Could biomass-fueled boilers be operated at higher steam temperatures? Part 3: Initial analysis of costs and benefits

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ABSTRACT: The efficiencies of biomass-fueled power plants are much lower than those of coal-fueled plants because they restrict their exit steam temperatures to inhibit fireside corrosion of superheater tubes. However, restricting the temperature of a given mass of steam produced by a biomass boiler decreases the amount of power that can be generated from this steam in the turbine generator.

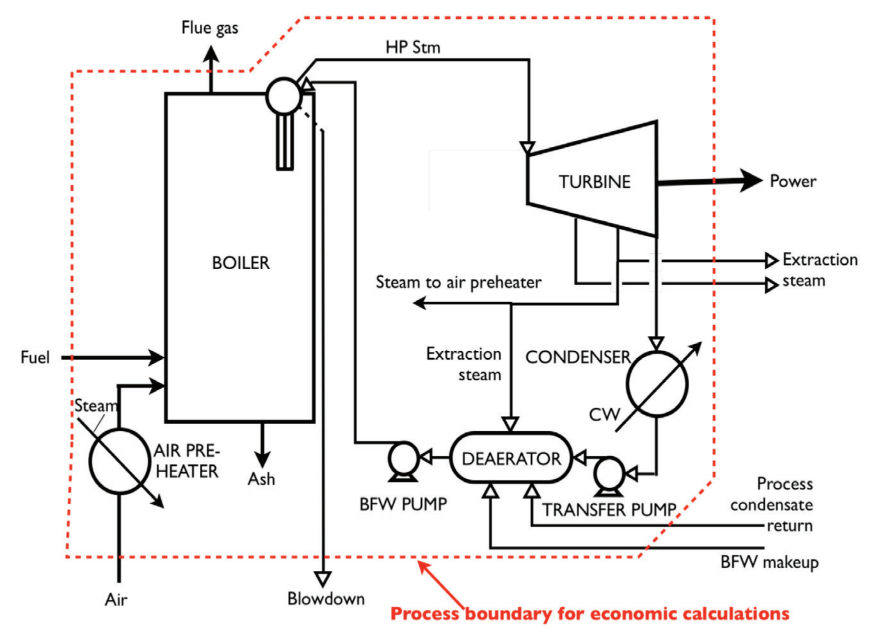
This paper examines the relationship between the temperature of superheated steam produced by a boiler and the quantity of power that it can generate. The thermodynamic basis for this relationship is presented, and the value of the additional power that could be generated by operating with higher superheated steam temperatures is estimated. Calculations are presented for five plants that produce both steam and power. Two are powered by black liquor recovery boilers and three by wood-fired boilers. Steam generation parameters for these plants were supplied by industrial partners. Calculations using thermodynamics-based plant simulation software show that the value of the increased power that could be generated in these units by increasing superheated steam temperatures 100°C above current operating conditions ranges between US$2,410,000 and US$11,180,000 per year. The costs and benefits of achieving higher superheated steam conditions in an individual boiler depend on local plant conditions and the price of power. However, the magnitude of the increased power that can be generated by increasing superheated steam temperatures is so great that it appears to justify the cost of corrosion-mitigation methods such as installing corrosion-resistant materials costing far more than current superheater alloys; redesigning biomass-fueled boilers to remove the superheater from the flue gas path; or adding chemicals to remove corrosive constituents from the flue gas. The most economic pathways to higher steam temperatures will very likely involve combinations of these methods. Particularly attractive approaches include installing more corrosion-resistant alloys in the hottest superheater locations, and relocating the superheater from the flue gas path to an externally-fired location or to the loop seal of a circulating fluidized bed boiler.

Application: The value of additional power that could be generated by raising biomass boiler steam temperatures by 100 Celsius degrees appears to justify substantial expenditures to avoid superheater corrosion at the higher temperature, including the use of much more expensive corrosion-resistant alloys or substantial design and operational changes, particularly if the high temperature superheaters were designed for rapid replacement.

The 1997 Kyoto Protocol set the goal of stabilizing greenhouse gas concentrations in the atmosphere at a level that would avoid dangerous climate change by obliging industrialized countries to reduce such emissions. European countries that ratified this protocol have adopted systems of incentives and penalties to reduce greenhouse gas emissions. Many have developed and implemented technologies that improve the efficiency with which steam and power can be generated from biomass fuels.

Biomass fuels are attractive for power generation because they are renewable and almost carbon-neutral. However, the combustion of biomass produces superheater ashes that contain corrosive elements like chlorine, potassium and sodium. When climate change and renewable fuels were of less concern, outlet steam temperatures of biomass-fueled boilers were kept low to avoid fireside corrosion of superheater tubes and/or pluggage in the convective sections. Such temperature limitations restricted the power that could be generated from biomass fuels.

The United States (U.S.) Department of Energy (DOE) has funded a project to evaluate corrosion mitigation strategies that would enable biomass-fueled boilers to operate with higher superheater steam temperatures. Raising superheated steam temperatures would increase the efficiency of biomass-fired Combined Heat and Power (CHP) plants. The use of U.S.-grown renewable biomass fuels would reduce the U.S. dependence on imported fuels and fossil fuels. This DOE-funded project includes a review of the science and technology of superheater



1. Process mass and energy streams included in the software model.

corrosion in biomass boilers; calculations of the economic benefits of increased steam temperatures; and laboratory and field evaluations of alternative tube alloys at temperatures near and beyond current operating temperatures.

Previous results from this project have been published in a series of three papers. The first reviewed European approaches to inhibiting superheater corrosion in biomass boilers by using corrosion-resistant alloys, modifying boiler designs, and using process additives [1]. The second reviewed the performance of corrosion-resistant alloys that may be suitable for biomass boiler superheaters operating at higher temperatures [2]. The third paper described tests to evaluate the corrosion resistance of candidate alloys at higher temperatures in a black liquor recovery boiler that operates with unusually corrosive superheater conditions [3]. Two other papers report laboratory tests of the corrosion resistance of candidate superheater alloys for higher temperature operation [4] and field tests of candidate alloys in operating boilers [5].

The work on which the current paper is based analyzed the economic impacts of higher superheater temperatures in biomass-fueled boilers. Boiler performance and process conditions were estimated using proprietary thermodynamics-based plant simulation software. We present financial calculations of the benefits of increased superheated steam temperatures based on the analysis of steam and power production in five example boilers burning biomass. These financial benefits are compared with the additional costs of alloys that could resist corrosion at the higher superheater temperatures. Where the financial benefits exceed these costs, using more corrosion-resistant alloys to enable higher steam temperatures offers a net financial benefit to the boiler operator. Second, we compare the financial benefits of higher steam temperatures with the cost of fuel treatments or additives [1] applied to reduce the concentration of corrosives in the superheater ash. Third, we compare the financial benefits with the cost of boiler redesign, e.g., of constructing a circulating fluidized bed (CFB) boiler with the superheater in the loop seal [1] instead of in the convective pass.

CALCULATION METHODS

The primary tool used for these calculations is a thermodynamic software program called StmPowr® (Table Mountain Consulting; Golden, CO, USA), which models CHP systems that supply process steam to an adjacent plant (or sell it for district heating) and simultaneously generate electricity for plant use or external sale. For example, in a pulp and paper mill, a typical steam turbine would supply high-, medium- or low-pressure steam to dry paper, evaporate water from black liquor, and heat process units such as pulp digesters. It would also generate electrical power.

The StmPowr software calculates the net electrical power and process steam generated from a Rankine cycle power plant. Almost all power plants use the Rankine cycle as their heat engine. This cycle has four components. First, the working fluid (boiler feedwater) is pressurized by a pump. The high pressure water is heated at constant pressure to become a dry saturated vapor (steam). This dry steam expands through a steam turbine, generating power and lower pressure process steam. The remaining turbine exhaust steam is condensed immediately or later to a saturated liquid. The working fluid (condensate) is recirculated and heated to become boiler feedwater, continuing through a closed condensate – boiler feedwater – steam loop.

Required inputs to the model include the rate of fuel input,

Specified Input Conditions	Specified Exit Conditions	Calculated Parameters
Fuel input rate and temperature, gross heating value of dry fuel, fuel moisture content, and elemental composition	Temperature and pressure of the superheated steam produced	Thermal efficiency of boiler
Combustion air input rate, temperature, and moisture content	Blowdown rate	Rate of generation of high pressure, superheated steam
Boiler feedwater temperature and pressure		Boiler feedwater input rate
Internal steam used for air heating and soot-blowing (pressures, temperatures, and flows)		Flue gas exit temperature
Correlation between flue gas exit temperature and fuel input rate		Ash output rate

I. Components of boiler sub-module.

Specified Input Conditions	Specified Exit Conditions	Calculated Parameters
Flow rate of high pressure superheated steam to the turbine inlet	Pressures and flow rates of process steam extracted from the turbine	Power generated for the steam conditions specified
Temperature and pressure of steam delivered to the turbine		Temperatures of process steam extracted from the turbine
Isentropic efficiency of the turbine		

II. Components of the steam turbine sub-module.

the fuel characteristics (elemental composition, gross heating value, and temperature), and process and equipment parameters for various unit operations that will be described later in this paper. The software uses the flow rate, temperature and pressure of the inlet steam and turbine efficiency parameters to predict the temperature, pressure, and flow rates of the steam extracted from the turbine and the power generated. **Figure 1** shows the configuration and the process mass and energy streams included in the model. The program calculates the flow rates and conditions of the process streams that cross the process boundary (red dashed line) in this figure.

COMPONENTS OF THE STEAM POWER CYCLE CALCULATION MODULE

The Rankine cycle analyzed by the StmPwr software program consists of seven unit processes, which are discussed in the following sections:

1. Boiler
2. Steam turbine
3. Exhaust steam surface condenser
4. Condensate transfer pump
5. Deaerator
6. Boiler feedwater pump
7. Combustion air preheater

Boiler

The boiler sub-module calculates the net rate of high-pressure steam generation at specified steam conditions (T, P) and other specified parameters from the fuel input rate, as shown in **Table I**. The steam rate calculation is based on the heat loss method [6,7].

Steam turbine

The steam turbine sub-module calculates the power generated by the calculated flow of superheated steam generated by the boiler. The turbine operates at its own specified isentropic efficiency. The power generated is calculated from the temperature, pressure, and flow rate of the steam supplied to the turbine; the temperatures, pressures, and flow rates of process steam extracted from the turbine; and the temperature, pressure, and flow rate at the turbine exhaust, as shown in **Table II**.

Exhaust steam condenser

For condensing turbines, this sub-module calculates the cooling water flow required to condense the exhausted steam at its specified temperature, pressure, and flow rate, as summarized in **Table III**. The condensate returns to the deaerator for reuse as boiler feed water.

Condensate transfer pump

The condensate transfer pump moves the condensate from

Specified Input Conditions	Specified Exit Conditions	Calculated Parameters
Temperature, pressure and flow rate of turbine exhaust steam	Temperature and pressure of condensate	Flow of cooling water required to condense exhausted steam
	Inlet temperature of cooling water	
Feed water make-up rate and temperature	Outlet temperature of cooling water	

III. Components of exhaust steam condenser sub-module.

Specified Input Conditions	Specified Exit Conditions	Calculated Parameters
Temperature, pressure and flow rate of condensate from the condensate sump	Deaerator pressure	Power required by condensate transfer pump
Pump and motor efficiency		

IV. Components of condensate transfer sub-module.

Specified Input Conditions	Specified Exit Conditions	Calculated Parameters
Temperature, pressure and flow rate of condensate return to deaerator	Boiler feedwater temperature	Flow rate of steam extracted from the turbine to the deaerator at the specified temperature and pressure
Temperature and flow rate of boiler feedwater make-up		
Temperature, pressure, and flow rate of steam used for deaerator heating		

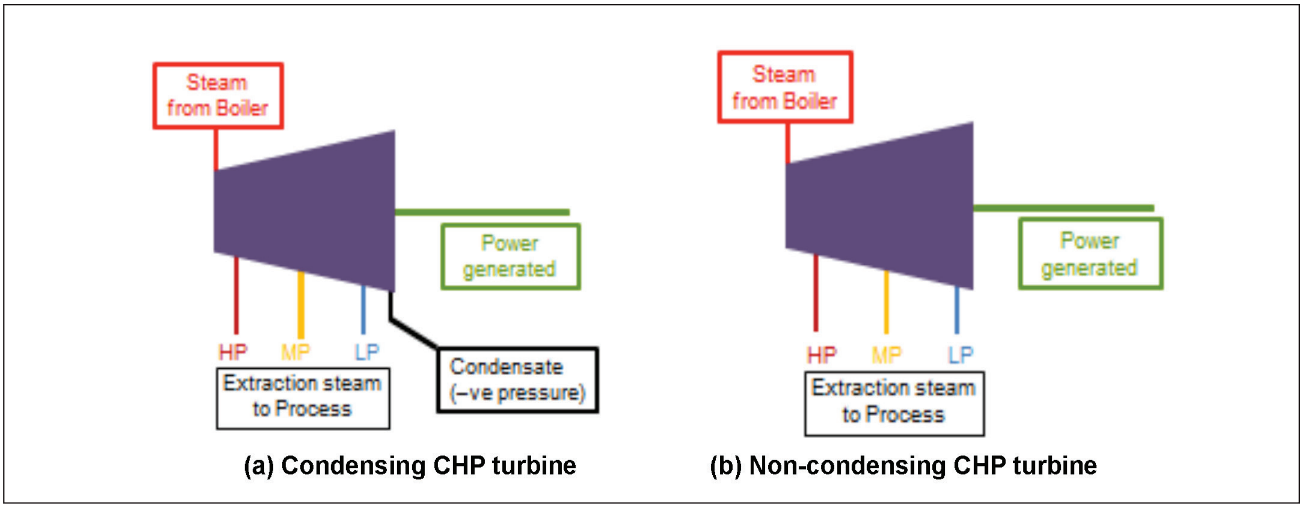
V. Components of the deaerator sub-module.

Specified Input Conditions	Specified Exit Conditions	Calculated Parameters
Temperature, pressure and flow rate of boiler feedwater flow from deaerator	Pressure of feedwater at boiler inlet	Power required by boiler feedwater pump
Efficiency of the feedwater pump and motor		

VI. Components of the boiler feedwater pump sub-module.

Specified Input Conditions	Specified Exit Conditions	Calculated Parameters
Temperature and pressure of steam extracted from turbine to heat combustion air	Temperature of combustion air entering boiler	Required flow rate of steam extracted from turbine to heat combustion air
Temperature of ambient air entering preheater		

VII. Components of the combustion air sub-module.



2. Types of steam turbines used in calculations of costs and benefits of increasing superheater steam temperature.

the turbine steam condenser sump to the deaerator. Components of the sub-module are shown in **Table IV**.

Deaerator

Boiler makeup feedwater is added to the condensate in the deaerator. This combined feedwater is heated to the saturation temperature at the deaerator pressure by steam extracted from the turbine. The components of the deaerator sub-module are listed in **Table V**.

Boiler feedwater pump

The boiler feedwater pump raises the pressure of the boiler feedwater from the pressure in the deaerator up to the boiler inlet pressure, as shown in **Table VI**.

Combustion air preheater

The combustion air preheater is a heat exchanger that uses turbine extraction steam to heat the outside air from ambient temperature to the temperature required for fuel combustion, as summarized in **Table VII**.

BOILER SYSTEMS ANALYZED

To determine the magnitude of the economic costs and benefits of higher superheater steam conditions, we asked industrial collaborators in the project to supply data from typical biomass-fueled boilers.

Calculations were made with data from five boilers: two recovery boilers and three boilers burning hogged wood. Hog fuel is produced from waste bark or wood that has been processed by a disintegrator, or hog, that processes the wood into chips or shreds of practically uniform size.

The two boilers used for the calculations, designated recovery boiler B and recovery boiler M, were based on models. Data for recovery boiler B were supplied by a boiler manufacturer as part of a software model of a recovery boiler in a typical pulp mill where process steam is extracted from the turbine. Steam data for recovery boiler M came from a WinGEMS (Metso Automation; Helsinki, Finland) software model of a 1000 o.d. tons/day unbleached pulp mill with a recovery boiler operating at 1450 psi. These two recovery boilers produced power outputs of 52 MW and 53.6 MW, respectively, with conventional steam conditions.

All three biomass boilers were actual units. Biomass boiler C operates on the Pacific Coast and is fired by hogged fuel produced from sea-floated logs. Biomass boiler H also operates on the Pacific Coast, but fires about 2/3 beetle-killed pine, about 1/3 sea-floated logs and a small amount of wood from construction waste. Biomass boiler M is a biomass boiler recently converted to bubbling fluidized bed operation by a boiler manufacturer. It burns hogged wood.

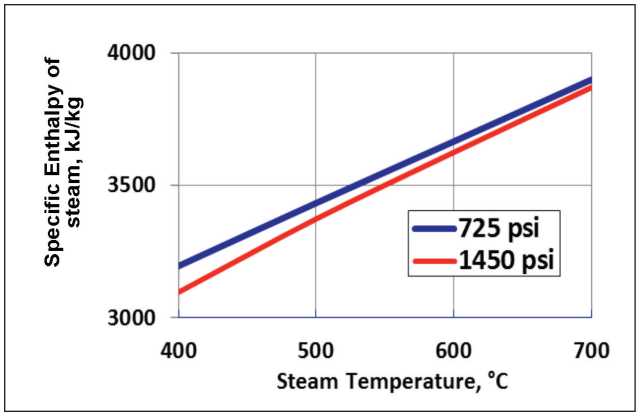
Figure 2 illustrates the difference between the two types of steam turbine that are used in the calculations that follow. Condensing CHP turbines are shown schematically in Fig. 2a. Steam used to turn the rotor is extracted at high, medium, and low pressures (or sometimes at only two pressures). Any remaining steam is then condensed in water-cooled tubes in a surface condenser. Non-condensing (back-pressure) turbines, shown schematically in Fig. 2b, extract all the steam used to turn the turbine rotor as process steam to be used in an adjacent plant.

Both of the example recovery boilers deliver their steam to condensing turbines while all three wood-fired boilers deliver their steam to non-condensing turbines. Condensing turbines use all the steam supplied by the boiler to turn the turbo-generator rotor and generate power. Steam that has passed through the full length of the turbine is condensed on water-cooled tubes in a surface condenser. This condensation decreases the volume of the steam by about 1800 times and creates a vacuum in the condenser. Surface condensers can produce pressures of 90 to 100 kilopascals (13 to 14.5 psi) below atmospheric pressure. Creating this vacuum allows the steam supplied by the boiler to expand much more, producing a larger enthalpy change through the turbine and increasing the turbine efficiency. For this reason, utility boilers, where efficiency is of primary importance, always use condensing turbines. Note that the vacuum pressure developed by the surface condenser depends on the temperature of the cooling water, which could be subject to seasonal changes, and on the partial pressures exerted by non-condensable gases (NCGs) accumulated in the feedwater. Because the turbine efficiency increases as the condenser vacuum increases, accumulated NCGs should be stripped out and the condensing temperature should be kept as low as possible. The steam condensate, stripped of NCGs, is returned to the boiler as feed water.

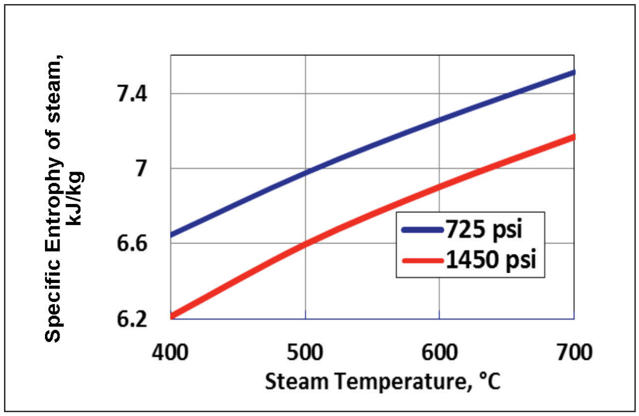
The simplest non-condensing (back-pressure) steam turbine would extract all the steam used to drive the turbo-generator rotor as process steam at a series of decreasing pressures. "Back-pressure" simply indicates that the steam is extracted at pressures above atmospheric. The process steam flows are extracted at the pressure(s) required by the process operations, regardless of the load on the turbine. This is achieved by controlling the steam flows at the extraction points. The extraction pressures are chosen to suit the particular process steam requirements of the plant where the boiler is located. The extracted steam can be used in an adjacent process plant (e.g., a pulp and paper mill or chemical plant) or for district heating. The steam condensate is later augmented by make-up boiler water, deaerated, and returned to the boiler.

Once saturated steam has been generated in a boiler, relatively little additional fuel energy is required to raise its temperature and pressure to the superheat required to provide more efficient power generation. Therefore, if a process plant already needs a substantial amount of process steam, adding a non-condensing turbine offers a simultaneous supply of relatively inexpensive power without the need for the substantial volumes of cooling water that would be required to operate a surface condenser in a condensing turbine. However, the capacity of a turbine to generate power falls substantially when process steam is extracted at appreciable pressure instead of being expanded into a vacuum in a surface condenser.

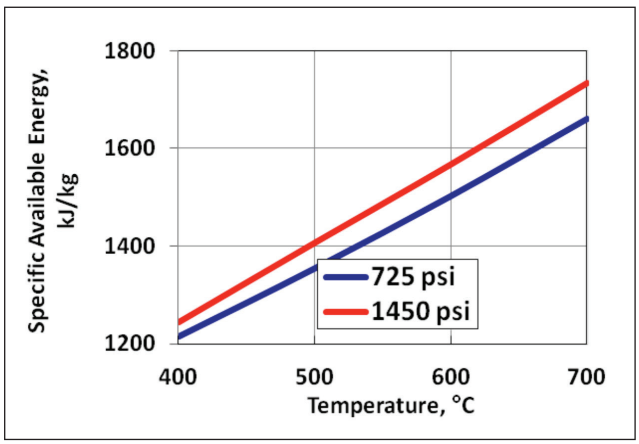
The biomass-fueled boilers studied in the current project all produce a combination of heat and power (CHP). All of them provide process steam to an adjacent plant and all of them generate power. All are once-through turbines that do not take advantage of the efficiencies of reheating the steam in the boiler between various turbine stages.



3. Increase of specific enthalpy of steam with temperature at 50 and 100 bars pressure (725 and 1450 psi).



4. Increase of specific entropy with temperature at 50 and 100 bars pressure (725 and 1450 psi).



5. Increase of specific available energy with increasing steam temperature at 50 and 100 bars pressure (725 and 1450 psi).

THERMODYNAMIC BASIS FOR THE INCREASING VALUE OF STEAM WITH INCREASING TEMPERATURE

The principle that underlies the work described in this paper is that the availability of energy in steam increases as the temperature of the steam increases. Availability, also called available energy, is a thermodynamic property like enthalpy. Gibbs introduced this concept in 1873 [8] by defining "capacity for entropy" as the amount by which the entropy of a body can be increased without changing the energy of the body or increasing its volume. For steam, the available energy is the maximum amount of mechanical work that can be obtained from it in an ideal engine by bringing it to the temperature and pressure of a reference atmosphere without allowing heat to pass into it or out of it, i.e.:

Available energy = Enthalpy of steam – (Entropy of steam) x (Temperature of surroundings) (1)

Boiler Type and Identifier Code	Recovery Boiler		Biomass (wood)-Fired Boiler		
	B	M	C	H	M
Steam production, kg/sec	91.8	101.68	119.7	59.98	60.48
Steam pressure, bar	61.22	99.66	41.84	89.63	89.63
Steam temperature, °C	465.6	471.1	399.0	482.2	480.0
HP steam pressure, bar	N/A	N/A	N/A	N/A	28
HP steam temperature, °C	N/A	N/A	N/A	N/A	328.2
HP steam enthalpy, kJ/kg	2933.74	2838.42	3132.56	3146.11	3069.18
HP steam extraction flow, kg/sec	0	0	0	0	15.12
MP steam pressure, bar	12.75	12.75	11.22	12.75	12.75
MP steam temperature, °C	247.8	190.86	335.2	330.2	287.4
MP steam enthalpy, kJ/kg	2923.63	2814.46	3124.03	3110.13	3016.76
MP steam extraction flow, kg/sec	8.82	39.31	15.12	15.00	6.05
LP steam pressure, bar	5.10	5.10	4.15	4.15	4.15
LP steam temperature, °C	152.60	152.60	177.1	175.9	167.9
LP steam enthalpy, kJ/kg	2768.81	2756.43	2811.52	2808.91	2791.51
LP steam extraction flow, kg/sec	63.76	48.26	104.58	44.99	39.31
Exhaust steam pressure, bar	0.14	0.14	N/A	N/A	N/A
Exhaust steam temperature, °C	100	100	N/A	N/A	N/A
Exhaust steam enthalpy, kJ/kg	2715.63	2711.29	-	-	-
Exhaust steam flow, kg/s	19.22	14.11	0	0	0
Condensate flow, kg/s	72.58	87.57	119.7	59.98	60.48
Condensate pressure, bar	18	18	1.24	1.24	1.24
Adj. condensate temperature, °C	108.5	108.5	100	100	100
Intrinsic Turbine Stage Efficiencies					
High pressure stage	0.890	0.890	0.813	0.813	0.813
Medium pressure stage	0.459	0.459			
Low pressure stage	0.887	0.887			
Exhaust stage	0.650	0.650			

VIII. Steam system parameters for the five boilers studied.

More rigorously:

$$a = h - T_0 s \qquad (2)$$

where:
a = specific available energy, kJ/kg
h = specific enthalpy, kJ/kg
T_0 = absolute temperature of the surroundings, °K
s = specific entropy, kJ/kg

Consider the effect of increasing temperature on the steam parameters in this equation. **Figure 3** shows that, as the temperature of a unit mass of steam at constant pressure increases, its specific enthalpy increases. **Figure 4** shows that the specific entropy of the steam also increases with the steam temperature at constant pressure.

The availability of energy from the steam increases with increasing temperature because the specific enthalpy of steam increases proportionally more with temperature than does the specific entropy of steam. This conclusion is demonstrated in **Fig. 5**, which shows the temperature dependence of the specific available energy of steam at boiler pressures of 50 bars (725 psi) and 100 bars (1450 psi) within the temperature range of interest in this work. These data lead to the practical conclusion that, for a turbine to derive the most energy from the steam produced by a boiler fuel, the boiler should be designed to produce steam at the highest temperature that its superheater metallurgy allows.

It is important to note that the volume of a given mass of steam heated by burning a given amount of fuel will fall as the final temperature of the steam increases. In the data presented in Fig. 4, raising the steam temperature from 500°C to 600°C without changing the fuel input to the CHP plant reduces the volume of steam produced by 6.6% at a pressure of 50 bars (725 psi) and by 7.2% at a pressure of 100 bars (1450 psi). Whether or not this reduction in steam volume presents a

Type of Boiler and Identifier	Recovery Boiler	
	B	M
Condition/data		
Current power generation	52.0 MW	53.6 MW
Power generated with steam temperature 50°C higher	56.4 MW	60.8 MW
Additional power generated	+4.4 MW	+7.2 MW
	+8.4%	+13.4%
Value of this additional power @ $40/MWh	+$1.54 million/year	+$2.52 million/year
Value of this additional power @ $80/MWh	+$3.08 million/year	+$5.05 million/year
Power generated with steam temperature 100°C higher	59.0 MW	66.3 MW
Additional power generated	+7.0 MW	+12.7 MW
	+13.4%	+23.7%
Value of this additional power @ $40/MWh	+$2.45 million/year	+$4.45 million/year
Value of this additional power @ $80/MWh	+$4.91 million/year	+$8.90 million/year

IX. Value of increased energy production in the two example recovery boilers. (All currency in USD.)

problem in plant operation will depend on the process steam requirements and the turbine design. In a condensing turbine, the smaller volume of steam produced at a higher temperature could, in principle, be redistributed among the extraction stages by controlling the steam flows at the extraction points. However, in a back-pressure turbine, it may not be possible to maintain the process steam flows if the steam volume is reduced by heating the steam to a higher final temperature.

Table VIII lists the steam parameters for the two recovery boilers and the three wood-fired boilers studied in the economic calculations. The boiler parameters were supplied by project partners. Three of these example boilers used for the calculations were also used for field tests to measure the corrosion resistance of candidate alloys in higher temperature superheater environments.

The steam extraction temperatures used in the calculations were recalculated from the extraction pressures using standardized turbine stage efficiencies to determine the entropy of the steam extracted. The condensate temperatures were adjusted to those of saturated condensate at atmospheric temperature. These calculations used the procedures proposed by Ulrich [9], although similar calculation procedures are presented in other engineering thermodynamics and process design texts. The turbine stage efficiencies used for the recovery boiler calculations were provided by an industrial partner [10], and the turbine stage efficiencies used for the biomass boiler calculations were estimated from data presented by Ulrich [9].

ECONOMIC CALCULATIONS

Many different approaches could be taken for calculations of the effects of increasing the outlet steam temperatures of a biomass-fueled boiler. Different sets of constraints could be applied to evaluate the effects of specific local factors, such as changing needs for process steam, opportunities to sell high-priced power, or a decision to install a new high-efficiency turbine.

The purpose of the current project was to estimate the economic benefits that would accrue to a boiler operator if a biomass-fueled boiler could be operated with substantially higher exit steam temperatures. To make these estimates, calculations were made with the data from **Table VIII**. The value of the increased steam and power production that would be obtained by increasing the steam temperature by 50°C and by 100°C was calculated for each of the five example boilers, using the following assumptions:

1. The existing turbine could operate with the higher temperature steam.
2. The heat produced by the combustion of the fuel would be unchanged when the final steam temperature was increased.
3. The product of specific steam enthalpy and steam flow would be unchanged when the final steam temperature was increased.
4. The amount of steam extracted from the turbine to meet process heating requirements would remain unchanged when the final steam temperature was increased.

We will first review the results of calculations made with these assumptions and later discuss the uncertainties associated with these assumptions.

Table IX shows the value of the increased power that would be produced in the two example recovery boilers that would accrue to the owners of these boilers if they could increase the exit steam temperature by 50°C or 100°C above the current operating temperature. Because the value of electrical power varies both with location and with time, the value of the additional power generated was calculated for power prices of both US$40/MWh and US$80/MWh. Current power prices typically lie within this range.

In related work, three types of virtual turbine were studied

Type of Boiler and Identifier	Wood-Fired Boiler		
	C	H	M
Parameter	42.8 MW	27.5 MW	27.4 MW
Current power generation	42.8 MW	27.5 MW	27.4 MW
Power generated with a steam temperature 50°C higher	51.2 MW	31.3 MW	31.0 MW
Additional power generated	+8.4 MW	+3.8 MW	+3.6 MW
	+19.6%	+13.8%	+13.1%
Value of this additional power @ $40/MWh	+$2.94 million/year	+$1.33 million/year	+$1.26 million/year
Value of this additional power @ $80/MWh	+$5.87 million/year	+$2.66 million/year	+$2.52 million/year
Reduced volume of steam generated with a steam temperature 50°C higher	3.22 kg/s	2.18 kg/s	2.2 kg/s
Power generated with a steam temperature 100°C higher	58.8 MW	34.9 MW	34.3 MW
Additional power generated	+16.0 MW	+7.4 MW	+6.9 MW
	+37.3%	+26.9%	+25.1%
Value of this additional power @ $40/MWh	+$5.59 million/year	+$2.59 million/year	+$2.4 million/year
Value of this additional power @ $80/MWh	+$11.18 million/year	+$5.17 million/year	+$4.82 million/year
Reduced volume of steam generated a stem temperature 100°C higher	8.09 kg/s	4.15 kg/s	4.2 kg/s

X. Value of increased power that could be produced by raising exit steam temperatures by 50°C and by 100°C in the three example wood-fueled boilers. (All currency in USD.)

to evaluate the effects of higher steam conditions in recovery boiler M. In the first case, the turbine generator was optimized for the original (conventional) steam conditions and was therefore less efficient at the higher steam temperatures. In the second case it was assumed that the turbine generator used for higher steam conditions was optimized for these conditions, i.e. that the turbine efficiency remained constant as the steam conditions were increased. In the third case a reheater was added between the high pressure and medium pressure turbine extractions. These calculations showed that increasing the isentropic efficiencies of the various turbine stages towards the maximum attainable efficiency increases the amount of power generated as much as increasing the steam temperature. This shows the value of using a steam turbine designed for higher steam conditions when redesigning a boiler to produce higher temperature steam.

Table X shows the value of the increased power that would be produced in the three example wood-fired boilers assuming that the isentropic efficiency of the steam turbine was maintained at the higher input steam temperature.

Table XI summarizes the calculated economic benefits of increased exit steam temperatures in all five example boilers under the previously-stated assumptions. These results indicate that very substantial economic benefits would accrue if biomass boilers could be designed to operate with higher superheater steam temperatures.

The magnitude of the increased power generated at higher temperatures in these calculations is similar to that published by groups in Sweden [11] and Denmark [12]. Stålenheim and Henderson [11] have presented similar plots of the increase of electrical efficiency with final steam temperature at various steam pressures in advanced steam cycle units. Kamuk [12] commented that the electrical efficiency of biomass-fueled boiler systems is typically limited to about 35%, compared to about 49% for coal-fired boiler systems, because of superheater corrosion. She also noted that achieving higher steam conditions is the key to raising electrical efficiency.

The most attractive route to achieving higher steam temperatures appears to be to identify new superheater alloys or composite tube materials that can resist corrosion and creep in the flue gas and fuel ash environment around superheater tubes in biomass boilers. If suitable tubing were installed in the hottest portions of a biomass-fueled boiler's superheater, the boiler owner would make a net profit if the additional cost of this tubing did not exceed the value of the additional steam generated. For example, if 5 m of high alloy tubing were installed in each of ten superheater loops in 45 platens (for a total of 2250 m) and served for 5 years before being replaced, tubing costs of less than US$5378/m to US$24911/m would more than pay for a 100°C increase in steam temperature. Current costs of superheater tubing are about two orders of magnitude lower than the lowest of these estimates of the justifiable cost. To gain the full financial advantage of tubes designed for a five-year replacement life, it would be useful to also design the superheater for rapid replacement. We noted in an earlier publication [1] that the superheater of a 67 MW waste-fired boiler operated by the City of Amsterdam, which had been

Parameter	Recovery Boilers		Biomass Boilers		
	B	M	C	H	M
Steam temperature 50°C higher					
Increased value @ \$40/MWh	+\$1.54 million/year	+\$2.52 million/year	+\$2.94 million/year	+\$1.33 million/year	+\$1.26 million/year
Increased value @ \$80/MWh	+\$3.08 million/year	+\$5.05 million/year	+\$5.87 million/year	+\$2.66 million/year	+\$2.52 million/year
Steam temperature 100°C higher					
Increased value @ \$40/MWh	+\$2.45 million/year	+\$4.45 million/year	+\$5.59 million/year	+\$2.59 million/year	+\$2.41 million/year
Increased value @ \$80/MWh	+\$4.91 million/year	+\$8.90 million/year	+\$11.18 million/year	+\$5.17 million/year	+\$4.82 million/year

XI. Summary of calculated value of additional power generated by raising exit steam temperatures by 50°C and 100°C. (All currency in USD.)

designed for rapid replacement, was recently replaced in 48 hours, from fire-to-fire.

A second route to enabling higher steam conditions would be to chemically treat the biomass fuel to remove corrosive components before or during combustion. This could involve diluting a corrosive biomass fuel with a less-corrosive fuel, leaching corrosives out of biofuels, or using additives (such as ammonium sulfate or SO_2) that convert alkali chlorides to less corrosive sulfates, or additives such as kaolin (40-60 wt% $Al_2O_3.SiO_2$) that convert alkali salts to less-corrosive silicates. More details about these approaches can be found in [1]. If the corrosivity of the biomass fuel could be reduced by pretreatment or by combustion additives, the fuel processing would have to cost less than US\$2,420,000 to US\$11,210,000 per year to justify the increased value of the power generated by producing steam 100°C hotter than current values.

Other approaches to enabling higher steam conditions that have been implemented in Europe [1] involve redesigning biomass-fueled boilers to maximize the service life of superheater tubes by separating the superheater tubes from the corrosive fly ash (either by adding an empty pass between the furnace and the superheater or by condensing the fly ash on low temperature tubes in a “chlorine trap”); by increasing the superheater temperature above the dew point temperature of corrosive components of the fly ash; by moving the superheater of a circulating fluidized bed boiler (CFB) out of the flue gas passage into the recirculated fluidizing medium; and by using an external superheater fired by a less corrosive fuel. With the current abundance and relatively low cost of natural gas in the U.S., this last approach appears particularly attractive. To justify the financial benefit of the increased power production provided by a 100°C steam temperature increase within five years, the capital costs of boiler design changes would have to be less than US\$12,000,000 to US\$56,000,000. The magnitude of these financial gains associated with increased steam temperatures appears to justify substantial boiler redesign or fuel treatment.

ISSUES RAISED BY SIMPLIFYING ASSUMPTIONS

We will now review the credibility of the simplifying assumptions that were used to calculate the potential benefits of increased steam conditions. The first assumption, that the existing turbine could handle the higher temperature steam, is probably not true. Steam turbines have designs and materials of construction optimized for particular steam conditions, and the calculations described previously for recovery boiler M indicate that the efficiency of an existing turbine would be substantially lower if it operated with a steam temperature 100°C higher than its design conditions. Substantial infusions of capital could be required to simultaneously upgrade both biomass-fueled boilers and their turbines to take advantage of the increased power generation potential of hotter steam. However, we have shown previously that the value of the additional steam generated would more than justify the cost of any foreseeable corrosion-resistant alloy tubing and that the increased cost of a turbine designed to handle higher temperature steam could probably be paid off by the value of the additional steam generated in one or two years. New biomass-fueled boilers are being built every year and will very likely be designed for efficient combustion and efficient steam generation, following the approaches discussed here.

The second assumption in the calculations is that the heat produced by the combustion of the fuel remains unchanged. This assumption appears reasonable. The firing of the fuel in the furnace and the volume of water supplied to the boiler would not be changed, but the steam would be heated to a higher final temperature in the superheater. The final steam

Recovery Boiler	Case	Steam Flow, kg/sec				
		HP Extraction	MP Extraction	LP Extraction	Exhaust	Total
B	Current operation	0	8.82	63.76	19.22	91.80
B	Steam temperature 50°C higher	0	8.82	63.76	16.04	88.62
B	Steam temperature 100°C higher	0	8.82	63.76	13.12	85.70
M	Current operation	0	39.31	48.26	14.11	101.68
M	Steam temperature 50°C higher	0	39.31	48.26	10.27	97.84
M	Steam temperature 100°C higher	0	39.31	48.26	6.82	94.39

XII. Calculations of redirected steam flows in the steam turbines of recovery boilers B and M as the inlet steam temperature is raised by 50°C and by 100°C.

Biomass Boiler	Case	Steam Flow, kg/sec				
		HP Extraction	MP Extraction	LP Extraction	Exhaust	Total
C	Current operation	0.00	15.12	104.58	0.00	119.70
C	Steam temperature increased by 50°C	0.00	14.59	100.89	0.00	115.48
C	Steam temperature increased by 100°C	0.00	14.10	97.51	0.00	111.61
H	Current operation	0.00	15.00	44.99	0.00	59.99
H	Steam temperature increased by 50°C	0.00	14.45	43.35	0.00	57.80
H	Steam temperature increased by 100°C	0.00	13.96	41.87	0.00	55.83
M	Current operation	15.12	6.05	39.31	0.00	60.48
M	Steam temperature increased by 50°C	14.57	5.83	37.88	0.00	58.28
M	Steam temperature increased by 100°C	14.07	5.63	36.58	0.00	56.28

XIII. Calculations of steam flow reductions in the steam turbines of biomass-fueled boilers C, H, and M as the inlet steam temperature is raised by 50°C and 100°C.

temperature would be raised by extracting more heat in the superheater, most likely by redesigning the superheater to add more heat transfer surface. Increasing the heat transfer surface in the superheater would require installing additional tube platens or extending the existing platens. Although the costs of this type of rebuild are highly plant-specific, the financial calculations suggest that these capital costs could be paid for by two to five years of additional power production.

The third assumption, that the product of the steam enthalpy and the steam flow would be unchanged, is closely related to the second assumption. It assumes that the amount of heat transferred to the steam is unaffected by raising the final temperature of the steam. This assumption also seems reasonable.

The fourth assumption in the calculations is that the amount of steam extracted from the turbine for process heating would remain constant. The provision of process steam is a critical function of CHP turbine generators. However, we noted previously that raising the final temperature of steam in a boiler reduces the total volume of the steam produced. In condensing turbines, it may be possible to adjust the extraction flows so as to maintain the existing requirements for process steam while reducing the steam flow to the surface condenser. **Table XII** shows calculations of the steam flows in the turbines used by recovery boilers B and M as the temperature of the steam delivered by the boiler is raised by 50°C and by 100°C above current operating conditions. The total volume of steam produced falls by 6.6% in boiler B and by 7.2% in boiler M as the temperature is raised by 100°C. Fortunately, for both of these boilers, it would be possible to maintain the flows of medium and low pressure steam from the turbine by reducing the volume of steam exhausted to the surface condenser (Table XII).

The three wood-fueled boilers in this study all use non-condensing, back-pressure turbines. These have no exhaust flow to make up for the reduced volume of hotter steam that would be produced if their final steam temperature were increased. The steam flow calculations for these turbines presented in **Table XIII** are similar to those for the condensing recovery boiler turbines in Table XII. As with the recovery boilers, the total volume of steam produced falls as the final steam temperature is raised. This would reduce the total steam flow by 6.76% in boiler C, by 6.93% in boiler H, and by 6.94% in boiler M. The steam flows from the various turbine extraction points would be correspondingly reduced. Although a pulp and paper mill that has implemented substantial energy savings since its non-condensing turbine was installed might be able to operate with these reduced flows of process steam, this will generally not be possible. However, three other approaches could be used to maintain the volumes of process steam while still obtaining the benefits of increased power generation. Probably the most economic would be to attemperate the steam, either by a water spray or by passing some of it through a heat exchanger cooled by boiler feedwater. Other approaches would be to fire slightly more wood fuel in the boiler or to purchase a small amount of make-up steam from another source.

ENVIRONMENTAL BENEFITS OF HIGHER STEAM CONDITIONS

Increasing the energy efficiency of biomass-fueled boilers would directly improve energy efficiency in all industries that use biomass fuels. In addition, improvements in energy efficiency would make renewable fuels more attractive as replacements for fossil fuels.

Table XIV and **Table XV** show the cumulative savings resulting from the replacement of natural gas with biomass, assuming there are at least 500 biomass-fired boilers in the U.S. that could be converted within a ten-year period to operate with final steam temperatures 100°C above current conditions and that the additional energy generated would replace energy currently produced from fossil fuels. These calculations assume that power production would increase 25% with a 100°C increase in final steam temperature, based on calculations submitted by a project partner [13].

	Year 2020	Year 2025
Total primary energy displaced	268 trillion Btus	1,406 trillion Btus
Cumulative economic benefit	$1.5 billion/year	$8.5 billion/year

XIV. Cumulative energy benefits from using additional energy produced in improved biomass-fired boilers to displace energy from fossil (natural gas) fired boilers. (All currency in USD.)

	Year 2020	Year 2025
CO_2 emissions displaced (C equivalent)	5.3 million tons	27.4 million tons
NO_x reductions	47,000 metric tons	243,000 metric tons

XV. Cumulative environmental benefits from using additional energy produced by advanced biomass-fired boilers to displace energy from fossil (natural gas) fired boilers.

	Year 2020	Year 2025
Total primary energy displaced	160 trillion Btus	866 trillion Btus
Cumulative economic benefit	$774 million/year	$4,300 million/year

XVI. Cumulative energy benefits from replacing natural gas fired boilers with biomass-fired boilers. (All currency in USD.)

	Year 2020	Year 2025
CO_2 emissions displaced (C equivalent)	2.31 million tons	12.5 million tons
NO_x reductions	17,000 metric tons	92,000 metric tons

XVII. Cumulative environmental benefits from replacing fossil fuel (natural gas) fired boilers with biomass-fired boilers.

Replacing fossil fuel boilers with renewable fuel boilers would also bring substantial economic benefits. Assuming that state-of-the-art biomass-fired boilers could economically replace fossil fuel units, then for 500 installed units with a 2% growth rate per year, an ultimate potentially accessible market of 90% and a likely technical market share of 90%, there could be 21% market penetration in 2020 and 71% penetration in 2025. The savings shown in **Table XVI** and **Table XVII** are based on the replacement of fossil fuel (natural gas) fired boilers.

DISCUSSION AND CONCLUSIONS

We noted earlier that biomass-fueled boilers typically operate with electrical efficiencies of about 35%, substantially lower than those of coal-fired units [12] because their final steam conditions are limited in order to restrict fireside corrosion of the superheater tubes. In Europe, where the development of power from renewable fuels has been defined as a strategic priority by many nations, innovative approaches have been developed to improve the efficiency of biomass-fueled boilers, not only by identifying alloys with greater corrosion resistance [2], but also by using combinations of design modifications, process modifications, and corrosion-resistant alloys to enable higher steam conditions [1].

The calculations presented here using data from two recovery boilers and three wood-fired boilers suggest that the value of the increased power that could be generated if the steam in a biomass-fired boiler could be heated 50°C above current operational temperatures would be worth between about US$1,260,000 and US$5,890,000 per year. If the steam could be heated 100°C above current operational temperatures, the increased value of the power generated would be between about US$2,420,000 and US$11,210,000 per year. Gains for other biomass-fueled boilers would depend on local plant conditions and the price of power. The calculations indicate that the increased steam value could justify the use of corrosion resistant alloys costing orders of magnitude more than current superheater alloys if the use of more corrosion-resistant alloys were coupled with the introduction of superheater designs that allowed very rapid superheater replacement.

Most modern wood-fired boilers in Europe also incorporate design improvements to remove corrosive fly ash before it reaches the superheater, or to remove the superheater from the flue gas path altogether. Given the likelihood that U.S. natural gas prices will remain relatively low for many years, the option of installing an external superheater fired by this less-corrosive fuel seems a particularly attractive route to higher superheated steam temperatures. To achieve a five-year payback, a boiler redesign and rebuild to achieve a 100°C steam temperature increase would have to cost less than US$12,000,000 to US$56,000,000. A wood-fired boiler at Nässjö near Jönköping in Sweden, which has its superheater located in the loop seal, already operates with a steam temperature of 540°C, and another boiler with a loop seal superheater at Avedøre in the suburbs of Copenhagen, Denmark, which fires coal with straw containing up to 1% chloride, already operates with a steam temperature of 580°C [1].

Another approach widely used in Europe to achieve higher superheated steam temperatures in biomass-fueled boilers without excessive corrosion is the use of combustion additives to convert (corrosive) potassium chloride into less-corrosive sulfates or silicates. The increased value of higher steam conditions could offset the cost of such corrosion control additives.

Although the costs and benefits of achieving higher superheated steam conditions in specific biomass-fueled boilers depend on local conditions, the magnitude of the increased power that can be generated by increasing superheated steam temperatures are so substantial that ongoing studies of technical pathways to achieving substantial steam temperature increases (such as the 100°C increase studied in the current project) are likely to pay substantial dividends. The most economic pathways to higher steam temperatures will almost certainly involve combinations of more corrosion-resistant alloys and either boiler redesign or the removal of the superheater from the flue gas path. **TJ**

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Efforts to use renewable fuels have been hindered by the inefficiency of biomass combustion, which arises because biomass fuels corrode hot boiler tubes. As energy prices rise, there will come a time when it makes financial, as well as environmental, sense to learn how to burn renewable biofuels efficiently.

This third part of the research in this issue of *TAPPI Journal* (see also [4-5]) examined the costs and benefits of operating biomass-fueled boilers more efficiently. Our conclusions here are consistent with limited data available from European sources (e.g., Kamuk [12]).

In this study, it was difficult to obtain real steam system data, but a few industrial partners provided data sets. In addition, the thermodynamic modeling was quite complex.

It was surprising and gratifying to find that even with today's low energy prices, high efficiency burning of biomass fuels seems an economically attractive option. Our results indicate that installing high efficiency biomass boilers and turbines designed for high temperatures is a viable option for mills that are rebuilding their biomass boilers.

Our next step is to gather long-term data on the corrosion resistance of attractive alloy materials installed in operating biomass-fueled boilers.

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