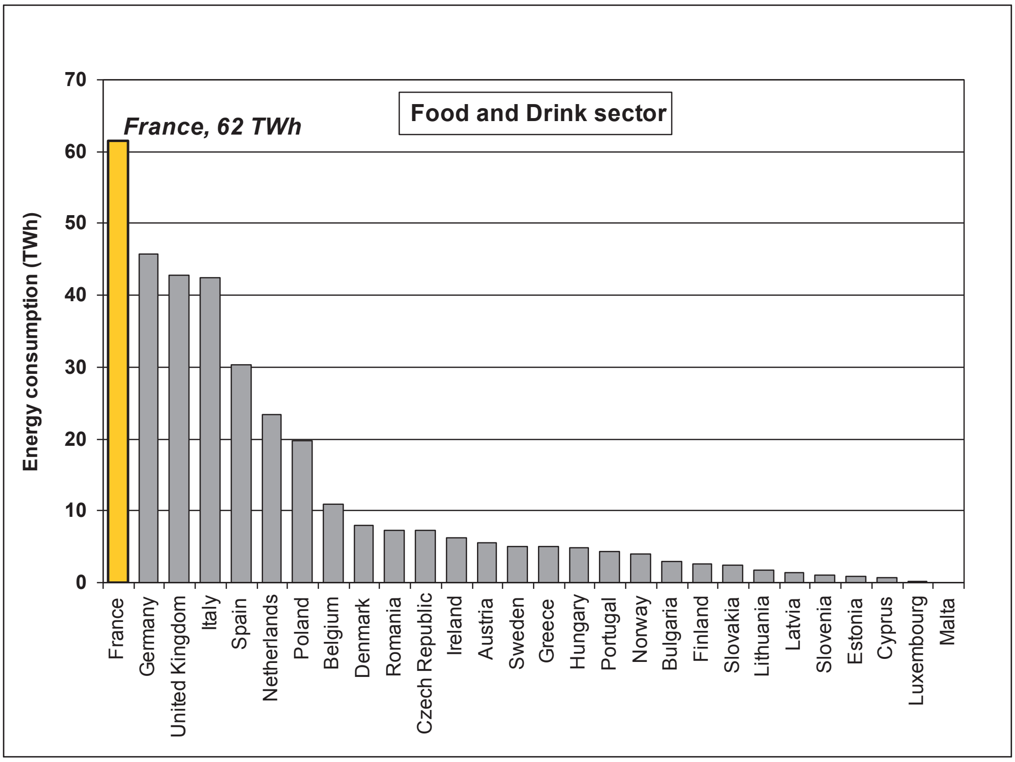

Figure 1: Annual energy consumption in food and drink sector, in Europe (2005-ENERDATA).

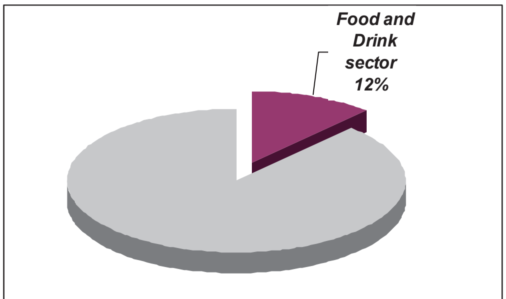

Figure 2: Share of food and drink sector in French total industry energy consumption.

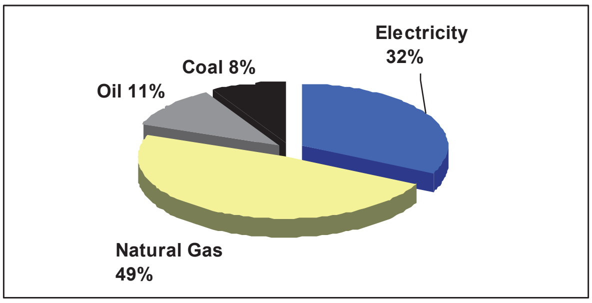

Figure 3: Energies consumed in French food and drink sector.

THE FRENCH FOOD AND DRINK INDUSTRY

French food and drink sector is the most energy consuming in Europe (Figure 1), with 62 TWh/year. Food and drink sector represents around 12 % of the French total industry energy consumption (Figure 2). It is the third consuming sector after steel industry and chemistry sector [Enerdata 2005].

Natural gas is widely used in food and drink sector (around half of the energy consumption), followed by electricity (around 30 %). Other energies (coal and oil) are declining for years, in 2005 they represent less than 20 % of the total energy consumption (Figure 3).

Food and drink sector can be considered as a non energy intensive industry (except for some subsectors like sugar and starches products). Relevant indicators for this segmentation are:

- a low share of energy cost in the total production cost,
- a low amount of energy consumed by production plant,
- a high number of products and processes.

The later point will induce a particular way of modelling this kind of industrial sector as it will be explained later on the paper.

In the food industry, heat has an important influence on food processing because it is the most convenient way of extending the shelf life of foods. Indeed, heat will destroy enzymatic or microbiological activity or remove water to inhibit deterioration. So there is a lot of processing by application of heat (baking, pasteurization, heat sterilization, blanching …) or by removal of heat (chilling, freezing, freeze drying). But processing temperature is usually low, not too high to destroy food quality product. So, many end uses are in the [60–140 °C] temperature class, well adapted to the level of temperature reached by heat pumps.

HEAT PUMPS FOR HEAT RECOVERY

Industrial heat pumps, using waste process heat as the heat source, deliver heat at higher temperature for use in industrial process heating. They represent a worthwhile method of improving the energy efficiency of industrial processes, and/or reducing final energy consumption and avoiding CO_2 emissions. The heat pump is now benefiting from advances in research and higher fossil energy prices.

A heat pump is essentially a heat engine operating in reverse. Its principle is illustrated below:

From the first law of thermodynamics, the amount of heat delivered Q_D at the higher temperature T_D is related to the amount of heat extracted Q_S at the low temperature T_S and the amount of high grade energy input W by the equation:

$$Q_D = Q_S + W$$

The coefficient of performance (COP) can be defined as: $COP = Q_D/W$. If you consider that the heat delivered (Q_D) by the heat pump replaces the heat provided by a heat exchanger using steam coming from a boiler, the COP is thus the ratio between the amount of heat that can be saved from the boiler and electricity consumption of the heat pump. It is an indicator of the energy gain achieved by installing a heat pump.

The installation of a heat pump corresponds to an additional investment cost and leads to savings on operating costs. The profitability depends on the initial investment cost and energy prices.

Heat pumps are currently providing heat up to 80 °C. There are many laboratory developments for high temperature heat pump. EDF works on several French R&D programs for the development of industrial high temperature heat pumps providing heat up to 140 °C [2]. 2015 is the target date for their arrival on the market.

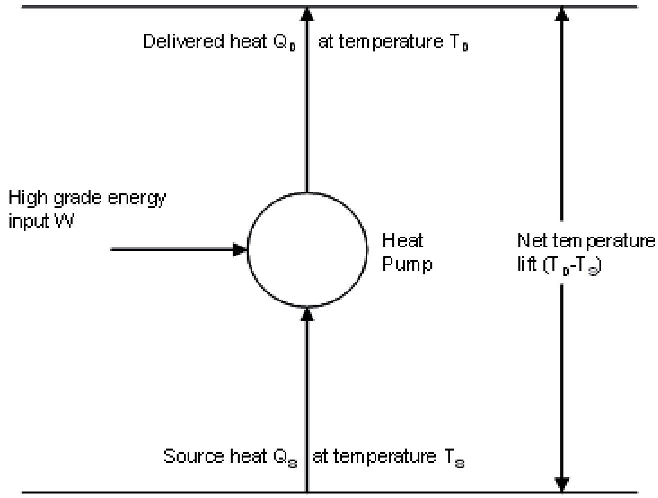

Figure 4: heat pump principle [1].

The interest of TIMES model

THE TIMES MODEL AIMS TO SUPPLY ENERGY SERVICES AT A MINIMUM GLOBAL COST

TIMES is an energy prospective model. It is a recent development in the evolution of the MARKAL framework, created by the IEA Energy Technology System Analysis Programme (ETSAP) [3]. Like MARKAL, TIMES is an economic linear programming model generator for local, national or multi-regional energy systems, which provides a technology-rich basis for estimating energy dynamics over a long-term, multi-period time horizon. It is usually applied to the analysis of the entire energy sector, but it may also be applied to study in detail single sectors, like the food and drink industrial sector in our case. The model aims to supply energy services at a minimum total production cost by simultaneously making the best choices in equipment investments and energy supply.

TIMES model is based on a reference energy system, which is usually a network describing the flow of commodities through various processes. This energetic description is well suited to energy intensive industry because the industrial process is fairly well defined by a sequence of unit process steps, from raw materials to the finished main product [4]. But this method is difficult to apply for non-energy intensive industry because of a considerable number of products and processes. This explains our choice to develop a modelling approach by energy end uses. We defined eleven families of energy end use. Some are thermal uses and others are not; the 11 modelised end uses are; drying, liquids and gases heating, cooling, air compressors, evaporation & concentration, heat treatment, building heating, chemicals reactions, melting, lighting, and others. This approach allows us to build a generic model unlike the energy intensive industry where we have to model each sector differently. By adding the amounts of energy consumed in each energy end-use, we can calculate the total energy consumption of each industrial sub-sector.

A full TIMES scenario consists in four types of input: the final demand for energy services, the resource prices, the environmental policy, and the description of a set of technological process options. TIMES is a demand-driven model, usually used for prospective studies. Here we used the model in a stationary mode. We fixed the economical conditions for the whole study period (i.e. constant energy prices, constant industrial production, and no particular environmental policy) and we consider the heat pump as a unique technological process option for energy savings.

COUPLING ENERGY DEMAND, ENERGY RECOVERY OPPORTUNITIES AND ECONOMIC PROFITABILITY.

The heat recovery potential in industry is important, but there are two difficulties to assess the real energy saving potential. First, as you cannot transfer on a long distance the recovered heat, you must have a heat demand near the recovery source. And the levels of temperature required by the heat demand must fit with the heat pumps technologies. Secondly, this operation must have a sense economically, the recovered heat must be cheaper than the original heat provided by boilers.

So the main difficulty of the assessment of the potential of heat recovery is to match the heat recovery opportunities with the heat demand and with an acceptable economic cost.

TIMES is an interesting model because you can have in the same model, the heat demand, the heat recovery opportunities, and you can calculate the economic cost of the recovered heat.

The heat demand in French food and drink sector

In order to target relevant industrial sectors and energy uses, EDF R&D bought detailed surveys about energy consumptions per industry branch [5][6]. We considered the French economic activity classification (NCE), and we aggregated the similar

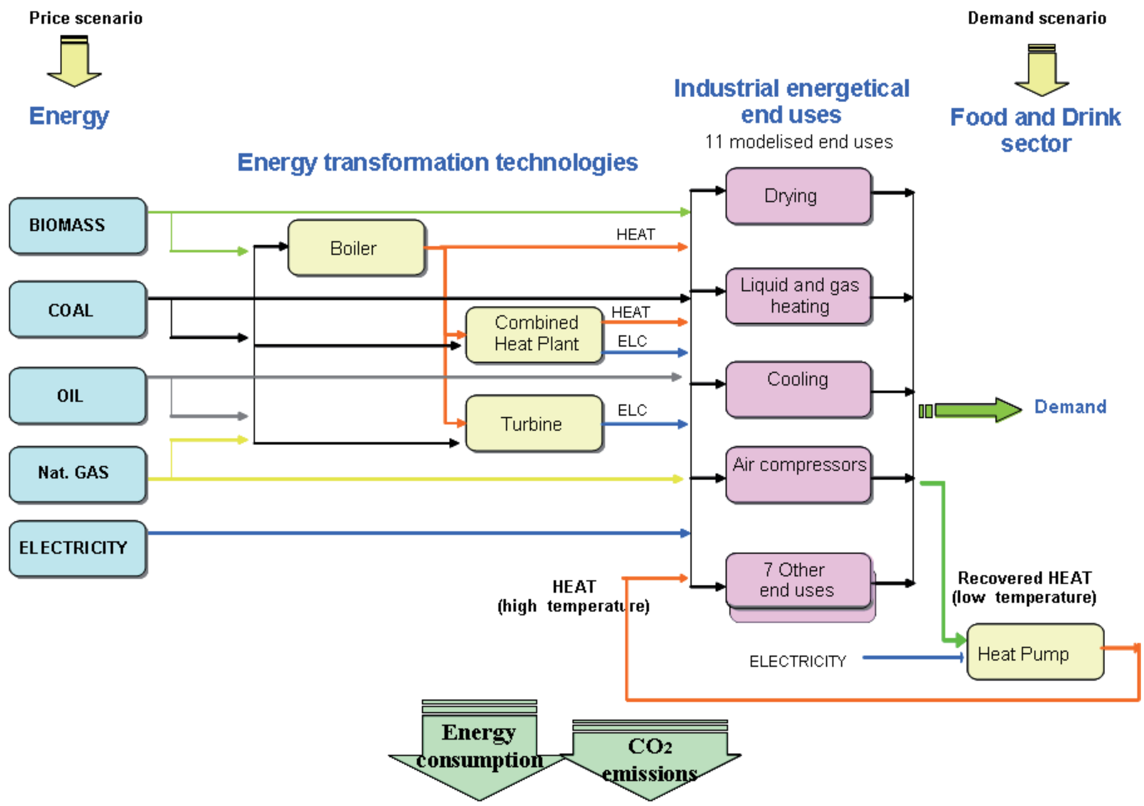

Figure 5: Reference Energy System for a non energy intensive industrial sector like food and drink sector.

sub-sectors in food and drink sector in order to consider only 20 homogenous sub-sectors. In each class, heat recovery opportunity must fit the heat demand to be considered as a real heat recovery opportunity. We assumed that this level of segmentation is enough to consider that heat demand fits with heat recovery source.

In the building sector, the heat recovered by a heat pump mainly comes from outside air or from the ground, and then is almost always available. Conversely, in industry, the potential of these conventional heat pumps would be limited because the major part of heat demand is at higher temperature level. Hence, it has been decided to reconsider the entire problem of the heat pump for industry including higher temperature level not yet accessible with existing equipments, but with higher potential in terms of energy savings and CO_2 emissions. As a consequence, the paper will consider the 60–200 °C range of temperature, with 7 temperature class, considering than current heat pump can reach 80 °C, and future heat pumps could reach 140 °C.

The Figure 6 represents the heat demand in the 20 sub-sectors with the 7 temperature range levels. As it can be noticed the heat demand is very depending of the kind of production in each class, and thus this validates the need of a precise survey in each branch of industry.

The heat recovery opportunities in French food and drink sector

In industry, it is possible to find heat source in the temperature range of [30–60 °C] on several equipments. This paper particularly focuses on 3 of them that are widespread in every sub sectors. The 2 first are subject to a standardized action in the French white certificate mechanism, so they are more detailed. The last one aggregate all the others thermal end uses.

- Air compressors,
- Chillers,
- Other thermal end uses

These equipments can provide heat between 30 and 60 °C. For the TIMES calculations, we used an average temperature of 45 °C. This heat is at a too low temperature to be recovered by an exchanger and used directly in industrial processes. So this heat is currently wasted and heat pumps represent a way to recover it.

Heat recovery on air compressors

Compressed air is a major end use in industry. However, compressed air is also one of the most costly end uses. Indeed, around 90 % of the input energy to air compressor is lost as waste heat [7], and almost never recovered. For example, water cooled compressors can provide warm water around 60 °C, whereas air cooled compressors can provide water only around 30–40 °C [8].

Waste heat recovery on air compressors is subject to a standardized action in the French white certificate mechanism. It is said in this text that 70 % of the air compressor input energy can be recovered as heat. In this paper, we used a rate of 50 %, but we considered that there are not sub sectors already equipped with heat recovery systems.

$$\text{Heat recovered}_{\text{air compressors}} = 50\ \%\ \text{Input energy}$$

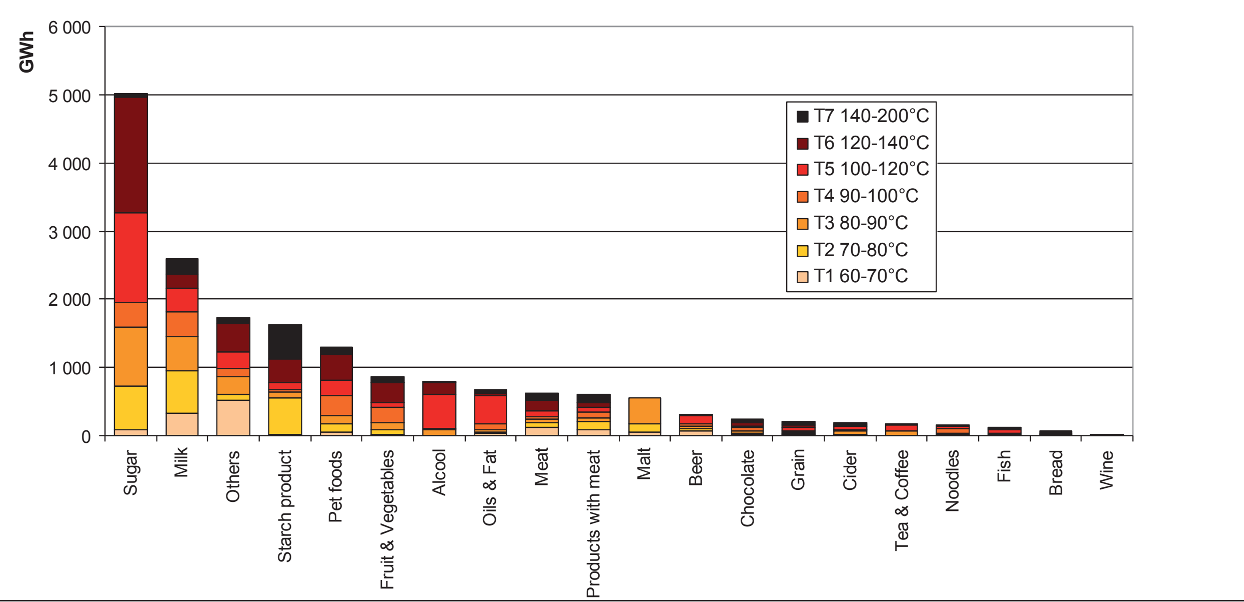

Figure 6: Heat demand in the French food and drink sector [CEREN 2005].

Heat recovery on chiller condensers
Cooling is also a major end use in industry. The energy efficiency ratio (EER) of chillers allows them to supply more energy than their input energy. However, the heat available at their condenser is generally wasted into the air. For example, condensers of cold generating equipments can provide warm water at a temperature between 35–45 °C. The waste heat at the condenser has to be deduced using the two following equations in which W represents the power transferred as work by the compressor to the refrigerant, Qc the heat lost by the refrigerant in the condenser, Qe the heat recovered by the refrigerant in the evaporator, and EER is the energy efficiency ratio of the chiller and E the electric power used:

$W + Qe = Qc$	Energy conservation equation in the refrigerant cycle
$EER = Qe / E$	Calculation of the EER of the machine

In order to simplify these equations, we considered a no loss compressor so that its electric input power E is always equal to the power transferred as work to the refrigerant. As a consequence, the two equations become only one:

$$Qc = (EER + 1)E$$

The chiller EER during an entire year is estimated around 2.5. We also considered that only 70 % of Qc is recovered by heat pumps.

$$\text{Heat recovered}_{\text{chiller condensers}} = 70\ \%\ (2.5 + 1)\ \text{Input energy}$$

Heat recovery on other thermal end-uses
We considered that there are other end uses where heat is lost (liquids and gases heating, heat treatment). As it is difficult to identify precisely all the end uses, we assumed an average heat recovery potential of 15 % on all the other thermal uses.

$$\text{Heat recovered}_{\text{thermal end uses}} = 15\ \%\ \text{Input energy}$$

Synthesis on heat recovery opportunities
Considering the 11 energy end uses in the 20 sub-sectors of French food and drink sector, we calculated the heat recovery opportunities in 2005.

We calculated that the total heat recovery potential is 22 550 GWh/year. But, as you cannot use more heat than you need for each sub-sector in the [60–140 °C] temperature range demand, the technical heat recovery potential is:

$$\sum_{subsector=1}^{20} \min(\text{heat demand},\ \text{heat recovery potential})_{subsector}$$

In this case, the technical heat recovery potential drops to 11,068 GWh/year. This potential does not consider economic cost of recovered heat, it is only a technical potential. However, there might be even more technical restrictions depending on each industrial site like space considerations, matching heat flows over time, that cannot be taken into account in such a global model. The aim of this work is to assess the potential of heat pumps for the whole French food and drink industry, not to evaluate the interest of heat pump for one particular site.

TIMES model allows integrating an economic analysis to the assessment of the potential of heat recovery

We assumed that recovered heat by heat pumps replace the heat supplied by existing boilers. So, the installation of a heat pump corresponds to an additional investment cost and leads to savings on operating costs. The profitability depends on the initial investment cost and economic conditions of production of heat. TIMES model is able to accurately assess those costs in each sub sector according to specific conditions of production of heat.

The model aims to supply energy services at a minimum global cost by simultaneously making the best choices in equip-

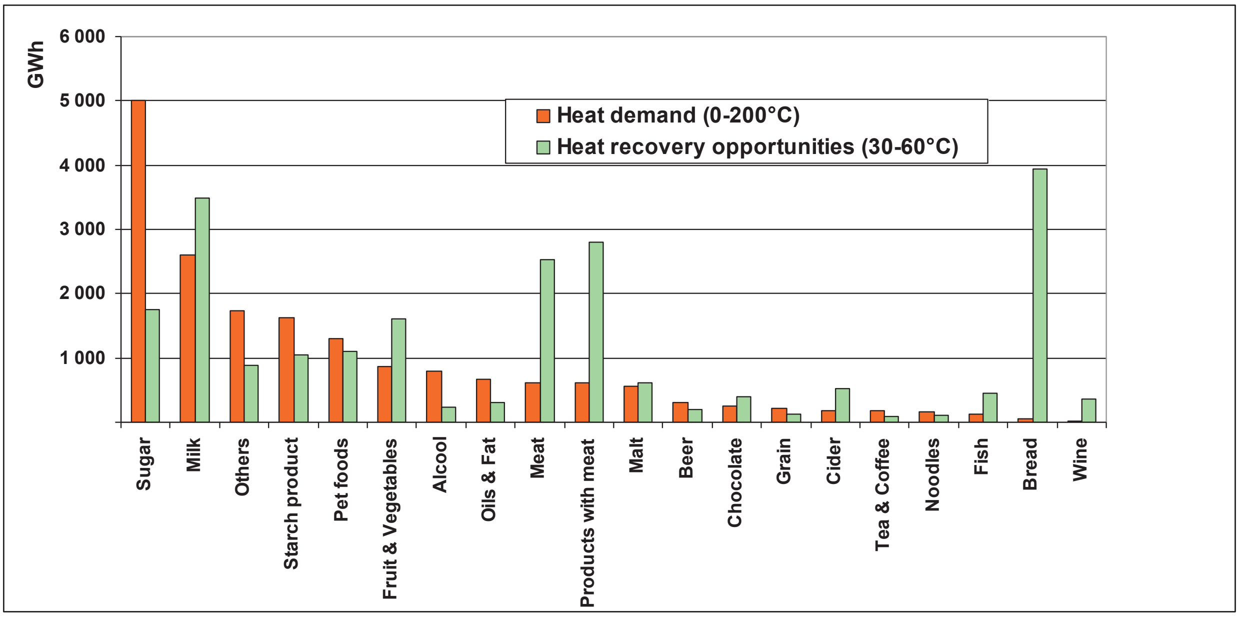

Figure 7: Heat demand and recovery opportunities in the French food and drink sector [TIMES calculation based on 2005 CEREN data].

Table 1: Energy prices in France for food and drink sector in 2005 [AGRESTE 2005].

Sub sector (2005)	Electricity	Nat. Gas	Oil	Coal
Sugar	52 euros/MWh	17 euros/MWh	17 euros/MWh	11 euros/MWh
Milk	49 euros/ MWh	21 euros/MWh	24 euros/MWh	11euros/MWh
Other food and drink sub sector	50 euros/MWh	21 euros/MWh	24 euros/MWh	11 euros/MWh

ment investments and energy supply. We assumed a discount rate of 4 %.

We made the calculations with the 2005 French economical conditions, in terms of industrial production and specific energy prices for food and drink sector. This is in accordance with the date of the CEREN survey on energy consumption per industry branch.

The price of a heat pump is very depending on their working conditions. Heat pumps that produce hot water at temperatures below 70 °C are often derived from air conditioning systems and industrial refrigeration. They are produced in large quantities and therefore they are much less expensive than other machines dedicated to higher temperatures. We assumed a standard machine (up to 100 °C) costs 1,500 Euros/kW$_{electrical}$ (installed on site), while an efficient heat pump (up to 140 °C) costs 20 % more, 1,800 Euros/kW$_{electrical}$ [1] &[2].

The coefficient of performance (COP) is an important indicator of a heat pump. It is linked to the temperature difference between the heat source and the heat demand. If the temperature difference is too high, a heat pump can become inefficient and/or incapable to provide the required heat. We assumed that the real COP is lower than the theoretical COP (Carnot COP) using the following formula:

$$COP = 0.55\ COP_{Carnot}$$

We calculated the following value for the COP, depending of the heat demand temperature class, and considering that recovered heat source is in the [30–60 C°] class.[1]

$$COP = 0.55\ T_{D*}/(T_{D*}-T_{S*})$$

T_{D*} and T_{S*} are the temperatures of refrigerant and not the temperature of the hot source and cold source (external fluids of the heat pump). The temperatures of the external sources are close to the temperatures T_D and T_S, depending on the exchanger pinch value (p). Depending on circumstances (air or liquid exchanger) this pinch value can be more or less important. On a liquid, the pinch value may be limited to 2 °C while it is nearly 10 °C for an exchange with air. We assumed p= 5 °C, and we used the following formulas $T_{D*} = T_D + p$ and $T_{S*} = T_S - p$.

We made the calculations with 2 hypotheses on the efficiency of heat pumps. The first simulation only considers the current heat pumps, which can provide heat only at 80 °C. The second simulation considers that heat pumps can provide heat up to 140 °C, assuming that efficient heat pumps currently in laboratory development are available.

Figure 8 shows the results for the second simulation, assuming the availability of heat pumps up to 140 °C. In each sub

1. The temperature are expressed in Kelvin for the calculations.

Table 2: Calculations of COP of the heat pumps.

Temperature of heat demand	60–70 °C	70–80 °C	80–90 °C	90–100 °C	100–120 °C	120–140 °C
T_D*= $T_{D\ average}$ + 5°C	70 °C	80 °C	90 °C	100 °C	110 °C	135 °C
Temperature of heat source	30–60 °C	30–60 °C	30–60 °C	30–60 °C	30–60 °C	30–60 °C
T_S*= $T_{S\ average}$ - 5°C	40 °C	40 °C	40 °C	40 °C	40 °C	40 °C
COP	**6.29**	**4.85**	**3.99**	**3.42**	**2.85**	**2.36**

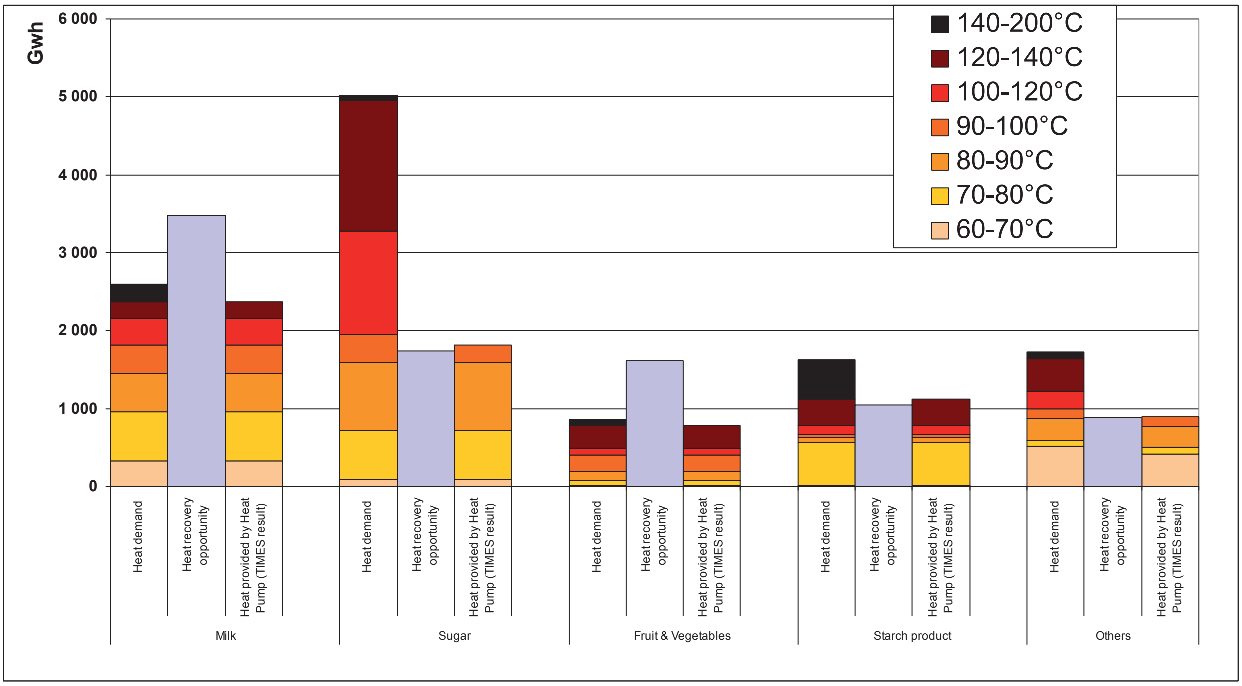

Figure 8: TIMES calculations: Amount of heat economically recoverable by heat pumps in 5 food and drink sub sectors (2005 French economic situation, heat pumps available up to 140 °C)

sectors we can find the previous heat demand and heat recovery opportunity, and what amount of heat is economically recovered. These amounts are depending of the economical conditions in each sub sector (specific energy prices, and specific prices for heat produced by boilers). The recovered heat is heat at low temperature. By raising the temperature levels with heat pumps, electrical energy is added in the final heat delivered by the heat pump. This explains why the heat provided by heat pump (TIMES result) can be higher than the heat recovery opportunity in some industrial sub sectors.

Finally, we calculated the electricity consumed by heat pumps in every sub sectors (depending on COP values in each temperature classes) for deducing the net energy savings (Figure 9). Energy is expressed in final energy. Heat recovery with heat pumps allow to save fossil fuels, and due to the low carbon content of the kWh in France, the CO_2 emissions avoided would be estimated around 2 Mt CO_2/year (Table 3).[2]

2. Considering French emission factors for the combustion of natural gas, coal, oil respectively equal to 210 gCO2/kWh, 340 gCO2/kWh, 280 gCO2/kWh, and the CO2 emissions of the production, transportation and distribution of electricity equal to 57 gCO2/kWh.

The maximal (technical) substitutable heat is estimated around 11 TWh/year on the whole [60–140 °C] heat demand of food and drink sector. When you consider the energy prices in France in 2005, around 30 % is already economically interesting to recover (3,578 GWh/y on 11,068 GWh/y) with current efficiency of heat pumps. Heat pumps are in laboratory development to be able to provide heat up to 140 °C. With the availability of these very efficient heat pumps, this ratio could reach 100 %. This maximal value is due to the particular energy prices in France and the hypotheses on high temperature heat pumps prices. If the current heat pumps (up to 80 °C) are well documented (prices are available [1]), the prices for high temperature heat pumps come from an assumption (+20 %).

So, the potential of net final energy savings in French food and drink using current heat pumps is around 3 TWh/y, representing around 5 % of the total consumed energy in this industrial sector (3 on 62 TWh/y). With the availability of efficient heat pumps, the net final energy saving could reach 8.4 TWh/y, representing more than 13 % of the total consumed energy.

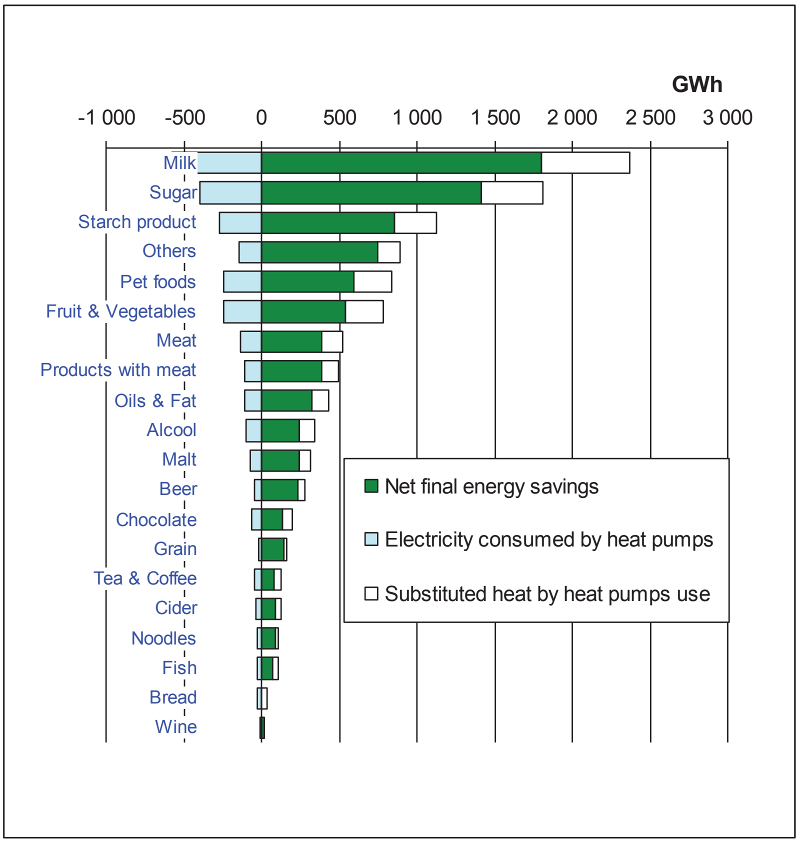

Figure 9: TIMES calculations: Net final energy savings in food and drink sub sectors (2005 French economic situation, heat pumps available up to 140 °C).

Table 3: TIMES calculations: Potential of heat recovery in food and drink sub sectors (2005 French economic situation).

Scenario	Technical substitutable heat	Calculated substituted heat by heat pumps use (included recovered heat and electrical energy consumed by heat pumps)	Electricity consumed by heat pumps	Net final energy savings	CO_2 avoided
French F&D sector, 2005 economic conditions, heat pumps available up to 80 °C	11 068 GWh/y	3 758 GWh/y	639 GWh/y	3 119 GWh/y	0.71 Mt CO_2/y
idem except heat pumps available up to 140 °C	11 068 GWh/y	11 098 GWh/y	2 649 GWh/y	8 449 GWh/y	2.14 Mt CO_2/y

Few published studies exist on the same subject (industrial heat pumps and French food and drink sector). The more relevant study is the "Survey of availability of heat pumps in food and beverage fields" written by the Heat Pump & Thermal Storage Technology Center of Japan" [9]. They have done an assessment of the potential of CO_2 reduction after the application of heat pumps in different countries, including France. They found a figure of 3 Mt CO_2/year for France, slightly higher than the 2.14 Mt CO_2/year we estimated in this study. The main differences are:

- They assumed a 60 % fixed share of heat hump substitutable fuel consumption relative to consumption of fuels for steam boilers in the food sector (like in Japan). In France this figure seems too high because heat recovery opportunities do not match with heat demands in every sub sectors as we showed it.
- They assumed the availability of heat pumps up to 100 °C. We considered a higher temperature of 140 °C. We are more optimistic in this case and this leads to a higher figure for CO_2 reduction than it would be with the same restricted performance.

Conclusion

The main difficulty of the assessment of the potential of heat recovery is to match the heat recovery opportunities with the heat demand and with an acceptable economic cost.

TIMES is a powerful energy prospective model. But it is also an interesting model because you can have in the same model, the heat demand, the heat recovery opportunities, and you can calculate the economic cost of the recovered heat.

The technical substitutable heat is estimated around 11 TWh/year on the whole [60-140 °C] heat demand of French food and drink sector, representing around 15 % of the total consumed energy in this industrial sector. When you consider the energy prices in France in 2005, around 30 % is already economically interesting to recover with current efficiency of heat pumps. Heat pumps are in laboratory development to be able to provide heat up to 140 °C. With the availability of these very efficient heat pumps, and with an hypothesis of a 20 % higher price, this ratio could reach 100 %. Heat recovery with heat pumps allow to save fossil fuels, and due to the low carbon content of the kWh in France, the CO_2 emissions avoided would be estimated around 2 Mt CO_2/year.

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