AN ENERGY EFFICIENCY INDEX FOR THE SOUTH AFRICAN SUGAR INDUSTRY

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Abstract

South African sugar plants produce a range of products including sugar, ethanol and various other chemicals. They also sometimes sell excess energy to others. The project was to consider the energy efficiency of the various plants both for internal consideration and comparison between plants. A detailed model of the energy flow was derived allowing analysis of each process, and a simplified bulk approach to energy was used to provide an overall estimate of energy efficiency.

1 Introduction

South African sugar refineries produce sugar for both the domestic and international markets. They also use sugar cane to produce several other products in varying quantities. The number of potential products depends on a number of factors and a past study group considered the optimization of profit by considering different product prices and capital outlays required (see [1]).

The industry as a whole is very good at recycling the input materials to create an almost totally self-sufficient process. Cane is crushed and separated early in the process and the discarded matter, bagasse, is burned to generate the energy required to run almost the entire process. Steam drives a turbine that produces electricity

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and is also used for heating to further separate the sugar from water. Water from the cane is also utilized throughout to minimize the external supply.

In the following we consider the energy requirements of different parts of the process. A flow diagram of the full process allows a clear understanding of the components of the plant. The energy requirements of each stage of the process can then be computed. Additional processes and diversion of energy from the primary purpose can then be incorporated as needed.

Once this flow of resources is clearly delineated a simpler measure of energy efficiency can be derived. Therefore, the study group was asked to consider the following;

- the development of a configuration independent measure of energy efficiency of each operation
  - Internal comparison for continuous improvement
  - Inter factory comparison to highlight effective changes for improving energy efficiency
  - Motivation tool for capital investment
- find an overall index to express factory progress

2 Comparison across the sector

Some data on the various processes across the South African sugar refineries was provided. An examination of this was undertaken to get a feeling for current practices and efficiencies in the industry and also to get an idea of the nature of the industry in South Africa. The data showed plants crush cane over the range from 140-420 tons/hour across the sector, so that the largest refinery is roughly three times the size of the smallest.

In general terms the data provided suggest that the production conditions across the nation are sufficiently similar that no geographical adjustments need to be made in defining an energy index. The quality of cane does not vary from one plant to the next but there is some variability over the year with the highest quality cane (with the highest sugar content) being produced in June/July and the worst in November/January. Also, energy requirements will vary because of seasonal temperature variations. Thus, seasonal variations in the energy budget will occur across all plants and such effects will be reflected in the energy index. These seasonal variations in the index can be accounted for by appropriate averaging.

3 Sugar Production Process

Here we outline the full process by which cane is converted to sugar so that we can see the processes over which the energy is divided and hence the energy flow. The cane arrives at the plant and is then shredded. What follows is one of the major

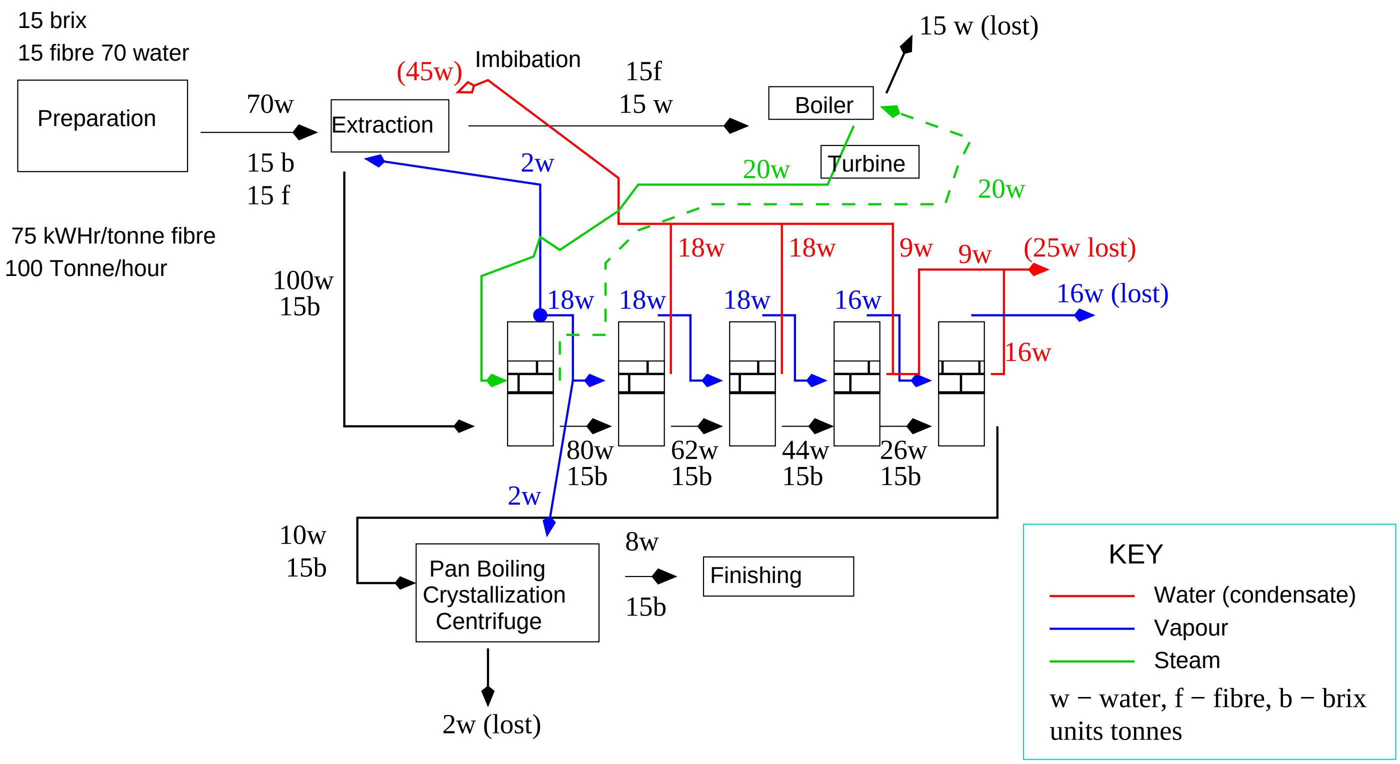

Figure 1: *Flow diagram for a sugar plant producing only sugar. Numbers are in tonnes unless otherwise stated. The 'b', 'w' and 'f' refer to brix, water and fibre.*

parts of the process as the shredded cane is placed in the *diffuser* in which it is carried along by a conveyor and repeatedly washed by water that flushes out the sugar. The water is sourced from the condensate of the evaporators and hence is clean and warm. The water is recycled through from downstream to upstream in the passage of the shredded cane to maximize the output of sugar. If more water is run through the diffuser then a higher proportion of sugar can be recovered. However, at the end of the process extra energy must be consumed to remove the extra water from the sugar-water juice and this may use more energy than is worthwhile. In the end this decision will usually be made based on the relative price of the output product and energy production rather than energy efficiency. A consideration of the process in the diffuser was undertaken in two earlier study groups [2, 3].

The juice produced in the diffuser is diverted to a series of *evaporators* (often 5 but sometimes 4) which reduce the water content to the point where it is 60% sugar (by volume). After this, it enters the finishing phase in which it is dried and crystallized. The waste from the diffuser (*bagasse*) is diverted to the *boiler* in which it is burned to generate steam that is used to power most of the plant. If more water needs to be removed in the evaporator phase then it may be necessary to burn some coal to generate sufficient energy, but in normal operation this is not required.

Water that is taken off the juice in the evaporators can either be recycled through the boiler if it is clean enough, or used as the supply for the diffuser input. Steam produced by the boiler is used to either evaporate the water from the juice or drive a *turbine* to generate electricity to drive the pumps, conveyor, shredder and other processes that require direct input.

Figure 1 shows a schematic of the flow between the major components. The flow of water, steam, fibre, brix and juice is illustrated to provide a general picture. In some cases complicated processes have been simplified for clarity but overall it is a good reflection of the process. The energy requirements associated with each stage of the processing can be readily quantified using standard engineering results and principles. For example, steam flowing into an evaporator at a certain temperature and out as water at a certain temperature and pressure releases energy from the changes in temperature and the condensation, which is used in other processes such as evaporation of the water from the juice.

4 Processes, resource flow and energy accounting

The group developed an input/output resource flow model for each stage of the production, detailing the transformations occurring and their associated energy requirements.

To this end the following variables were defined:

p_i	Processes within the factory
$x_{r,i}$	Input of resource r to process i
$y_{r,i}$	Output of resource r from process i
$f_{r,i,j}$	Flow of resource r from process i to j
$e_{r,i}$	External input of resource r to process i
$s_{r,i}$	Sales of resource r from process i
$w_{r,i}$	Waste of output r from process i
ω_i	Energy wastage (KJ) in process i

In order to perform an initial efficiency assessment of a particular plant, it is assumed that a finite set of processes $\{p_i \| i = 1, 2, ..., n_p\}$ and resources $\{r \| r = 1, 2, ..., n_r\}$ can be identified. It is also assumed that the flow of resources (excluding any wastage) can be measured within the plant: inputs (internal and external), outputs and sales of each resource at each process. Figure 2 gives an illustration of such a balancing process for some important processes in the plant.

In terms of practical implementation, it is likely that the external inputs and sales are already well-monitored, but additional measurements may be necessary in order to track the inputs/outputs of each process. If this is done correctly, the required quantity of the inputs into any process should be equal to the sum of the flow of resources into the process and/or the external inputs used. This condition gives rise to the following equation:

$$x_{r,j} = \sum_i f_{r,i,j} + e_{r,j},$$

which should be satisfied for all processes $j = 1, 2, ..., n_p$ and resources $r = 1, 2, ..., n_r$. If either $x_{r,j}$ or at most one of the terms in $\sum_i f_{r,i,j}$ is unknown, these equations can be used to solve for the missing data.

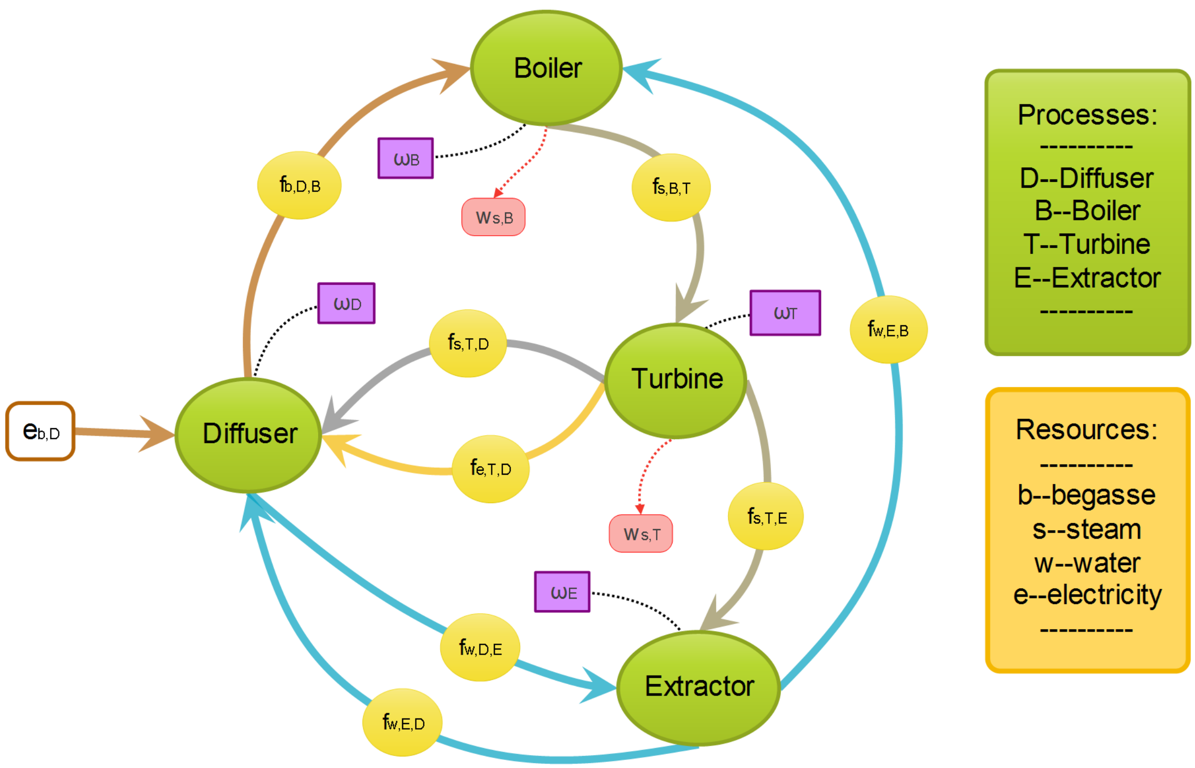

Figure 2: *A diagram illustrating the flow of begasse, steam, water and electricity between four major processes in a sugar plant*

If the flow, input and output variables can be measured or estimated, the wastage in the factory can be calculated using the following equation:

$$w_{r,i} = y_{r,i} - \left(\sum_j f_{r,i,j} + s_{r,i} \right),$$

which implies that the wastage of any given output r from process i is the difference between the total amount of resource r that is produced and the total amount of resource r that is used in the plant and/or sold. The wastage calculated here will be due to factors such as dumping (in order to reduce dangerous water/pressure levels), leaks and heat loss in pipes.

The second set of wastage variables ω_i are measured in units of energy and are therefore not tied to a specific resource, but rather to the efficiency of energy conversion within each process $i = 1, 2, ..., n_p$. The energy balance equations which apply to these variables are unique to each process and may differ from plant to plant according to the type of equipment used. A few examples will be illustrated below.

1. Turbine
   The turbine takes in high-pressure (P_1) steam, which is used to turn the blades in order to generate electricity. The same quantity of steam is released from the back of the turbine, but at a lower pressure(P_2). If the change in enthalpy resulting from this pressure drop is equivalent to the amount of electrical energy generated then there is no wastage and $\omega_{turbine} = 0$. In reality, however, this conversion process is often very inefficient and the following equation must be used to calculate $\omega_{turbine}$

$$\omega_{turbine} = \left[(\text{kg steam in}) \left(\overbrace{H_{P_1} - H_{P_2}}^{\text{change in enthalpy}} \right) \right] - \left[\text{Electricity (KWh)} \times \overbrace{3600}^{\text{KJ/KWh}} \right]$$

2. Boiler
   The boiler is the main source of energy in the plant. It takes in bagasse as fuel and condensate at a low temperature (T_1). The burning bagasse is used to heat the condensate and produce steam which is then super-heated (T_2). Formulae are available to calculate the energy contained in the begasse depending on the amount of ash, moisture etc. that it contains. This energy must be balanced with the amount of energy required to raise the condensate to boiling temperature, the latent heat required for a phase change and the additional energy required to raise the temperature to T_2

$$\omega_{boiler} = \left[\left(\text{kg bagasse}\right) \times \overset{\text{KJ}}{H_{bagasse}} \right]$$
$$- \left[\left(\text{kg condensate}\right) \left(\overset{\text{heating water}}{T_{vap} - T_1} \right) (c_p) + \overset{\text{latent heat}}{L} + \left(\overset{\text{heating steam}}{T_2 - T_{vap}} \right) c_p^{steam} \right]$$

3. Diffuser

   The diffuser requires a certain amount of mechanical energy in order to maintain the flow of bagasse. Since the bagasse is fed in at a constant rate, there is very little acceleration and this mechanical energy is therefore mostly used to counteract the effects of friction.

   Mechanical: $\omega_{mech} = 0.9\text{MW}$

   Heat: The diffuser uses steam (T_1) to heat water and begasse. The steam is released as condensate and the energy released as the steam cools to boiling temperature (T_{vap}) and the latent heat released during condensation must be balanced with the energy required to heat the begasse and water by ΔT_3 degrees.

$$\omega_{\text{diffuser}} =$$
$$\left[\left(\text{kg steam in}\right) \left(\left(\overset{\text{steam cooling}}{T_1 - T_{vap}} \right) \left(c_p^{steam} \right) + \overset{\text{Latent heat}}{L_{p1}} + \left(\overset{\text{water cooling}}{T_{vap} - T_2} \right) \left(c_p^{water} \right) \right) \right]$$
$$- \left[\left(\text{kg water in}\right) \left(\Delta T_3\right) \left(c_p^{water}\right) + \left(\text{kg fibre in}\right) \left(\Delta T_3\right) \left(c_p^{fibre}\right) \right]$$

4. Evaporator

   This is a multi-step process which consists of four or five evaporators which take in a sugar solution and heat it in order to boil off excess water and increase the sugar concentration. The heating is done via steam, which loses energy as it cools and condenses. Since each evaporator operates at a different pressure and temperature, the temperature and pressure constants in the following equation describing energy loss will need to be adjusted accordingly.

$$\omega_{\text{evaporator}} = \left[\left(\text{kg steam in}\right) \left(L_{P_1}\right) \right]$$
$$- \left[\left(\text{kg water evaporated}\right) \left(\left(T_1 - T_{vap}\right) \left(c_p^{water}\right) + L_{P_2} \right) \right]$$

4.1 Model implementation

The model described in this section was implemented in the package *Mathematica*. Initially the programme was constructed to track the flow of resources from one process to another and return the wastage of resources transferred from one process to another. This model could be exceptionally helpful in identifying unnecessary wastage of resources due to things like heat loss or leakage. However, this model does not take into account wastage that occurs within processes. Although this factor is somewhat beyond the control of the plant staff, it still plays a significant role in the overall efficiency of the plant. The model was therefore modified to include the energy loss calculations for certain processes in the plant.

5 A simple index - bulk accounting

An examination of Figure 1 reveals that the whole process is powered via the energy generated in the boiler. Whatever is generated in this, whether it is by burning bagasse or burning coal, must compensate for all of the losses in the system. The "losses" in this case means all energy that is not re-used within the system, so will consist of three components;

- water "dumped" after it has all useful energy extracted,
- losses through surfaces, friction and inefficiency of conversion processes,
- energy used to drive the diffuser, crusher, pumps etc. .... as electricity.

All of these can be quantified as they were in the previous section, but here we are only interested in a bulk measure of energy efficiency. In the past when the factories were only making a single product, then a sensible choice for the Efficiency Index was simply

$$EI_{\text{OLD}} = \frac{\text{Steam Energy } (S_T)}{\text{Cane input } (C_I)}$$

This produced a reasonable and consistent estimate because the steam output is proportional to the energy input (not including any coal burned) and the cane is equivalent to the amount of sugar entering the system at least in relative terms as the amount of sugar in the cane is relatively constant, varying only slightly over the year and across the different plants.

However, modern plants produce a range of products and so it is no longer appropriate to use quite such a simple calculation as each "new" product diverts energy from the sugar refinement process and may have very large relative energy requirements. It is still true that the energy input from the boiler must compensate for all energy losses, but the losses associated with each process and between different plants (which may or may not be making the same products) may also differ.

In the modern context it is still true that a certain amount of energy is required to run the plant and a certain amount of sugar enters via the cane. Therefore a modern reflection of the energy efficiency that is comparable to the old measure should use this commonality. It is still possible to account for the total energy required to drive the system, so it is the output measures that need to be adjusted in some way. It is important that each of the different products is counted in an equivalent way. For example, each uses some proportion of the sugar laden juice that is taken from the diffuser. An intermediate number that could be computed is the ratio of the energy input to the diffuser to the volume of sugar in the juice, i.e.

$$EI_U = \frac{\text{Total diffuser energy usage}, E_D}{\text{Volume of sugar in juice}, S_J}$$

This could be coupled with the ratio of the total energy input to the total sugar content of all of the products (no matter what they may be).

$$EI_D = \frac{\text{Total energy - diffuser energy usage}, E_T - E_D}{\text{Volume of sugar in all final products}, S_J}$$

These two numbers indicate the differences in relative energy use in the two parts (pre- and post-diffuser). In the calculation of input energy all sources should be included, not only steam but coal as well, and it is best to work in energy units rather than volume of steam. If energy is being sold then it should be removed from the calculation and set aside. Estimates of historical values could be made from adjusting the old energy index records.

These two numbers, however, would not allow an accounting of the fact that some processes are more energy intensive than others. To obtain a clearer breakdown of energy consumption (without the full fine-scale approach suggested above), several further numbers could be obtained, one for each of the products. In Figure 3 an example is shown in which 10% of the juice is diverted to production of ethanol. However, while the ongoing sugar production process may require 10% less energy, this may not all be required for the ethanol production (or may not be sufficient).

Suppose there are N products from the plant, e.g. sugar, ethanol, ... then input energy is diverted to those processes. In order to account for each of the processes, if possible, then the amount of energy diverted to the individual product line *after* the diffuser energy has been removed, could be divided by the amount of actual sugar-equivalent in the final output.

$$EI_k = \frac{\text{Energy diverted to process } k, E_k}{\text{Sugar tied up in product } k, S_k}\ , \qquad k = 1, 2, \ldots, N$$

The advantage of this is that it is easier to monitor output products than work out how much cane has gone into the production of each component. Keeping separate calculations for each component allows a sensible comparison of like with like.

Thus, there would be a set of $N + 2$ numbers for each plant, where N is the number of individual products being produced. The values of these numbers would initially mean little but would become meaningful as historical data were collected. As a final step, each process would have some expected value of energy usage,

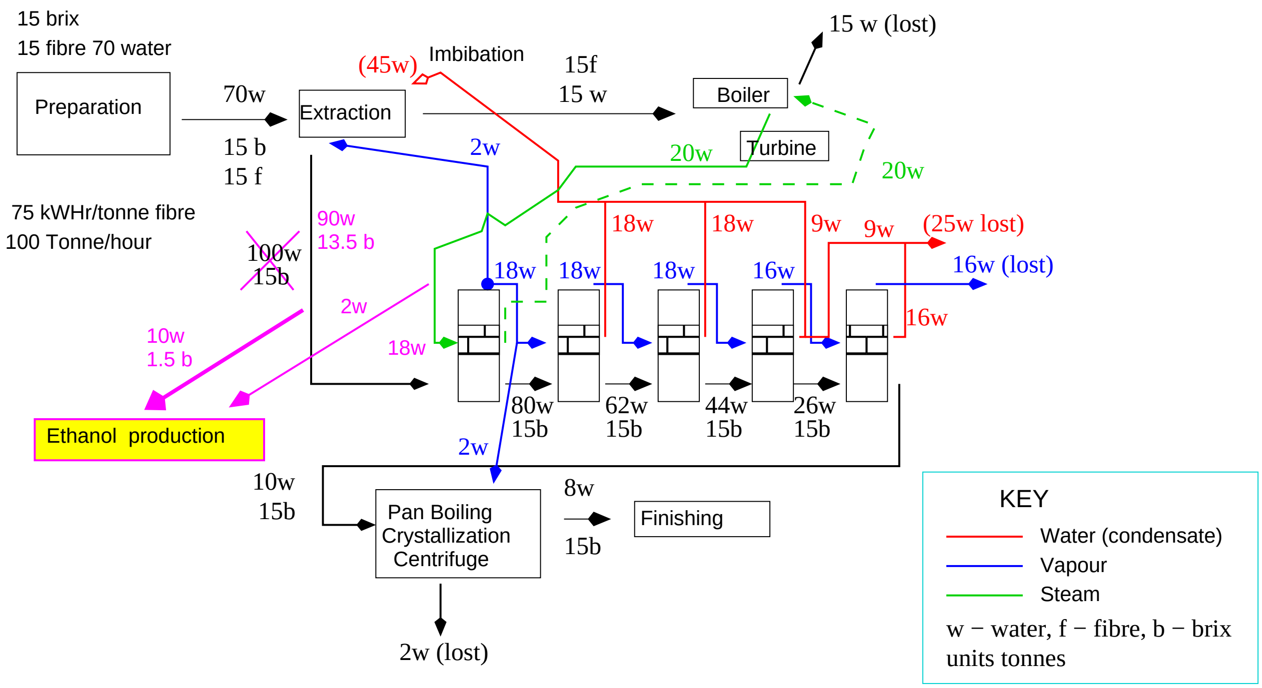

Figure 3: *Flow diagram for a sugar plant if another process (e.g. ethanol) is brought on line. Energy must be diverted to the new process, but other resources are also diverted.*

and so each of this final set of numbers could be normalized by dividing by the expected (or historical average) ratio for that particular product (thus making the final number non-dimensional). For example the process dependent numbers EI_k would be modified to

$$R_{E_k} = \frac{EI_k}{\overline{EI_k}}$$

where $\overline{EI_k}$ is the historical average (or alternatively the expected value). This set of non-dimensional quantities could then be compared directly with each other.

The collection of these data would provide a sound historical record of efficiency of the processes within the plants. If an improved process were developed then this should be seen in an increase in the appropriate number for that product (once determined the denominator should be kept the same). Furthermore, given such a detailed historical reference, future planning would become more soundly based. For example, if a carbon pricing scheme or similar is introduced to South Africa then the energy required from renewable energy sources for the full process or sub-processes could be easily computed.

6 Concluding Remarks

The problem considered was to develop an efficiency index for comparison of different plants and processes. During the study group a framework was developed to build a sophisticated model for calculation of all energy and mass flows and to compute wastage. Over time this could be extended to include each new process as it comes on line. A reasonably accurate model such as this could be used to drill down to the individual processes to determine the efficiency of each step.

We have also proposed a set of new non-dimensional bulk indices that may provide a quick estimate of energy efficiency, a direct comparison between general stages of the process and a comparison between plants. This set of numbers need not be as proposed but could be determined by the operators. However, they should all retain the non-dimensional property so they can be easily compared, and they all need to be repeatable and relatively easy to calculate from bulk data. If carefully designed, a model of costing could be layered over this set of numbers to provide optimal production of the individual products. The proposed choice seems to fit these requirements and give enough information without becoming too difficult to implement.

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