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Green Industry: Energy Efficiency Improvement of Steam Generation in a Moroccan Plastic Recycling Industry

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Abstract: Steam systems in industry represent a substantial share of industrial energy consumption. Therefore, improving the energy efficiency of these systems is necessary to reduce fossil fuel consumption and greenhouse gas emissions in the context of energy transition. This improvement not only leads to environmental benefits but also enhances financial gains, thereby increasing industrial competitiveness. The objective of this study is to identify energy-saving opportunities in a plastic recycling plant in Morocco while adopting a system approach based on thermodynamics fundamentals. After conducting a benchmark analysis based on a scoping tool questionnaire, the steam generation section is diagnosed to quantify major losses. Subsequently, an action plan is suggested for more efficient thermal energy use. The assessments focus on energy loss reductions along with waste heat recovery. The implementation of these actions results in a potential saving of 22%, achieving an energy gain of 5574 GJ/y, a financial benefit of 96 884 $/y, and a reduction in CO_2 emissions by 332.15 tons annually. The global payback period does not exceed one year. The study conducted encourages the adoption of cost-effective energy efficiency measures by industry stakeholders, in line with the Sustainable Development Goals. Furthermore, it benefits all industries utilizing boilers in their steam production systems, regardless of the diversity of industrial systems.

Keywords: steam systems; energy consumption; energy efficiency; greenhouse gas emissions; energy-saving; industry; energy transition; sustainable development

Nomenclature:

P: Pressure in Bar gauge (bar) or Bar absolute (bara)
T: Temperature in °C
H: Specific Enthalpy in kJ/kg
$\dot{m}$: Mass Flow in t/h
β: Blowdown rate in kg/h
E: Energy in GJ
HHV: Fuel Higher Heating Value in MJ/kg
X: Thermodynamic quality (mass basis)
η: Efficiency
σ: Savings
λ: Loss
K: Operating cost in $
$\dot{Q}$: Heat transfer rate
$\dot{W}$: Power

1. INTRODUCTION

The industrial sector consumes nearly 40% of global energy. Relying on fossil fuels, it is responsible for 20% of total CO2 emissions [12]. Upon closely examining energy use in this sector, half of the consumed energy is used for process heating, primarily through steam production systems, which represent 30% of the final energy use in industry [21]. Indeed, steam is an adaptable energy transfer medium, effectively

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serving both process heating and power generation with exceptional flexibility. Steam is generated in the boiler, a pressure vessel that heats water by convection heat transfer of flue gas resulting from burning the fuel. To improve the boiler and the overall system efficiency, it is necessary to reduce boiler losses and recover the resulting waste energy [2]. Consequently, fuel consumption and GHG emissions would be reduced. Fig. 1 details the diagram of a fire-tube boiler, highlighting the various energy losses. The most significant are, in descending order, stack loss, blowdown loss and shell loss. In scientific literature, several studies have focused on steam system optimization [20]. The work of [14] determines a method to compute the optimal excess air value for fuel combustion in the boiler's burner, as this value impacts the stack loss and the boiler efficiency. In the case study of [17], boiler energy efficiency has been improved using a variable speed drive in the fan motor supplying the boiler combustion air. The authors in [7] propose energy-saving measures for steam generation in the US industry, leading to an 18% economic potential of total boiler energy use. The research of [5] proposes a closed tank system to eliminate energy losses, improving the coefficient of efficiency by about 6%.

In Morocco, some case studies have addressed energy efficiency in industrial sectors, focusing on either the electrical [3], [4], [6] or thermal [1], [13] aspects. The thermal side has included other sides such as furnaces. However, rare case studies have addressed the boiler performances [16] and have yet to be dedicated to the optimization of the overall industrial steam system. Additionally, it has been identified that there needs to be more energy efficiency case studies in the country that use benchmarking tools, as well as limited diversity in the studied industrial sectors within the context of energy transition [11]. The present study contributes to filling these gaps by adopting a system approach to modeling and improving the energy efficiency of a steam system in a plastic recycling industry located in Morocco. This approach results in significantly greater energy and cost savings compared to an analysis conducted at the component level. This work covers diagnostic, metering and optimization research categories of energy efficiency [10]. First, the actual steam system is benchmarked using a scoping tool questionnaire. The energy loss investigation was conducted in the lowest-rated part of the steam system, the boiler house, to propose energy-saving actions. These opportunities aim at improving thermal energy efficiency by both reducing and recovering the major boiler losses, namely stack and blowdown losses. Each action is quantified in terms of economic and energy saving, along with Greenhouse Gas (GHG) emissions reduction. Although industrial systems are highly diversified, they share the common elements of steam production systems, making this case study useful for various industrial sectors as well.

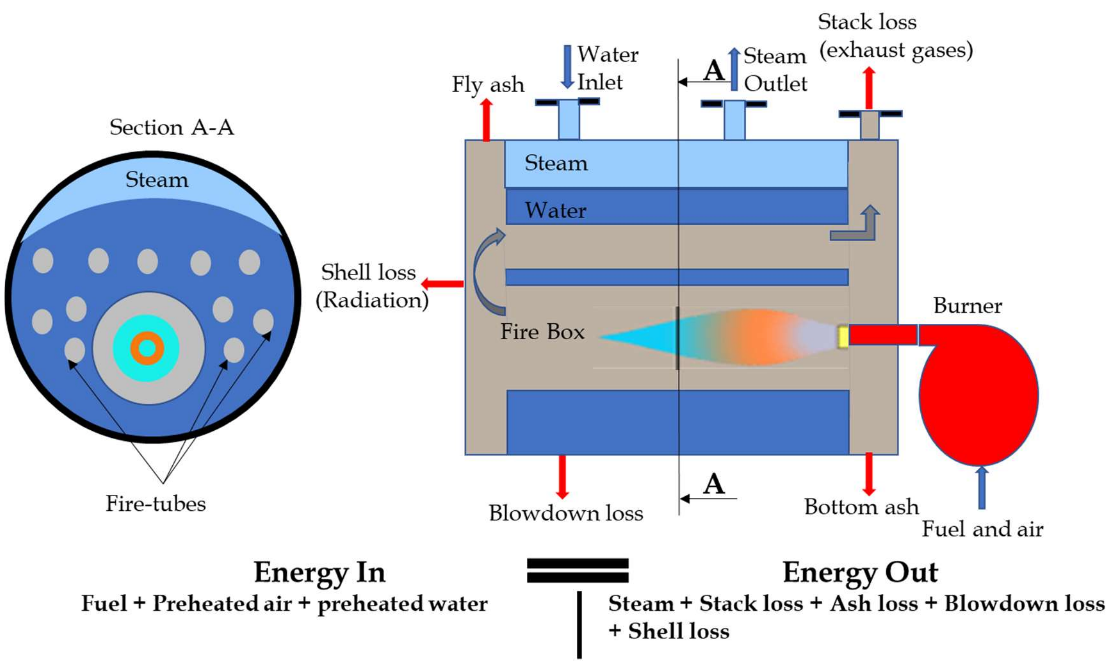

Fig. 1. Energy losses of a fire-tube boiler adapted from [8]

2. METHODS

2.1. Process & Steam System Description

2.1.1. Process Description

In this recycling industry, Polyethylene Terephthalate (PET), sourced from discarded plastic bottles, undergoes three main production stages: washing, extrusion, and finishing (see Fig. 2).

In the washing line, PET bottles are shredded, screened, and manually sorted. After grinding with cold water, the material passes through a series of separators and flotation units to remove labels and residues. It is then filtered, hot-washed at 90°C using steam via heat exchangers, rinsed, and screened again to eliminate small particles and colored fragments. In the extrusion line, the cleaned PET is first dried in ovens to remove moisture before entering extruders, where it is molded into specific diameters. The product is stabilized in boxes using direct steam injection to ensure material integrity and precise temperature control. In the finishing line, the extruded material is cooled and solidified using steam-heated water to ensure consistent fiber quality. This process prepares the recycled PET (rPET) for its final application in the textile industry.

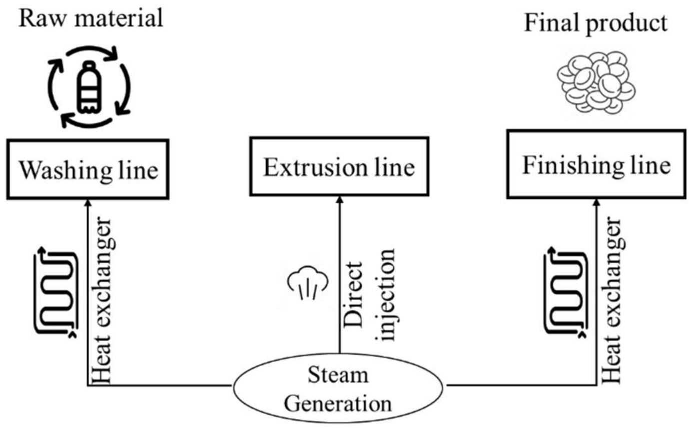

Fig. 2. Process description

2.1.2. Steam System Description

A typical steam system consists of four main areas, namely generation, distribution, end-use, and recovery. The generation part takes place in the boiler room, where the combustion process transfers energy from the fuel to the water, converting it into steam. The boiler used in this system is a fire-tube boiler constructed in 2020. One inherent efficiency advantage of this type over the water-tube type is that shell loss is minimal. Propane is used as the fuel, and the makeup water is treated with softeners. The boiler room is located next to the entrance of the first production line (washing line). The generated steam, produced at a flow rate of 2 t/h at 6 bar, is then distributed through pipes and valves to the end-use processes, either with direct injection or through heat exchangers. Finally, the recovery of the formed condensate allows it to be reused in the boiler room for steam generation; the condensate recovery rate of the studied system is 80%. In this article, a systems approach is adopted, as it leads to significantly higher energy and cost savings compared to a component-level analysis. However, the energy efficiency improvement actions are focused on the steam generation part. Fig. 3 illustrates the steam system areas.

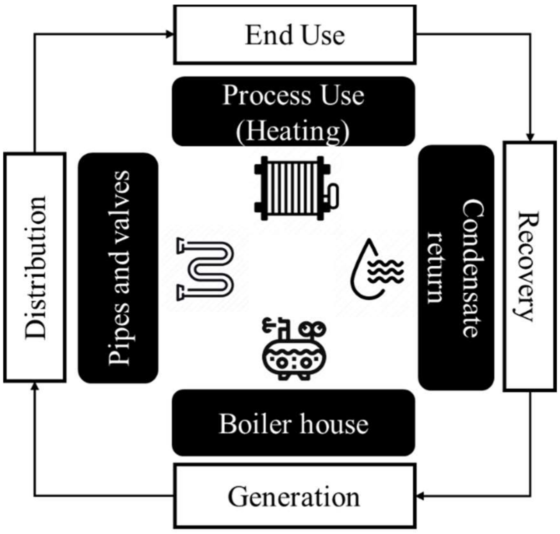

Fig. 3. Steam system description

2.2. Data Collection

The first step in data collection was conducting an interview with the plant's technical director based on a questionnaire of 26 questions divided according to four levels of steam system management. This questionnaire is called the Steam System Scoping Tool (SSST), developed by the United States Department of Energy [18]. Its role is to benchmark the studied system against best practices in industries that use steam in their processes. Next, a site visit was conducted to closely observe the different parts of the steam system and to complete and confirm the questionnaire responses. The subsequent phase was a measurement campaign focused on the steam generation part using portable measuring devices, namely the conductivity meter and the combustion analyzer, whose specifications are in Table 1. The measured data included the conductivities of the feedwater and blowdown water, as well as the oxygen content and temperature of the combustion gases in the stack. Data collection also included recording the data displayed on the plant's on-site equipment.

Table 1. Measurement Instruments Technical Specification

Item	**General specifications**
Conductivity and TDS meter	Measure norm: EN 50581:2012 Accuracy: ±2%
Combustion analyzer	Temperature Accuracy: ±0,5 °C O_2 in flue gas Accuracy: ±0,2%

2.3. Analysis Tools

2.3.1. Mass and Energy Balance

The laws of mass and energy balance are used for the calculation in this study. In the control volume (Fig. 4), the mass conservation law states that mass is neither created nor destroyed Eq. (2.1).

$$\sum \dot{M}_{in} = \sum \dot{M}_{out} \tag{2.1}$$

In the energy conservation law, energy can neither be created nor destroyed in the control volume (Fig.4). It can only be changed from one form to another Eq. (2.2).

$$\dot{W} + \sum \dot{M}_{in} \times h_{in} + \dot{Q} = \sum \dot{M}_{out} \times h_{out} \tag{2.2}$$

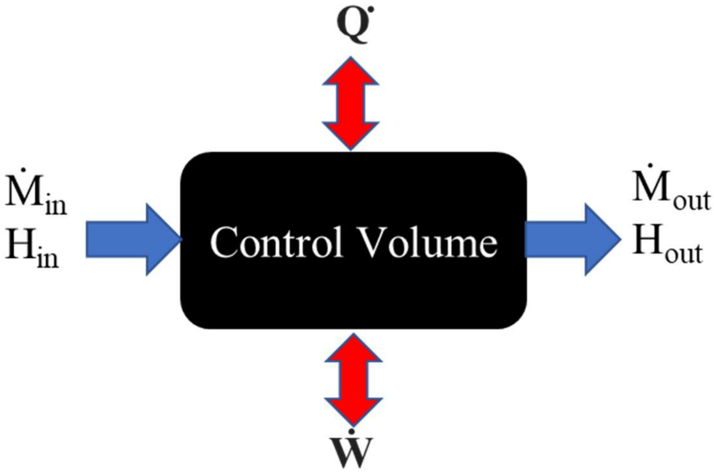

Fig. 4. Mass and energy balance in a steady state steady flow

2.3.2. MEASUR Software

In order to generate steam system models, the free online tool named Manufacturing Energy Assessment Software for Utility Reduction (MEASUR) has been used, developed by the U.S. Department of Energy's Advanced Manufacturing Office (AMO) [22]. MEASUR provides a suite of analytical tools and resources that assist in identifying opportunities for energy savings, improving efficiency, and reducing utility costs. It includes features such as system-level assessments, detailed energy modeling, and simulation capabilities for various manufacturing processes.

3. RESULTS AND DISCUSSION

3.1. Benchmarking Results

An extensive interview with the plant's energy manager, combined with an on-site visit that focused specifically on the steam system, produced results on the SSST, which are summarized in Table 2. The total obtained score is 32.1%, which is relatively low compared to industries operating with steam systems on an international scale. The SSST results are given as Supplementary Material N°1. The results of this preliminary evaluation have facilitated the prioritization of the steam sections to address for proposing potential energy-saving actions. This article will concentrate on the area that received the lowest score (25%), namely “Boiler Plant Operating Practices”.

Table 2. Summary Of Steam Scoping Tool Results

Steam section	*Possible Score*	*Plant Score*	*% Score*
Boiler Plant Operating Practices	80	20	25,0%
Steam System Profiling	90	24	26,7%
Steam System Operating Practices	140	49	35,0%
Distribution, End Use, Recovery Practices	30	16	53,3%
Total Scoping Tool Questionnaire Score	**340**	**109**	**32,1%**

3.2. Collected Data

The data is either measured using portable measuring devices or collected from the factory's on-site equipment. All measurements are in metric units, based on the International System of Units (SI). Table 3 summarizes the collected data.

Table 3. Data Collection Values

Parameter	Value	Source
Plant Operating Hours	4000 h/y	Plant data
Fuel Type	GPL- Propane (C_3H_8)	Plant data
Fuel HHV	50 MJ/kg	Plant data
Fuel Emission Rate	60 kg CO_2/GJ	Plant data
Make-up Water Temperature	20 °C	In site instrumentation
Feedwater Conductivity	1500 µs/cm	Measured
Blowdown Conductivity	9000 µs/cm	Measured
% O_2 in Flue Gas	17%	Measured
Flue Gas Temperature	151°C	Measured
Steam Pressure	6 bar- saturated steam	In site instrumentation
Steam Flow	2 t/h	In site instrumentation
Condensate Recovery Rate	80%	In site instrumentation
Condensate Return Temperature	65°C	In site instrumentation

3.3. Data Analysis

First, we calculate the boiler combustion efficiency using the stack loss calculator in MEASUR. This data is influenced by the percentage of oxygen in the combustion gases (17%) and the temperature of these gases (151°C), both measured by the combustion analyzer at the stack. Fig. 5 shows the obtained boiler combustion efficiency of 74.3% with a stack loss (λ_{stack}) of 25.7% (Eq. 3.1).

$$\eta_{combustion} = 100\% - \lambda_{stack} \quad (3.1)$$

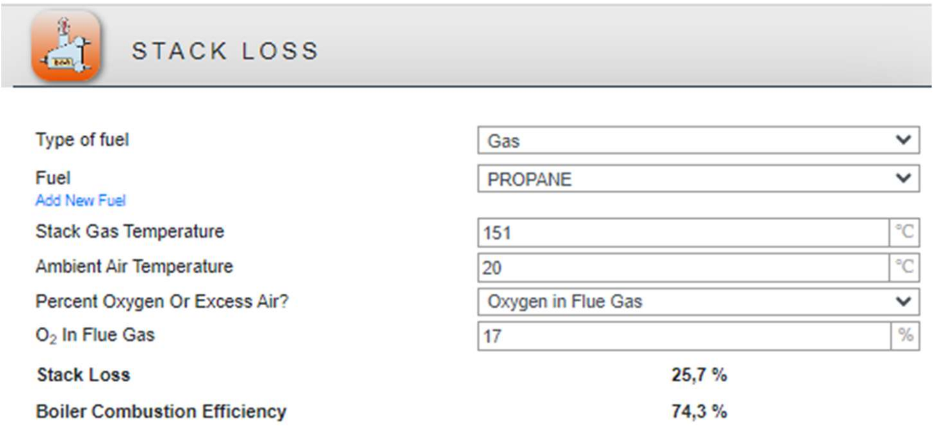

Fig. 5. Stack loss calculator in MEASUR-Baseline

Boiler stack loss is typically the largest source of efficiency loss during boiler operation. Various factors influence this loss, but the primary contributors are the flue gas temperature and the amount of excess air. In practice, achieving a perfect stoichiometric mixture of fuel and air is nearly impossible, which is why excess air is required to ensure complete combustion. While excess air is essential for complete combustion, too much of it can reduce efficiency, as additional energy is needed to heat the unnecessary air. Therefore, the key to optimizing boiler performance is finding the right balance – enough excess air to guarantee combustion without incurring significant thermal losses. In the case of a fire-tube boiler using propane as fuel, like the one under study, the optimal percentage of excess air typically falls between 5% and 10%. This corresponds to a flue gas oxygen concentration of 1% to 2%, as calculated in Eq. (3.2) [9].

$$\%\ excess\ air = \frac{\%\ O_2}{21 - \%\ O_2} \quad (3.2)$$

The analysis conducted here relies on combustion principles, with the primary inputs or measured data being the flue gas exit temperature, ambient temperature, and flue gas oxygen content. The evaluation of combustion efficiency, based on stack losses, is divided into two main components: the effect of flue gas temperature at a constant oxygen percentage (17% in the reference model) and the effect of excess air at a constant flue gas temperature (151°C in the reference model). As shown in Fig. 6, the sensitivity analysis reveals a clear trend: boiler combustion efficiency decreases as the oxygen content in the flue gas increases and as the flue gas temperature rises.

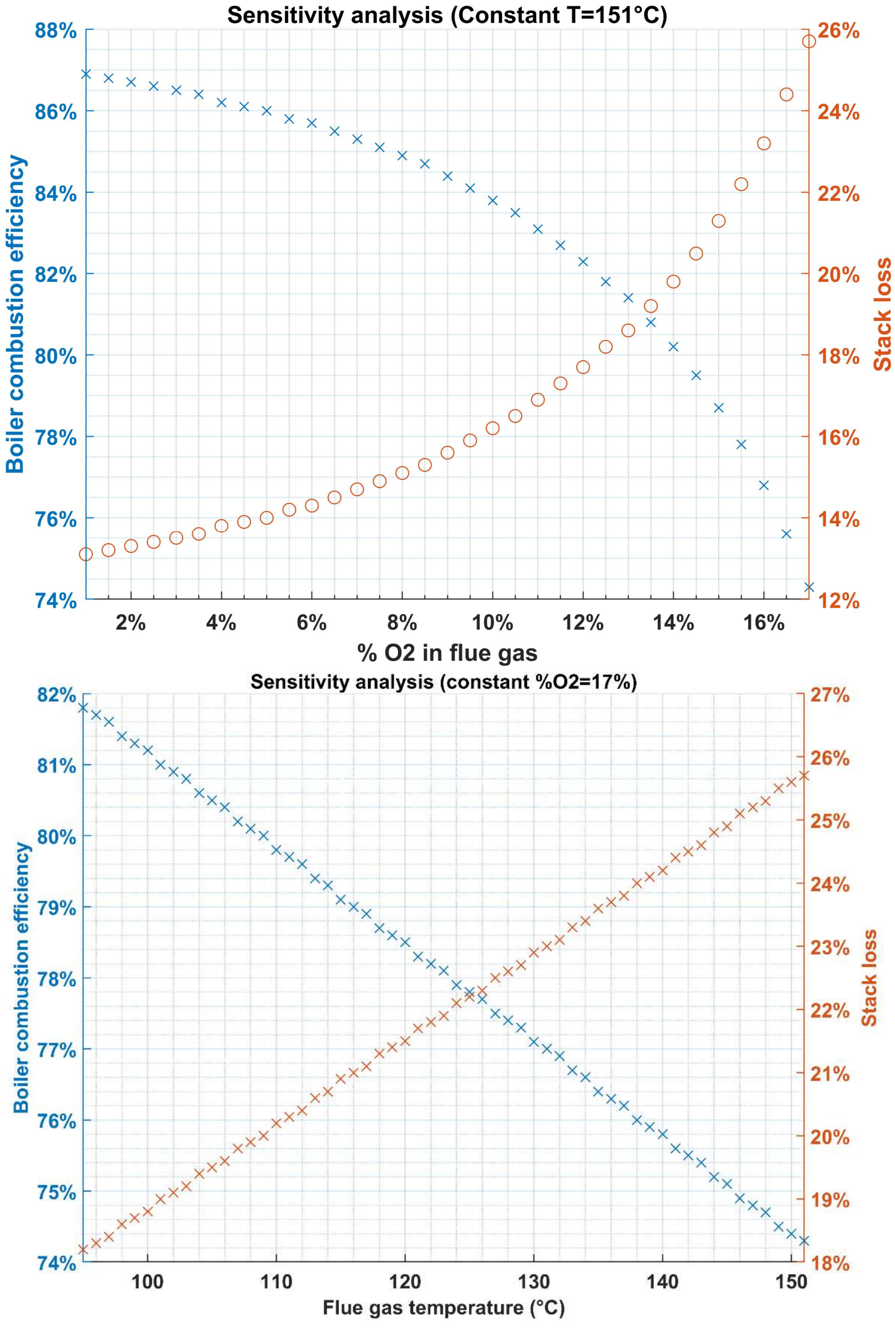

Fig. 6. Combustion efficiency analysis

The indirect method for efficiency calculation focuses on each kind of boiler losses [15], mainly stack (λ_{stack}) and blowdown ($\lambda_{blowdown}$) losses. While the direct method uses steam, feedwater and fuel properties, referring to the amount of thermal energy absorbed by feedwater to make steam [19].

The fuel flow is calculated based on the previous boiler combustion efficiency using the formula for direct efficiency calculation Eq. (3.3):

$$\eta_{boiler} = \frac{\dot{m}_{steam} \times (h_{steam} - h_{feedwater})}{\dot{m}_{fuel} \times HHV_{fuel}} \tag{3.3}$$

where

- $\dot{m}_{steam}$ (steam flow) $= 2$ t/h;
- h_{steam} ($P = 7$ bara; $X = 1$) $= 2762.83$ kJ/kg (X refers to the quality of steam (saturated));
- $h_{feedwater}$ ($P = 1$ bara; $T = 100$°C) $= 419$ kJ/kg (bara is the absolute pressure);
- $\dot{m}_{fuel} = 130$ kg/h;
- $HHV_{fuel} = 50$ MJ/kg.

The boiler efficiency η_{boiler}, calculated by the direct method, is then 72%.

The blowdown rate can be calculated in Eq. (3.4) or using MEASUR Calculator:

$$\beta = \frac{\gamma}{1-\gamma} \tag{3.4}$$

where $\gamma = \frac{Feedwater\ conductivity}{Blowdown\ conductivity}$ [18].

The obtained value is a 20% blowdown rate.

The blowdown flow, from energy and mass balance, is calculated in Eq. (3.5):

$$\dot{m}_{Blowdown} = \left(\frac{\beta}{1-\beta}\right) \times \dot{m}_{steam} = 500 \text{ kg/h}. \tag{3.5}$$

Eq. (3.6) is used to quantify the boiler energy losses from blowdown. However, Eq. (3.7) is the adequate formula to calculate the overall system losses due to blowdown. Indeed, the water discharged during the purging process is replaced by makeup water at ambient conditions from a system approach rather than feedwater when calculating efficiency at the boiler level. The results show that these losses at the boiler level reach 557 GJ/year and at the system level reach 1227 GJ/year. This latter value corresponds to an annual financial loss of $20860.

$$\dot{Q}_{Boiler\ blowdown\ losses} = \dot{m}_{blowdown} \times (h_{blowdown} - h_{feedwater}) \tag{3.6}$$

$$\dot{Q}_{System\ blowdown\ losses} = \dot{m}_{blowdown} \times (h_{blowdown} - h_{makeupwater}) \tag{3.7}$$

where $h_{makeupwater}$ ($P = 1\ bara$; $T = 20$ °C) $= 84.01$ kJ/kg.

At this stage, the percentage of energy losses due to blowdown ($\lambda_{blowdown}$) relative to fuel consumption is calculated by Eq. (3.8) and Eq. (3.9). This value is 2.2%. The blowdown rate of the studied boiler is 20%, which is significantly higher than the normal values typically observed in similar boilers. This elevated blowdown rate is primarily attributed to the poor quality of the makeup water used in the system, which has a high conductivity of 1500 μS/cm. Additionally, the blowdown is not conducted on a regular basis, further contributing to the high conductivity of the blowdown water.

For comparison, high-quality water systems often have a blowdown rate of less than 1%, while low-quality water systems may exhibit blowdown rates as high as 10%. Thus, the 20% blowdown rate observed in our case far exceeds these typical ranges. This highlights the challenges faced by our system due to suboptimal water quality and inconsistent blowdown practices.

$$\lambda_{blowdown} = \frac{\dot{Q}_{Boiler\ blowdown\ losses}}{\dot{Q}_{fuel}} \tag{3.8}$$

$$\dot{Q}_{fuel} = \dot{m}_{fuel} \times HHV_{fuel} \tag{3.9}$$

$$\eta_{Boiler\ indirect} = 100 - \lambda_{stack} - \lambda_{blowbdown} - \lambda_{othe} \tag{3.10}$$

The most significant boiler losses are stack and blowdown losses, while other losses, such as shell loss, are neglected. The boiler efficiency calculated using the indirect method (Eq. 3.10) is 72.1%, which is very close to the 72% efficiency obtained using the direct method. The slight difference may be attributed to uncertainties in the measurement instruments. This efficiency is slightly lower than the combustion efficiency since it accounts for blowdown energy losses, but it is more accurate.

The accuracy of the results is intrinsically linked to the quality of the input data. In our study, we took care to ensure the reliability of the data by verifying and cross-referencing it with historical plant records and manufacturer specifications, which provided an additional layer of validation. Regarding the calculation of boiler efficiency using the indirect method, although this approach is more complex, it is generally more precise. This is because the potential errors, despite being relatively larger in a proportional sense, only affect the measurement of losses, which represent a fraction of the total energy introduced. For instance, when measuring the oxygen content in the flue gas using a combustion analyzer, the equipment accuracy is specified as ±0.2%. In practical terms, this means that if the measured oxygen percentage is 17%, the true value could lie between 16.966% and 17.034%. This small variation in oxygen measurement results in a slight fluctuation in calculated combustion efficiency, ranging from 74.1% to 74.3%. Such precision underscores the importance of both accurate measurement tools and the indirect method in obtaining reliable efficiency results, while also highlighting that minor deviations in data can influence the outcomes.

3.4. Reference Model

The MEASUR model depicts the steam system under study, as shown in Fig. 7. It provides a detailed overview of the various components of the steam system, starting from steam generation to condensate recovery, encompassing steam distribution and its process end-use. The thermodynamic model is given as a Supplementary Material N°2. Table 4 summarizes the key steam system results. The total operational cost, including fuel and water consumption, is 446 664 \$/y. For its part, CO_2 emissions amounts to 1552.35 t/y.

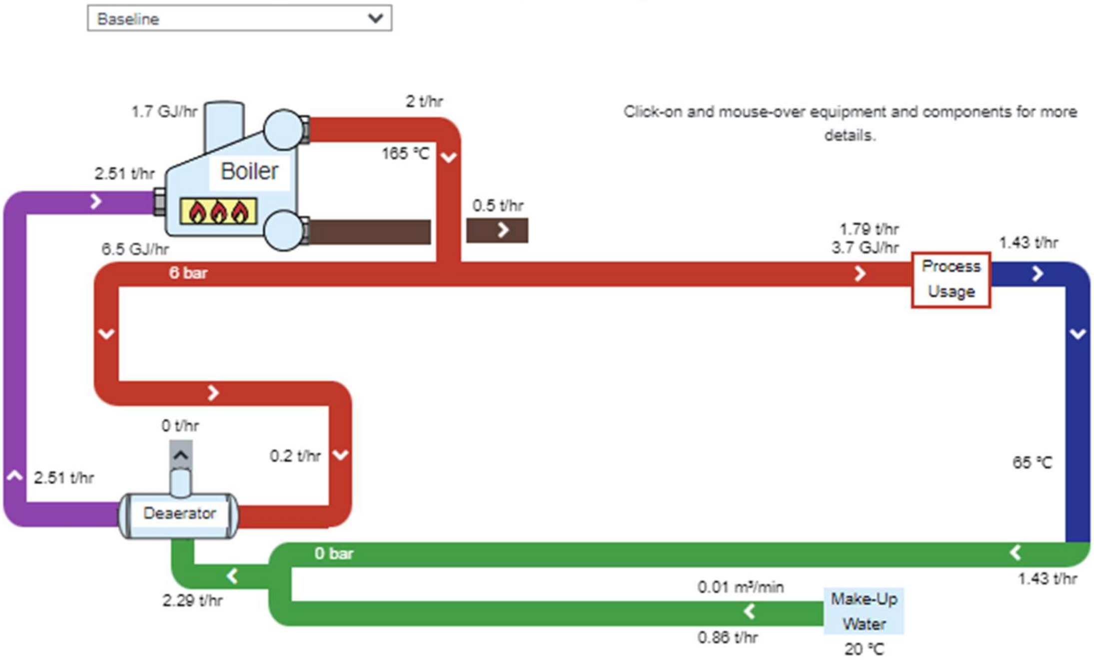

Fig. 7. Baseline model in MEASUR

Table 4. Steam System Summary

Fuel data		Water and steam data	
Boiler Fuel Use	26 050.94 GJ/y	Make-Up Water Required	3453.21 m^3
Boiler Fuel Cost	442 866 \$/y	Make-Up Water Cost	3799 \$/y
Emissions From Fuel	1552.35 t CO_2/y	Steam Generated	2 t/h
Total Operation Cost	446 664 \$/y	Marginal Steam Cost	62.38 \$/y

3.5. Energy Saving Opportunities

3.5.1. Stack Loss Improvement

Excess air and temperature of exhaust gases are two major factors impacting the energy efficiency of the boiler. In this section, the focus will be on these two parameters to enhance energy efficiency. The evaluation of energy, financial, and environmental savings will be examined.

- *Excess Air Control*

The actual value of 17% oxygen in flue gas suggests an excess air level of around 700-800%, which is far beyond normal operational parameters. In this improvement action, we suggest installing an Automatic O_2 Trim Control. The reduction of % O_2 from 17% to a typical value of 2% will improve the boiler efficiency from 74.3% to 86.7%, as shown in the calculator in Fig. 8.

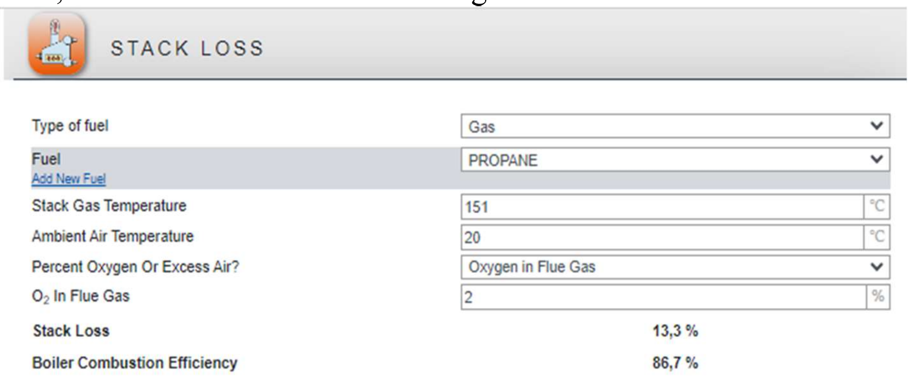

Fig. 8. Stack loss calculation – O_2 reduction

The annual potential savings from this action, calculated from Eq. (3.11), are 63 340 \$, corresponding to 3725.8 GJ, with an emissions reduction of 222 t CO_2.

This represents a saving of 14% relative to the plant thermal energy bill.

$$\sigma_{saving} = K_{boiler} \times \left(1 - \frac{\eta_{actual}}{\eta_{new}}\right) \tag{3.11}$$

where K_{boiler} is the total fuel operating cost.

- *Stack Loss Recovery*

The proposed economizer will decrease the flue gas temperature from 151 to 105°C. Using this heat exchanger to preheat feedwater will reduce the thermal loss in the stack from 25.7% to 19.5%, improving the boiler efficiency from 74.3 to 80.5% (See Fig. 9).

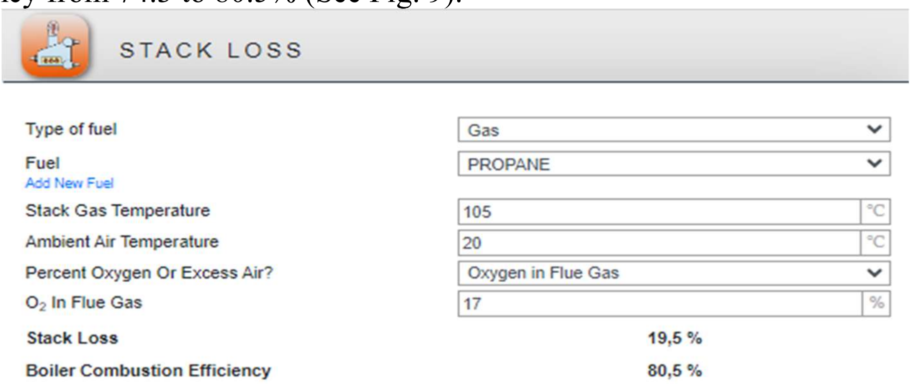

Fig. 9. Stack loss calculation – Waste heat recovery

The annual savings from this energy-saving action amount to 34 109 \$/y, representing 2006.4 GJ/y, with emissions reductions of about 120 t CO_2/y. From an energy bill perspective, a saving of 8% is expected.

3.5.2. Blowdown Loss Management

As calculated in the data analysis section 3.3, the studied steam system has a relatively high blowdown rate of 20%. Reducing this rate or recovering the blowdown thermal energy will certainly reduce fuel consumption. These two actions are investigated in this stage.

- *Blowdown rate reduction*

The reduction of the blowdown rate from the actual value to a fair value of 1% requires close monitoring of makeup water chemical treatment. The water treatment station based on softeners must be periodically checked, and the conductivities monitored. Additionally, it is suggested to install an automatic blowdown controller for intermittent bottom blowdown. This modification results in a financial saving of 29 301 \$/y, an energy conservation of 1599 GJ/y and an emissions reduction of 95 t CO_2/y. This is embodied by a 7% saving on fuel consumption.

- *Blowdown energy recovery*

In this action, it is suggested that blowdown heat recovery equipment be installed to preheat makeup water. The potential savings are 27 210 \$/y, 1593 GJ/y, 95 t CO_2/y and a 6% saving reported to the fuel bill. Fig. 10 outlines the impact of the two modifications regarding blowdown management in comparison to the reference model.

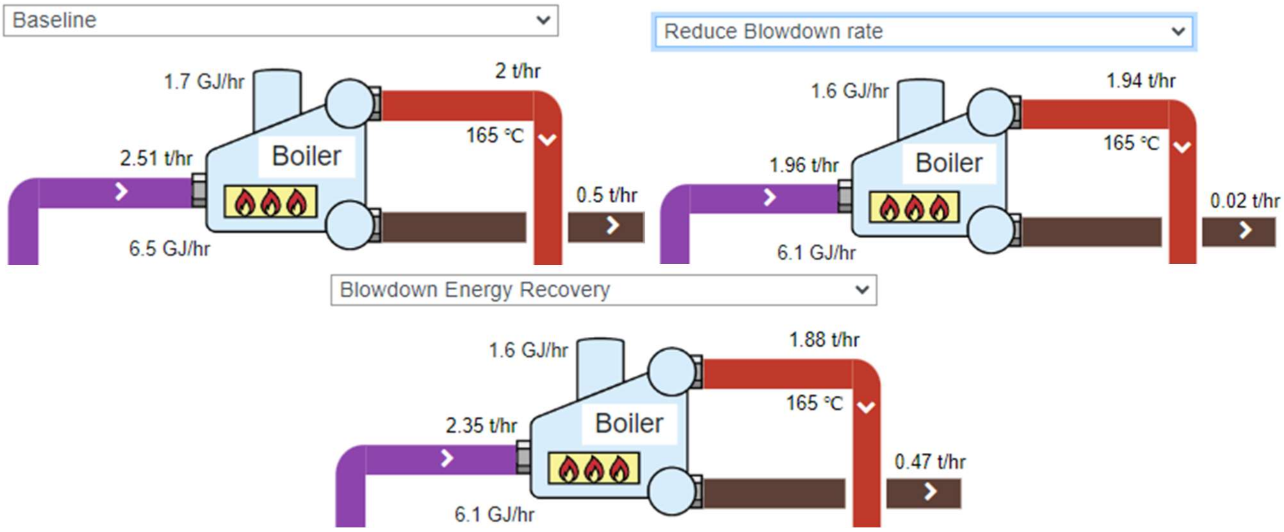

Fig. 10. Baseline vs. blowdown reduction and recovery models

3.5.3. Combined Opportunities Scenarios

The combination of the four proposed improvement actions leads to an energy savings of 22%, resulting in an annual decrease in fuel consumption by 111.5 tons and a reduction in CO_2 emissions by 332.15 tons and a financial saving of 96 884\$/y. The details of the achieved savings are summarized in Table 5.

Table. 5. Savings from actions combination

	Baseline	Assessments Combination	% saving
Energy Input (GJ/y)	26 050.9	20 476.9	21.4%
Fuel Usage (t/y)	521	409.5	
Fuel Cost (\$/y)	442 866	348 108	
Annual Emissions (tonne CO2)	1 552.35	1 220.2	
Make-up Water Cost (\$/y)	3 799	1 673	56%
Annual Cost (\$)	446 664	349 781	21.7%

The Sankey diagrams in Fig. 11-a and Fig. 11-b illustrate the energy flows before and after adopting the combined actions scenario. The primary energy losses in steam generation – specifically stack losses and purge losses – were originally 24.5% and 5.3%, respectively, at the system level. These losses have now been significantly reduced to 11.4% for stack losses and 0.04% for purge losses. Additionally, the end-use process has improved its energy utilization efficiency, using 71.8% of the supplied energy compared to just 56.1% in the reference model.

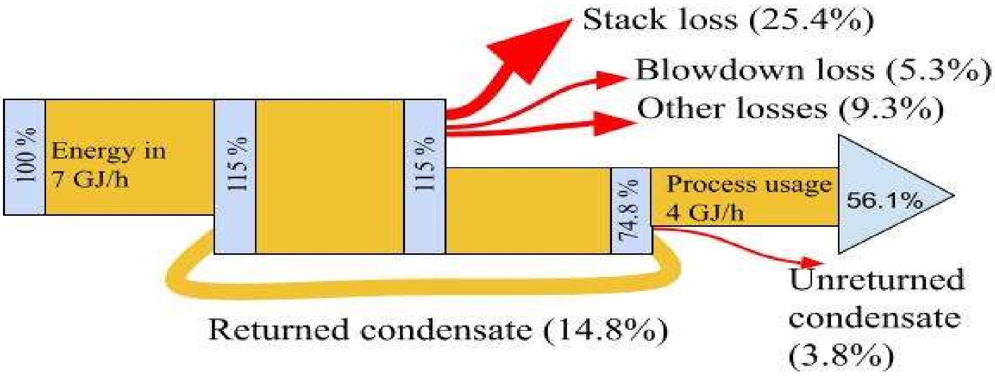

Fig.11-a. Sankey diagram of energy losses-Baseline

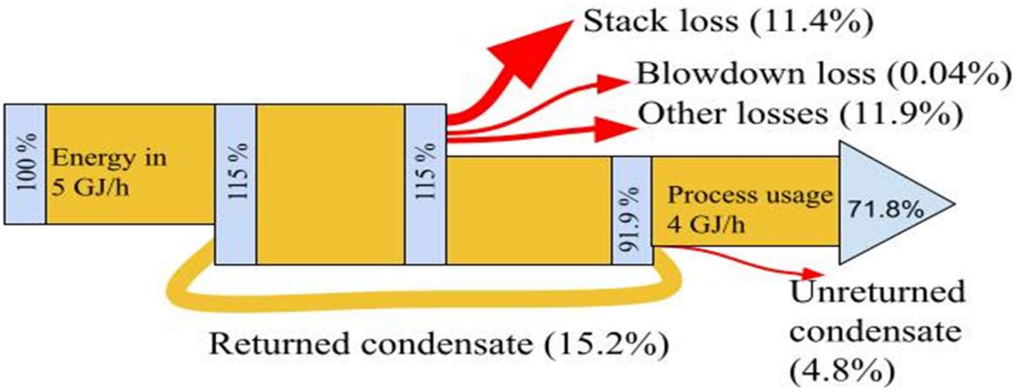

Fig.11-b. Sankey diagram of energy losses-Actions combination

CONCLUSION

This paper presented the roadmap and methodology of a steam system optimization carried out for a Moroccan plastic recycling industry. The benchmarking study disclosed that the "Boiler Plant Operating Practices" area needs the most attention in efficiency improvement, as it is the lowest-rated zone (25%). The diagnostic of the current situation in the boiler house revealed many thermal energy losses at the system level, namely the stack (25.4%) and the blowdown losses (5.3%). These percentages, reported to the fuel cost, present a financial loss of 135 960 $/y.

To mitigate the impact of these losses, four energy-saving opportunities were presented. Their objectives are to reduce and recover energy losses. Two actions focus on reducing stack losses: decreasing excess air in combustion with an automatic air trim controller and preheating feedwater using an economizer in the chimney. The other two actions address blowdown management: reducing the blowdown rate and recovering heat from it. This involves using an automatic blowdown system, enhancing makeup water treatment, and installing blowdown recovery equipment to preheat makeup water. The combination of the precited actions leads to 22% potential savings, resulting in an energy gain of 5574 GJ/y, financial benefit of 96 884 $/y and CO_2 emissions reduction of 332.15 t/y. A preliminary cost analysis has shown that the implementation of these actions has a payback period of less than one year.

The current modeling approach provides a solid foundation for analyzing and improving the energy efficiency of the steam system. While the developed model allows for the adjustment of system parameters online, facilitating the assessment of their impact on energy savings, it currently lacks real-time simulation capabilities. Our study has primarily focused on optimizing the system using static data and specific operational scenarios. However, we recognize the potential value of incorporating dynamic modeling to account for real-time fluctuations in system behavior, and this represents a promising area for future research. Specifically, we aim to explore the integration of dynamic simulation tools that would enable continuous monitoring and real-time adjustment of system parameters, potentially uncovering additional opportunities for optimization. Moreover, incorporating more advanced mathematical models, performing sensitivity analyses, and regularly validating and calibrating the models – along with employing sophisticated simulation tools – could significantly enhance both the accuracy and efficacy of the modeling approach. These improvements would not only increase the reliability of the outcomes but also identify further possibilities for energy savings and system optimization.

The motivation behind this case study is to demonstrate to industrialists that significant energy savings can be achieved by improving the energy efficiency of the existing system without the need for capital-intensive investments to change the current technologies. Even though this study adopts a systemic approach, it has focused solely on improving the steam generation aspect in its improvement actions. In continuation of this work, we intend to address other parts of the steam system, namely distribution, end-use, and recovery. Additionally, we plan to conduct a financial analysis of the energy-saving opportunities to demonstrate their cost-effectiveness.

ACKNOWLEDGEMENT

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