The Sugarcane Industry : the Largest Global Thermal Renewable Sector

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Part II : Commercial and Environmental Factors

Abstract

There is a temptation with all generation and cogeneration projects to push the boundaries of technology in order to maximise the output of electricity. Drawing on the experience of the sugarcane industry it is possible to show that that is far from commercially wise, both in terms of the high pressure end of the cycle and the low pressure end.

Many people see the industry as a dirty, highly polluting one but that would be inaccurate when looking at the modern industry. Again there are lessons to be learnt for the UK but caution too when it comes to assessing the potential for electricity from fibrous fuels.

Power Station Thermodynamics 1.0.1

In theory, a steam turbine operates with a Rankine Cycle. Plotting the theoretical process on a temperature / entropy [T/s] diagram emphasises why it is called a cycle :

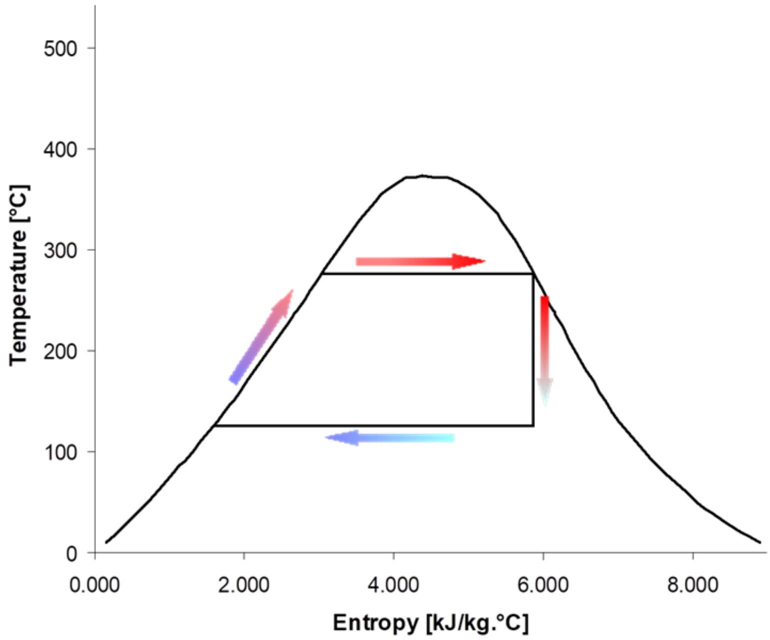

Figure 1 : Rankine Cycle on T/s Diagram

The First and Second laws tell us that, for reversible processes, the work done in the cycle is equal to the heat flux :

$$\oint \delta W = \oint \delta Q$$

and that the heat flux is related to the temperature and the change in entropy :

$$\oint \delta Q = \oint T ds$$

It therefore follows that :

$$\oint \delta W = \oint T ds$$

So, the work done is a function of the integral of the temperature and the change in enthalpy and an integral is the area under a curve :

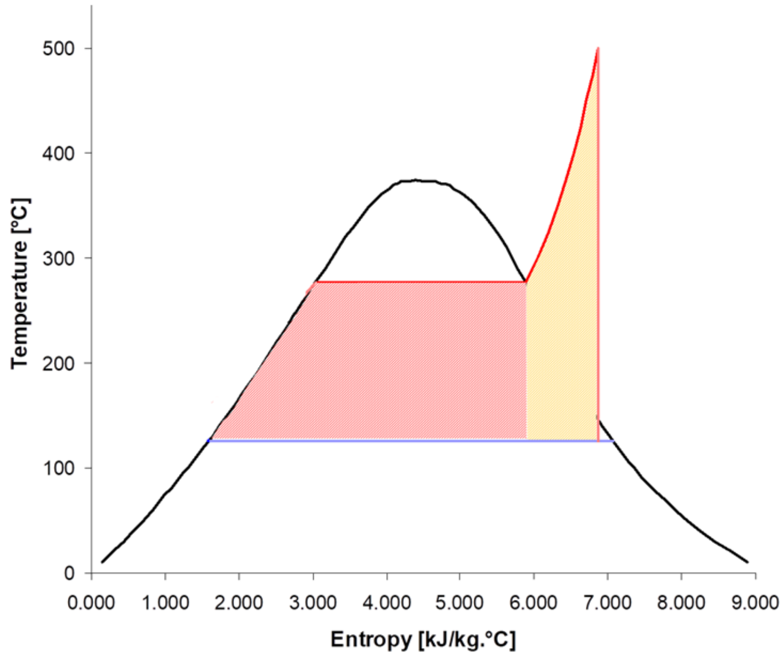

Figure 2 : Work Done on T/s Diagram

The diagram shows the work done for a simple cycle and the effect of adding superheat to the cycle. The fact that these are T/s diagrams emphasises the importance of HP steam temperature rather than HP steam pressure when discussing the station although the two are, of course, related under saturation conditions.

Note that this paper discusses industrial power stations so there is no mention of complex matters such as multiple superheating or supercritical conditions.

Station Efficiency : Steam Conditions

In the real world, efficiency distorts the isentropic perfection of the Rankine cycle so operating lines are sloped, the angle being proportional to the efficiency. Whilst it should be self-evident that selecting a higher saturation temperature gives more work, what is not so well understood is that there is an optimum HP steam temperature for any one saturated steam condition :

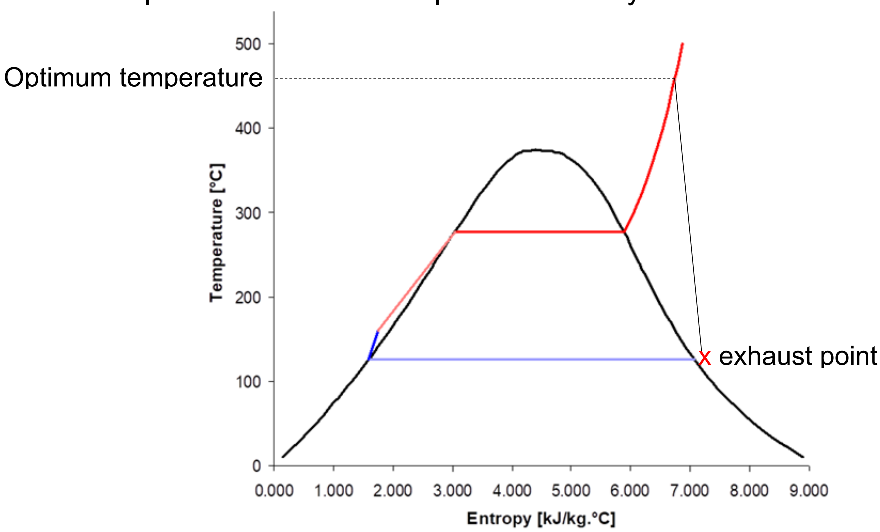

Figure 3 : Optimum HP Steam Temperature

HP Steam Conditions

The data can be proven mathematically but visual presentations allow more ready assimilation.

Figure 3 shows the optimum HP steam temperature for a particular HP steam pressure – which dictates the [horizontal] HP steam saturation temperature – and a particular turbine efficiency – which dictates the slope of the machine operating line. It is the optimum because if a higher temperature is selected then the exhaust will have too much superheat and if a lower temperature is selected then the exhaust will not have enough superheat or might even be wet, to the detriment of the back-end blades.

So, for any one machine, there is a nest of operating curves for a series of HP steam saturation temperatures and hence pressures :

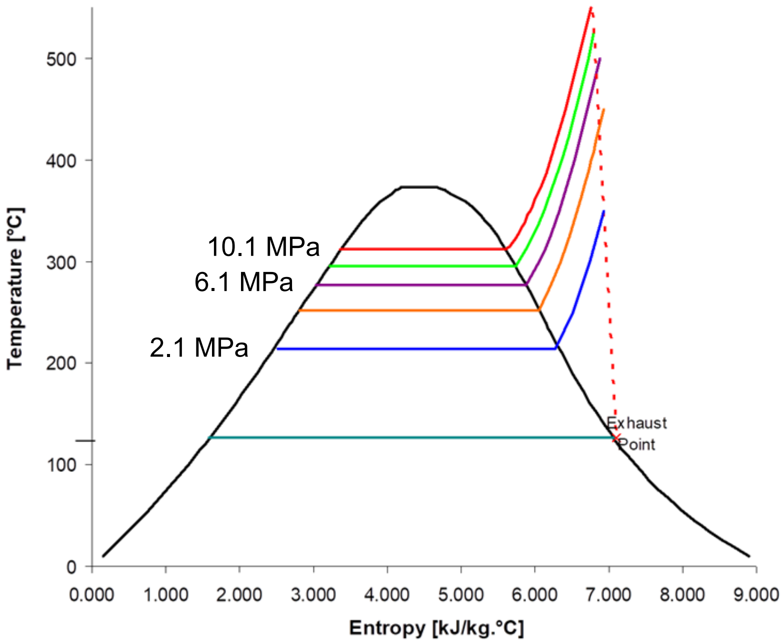

Figure 4 : Work Done at Different HP Steam Conditions

Note that the saturation temperature increments decrease with each pressure increment and, in addition, the length of the saturation temperature line decreases. In other words, the incremental area under the curve and hence the incremental work done is decreasing : increasing HP steam conditions takes one into an area of diminishing returns.

Another way of visualising that is to plot the relative work obtained [electricity exported] for each HP steam pressure at machine optimal conditions :

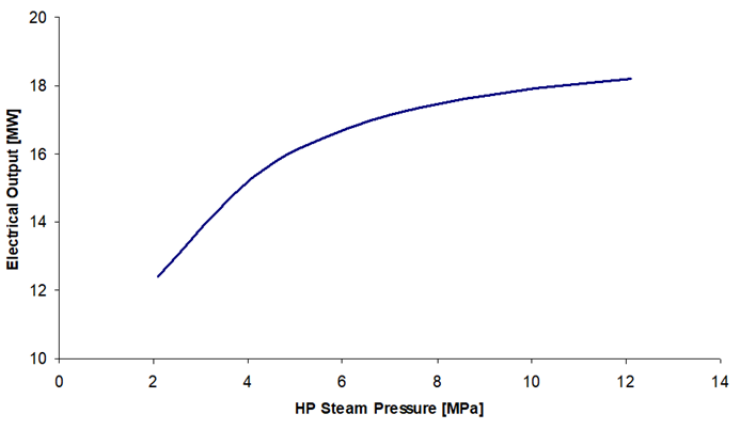

Figure 5 : Work Done at Different HP Steam Conditions

The diminishing returns are clear to see in Figure 5 as the curve asymptotes with increasing pressure.

LP Steam Conditions

The reverse is true at the LP end of the cycle : the bell curve widens with reducing temperature so incremental work done increases with each increment of saturation temperature reduction. The difference is that the LP temperature is determined by the ability to achieve lower temperatures and not by the saturation pressure.

At the lower end of the range, a 2 °C temperature reduction can deliver a 1% increase in work done. On that basis, it is worthwhile to design for close approach temperatures – both in the condenser and in the cooling tower. Perhaps one day one will also see heat pumps used to cool the condenser with the heat being used to reheat the boiler feedwater.

Basic Economics

It has already been shown that the curve of electrical output over HP steam conditions is asymptotic. In order to understand the economics it is necessary to understand the relationship between HP steam conditions and cost. In this paper it is the capital cost which is considered.

The high pressure implications for a boiler's pressure parts are relatively straight forward. Drum thickness is calculated from first principles but flanges, piping and tubing, for instance, come in standard sizes and thicknesses so there are step changes in capabilities not dissimilar to the standard frame size issue with mechanical equipment.

As an example, there may be little difference in the cost of the pressure parts for a boiler designed for 4 000 kPa compared to a 3 000 kPa one of the same capacity but a substantial difference for a 4 200 kPa one because the manifolds all go up one schedule in thickness and the boiler flanges, valves and mountings have to change from a Class 300 rating to a Class 600 rating.

We all tend to think of boiler pressures in standard steps, often linked to old imperial standards : 3 100 kPa [~450 psig], 4 100 kPa [~600 psig], 6 100 kPa [~900 psig] and so on. In fact that has been the case in this paper. However, it is more important to think in terms of the cost steps imposed by readily available materials than to think in terms of such historical pressure steps.

Additionally, it is not the operating pressure that counts, it is the highest pressure in the system, usually many hundreds of kilopascals above the operating pressure because of the pressure drop across the superheater(s), the static head, operating margins and allowances for safety valve settings.

Neither is it solely a question of pressure : pressure part components must be designed for the maximum mean wall temperature that the components are exposed to. For boiler tubes exposed to furnace radiation this is in the order of 50°C higher than the saturation temperature at the highest steam drum safety valve setting and for superheater tubing the design temperatures are even higher to take into account :

- lower internal heat transfer coefficients;
- variations in steam flow during sudden load changes;
- variations in steam flow due to poor flow distribution;
- variations in heat fluxes resulting from uneven gas flows in the boiler;

In summary, as HP steam conditions increase not only do material thicknesses increase but so too do material specifications.

The other major implication for higher HP steam conditions is the quality of feedwater, boiler water and steam. Above about 60 bar the water quality requirements become far more stringent and demineralisation and volatile treatments becoming a necessity. The control of boiler water quality becomes critical to minimise steam impurities and prevent deposits forming in the superheater(s), control devices and turbine blades.

Similar implications exist for the turbine although the turbine inlet conditions are slightly below the boiler outlet conditions. These limitations are, of course, a function of material selection as well as material thickness in the inlet sections and they vary from manufacturer to manufacturer, the first temperature break point typically being somewhere between 480 °C to 510 °C.

Overall, the material limitations on turbine inlet sections follow the same engineering issues as for steam piping, i.e. the temperature limitations of a given material quality of a specified thickness is basically a function of the operating pressure. However, in addition to the pressure/temperature limitations on the materials from a creep life and softening point of view, additional limitations may be set by the physical design of the inlet valves and distribution pipes and wheel chamber design limitations come into play – above certain pressures and/or temperatures, a manufacturer's design might require an inner casing to protect the outer casing from excessive stresses.

Higher temperatures may also require a change in rotor material – and, in particular, temperatures above 525 or 530 °C may require relatively advanced alloys to maintain the integrity of the equipment.

In the end a series of very thorough costing exercises is required but in order to limit the amount of effort it is useful to have a 'scale-up' factor in the form of :

$$Price' = Price \times \left(\frac{P'}{P}\right)^{x}$$

The value of 'x', the power to which the pressure ratio is raised, seems to be in the range of 0.3 to 0.4 in the real world. Figure 6 uses a value of 0.35 to overlay the relative capital cost onto the curve of Figure 5 :

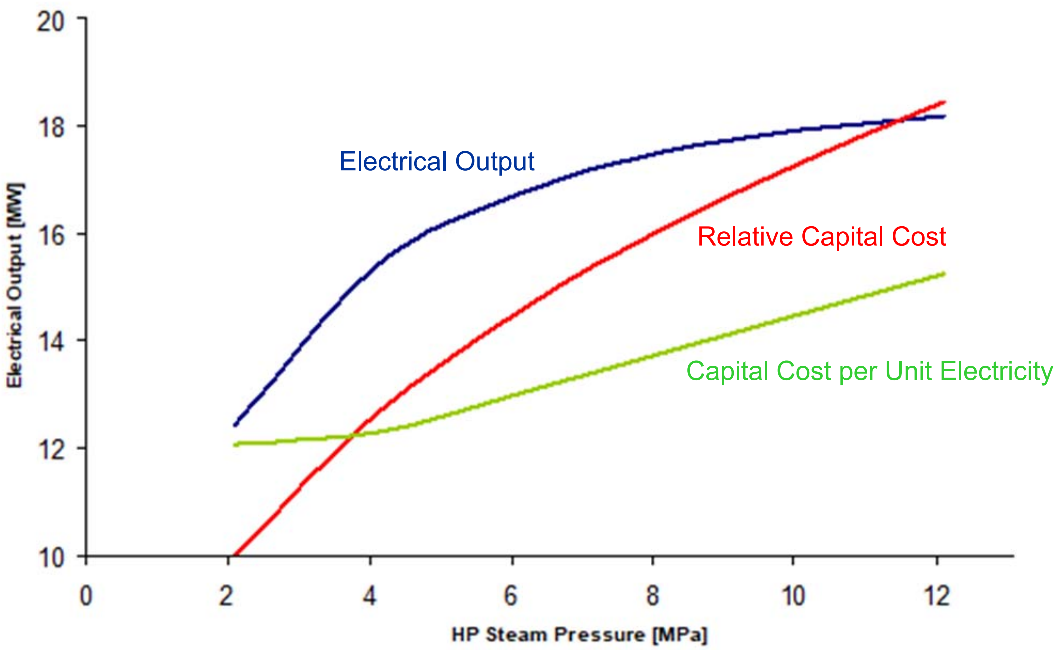

Figure 6 : Relative Capital Cost and kW/$ Overlays

The data in Figure 6 is taken from a real case in a country with poor electricity selling prices. The capital costs were subsequently verified by costing exercises. It can be seen that, in this case, it was not possible to justify HP steam conditions greater than 4 000 kPa.

In many other sugarcane industry cases the optimum has been found to be at somewhere between 6 000 and 8 000 kPa but never more than 8 500 kPa. That has not stopped certain factory owners from racing ahead to install 11 000 and even 12 000 kPa stations [where the optimum HP steam temperature is in excess of 530 °C] in some mad 'mine is better than yours' competition.

The discussion on LP condition economics is in the next section.

Station Efficiency : Generation and Cogeneration

If the LP temperature is so important to cycle efficiency then it seems anomalous to contemplate cogeneration rather than generation because most instances of commercially viable cogeneration require relatively energetic LP temperatures. There is no anomaly in fact.

Generation

Most of the energy input to raising steam is for the [latent] heat of vapourisation and in generation that is reversed in the condenser without any work being done :

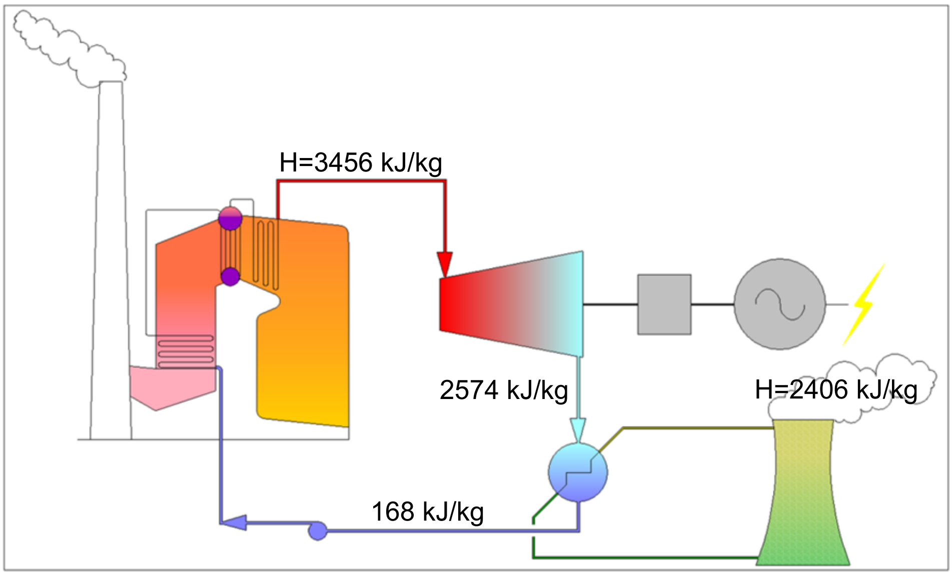

Figure 7 : Enthalpies in a Typical Industrial Cycle

In Figure 6, for industrial generation conditions, about 70% of the HP steam enthalpy is dumped to atmosphere so, no matter how efficient the boiler or the turbine, the overall station efficiency is very poor. Clearly, for utility stations, a lot of effort is made to reduce the atmospheric dumping but the principle is still the same.

Cogeneration

Co-generation, as the name implies, couples a user of low-grade heat to the power station. Many of these users are industrial but there have been examples of district heating schemes [the Battersea / Pimlico scheme in London comes to mind] using the latent heat. The user is referred to as the ‘host’.

In the sugarcane industry, the LP vapour is used to drive the multiple effect juice evaporator. Although the LP temperature is much higher than in the generation case [and therefore less work is done in the turbine], the efficiency of the overall cycle is much higher :

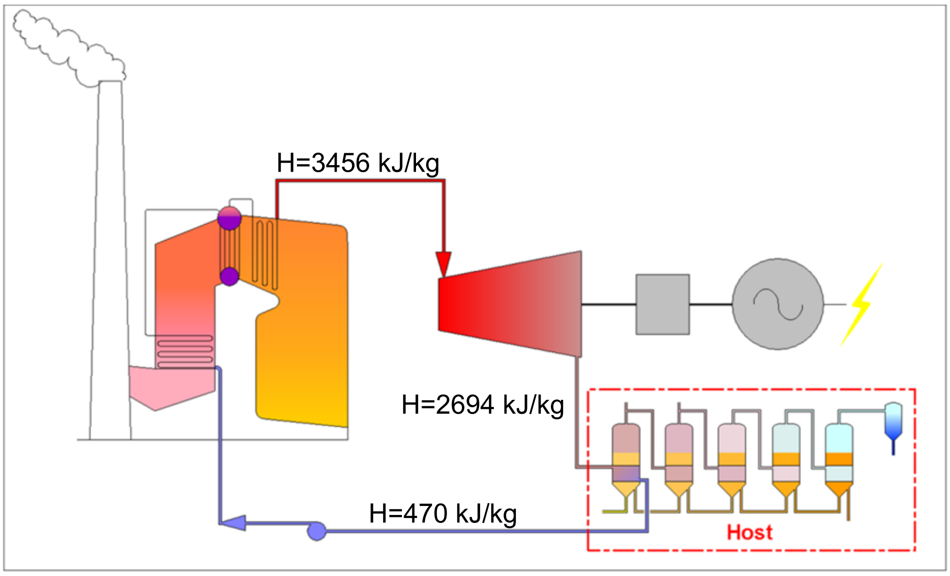

Figure 8 : Enthalpies in a Typical Industrial Cogeneration Cycle

Again, a more easily assimilated but less technical approach is to look at an energy flow diagram :

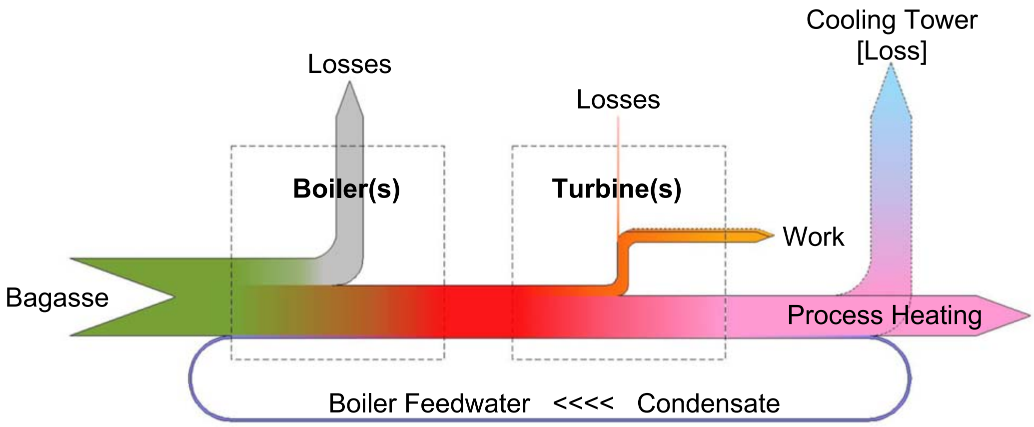

Figure 9 : Energy Flow Diagram for Both Generation and Cogeneration

At a global scale, the problem with cogeneration is in finding suitable hosts to make use of the vapour from the turbines. This is particularly the case where stations are in rural areas which is why a highly distributed grid with small stations might be a future trend, even to the extent of creating domestic 'power stations'. However, that extreme would almost certainly exclude the use of fibrous fuel.

Another approach which has been mooted is to use a combined cycle cogeneration system with a low temperature generator acting as the host : a steam cycle followed by a [say] ammonia cycle, both generating electricity.

LP Condition Economics

The sugarcane industry is, regrettably, very conservative and its engineers cautious but it is perhaps typical of many cogeneration industries. As a result, many factories operate with exhaust steam at 120 °C and some operate at 125 or even 130 °C.

The only reason for that is that capital cost has been saved by installing small HT surface area equipment. That was done despite the fact that sugar is heat labile so higher temperatures lead to greater losses, a sad reflection on companies driven by accountants and the like.

In practice, there is no duty in the factory which requires a temperature above 90 °C so when electricity export becomes a likelihood the first duty of the engineers should be to optimise the factory. In terms of the LP condition that means driving down the exhaust steam condition and hence spend on HT surface area. However, it has already been shown that small changes in the LP temperature can have a significant effect on work done and LP surface area is much cheaper than the HP surface areas of the boiler.

Equally important is to drive down the steam consumption ['percent steam on cane']. That too is counter-intuitive because it leads to surplus bagasse which must be used for generation rather than cogeneration if a disposal cost is to be avoided. However, the bagasse is almost free and, if it makes sense, with suitable storage it can be used to generate out of crop and so extend the period over which electricity is exported.

In practice, these aspects of project optimisation are much more complex and hence more difficult to optimise than the HP steam condition.

The 'Green' Power Station

Whilst thermal power stations are polluting in one way or another, they have an important role to play in energy infrastructure. Fibrous fuel burning stations had a worse reputation than most because of the particulates issue but that is no longer true.

As an example, US Sugar's bagasse fired #9 boiler, commissioned earlier this year, passed the following EPA standards, among many others :

$PM_{2.5}$	0.0268 lb/MMBtu [absolute]
NO_x	0.10 lb/MMBtu [30 day rolling]
CO	900 ppmvd @ 3% O_2 [30 day rolling]

The $PM_{2.5}$, at 0.0268 lb/MMBtu, is approximately 38 mg/Nm^3 at 6%O_2 by volume dry. That is not dissimilar to the European requirements for particulates. It is achieved on #9 boiler by a 5 field ESP with the ID fan protected by a scrubber system as discussed in the first paper.

The NOx, at 0.10 lb/MMBtu, is approximately 154 mg/Nm^3 at 3% O_2. Again, that is not dissimilar to the European requirements. On #9 boiler it is achieved by selective non-catalytic reduction [SNCR] using urea injected directly into the furnace. Care was taken to protect the membrane walls in proximity to the injection points as corrosion is a potential issue.

The CO limit is also not dissimilar to the European requirements and, of course, it is in the Owner's interest to minimise CO emissions because the combustion of carbon to CO releases only one third of the energy that its combustion to CO_2 achieves. [Low CO is achieved by careful detailing of the over-fire air system but when NO_x is an issue some CO release has to be accepted as reducing CO increases NO_x.]

Carbon Capture

Sugarcane is a highly efficient user of solar energy compared to many crops and, in addition, it has been shown to locally reduce the ambient temperature by almost 1 °C due to its transpiration rate. In converting solar energy to chemical energy it uses CO_2 of course so is a useful means of carbon capture.

Broadly speaking, half of the carbon goes to the sucrose and half to the fibre so, even though the power station emits CO_2, it is emitting only half of the carbon that was captured.

The sucrose from sugarcane doesn't have to be the product in its own right, it can readily be converted to ethanol for use as a liquid fuel as can be seen in Brazil for instance. One model that is put forward as a readily accomplished, near time horizon action to combat climate change is therefore to develop the industry along the lines of Brazil, producing a renewable fuel to displace oil products and surplus electricity from a renewable source. The distillery can also operate throughout the year, exporting electricity on a 'firm' basis.

A 2017 paper in the journal Nature Climate Change suggests that a land area of 116 million hectares under cane would reduce global CO_2 emissions by 5.6% and states that that land area is not much more than the land area devoted to corn and soya production in the USA.

UK Fibrous Fuel Potential

The potential for fibrous fuel fired power stations in the UK is limited. The fundamental issues are those of fuel availability, transport and storage.

Energy Power Resources' straw burning station at Ely is rated at 36 MW nominal net export and that requires 200 000 t/a straw. The best estimate for straw availability seems to be ~1.5 t/ha of cereal crop land which means that 133 000 ha of cereal crop are required each year to run Ely. In other words the land requirement is 3 700 ha per MW for agricultural waste in any year.

Another crop residue which has been mentioned is that from oilseed rape. The UK has about ~500 000 ha of rape in any one year and the residue yield again seems to be ~1.5 t/ha of rape which means that the country has available ~750 000 t/a of residue which is equivalent to say 135 MW of generating capacity.

The rape example doesn't mean that a 135 MW station makes sense : the crop is scattered throughout the country and, being a fibrous fuel, transport is by volume rather than by mass so is relatively expensive.

It is clear that without energy crops – which would provide a greater energy density – the UK will not be able to generate any substantial amount of fibrous fuel electricity, no matter what the technology. On the other hand, what capacity is established will be able to offer the same availability as comparable fossil fuel stations – perhaps three times that offered by wind power.

European Beet Industry

It is tempting to assume that the [temperate climate] sugarbeet industry follows the same model as the sugarcane industry but that is not correct. Sugarbeet is a biennial root crop and there are two crucial differences between it and sugarcane : it has a 50% higher sucrose content than cane and it has a much lower fibre content – typically 4% compared to 12 to 14% in cane. The fibre yield per ton of sugar is therefore very low.

To compound the problem, the fibre is essentially pith which is even more difficult to de-water mechanically. A typical pulp from the presses might only be 30% DS.

Accordingly, the sugarbeet industry has developed a market for its pulp as a cattle feed and is a fossil fuel based sector.

Drax

To pull these two papers together, it is worth mentioning Drax power station which is rated at 3.9 GW. After testing co-firing fibrous fuel some fifteen years ago, four of its six boilers have been converted to only firing fibrous fuels, the vast majority of which comes from North America as wood chips and/or pellets.

In September of 2019 the CEO of the Drax group was quoted in The Times as saying that he hoped to switch some of his supply to bagasse from Louisiana.

Conclusions

A review of industrial scale power station thermodynamics reminds one that the higher the HP steam conditions and the lower the LP temperature, the greater the amount of work done [electricity generated]. It shows that for any one turbine there is an optimum superheat temperature for any selected HP steam pressure.

In practical terms, the problem with ever higher HP steam conditions is the reducing incremental improvement in work done for ever higher capital cost increments. It is possible to find an optimum set of conditions by calculating the capital cost per unit of electricity. That has to be moderated by the impact on the operating costs but that is outside of the scope of this paper. In many cases the optimum pressure has been found to be at somewhere between 6 000 and 8 000 kPa, the optimum temperature being a function of the barrel efficiency of the turbine(s).

The LP end of the cycle is more generous due to the bell-curve nature of the T/s diagram for water : even small reductions in the condenser temperature can give significant improvements in work done. That leads one to question the wisdom of cogeneration which today rarely works with temperatures as low as can be obtained with cooling water systems in generation. However, generation cycles are not at all efficient because most of the residual energy in the LP vapour is dumped to atmosphere. Cogeneration uses that energy to drive the thermal processes of the host.

The main issue with cogeneration is matching hosts with power stations. It works well when the main economic driver is the host but rarely works when the driver is a power station. Ways need to be found for new types of host such as low temperature cycles or even, in the perhaps distant future, low temperature thermovoltaic cells.

There is no issue with achieving world class emissions when burning fibrous fuel, the issues for the UK are fuel availability and the cost of transport and storage of those fuels. Agricultural wastes offer only small scale possibilities [which is not say that those opportunities should not be taken] so energy crops are required. Beet sugar is not one of those and Drax has found that it needs to import agricultural wastes from North America – and is now considering using bagasse.