REFEREED PAPER

MODELLING STEAM SYSTEMS TO EVALUATE ENERGY OPTIMISATION OPPORTUNITIES TO SAVE COAL AND EXPORT ELECTRICITY

PARKIN JB

Gledhow Sugar Mill, PO Box 55, KwaDukuza, 4450, South Africa
Now at Illovo Sugar Limited, Maragra Mill, Mozambique
bparkin@illovo.co.za

Abstract

The increasing cost of coal and the opportunity to export electricity has caused many sugar factories to review the energy efficiency of their operations. The optimisation of the steam system can benefit factories that burn coal or other fuels by reducing their fuel bill. Factories considering generating surplus electricity for export or to support estate agricultural operations such as irrigation, often need to evaluate projects to improve steam economy and predict electrical energy that can be generated using available bagasse.

The development of an accurate and reliable model of the thermodynamic behaviour of the steam system of a sugar factory is a logical starting point for this analysis. This paper describes how an energy, mass and economic model can be built for the steam system of a sugar factory using freely available software that can be downloaded from the internet. This software, called SSAT, is capable of modelling the steam system of the sugar mill, including boilers, turbines, deaerator and steam distribution system, as well as steam end use and condensate recovery. Once the base case has been modelled, the energy and economic impact of projects to improve energy efficiency of the factory can be evaluated.

A case study demonstrating how SSAT is used to evaluate energy improvement projects such as boiler efficiency improvements and the replacement of turbine drives on mills with electric motors, is presented.

Keywords: energy efficiency, steam, boilers, turbines, co-generation, software, modelling

Introduction

As reported by Loubser (2004), there are many software products available on the market for solving heat and mass balance problems. The majority of these products are relatively expensive and require specialist training and knowledge of the software to build meaningful mathematical models to describe the behaviour of a steam system in a sugar factory. The cost of the software and associated requirements for skilled model building takes the purchase and use of this software beyond the reach of typical factory personnel and many consultants tasked with optimising the performance of sugar factories. Also, most software developed with the purpose of modelling juice and sugar flows often the lacks ability to model boiler, turbine and steam system behaviour. This means that spreadsheet or hand calculations are required to provide data input into certain software packages.

User-developed spreadsheets are a popular alternative to purchased software; however, developing an energy and mass balance spreadsheet is a difficult and complicated task. An approach to a user-developed spreadsheet-based solution is described by Hoekstra (2000). The task of user-developed energy and mass balance spreadsheets is complicated because many of the equations describing the thermodynamic behaviour of water and steam are non-linear. The thermodynamic properties of steam and water (specific mass, enthalpy and entropy) are estimated by equation fitting, or are looked up and entered manually as inputs into the spreadsheet. This necessitates an iterative process to be followed to achieve results with acceptable accuracy. Analysis of a steam system that includes turbines adds another dimension of complexity, because steam changes from a superheated vapour to a saturated mixture of vapour and liquid as energy is extracted and converted into shaft power.

User-developed spreadsheets are usually not only specific to a particular factory, but are best used only by the person who developed the spreadsheet, since he/she is the only person who understands how the spreadsheet works and its limitations. Also, depending on the skill of the person who developed the spreadsheet, the spreadsheet solutions may vary in accuracy.

Pinch analysis and the steam system assessment tool (SSAT)

Pinch analysis is a systematic method of analysis for achieving energy savings. This is done by calculating thermodynamically feasible energy targets and achieving them by optimising heat recovery systems, energy supply methods and process operating conditions[(1)].

The techniques were first developed by Bodo Linnhoff at the University of Leeds in the late 1970s. Linnhoff went on to set up a consultation firm known as Linnhoff March International, which developed a software tool called ‘Pro-Steam’ which is a commercially available Excel spreadsheet-based product that performs pinch analysis on steam and utility systems.

As part of the drive toward energy efficiency in the United States, the Steam System Assessment Tool (SSAT) was developed for the US Department of Energy, under contract with the Oak Ridge National Laboratory, by Linnhoff March and others[(2)]. This software is a reduced version of Pro-Steam and was developed to make analysis of steam systems accessible to the general user in industry. SSAT is a spreadsheet-based software tool that is freely available to download from the Advanced Manufacturing Office website hosted by the US Department of Energy[(3)]. The steam system model produced by SSAT is not only an energy and mass balance, but is also an economic model of the system which calculates marginal cost of steam at each header pressure, cost of generating power from turbines and annualised fuel and water costs.

The South African Industrial Energy Efficiency project is an initiative of the South African Government (Department of Energy) and various international sponsors. The project is hosted by the National Cleaner Production Centre (NCPC), which is a division of the Council for Scientific and Industrial Research (CSIR) and is supported by the United Nations Industrial Development Organisation (UNIDO). The goal of this project is to equip industry with the skills and tools to optimise energy efficiency.

---

[1] Definition of Pinch Analysis, http://en.wikipedia.org/wiki/Pinch_analysis
[2] US Department of Energy, Steam System Assessment Tool Version 3 User guide, https://www1.eere.energy.gov/manufacturing/tech_deployment/pdfs/ssat_user_manual.pdf
[3] SSAT download site: https://www1.eere.energy.gov/manufacturing/tech_deployment/software_ssat.html

The steam system optimisation module of the Industrial Energy Efficiency project includes training on the SSAT. Although it is possible to download and use SSAT without training, the training offered by NCPC is very reasonably priced and is a useful refresher on steam system thermodynamics and practical steam system optimisation that includes instruction and coaching on the use of SSAT and other software tools used to analyse and optimise steam systems. NCPC also runs Expert Level courses on Steam Systems – which takes the theory into the plant and trains candidates to use the software tools together with portable instrumentation to analyse steam systems in practise and identify optimisation opportunities.

Using SSAT

Since SSAT does not include the same flexibility as Pro-Steam, it does have some limitations. Nevertheless, it can be used to model any steam system for the purpose of steam system optimisation. Since SSAT steam system models are very quick and easy to build, complex steam systems can be modelled by developing a number of individual models and averaging or combining the results of each sub-model to describe the overall system.

Figure 1 shows that analysis can be done in metric or imperial units and the user is presented with the choice of modelling a one, two or three header steam system. Steam systems with more than three header pressures can be modelled as a sequence of independent models, however this is rarely necessary. The steam system of a typical sugar factory can be modelled as a two header system – with the two headers being the high pressure header (31 barg) and the exhaust steam header (1 barg). Some factories operate a medium pressure header (17 barg) and this can be modelled using the three header model.

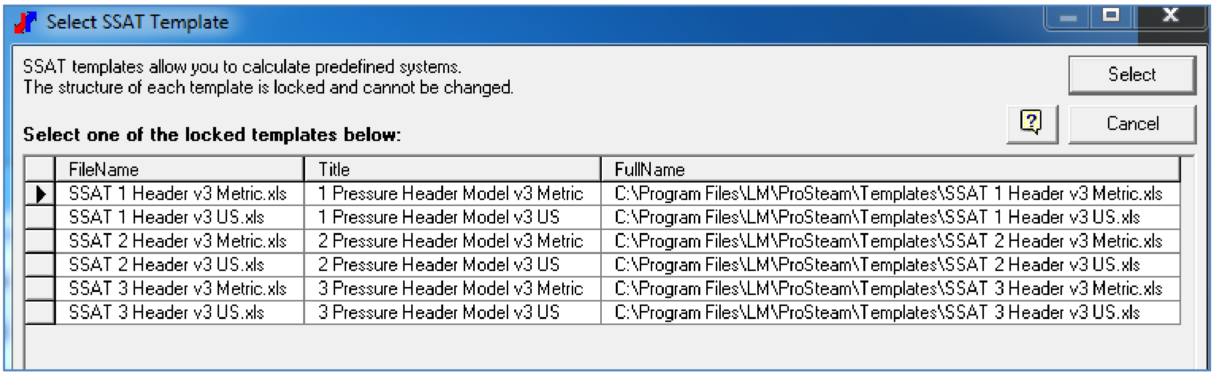

Figure 1. Steam system assessment tool (SSAT) template selection table.

Once the choice of number of headers to be modelled and units has been made, the software tool opens as a seven worksheet Excel spreadsheet.

The first sheet is the input sheet, into which the various inputs required to build the model are entered. The second sheet is a graphical representation of the model and includes displays of the temperature and mass flows of each stream in the model. The first and second sheets describe the steam system as it currently exists.

The third sheet is the Projects Input sheet which allows the user to model the influence of various efficiency improvement projects. The fourth sheet is a graphical representation of the system after the optimisation projects have been applied. The fifth sheet is a results sheet that provides an economic summary of both the base case and the system after projects have been applied. The sixth sheet is a boiler efficiency calculation utility. With the fuel and flue gas temperature and oxygen as inputs, in-built combustion models return a calculated value for stack losses. The last sheet is the only sheet that is not protected and is a blank sheet that can be used for the modeller's notes and calculations.

The approach taken in modelling in SSAT is to model the entire steam system so that interactions between different components of the system are accounted for. The entire system includes the steam generating plant (i.e. boilers), the steam distribution system including steam turbines and pressure reducing stations, the end use of steam (i.e. that part of the plant where steam is condensed) and the condensate recovery system which includes the de-aerator as well as the feed water make-up.

The software that drives SSAT includes built in sub-routines that perform multiple iterations until the solution to the mass and energy flow calculations is converged upon.

The SSAT software employs a template of a steam system with all possible components built in. Selections are made on the inputs sheet of SSAT to choose whether each component of the system exists in the system being modelled, and how each component is operated. In this way, SSAT is capable of modelling any steam system. Since SSAT uses protected worksheets into which the user inputs data in response to various questions, an energy and mass balance of a steam system can be developed within a few minutes without having to look up any thermodynamic properties of steam or water.

Building a model in SSAT

When SSAT is launched, it opens with a fully populated model of a of a steam system. All values that define the steam system are the 'default' values, and the user is required to replace the default values with values that are specific to the steam system at the site applicable to the user.

The data entry form of SSAT is split into two sections. 'Quick Start' enables entry of a minimum amount of information about the site before starting to model the system. The 'Site Detail' section includes more detailed information to refine the accuracy of the model created. The information required for the Quick Start section is information which is usually known to the steam system operator, and includes:

- Site electric power usage (which is negative when the site exports power) and site power cost.
- Operating hours – this is useful if multiple models are done to represent different operating conditions at different times of the year.
- Make-up water – cost and temperature.
- Boiler fuel – SSAT was developed for the United States market and therefore includes the specifications of several fuels commonly encountered in the USA. However, there is a facility to specify a 'User Defined' fuel, where bagasse may be modelled as a user-defined fuel. All that is required to specify a user defined fuel is knowledge of its GCV (higher heating value, US terminology), and its cost per GJ.
- The steam distribution is described by specifying the header pressure at each of the headers and the steam usage at each header pressure. In the case of a typical sugar factory, steam used at the high pressure header (31 barg) is usually zero, since it is rare for steam to be condensed directly from 31 barg without first going through an intermediate header pressure or turbine. The steam use at the low pressure header is the

quantity of exhaust steam condensed in the raw house. The steam consumption by the raw house can be calculated by performing a balance across juice heaters and evaporators. Since it is common practice to measure the steam flow at the boiler, the accuracy of the estimation of steam flow predicted by doing a raw-house balance can be verified by cross-referencing with boiler steam flow once the model is populated.
- The existence of turbines in the steam system is specified as a data input in the quick start section.
- The number of steam traps at each header level is a required input in this section.

The second section of the Input sheet is the Site Detail. This is used to refine the accuracy of the model and includes specification of the following information:

- Boiler conditions – This includes boiler efficiency, boiler blow-down rate and steam temperature exiting the boiler. The boiler efficiency figure used by SSAT is simply 100% less the stack losses. Stack losses can be calculated using the SSAT stack loss calculator.
- Information that describes turbine operation is turbine entropic efficiency, and limitations placed on turbine operation, i.e. the particular range of power or steam flow within which the turbine operates. In the case of a condensing turbine the condenser pressure is specified.
- Pressure reducing stations are specified with provision to input the de-superheater temperature control set point.
- The deaerator is described by specifying its operating pressure and vent flow.
- Heat recovery from either the condensate storage tank or from boiler blow-down is described.
- Process condensate recovery percentage and temperature are described.
- Estimations can be provided for steam leaks, trap leaks and insulation heat losses.

After inputting the data a graphical representation of the steam system is presented on the second sheet of SSAT.

The graphical representation of the steam system is annotated with all the mass flows and temperatures across the system. Any power generated by turbines is shown and the temperature, pressure and steam quality at each header are calculated. The consumption by process users is specified not only by mass flow of steam, but also by thermal power consumption. All losses, including condensate losses, insulation heat losses, trap losses and leaks are shown. Make-up water flow and temperatures are indicated, including the influence of any make-up water heating. Dearator steam flow and feed water flow and temperature are calculated. Also a table presenting an economic summary of operating costs appears.

The accuracy of the model can then be verified by taking field measurements of steam or water flows and temperatures. Should discrepancies be found, they can be investigated and inputs to the model corrected. It should always be checked that the LP vent is zero – if not the system is out of balance and the quantity of steam being produced for power generation exceeds the capacity of the process users to condense the steam.

Evaluation of steam system optimisation projects

With the Base Case (current operation) model built and verified, various opportunities for improvement of the system can be modelled and compared with the base case.

The Projects Input sheet of SSAT allows the user to model any combination of 15 different projects. These projects include the impact of:

- Steam demand savings by process users at each header pressure. Should steam demand be increased, this can be modelled as a negative saving. The influence of improved insulation, repairs to steam traps and steam leaks can be modelled as a steam demand saving.
- Changes in boiler fuel, boiler efficiency, and final steam temperature and boiler blow-down rate are also candidates for optimisation projects. The influence of boiler combustion tuning or additional heat recovery equipment would be modelled as a boiler efficiency project.
- Blow-down heat recovery, such as recovery of boiler blow-down flash to exhaust steam or make-up water preheating are viable energy optimisation projects that are seldom seen in South African sugar mills.
- Changes to the operation of steam turbines are another range of projects that are often considered in energy optimisations. A case study is presented later in this paper which evaluates the replacement of mill drive turbines with electric motor drives.

Case Study – Application of SSAT at hypothetical sugar mill with milling tandem

Consider a hypothetical sugar mill crushing 280 t cane/h, producing steam from three boilers (one boiler coal fired, one boiler coal and bagasse fired, one boiler bagasse fired) with live steam pressure of 31 barg and exhaust steam pressure of 1 barg, six mills (all turbine driven), shredder (turbine driven), and two back pressure turbo-alternators (TAs). The mill sells bagasse to a downstream user resulting in 50 t/h bagasse being available for the mill boilers. The mill electrical system operates islanded from the grid and the factory electrical load is 7.5 MW. Including gearbox efficiency losses, the power required to drive the shredder is 1.6 MW and the power required to drive the individual mills is 0.5 MW each. The isentropic efficiency of the powerhouse turbines is 80% and the isentropic efficiency of the smaller turbines is 45%. Exhaust steam is used for juice heating (5 t/h) and in the evaporators (145 t/h). In addition, exhaust steam is used in the deaerator and this is calculated by SSAT. The cost of coal is R1000/t. In the absence of a market for the remaining bagasse, the value of the bagasse used by the boilers is zero.

The SSAT input sheet is limited to inputting data for one boiler, one turbine between each header pressure, and one end use of steam at each header pressure. Hence, for steam systems with multiple boilers, multiple turbines and multiple steam end uses; the modeller needs to decide the most appropriate method of modelling the system. Often it is necessary to build models for different operating cases. For example, when modelling a system with multiple boilers the modeller must decide whether to model one boiler only or to model the entire boiler station as a unit. When modelling a boiler in SSAT, the necessary inputs are a definition of the fuel used, the boiler efficiency and the final steam temperature, so that when multiple boilers are modelled as a unit, weighted averages of these parameters are used.

Usually there is one boiler that is operated to take the load swings and any increase or savings of steam will impact the operation of this boiler (the impact boiler). A good approach is to initially develop a model of the entire boiler station as a unit and then refine the savings predictions by modelling the impact boiler. In the case study, the boiler station is modelled initially as a single boiler with efficiency, fuel characteristics and steam temperature the weighted average of the parameters of the individual boilers. The data associated with the case study boiler station are given in Table 1.

Table 1. Hypothetical sugar mill boiler details.

	Boiler 1	**Boiler 2**	**Boiler 3**	**Weighted average**
Fuel	Coal	Bagasse/Coal	Bagasse	User defined
Fuel GCV (MJ/t)	28,380	Coal 28,380 Bag 8,956	8,956	11,053
Measured average operation				
Steam (t/h)	47.5	65.5	37	150
Estimated coal use (t/h)	5.70	0.35		56.05
Estimated bagasse (t/h)		29.86	20.14	
Steam temp (°C)	380	390	360	380
Boiler efficiency (%)	80	65	55	67.28
Fuel cost (R/t steam)	120.11	5.34	0.00	40.34

Boiler efficiency can be calculated by either the direct or indirect method.

The direct method requires accurate measurement of boiler feed water, steam and fuel flow as well as accurate measurement of fuel calorific value. Accurately measuring steam flow is difficult because steam flow meters are typically only accurate to within 5% at design flow, but as the actual flow varies away from the design point so the accuracy of flow measurement reduces. Similarly, the sampling and weighing of fuel to determine fuel consumption and calorific value results in inaccuracies. These inaccuracies in measurement make the direct method difficult to apply practically.

In the indirect method, boiler efficiency is 100% less measured losses. The measured losses include the stack losses, blow-down losses, unburnt fuel losses and the shell losses. Blow-down losses are accounted for by specifying the percentage blow-down in SSAT. Unburnt fuel losses can be calculated by an analysis of the boiler ash. Shell losses can be estimated from tables, and both shell losses (max 2%) and unburnt fuel losses (max 2%) make a small contribution to overall losses. Stack losses can be measured directly with a portable flue gas analyser or read from combustion tables such as those in Annexure 1.

SSAT also includes a built in stack loss calculation utility. The SSAT stack loss calculation utility is limited to seven commonly available industrial boiler fuels – 'Typical Eastern Coal' being a bituminous coal, is a good approximation of South African coal, and 'Typical Green Wood' can be used as an approximation of bagasse. The fuel used by a boiler has a major impact on the efficiency of the boiler, with coal fired boilers being inherently much more efficient than bagasse fired boilers.

Since two boiler fuels are used in three boilers, with each boiler having a different steaming rate, fuel consumption and steam temperature, a weighted average approach is taken and the boiler station is modelled as a single boiler.

In a similar way the all steam turbines on the site operating between the high and low pressure steam headers are modelled as a single turbine with isentropic efficiency equivalent to the weighted average of the isentropic efficiencies of each individual turbine. The total shaft power developed by all turbines is 12.5 MW and the weighted average turbine isentropic efficiency is 67.12%

Using the input data given above, the SSAT model shown in Figure 2 can be developed.

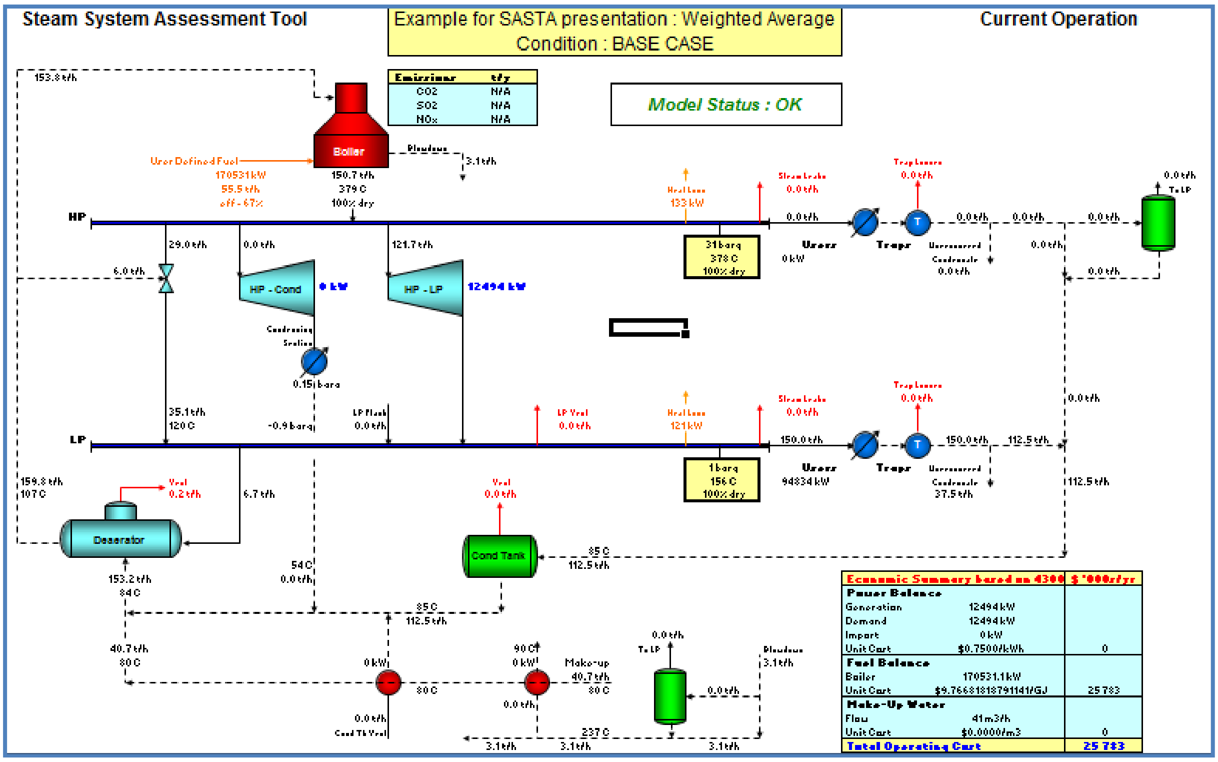

Figure 2. Hypothetical sugar mill steam system model: Base Case.

Field measurements can be taken to verify that the model is an accurate representation of the actual steam system. It should be noted that, since the model is derived using weighted average figures, the economic summary table should reflect the actual fuel costs incurred to operate the plant.

This model can be used to evaluate optimisation projects as detailed below.

Example 1: Boiler efficiency improvement

It is known that Boiler 3 efficiency is low because this boiler is not fitted with an economiser. By installing an economiser the efficiency of this boiler can be improved to 65%. Improving the efficiency of Boiler 3 means that more steam is produced by burning all the available bagasse. Consequently, Boiler 1 needs to produce less steam resulting in a saving of the coal consumption of Boiler 1. The question that arises is whether the savings in coal are enough to justify the cost of installing the economiser on Boiler 3?

The effect of the increase in efficiency of Boiler 3 is that the overall efficiency of the boiler station increases and the annual operating cost is reduced from R25.357 million/year to R22.445 million – a saving of R2.912 million/year (Figure 3).

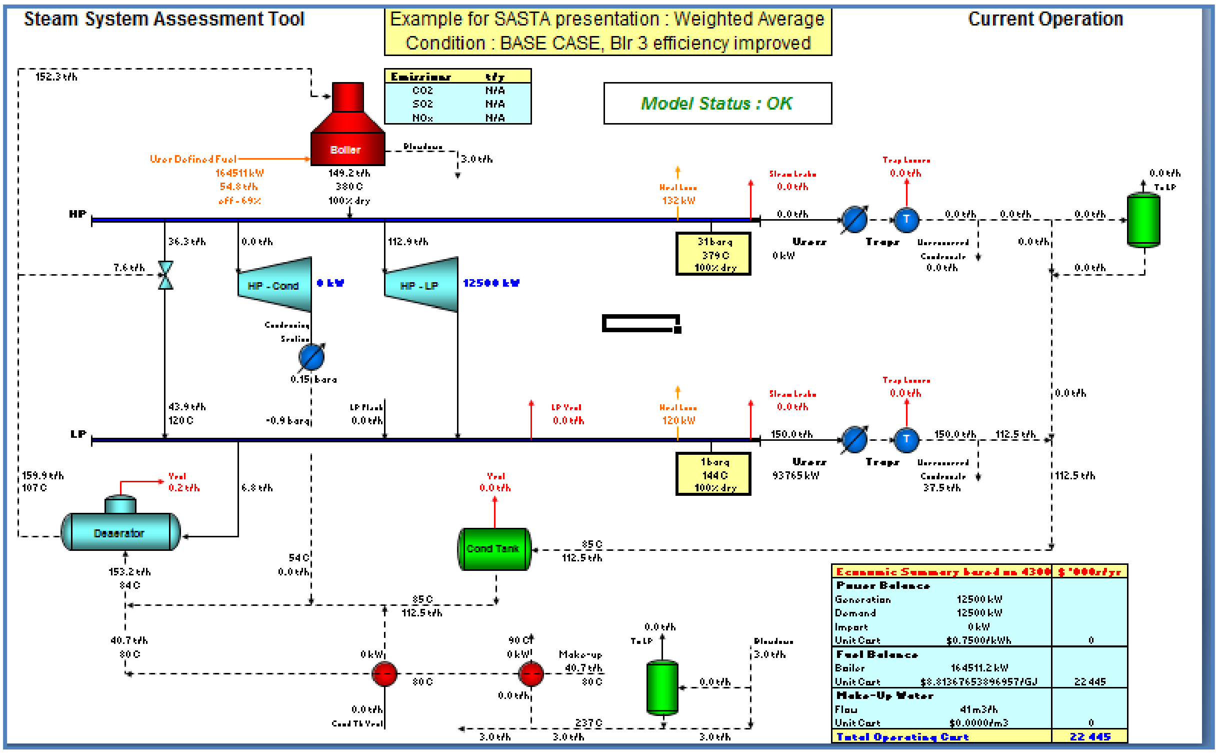

Figure 3. Hypothetical sugar mill steam system model: Project Boiler Efficiency Improvement.

Example 2: Replacing mill turbines with electric motors

Reviewing the boiler data table it is clear that Boiler 1 (the coal fired boiler) is the impact boiler. Any savings in steam consumption by the system will result in less steam being produced by Boiler 1. To evaluate the economic impact of energy savings the system can be modelled using the fuel parameters of Boiler 1, the impact boiler.

Modelling the system as if all the steam produced was produced by the most expensive-to-operate boiler (impact boiler) does not attempt to recreate the actual operating conditions. It shows how operating costs change as steam consumption changes, because the only boiler where the operation will change with a change in steam consumption is the impact boiler. A base case model is shown in Figure 4 for the sugar mill as if all steam was produced using one large single boiler with fuel and characteristics of Boiler 1.

Consider a steam saving project such as replacing steam turbines on the mill drives with electric motors. In this case we have a trade-off between increasing the electrical load on the power station which will increase the steam flow through the power station turbines vs. reducing the steam flow through the mill turbines.

The absorbed power required to drive the mills does not change, irrespective of whether the mills are driven by motors or turbines; so, if the six mill turbines developed 500 kW of shaft power each, then the six motors will likewise be required to develop 500 kW of shaft power. The difference between shaft power and electric power is in the motor efficiency. The efficiency of a 500 kW motor varies from 90 to 95% (when new) depending on percentage of full rated motor load [(4)]. So to deliver 500 kW shaft power the motor needs at least 526 kW of electric power. As it is necessary to vary the speed of the mill by varying the speed of the

[4] Energy Management for Motor Driven Systems
http://www1.eere.energy.gov/manufacturing/tech_deployment/pdfs/NN0116.pdf

motors variable speed drives are required, and these drives are also around 95% efficient. The electric power required from the power station to drive each VSD is thus 550 kW. The turbine in the power house drives an electric generator, and there is an energy loss between the shaft power from the turbine to the electric power from the generator of at least 5%. The shaft power required from each turbine and turbine isentropic efficiency of the two cases is summarised in Table 2.

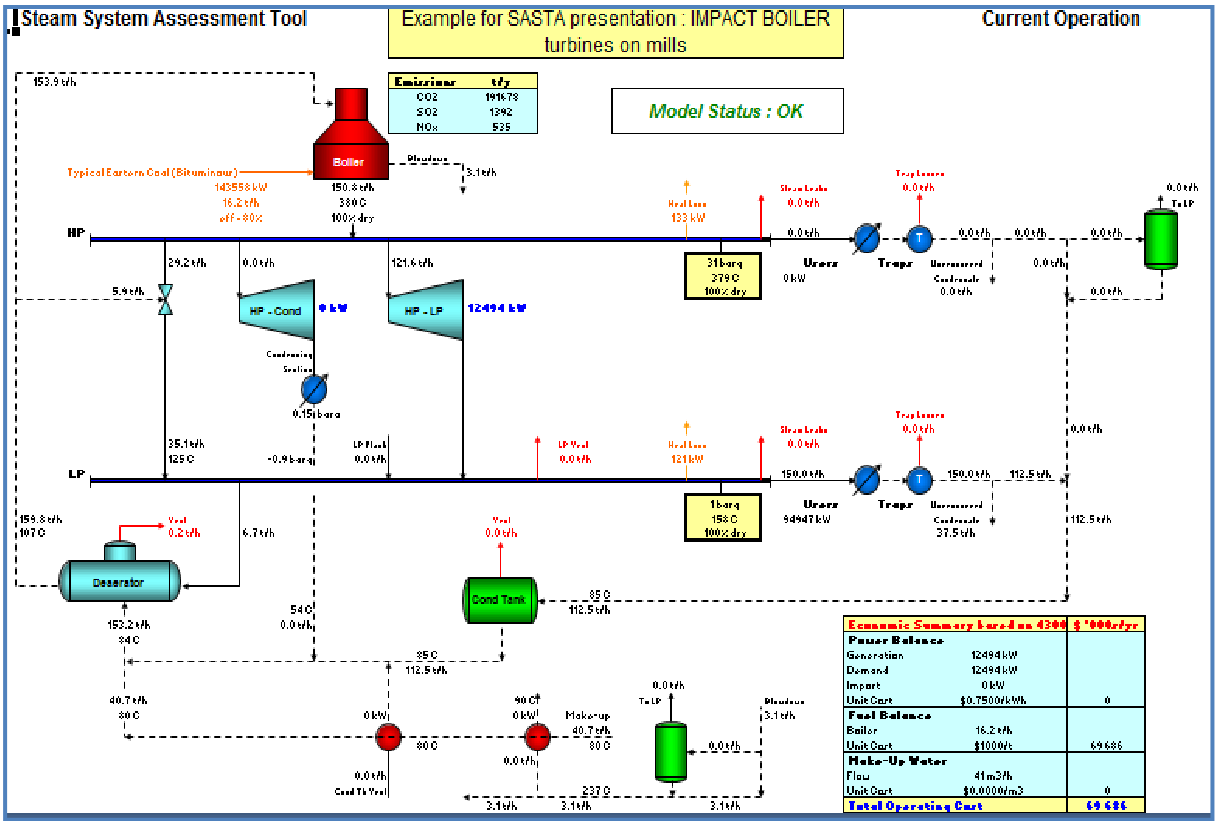

Figure 4. Hypothetical sugar mill steam system model:
Base case – Impact Boiler used to determine cost impact of steam savings.

Table 2. Comparison of power required to drive mills: Turbine vs Motor Drives.

	Base case: Keep mill turbine drives	Project: Electric motors on mills
Base powerhouse electric load (kW)	7,500	7,500
Electric load added by mill motors (kW)	0	6 x 550 = 3,300
Power House electric load (kW)	7,500	10,800
Generator efficiency (%)	95	95
Power house turbine shaft power (kW)	7,894	11,368
Power house turbine isentropic efficiency (%)	80	80
Mill turbine shaft power (kW)	6 x 500 = 3000	0
Mill turbine isentropic efficiency (%)	45	45
Shredder turbine shaft power (kW)	1600	1600
Shredder turbine isentropic efficiency (%)	45	45
Total turbine shaft power (kW)	12,494	12,968

The first law of thermodynamics is the law of conservation of energy – the energy going into a system equals the energy out. The thermal efficiency of a boiler, or a motor or an electric generator, is defined by performing an energy balance across the unit. The energy efficiency of the unit is the percentage of usable output energy compared with the input energy. Another way of stating this is the energy efficiency is 100% less the energy losses. In the case of boilers, motors and generators, the energy loss is in the form of heat that is lost to the system. When performing an energy balance across a turbine, a significant amount of energy leaves the turbine with the exhaust steam. This heat is not lost to the system because the exhaust steam goes on to process heating. The only losses of energy from a turbine are the bearing cooling heat loss and any heat loss due to poor thermal insulation. Hence the thermal efficiency of a turbine is practically 100%.

The second law of thermodynamics is concerned with the concept of entropy and irreversibility of heat to power relationships. When applied to turbines this means that not all the heat in steam can be converted to shaft power. The isentropic efficiency of a turbine is a measure of how much heat energy in the steam is converted into shaft power by the turbine. As isentropic efficiency increases, so less steam is required for the same shaft power, because more energy is extracted from the steam. As more energy is extracted from the steam, so the turbine exhaust steam temperature goes down. Thus, a turbine with high isentropic efficiency will use less steam per kW of shaft power, and the exhaust steam temperature of this turbine is lower. A let-down station can be considered as a turbine with an isentropic efficiency of zero, since steam pressure is reduced without any shaft power being produced.

$$\eta_{isentropic} = \frac{Actual\ Turbine\ Work}{Isentropic\ Work} = \frac{\dot{W}_{shaftpower}}{\dot{m}_{steam}\left(h_i - h_e\right)_{isen}}$$

Due to the non-linear relationship between steam demand, turbine efficiency and shaft power produced it is necessary to develop a SSAT model for each of the turbines to determine steam flow through each turbine; this is presented in Table 3. Knowing the steam mass flow, steam conditions at turbine inlet and shaft power developed it is possible to calculate the isentropic efficiency of a single turbine that represents all the turbines in the steam as presented in Table 4.

Table 3. Turbine steam flows.

	Base case: Keep mill turbine drives	**Project: Electric motors on mills**
Power house turbine steam flow (t/h)	59.8	86.1
Mill turbine steam flow (t/h)	6 x 6.7 = 40.2	0
Shredder turbine steam flow (t/h)	21.6	21.6
Total steam flow through turbines (t/h)	121.6	107.7
Isentropic efficiency of equivalent turbine to represent all turbines in system (%)	62.30	72.98

Table 4. Comparison of model outputs: Turbines vs motor drives on mill turbines.

	Base case: **Keep mill turbine drives**	**Project:** **Electric motors on mills**
Turbine power (kW) and isentropic efficiency (%)	12,494 62.30	12,968 72.98
Steam to be raised by boiler (ton steam/h)	150.8	151.0
Steam flow through turbines (ton steam/h)	121.6	107.7
Turbine exhaust steam temperature (°C)	166	137
HP steam to let-down (ton steam/h)	29.2	43.9
De-superheat water flow (ton water/h)	5.9	8.9
De-superheated let-down steam flow (ton steam/h)	35.1	52.8
Combined LP steam temperature (°C)	158	133
Thermal energy to LP steam users (kW)	94,947	94,947
LP Steam flow to process (ton steam/hr)	150.0	153.5
Boiler fuel consumption (ton coal/h)	16.2	16.2

The above data is entered into a SSAT model to produce a model of the system. Figure 4 illustrated the base case (retain turbine driven mills), and Figure 5 illustrates the project case (mills converted to motor drives). In both cases let-down steam is de-superheated to 125°C.

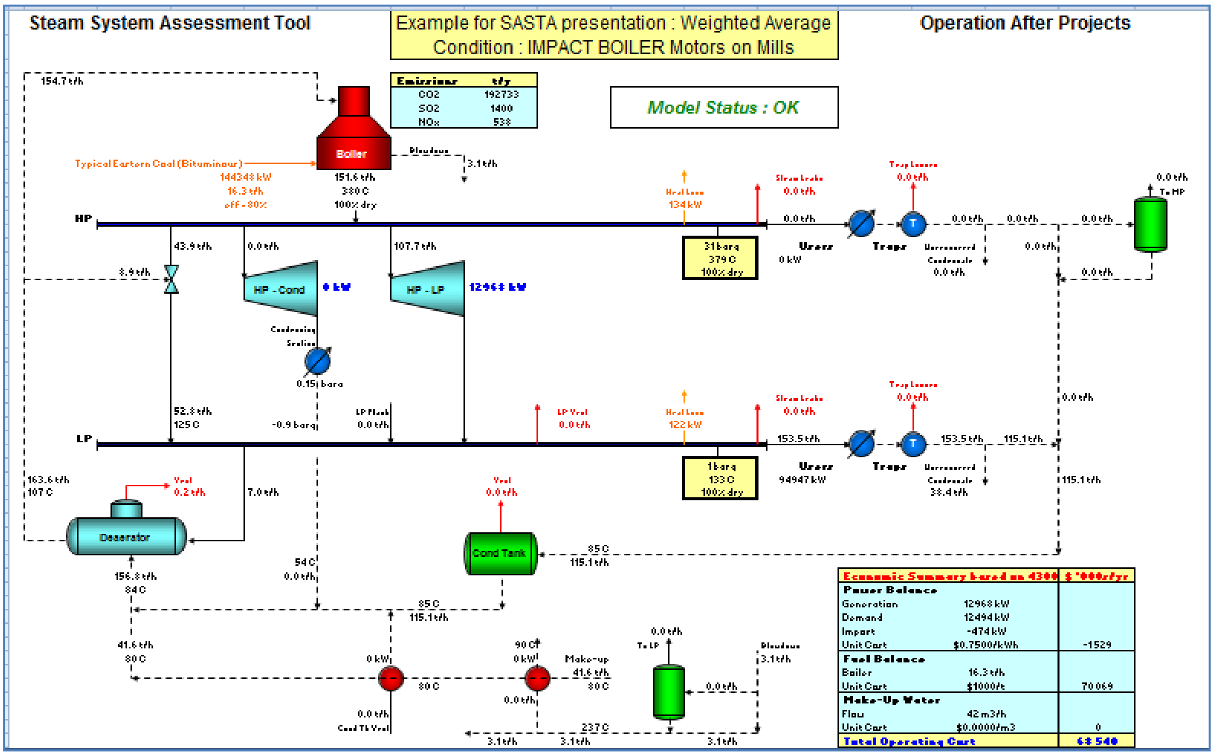

Figure 5. Hypothetical sugar mill steam system model: Project – Impact boiler replace turbine drives on mills with electric motors.

As indicated in Table 4, the steam demanded from the boiler and the fuel used by the boiler is the same in both cases. In the base case (retaining the turbines to drive the mills) more steam goes through the turbines and the let-down steam flow is lower. By making the turbines more efficient in the project case, less steam is demanded by the turbines, but, to balance process heat demand, more steam must go through the let-down station.

In both cases, the let-down steam is de-superheated to 125°C. Since the turbines in the base case have a lower isentropic efficiency, the turbine exhaust steam temperature is higher. The total low pressure (LP) steam to process is a mixture of let-down and turbine exhaust steam. In the base case, the LP steam temperature is higher, due to the higher turbine exhaust steam. (This means that the energy contained in the LP steam to process in the base case is higher than the energy in the LP steam in the project case.)

Replacing steam turbines with electric motors becomes economically viable if electricity can be purchased into the mill at a lower cost than it can be generated from steam raised on site.

A scenario where replacing turbine drives with electric motors is essential occurs when the steam flow though the let-down station is reduced to the point where let-down steam flow is practically eliminated. This can be achieved in two ways – process steam economies can be achieved to reduce the exhaust steam demanded by process, or when additional shaft power is required such as a situation where the mill exports electricity.

In this scenario more steam will flow through the turbines to generate the necessary shaft power than can be condensed by the process. Inevitably this will result in the steam pressure on the LP header increasing until safety vents are opened on the LP header to vent LP steam to atmosphere or to vapour 1. In a sugar mill this means that, as evaporators using exhaust steam become fouled, their heat transfer capacity drops to the point where exhaust steam cannot be condensed at the rate that it is delivered to the evaporators. This causes the exhaust steam pressure to increase until a maximum threshold is reached. Once the maximum exhaust steam pressure is reached, the pressure in the exhaust steam range must be relieved by letting down to vapour 1 or blowing off to atmosphere.

When low isentropic efficiency turbines are replaced with electric motors, the let-down margin of the factory can be increased. This is because the low isentropic efficiency turbines produce a lot of exhaust steam per kW shaft power. When mills are driven by electric motors, although there is no reduction in energy required, the amount of exhaust steam produced by the power house turbines for the additional electric load is less than the amount of exhaust steam produced by the turbine drives that have been displaced. Power house turbines are generally multistage machines with higher isentropic efficiency, meaning that they produce less exhaust steam per kW of shaft power and that the exhaust steam temperature is also considerably reduced.

An alternative to replacing electric motors on mills to increase let-down margin is the installation of a condensing turbine to develop the necessary shaft power to drive power house turbines. A condensing turbine can be modelled in SSAT. In the project case where electric motor have been installed to increase let-down steam flow to 40.8 t HP steam/h, the same effect can be achieve by retaining the turbine drives on the mills and shifting a portion of the power house shaft power onto a condensing turbine. This is illustrated in Figure 6.

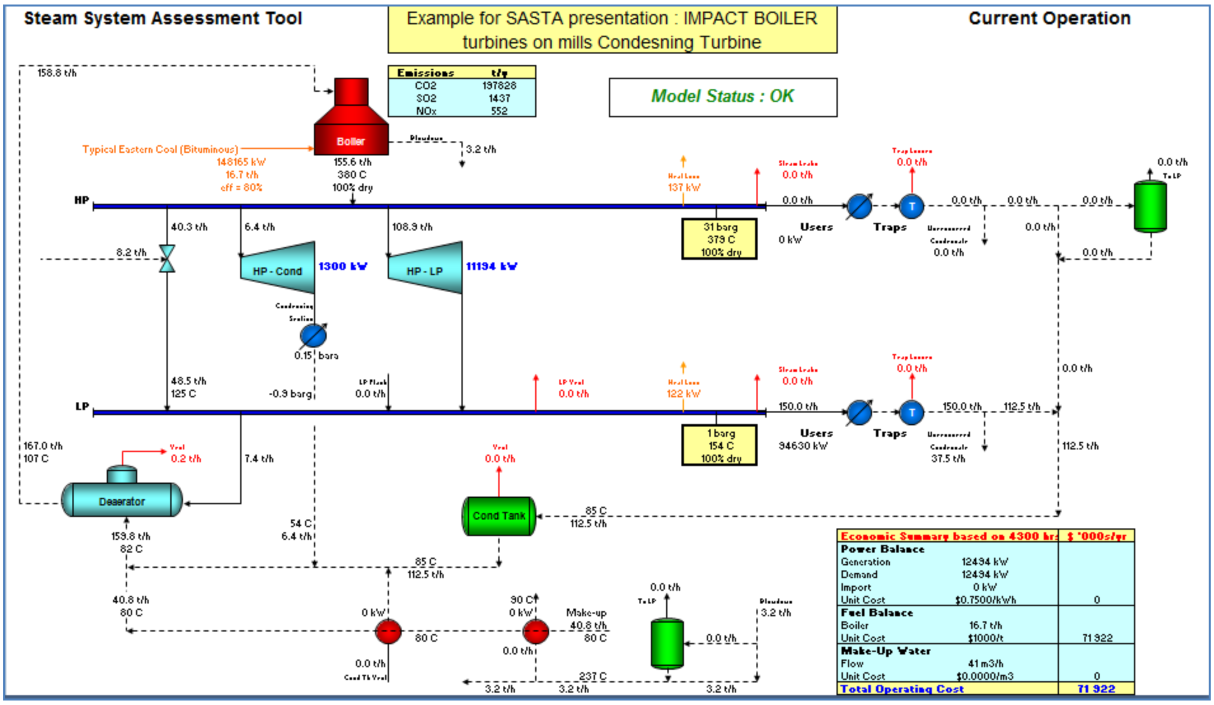

Figure 6. Hypothetical sugar mill steam system model: Project – Impact boiler turbine drives on mills, condensing turbine to increase let-down margin.

In the case of the condensing turbine the steam is not as energy efficient as the base case (turbine driven mills) and the Project case (motor driven mills). This is because additional energy leaves the system in the form of heat lost in the condenser associated with the condensing turbine. The effect of this is that slightly more HP steam (additional 5 t HP steam/h) needs to be produced by the boilers at he cost of additional boiler fuel (0.5 t coal/h).

Good candidate projects for improving energy efficiency

The above two examples show how SSAT can be used to model projects on steam systems to determine the feasibility of these projects. Several other projects/initiatives can be performed to improve the energy efficiency of a steam system. These projects can be modelled in SSAT to verify the feasibility of each project. Modelling with SSAT also shows how a project on one component of the system influences the overall system. Good candidate projects for improving the energy efficiency of a sugar factory can be divided into the following two categories.

Projects to improve boiler efficiency

Changes in boiler efficiency, boiler blow-down rate and boiler fuel can all be easily modelled in SSAT. Projects to improve boiler efficiency include:

- Boiler combustion tuning: This is most often the most cost effective method of improving fuel costs. This combustion tuning should include regular adjustment of fuel to air ratios to achieve flue gas oxygen no more than 6% when measured at the exit of the generating bank. Ideally, the combustion tuning is automated by operating the boiler with an on-line oxygen analyser and trim controls on the draft through the boiler. Even with on-line oxygen analysers, the use of a portable flue gas analyser is recommended to identify sources of fugitive air entering the boiler.

- Heat recovery equipment: When the boilers are not fitted with heat recovery equipment such as air heaters and economisers which bring the flue gas exit temperature (before wet scrubbers) down to at least 170°C, there is an opportunity to recover heat from the flue gases. Due to the historical situation in the sugar industry when there was no viable market for bagasse or electric power to be exported from sugar mills, many sugar mill boilers do not have economisers, or the economiser is too small to maximise heat recovery.
- Automatic blow-down and caustic dosing: Significant energy savings with modest investment can be achieved by installing a control system on the continuous blow-down. This control system measures blow-down conductivity to control boiler blow-down rate to within a narrow range, reducing wasteful excessive blow-downs. Another opportunity is measuring blow-down pH to increase the accuracy at which caustic is dosed into the boiler. Not only does this minimise caustic usage, but it also reduces the contribution of caustic to increasing boiler water conductivity.
- Minimising bagasse moisture: The energy in bagasse is described by Wienese (2001) with the equation:

  $$\text{LCV Bagasse} = 18260 - 31{,}14\ (\text{Bx\%}) - 207{,}6\ (\text{moisture\%}) - 182.6\ (\text{Ash\%})$$

  A review of the above equation illustrates the impact that bagasse moisture has on the energy available in bagasse. Any improvement of bagasse moisture by tuning of mills has a direct and measurable influence on bagasse calorific value used in energy models such as SSAT.

Projects to change steam demand

Changes in steam demand are created by changing process heating demands, shaft power requirements, or changes in the condensate recovery circuit. Projects to reduce steam demand include:

- Boiler blow-down heat recovery – even in situations with very low boiler blow-down rates there is an opportunity to recover heat from boiler blow-down, either by flashing from the blow-down vessel to the exhaust steam header, as described by Singh and Weyers, (2001), or recovering heat from the liquid fraction of the blow-down before it discharges to drain. Both these opportunities can be evaluated using SSAT.
- Reduction in evaporative steam demand by reducing dilution of juice. This includes minimising imbibition by optimising the energy vs. extraction trade-off. Other opportunities for reducing evaporative steam demand include reduction of water addition in the raw house (clear juice dilution, floor washing and holding pans on water).
- Installing additional heat exchange surface area – although this may be a costly approach, depending on the fuel blend being used by the mill such costs may be justified.
- Flash steam recovery – any unrecovered flash steam represents an opportunity to re-use this steam at lower vapour pressure.
- Increasing condensate collection and preserving condensate temperature by improved thermal insulation.

Conclusion

SSAT is an effective tool that can be used together with an understanding of the thermodynamics of the steam system to model and optimise the steam system of a sugar factory with a high degree of accuracy and reliability. This model can be used to predict the behaviour of the steam system under different operating conditions, and the model can be used as a starting point for fuel budgeting. Energy saving opportunities can also be modelled to determine the economic viability of these projects.

Acknowledgements

The author thanks Gledhow Sugar Company for allowing this paper to be published. Thanks are also due to Riyaz Papar, UNIDO steam system expert, for his advice and for sharing his knowledge of SSAT and steam system optimisation; Alf Hartzenberg and the team from NCPC for their work on the Industrial Energy Efficiency Project; and Dr Greg Harrel for the stack loss combustion tables in Annexure 1.

REFERENCES

Hoekstra RG (2000). The use of linear programming in power generation decisions. *Proc S Afr Sug Technol Ass* 74: 267-273.

Loubser RC (2004). Heat and mass balance using constraint equations, a spreadsheet, and the Newton-Raphson technique. *Proc S Afr Sug Technol Ass* 78: 457-471.

Singh I and Weyers F (2001). Boiler blow-down flash recovery. *Proc S Afr Sug Technol Ass* 75: 272-274.

Wienese A (2001). Boilers, boiler fuel and boiler efficiency. *Proc S Afr Sug Technol Ass* 75: 275-281.

ANNEXURE 1
Combustion Tables

Stack Loss – Coal (3.3% Water, 14.2% Ash)

- Stack loss table is developed for negligible combustibles and no condensation

Stack Loss Table for			Coal (3.3% Water, 14.2% Ash)											
Flue Gas Oxygen Content Wet Basis [%]	Flue Gas Oxygen Content Dry Basis [%]	Comb Conc [ppm]	Stack Loss [% of fuel Higher Heating Value input] Net Stack Temperature [Δ°C] {Difference between flue gas exhaust temperature and ambient temperature}											
			130	145	160	175	190	205	220	235	250	265	280	295
1.0	1.1	0	8.2	8.8	9.4	10.0	10.6	11.2	11.8	12.4	13.0	13.6	14.2	14.8
2.0	2.1	0	8.5	9.1	9.7	10.3	10.9	11.5	12.2	12.8	13.4	14.1	14.7	15.3
3.0	3.2	0	8.7	9.4	10.0	10.7	11.3	12.0	12.6	13.3	13.9	14.6	15.3	15.9
4.0	4.2	0	9.0	9.7	10.4	11.1	11.7	12.4	13.1	13.8	14.5	15.2	15.9	16.6
5.0	5.3	0	9.3	10.1	10.8	11.5	12.2	13.0	13.7	14.4	15.2	15.9	16.6	17.4
6.0	6.3	0	9.7	10.5	11.2	12.0	12.8	13.6	14.3	15.1	15.9	16.7	17.5	18.3
7.0	7.3	0	10.1	11.0	11.8	12.6	13.4	14.2	15.1	15.9	16.7	17.6	18.4	19.2
8.0	8.3	0	10.6	11.5	12.4	13.3	14.1	15.0	15.9	16.8	17.7	18.6	19.5	20.4
9.0	9.3	0	11.2	12.2	13.1	14.0	15.0	15.9	16.9	17.9	18.8	19.8	20.8	21.7
10.0	10.4	0	11.9	12.9	13.9	15.0	16.0	17.0	18.1	19.1	20.2	21.2	22.3	23.3
Actual Exhaust T [°C]			150	165	180	195	210	225	240	255	270	285	300	315
Ambient T [°C]			20	20	20	20	20	20	20	20	20	20	20	20

Bagasse Stack Loss Table

Oxygen	Stack Temperature (deg C)									
Wet Basis [%]	100	115	130	145	160	175	190	205	220	235
2.0	26.0	26.8	27.5	28.2	29.0	29.7	30.5	31.2	32.0	32.7
3.0	26.3	27.0	27.8	28.6	29.3	30.1	30.9	31.7	32.5	33.3
4.0	26.5	27.3	28.1	28.9	29.8	30.6	31.4	32.2	33.1	33.9
5.0	26.8	27.6	28.5	29.4	30.2	31.1	32.0	32.8	33.7	34.6
6.0	27.1	28.0	28.9	29.8	30.7	31.7	32.6	33.5	34.4	35.4
7.0	27.4	28.4	29.4	30.4	31.3	32.3	33.3	34.3	35.3	36.3
8.0	27.9	28.9	29.9	31.0	32.0	33.1	34.1	35.2	36.2	37.3
9.0	28.3	29.4	30.6	31.7	32.8	33.9	35.1	36.2	37.3	38.5
10.0	28.9	30.1	31.3	32.5	33.8	35.0	36.2	37.4	38.7	39.9
11.0	29.6	30.9	32.2	33.6	34.9	36.2	37.6	38.9	40.3	41.6