INDUSTRIAL HEAT RECOVERY AND HEAT PUMPS SYSTEMS

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ABSTRACT

The growing costs of fuels and supply security concerns make it necessary to reduce energy consumption in industrial processes. The use of heat recovery technologies like Heat Pumps (HPs) is an effective way of achieving an energy saving and a significantly reduction in CO_2 emissions. Around one third of the final energy used for thermal purposes[1] is subsequently wasted through losses. The lowest temperature range of this heat could be technically recovered through HPs systems from energy end-uses like dryers, refrigeration systems, air compressors etc. HPs have made great technological progresses by providing at the same time useful heat at higher temperatures and the possibility of replacing boilers which consumed traditional fossil combustible to provide heat. The purpose of our work is a prospective energy analysis up to 2020, to highlight the availability and opportunities of existing and innovative high temperature heat pumps systems in French Food & Drink (F&D) industry. For that purpose, we implement a sectoral energy system optimization model using the ETSAP TIMES[2] framework. It is a "Bottom up" technical economic model which provides a technology rich basis for estimating energy dynamics over a medium or long-term and a multi-period time horizon.

Keywords

Energy policy, Climate change, Heat Pump system, Heat recovery, Industrial waste heat, energy efficiency, TIMES.

1. INTRODUCTION

Almost three-quarters of final energy consumption in industries are used for thermal purposes (boilers, thermal end-uses) and this heat is mainly produced by combustion of fossil fuels which generate great amounts of CO_2 emissions. However, around one third of the final energy used for thermal purposes is subsequently wasted through losses (fumes and waste water). Under Energy Savings Certificate (ESC or White certificates), some measures such as boilers economizers and variable speed drives have been applied because of their high potential of energy efficiency and simple implementation on industrial site. However, estimating precisely energy savings for more complex projects is not simple. Between 10% and 30% of final energy consumption are in theory possible to recover in the losses on thermal equipments which represent around 30 to 100 TWh per year for France in industry. Thus, our modeling problematic is heat recovery on industrial processes which could be developed and recognized as eligible for ESC.

The lowest temperature range of this heat could be technically recovered through heat pumps (HPs) systems from thermal energy end-uses like dryers, ovens…etc. But we can recover refrigeration systems, air compressors etc... They can be used to raise the temperature of waste heat so that it can be also re-used for processes and space heating purposes. However, it is seldom re-used today. HPs have made great technological progresses by providing at the same time useful heat at higher temperatures and the possibility of replacing boilers which consumed traditional fossil combustible to provide heat. Therefore, it seems important to recover and re-use this heat in order to achieve the 20/20/20 EU scheme against climate change for an energy efficient and low-carbon economy. Heat pumps represent an important technology which can significantly reduce CO_2 emissions and provide attractive opportunities for energy conservation in industry. But their adoption will depend mainly on their economical competitiveness.

The purpose of our work is a prospective energy analysis up to 2020, to highlight the availability and opportunities of existing and innovative high temperature heat pumps systems in French F&D industry which considered as Non-Energy Intensive (NEI) industry [1]. We focused on this sector by his energy and economical importance in industry. This sector represents around 13% of total industrial value added for around 15% of total final energy consumption in French industry with about 63 TWh for 2005 [2][3]. It is the third greatest energy consumer sector after iron & steel sector and chemistry sector.

Heat is very important in food processing (drying, baking, pasteurization, heat sterilization, blanching...) which will allow destroying enzymatic or microbiological activity or removing

[1] Almost three-quarters of final energy consumption in industries are used for thermal purposes (boilers, thermal end-uses) and this heat is mainly produced by combustion of fossil fuels which generate great amounts of CO_2 emissions.

[2] The Integrated Markal-Efom System.

water to inhibit deterioration. We observed that 85% of the total heat demand is consumed by only four energy end-uses (dryers, heating liquid and gazes, heat treatment and evaporation concentration). And around 95% of this heat needed which means approximately 25 TWh is between 60°C-200°C. The heat demand on the 60-100°C range represents almost 45% while in the 100-140°C; the heat demand is around 40% of the total. Three subsectors such as Dairy, Starches and Sugar consumed 55% of the total heat demand of French food and drink[3].

2. THE TIMES MODEL

We implement a sectoral energy system optimization model using the ETSAP TIMES framework. TIMES is developed and maintained by the Energy Technology Systems Analysis Programme (ETSAP), an implementing agreement under the aegis of the International Energy Agency (IEA). TIMES is an economic linear programming model generator for local, national or multi-regional energy systems. It is a "Bottom up" technical economic model which provides a technology rich basis for estimating energy dynamics over a medium or long-term and a multi-period time horizon. It is usually applied to the analysis of an entire energy sector like industry, but it may also be applied to study in detail single sectors, like the Food and Drink industrial sector here (Fig. 1) [4].

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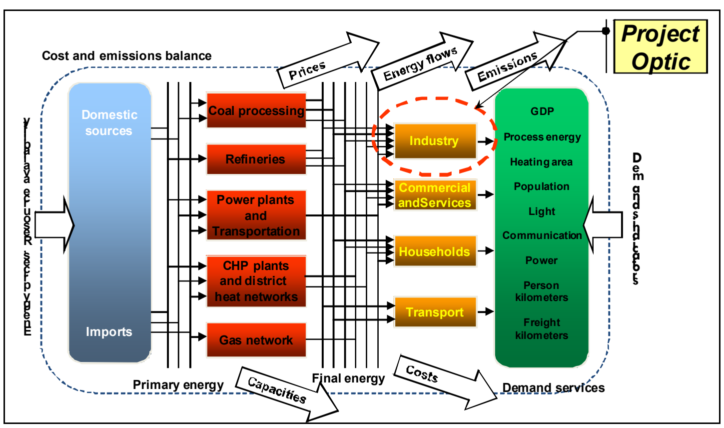

Fig. 1 : Overview of TIMES model.

The TIMES objective is to minimize the total cost of the system which includes capital costs, Operation & maintenance costs, exogenous imports or exports, taxes and subsidies…etc. All costs elements are discounted to a chosen reference year. Furthermore, TIMES is a partial equilibrium computation on energy markets. This means that the model computes both the flows of energy forms and materials as well as their prices, in such a way that, at the prices considered by the model, the suppliers of energy produce exactly the amounts that the consumers are willing to buy [5]. The cost discounted explains why we have to choose a global discount rate (see after) but we can specify it for each technology such as heat pump

[3] The Food & Drink industry is subdivided in 20 subsectors according to the Statistical classification of economic activities in the European Community (NACE).

It is based on a Reference Energy System (RES) which is a network describing the flow of commodities through various and numerous processes [6]. The energy description has to be done by process step because the process flows could be fairly well defined for a single broad product line by unit process step (iron and steel, paper and allied products, glass and glass products…). This technological description is well suited to Energy Intensive (EI) Industries. However, in the case of NEI Industry like F&D sector, this method is difficult to apply, and so it requires another approach because of the diversity and the large number of end products and unit processes. This explains our choice to develop a modeling approach by energy end-uses (e.g. drying, heat treatment…) (Fig. 2). In this work, we assume eleven energy end-uses which represent an aggregation of existing unit processes (we can see some examples in Fig. 2) in food and drink sub-sectors.

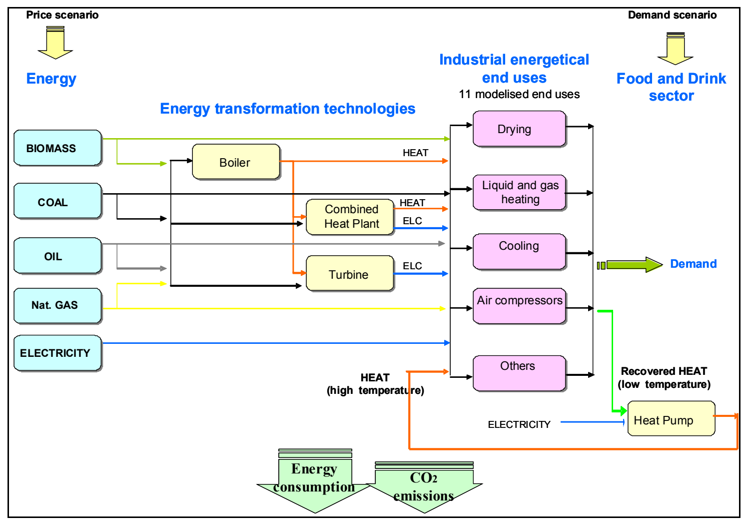

Fig. 2 : Reference Energy System for Food and Drink sector.

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. We have to define four types of input to obtain a complete scenario in TIMES. These inputs represent energy service demands, primary resource potentials, a policy setting, and the descriptions of all technologies (efficiency, all costs such as investment cost, O&M cost…etc)..

3. DESCRIPTION OF DIFFERENT HYPOTHESIS AND SCENARII

We considered a highly disaggregated level (4-digit level of NACE classification) of the Food and Drink industry, such as 35 sub-sectors.

- ***Heat pump systems***

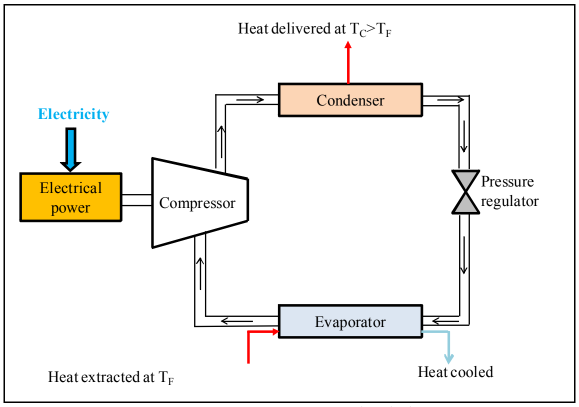

Fig. 3 : Heat pump principle.

From the first law of thermodynamics, we can define the relation between the amount of heat extracted Q_F at the temperature T_F, the amount of heat delivered Q_C at the temperature $T_C > T_F$, and the mechanical energy W supplies to the system:

$$(1) \quad W + Q_F = Q_C$$

The theoretical Coefficient of Performance (the Carnot COP) which is the efficiency of the HP is defined by:

$$(2) \quad COP_{theoretical} = \frac{Q_C}{W} = \frac{Q_C}{Q_C - Q_F}$$

We can deduce from the Clausius equation, the relation between the theoretical COP and the different temperature for an ideal thermodynamics HP:

$$(3) \quad COP_{theoretical} = \frac{T_C}{T_C - T_F}$$

But the COP of real systems which are irreversible is around the half of the values obtained in the (3) relation [7]. And so, we assume that the real COP is defined from the Carnot COP with a factor according to industrial experts [8]:

$$COP_{real} = 0.55 * COP_{theoretical} = 0.55 * \frac{T_C}{T_C - T_F}$$

In this paper, we will subdivided in seven temperature ranges between 60°C-200°C the heat demand in the F&D subsectors, such as four 10°C ranges between 60-100°C, two 20°C ranges between 100-140°C and the last range 140-200°C. Heat pumps are currently providing heat up to 100°C. We have many developments for high temperature heat pump in many laboratories. We have the example of EDF which works with several French R&D programs for the development of industrial high temperature heat pumps providing heat up to 140°C [7]. First prototypes will be tested in Lab perhaps in these two next years. We considered this generation of HP will be on market in three or four years from now. This analysis allowed seeing the possibility of their penetrations. Their investment costs are 20 or 30% more expensive than those of the heat pump up to 100°C.

According to the temperature of heat extracted at 45°C as we said before, we can calculate the different COP for different HP in each temperature range:

Temperature ranges	**60 to 69° C**	**70 to 79° C**	**80 to 89° C**	**90 to 99° C**	**100 to 119° C**	**120 to 139° C**
COP	6,29	4,85	3,99	3,42	2,85	2,36

Table 1 : Considered COP for Heat pumps

Their adoption will mainly depend on their economical competitiveness with their investment costs and the evolution of energy prices up to 2020.

➢ ***Heat recovery opportunities on energy end-uses***

In F&D industry, heat is mostly wasted with the temperature between 30 and 60°C in the industrial energy end-uses. So in this modeling, we considered an average temperature of 45°C. This heat temperature is too low to be recovered by an exchanger and re-used in industrial end-uses. So, HPs can be used to raise the temperature of waste heat so that it can be also re-used for processes and space heating purposes. We distinguished, as we said before, eleven energy end-uses.

Heat recovery on air compressors

Compressed air represents around 7% of total electricity consumption in French F&D. It is a major energy end-use in industry. An estimation of over 90% of the input energy (electricity) to air compressor is lost as waste heat [9].

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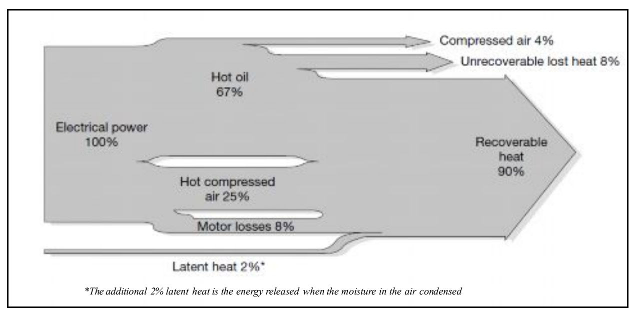


Fig. 4 : Energy flow in air compressors (example of oil injected screw compressor).

But if we assume that almost 5 to 20% of additional losses is possible in the case we have an extensive or short ductwork to the HP, this estimation goes down between 70% and 85% of the input energy which can be recovered as heat. In this paper, we used a heat recoverable in air compressor of 70% in pessimist view.

$$Heat\ recoverable_{Air\ compressors} = 70\% * Energy\ input$$

Heat recovery on chiller condensers

Cooling is also a major end use in industry and represent almost one quarter of total electricity consumption in F&D industry. The heat available at their condenser is generally wasted and the calculation of heat recoverable is based on the first law of thermodynamics and the definition of the energy efficiency ratio (EER). Thanks to the mechanical energy W supplied to this system, E the electric input power, we absorb to the heat source in the temperature thermodynamics T_F with the heat energy Q_F and we reject the heat at the condenser to the temperature T_C with the heat energy Q_C:

$$W + Q_F = Q_C \quad \text{First law of thermodynamics}$$

$$EER = \frac{Q_F}{E} \quad \text{Definition of the EER of the machine}$$

We deduced from these two equations[4] the total heat which is lost at the condenser:

$$Q_C = (1 + EER) * E$$

In this paper, we assume, according to industrial experts at EDF R&D, the chiller EER during an entire year is estimated around 2.5 and we also considered that only 70 % of Q_C is recoverable by heat pumps [10].

$$Heat\ recoverable_{Chiller\ \ condenser} = 70\% * (1 + 2.5) * Energy\ input$$

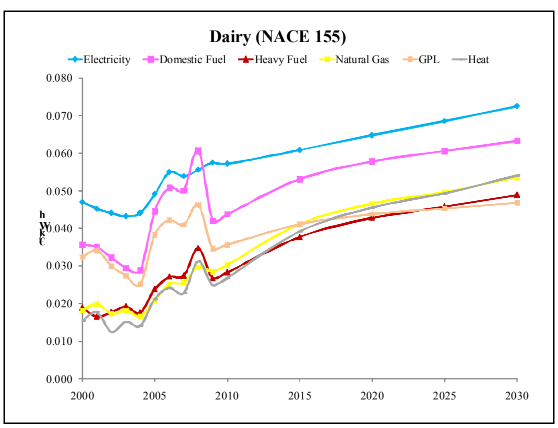
Heat recovery on other thermal end-uses

Due to the difficulty to obtain data at the end-uses level, we assume that for all other end-uses unless air compressors or end-use of cooling and refrigeration, the heat recoverable is between 15%-25% of total input thermal end-uses in average with industrial experts at EDF R&D. In some studies, we observed that this waste heat could be more important up to 55% like in some US industries [11]. Indeed, we assume a factor which is 15% meanwhile having an accurate estimation for each end-use due to the good French policy in energy efficiency in industry.

$$Heat\ recoverable_{Other\ \ thermal\ \ end-uses} = 15\% * Energy\ input$$

- ***Energy prices scenario***

We built our scenario by starting from the real energy prices noticed historically (between 1993 and 2009) in each subsectors of NEI industry.



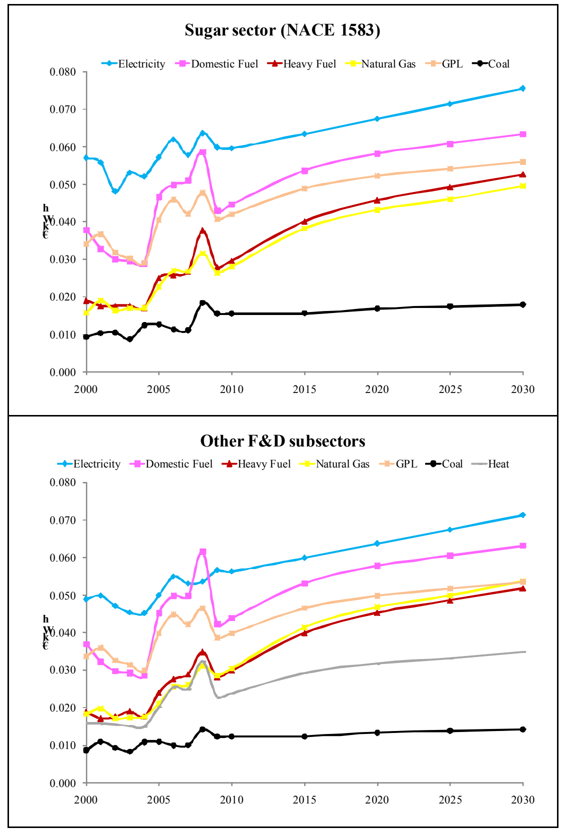


Fig. 5 : Scenarii of energy prices for all subsectors in French F&D industry.

Indeed, the projections of energy prices stemmed from models such as POLES[5] or the World Energy Outlook 2010 reflect more those of the EI industries. The energy contracts signed by NEI industry with energy operators are totally different to those of EI industry due to the energy consumption weight. The hypothesis which we made is to start at the real levels of historic energy prices used in the NEI sectors, then to prolong them by using the same projections as IEA with specific elasticity.

4. RESULTS

To know the impact of HP on the final energy consumption and the CO_2 emissions in French F&D industry, we compare two scenarios.

The first scenario represents the Business-As-Usual Scenario (Sc_BAU), in which no change in policies is assumed. This scenario could be called the Reference Scenario, is attended to serve as a baseline against which the impact of new policies can be assessed. The second scenario is the Heat Pump Scenario (Sc_HP), in which we assumed that heat pumps are on the market and could be used for heat recovery for an energy efficiency policy.

- ***Evolution of final energy consumption***

[4] For simplification, we assume that it is a perfect compressor with no loss. And thus the electric input power E is equal to the power transferred as work to the refrigerant.

[5] Prospective Outlook on Long-term Energy Systems, developed by the LEPII (A research lab in economy and energy policy) which is at Grenoble (France)

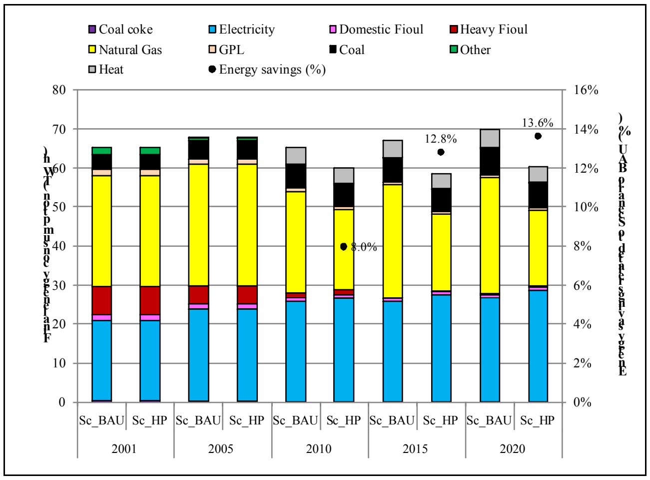


Fig. 6 : Impact of HP on the evolution of final energy consumption in French F&D up to 2020.

Finally, we obtained an evolution of the final energy consumption about -7.5 % relative to the level of 2001 (-12.1 % relative to the level of 1990) thanks to the deployment of HP in F&D industry, i.e. approximately 60.35 TWh up to 2020. On the other hand, without the implementation of these HP in F&D industry, we would have obtained an increase of the final energy mix of 7.1 % compared with 2001 (+1,7 % compared with 1990) to reach 69,9 TWh.

We finally achieve around 9.5 TWh of energy savings up to 2020 which represent approximately 13.6 % of the final energy consumption in French F&D industry (Fig. 6). It is distinguished by subsector for a better screening of the impact of HP in F&D industry (Fig. 7). These energy savings corresponds to a substitution of around 2 TWh of electricity against approximately 11,5 TWh of fuels (90,8 % of natural gas, 3,7 % of coal and 5,4 % of bought heat).

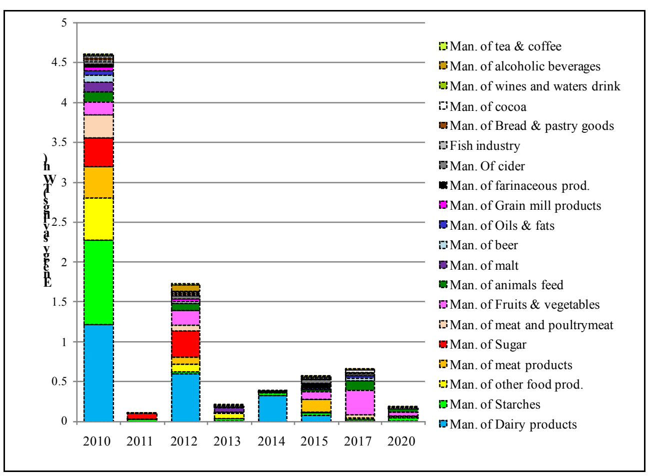


Fig. 7 : Evolution of energy savings by subsector in french F&D industry.

➢ ***Range temperature economically achieve by subsectors***

Fig. 20 below present the levels of heat demand, the heat production of HP and their penetration rate as well as the temperature ranges reached at a subsectoral disaggregation in French F&D industry up to 2020. We grouped all subsectors in three graphs presented from the highest heat demandto the lowest.

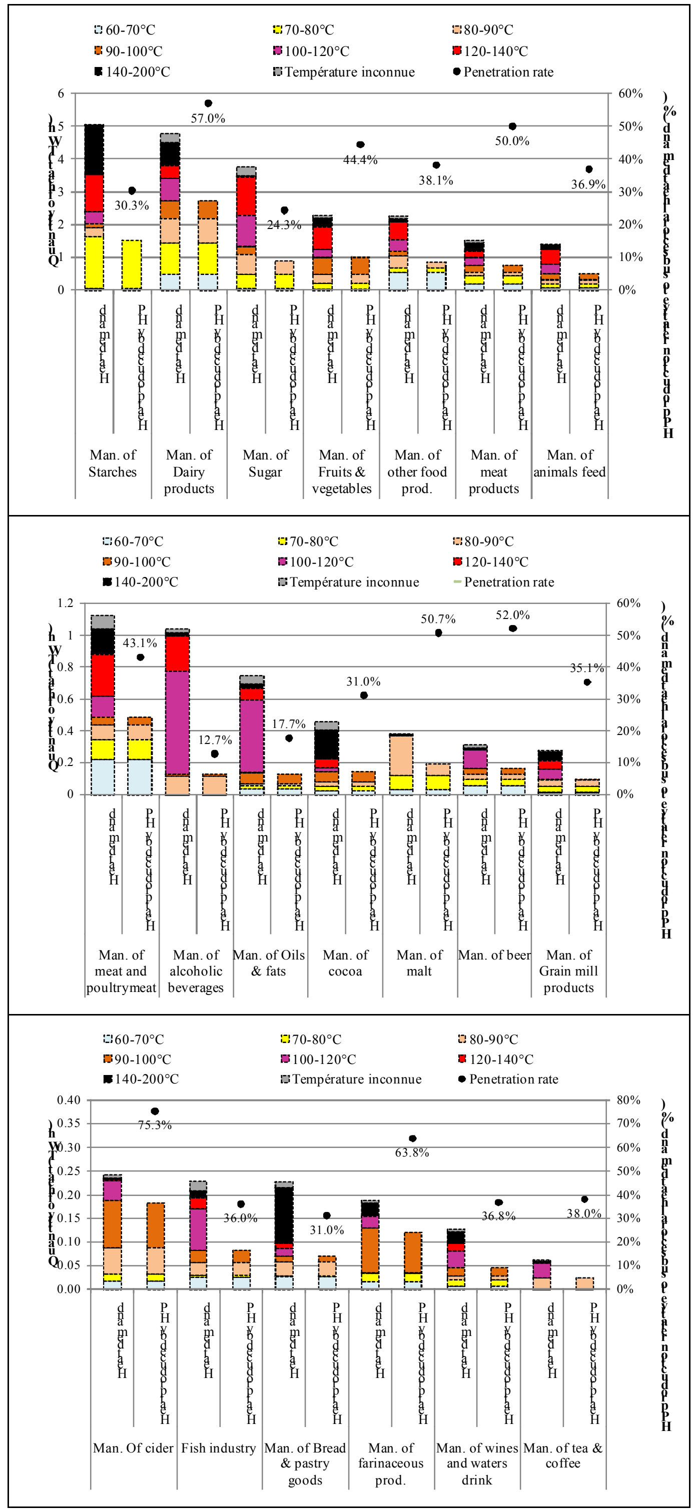


Fig. 8 : Range temperature economically achieved by subsectors in French F&D industry up to 2020.

We deduct that from it the level of the penetration rate of HP systems is not directly correlated to the level of the subsectoral heat demand, but rather to the most established temperature ranges, the seasonality of production and the economic environment (relation between electricity and natural gas prices). **Furthermore, these results show that HP high temperature (beyond 100°C) is not economically feasible in F&D industry until 2020.**

➢ ***Evolution of CO2 emissions***

Due to the reduction in the final energy consumptions in F&D industry with introduction of HP, we also observe a decrease of CO_2 emissions. Fig. 9 shows the evolution of reduction emissions achieved up to 2020.

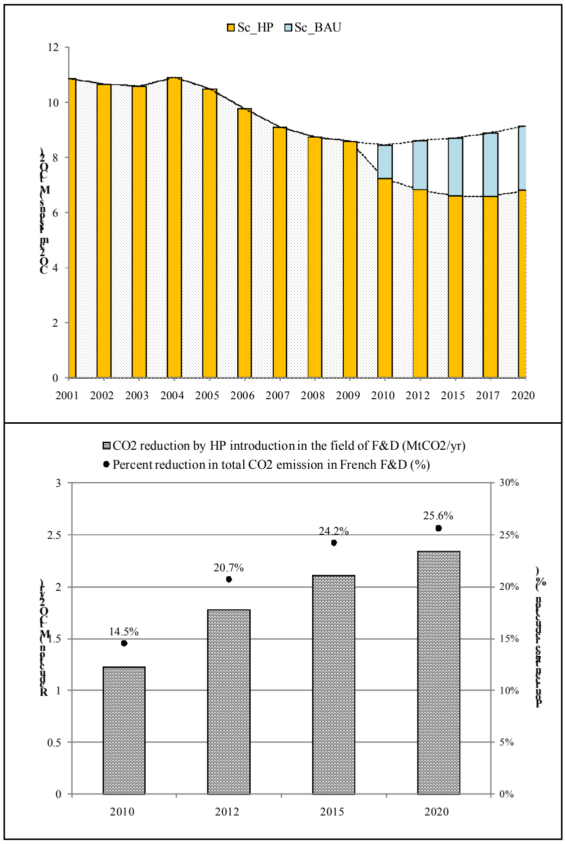


Fig. 9 : Impact on evolution of CO_2 emissions in French F&D industry.

The BAU scenario shows that CO2 emissions post(show) a decline until 2010 because of the impact of the economic recession. So, we notice a decrease of -19.5 % of emissions in 2010 compared with the level of 2005 (-5,1 % with the level of 1990). It followed by a progressive increase of emissions to reach 9,15 $MtCO_2$ due to the revival of the economic growth, that is approximately +2,8 % relative to the level of 1990). **The introduction of HP allows F&D industry to achieve a reduction of CO_2 emissions of around 25.6% compared with the BAU scenario in 2020, corresponding to an effort of 23.5% relative to the level of 1990**.

5. CONCLUSION

This implementation of heat pumps until 2020 represents around 15% of energy savings in the total final energy consumed and almost one quarter of CO_2 emissions avoided by F&D until 2020. A disaggregation for this energy savings and emissions avoided was done on all subsectors by temperature range and by energy end-uses, and shows a strong heterogeneity in this industry.

Furthermore, these results show that the economically feasible HP correspond to the temperature ranges below 100°C, we can aspire to reductions of CO_2 emissions around 35 % on the horizon 2020 compared with the level of 2005. Within the framework of the Package Energy Climate, France hopes to achieve 18.3 % of emissions reduction with sectors not covered by the EU-ETS such as those of the NEI industry, between 2005 and 2020 . This industry could contribute so effectively to the objectives fixed by action plans for the energy efficiency of the European Union thanks to the promotion of heat recovery with HP systems.

Heat pump is an excellent and very promising technology which is expected to be adopted widely in industrial sectors through further technology research and development. By applying them, it is possible to obtain value-added benefit such as reduction of CO_2 emissions; energy cost savings and is a pragmatic technology to fight global warming.

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