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UPGRADING THE UTILITY PLANT MODULE FOR THE GENERIC SUGAR MILL MODEL

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Abstract

The Sugar Milling Research Institute NPC published a MATLAB® model of a generic sugar mill, consisting of mass and energy balances of the individual units of a diffuser factory with mud filtration, five-effect evaporation and a three-boiling partial remelt scheme. The original model did not provide a means for balancing electrical power and steam production and demand and therefore was not able to predict the impact of process changes on overall energy consumption. The objective of this study was to expand the original model by including a power house and considering steam and electrical power balances.

The upgraded utilities model included a simplified mass and energy balance model of the boiler with high pressure (HP) steam generation calculated to meet the various mechanical and thermal demands of the raw sugar factory, and to supply a back-pressure turboalternator. The turboalternator was modelled to supply the electrical power demand of the raw sugar factory and external power consumers. Prime movers for cane knives, shredder and bagasse drying mills can make use of either HP steam or electricity for motive power. The model allows the split between these two power sources to be varied. Simulations for a range of power splits were used to generate HP steam distribution values, which were compared to published models of energy supply for raw sugar mills in lieu of a rigorous validation of the utilities model.

Model simulations demonstrated that design of the split between electrically and steam driven motive power for prime movers does not inherently influence factory energy efficiency; instead, a higher degree of electrification could enable generation of power for external customers at marginally increased fuel cost or reduction of exhaust steam demand in the backend for reduced factory fuel consumption.

Keywords: sugar mill model, utility plant, energy balance, electrification, steam balance

Introduction

Starzak and Davis (2017) presented a model of a generic raw sugar factory, built in MATLAB®. Their work focussed on the process description and validation of the model using published data from a selection of South African mills across one milling season. One identified limitation of the model was that the energy (steam and power) supply was simply described and could not be included in the model validation since the data used for validation included only sugar stream information. The model predicted a high pressure (HP) steam consumption of 39.6 tonnes/100 tonne cane (t/100 tc). Rein (2007) quotes a normal range of 40 to 60 t/100 tc. The authors believe that the normal range for South African mills may be even higher than these values.

The objective of this study was to upgrade the utility plant module of the steady state sugar mill model to provide a more realistic overall factory steam consumption and to allow design choices for HP steam, power and exhaust steam to be interrogated.

Definition of the upgraded utility model

The model of the utilities plant in Starzak and Davis (2017) was composed of two sections: the boiler and the cooling tower. The boiler model produced HP steam to supply the calculated factory demand and estimated the fuel consumption from a fixed steam-to-fuel ratio. Although it was understood that simultaneous production of electrical power would also take place, the electricity generation and its balance across the sugar mill were not discussed. In this study, the utilities model was expanded to include a power house and to describe steam and electrical power balances explicitly.

For the upgraded model, the following principles were applied:

- The boiler was modelled as a simplified mass and energy balance.
- It was assumed that the total bagasse flow is available as boiler feed, but in the case of bagasse shortage, the model calculates an energetically equivalent amount of coal to make up the difference.
- No allowance was made for external customers for HP and exhaust steam.
- Prime mover power may be supplied by either steam-driven turbines or electrical drives.
- Power to drive boiler feed water pumps was similarly divided into electrical power and HP steam driven duties.
- Total electrical power demand was made up of explicitly calculated duties in extraction and for boiler feed water pumping, power for other sugar mill operations, and provision was made for supplying electrical power to external users.
- Isentropic efficiencies were defined independently for prime mover turbines, turboalternators, boiler feed water pump turbines, and boiler feed water pumps. Gearing and transmission efficiencies were defined for all other power conversions.
- The process flow configuration was as described in Starzak and Davis (2017).

The description for each process stream tag and model parameter described in this paper is included in the table of nomenclature.

Modelling of steam and electricity use in the diffusion plant

The upgraded utility model assumes that power required by cane knives, shredder and bagasse mill units is partially supplied through steam-driven turbines and electricity-driven motors. For each unit the power absorbed by the process flow is a function of either the cane flow (cane knives and shredder) or the megasse fibre flow (bagasse mills). The source of the power for these operations is defined by the split ϕ_{ST}, a pre-specified design parameter expressed as the ratio of the power used to run the turbine-gearbox system to the total power for each set of prime movers. For the sake of simplicity, it was assumed that all turbine gearbox mechanical efficiencies η_{GS} and all motor gearbox mechanical efficiencies η_{GE} are equal. Under these assumptions, the power split between electrically and steam driven units for each of the cane knives, shredder and bagasse mills are the same. The purpose of this construct is to allow the user to vary a single parameter ϕ_{ST} to change the extent of electrification in the factory front end, without needing to choose which of the various machines are to be electrified, and the simulation predicts the average effect of such a change. This approach can be visualised in terms of the model having parallel preparation lines including cane knives, shredder, a common diffuser and parallel lines for drying bagasse mills where the knives, shredder and drying mills of one line are electrically driven while the other line is equipped with steam turbines (Figure 1).

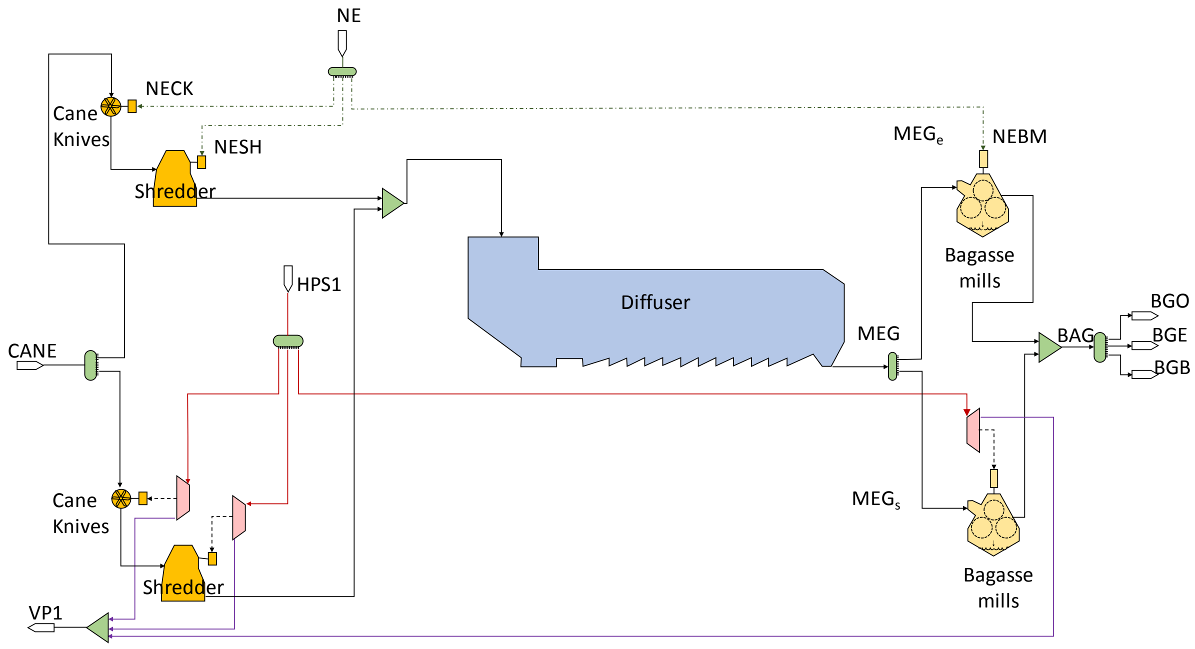

Figure 1. Visualisation of energy supply to prime movers in the extraction section. Only the process-side flows associated with fibre are shown.

The total flow of cane to each line is:

$$\frac{F_S^{CANE}}{F^{CANE}} = \frac{F_{fib,s}^{MEG}}{F_{fib}^{MEG}} = \frac{\phi_{ST} \cdot \eta_{GS}}{\phi_{ST} \cdot \eta_{GS} + (100 - \phi_{ST})\eta_{GE}} \quad \text{for steam driven units}$$

and

$$\frac{F_e^{CANE}}{F^{CANE}} = \frac{F_{fib,e}^{MEG}}{F_{fib}^{MEG}} = 1 - \frac{\phi_{ST} \cdot \eta_{GS}}{\phi_{ST} \cdot \eta_{GS} + (100 - \phi_{ST})\eta_{GE}} \quad \text{for electrically driven units}$$

where F^i is the total mass flow of stream *j*, $j = [CANE(\text{input cane}), MEG(\text{megasse})]$
F_k^i is the total mass flow of component *k* in stream *i*, $k = [fib(\text{fibre})]$
F_e^i or $F_{k,e}^i$ is the mass flow of stream *j* or component *k* in stream *j* that passes through electrically driven prime movers
F_s^i or $F_{k,s}^i$ is the mass flow of stream *j* or component *k* in stream *j* that passes through steam driven prime movers

then the power consumed by steam-driven systems can be calculated as

$$N_S^{NEj} = \frac{\eta_{GE}}{\eta_{GS}} \mu_{NEj} F_S^{CANE}$$

For prime movers in the extraction section, *Ej*
where $j = [CK(\text{cane knives}), SH(\text{shredder}), BM(\text{bagasse mills})]$

while the power consumed by electricity-driven systems is:

$$N_e^{NEj} = \mu_{NEj} F_e^{CANE}$$

Energy consumption coefficients μ_{NEj} are defined as the amount of electrical energy required to process one tonne of the given material in the corresponding electrically-driven system, since power absorbed data is typically reported in terms of power draw on electric drives.

Utility plant configuration

The upgraded utility plant model is composed of three interacting parts: the boiler house, the power house and the cooling tower. The boiler house includes boilers, a blowdown valve, a deaerator and two boiler feed water pumps (one driven by steam, the other by electricity). The boilers are represented in the model by a single unit which generates superheated steam at a user defined pressure and temperature, with default values of 31 bar(a) and 390ºC. The boiler efficiency (on gross calorific value, GCV, of fuel) η_{blr} is defined by the user with a default value of 60%. The boiler model estimates the bagasse burned based on the energy that must be supplied by the fuel and the bagasse condition (moisture, ash and brix content), using the Don *et al.* (1977) correlation for calorific value of bagasse. If there is insufficient bagasse to meet the fuel demand, the amount of supplementary coal required is calculated. The power house includes a letdown throttling valve, a desuperheater and two back-pressure turbines. One of the turbines is coupled with an alternator for power generation, while the other drives the steam-driven boiler feed water pump.

The steam and power distribution are shown in Figure 2.

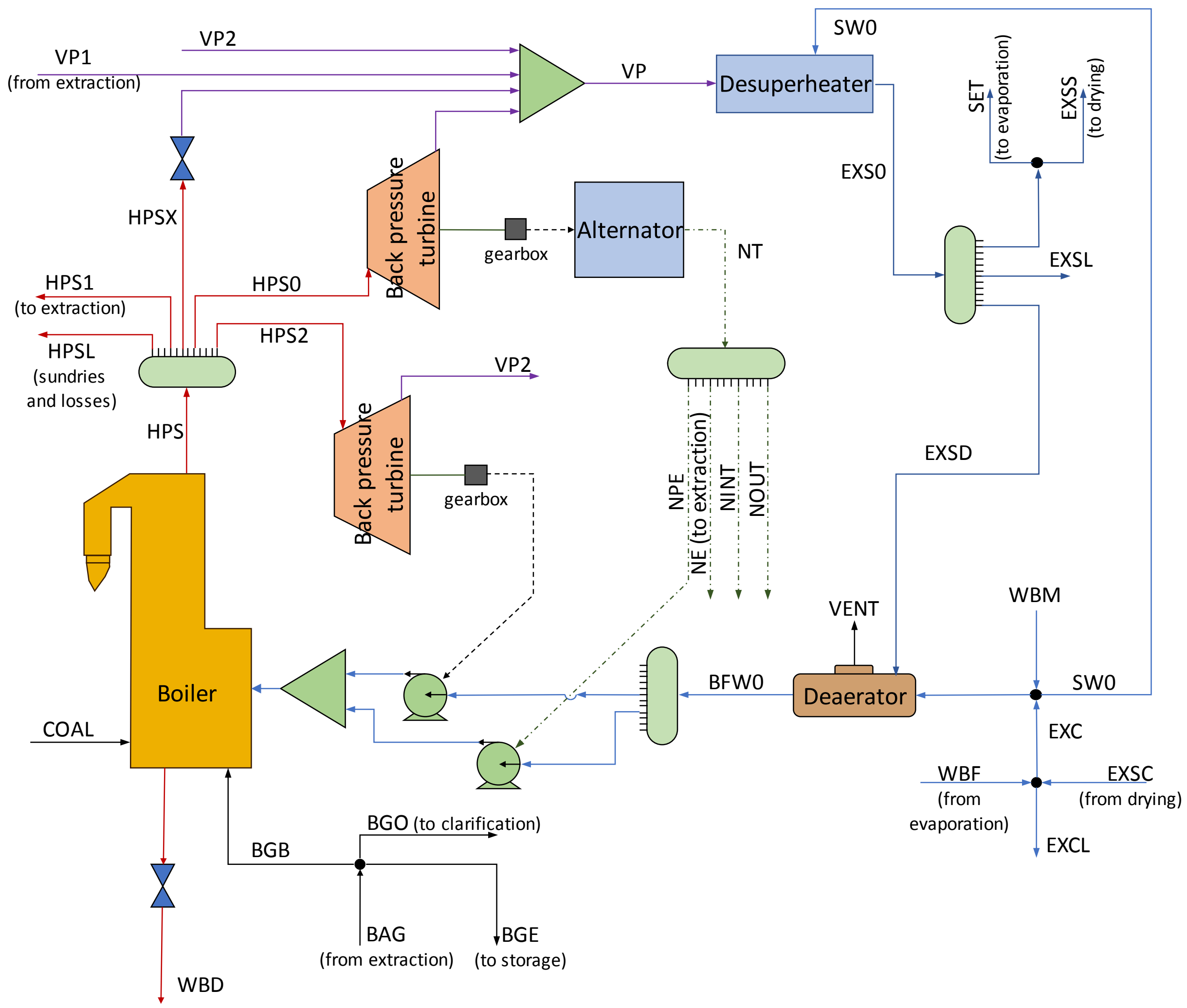

Figure 2. Steam and power generation and distribution diagram for the upgraded utilities model.

The high-pressure steam (HPS) stream generated by the boiler is sent to four destinations:

(1) the back-pressure turbine producing exhaust steam and electricity (HPS0).
(2) the extraction plant to run the cane knives, shredder and bagasse drying mills (HPS1).
(3) the back-pressure turbine running one of the boiler feed water pumps (HPS2).
(4) the letdown valve (HPSX).

An additional stream is provided to account for sundry boiler steam uses not otherwise defined in the model, and any losses (HPSL).

The combined exhaust steam (VP) from both turbines, the letdown valve and the extraction plant enters the desuperheater where it is cooled with a portion of steam condensate (SW0) to produce exhaust steam (EXS0) used by the evaporation and drying plants. A small portion of the exhaust steam, EXSD, is used internally to remove inert gases from the boiler feed water in the deaerator. Condensed steam (EXC) from the evaporation and drying plants is used as the boiler feed water. The recovered condensate is assumed to retain its original purity. The boiler feed water circuit is not perfectly closed because of losses from the deaerator vent (VENT), boiler blowdowns (WBD), inevitable exhaust steam losses (EXSL) and condensate losses (EXCL) across the sugar mill. Provisions have been made for losses in temperature δ_{TEXC} and/or pressure δ_{PEXC} of condensate between recovery from the process and reuse as boiler feed water.

The electrical power generated by the turboalternator is used in four duties:

(1) A throughput-dependent load is supplied to electrically-driven cane knives, shredder and bagasse mills in the extraction plant (NE).
(2) Power is supplied to electrically driven boiler feed water pumps (NPE).
(3) A throughput-dependent load is supplied for internal use other than prime movers in the extraction section, and boiler feed water pumping (e.g. conveyors, centrifuges, air blowers, fans, unspecified pumps, lights, air-conditioning) (NINT).
(4) A fixed power load is supplied to external users, such as the mill village, pumping station and agricultural estate (NOUT).

The split of the boiler feed water stream through the two pumps feeding the boiler is given by a pre-specified design parameter ϕ_{SP}, which represents the percentage of the total boiler feed water flow taken by the steam-driven pump.

The model of the cooling tower section was not changed from that in Starzak and Davis (2017).

Utility model parameter values
Values for conversion efficiency and specific energy use parameters were collected from literature and from anecdotal information provided by energy specialists among the sugar technology fraternity. These data are presented as ranges with the model default value listed in Table 1.

The specific power absorbed values are design or measured values of actual power consumption, and specifically, the power required by the prime mover drive under fairly stable operating conditions. The absorbed power values may be substantially smaller than installed power values, since the installed drive must be able to accommodate peak loads.

Values of energy conversion efficiencies are listed in Table 2.

Table 1. Specific energy absorbed and conversion efficiency parameters.

Parameter	Units	Range	Model[1]	References
Cane knives power absorbed, μ_{NECK}	MJ/tc	14- 42	15	Reid (1994), Rein (1995), Rein (2007), Renton (1974)
Shredder power absorbed, μ_{NESH}	MJ/tc	7-33	22	Boshoff (1994), Crossman (1994), Edwards (1982), Moor (1994), Parkin (2013), Rein (1995), Rein (2007), Reid (1994)
Bagasse mill power absorbed, μ_{NEBM}	MJ/tonne fibre (MJ/tf)	43-137	47[2]	Parkin (2013), Voigt and Hulley (2014), Wienese (1995)
Power for internal factory operations $\acute{\mu}_{NINT}$.[3]	MJ/tc	74-112	μ_{NINT} = 80	Goel (1992), Reid and Rein (1983), Dunn et al. (2009), Rein (2007), Belotti and Moreau (1996), Kinoshita (1999), Parkin (2013)

(1) Value used as default (base case) value in simulations.
(2) For each of two drying mills in series.
(3) The model uses μ_{NINT}, power for internal factory operation excluding cane preparation and BFW pumping. The literature values presented in this table are for all internal power consumption $\acute{\mu}_{NINT}$.

Table 2. Default value for energy conversion efficiencies used in simulations.

Parameter	Value
Cane knives turbine isentropic efficiency, η_{TCK}	0.55
Shredder turbine isentropic efficiency, η_{TSH}	0.63
Bagasse mill turbine isentropic efficiency, η_{TBM}	0.48
Back-pressure turbine (for power generation) isentropic efficiency, η_{TTA}	0.80
Back-pressure turbine (for boiler feed water pumping) isentropic efficiency, η_{TFP}	0.50
Isentropic efficiency of electrically driven boiler feed water pump, η_{PE}	0.80
Isentropic efficiency of steam driven boiler feed water pump, η_{PS}	0.80
Transmission efficiency of electrically driven prime movers, η_{GE}	0.72
Mechanical (gearbox) efficiency of steam driven prime movers, η_{GS}	0.72
Alternator efficiency, η_{GA}	0.97
Mechanical efficiency of steam driven pump gearbox, η_{GFP}	0.72

Efficiencies for the boiler, turbines, pumps and various gearing/transmission efficiencies in a sugarcane factory can vary widely with different equipment types, state of maintenance, operating regime and capacity utilisation. The available literature was reviewed (Edwards, 1982; Goel, 1992; Rein, 1995) and input sought from energy experts to select a set of efficiency values for the model (Table 2). Information relating to steam turbine isentropic efficiencies for prime movers could not easily be disaggregated into specific values per prime mover type since the efficiency relates to the design of the turbine and is not specific to the unit operation that the turbine drives.

The model also requires several other process-specific parameters to be chosen. Values used in the model are presented in Table 3.

Table 3. Additional parameters used in the utilities model.

Parameter	Default value
Boiler efficiency (on GCV), η_{Blr}	60%
Boiler water blowdown % of boiler feed water, ϕ_{WBD}	2%
Excess deaerator steam consumption % of theoretical demand, ϕ_{DEA}	100%
Physical loss of return condensate % of total return condensate, ϕ_{fEXC}	0%
Temperature drop of return condensate, δ_{TEXC}	5ºC
Pressure drop of return condensate, δ_{PEXC}	0.1 bar
Additional power load to external users, μ_{NOUT}	1.5 MW

Validation of the energy model

Starzak and Davis (2017) validated the underlying sugar mill model using data from the 90th Annual Review of the Milling Season in Southern Africa 2014/15 (Smith *et al*., 2015) and generally accepted estimates. Data from seven South African mills with diffusers and mud filtration were used to define ranges for 56 factory performance indicators. A list of 194 process parameters were varied to minimise a least-squares objective function made up of the squared difference between the model predicted factory performance indicators and the average value from the factory performance data. The parameter estimation was deemed to be sufficiently good when all the predicted performance indicators fell within one standard deviation of the average factory performance indicator (Starzak and Davis, 2017).

Ideally the upgraded utilities model should be validated in the same way, viz. using data from real sugar factories. However, a complete set of South African factory energy data to validate the model reliably is not available in the public domain. In addition, there is a wide variability in utilities design of sugar factories. The process-side designs of South African factories have, as their primary objective, extraction and recovery of the maximum amount of sucrose at high purity and low raw sugar colour. Although there are many design details that may be varied, this overriding objective provides a degree of similarity between different factories. In contrast, the energy design could have several different objectives. Several authors have demonstrated how the competing needs of process steam, power generation and fuel availability influence the choices made for the steam and energy design of a factory (Reid and Rein, 1983; Schorn *et al*. 2005). Some of the factors that must be considered are:

- On-site power requirements
- Local power requirements (e.g. for the mill village, agriculture)
- Power sales potential
- Bagasse sales potential
- Future expansion potential.

Thus, even if full data sets were available for the utilities model validation, the agreement between different energy data sets is likely to be much less than the equivalent process data. To demonstrate validity of the proposed utilities model structure, literature models by reputed authors were summarised to show the HP steam balance normalised for cane throughput (Table 4). Since the upgraded Sugar Milling Research Institute (SMRI) sugar mill model does not have provision for condensing extraction steam turbines (CEST), published models incorporating CEST were not included in the summary. The streams of interest for validation are identified by model tag names in Figure 3.

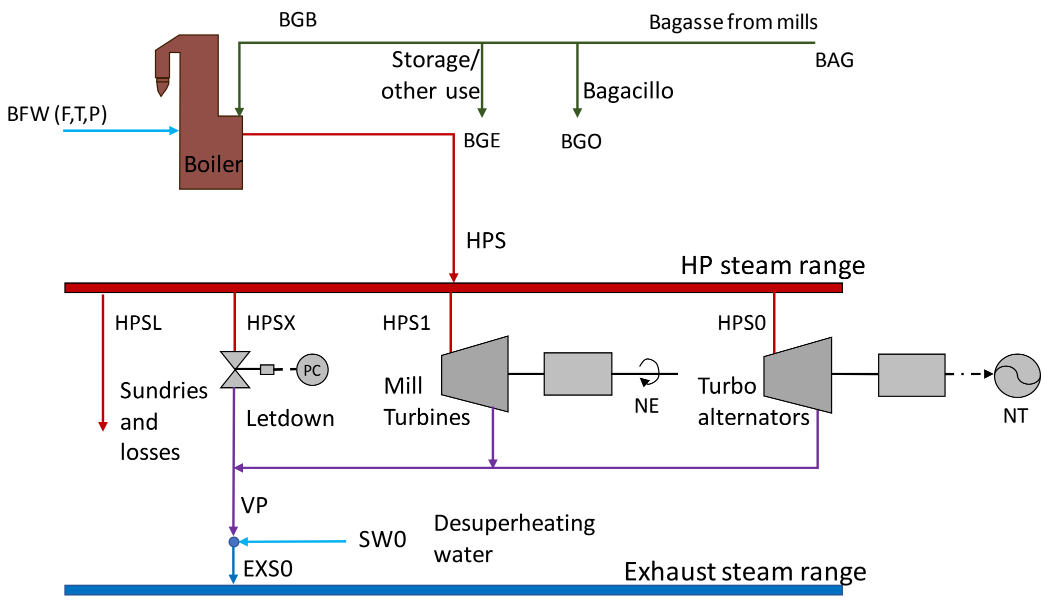

Figure 3. Schematic diagram of the HP steam distribution for the upgraded utilities model.

Stream names are identified by their model tag names. These are defined in Table 4.

Table 4. Results of validation simulation using model default parameter values(1).

Calculated stream flow	Units	Range from published models(2)	Model output $\phi_{ST} = 50\%$
Bagasse from mills, F^{BAG}	t/100 tc	28.4 - 36.9	30.8
Bagacillo, F^{BGO}	t/100 tc	0.5 - 1.2	0.84
Excess bagasse, F^{BGE}	t/100 tc	1.22 - 12.7	6.06
Bagasse to boilers, F^{BGB}	t/100 tc	22.4 - 31.5	23.9
HP steam, F^{HPS}	t/100 tc	47.8 - 70.1	48.6
HP steam to turboalternators, F^{HPS0}	t/100 tc	12.0 - 59.1	27.7
HP steam to mill turbines, F^{HPS1}	t/100 tc	4.3 - 27	7.86
HP steam to letdown, F^{HPSX}	t/100 tc	9.3 - 17.5	12.6
HP steam losses and sundries, F^{HPSL}	t/100 tc	1 - 2.7	1.48
Desuperheating water, F^{SW0}	t/100 tc	0.8 - 5.6	3.58
Exhaust steam, F^{EXS0}	t/100 tc	40.8 - 58.92	51.7
Power from turboalternators, P^{NT}	MJ/tc	102 - 288	129

(1) HP steam to the steam driven boiler feed water pump is not included in published models. The flow of steam to this turbine (F^{HPS2}) is negligible, less than 0.5 t/100 tc, and has been ignored in the validation exercise.
(2) Published models included in this study were Belotti and Moreau (1996), Reid and Rein (1983), Rein and Hoekstra (1994) and Rein (2007).

The simulation was run using the model parameter values shown in Tables 1 to 3 and using a value for extent of electrification of prime movers ϕ_{ST} of 50%, i.e. 50% of power required for cane knives, shredder and drying mills is supplied by steam turbines. The simulation outputs are presented in Table 4 in the fourth column (model output), with all normalised HP steam flows, the normalised total exhaust steam flow and bagasse flows falling within the range of the published models. This exercise does not validate the model structure or parameter choices since the ranges quoted are wide, given the wide variation in design choices of the published models. However, it does provide some confidence that simulation results are not unreasonable.

Simulation results: varying extent of electrification

The upgraded utility model allows for user variation of any of the power consumption or efficiency parameters, but in its present form, the MATLAB® implementation of the model does not facilitate major changes in configuration. However, the parameters ϕ_{ST} and ϕ_{SP} allow the extent of electrification to be varied such that the impact of selecting electrically driven, or steam driven prime movers (or a combination of these) can be tested.

Figure 4 presents the results of a series of simulations using the base case model parameter values, but with ϕ_{ST} varying between 0% (all extraction prime movers are electrically driven) to 100% (all extraction prime movers are steam driven). For all simulations, the boiler feed water pumping duty was split between steam and electrical drives in a ratio of 25:75 (ϕ_{SP} = 25 %).

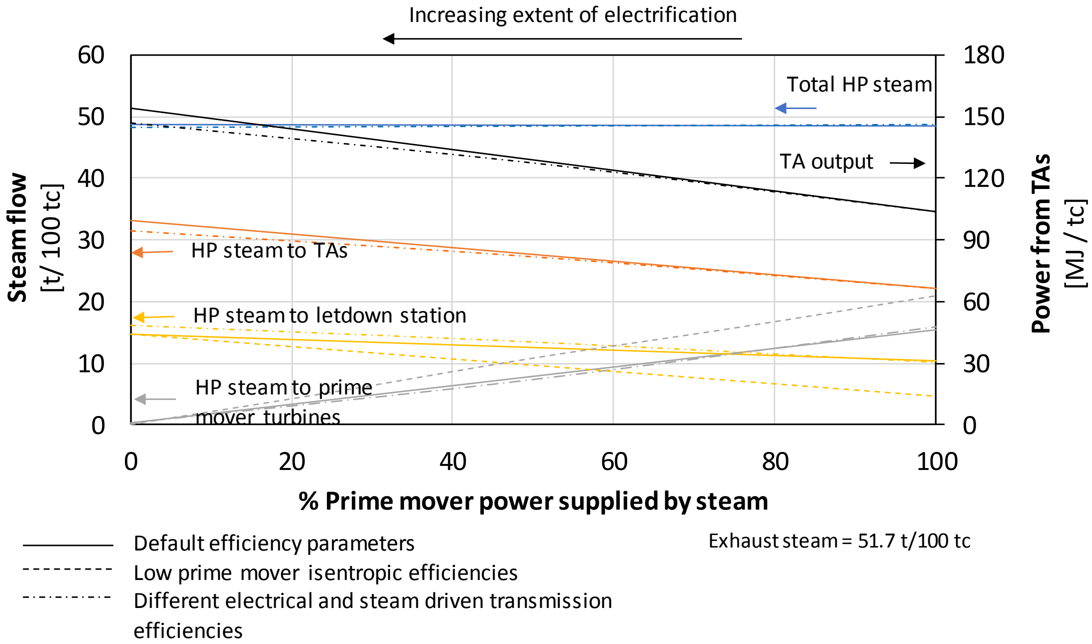

Figure 4. Simulation outputs using base case model parameters and varying proportion of prime mover power supplied by steam.

Solid lines indicate simulations using default parameters (Turbine efficiencies: $\boldsymbol{\eta_{TCK}}$ 55%, $\boldsymbol{\eta_{TSH}}$ 63%, $\boldsymbol{\eta_{TBM}}$ 48%; transmission efficiencies: $\boldsymbol{\eta_{GE}}$ 72%, $\boldsymbol{\eta_{GS}}$ 72%). Dashed lines indicate simulations with lower prime mover efficiencies ($\boldsymbol{\eta_{TCK}}$ 40%, $\boldsymbol{\eta_{TSH}}$ 45%, $\boldsymbol{\eta_{TBM}}$ 35%). Dot-dash lines indicate simulations with changed transmission efficiencies ($\boldsymbol{\eta_{GE}}$ 85%, $\boldsymbol{\eta_{GS}}$ 70%).

The exhaust steam consumption was kept constant at 51.7 t/100 tc. As anticipated, the amount of power produced by turboalternators (TA output, NT, Figure 4) increased with increasing extent of electrification (decreasing ϕ_{ST}) and similarly, the amount of HP steam going to the turboalternators (HP steam to TAs, HPS0) increased. However, the total HP steam required to power the turboalternators, the prime movers, and letdown steam to make up the required factory exhaust steam demand (total HP steam, HPS) was almost completely insensitive to changes in extent of electrification.

Extent of electrification: effect on overall factory energy efficiency

The upgraded utilities model allows a general analysis of the impact of electrification on overall efficiency. The back-pressure turbines that drive the alternators are usually a more efficient design than the prime mover turbines. For the solid lines in Figure 4, the efficiency for the back-pressure turbine was chosen at 80%, while those for the prime movers were between 48 and 63%. These efficiencies do not describe any energy wastage, but rather the isentropic efficiency of the change in condition of the steam from the HP to the exhaust side.

Briefly, the isentropic efficiency is defined as the amount of energy removed from the steam flow, relative to the amount that could be removed in the thermodynamic ideal case of a reversible, or isentropic process, discharging exhaust at the same pressure as the real process. This is classically shown on an entropy-enthalpy diagram such as the example in Figure 5, where the energy extracted from the steam is the difference in enthalpy between the HP (1) and exhaust steam (2).

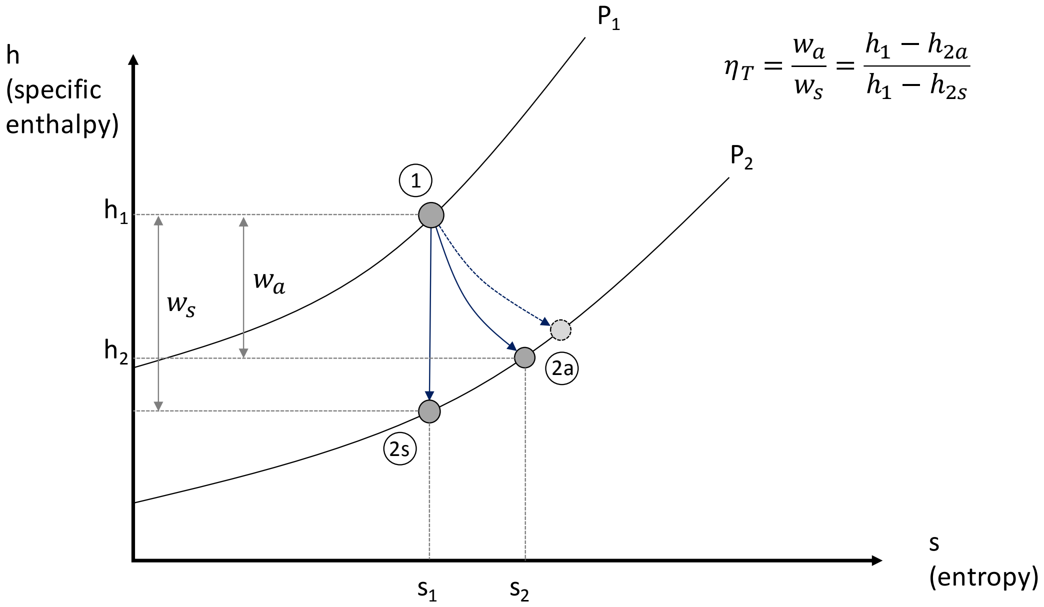

Figure 5. Enthalpy-entropy diagram for expansion of steam through a back-pressure turbine from pressure P_1 to P_2.

For the real process, steam expands from pressure P_1 to P_2 to a condition (2a) with a higher entropy than that of the initial HP steam. The energy extracted is the change in steam enthalpy, shown as w_a. The enthalpy change for the corresponding isentropic expansion to the same final pressure is w_s. All real processes are irreversible, so the isentropic efficiency is always less than unity. However, this efficiency does not imply that energy is *lost* in the expansion; the difference between w_s and w_a remains in the exhaust steam. The dashed arrow shows a less efficient expansion than the solid arrow.

The only routes for energy loss are thermal heat losses, e.g. through uninsulated pipes and vessels, and in energy conversions (e.g. from thermal to electrical energy, thermal to motive energy or electrical to motive energy conversions) such as in the gearboxes and couplings of the various drives. In the latter case, losses manifest as further thermal losses, friction and vibration losses and as noise. The magnitude of these losses is equipment dependent with modern gearings and couplings allowing lower transmission losses than traditional gearboxes and couplings (Rein, 2007).

Total HP steam demand is a direct measure of the total energy demand of the factory, which is made up of thermal, mechanical and electrical energy demands and losses. Changing the way mechanical energy is supplied to prime movers does not change the underlying mechanical energy demand. When the extent of electrification increases, from say 50% (base case) to 75% (e.g. ϕ_{ST} decreases from 50% to 25%) the amount of HP steam to the turboalternator increases and the amount going to prime mover turbines decreases. Because of the higher isentropic efficiency, more work is extracted *per tonne* of HP steam in the turboalternator than in prime movers, so overall, less mass flow of HP steam is required than for the base case. Thus, the collected exhaust from turboalternator and prime movers (VP, Figures 2 and 3) in the more electrified scenario has a smaller mass flow than in the base case. This stream also has a lower specific enthalpy than in the base case, such that the total enthalpy (specific enthalpy x flow) of VP is smaller in the 75% electrified scenario compared to the base case. However, the factory heating duties have been fixed at an exhaust steam demand of 51.7 t/100 tc for the base case simulation. The difference in flow of collected exhaust, VP, from the two scenarios and the exhaust steam demand is made up with letdown HP steam and the final exhaust steam quality is corrected with desuperheating water (SW0). Thus, if the total HP steam to turboalternators and prime movers decreases in the more electrified scenario, the total letdown steam must increase to make up the difference between collected exhaust and exhaust steam demand. There are small differences in the amount of desuperheating water required in the two scenarios, because of the difference in collected exhaust steam quality, but this does not materially affect the total HP steam demand.

Extent of transmission losses on overall factory energy efficiency

The effect of transmission losses is shown in Figure 4 as dash-dot lines. The simulations were re-executed after increasing the overall electrical transmission efficiency from 72 to 85%, and reducing the steam turbine transmission efficiency from 72 to 70%. A minimal additional amount of total HP steam must be generated when most prime mover power is supplied by steam, corresponding to the small increase in transmission losses in steam driven prime movers of 2%. This can be seen on the $\phi_{ST} = 1$ axis where the default parameters give a HP steam flow of 48.6 t/100 tc, while the changed transmission efficiencies increase this flow marginally to 48.7 t/100 tc. At the high electrification end of the graph ($\phi_{ST} \rightarrow 0$), there is a significant reduction in transmission losses, because the overall electrical transmission efficiency has increased by 13% relative to the default parameter case. A reduction in total power demand (TA output) results (at $\phi_{ST} = 0$ the default parameters give 154 MJ/tc, and the changed parameters give 147 MJ/tc). Nevertheless, the transmission efficiencies do not change the total HP steam demand significantly.

Extent of isentropic efficiency losses on overall factory energy efficiency

Figure 4 also shows the effect of the value of isentropic efficiency of prime movers on energy distribution. The dashed line is the result of simulations where the cane knife, shredder and drying mill turbines were reduced from 55, 63 and 48% to 40, 45 and 35%, respectively. The lower prime mover efficiencies have no effect at all on the total steam demand, because the underlying mechanical energy demand and energy losses have not changed in this simulation. Significant changes were seen in the distribution of HP steam between the letdown station and the prime movers to ensure that exhaust steam production remained unchanged.

Clearly, when the design exhaust steam demand is kept constant, the extent of electrification affects the amount of exhaust steam that is supplied by letting down HP steam, but does not in itself change the overall HP steam demand substantially.

Simulation results: Balancing function of letdown steam flow

A good factory energy design will have an appropriate portion of the exhaust steam supplied by letdown HP steam. The letdown station provides a buffer between dynamics in exhaust steam demand and electrical and mechanical power demand, and is ideally sized to ensure that exhaust steam from turbines never exceeds the factory thermal energy demand. Rein (2007) indicates that the letdown steam flow should be between 5 and 25% of the exhaust steam demand. Figure 4 showed that at default model parameters and high extent of electrification, the flow rate of letdown steam is higher than Rein's recommended range, reaching more than 30% of the total steam flow.

If, instead of fixing the exhaust steam demand, the total flow of steam through the letdown station is fixed to a value of 20 t/h, what other parameters could be changed to match HP steam supply to exhaust steam demand? In the following simulations, extent of electrification ϕ_{ST}, factory exhaust steam demand, F^{EXS0} and external power demand μ_{NOUT} were varied in such a way that the letdown steam flow was as close to 20 t/h as possible for each scenario. These simulations demonstrated that different design decisions could be made for the energy supply side, or the energy demand side of the factory, depending on the overall energy needs of the factory.

Extent of electrification: significance for energy supply design

If there is an external customer for power, e.g. power for agricultural operations is supplied by the factory instead of buying power from the grid, this can be shown as increasing the value of additional power load to external users, μ_{NOUT}.

Figure 6 shows the effect of increasing μ_{NOUT} for a 250 tc/h factory with a fixed exhaust steam demand of 51.7 t/100 tc, and a target letdown steam flow of 20 t/h.

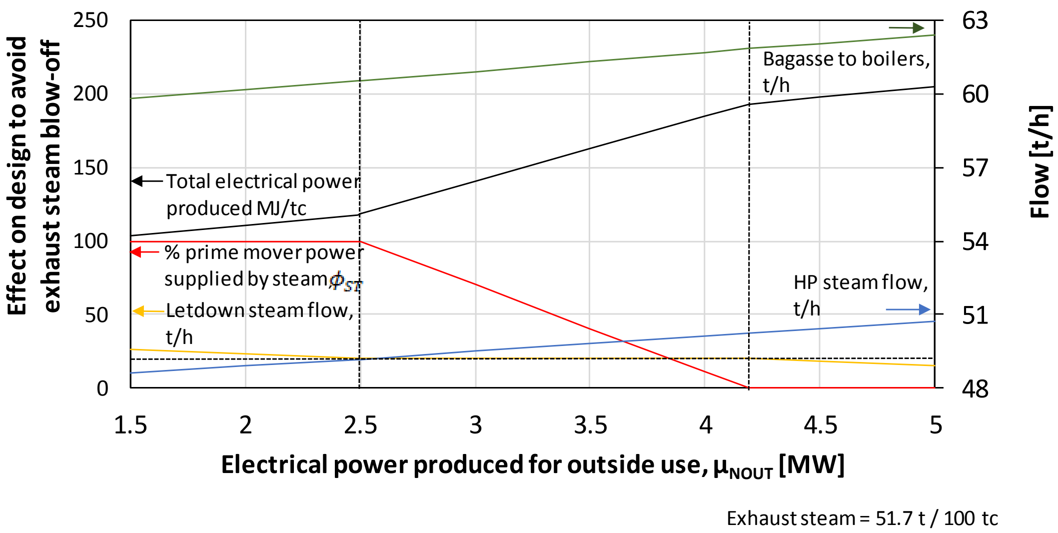

Figure 6: Effect of increased external power supply on factory energy design for a fixed exhaust steam demand and a target letdown steam flow rate of 20 t/h.

For each value of external power generation, the required extent of electrification to be able to supply the factory exhaust steam demand without decreasing the letdown flow rate or blowing off exhaust steam was determined. For less than 2.5 MW additional power, no electrification is required (100% prime mover power supplied by steam), and more than 20 t/h of HP steam must go through the letdown valve to supply the exhaust steam demand. However, when μ_{NOUT} exceeds 2.5 MW, some of the mill turbines must be electrified to maintain the letdown flow rate at 20 t/h. When μ_{NOUT} reaches 4.2 MW, all prime mover drives must be electrified to avoid producing too much exhaust steam. Above this value, the design letdown steam flow rate must drop below the target of 20 t/h, and the factory is at risk of blowing off exhaust steam during unsteady operations. For this series of simulations, the design condition would result in a net blow-off of exhaust steam when the external power demand exceeds 7.4 MW, since the combined turbine exhaust steam flow will exceed the factory exhaust demand.

In Figure 6 total thermal and mechanical loads have not been changed, but the electrical load has. The cost of this increased power generation is a greater amount of HP steam from 48.6 to 50.7 t/100 tc, and an increase of fuel from 59.8 to 62.4 t bagasse burned/h. Again, the extent of electrification has not made the factory more efficient, but has enabled a significantly larger amount of power to be produced at a marginally increased fuel cost.

Extent of electrification: significance for energy demand design

Figures 4 and 6 demonstrate that the total HP steam flow is dictated by the factory exhaust demand, suggesting that efforts to increase factory energy efficiency should be focussed in the back end. For a factory with no special thermal energy customers, such as a back-end refinery, and no external power customers, the energy design that gives no net surplus or shortage of bagasse may be far less efficient than is theoretically possible. Reductions in exhaust steam use might be possible through greater use of vapour bleeds or by using vapour bleeds from later evaporator effects for low grade heating duties, or through a variety of waste heat recovery and/or upgrade measures. These would have capital implications and might complicate factory control. Investment in improved exhaust steam use efficiency would not be supported if it would result in a large excess of bagasse. But, if the factory had an alternative market for bagasse, there may be benefits to driving down exhaust steam consumption.

A series of simulations was generated to show the extent of electrification required to maintain a target letdown flow rate for different values of exhaust steam demand. For these simulations, the target letdown flow was set at 20 t/h and the default values for external power demand and the various energy conversion efficiencies were used (Figure 7).

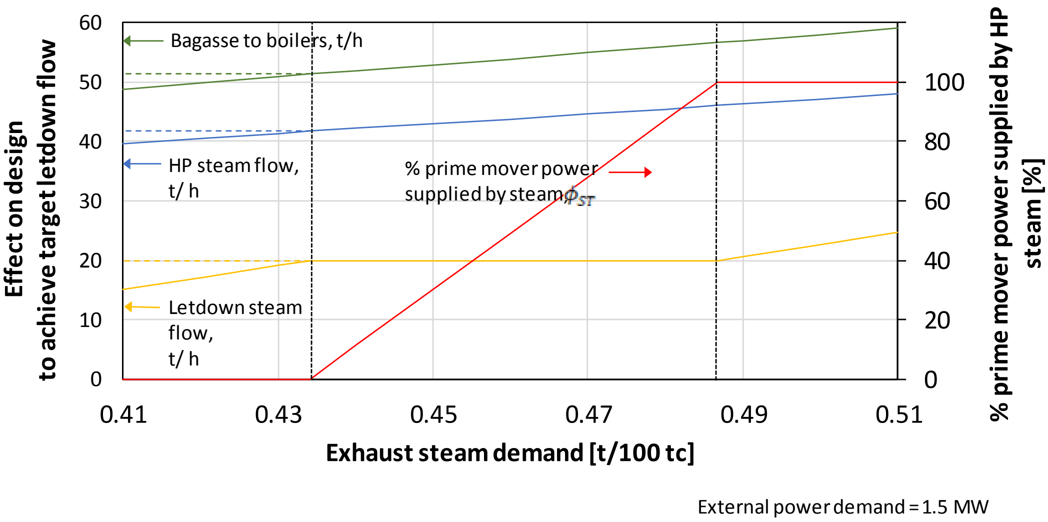

Figure 7. Effect of factory exhaust steam demand on factory energy demand for a fixed external power demand and a target letdown steam flow rate of 20 t/h. Dashed lines show bagasse and HP steam flow when the design value for letdown steam flow is not permitted to drop below 20 t/h.

When the exhaust steam demand was greater than 48.7 t/100 tc, with no electrification of prime movers, the letdown steam flow rate exceeded 20 t/h. Below this exhaust steam demand, the extent of electrification needed to increase (ϕ_{ST} decreased) to prevent the letdown steam flow from exceeding 20 t/h. Below 43.4 t exhaust steam/100 tc, even with full electrification of prime movers, the design letdown flow would be less than the target value. The simulations predicted that the factory would have a net surplus of exhaust steam when the demand for exhaust dropped below 33.5 t/100 tc. Incidentally, this result compares well with estimates of minimum steam usage of 33 to 35 t/100 tc determined by various authors (Rein, 2007).

For these simulations, the underlying energy demand of the factory decreased because of operating and design changes in the factory. This has led to a decrease in HP steam flow, and consequently fuel consumption. The key feature of Figure 7 is the relationship between extent of electrification and exhaust steam demand at the target letdown steam flow rate. If the factory design targets an exhaust steam demand below 48.7 t/100 tc to keep fuel consumption down, then, if there is no electrification of prime movers, the factory can expect to blow off exhaust steam regularly. Under these conditions, the HP steam must be made, regardless of back end efficiency, to drive the cane preparation equipment, and the investment in reduced exhaust steam consumption will not have any benefit for fuel consumption. This effect is depicted by dashed lines (Figure 7) at exhaust steam flow rates below 43.4 t/100 tc. Therefore, while not the *cause* of improved steam and fuel consumption efficiency, electrification of prime movers, can *enable* improvements in back end efficiency while maintaining a reasonable balance between HP and exhaust steam demand.

Other energy design considerations

The upgraded utilities model has been used to perform simulations for many different energy design scenarios for one generic 250 tc/h factory with the same sugarcane, extraction and sucrose recovery characteristics. On the steam and power supply side, the possible design options involving extent of electrification as a balancing variable were explored, and the significance of the design choices in terms of energy efficiency, power generation for external use and fuel consumption have been explored. However, there are other factors that must be considered in energy design decisions. Boshoff (1994) and Rein (2007) present the relative advantages and disadvantages of turbine and motor drives for prime movers. These include the relative costs of the technologies, distance from boilers for HP steam reticulation, speed/torque characteristics, ease of maintenance and ease of operation. Typically, the design of a new build or retrofit factory steam and power network will be an iterative process balancing fuel availability, electrical power demand, capital costs, operability and also potential expansion opportunities in the future (Schorn *et al*., 2005). Reid and Rein (1983) analysed various scenarios for the design of the Felixton II mill expansion that illustrate these interacting aspects and demonstrate the effect of design decisions on the overall factory energy efficiency and flexibility for future expansion and modification.

Conclusion

The upgraded utilities model provides a more realistic representation of energy consumption in a raw sugar mill than that of the originally published raw sugar mill model (Starzak and Davis, 2017). Model parameters selected from published work on specific energy consumption and conversion efficiencies were used in simulations, and model outputs compared well with other published models, indicating that the upgraded utilities model was able to describe HP steam distribution at least as well as the published models.

Simulations for varying values of the parameter for extent of prime mover electrification illustrated the various ways in which increasing the extent of electrification can be exploited to improve overall factory energy efficiency and fuel consumption. While increasing the proportion of prime mover power supplied by electric drives does not directly improve HP steam demand or fuel consumption, benefits of electrification could be realised through (1) enabling higher amounts of electric power to be produced for external customers at marginally increased fuel costs; or (2) by permitting lower exhaust steam generation for the same underlying process energy characteristics, thereby providing an incentive to reduce back end steam demand for factories where reduction in fuel consumption is a major driver. In both these scenarios, the extent of electrification is part of a series of design and investment decisions that must be made to realise improved energy efficiency.

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Nomenclature

Stream tags

BAG	Bagasse from diffuser
FW0	Boiler feed water before pumps
BFW	Boiler feed water after pumps
BGB	Bagasse to boilers
BGE	Excess bagasse
BGO	Bagacillo to filtration
CANE	Cane input to factory
EXSL	Exhaust steam sundries and losses
EXSS	Exhaust steam to sugar drying
EXSE	Exhaust steam to evaporator train
HPS	Total HP steam
HPS0	HP steam to the turboalternators
HPS1	HP steam to prime movers
HPS2	HP steam to the steam driven pump
HPSL	HP steam sundries and losses
HPSX	HP steam to the let down station
MEG	Megasse flow from diffuser
NE	Power drawn by prime movers
NEBM	Power drawn by bagasse mills
COAL	Supplementary fuel
EXC	Return exhaust condensate
EXCL	Exhaust steam condensate losses
EXCS	Exhaust condensate from drying
EXCE	exhaust condensate from evaporators
EXS0	Desuperheated exhaust steam
EXSD	Exhaust steam to Deaerator
NECK	Power drawn by cane knives
NESH	Power drawn by shredder
NINT	Internal factory power demand
NOUT	Power drawn by external consumers
NPE	Power drawn by feed water pumps
NT	Total power from turboalternators
SW0	Desuperheating water
VENT	Deaerator vent
VP	Exhaust steam before desuperheating
WBD	Boiler blow down
WBM	Boiler feed water makeup

Ratio parameters

ϕ_{ST}	Fraction of prime mover duty supplied driven by steam turbines
ϕ_{SP}	Fraction of boiler feed water pumping duty supplied driven by steam turbines
ϕ_{WBD}	Fraction of boiler feed water that is lost as boiler blow down
ϕ_{fEXC}	Fraction of return exhaust condensate that is not available for use as boiler feed water or desuperheating water
ϕ_{DEA}	Deaerator excess steam demand ratio, the ratio of exhaust steam in excess of the minimum amount to achieve the boiler feed water temperature and pressure specification, to the theoretical minimum exhaust steam flow.

Delta parameters

δ_{TEXC}	Condensate temperature drop; Difference in temperature between collected exhaust steam condensate and the process outlet condensate temperature
δ_{PEXC}	Condensate pressure drop; Difference in pressure between collected exhaust steam condensate and the process outlet condensate pressure

Power consumption parameters

$\acute{\mu}_{NINT}$	Specific power utilisation for factory operations
μ_{NINT}	Specific power utilisation for factory operations excluding boiler feed water pumping and prime movers in the extraction plant
μ_{NEj}	Specific power consumption in the extraction section for unit j
μ_{NECK}	Specific power consumption for cane knives
μ_{NESH}	Specific power consumption for shredder
μ_{NEBM}	Specific power consumption for bagasse mills
μ_{NOUT}	Total power drawn by external consumers

Energy conversion efficiency parameters

η_{blr} Boiler efficiency on GCV
η_{TCK} Cane knives turbine isentropic efficiency
η_{TSH} Shredder turbine isentropic efficiency
η_{TBM} Bagasse mill turbine isentropic efficiency
η_{TTA} Back-pressure turbine (for power generation) isentropic efficiency
η_{TFP} Back-pressure turbine (for boiler feed water pumping) isentropic efficiency
η_{PE} Isentropic efficiency of electrically driven boiler feed water pump
η_{PS} Isentropic efficiency of steam driven boiler feed water pump
η_{GE} Transmission efficiency of electrically driven prime movers
η_{GS} Mechanical ("gearbox") efficiency of steam driven prime mover
η_{GA} Alternator efficiency

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