REFEREED PAPER

STRATEGIES FOR MONITORING ENERGY CONSUMPTION IN SUGARCANE PROCESSING FACTORIES

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Abstract

Sugarcane processing facilities throughout the world are attempting to improve energy efficiency for cost-saving and/or fibre recovery. Other industries have shown that significant savings can be made by monitoring energy consumption within the process and using this information to reduce unnecessary consumption. Energy use measurements before and after capital upgrades also provide metrics for assessing the effectiveness of the investment.

This paper reviews the energy monitoring literature both within the sugarcane processing industry and in other industries to establish best practice principles for energy monitoring. Two clear principles emerge: firstly, emphasis should be on monitoring energy consumption that is influenced by controllable factors, and secondly, information on energy use should be made available to the individuals who are responsible for the decisions that influence energy consumption.

Preliminary experiences with obtaining energy monitoring data from a local factory are presented.

This work is part of an SMRI research project to develop energy benchmarking indices in sugarcane processing factories.

Keywords: Energy monitoring, energy benchmarking, instrumentation

Introduction

The South African sugarcane processing industry has some of the highest efficiencies in sucrose extraction and recovery in the world. This can be attributed in part to the detailed monitoring and benchmarking of operations undertaken by the South African Sugar Association (SASA) Cane Testing Service (CTS), mill laboratories and the Sugar Milling Research Institute NPC (SMRI). Weekly, monthly and annual publishing of factory performance figures provides a rich database for performance evaluation. The factory performance figures are primarily concerned with cane, sucrose and molasses flows and compositions. However, the only specific parameters relating to energy use that are published are supplementary fuel and coal usage as a function of tonnes cane processed, totalled per mill over each milling season.

The amount of energy used as a function of cane throughput can differ significantly between mills, depending on the raw factory configuration, the presence or otherwise of a back-end refinery or other downstream processing facility, throughput as a function of installed capacity, and unsteady operation. Because no two factories are identical, standard energy use indicators, such as the amount of high pressure (HP) steam generated per tonne of cane processed (reported as steam % cane), are usually not comparable between factories, making the setting of achievable energy targets difficult.

At present, there is no general agreement on what minimum levels of energy efficiency could be achieved in existing sugarcane processing factories with existing technology, either theoretically or practically. However, these numbers would be of significant value to factories and sugar companies to assess the benefit of changes to equipment, configuration or operation to improve factory profitability.

The STEP-Bio Energy Monitoring study

A sub-project to monitor energy use in sugar factories for the purposes of establishing energy use benchmarks was proposed by the SMRI and Stellenbosch University as part of the STEP-Bio[1] project, *Assessment of energy use reduction and monitoring opportunities in sugar factories.* The latter is a South African Department of Science and Technology (DST), SMRI and South African Sugar Millers' Association NPC (SASMA) co-funded project. The energy monitoring study aims to establish a universally accepted energy reporting system that calculates indices for performance relative to target.

The system should:

(i) Calculate energy use targets based on variable inputs e.g. cane quality, throughput, time-of-season;
(ii) Identify causes of high use within a factory;
(iii) Integrate with existing process indicators; and
(iv) Translate into cost-of-lost-opportunity in terms of coal burned or power/co-product not made.

In addition, the system should aim to support operations within the factory and, ideally, allow rational comparison between factories.

The purpose of this paper is to provide a review of literature on energy monitoring and benchmarking in the sugarcane processing industry and other industries towards developing a system for energy monitoring and benchmarking in the South African sugar industry. The paper closes with some preliminary experiences in collecting energy data in South African factories.

Review of sugarcane processing literature on energy monitoring and benchmarking

Factors influencing energy consumption

If a factory's energy management target is to operate as efficiently as possible, then the staff need to ensure that they have a reasonable understanding of what is possible. Energy consumption for a particular throughput in a factory depends on two categories of influence: firstly, the overall configuration and installed equipment of the factory impose a theoretical

[1] Sugarcane Technology Enabling Programme for Bioenergy (STEP-Bio) - A Bridge to a Fully Integrated Sugarcane Biorefinery

limit on what can be achieved; secondly, operational decisions, process dynamics, whether avoidable or not, and upsets and incidents will all influence how far above the design minimum energy consumption the factory performance will be.

Energy design

The overall steam cycle can be depicted as a heat engine where the sugar-processing section of the factory functions as a condenser (**Figure 1**). The steam system can be divided into the HP or boiler steam side and the process or exhaust steam side. This is depicted by a dashed line through the turbines and let-down station in **Figure 1**. The HP steam side supplies electrical and mechanical energy to the sugar factory, and potentially other customers, and generates exhaust steam to satisfy the thermal energy demands of the sugar-making process. The energy balance must simultaneously satisfy electrical, mechanical and thermal energy requirements, taking into account possible variations in operating conditions. Ideally, the factory energy requirement, including any downstream processing, should be met using the available fuel source without excessive accumulation of bagasse, and minimising the requirement for supplementary fuel (Schorn *et al.*, 2005).

There is no generic process flow sheet that describes all sugarcane processing factories. Key features such as the number of evaporator effects and the number of electrified mill drives influence the amount of exhaust and HP steam required, respectively (Reid and Rein, 1983; Schorn *et al.*, 2005). These choices influence the availability of vapour bleeds for reuse in pans and heating duties, and thus the amounts and types of energy consumed (and produced) in other unit operations of the factory. In South Africa, each sugar factory has a different energy balance depending on the constraints in place during the initial design process and subsequent alterations and upgrades. Table 1 presents a summary of five studies on theoretical or actual sugar mills where the total HP or exhaust steam consumption per unit throughput was calculated. Some of the main design features of each simulation are reported in the table. However, these are just a few of the many design decisions that would have been made to achieve the calculated energy consumption values.

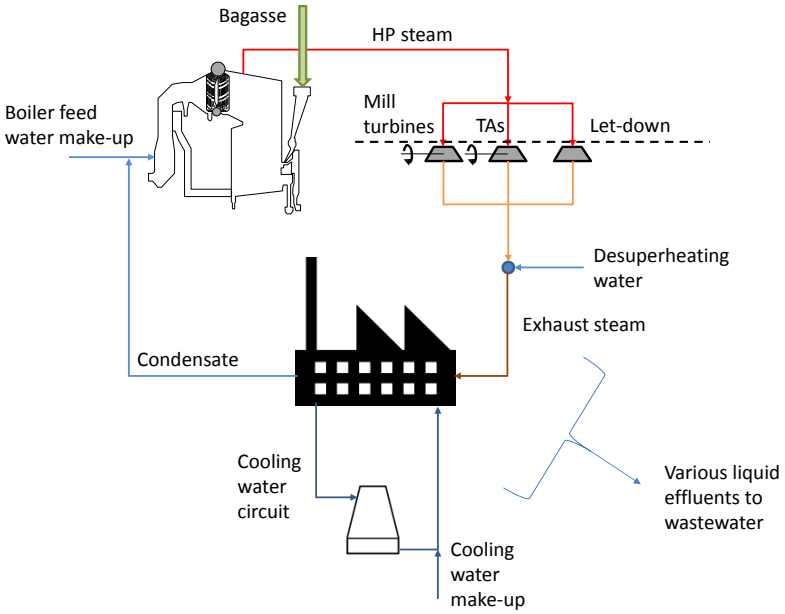

Figure 1: Typical steam circuit for a sugar factory

Table 1: Summary of a selection of studies predicting steam consumption in actual and simulated sugar mills

Authors	Evaporator config-uration	Lowest grade vapour reused	Highest boiler pressure (MPa (g))	Turbines	Electri-fication of shredder and mill drives	Additional energy efficient technology	Additional steam demand	t HP steam/ 100 t cane	t exhaust steam/ 100 t cane
Reid and Rein (1983)	5- effects	V1	3.1	Back-pressure	No			53.1	
	5- effects	V2	3.1	Back-pressure	No			48.0	
	6- effects	V2	3.1	Back-pressure	No			46.9	
	5- effects	V2	3.1	Back-pressure	No	Thermocompression of vapour bleeds		46.5	
	5- effects	V2	3.1	Back-pressure	No	Mechanical vapour recompression		44.7	
Singh *et al.* (1997)	4-effects	V3	3.1	Back-pressure	No		Refinery	54.2	
Peacock and Cole (2009)	4-effects (plus flash vessel)	V4	8.6	Condensing and back-pressure turbines	Yes	4^{th} effect at 35 kPa	Significant power export		38
	5-effects	V3	3.1	Condensing and back-pressure turbines	Yes		Significant power export		41
Lavarack *et al.* (2004)	6- effects	V4	6.5	Condensing and back-pressure turbines	Yes	Heat preservation and recovery from condensates			39.2
Broadfoot (2001)	5-effect	V5	not specified	not specified	not specified	Process water substituted with clear juice			33

The overall factory design will likely have the largest impact on specific energy consumption over the entire factory; to change the overall energy balance requires a large amount of redesign work and capital investment. The plethora of energy balance designs suggests that the construction of a generic monitoring system and specifically the development of benchmark indices for energy consumption will have many challenges.

Operational factors influencing energy and fuel use

The following factors were reported as commonly encountered in factories, contributing to energy consumption, or fuel consumption, in excess of that required for efficient processing:

- Excessive water addition
    - High imbibition application rates (Peacock and Cole, 2009; Reid, 2006)
    - Use of wash water, pan movement water and tank make-up water (Allan, 1985; Reid, 2006; Rein, 2007)
    - Poor remelter or blow-up tank brix control (S Peacock, personal communication)
    - Poor dryer cyclone water management resulting in high sweet water volumes, encouraging high water addition rates (S Peacock and S Davis, personal communication)
- Increased recycle in the factory
    - Poor exhaustion, especially in the A-pans (Rein, 2007)
    - High volumes of rejected sugar returned to process
- Inadequate removal of water
    - Low syrup brix (Rein, 2007)
    - Poor dewatering mills operation (Reid, 2006)
- Inefficient operation
    - Poor overall time efficiency (OTE) (Reid and Rein, 1983; Damms, 1986; Wienese, 1998; Rein, 2007; Foxon, 2014)
    - Use of steam or vapour at a higher grade than designed for (Rein, 2007)
    - Unsteady operation, resulting in fluctuations in steam pressure, increasing the incidence of steam (or vapour) let-down and blow-off (Reid, 2006)
    - Excessive mixed juice heating resulting in high energy losses during flashing (Rein, 2007)
    - Leaking steam traps (Damms, 1986; Singh, 2001; Merle, 2001)
    - Poor insulation (Brahim *et al.*, 2015)
- Poor condensate management
    - Low boiler feed water temperature, high boiler feed make-up, or elevated blowdown levels from boilers due to inefficient operation or poor make-up water quality
- Low boiler efficiency (Reid, 2006; Rein, 2007)
    - Excessive air flow resulting in high excess oxygen
    - Poor fuel distribution resulting in high unburned carbon in ash
    - Excessive blowdown resulting in excess boiler feed water makeup

In addition to these factors, there are conditions outside of the factory's control that will affect energy consumption, such as cane moisture and fibre content and cane supply.

Energy monitoring

All South African sugar milling companies have internal systems for the calculation of energy consumption; some companies also calculate indices for monitoring energy use. However, there are relatively few studies around energy monitoring published at the South

African Sugar Technologists' Association (SASTA) Congress and other fora. Previous studies have highlighted the following key success factors for energy management projects involving a level of energy consumption monitoring:

- Buy-in of staff at management and operator level (Damms, 1986; Singh, 2001);
- Reliable measurement of energy flows (Damms, 1986; Singh, 2001);
- Measurements focused on energy sensitive processes (Singh, 2001);
- Measurement and control of movement and wash water streams (Damms, 1986);
- Focus on boiler efficiency (Damms, 1986);
- Focus on factors that can be controlled within the factory (Mann, 1988);
- Focus on continuous improvement by identifying opportunities for energy use reduction (Webb and Koster, 1991; Mann, 1988).
- Reporting at appropriate time intervals (daily reports assist in monitoring the process, but weekly reports provided better data for supporting decisions for process improvements, Damms, 1986)

Studies reported the following challenges with energy monitoring:

- Difficulty in obtaining reliable steam measurement (Damms, 1986);
- Linking energy consumption problems to the cause (Damms, 1986; Stolz, 2014); and
- Establishment of meaningful benchmarks (Singh, 2001; Stolz, 2014).

These learnings provide a useful starting point for establishing a monitoring system and should be included in the methodology and implementation of such a system.

Measurement of energy flows

Damms (1986) reported that reliable flow rates of HP steam would greatly assist in the determination of energy use, but regular, accurate measurements of HP steam flow and boiler efficiencies were difficult.

Allan (1985) prepared a report on instrumentation for monitoring steam flow at the then Ubombo Ranches Limited mill. The instrumentation was intended to assist the mill in establishing a steam audit for assisting in energy management. This report recommended types and locations of measuring equipment. The author commented on the ubiquitous challenges associated with multiple parallel water and steam lines coming from and feeding the boilers, requiring many different measurements to get one value for monitoring purposes. He also noted that most flow meters required a straight run of pipe with sufficient length relative to the pipe diameter to give accurate measurements, and that suitable pipe runs in the factory were not always available.

While these and other authors have made reference to energy measurement issues, these tend to be handled on an *ad hoc* basis by individual factories and are not made the subject of general publications.

Benchmarking energy use

In current mill operations, there are a variety of indices used to monitor energy consumption, including GJ/tonne sugar produced, GJ/tonne cane crushed, HP steam % cane and exhaust steam % cane. However, there are no widely accepted benchmarks for good performance in terms of these indices. Table 2 presents a list of different measures and indices listed in published studies, ordered by reference.

Table 2: Parameters measured or calculated in published energy monitoring studies for raw sugar factories

<table>
<tr><th colspan="2">Damms (1986)</th><th>Mann (1988)</th><th>ICEN (as reported by Wienese, 1998)</th><th>Wienese (1998)</th></tr>
<tr>
<td><u>Overall indicators</u>
Tonnes cane crushed
Tonnes coal burned
TJ[2] in fuel burned
Tonnes brix to process
Tonnes brix/TJ in fuel (target and actual)
HP steam % cane

<u>Factory performance</u>
TJ used in production
OTE[3]
Tonnes brix in MJ[4]/TJ used
Tonnes brix/MWh generated

<u>Milling Department</u>
Bagasse moisture content

<u>Boiler operation</u>
The author indicated that the second half of the daily energy report was dedicated to boilers and steam flow.</td>
<td><u>Process department</u>
Imbibition % fibre
kg water/tonne brix in MJ in:
• Draught juice
• Press water mud
• MJ
• Filter wash
• Sump returns CJ[5]
• CJ make up
• Total CJ to evaporators
• Evaporator syrup
• Hot water makeup
• Sweet water makeup

kg water/m^3 raw massecuite in:
• Raw pan movement water
• A centrifugal wash
• B&C centrifugal wash

Tonnes rejects remelted</td>
<td><u>Boiler Station</u>
Excess O_2
Unburned carbon % ash
Coal burned

<u>Extraction</u>
Imbibition % fibre

<u>Raw House</u>
Evaporator makeup
Syrup brix
Filtrate brix
Movement water
Blow up brix (A and B)
Remelt brix
Sweetwater brix</td>
<td>Fibre % cane
Imbibition % fibre
Moisture % bagasse
Ash % bagasse
Prime mover steam % cane
Exhaust steam% cane
Vapour bleed % exhaust steam
Filter wash water % MJ
Brix % syrup
Boiler efficiency %
HP steam % bagasse
fuel energy/unit electricity
Electrical power/cane (kWh/tonne)
Prime mover power/cane
OTE</td>
<td>OTE
Boiler efficiency
HP steam on power (t/MWh or kJ/MWh)
Raw house exhaust steam/cane (%)
Refinery exhaust steam/sugar (%)
Kinoshita (1999)
Cane
Fibre % cane
Boiler bagasse
Electricity generated
Electricity consumed
Electricity exported
Exported bagasse
Imported fuel
Exported steam
Imported steam
Steam generation pressure

Gross power generation: cane processed
HP steam consumed: cane processed
Imported fuels % bagasse produced
Net power generation: Cane fibre</td>
</tr>
</table>

[2] TJ: 1 Terrajoule is 10^{12} J or 10^6 MJ
[3] Overall time efficiency
[4] MJ: mixed juice
[5] CJ: clear juice (evaporator supply juice)

Table 2 *cont.*

Singh (2001) and Singh (2008)				Stolz (2014)
Extraction plant Tonnes cane crushed Capacity index OTE Fibre % cane Ash % cane Extraction % Imbibition % fibre in bagasse moisture % bagasse Brix % MJ MJ % cane Lost time % available Filter wash index **Juice preparation** MJ % Cane MJ - CJ brix %	**Evaporators** Exhaust steam pressure Exhaust steam temperature V1 pressure V2 pressure V3 pressure V4 pressure Evaporator Efficiency Brix % syrup Exhaust condensate flow Raw water temperature **Raw sugar** A massecuite exhaustion B massecuite exhaustion Brix % remelt Brix % A molasses Brix % B molasses CJ % A and B massecuite Total volume massecuite per tonne Brix in MJ Movement water % massecuite	**Bagasse** Tonnes bagasse Ash % bagasse Tonnes bagasse/h Bagasse export Moisture % bagasse Tonnes coal Bagasse store level Bagasse imports Bagasse LCV[6] Crushing hours **Steam Produced** Boiler run time Water flow Steam produced Boiler efficiency **Steam consumption** Steam through desuperheater Mill turbine steam ID[7] fan turbine steam flow Deaerator steam flow Total exhaust steam flow	**Power generation** Power exported Power imported **Boiler feedwater** Softener makeup Exhaust condensate Boiler feed temperature Other utilities Auxiliary water flows Return/waste water flows **Performance indicators** HP steam % cane HP steam/coal Alternator steam/electricity generated HP steam/sugar made Coal/cane Let down steam % HP steam	Energy input/tonne cane Energy input/tonne crystal HP steam % cane (excluding refinery) Total HP steam % cane OTE

[6] LCV = lower calorific value
[7] ID: Induced draft

Damms (1986) used a historical best performance philosophy in selecting energy use targets. He reasoned that "*if it has been achieved once, it should be possible to improve upon or at least repeat*". Singh (2001) reported that a Malalane Mill energy management project used benchmarks calculated from plant design data and historical performance.

Singh (2001) presented a concise and insightful assessment of factors affecting benchmarking between factories. Steam % cane, specifically HP steam/100 t cane processed, is by far the most common measure of energy use, but it is only regarded as meaningful for inter-factory comparison when the cane quality is similar and the factories have similar configurations. In particular, he pointed out that the fibre content of the cane would have a significant influence on the energy content of the bagasse and the amount of steam that could be raised per tonne of cane.

Kinoshita (1999) proposed a universal energy index *net power generation: cane fibre rate* in an attempt to provide a unified basis for comparing sugar factories, specifically with the objective of maximising energy generation from cane fibre for co-generation. This index proposes a means of comparing energy generation within a raw factory that compensates for supplementary fuels, bagasse, steam, vapour and electricity transfers so that the energy use for making raw sugar from a specific fibre input rate can be calculated, regardless of what else is happening in the factory. The proposed approach converts all energy inputs and outputs, including energy supplied to refineries, distilleries or other downstream processing, into units of electrical energy. The authors indicate that one of the following two measures must be used to calculate the electric energy equivalence of the fuel:

- The bagasse-to-electricity conversion ratio of the installed factory equipment at full load, i.e. the total electric power generation rate at full load (kW) divided by the total fuel consumption rate in bagasse equivalents (t bagasse/h). This is effectively a design value; and
- The heat rate (kWh/MJ) combined with the bagasse heating value (MJ/kg). This is a measured value.

Singh (2001) commented that the usefulness of the *net power generation: cane fibre rate* for benchmarking was limited by the fact that no South African factories were calculating it. It also does not, in its recommended form, make any allowance for import or export of brix-bearing streams other than bagasse, molasses and raw sugar or variations in raw sugar quality.

Wienese (1998) described *inter alia* an index comparing HP steam production to power output as a measure of the efficiency of power production from HP steam. Wienese indicates that this could be calculated as follows:

$$\frac{\text{Energy}_{\text{HP steam}} - \text{Energy}_{\text{exhaust steam required for process}}}{\text{Electrical power output from turbines}} \ (kJ/MWh)$$

This quantity is equivalent to the inverse of the combined turbine efficiencies, taking the let-down steam into consideration.

Stolz (2014) calculated energy targets for an energy dashboard based on the crush budget for the milling week and a mass and energy balance of the sugar factory, and the crushing conditions obtained for the same week in the previous season. This approach provided a dynamic target prediction based on the expected cane throughput and quality, but proved to be cumbersome to update when the crush budget changed.

These and other studies suggest a range of measures and indices for reporting and benchmarking energy use. These may both be further sub-divided into three types:

1) Contributing factors – factors known to influence energy consumption negatively;
2) Factory specific absolute energy consumption – absolute measures of masses, flows or amounts that can be translated directly to a rand value for a specific mill (e.g. tonnes coal burned, kWh electricity exported); and
3) Intensity factors – indices representing relative energy use, i.e. calculated as consumption per unit input or output (e.g. steam % cane, MJ/tonne sugar produced, OTE).

Although some of the benchmark factors or indices were common across several studies, no unique and complete set of indicators emerged from the review.

The studies presented in Table 2 may be roughly divided into those presenting monitoring and reporting strategies (Damms, 1986; Mann, 1988; Singh, 2001; Singh, 2008; Stolz, 2014), and those proposing energy indices for inter-factory benchmarking (ICEN, as reported by Wienese, 1998, Wienese, 1998; Kinoshita, 1999). Within the former set, the list includes both measured variables and calculated performance indicators.

Table 3 presents a list of the variables, or equivalent variants thereof, that stand out as common between the different studies. The second column of Table 3 shows a list of calculated or recorded performance indicators that have been used in a variety of ratios to provide overarching performance metrics.

Table 3: Process measures and performance metrics for energy monitoring

Commonly measured, calculated or inferred process and operating variables impacting on energy consumption	**Components of commonly reported performance metrics** (indices may be calculated from ratios of any one of these measures to any other of the measures)
Stream flow rates	Cane, brix and fibre throughput
Brix concentrations	Raw sugar output
Massecuite volumes	Additional fuel burned
Overall time efficiency	HP steam produced
Imbibition	Electrical power produced
Water addition to the process	Steam consumed by prime movers
Excess O_2 in flue gases	Exhaust steam consumed by process
Unburned carbon in ash	Fuel, steam or electricity exported
Water stream temperatures	Fuel, steam or electricity imported

Advanced monitoring and control systems

Avram-Waganoff *et al.* (2006) used a consistent on-line mass and energy balance model into which on-line and laboratory measurements were fed, providing an overall consistent insight

into the status of the entire factory. The system required approximately 100 process parameters to estimate the condition of the factory, and the rest were estimated by the simulation. The approach of integrating all data into a single predictive system with data reconciliation constitutes the state of the art for process monitoring. In factories where limited energy monitoring data are reported, this may be an ambitious target for the near future, but could be both feasible and extremely useful if sufficient energy flow data were available.

Literature from other industries

There is an international trend towards global industrial energy efficiency benchmarking but most industries face the same challenges as the sugar industry around diversity of plant design, differences in product portfolio and differences related to geography and socio-political context. As a result, a number of techniques for benchmarking performance in dissimilar systems have been developed.

The combined literature on industrial energy monitoring and benchmarking is massive. Much of the literature is concerned with international and regional benchmarking of energy performance for specific industries on a macro-indicator level (Phylipsen *et al.*, 2002). The key performance indicators (KPI) of energy efficiency are relationships between an activity and the amount of energy consumed in that activity. These are typically reported as aggregated physical or economic values associated with the production process, such as unit mass of output product or economic output (turnover, value of product etc.). These can be variously defined as specific energy consumption (SEC, in energy per mass of output or input) and energy intensity (EI, energy per unit economic output) (Bunse *et al.*, 2011). Phylipsen *et al.* (2002) propose an energy efficiency index which is the ratio of the SEC for a facility to the best-in-class SEC for an industry with a sufficiently similar process.

Bunse *et al.* (2011) reviewed some of the challenges with macro-level benchmarking and identified the need to integrate energy efficiency management with production management. The following tools were found to be useful in implementing energy management systems (Bunse *et al.*, 2011):

- Energy audit programmes account for energy use across a facility at a particular time. These are useful for identifying improvement opportunities;
- Energy balance sheets provide a breakdown of energy use at an appropriate process level at discrete time steps or in near-real time, depending on the available instrumentation; and
- Integrated monitoring systems based on a plant-wide model. This is the same concept as presented by Avram-Waganoff *et al.* (2006) for sugarcane processing where a model of the facility is built and interfaces with real-time or near real-time process and energy monitoring data. This type of system aims to overcome the challenges associated with collecting and interpreting sparse data in a system where energy demands are constantly changing in response to both identifiable discrete events, such as a machine coming on or off line, and facility wide energy draws, including lighting and ventilation (Arinez *et al.*, 2010).

Despite the availability of a number of tools and standards for energy monitoring and benchmarking, Bunse *et al.* (2011) found that most industries lacked standardised energy efficiency KPIs at machine, process and plant level. Even where these exist, many industry representatives expressed a need for conceptual frameworks for performance evaluation to

ensure that information on energy consumption collected could be translated into knowledge leading to improved energy efficiency.

Several publications in recent years have attempted to provide methodologies for developing SEC benchmarks at a machine or process level. A selection is listed below:

Benchmarking to best-in-class

- The most widely known best-in-class benchmarking system is the Energy Star® programme, which includes a range of tools to build an energy programme, monitor energy use, benchmark against peers and obtain recognition from customers through product labelling (Energy Star, n.d.).
- The Solomon benchmarking system (Solomon Associates, n.d.) provides subscribers with KPIs across production facilities and normalises these across plant types, sizes and geographies so that individual plants can compare their performance to a large range of other facilities, irrespective of differences in capacity. The methodology of this system is proprietary. It is best known for benchmarking in the petrochemical refining industry (He, 2015).

Benchmarking to best-in-class for all industries carries the same challenge as it does in the sugar processing industry, i.e. factories engaged in the same general activity may have different capacity, equipment, product specifications, feedstock and configuration, all of which influence the specific energy consumption of the factory. The Energy Star® programme has developed a methodology to calculate an energy performance indicator that attempts to answer the question: *"How would my plant compare to everyone else in my industry, if all other plants were similar to mine?"* (Boyd *et al.*, 2008). The approach is based on *stochastic frontier analysis* (SFA), a technique used in economic modelling. This technique was developed for the analysis of system efficiency where deviations from the theoretical minimum efficiency might not be entirely within the control of the entity being evaluated (Greene, 2008). SFA identifies the theoretical minimum *cost function* that can be incurred in a system which has the same type of features as other systems, but where the features are similar rather than identical, by determining the contribution of those features to the total cost. Thus the minimum cost function for a particular system, its benchmark, depends on the features of the system, not just the overall inputs and outputs.

Benchmarking to an optimised best case

Yang *et al.* (2016) describe an algorithm for optimising energy use in a chemical process. The algorithm calculates the energy consumption for a series of process configuration scenarios and updates the benchmark value to be the lowest energy consumption of any of the scenarios simulated. This approach provides the theoretical minimum energy consumption for specified process objectives based on a steady state simulation. This study did not consider application of the approach to continuous monitoring or derivation of benchmark values from real measurements.

Benchmarking to a theoretical ideal case

Pitis *et al.* (2014) observed that the use of a best-in-class reference for benchmarking has the limitation that whenever the best-in-class gets better, the reference values must be updated and all performance values for all subscribers to the benchmarking system must then also be updated. This may be a significant effort and also means that the interpretation of performance relative to the reference changes with time. This can be described using an analogy in sugar technology processing performance: a factory that consistently achieves the

same extraction from one year to the next would have their performance index change for the worse because improvements at another factory had improved the benchmark value[8].

Pitis *et al.* (2014) proposed a method of energy benchmarking based on a theoretical minimum energy consumption calculated from the physics of the process called the *theoretical energy* or E_{ideal}. The difference between this and the actual energy consumption was called *energy at risk* or E@R. By definition, the benchmark value could never be achieved, but systematic improvements in performance can be tracked. Loubser (personal communication[9]) proposed a similar approach for benchmarking sugarcane processes using a value chain concept where energy consumption in a unit is normalised against an ideal energy for the unit.

Benchmarking case study

Laurijssen *et al.* (2013) undertook a study on 23 paper mills in the Netherlands, where the authors attempted to determine specific energy consumption (SEC, energy consumption per unit product made) at a process unit level in order to establish benchmarks for energy use targets. They found that only a few of the processes within a typical paper production facility had SEC values within a range narrow enough for the definition of benchmarks. Most processes showed wide variability in SEC between paper mills and there was evidence that SEC trade-offs between different units in the same mill exist. The same will be true in sugar factories. This study demonstrates the limitation of using simple efficiencies for indexing performance at a process unit level and provides a strong motivation for using a best-in-class benchmarking approach based on SFA or similar dependency modelling.

Synthesis of the literature review

The sugarcane processing literature review demonstrates that there is a wealth of information, knowledge and wisdom relating to energy management available in the industry. It is clear that the installed plant design plays a large role in determining the overall energy demand of the factory; to change this requires large capital investment and may also carry a high degree of technical risk. It has also been shown that there are several controllable operating parameters that are known to contribute to poor energy efficiency and that these can be managed if appropriate data are available and the necessary focus applied.

Several of these studies further indicated that the reliable measurement of steam flows was a major challenge that would need to be overcome to achieve the full potential of an energy monitoring system.

None of the monitoring systems described were capable of connecting specific practices or events to overall factory energy consumption performance, but rather relied on the technical insight of factory staff to interpret the figures obtained. Similarly, none of the monitoring programmes, which, to be fair, were designed for *in factory* control, produced energy consumption data that could be directly compared to other factories. Finally, Damms (1986)

[8] While this is a valid complaint, there is definitely an argument for accepting a changing benchmark value; presumably a factory that monitors and improves energy performance would want to be aware of improvements in the state-of-the-art and how they perform relative to the new benchmark.

[9] Loubser RC, Foxon KM, Hocking GC, Gibson E, Mitchell, S, (submitted). The process energy value chain. Submitted to the XXIX ISSCT Congress 2016. Chiang Mai.

commented that the usefulness of the monitoring system would be significantly enhanced if it could quantitatively indicate causes of high energy usage.

The review of energy monitoring and benchmarking for other industries, albeit rather superficial, shows that there are a number of different ways of constructing a benchmarking system, each with its own pros and cons. All require reliable data for energy consumption. Many authors comment on the challenges of obtaining sufficient and accurate data with which to calculate meaningful benchmarks and point to the importance of standardisation of measurement and reporting across plants for benchmarks to have a meaning outside of the factory in which they were calculated.

While a complete and consistent energy balance sheet for energy consumption at process unit level would be useful, the additional instrumentation required would be massive with a highly debatable return on investment. Thus an important principle identified by several sugar technology authors either explicitly or implicitly is that monitoring efforts should focus on points in the factory where controllable waste of energy is likely to occur, thereby improving the return on investment. Furthermore, by combining these critical measurements with a mass and energy balance model and any existing distributed control system (DCS) and Laboratory Information Management System (LIMS) data, it may be possible to eventually implement a plant-wide energy balance calculator that is sufficiently precise to be used for monitoring and control.

Both the sugar and wider industrial literature indicate that the right people should receive the right information if an energy monitoring system is to bring positive benefits in terms of overall plant sustainability. Thus the design of the reporting system is of paramount importance. This leads to the second important principle for designing an energy monitoring system: information on energy use should be made available to the individuals who are responsible for the decisions that influence energy consumption.

Clearly there is no *right way* to monitor and benchmark energy consumption. There must be a series of assumptions and choices that lead to a universally accepted and useful system. Probably the single most important factor that will influence the success of a sugar industry-wide system is the buy-in of stakeholders at a mill and sugar company level.

Progress of the STEP-Bio energy monitoring project

In 2015 and 2016, researchers from the SMRI approached a selection of South African sugar mills to become involved in this project. No results can be reported yet, but the following observations have been made:

- The mills have demonstrated an overwhelming willingness to get involved and have all supported the concept that effective monitoring, reporting and benchmarking of energy alongside process measures will assist in reducing costs of operation;
- The amount, type and location of instrumentation vary enormously between different factories. Some factories have a large number of measurement points linked to a DCS, while others have discrete control and measurement points. All factories have some instrumentation that is not connected to the central data management system at all. Apart from the standardised LIMS that contain some data relevant to energy management, each factory visited has had a different software platform for the management of online process data;

- While factories have a reasonable idea of their overall energy consumption, the explanations for changes in performance may differ between personnel. It is believed that this is a function of the distributed and often limited nature of the information on energy performance, which makes it difficult for any one person to have a broad overview of the situation;
- The accuracy or availability of measures for overall supplementary fuel consumption (where relevant) is influenced by the reason for needing to burn coal. Where bagasse is sold to a third party or downstream processing, the measurement is more detailed than when additional fuel is required to power internal demand;
- Accurate measures of total HP and exhaust steam supplied to the factory are not easily determined;
- In all factories, the steam and water supply lines are often complex networks of piping with sections in series and parallel. It can be difficult to identify suitable locations for instrumentation in these networks; and
- Start-up, stops, boil-off and other operations outside of continuous crushing are characterised by significant energy usage, often without the production of bagasse. These can consume a large amount of supplementary fuel and are believed to have a significant impact on the energy performance of a factory over the whole season.

To date, the team has established boundaries for sections of the factory that are to be monitored as subsets of the whole factory. A trial methodology for developing an energy monitoring system has been proposed. Two interns will spend the entire 2016/17 crushing season obtaining measurements of energy consumption in candidate factories in South Africa.

The researchers at the SMRI and Stellenbosch University are applying the learnings from the literature review and preliminary factory work to identify strategies for selecting new measurement points, for collecting and processing data, for defining section indices and for combining section indices into an overall factory index, such that intra- and inter-factory benchmarking can be realised.

Conclusions

This paper has reviewed literature from the sugar processing industry and other industrial and academic studies on energy monitoring and benchmarking. The main conclusions of this review are:

- Currently there is no agreed best practice for energy monitoring, reporting and benchmarking in the sugar industry;
- Individual mills and companies may have internal systems for managing energy consumption, but these do not yet allow inter-factory benchmarking and do not directly indicate the source of high energy consumption;
- There are significant challenges associated with collecting data for comprehensive energy monitoring, including the large number of measurements required and the difficulties of obtaining accurate measurements of these values;
- Monitoring should target those areas of the factory where *controllable* factors are known to lead to poor energy efficiency;
- Monitoring and benchmarking results should be reported such that the people who have the responsibility and ability to influence the way in which energy is used receive the monitoring information in a form that supports decision making; and

- Existing benchmarking methodologies each have drawbacks; benchmarking against best-in-class will cause the benchmark value to change as improvements are realised across an industry, leading to a changing basis for interpretation of the index, and recalculation by all factories subscribed to the system when the benchmark changes. Benchmarking against some absolute value requires assumptions and definitions about what constitutes the absolute benchmark.

A universal methodology for monitoring and benchmarking will need to be selected from the available candidates combined with an understanding of what process variables can be effectively monitored. The success of the system in terms of its usefulness for benchmarking and supporting energy management projects will be determined largely by the commitment and buy-in of stakeholders within the sugar industry.

The research team has begun collecting energy consumption data in South African sugar factories. They will progress to testing strategies and algorithms for calculating benchmarking indices for section and plant-level intra- and inter-factory benchmarking.

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