An energy efficiency assessment tool based on Process Energy and Exergy Analysis method

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Abstract
Manufacturing processes are diverse by nature. Consequently, classical energy assessment of each process requires specific analyses leading to significant costs that cannot be always sustained by Small and Medium-Sized Enterprises (SME). Therefore, Abou Khalil et al. introduced in 2008 an energy and exergy analysis method called Process Energy and Exergy Analysis (PEEA) in order to systematize process energy auditing and assessment. This method is based on the best available or possible process to transform the raw material into final product, while maintaining the same (or higher) product quality and plant productivity.

Directly derived from an application of the PEEA, this paper presents a scanning and auditing tool for industrial plants. This tool aims at identifying within the industrial plant, customized and pertinent process energy efficiency improvements, while quantifying the potential energy savings as well as payback time for investments. This way, SMEs in question have the possibility to carry out, with low cost, a thorough energy diagnosis focusing on the previously identified improvements.

Introduction
Concerns about sustainability issues are growing today, especially those related to energy resources depletion while energy demand increases and results in environmental damage such as greenhouse gas effect. Considering those issues with inevitable increase of fossil fuel prices, several political and economic measures have been taken at the national and international level in order to achieve better energy efficiency, such as white certificates trading systems in European Union.

Manufacturing sector is known to be a major contributor to world and European energy consumption, representing for instance one third of energy consumption in OECD Europe with about 450 Mtoe/yr according to 2005 statistics (IEA, 2007).Thus, increasing energy efficiency in industry significantly contributes to carbon emission reductions. While large manufacturing enterprises and energy intensive manufacturing industry (such as for example iron and steel; non-metallic minerals; chemical and petrochemical; glass and ceramics, paper and pulp and others) can afford energy management systems implementation and thorough energy audits, Small and Medium sized Enterprises (SMEs) have more difficulties to sustain such leading costs. Yet, SMEs significantly participate to global energy consumption and carbon emissions. For instance, manufacturing plants consuming between 10.8 and 144 TJ/yr represent 19% of French manufacturing sector energy consumption (EDF data, 2001).

Moreover, energy audits focus mainly on process utilities since they are far from the heart of the manufacturing trade and they obey one requirement which is meeting the needs of the process. Yet, the major energy saving opportunities are probably bound to manufacturing processes optimization and energy process integration within manufacturing plants, thus adapting the utilities to the minimum process needs before optimizing the utilities themselves. Consequently energy audits should rather deal with the manufacturing processes, process utilities and energy integration opportunities than focus only on process utilities or on one specific process.

Developing energy auditing tools dedicated to SMEs appears to be essential. It is all the more promising since those manufacturing industries are numerous, geographically sparse and their transformation processes and energy networks are relatively simple.

This paper presents how such a tool has been developed by applying Process Energy and Exergy Analysis (Abou Khalil, 2008; Abou Khalil et al., 2008). Before focusing on the energy efficiency assessment tool itself, the PEEA method will be introduced.

PEEA Method

The Process Energy and Exergy Analysis (PEEA) is inspired from process integration methods such as Pinch Analysis (Linnhoff and March, 1998) and from the Life Cycle Analysis approach (Ciambrone, 1997) since PEEA aims at analyzing the energy consumption of the product transformation from raw material to final product.

PEEA DESCRIPTION

The PEEA follows a three-step methodology.

Step 1: Process analysis

It is the fundamental step of the method. It analyzes the product transformation considering product quality and plant productivity as the only 2 criteria, and not the industrial process in place. This step is generic and is required once for every type of product or every transformation process operation regardless of the studied plant.

It aims at identifying minimum required energy (MRE) for product transformation and Best Transformation Processes applicable (BTP). To perform this analysis, transformation operation have to be studied first at a molecular level to know pertinent parameters taking product quality and plant productivity criteria into account. Then, an energy and exergy analysis has to be performed considering these parameters and applying process integration methods. This step has to be performed by energy and product transformation experts.

Step 2: Plant process mapping and Energy Consumption Inventory

This step consists in collecting energy consumption data by determining all the manufacturing process operations (plant process mapping) and energy fluxes going from the primary energy sources entering the studied plant to the final product and wastes leaving it.

Energy consumption inventory can be carried out at different quality level. For low level auditing, non accessible data can be substituted with estimations and the energy consumption inventory can for instance be performed only on the major operations detected in step 1. These major operations are the most energy consuming ones on which pertinent BTP have been identified.

Step 3: Energy analysis and identification of energy saving opportunities

This step consists in analyzing information collected in step 2 using results from step 1 in order to identify incremental and radical energy improvements. It is based on the decomposition of the energy consumption into the plant as follows : process energy (MRE), non-fatal energy losses that can be removed without affecting product quality by incremental and easy to implement energy saving solutions and fatal energy losses that could be minimized by radical improvements.

The PEEA method is suited for every energy audit level, depending on the acquired data collected in step 2. Results accuracy is directly influenced by the quality of the collected data, as well as audit cost.

APPLICATION TO DAIRY MANUFACTURING PROCESSES

This method has been experimented on several manufacturing processes, based on real and detailed audit data collected in a French dairy industry (Abou Khalil et al., 2008). This plant uses about 31 TJ/yr of electricity (16% of plant total energy consumption), 166 TJ/yr of heavy fuel (84%) to produce more than 7,000 t/yr of cheese.

These processes are the following ones:

- Concentration of liquid product : analysis performed on milk concentration can also be extrapolated to other liquid products in other manufacturing sectors, such as whey, juices or even liquid mechanical wastes. Indeed, the specificity of a given product analysis is given by the specific values of parameters identified and collected in the step 1.
- Drying of solid products.
- Milk heat treatment (heating and pasteurization) in order to increase product lifespan.
- Cleaning-in-place (CIP) operations that accounts for 20 % of energy consumption in such industries.

For each of these transformation operations, process analysis has first been performed to determine BTP. This paper will focus on concentration and heat treatment operations.

Process analysis results (step 1)

Concerning concentration operation, the BTP depends essentially on the product (nature, quality, productivity), the volumetric reduction factor (VRF) which is the ratio of concentration of output product by concentration of input product and even economic criteria that decision managers consider. The BTP is either nanofiltration membrane (NF), inverse osmosis (IO) or mechanical vapor recompression evaporators (MVR).

Concerning milk heat treatment, the BTP is low temperature preheating with minimized pasteurization pinch, which is about 4 K for milk products. In this case, preheating is done by a heat pump since direct total heat recovery is not possible. The related energy consumption is, considering that double pasteurization process is required for product quality, 15 kJ_{mec}/kg milk and 45 kJ_{th}/kg milk.

Plant and final analysis (step 2 and 3)

When performing following PEEA steps in the studied plant, the plant process mapping and energy consumption inventory revealed as expected two significant operations: whey concentration and milk pasteurization.

By comparing the specific consumption of the existing concentration installation and the specific consumption of several processes that could be implemented, significant energy sav-

Table 1. Energy savings and carbon emissions reduction of some identified energy efficiency solutions according to several European countries context

Energy efficiency improvements	Energy savings [1] (% of plant total energy bill)			CO_2-emissions reduction [2] (% of plant total energy emissions)		
	France	Germany	Sweden	France	Germany	Sweden
MVR implementation for concentration	14.4	8.0	11.1	36.7	23.6	38.2
Minimizing heat treatment pinch	0.20	0.17	0.19	0.30	0.24	0.31
Minimizing heat treatment pinch & Heat pump implementation for pasteurisation pre-heating	0.89	0.25	0.56	3.15	1.83	3.31

[1] Financial savings are calculated from following energy prices : 52.2 Euro/MWh electricity for France, 83.9 Euro/MWh electricity for Germany and 61.4 Euro/MWh electricity for Sweden (EUROSTAT, 2008); 189 Euro/t heavy fuel oil for France, 209 Euro/t for Germany and 183 Euro/t for Sweden (DGEMP, 2008). Note that considered heavy fuel prices dating from January 2009 are very low and will probably rise in future. All these prices exclude taxes.

[2] CO_2-emission reductions are calculated from following carbon emission factors based on LCA : 0.023 kg-eq C/kWh electricity in France ; 0.141 kg-eq C/kWh electricity in Germany; 0.012 kg-eq C/kWh electricity in Sweden and 0.087 kg-eq C/kWh (LHV) heavy fuel oil in all three countries (ADEME, 2007).

ings were estimated. For instance, the radical improvement consisting in implementing MVR led to almost total heavy fuel consumption removal in concentration operation but additional electricity would be consumed. It represents a reduction by more than 40% of plant heavy fuel consumption and an increase by 30% of plant electricity consumption, and so financial savings (table 1).

Concerning heat treatment operations, an incremental improvement consists in minimizing pinch temperature to 4 K in the double pasteurization process by increasing heat exchangers surface. It results in 5% fossil energy reduction. The radical improvement that consists in minimizing pasteurization pinch and implementing a heat pump to meet low temperature heat needs generates more than 40% of the heat treatment operation consumption, i.e. a reduction by 3% of plant heavy fuel consumption, assuming that heat is supplied as steam and considering steam production and distribution losses. Although additional electricity would be consumed by the heat pump (4% more in plant electricity consumption), financial savings are generated (table 1).

Both radical improvements that are presented above are substitution of fossil fuel technologies for electrical ones and result in total plant energy consumption reduction. Financial savings and carbon emission reductions are presented in table 1 referring to three different European countries where energy context is very different.

Thanks to PEEA, unobvious energy efficiency solutions on manufacturing process operations can be found in step 1, or even in step 3 in high-level audit case. Once these solutions are identified, they can be systematically studied on any similar plant. In low-level audit cases, adaptation is even unnecessary, but it results in less accurate results. Nevertheless, in SMEs auditing process, starting with performing a first systematic rough assessment in order to identify promising solutions is recommended. A thorough energy diagnosis focusing on these identified previously improvements can then be carried out.

Scanning and auditing tool

PEEA method inspired the development of a low-level energy assessment tool focusing mainly on manufacturing process operations.

TOOL OBJECTIVES AND SCOPE

The developed tool aims at identifying and roughly qualifying in a user-friendly way energy saving opportunities in manufacturing industries. It addresses especially process operations that are easily ignored in such auditing.

To be promising, such tool has to address a relatively large application range, in terms of variety and quantity. Furthermore, significant efforts on simplification and modeling have to be done to be applicable on several manufacturing sectors, and the simpler the plant to model, the simpler modeling is. That is why such tool has good reasons to be dedicated to SMEs and not to be too ambitious in terms of quantity and quality of data requirements. Moreover, to address SMEs such tool has to be user-friendly and the whole assessment process to be quick (i.e. cheap), whereas traditional energy analysis methods are rather time-consuming (and so costly) and complex to use in a non academic world. Therefore, non-experts in energy sciences must be able to use it, provided that they have some technical skills from studied products manufacturing.

The final developed tool meets all those requirements and is economically promising. Today developed on dairy industry, it is being extended to other manufacturing sectors.

TOOL METHODOLOGY AND PEEA

The tool is based on PEEA method since it helps the user perform PEEA steps 2 and 3 at a low level of auditing but in a simple way, provided the tool database has been previously filled with step 1 results (figure 1).

In fact, when a specific sector is chosen to be developed (dairy industry in the present case), the process analysis is performed by energy experts and results are integrated into the database, then technical analysis and calculation modules are developed. The database contains information concerning typical plant mapping, that is to say the list of products and

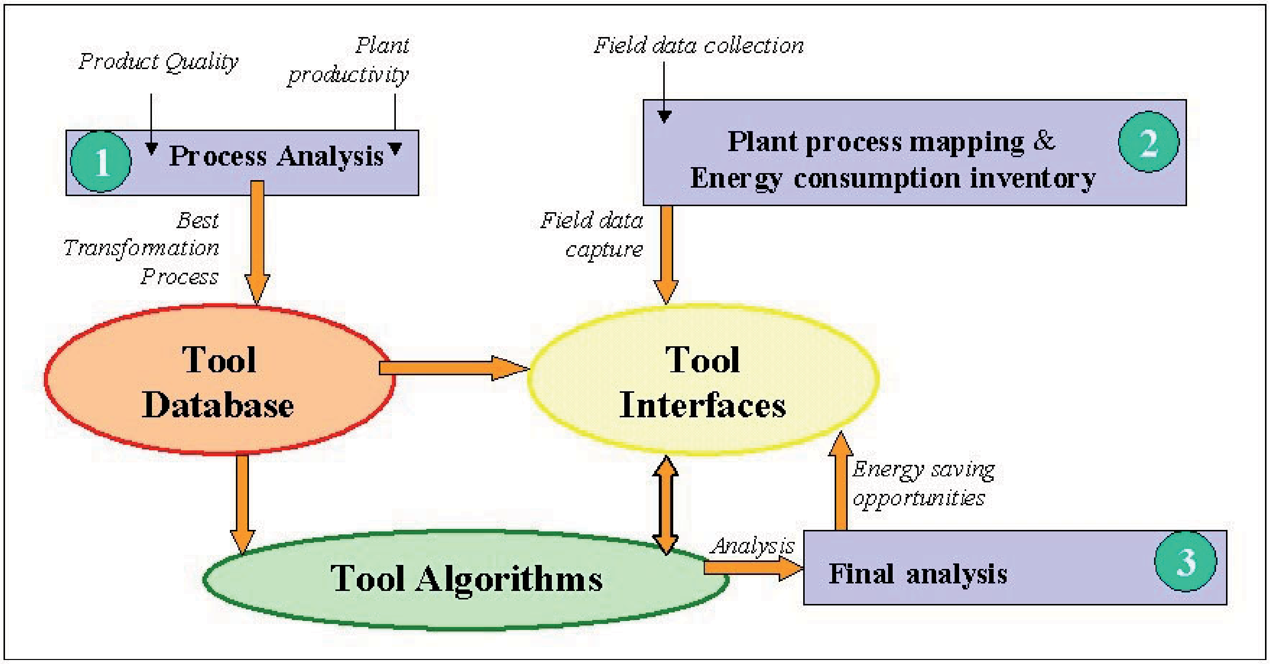

Figure 1. PEEA and Tool interactions

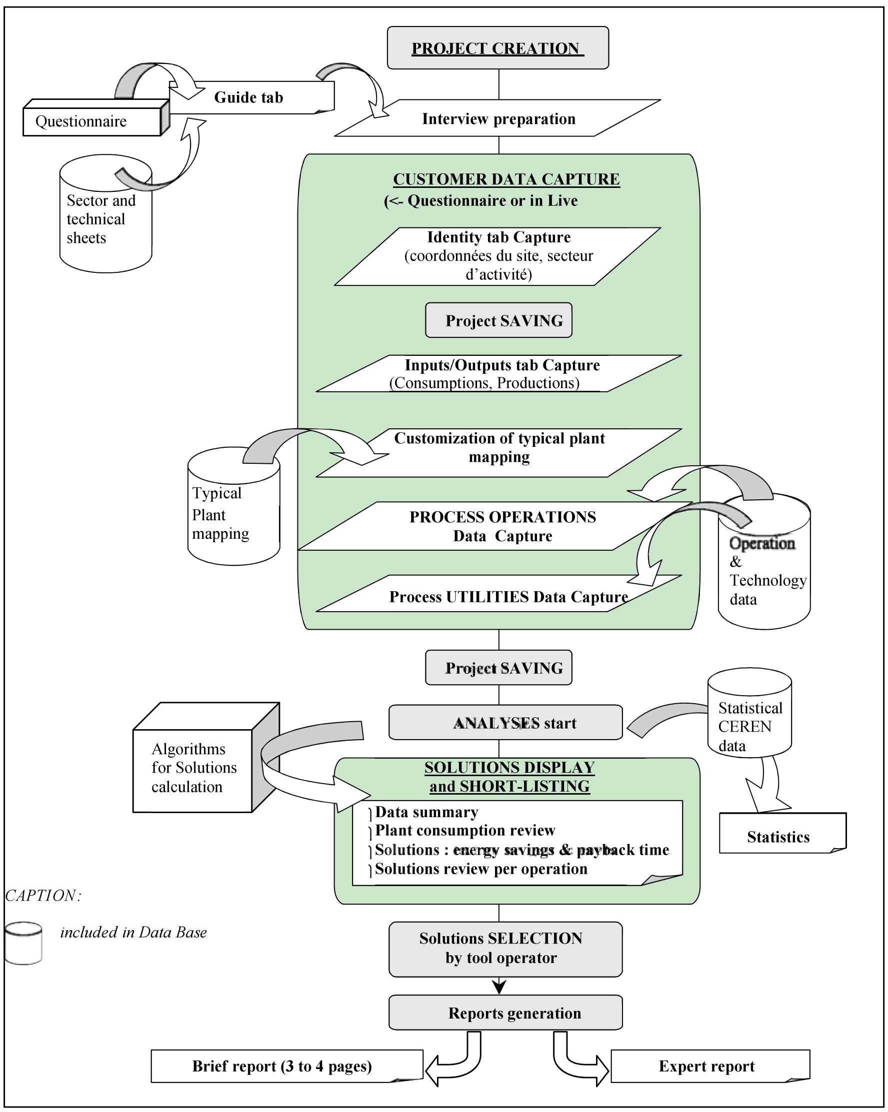

Figure 2. Simplified scanning tool principle

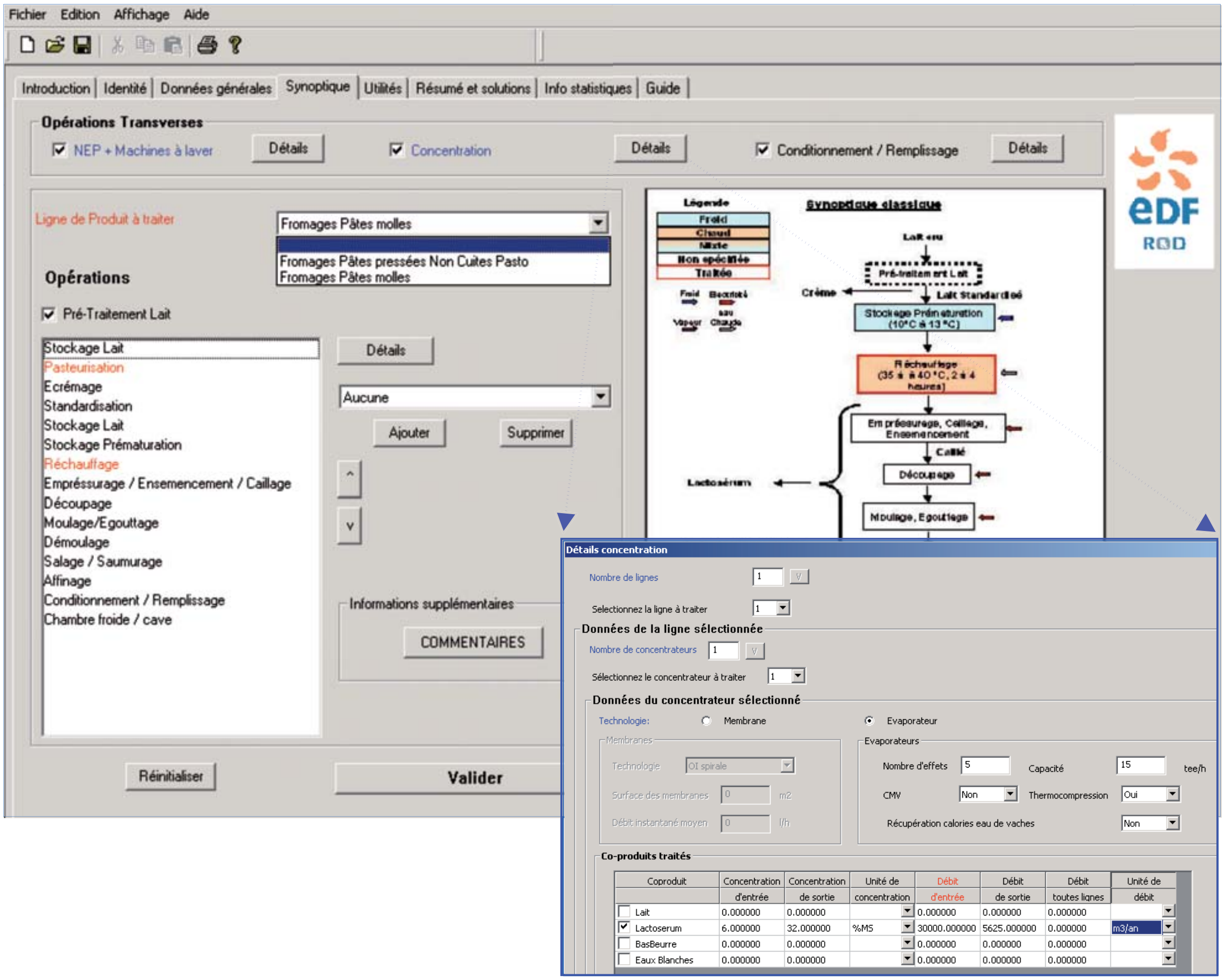

Figure 3. Tool screen captures

corresponding manufacturing process operations and technologies. Energy consuming operations are highlighted and they are modeled as technical modules. Each technical module focuses on a specific operation. It contains interfaces to collect relevant data from the operator and algorithms that analyze several energy efficiency improvements and quantify energy savings, corresponding carbon emissions reductions and assess payback time for investments. The database contains also specific energy consumption (or equivalent energy parameters) of modeled operations to estimate accessible energy savings and cost information on studied solutions in order to assess their economic viability. The developed interfaces aim at guiding the tool operator in a user-friendly way in order to collect the minimum number of data, but the most relevant ones to perform the energy efficiency assessment. Moreover, surfing in the tool is easy and the structure helps the operator to perform the energy audit (figure 2). To make data capture easier, many typical data collected during the PEEA process analysis step are systematically suggested to the tool operator in case field data could be standard or unavailable.

In particular, technical modules have been developed on each of the manufacturing processes studied in Abou-Khalil (2008). Figure 3 shows for instance plant process mapping and concentration module interfaces.

EXPERIMENTATION RESULTS AND FEEDBACK

The tool has been experimented on several dairy industries, according to the following procedure : a one-page questionnaire is sent to the plant contact person in order to prepare the next meeting ; later on a one to two hours interview by phone is led with him ; data is captured on the tool ; the tool analysis is launched and several solutions are suggested, some of them being short-listed ; once more interesting solutions according to industrial and context criteria are selected, a brief report is generated by the tool and is finally sent to the contact person.

Tool's results on another but similar plant are consistent with Abou Khalil PhD's thesis (2008), considering that the energy assessment performed with the tool is based on lower quality data (table 1). Industrial partners feedback was positive. They were interested in tool's results, especially because economical criterion was taken into account with the indicator of payback time for investments. Even the 1-2 hours phone interview has been well accepted and conclusive. However, given manufacturing plants' investments planning and 2008 economical context, few energy diagnosis lead by now to the implementation of a radical and innovative improvement solution.

Table 2. Examples of tool's results on a French cheese manufacturing plant (source: EDF).

Energy efficiency improvement	Heavy fuel oil savings (TJ/yr)	Electricity savings (TJ/yr)	Financial savings (kEuro/yr)[1]	CO_2-emission reduction (t CO_2-eq/yr)[2]	Payback time for investments (years)
MVR implementation (evap 1)	31.4	-4.2	310	2682	< 2
MVR implementation (evap 2)	12.6	-0.8	138	1095	2 to 4
IO implementation as pre-concentration (evap 1)	14.9	-0.9	164	1295	< 2
IO implementation as pre-concentration (evap 2)	6.8	-0.2	78	596	< 2
Heat pump for pasteurization pre-heating	10.6	-2.5	87	880	-
Heat pump for CIP pre-heating	24.1	-5.3	204	2010	-

[1] Financial energy savings are calculated from August 2008 French energy prices: 58.4 Euro/MWh electricity and 481 Euro/t heavy fuel oil (DGEMP, 2008). All these prices exclude taxes. When considering 2009 low fuel prices (DGEMP, 2009) financial savings are lower and payback time is greater than 4 years.

[2] CO2-emission reductions are calculated from French carbon emission factors based on LCA: 0.023 kg-eq C/kWh electricity and 0.087 kg-eq C/kWh (LHV) heavy fuel oil (ADEME, 2007).

WHICH FURTHER DEVELOPMENTS?

Today the tool is developed on dairy industries for application in France. The tool can easily (and will) be improved on this sector developing other technical modules, and it can also be extended to other manufacturing sectors, with existing or additional technical modules, provided that time and money are previously spent on performing the process analysis.

The tool could also be adapted to be used in other European countries. This would imply following modifications:

- Adapt the tool's database and interfaces to other languages
- Complete database with country's own data, such as energy parameters (price, carbon emission factor, etc.), technical solutions' costs or energy consumption statistical data, which may be difficult to get.

Conclusion

An energy assessment tool dedicated to SMEs has first been developed on dairy industry. Based on Process Energy and Exergy Analysis method, it helps the operator to identify promising incremental and radical improvements on manufacturing process operations thanks to a previous "process analysis" performed by energy experts. Experimentations with French SMEs were successful.

This tool is promising to tackle energy efficiency in SMEs since it helps to perform cheap energy assessments. It can easily be extended to other manufacturing sectors and countries, provided that time and money are previously spent on performing suitable Process Analyses.

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