Resource efficient manufacturing: can reduced energy efficiency lead to improved sustainability?

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Abstract

Industrial sustainability has been defined as 'the conceptualisation, design and manufacture of goods and services that meet the needs of the present generation while not diminishing economic, social and environmental opportunity in the long term'. This is not necessarily the same as industrial energy efficiency, although the two concepts are both desirable goals and are clearly related.

Industrial sustainability implies significantly reducing the consumption of non-renewed exergy stock. To illustrate this, a jaggery (sugar) production process is described from energy and exergy perspectives. Modifications were made to the process to improve process efficiency based on an energy analysis. The base case and the modified case are compared using exergy analysis based on the 2nd law of thermodynamics.

If the process is viewed as part of an integrated industrial system for which resource efficiency is the goal, the modifications required to minimise exergy destruction differ from what is required to maximise energy efficiency. This study highlights a possibility that increasing the local system efficiency may have a negative impact on the global system's resource consumption. These results provide an insight into how the design of industrial systems according to the 2nd law of thermodynamics can help to improve resource efficiency in furnace processes in the context of industrial ecology.

Introduction

It is often argued that one of the most effective ways to promote industrial sustainability is to focus attention on the energy efficiency of industrial systems. However, there are conditions under which this may actually have a detrimental impact. Within a large complex energy system, increasing the energy efficiency of a local sub-system alone can have a negative impact on the whole system. Furthermore, a failure to consider whether the input energy is renewable or not, may lead to poor decision making. For example, let us compare two energy systems. A thermally inefficient factory in which process heat is supplied from a hot spring may be argued to be more sustainable than a highly efficient factory that is powered by electricity from a grid supplied by coal burning power stations.

This paper presents a situation based on a jaggery (sugar) furnace case study. The system is studied using both exergy and energy analysis, and an attempt is made to quantify the resource efficiency of the process. However, before such an attempt can be made, it is necessary to clearly define what is meant by the resource efficiency of a process.

WHAT IS RESOURCE EFFICIENCY?

When used as a metric, the concept of efficiency quantifies how well a system produces a required output from a given input. What is normally implied by the term 'resource efficiency' of a system is a measure of how much value is created by the system during the conversion of non-renewable natural resources. Therefore any metric that is to quantify natural resource efficiency should be based on measurements of the consumption of non-renewable natural resources.

Although practitioners speak of energy consumption, from a first law perspective there is no such thing. Energy is a conserved quantity and cannot be consumed. It is a quantitative measure and does not take into account the variations in usefulness of different forms of energy. For example, the term energy does not differentiate between 100 Joules of electricity and the same amount of low grade waste heat from a system. However in reality, the electricity has a greater work potential than the low grade waste heat even though they are both 100 Joules. Both these energy forms are the same in quantity, but it can be said that they are of different quality. In manufacturing systems, various energy transformations are accompanied by a consumption of energy 'quality' which leads to natural resource consumption. For this reason the related concepts of entropy and exergy, which are based on the 2nd law of thermodynamics, may be more meaningful when attempting to quantify natural resource efficiency.

EXERGY DESTRUCTION: A MEASURE FOR RESOURCE EFFICIENCY

Since entropy and exergy are consumable quantities, researchers have tried to address the issue of resource consumption by using these 2nd law quantities. The consumption of non-renewable exergy has been understood to provide a quantitative measurement of non-renewable natural resource use (Szargut et al., 2002, Gößling- Reisemann, 2008). Similarly, (Rosen, 2009, Valero, 2006) considers exergy analysis a strong tool for measuring natural resource consumption. In another instance, (Connelly and Koshland, 1997, Connelly and Koshland, 2001) present an eco-system evolution analogy in which industrial systems are seen to 'evolve' into more sustainable systems that mimic nature. The work considers the removal of exergy from non-renewable resources a direct measure of their depletion. The exergy removed may be either due to losses in the transformation processes or irreversibilities within the system. Exergy destruction represents the portion of consumed exergy due to these irreversibilities. Therefore it is the part of exergy losses which cannot be recovered, nor channelled somewhere else for reuse.

This paper presents a methodology applied to a case study to quantify the exergy losses and exergy destruction within a manufacturing system. The base case is compared to an improved energy efficient version for a jaggery (sugar) production furnace. The results are then discussed in the context of resource efficiency.

Case study

Jaggery is a sugar-cane based product used in place of sugar. This small scale industry is prevalent around the world and this current study is based on a processing plant in India. Jaggery production constitutes 20 % of the sugar-cane based industry in India and has been produced since centuries. In a previous study, the energy analysis and optimization of the process was conducted (Sardeshpande et al., 2010). The data from the process was gathered experimentally and an energy analysis was carried out. Based on the energy analysis of the base case, the system was modified for improved energy efficiency. The base case was improved by controlling the fuel feed rate manually to decrease the bagasse consumption per kilogram of jaggery produced. The decreased bagasse consumption translates to higher process efficiency, lesser wall losses and a lower furnace operating temperature. This study extends the analysis using an exergy based approach, therefore providing an understanding towards natural resource efficiency.

The jaggery production steps involve extracting juice from sugar-case. It is then condensed to the specified level through evaporation and finally moulded in the required form. Figure 1 is a schematic of the processing setup. The juice from the sugar-cane is extracted using a crusher powered by a diesel generator. The juice is transported via a conveyer to four pans in this case. The juice in the pans is continuously stirred while being heated in the furnace up to a required temperature. The thermodynamic analysis of this system requires setting up of the mass, energy and exergy balance. All the inputs and outputs to the system are shown in Figure 2. Sugar-cane, bagasse and jaggery produced per batch were measured using a weighing scale. Oxygen, carbon monoxide and temperature measurements were taken from the flue gas. The mass and energy balances are formulated as follows,

Mass of juice + Mass of bagasse + Mass of combustion air + Mass of chemicals = Mass of flue gas + Mass of water evaporated + Mass of jaggery + Mass of ash + Mass of floating residue

Bagasse energy rate = Juice heating energy rate + Evaporation energy rate + Rate of energy carried in liquid jaggery + Flue gas energy rate + Losses energy rate + Ash energy rate

Further description of the technical framework for the analysis and details about the data collection process are provided in (Sardeshpande et al., 2010). The next section describes how the exergy analysis of the process can be conducted.

EXERGY ANALYSIS OF JAGGERY PROCESSING

Exergy is not a conserved quantity and upon setting up of the exergy balance, the portion that is consumed due to irreversibilities is termed as exergy destruction. This loss of exergy from the input resource flow can never be recovered as it is due to the entropy generated in the process, and is a variable of interest in this analysis. Figure 2 depicts the control volume of the jaggery furnace followed by its corresponding exergy balance.

The general exergy balance for a steady state system is as follows:

$$Ex_{in} = Ex_{out} + Ex_{dest}$$

The mass and energy flows in Figure 2 can be represented as exergy flows to form a balance as follows:

$$Ex_{juice} + Ex_{bagasse} + Ex_{air} + Ex_{chemicals}$$
$$= Ex_{jaggery} + Ex_{flue} + Ex_{wall\ losses} + Ex_{ash}$$
$$+ Ex_{vapour} + Ex_{residue} + Ex_{dest}$$

The mass of chemicals used per product is 30–50 g/kg of juice. Due to this minute quantity of chemical used, the exergy possessed by this stream can be safely neglected. Similarly, on the output side, the floating residue is 1.5 % of the sugar cane by mass and is at the striking temperature (118 °C). Therefore, the exergy of this floating residue can also be neglected. Finally, the air used in the combustion process is fresh air from the environment, and it posses zero exergy. The simplified balance is then as follows:

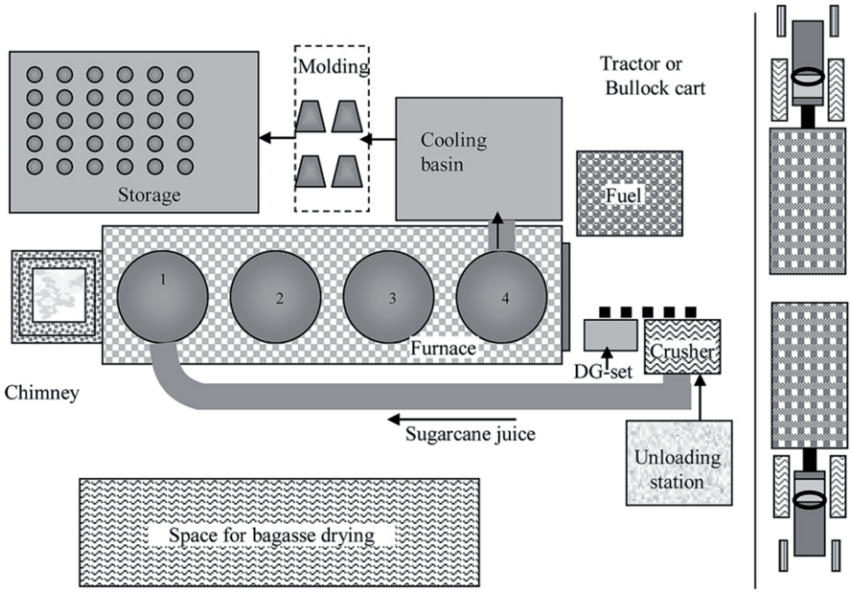

Figure 1. Jaggery processing setup (Sardeshpande et al., 2010).

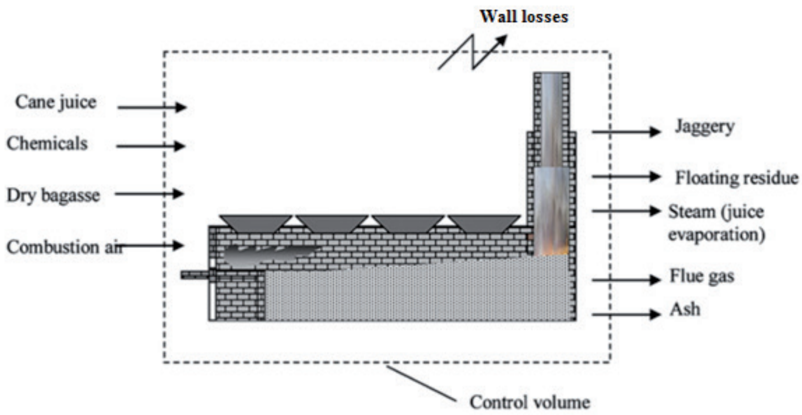

Figure 2. Jaggery furnace control volume, adapted from (Sardeshpande et al., 2010).

$$Ex_{juice} + Ex_{bagasse}$$
$$= Ex_{jaggery} + Ex_{flue} + Ex_{wall\ losses} + Ex_{ash}$$
$$+ Ex_{vapour} + Ex_{dest}$$

CALCULATION OF EXERGY BALANCE

Exergy can be broadly classified into chemical and physical exergy. A detail in exergy background and its suitability for manufacturing is not given here can be found in literature texts such as (Bejan, 1988, Sciubba and Wall, 2010, Brown et al., 2012, Dincer and Rosen, 2012). The calculation method of each term in the exergy balance corresponding to their respective exergy flow form is explained below.

Exergy of sugar cane juice

Since the juice does not have any work potential (neglecting is kinetic and potential energy), the exergy of the juice can be considered as the amount of work required to process the sugar cane through crushing to produce the juice. In the present case, an electrical motor of 7–9 kWh/ton of crushed sugar does the job. The calculated specific exergy of the cane juice is therefore 18.72 kJ/kg.

Exergy of bagasse

The chemical exergy (ε_0) of the dry bagasse is calculated as (Kamate and Gangavati, 2009)

$$\varepsilon_0 = \left[(NCV)_0 + wh_{fg}\right]\emptyset_{dry}$$

Where, NCV is the net calorific value. $\emptyset_{dry}$ & w are the ratio of the chemical exergy to the net calorific value of the fuel and fraction of moisture in bagasse respectively.

The value of $\emptyset_{dry}$ depends on the composition of carbon oxygen and hydrogen in the bagasse and is calculated as:

$$\emptyset_{dry} = \frac{1.0438 + 0.1882\left(\frac{h}{c}\right) - 0.2509\left[1 + 0.7256\left(\frac{h}{c}\right)\right] + 0.0383\left(\frac{n}{c}\right)}{1 - 0.3035\left(\frac{o}{c}\right)}$$

The specific chemical exergy of the bagasse which is 9 % wet for the jaggery process is calculated to be 13,228 kJ/kg. It should be noted here that bagasse is considered a renewable exergy source (Contreras et al., 2013, Contreras et al., 2009).

Exergy of the jaggery produced

The exergy of jaggery is due to its mass flow and thermal energy. For incompressible substances, it is stated as follows:

$$\dot{m}_{jaggery}\left[C_p\left(T_{jaggery}-T_0\right)-C_pT_0\left(\ln\frac{T_{jaggery}}{T_0}\right)\right]$$

Exergy of the vapour released from the juice

The cane juice is heated as a result of which water vapour leaves the system. The exergy leaving the system is stated as:

$$\dot{m}_{vapour}[(h-h_0)-T_0(s-s_0)]$$

The enthalpy and entropy values are taken from steam tables; the specific exergy of the vapour leaving the system is calculated to be 488,417 kJ/kg.

Exergy of the flue gas

The exergy of the flue gas leaving the system is stated as:

$$\dot{m}_{flue\ gas}\left[C_p\left(T_{flue}-T_0\right)-C_pT_0\left(\ln\frac{T_{flue}}{T_0}\right)\right]$$

Exergy of ash

The exergy of the ash is calculated similar to the jaggery as it is a solid substance:

$$\dot{m}_{ash}\left[C_p(T_{ash}-T_0)-C_pT_0\left(\ln\frac{T_{ash}}{T_0}\right)\right]$$

Exergy lost due to wall losses

The losses from the control volume are in the form of wall losses and unburned fuel in the normal operation. In the improved operation, complete burning is assumed therefore, only heat losses through the wall are considered. This includes all forms of heat losses from the furnace. A simplifying assumption is made here by considering these losses as one heat stream. The exergy of this heat stream is given as:

$$=\dot{Q}_{losses}(1-\frac{T_0}{T})$$

Where T is the temperature of the heat stream and is assumed to be the average of the flue and adiabatic flame temperature.

While it would be beneficial to accurately quantify the various types of heat losses and consequently their exergy values separately, the final results in Table 1 suggest there would be little effect on the main findings.

EXERGY DESTRUCTION

From the previously described exergy calculations of each term, the exergy destruction can be calculated through the exergy balance equation.

Energy and exergy efficiency

The efficiency of a process is useful in assessing its performance and is the ratio of the useful output to the supplied input. The energy and exergy efficiencies are therefore:

$$\eta_{energy}=\frac{E_{jaggery}+E_{evaporation}+E_{preheat}}{E_{bagasse}}$$

Where the energy used for preheating is the sensible heating of the cane juice up to the boiling point. $E_{evaporation}$ is the energy used during evaporation and $E_{jaggery}$ is the heat carried away by the finished product.

Even though all of the evaporated energy and part of the preheat energy is technically lost from the system, it directly contributes towards the useful product and is therefore considered a useful output energy flow.

The exergy efficiency is defined as:

$$\eta_{exergy}=\frac{Ex_{jaggery}+Ex_{vapour}}{Ex_{bagasse}}$$

Where $Ex_{jaggery}$ is the exergy of jaggery due to its heat content, Ex_{vapour} is the exergy carried away by the water vapour leaving the system and $Ex_{bagasse}$ is the supplied exergy for combustion.

Table 1 presents the results of the exergy balance of the normal and altered operation. It is interesting to note here that while both the energy and exergy efficiencies increase, the percentage exergy destruction also increases which is not a desirable side effect of the modifications made to the process.

Results analysis and discussion

It can be seen from Table 1 that both the energy and exergy efficiencies increase in the "improved" operating scenario. The exergy destruction also reduces from 403.5 kJ/s to 292.92 kJ/s however, the percentage of exergy destruction increased by 8.82 %. This exergy destruction is truly a lost resource and is not recoverable in any way. The lower fuel feed rate in the modified case implies lesser usability of the waste energy stream as is shown by the Sankey diagrams for the two operation scenarios (Figure 3 & Figure 4).

The flue gas exergy stream reduces from 30.01 % to 18.55 % in the improved efficiency version. Therefore, while process efficiency increases, the work potential of the waste flue gas stream reduces. Additionally, the proportion of exergy destruction increases. This fact has important implications when the optimised system is viewed as a part of a larger integrated system.

If the case under study is optimized in isolation where it is not integrated into a larger system, then the modification implemented improves system efficiency and natural resource savings without any ambiguity. This is due to the fact that a bigger portion of the energy/exergy goes into the useful output accompanied with a reduced quantity of exergy destruction. However, if this manufacturing system is integrated with another system, for example a coal burning steam power plant, other options become available.

Figure 5 depicts a fictitious scenario in which the jaggery furnace can provide its waste heat to the steam power plant. The whole system can be termed as an integrated or global system

Table 1. Exergy balance calculations.

<table>
<tr><th colspan="4">Normal Operation</th><th colspan="4">Altered Operation</th></tr>
<tr><th>Stream IN</th><th>Value (kJ/s)</th><th>Stream OUT</th><th>Value (kJ/s)</th><th>Stream IN</th><th>Value (kJ/s)</th><th>Stream OUT</th><th>Value (kJ/s)</th></tr>
<tr><td>Bagasse</td><td>769.5</td><td>Jaggery</td><td>0.64</td><td>Bagasse</td><td>476.6</td><td>Jaggery</td><td>0.64</td></tr>
<tr><td>Juice</td><td>3.12</td><td>Vapour</td><td>43.11</td><td>Juice</td><td>3.12</td><td>Vapour</td><td>43.11</td></tr>
<tr><td>Air</td><td>0</td><td>Flue</td><td>231.87</td><td>Air</td><td>0</td><td>Flue</td><td>89.01</td></tr>
<tr><td></td><td></td><td>Losses</td><td>92.2</td><td></td><td></td><td>Losses</td><td>52.79</td></tr>
<tr><td></td><td></td><td>Ash</td><td>1.32</td><td></td><td></td><td>Ash</td><td>1.32</td></tr>
<tr><td></td><td></td><td>Destruction</td><td>403.54</td><td></td><td></td><td>Destruction</td><td>292.92</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><th colspan="8">Performance Comparison</th></tr>
<tr><td colspan="3"></td><td colspan="2">Normal Operation</td><td colspan="3">Altered Operation</td></tr>
<tr><td colspan="3">Energy efficiency</td><td colspan="2">29 %</td><td colspan="3">40 %</td></tr>
<tr><td colspan="3">Exergy efficiency</td><td colspan="2">5.66 %</td><td colspan="3">9.12 %</td></tr>
<tr><td colspan="3">Exergy Destruction</td><td colspan="2">52.23 %</td><td colspan="3">61.05 %</td></tr>
</table>

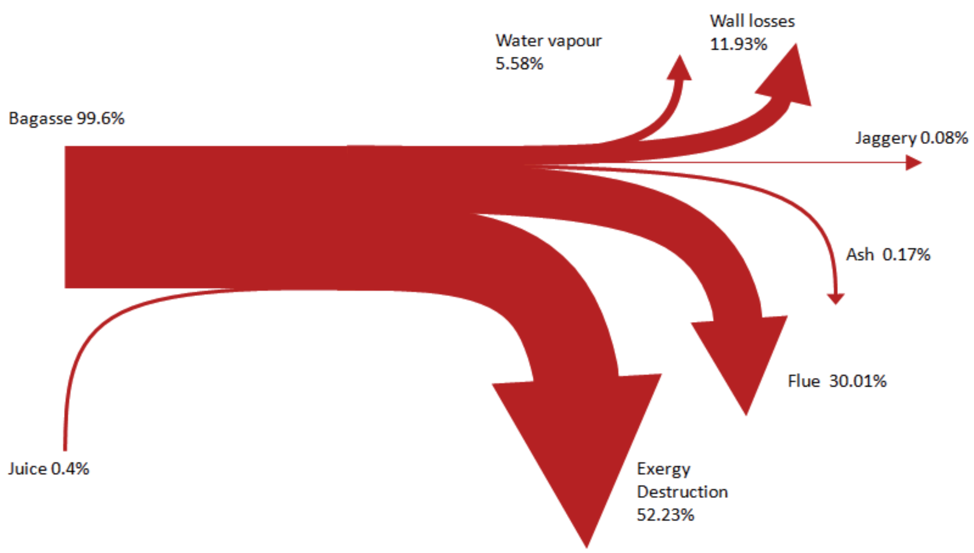

Figure 3. Sankey diagram of exergy flows (base case).

while the furnace and the power plant can be termed as local systems. In this setup, the performance of the global system is sought to be improved rather than the individual isolated systems. When the system operates under the base case scenario, a greater portion (30.01 %) of the supplied renewable exergy is delivered to the power plant accompanied with 52.23 % exergy destruction. In the modified scenario only 18.55 % of the supplied renewable exergy is delivered to the power plant accompanied with an increased exergy destruction of 61.05 %. This means that for a 3.46 % increase in exergy efficiency, 11.46 % lesser exergy is delivered to the power plant while 8.82 % more of renewable exergy is destructed (considering bagasse as renewable). Furthermore, the quantity of exergy delivered to the power plant is also reduced from 231.87 kJ/s to 89.1 kJ/s sug-

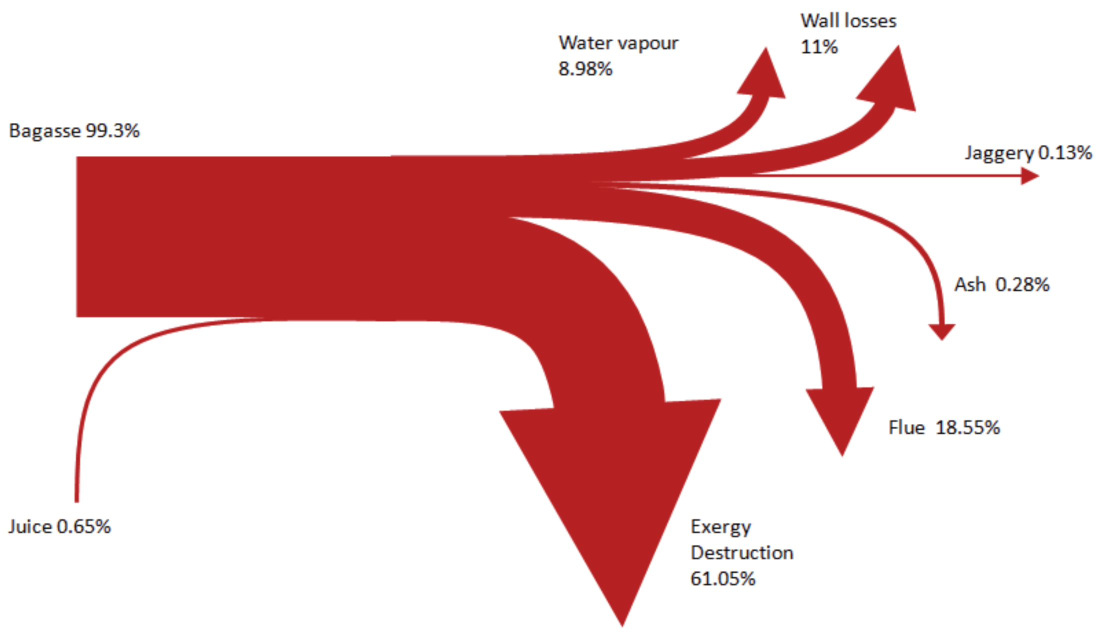

Figure 4. Sankey diagram of exergy flows (modified case).

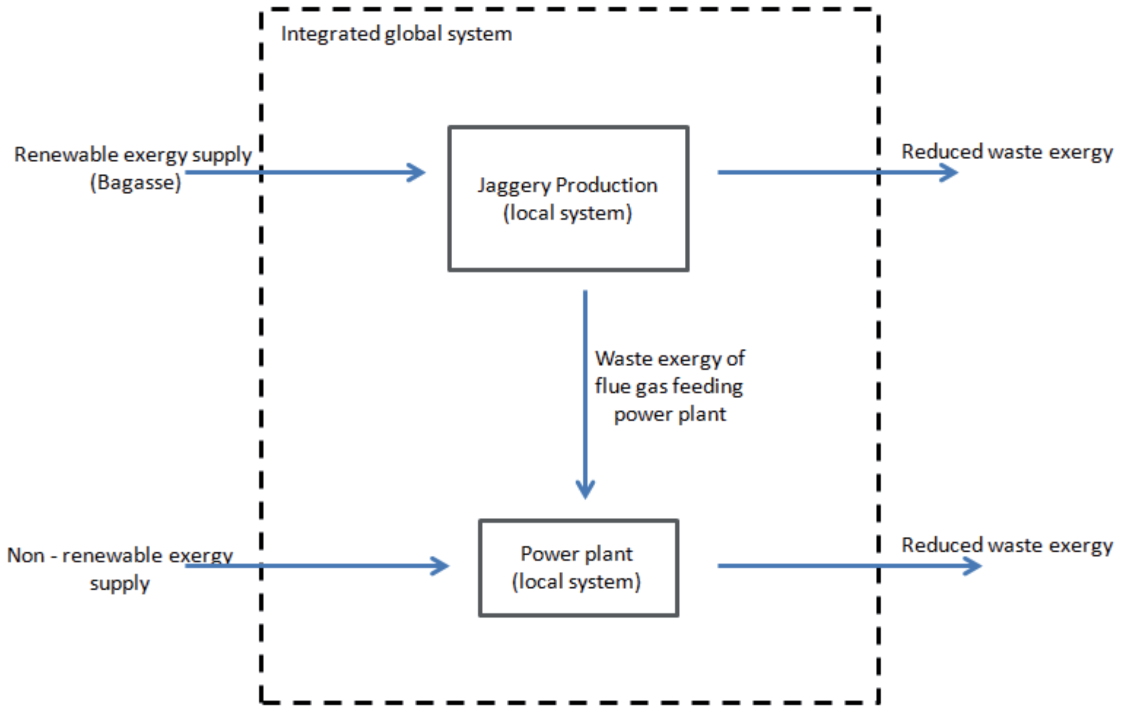

Figure 5. Jaggery furnace integrated with a power plant.

gesting that an additional 142.7 kJ/s input exergy from non-renewable sources has to be supplied to the power plant.

According to the previously discussed literature, the exergy destruction can be seen as a measure for natural resource depletion and consequently industrial sustainability. Therefore in the modified scenario the greater percentage of exergy destruction impacts the natural resource savings in a negative manner. This means that the process modifications not only have positive but also negative impacts on natural resource savings. While the improvement in process energy and exergy efficiency saves natural resources, the increased proportion of exergy destruction has an opposite effect. Analysing the process energy transformation, it can be seen that 3.46 % increased exergy efficiency is accompanied by 8.82 % more exergy destruction. Additionally 11.46 % lesser exergy is available for integration with a secondary process. However, the specific bagasse consumption reduces from 2.39 kg to 1.73 kg of bagasse for a kilogram of jaggery produced which is an improvement of 27 %. Since, the bagasse savings and improved exergy efficiency outweigh the negative impacts; the process modifications are beneficial for natural resource savings. Therefore in this specific case study, increasing energy and exergy efficiency are concurrent with increased natural resource savings and industrial sustainability. However, from this study it can be seen that this may not always be the case in furnace applications. Modifications for increased process efficiency that support lower operating temperatures in furnaces have to overcome increasing exergy destruction and lesser exergy available for integration in other processes. Perhaps a model of a general manufacturing system that is based on an integrated systems approach which attempts to minimize exergy destruction due to non-renewable resources would lend itself well to the development of more sustainable industrial systems. Finally, it is clear that such an insight would not have been possible with only energy analysis. The 2nd law of thermodynamics needs to be taken into account to assess industrial sustainability more genuinely.

Summary and conclusion

This paper describes how an exergy analysis can be used to assess the resource efficiency of a jaggery (sugar) processing furnace. The study compared two cases of the process based on experimental data, comparing the base case with an improved efficiency version. The exergy losses and exergy destruction have been quantified and the results analysed in the context of resource efficiency. The results from the case study show that modifications to the process improve its energy and exergy efficiency. On the other hand the exergy destruction and usability of the waste stream are reduced which are not desirable effects. It has been found that in certain scenarios of furnace applications increasing energy and exergy efficiency have positive as well as negative impacts on industrial sustainability. Furthermore, such insight is only possible if the 2nd law of thermodynamics is taken into account. In the analyzed case study, the benefits outweigh the negatives and therefore it can be concluded that the modifications improve the process sustainability. The finding suggests that an exergy based model of a manufacturing system that incorporates a holistic approach may be beneficial for designing or analysing sustainable industrial systems.

References

Bejan, A. 1988. Advanced engineering thermodynamics.

Brown, N., Khattak, S. & Greenough, R. Year. Suitability of exergy analysis for industrial energy efficiency, manufacturing and energy management. *In*, 2012. European Council for an Energy Efficient Economy.

Connelly, L. & Koshland, C. P. 1997. Two aspects of consumption: using an exergy-based measure of degradation to advance the theory and implementation of industrial ecology. *Resources, Conservation and Recycling,* 19, 199–217.

Connelly, L. & Koshland, C. P. 2001. Exergy and industrial ecology – Part 1: An exergy-based definition of consumption and a thermodynamic interpretation of ecosystem evolution. *Exergy, an international journal,* 1, 146–165.

Contreras, A. M., Rosa, E., Pérez, M., Van Langenhove, H. & Dewulf, J. 2009. Comparative life cycle assessment of four alternatives for using by-products of cane sugar production. *Journal of Cleaner Production,* 17, 772–779.

Contreras, A. M., Rosa, E., Van Langenhove, H., Santos, R., Pérez, M., Casas, Y. & Dewulf, J. 2013. Exergetic analysis in cane sugar production in combination with Life Cycle Assessment. *Journal of Cleaner Production*.

Dincer, I. & Rosen, M. A. 2012. *Exergy: energy, environment and sustainable development*, Newnes.

Gößling-Reisemann, S. 2008. What is resource consumption and how can it be measured? *Journal of Industrial Ecology,* 12, 10–25.

Kamate, S. & Gangavati, P. 2009. Exergy analysis of cogeneration power plants in sugar industries. *Applied Thermal Engineering,* 29, 1187–1194.

Rosen, M. A. Year. Enhancing ecological and environmental understanding with exergy: concepts and methods. *In:* Proceedings of the 4th IASME/WSEAS Int. Conference on Water Resources, Hydraulics & Hydrology (WHH'09) pp, 2009. 94–103.

Sardeshpande, V. R., Shendage, D. & Pillai, I. R. 2010. Thermal performance evaluation of a four pan jaggery processing furnace for improvement in energy utilization. *Energy,* 35, 4740–4747.

Sciubba, E. & Wall, G. 2010. A brief commented history of exergy from the beginnings to 2004. *International Journal of Thermodynamics,* 10, 1–26.

Szargut, J., Ziębik, A. & Stanek, W. 2002. Depletion of the non-renewable natural exergy resources as a measure of the ecological cost. *Energy Conversion and Management,* 43, 1149–1163.

Valero, A. 2006. Exergy accounting: capabilities and drawbacks. *Energy,* 31, 164–180.