

Efficiency improvements by geothermal heat integration in a lignocellulosic biorefinery

M. Imroz Sohel* and Michael Jack

Scion, 49 Sala St, Private Bag 3020, Rotorua, New Zealand

Abstract

In an integrated geothermal biorefinery, low-grade geothermal heat is used as process heat to allow the co-products of biofuel production to become available for higher-value uses. In this paper we consider integrating geothermal heat into a biochemical lignocellulosic biorefinery so that the lignin-enriched residue can be used either as a feedstock for chemicals and materials or for on-site electricity generation. Depending on the relative economic value of these two uses, we can maximize revenue of a biorefinery by judicious distribution of the lignin-enriched residue between these two options. We quantify the performance improvement from integrating geothermal energy for an optimized system. We then use a thermodynamic argument to show that integrating geothermal heat into a biorefinery represents an improvement in overall resource utilization efficiency in all cases considered. Finally, possible future technologies for electricity generation are considered which could improve this efficiency further.

Key words: bioenergy; biorefinery; geothermal energy; process heat; integrated approach.

1. Introduction

In order to meet our energy demands while moving away from fossil fuel dominated energy supplies, it will become increasingly necessary to improve the efficiency with which we utilize our renewable resources. Improved efficiency also enables decreased greenhouse gas emissions by displacing more emissions from fossil fuel per unit of renewable resource. The biorefinery concept (Demirbas, 2009; Ragauskas et al.,

* Corresponding author. Tel: +64 7 3435730; fax: +64 7 3435375;
E-mail address: mohammed.sohel@scionresearch.com

2006), where a range of high-value co-products are produced in addition to commodity fuel products, attempts to achieve increased efficiency by making full use of biomass feedstocks (Dodds and Gross, 2007; Elnashaie et al., 2008; Ragauskas et al., 2006; Zhang, 2008). Due to the potential cost reductions from this strategy, biorefineries are seen as a key step towards the commercial implementation of biofuels (Ragauskas et al., 2006). Biofuel technology research and development shows a clear trend towards lignocellulosic feedstocks for these biorefineries (IEA, 2008). Lignocellulosic feedstocks have a number of advantages over other feedstocks in that they: (i) mitigate competition for land and water used for food production; (ii) increase biomass production per unit of land; and (iii) require reduced inputs for biomass growth (Metzger and Huttermann, 2008; Schmer et al., 2008; Tilman et al., 2009).

A large percentage of the lignocellulosic biorefinery concepts that have so far been proposed are based on a biochemical conversion platform where the polysaccharides in lignocellulosic material are converted to liquid fuel using enzymes (Huber et al., 2006; Wooley et al., 1999). In these systems it has been proposed that the lignin by-product and other extractives can be used for higher value uses such as the production of high-value chemicals and materials (Dodds and Gross, 2007; Ragauskas et al., 2006). An alternative higher-value use is combusting the lignin for on-site electricity production (Larsen et al., 2008).

One of the major impediments to the lignocellulosic biorefinery concept is that the liquid fuel production from lignocellulosic biomass is a very energy intensive process (Cardona Alzate and Sánchez Toro, 2006; Piccolo and Bezzo, 2009; Ragauskas et al., 2006; Wooley et al., 1999). Current integrated biorefinery concepts use the lignin enriched residue as a fuel to meet process energy demands, reducing the possibility of higher-value uses of lignin. In this paper we propose an approach where low-grade geothermal heat is used to provide process heat for the biorefinery, allowing the lignin enriched residue to become available for higher-value uses (see Fig. 1).

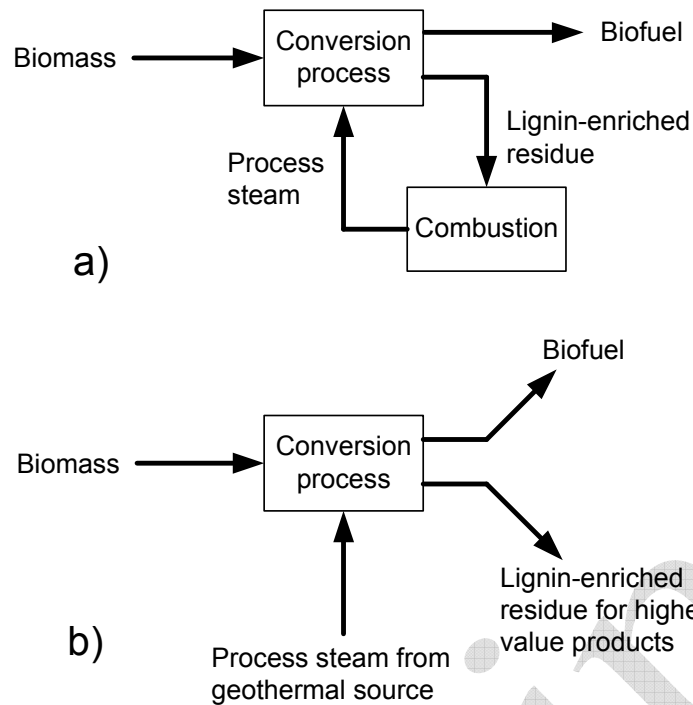


Figure 1: a) Current biorefinery concept, where the lignin is combusted to provide process steam b) Integrated geothermal biorefinery concept, where geothermal heat provides process steam and the lignin becomes available for higher-value uses.

Geothermal energy originates from two sources: original heat from the formation of the Earth by gravitational collapse, and radioactive decay of various isotopes (Kutscher, 2000). In normal areas of the world, the temperature increases as a function of depth at a fairly constant rate of 3 °C per 100 m. However, in anomalous regions associated with volcanic or tectonic activity, the temperature gradient is about 10-30 times higher than normal. In such regions temperatures of 300 °C are common at a depth of 1 km (Barbier, 2002). Geothermal energy can be divided into three groups according to the resource temperature: low (<90-150 °C), medium (<90-200 °C) and high (> 150-225 °C) (Etemoglu and Can, 2007). The typical steam requirements for the biofuel production process are around 190-200 °C, i.e., medium and high temperature geothermal resources are suitable for meeting process heat demand.

Exploiting the concept of an integrated geothermal biorefinery requires the co-location of geothermal and biomass resources. A number of countries, particularly around the Pacific Rim, have significant geothermal resources. A number of these countries also have existing or the potential for, increased production of biomass

resources (Campbell et al., 2008; Potapov et al., 2008; Schmitt et al., 2009) and could be candidates for the implementation of this concept. For example, in the central North Island of New Zealand, much of the country's sustainably managed plantation forest is co-located with its largest geothermal resource. It is estimated that the plantation forest within a 100 km radius of the geothermal resource could provide biomass at a sustained yield of 6-8 M m³/year (MAF 2009). Assuming this resource was used for biofuel production in a number of biorefineries in the area, it can be shown that the geothermal resource (with temperature 190 °C or above) in the area is 50 to 100 times the process heat requirements for these biorefineries (deVos et al., 2009).

In this paper we quantify the potential benefits of integrating geothermal energy into a biorefinery based on a process model of a biochemical technology. The biofuel production process that acts as a base case is described in Section 2. In Section 3, the performance improvement of integrating geothermal energy into a biorefinery with the objective of maximizing revenue is quantified. The lignin residue and the geothermal heat have a number of potential end uses. In Section 4, we use a thermodynamic argument to show that the integration of these two renewable resources in a geothermal biorefinery results in an overall improvement in resource utilization compared to a number of other potential uses of geothermal heat. As the efficiency of this resource utilization in a number of cases depends on the efficiency of producing electricity from lignin, alternative technologies for electricity generation are described in Section 5. In Section 6 we conclude.

2. The biofuel production process

There are currently two main technological pathways for converting lignocellulosic biomass into biofuels: a thermochemical route via gasification, and a biochemical route using enzymes (IEA, 2008). We limit our discussion to the biochemical route to ethanol production and analyse the possibilities associated with integrating geothermal energy for process heat into these systems.

Several process models for the production of ethanol from biomass have been reported in the literature (Cardona Alzate and Sánchez Toro, 2006; Piccolo and

Bezzo, 2009; Wooley et al., 1999). In particular, Wooley et al. (1999) have described in detail the overall process for ethanol production from wood chips via a process of simultaneous scarification and fermentation (SSCF). They considered a process that on average converts about 44.44 kg/s of wet biomass (47% moisture content) to 5 kg/s of ethanol. The process utilizes lignin enriched co-products to meet process heat demand. The model showed that such a plant can produce more energy than required for process demands. The model includes an integrated power plant capable of producing 44 MW of electricity (33 MW for internal use and 11 MW for export). A process model by Piccalo and Bezzo (2009) uses pinch analysis to further optimize the heat integration of the original system described by Wooley et al. (1999).

Biochemical conversion of lignocellulosic feedstocks to ethanol consists of three major chemical conversion process steps: pretreatment, enzymatic hydrolysis and fermentation. The supply chain of this conversion process includes feedstock growth, harvesting, handling, and transport; separation of the biomass to give small and homogeneous particles; fractionation of the polymers; separation of the solid component; end product recovery and distribution. An overview of the process is shown in Fig. 2. Table 1 presents the energy demand in various steps of the process as summarised by Piccolo and Bezzo (2009). It should be mentioned here that not all of the processes are endothermic; some are in fact exothermic such as the fermentation process. The heat requirements for the endothermic processes are presented in Table 1. It is notable that heat inputs in the distillation and dehydration steps in these process models differ significantly among authors. This is largely due to the level of heat integration considered in the various treatments.

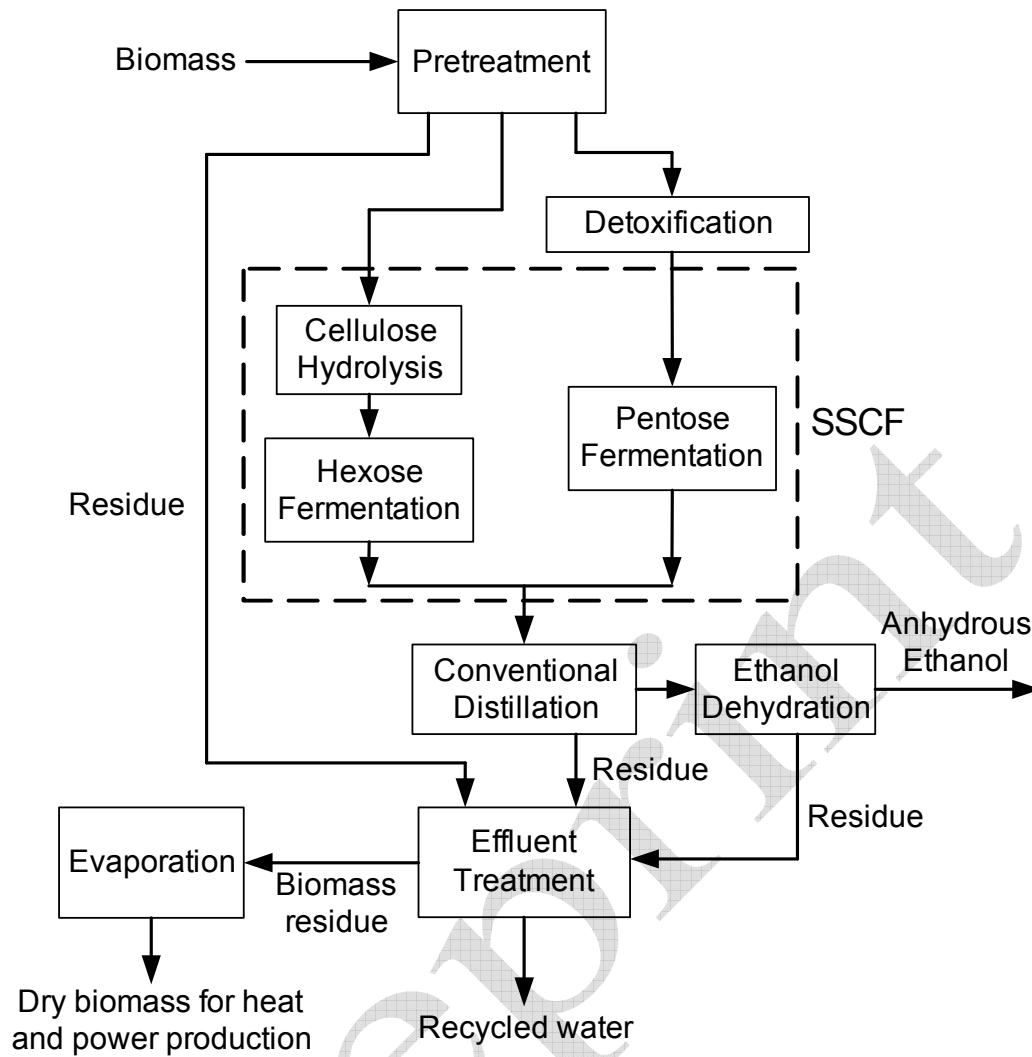


Figure 2: Block diagram of fuel ethanol production from lignocellulosic biomass.

Table 1: Process heat requirements in various steps of the bioethanol production chain (Piccolo and Bezzo, 2009)

Process step	Energy demand [MJ/L EtOH]
Pretreatment	2.5 - 4.7
Distillation + Dehydration	3.5 - 27.9
Evaporation	4.3

Following Piccalo and Bezzo (2009), the base case considered here is assumed to process 160000 kg of wet chip per hour, where the composition of the wood chip is 22% cellulose, 10% hemicellulose, 20% lignin and 48% moisture. The total process heat demand is about 134 MW, with 46 MW high quality steam (12.4 kg/s saturated

at 1313 kPa and 4.7 kg/s saturated at 444.4 kPa) and the rest low grade heat (Wooley et al., 1999).

3. Integrating geothermal resources into a biorefinery

Incorporating geothermal energy to meet the process heat demand in the biofuel production process described in Section 2 allows lignin enriched residue to become available as a feedstock for higher-value chemicals or materials or for on-site electricity generation. We can maximize revenue of a biorefinery by judicious distribution of the lignin-enriched residue between feedstock of chemicals and materials, and on-site electricity production. We consider three discrete cases:

- (i) *maximize lignin production* – in the case that the revenue from lignin as a feedstock for chemicals or materials is higher than the value of importing electricity,
- (ii) *maximize electricity production* – in the case that generating and exporting electricity from the lignin is of higher value than the value of lignin as a feedstock for chemicals or materials,
- (iii) *maximize lignin production while remaining self-sufficient in electricity* – in the case that the value of lignin as a feedstock for chemical production is in-between the value of importing and exporting electricity.

These three cases cover the options given the potential end-uses under consideration. The choice of which option to pursue in any particular case depends on the particular local market-environment of the biorefinery and potential future technology developments. It should be mentioned here that we have assumed the cost of geothermal heat is lower than lignin and electricity price. Therefore the price of lignin or electricity will not increase if geothermal heat is incorporated into the system. Based on the description of the process given in Section 2 above we can estimate the potential contribution geothermal energy can make in each of these three cases:

(i) maximize lignin production

To meet this objective without integrated geothermal heat requires that lignin is combusted to meet process heat demand, but electricity can be imported from the grid to meet electricity demand. Based on the model described in Section 2, this requires 4.56 kg/s of lignin, leaving 4.56 kg/s of lignin (or 0.7 kg lignin/L of ethanol) available

as a feedstock for chemicals and materials. In contrast, if geothermal heat is used to meet the process heat demand in the system then availability of lignin doubles to 1.4 kg lignin/L of ethanol. The electricity demand for the process can be met from an external source. If this is a renewable energy source, the overall greenhouse gas emissions can be maintained at a lower level.

(ii) maximize electricity production

To meet this objective without geothermal heat, 9.1 kg/s of lignin can be diverted to electricity production and process heat demand. Therefore, 44 MW of electricity is generated based on the model in Section 2. This assumes that low temperature process heat can be met through a cogeneration process where waste heat from electricity generation is utilized. Using geothermal heat to meet the process heat demand can increase the electricity production from 44 MW to 55 MW, representing a 25% increase. This result is based on the boiler assumed by Wooley et al. (1999). A number of alternative technologies are under development that increase the efficiency at which biomass can be turned into electricity and can lead to increased electricity production. This is discussed further in Section 5.

(iii) maximize lignin production while remaining self-sufficient in electricity

To meet this objective without geothermal heat requires 9 kg/s of lignin for process heat and electricity generation, leaving 0.11 kg/s (or 0.1 kg lignin/L of ethanol) available for export. If geothermal energy is incorporated into the system, the availability of lignin increases to 0.6 kg lignin/L of ethanol. Table 2 summarizes the potential performance gains in each of the three cases of integrated geothermal biorefinery (IGB).

Table 2: Available resources for three different cases

	(i) maximize lignin production	(ii) maximize electricity production	(iii) maximize lignin + self sufficient in electricity
Base case	0.7 kg lignin/ L ethanol	44 MW	0.1 kg lignin/ L ethanol
IGB	1.4 kg lignin/ L ethanol	55 MW	0.6 kg lignin/ L ethanol

4. Optimal resource utilization

In the previous section we have quantified the performance improvement possible by integrating geothermal heat into a lignocellulosic biorefinery. However, geothermal steam and the residual lignin resources could be used in a number of different energy products and it is necessary to determine if an integrated geothermal biorefinery represents the optimal utilization of these resources. To consider this question it is necessary to provide a measure of resource value that is consistent for both the geothermal steam and the residual lignin. By invoking the second law of thermodynamics we can place a value on the lignin by considering the potential of the lignin stream to produce thermodynamic work (work potential is also referred to as exergy (Bejan, 1997; Szargut et al., 1988)). This can then be compared with the exergy of the geothermal steam. A suitable definition for the resource utilization efficiency is given by Eq. (1).

$$\eta = \frac{\text{Exergy out}}{\text{Exergy in}} \quad (1)$$

This is essentially a measure of how effectively the exergy in the geothermal and lignin resources is converted into exergy in the electricity and process heat products. It would not be as useful to simply use “energy in” and “energy out” in the definition of resource efficiency as not all of the energy in heat is available for work (Bejan, 1997). Note that the output biofuel from the biorefinery is considered fixed in this paper and does not take part in our argument, and that the inefficiencies associated with the conversion of residual lignin to higher-value chemicals or materials are not considered here.

For the biorefinery systems we consider, potential contributions to the exergy input in Eq. (1) are the lignin stream, $\dot{m}_{\text{lignin}} \varepsilon_{\text{lignin}}$, where $\varepsilon_{\text{lignin}}$ and \dot{m}_{lignin} are the available chemical exergy and mass flow rate of the lignin, respectively, and the geothermal stream $\dot{m}_{\text{geo}} \Delta \varepsilon_{\text{geo}}$, where $\Delta \varepsilon_{\text{geo}}$ is the input exergy of the geothermal heat and \dot{m}_{geo} represents the corresponding mass flow rate of the geothermal fluid. Potential exergy outputs are the power generated by the biorefinery, P_{bio} , and the geothermal power plant, P_{geo} , (where we have assumed that the exergy of electricity is equal to the energy), and the exergy of the process heat demand $\sum_i (\dot{m}_{\text{proc}})_i (\varepsilon_{\text{proc}})_i$, where $\varepsilon_{\text{proc}}$

and \dot{m}_{proc} are the exergy and mass flow rate of the process heat, respectively. The heat demand is fixed in the present case and the subscript “ i ” in the sum represents process heat requirements at different operating conditions, e.g., high pressure/low pressure.

Work potential is calculated with respect to the environmental conditions, often referred to as the “dead state” (Szargut et al., 1988). The dead state temperature and pressure are assumed to be 25 °C and 100 kPa, respectively. The process heat exergy ε_{proc} , is calculated as:

$$\varepsilon_{proc} = h_{proc} - h_0 - T_0(S_{proc} - S_0) \quad (2)$$

Here, suffix $proc$ and 0 stand for process and dead state, respectively. The net exergy of the geothermal fluid $\Delta\varepsilon_{geo}$, can be calculated from the following equation:

$$\Delta\varepsilon_{geo} = h_{geo} - h_0 - T_0(S_{geo} - S_0) \quad (3)$$

Geothermal fluid reinjection conditions are also assumed to be the same as the dead state temperature. The chemical exergy of lignin enriched residue is assumed to be $\varepsilon_{lignin} = 25$ MJ/kg (Shieh and Fan, 1982).

We now analyse the resource efficiency corresponding to each of the three cases introduced in Section 3. It is difficult to formulate a general efficiency measure for all of the three cases as there may be different inputs and outputs for each them. However, for each of the three cases either the numerators or denominators in Eq. (1) are equal for the base case (BC) and the IGB. This means that either the outputs or the inputs of the BC and the IGB are the same allowing us to make a comparison within each case.

(i) *maximize lignin production*

In this case, the lignin has a higher value as a feedstock for chemicals and materials than as a fuel for electricity generation, so electricity is imported to meet the process electricity demand. The remaining process energy demand, in this case, is the process heat demand. In the BC, without geothermal heat, this needs to be met by combustion of lignin. In an IGB this is met by geothermal heat (See Fig. 3). The efficiencies for these two alternatives are:

$$\eta_{BC} = \frac{\sum_i (\dot{m}_{proc})_i (\varepsilon_{proc})_i}{\dot{m}_{lignin} \Delta \varepsilon_{lignin}} \quad (4)$$

$$\eta_{IGB} = \frac{\sum_i (\dot{m}_{proc})_i (\varepsilon_{proc})_i}{\dot{m}_{geo} \Delta \varepsilon_{geo}}$$

where the numerators are equal. In the base case, the resource efficiency, η_{BC} , is reduced due to the combination of two inefficiencies. The first inefficiency is due to the exergy destruction in combusting the lignin and the second is the direct reduction in temperature from the combustion temperature (815 °C for lignin) (Gani and Naruse, 2007) to that of the process heat (200 °C). The second inefficiency is bounded below by the Carnot efficiency (Bejan, 1997).

$$\eta_{Carnot} = 1 - \frac{T_L}{T_H} \quad (5)$$

where T_L represents the heat sink temperature and T_H represents the heat source temperature. In practice, the Carnot efficiency is not obtainable due to irreversibilities in the heat transfer process. Based on the NREL model (Wooley et al., 1999), the value of η_{BC} is 0.22.

In contrast, the efficiency of direct utilization of geothermal heat (η_{IGB}) can be quite high. The main inefficiency in this case is due to heat transfer of the geothermal heat to the process heat. Estimates of η_{IGB} range from 0.73 to 0.98 based on the geothermal resource enthalpy and heat exchanger effectiveness using standard approach (Holman, 1992). The heat transfer associated with exergy transfer ($\dot{m}_{geo} \Delta \varepsilon_{geo}$) is calculated from the following equation

$$\dot{Q} = \eta_{HEX} \dot{m}_{geo} \Delta h_{geo} \quad (6)$$

where \dot{Q} is the geothermal heat transfer and η_{HEX} is the heat exchanger effectiveness. The value of the geothermal fluid mass flow rate, \dot{m}_{geo} , is obtained by substituting the enthalpy flow value of the geothermal fluid, Δh_{geo} , and heat exchanger effectiveness, η_{HEX} , in Eq. (6). For calculating both Δh_{geo} and $\Delta \varepsilon_{geo}$, we use the thermo-physical properties database of pure water (REFPROP, 2007) with inlet conditions $T = 200$ °C and given value of h_{geo} (1000-2200 kJ/kg) and outlet conditions $T = 25$ °C and $p = 100$

kPa. We ignore the effects of dissolved minerals in the geothermal fluid. The heat exchanger effectiveness is assumed a typical value of $\eta_{HEX} = 0.8$.

We can also compare the efficiency of electricity generation from geothermal heat to the efficiency of using the geothermal heat directly as the process heat for the biorefinery. The efficiency in the case of geothermal heat being used to generate electricity is given by

$$\eta_{GP} = \frac{P_{geo}}{\dot{m}_{geo} \Delta \epsilon_{geo}} \quad (7)$$

where the denominator is the same as for η_{IGB} above. The value of P_{geo} is obtained from

$$P_{geo} = \eta_{th} \cdot \dot{Q} \quad (8)$$

The total process heat demand for the biorefinery is $\dot{Q} = 134$ MW (Wooley et al., 1999). We use the binary cycle thermal efficiency, $\eta_{th} = 12\%$ (DiPippo, 2004) to calculate P_{geo} . The process steam conditions are saturated vapour at 444.4 kPa and 1313 kPa. The calculated values of η_{GP} range from 0.36 to 0.49. Comparing these values with η_{IGB} calculated above shows that the direct use of geothermal heat is a more efficient use of the resource.

(ii) *maximize electricity production*

In this case electricity generation is the more valuable use of the lignin. The question then becomes: is it more efficient to use the lignin and geothermal resources to produce electricity (and also meet process heat demand) independently (which is the base case) or in an integrated biorefinery? The efficiencies for these options can be evaluated to be

$$\eta_{BC} = \frac{P_{bio}^{BC} + P_{geo} + \sum_i (\dot{m}_{proc})_i (\epsilon_{proc})_i}{\dot{m}_{lignin} \epsilon_{lignin} + \dot{m}_{geo} \Delta \epsilon_{geo}} \quad (9)$$

$$\eta_{IGB} = \frac{P_{bio}^{IGB} + \sum_i (\dot{m}_{proc})_i (\epsilon_{proc})_i}{\dot{m}_{lignin} \epsilon_{lignin} + \dot{m}_{geo} \Delta \epsilon_{geo}}$$

where the denominators are the same. P_{bio}^{BC} and P_{bio}^{IGB} are the electricity generated from lignin in the base case and in the integrated geothermal biorefinery, respectively. P_{geo} is the electricity generated from the geothermal resource if it is used for electricity generation instead of for meeting the process heat demand.

We have used $\dot{m}_{lignin} = 9.12$ kg/s, $P_{bio}^{BC} = 44$ MW (44000 kW), $P_{bio}^{IGB} = 55$ MW (55000 kW), $(\dot{m}_{proc})_{4.4 \text{ bar}} = 22.44$ kg/s and $(\dot{m}_{proc})_{13 \text{ bar}} = 28.11$ kg/s (Wooley et al., 1999); $P_{geo} = 6.85$ MW (6850 kW). The process heat requirement from the geothermal source in this case is only the high quality steam ($\dot{Q} = 46$ MW). The low quality heat can effectively be met from waste heat of electricity generation. The rest of the calculation is carried out in the same way as for objective (i) above. The calculated value of η_{BC} ranges from 0.37 to 0.38 (depending on the geothermal resource enthalpy). The calculated values of η_{IGB} are approximately 0.39 (see Table 3).

(iii) *maximize lignin while remaining self-sufficient in electricity*

In this case the energy demand of the system is given by the electricity and process heat demands. These energy demands can be met in two ways: using lignin (base case) or using lignin and geothermal energy. The efficiencies corresponding to these two alternatives are:

$$\eta_{BC} = \frac{P_{bio} + \sum_i (\dot{m}_{proc})_i (\varepsilon_{proc})_i}{\dot{m}_{lignin} \varepsilon_{lignin}} \quad (10)$$

$$\eta_{IGB} = \frac{P_{bio} + \sum_i (\dot{m}_{proc})_i (\varepsilon_{proc})_i}{\dot{m}_{lignin} \varepsilon_{lignin} + \dot{m}_{geo} \Delta \varepsilon_{geo}}$$

where the numerators are the same.

For calculating η_{BC} we have used $\dot{m}_{lignin} = 8.36$ kg/s and $P_{bio} = 33$ MW (33000 kW). The rest of the calculation is the same as for objective (i) above. For calculating η_{IGB} , we have used $\dot{m}_{lignin} = 6.84$ kg/s and $P_{bio} = 33$ MW (33000 kW). The rest of the calculation is performed in the same way as for objective (i) but assuming geothermal heat is used only to meet the high quality steam demand ($\dot{Q} = 46$ MW). The

calculated values are $\eta_{BC} = 0.35$ and η_{IGB} in the range from 0.38 to 0.39. A summary of the calculated values of η_{BC} and η_{IGB} for the three different objectives is presented in Table 3.

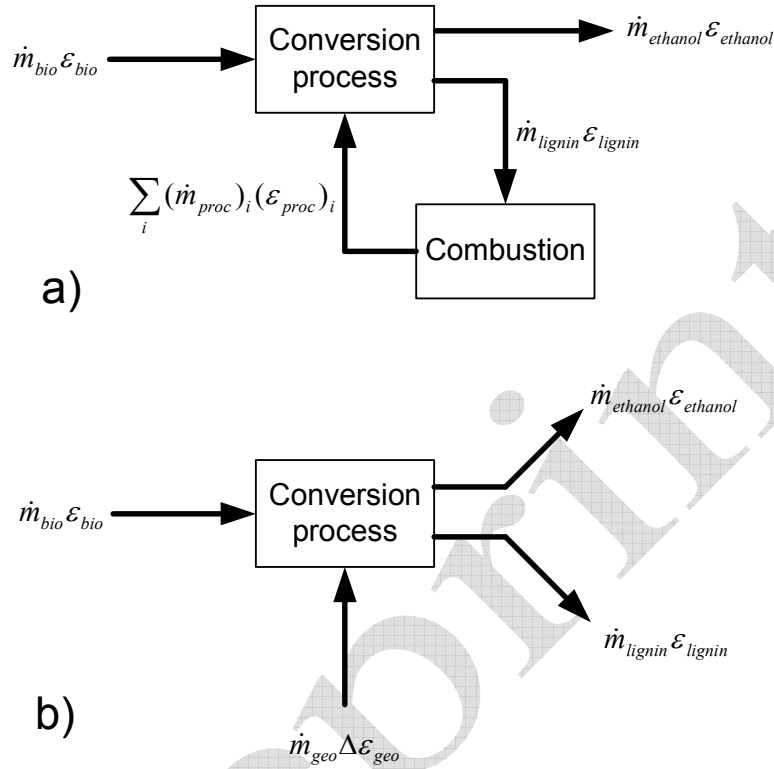


Figure 3: a) Exergy flow in current biorefinery concept, b) Exergy flow in integrated geothermal biorefinery concept.

Table 3: Resource utilization efficiencies for the three cases described in the text

Enthalpy of geothermal resource [kJ/kg]	Case (i)		Case (ii)		Case (iii)	
	η_{BC}	η_{IGB}	η_{BC}	η_{IGB}	η_{BC}	η_{IGB}
	[-]	[-]	[-]	[-]	[-]	[-]
1000	0.22	0.98	0.38	0.39	0.35	0.39
1300	0.22	0.85	0.37	0.39	0.35	0.39
1600	0.22	0.79	0.37	0.39	0.35	0.39
1900	0.22	0.76	0.37	0.39	0.35	0.39
2200	0.22	0.73	0.37	0.39	0.35	0.38

5. Technology developments in biomass combustion to electricity

In the previous section we have assumed a boiler thermal efficiency of $\eta_{th} = 62\%$ following Wooley et al. (1999). However the boiler design by Wooley et al. was not optimized for electricity production as its main aim was to produce steam for meeting process heat demand. If the boiler efficiency was more favourable, this would increase the efficiencies calculated in a number of cases in Section 4 above. There are other energy technologies that have the potential to improve the efficiency of electricity production from biomass. For example, gasification of biomass is an area of recent research and development (Brammer and Bridgwater, 2002; Henderick and Williams, 2000; Nieminen and Kivelä, 1998; Sharma, 2009; Syred et al., 2004; Vyarawalla et al., 1984). The syngas produced from biomass gasification has the potential to be used in internal combustion engines or in turbines with a potential thermal efficiency (η_{th}) in the range of 20% to 34% (Henderick and Williams, 2000) based on lower heating value (LHV). Using syngas for electricity production in a diesel engine, the electricity production can be increased from 55 MW to 82MW (η_{IGB} , objective (ii)). Table 4 summarises possible technologies for electricity production from syngas. Typical thermal efficiencies (η_{th}) are taken from Henderick and Williams (2000). Using these values of η_{th} and Equation (6), hypothetical resource utilization efficiencies (η_{IGB}) are obtained for various power cycles (heat engines) for maximization of electricity production (objective (ii), see Table 5).

Table 4: Thermal efficiency of possible technologies for electricity production from syngas

Diesel engine		Spark-ignition engine	Micro-turbine
Diesel only	Dual-fuel	($\eta_{th} = 21\%$)	($\eta_{th} = 28\%$)
($\eta_{th} = 34\%$)	($\eta_{th} = 27\%$)	(MW)	(MW)
(MW)	(MW)		
82	65	51	67

Table 5: Resource utilization efficiencies for the gasification process of case (ii)

Enthalpy of geothermal resource [kJ/kg]	η_{IGB} (diesel) [-]	η_{IGB} (dual) [-]	η_{IGB} (SI) [-]	η_{IGB} (micro turbine) [-]
1000	0.50	0.44	0.38	0.45
1300	0.50	0.43	0.37	0.44
1600	0.50	0.43	0.37	0.44
1900	0.50	0.43	0.37	0.44
2200	0.50	0.43	0.37	0.44

It is evident from Table 5 that both the diesel engine and micro-turbine can be good options for utilizing syngas. The spark-ignition engine is the least efficient. Using a diesel engine to utilize the syngas, electricity production can be increased about 49% (27 MW) compared to electricity production from lignin combustion and integrated geothermal energy for process heat demand (55 MW). Table 5 summarises the resource utilization efficiency of various technologies that use syngas. The effect of geothermal resource enthalpy is found to be negligible in all cases as the geothermal heat is used for only the high quality (200 °C) heat demand. The low quality heat demand is met efficiently from the waste heat of electricity production. Thus, the quantity of geothermal heat is low (46 MW) and the geothermal resource enthalpy has little effect on the overall resource utilization efficiency. There are several issues however to be addressed before syngas can be adopted commercially, including the corrosion and erosion caused by particles of the syngas, as well as accumulation of tar from it (Syred et al., 2004).

6. Conclusion

This paper has considered the effect of integrating geothermal heat into a biochemical biorefinery so that the lignin enriched residue which is normally combusted to provide process heat becomes available for higher-value uses, such as, the production of high-value chemicals and materials or electricity generation. In all scenarios considered: (i) maximize lignin production, (ii) maximize electricity production, and (iii) maximize lignin production while remaining self-sufficient in electricity, it was found that

incorporating geothermal energy both increased production and resulted in improved utilization of both biomass and/or geothermal resources.

Acknowledgement

We would like to thank Dr Katharine Challis for insightful review and suggestions.

References

- Barbier E. 2002. Geothermal energy technology and current status: an overview. *Renewable and Sustainable Energy Reviews* 6(1-2):3-65.
- Bejan A. 1997. *Advanced Engineering Thermodynamics*: John Wiley & Sons, Inc.
- Brammer JG, Bridgwater AV. 2002. The influence of feedstock drying on the performance and economics of a biomass gasifier-engine CHP system. *Biomass and Bioenergy* 22(4):271-281.
- Campbell JE, Lobell DB, Genova RC, Field CB. 2008. The global potential of bioenergy on abandoned agriculture lands. *Environ Sci Technol* 42:5791-5794.
- Cardona Alzate CA, Sánchez Toro OJ. 2006. Energy consumption analysis of integrated flowsheets for production of fuel ethanol from lignocellulosic biomass. *Energy* 31(13):2447-2459.
- Demirbas A. 2009. Biorefineries: Current activities and future developments. *Energy Conversion and Management* 50(11):2782-2801.
- deVos R, Fortuin S, Heubeck S, Harvey C, King P, Edbrooke S, Stagpoole V, Isaac M, Allum K, Berger Jd, Hooper G. 2009. Section 4 Earth Resources. *EnergyScape™ Basis Review* www.energyscape.co.nz.
- DiPippo R. 2004. Second Law assessment of binary plants generating power from low-temperature geothermal fluids. *Geothermics* 33(5):565-586.
- Dodds DR, Gross RA. 2007. Chemicals from Biomass. *Science* 318:1250-1251.
- Elnashaie SSEH, Fateen SE, El-Ahwany A, Moustafa TM. 2008. Integrated system approach to sustainability bio-fuels and bio-refineries. *Bulletin of Science, Technology and Society* 28(6):510-520.
- Etemoglu AB, Can M. 2007. Classification of geothermal resources in Turkey by exergy analysis. *Renewable and Sustainable Energy Reviews* 11(7):1596-1606.
- Gani A, Naruse I. 2007. Effect of cellulose and lignin content on pyrolysis and combustion characteristics for several types of biomass. *Renewable Energy* 32(4):649-661.
- Henderick P, Williams RH. 2000. Trigeneration in a northern Chinese village using crop residues. *Energy for Sustainable Development* 4(3):26-42.
- Holman JP. 1992. *Heat Transfer*: McGraw-Hill. p 354 p.
- Huber GW, Iborra S, Corma A. 2006. Synthesis of Transportation Fuels from Biomass: Chemistry, Catalysis, and Engineering. *Chem Rev* 106:4044-4098.
- IEA. 2008. *From 1st to 2nd Generation Generation Biofuel Technologies*.
- Kutscher CF. 2000. *The Status and Future of Geothermal Electric Power*. American Solar Energy Society (ASES).
- Larsen J, Petersen MØ, Thirup L, Li HW, Iversen FK. 2008. The IBUS Process – Lignocellulosic Bioethanol Close to a Commercial Reality. *Chem Eng Technol* 31(5):765–772.

- Metzger JO, Huttermann A. 2008. Sustainable global energy supply based on lignocellulosic biomass from afforestation of degraded areas. *Naturwissenschaften* 96:279-288.
- Nieminen J, Kivelä M. 1998. Biomass CFB gasifier connected to a 350 MWth steam boiler fired with coal and natural GAS-Thermie demonstration project in lahti in Finland. *Biomass and Bioenergy* 15(3):251-257.
- Piccolo C, Bezzo F. 2009. A techno-economic comparison between two technologies for bioethanol production from lignocellulose. *Biomass and Bioenergy* 33(3):478-491.
- Potapov P, Yaroshenko A, Turubanova S, Dubinin M, Laestadius L, Thies C, Aksenov D, Egorov A, Yesipova Y, Glushkov I, Karpachevskiy M, Kostikova A, Manisha A, Tsybikova E, Zhuravleva I. 2008. Mapping the World's Intact Forest Landscapes by Remote Sensing. *Ecology and Society* 13(2).
- Ragauskas AJ, Williams CK, Davison BH, Britovsek G, Cairney J, Echert CA, Jr. WJF, Hallett JP, Leak DJ, Liotta CL, Mielenz JR, R M, R T, Tschaplinski T. 2006. The path forward for biofuels and biomaterials. *Science* 311:484-489.
- REFPROP. 2007. National Institute of Standards and Technology (NIST), <http://www.nist.gov/>.
- Schmer MR, Vogel KP, Mitchell RB, Perrin RK. 2008. Net energy of cellulosic ethanol from switchgrass. *Proc Natl Acad Sci USA* 105:464-469.
- Schmitt CB, Burgess ND, Coad L, Belokurov A, Besançon C, Boisrobert L, Campbell A, Fish L, Gliddon D, Humphries K, Kapos V, Loucks C, Lysenko I, Miles L, Mills C, Minnemeyer S, Pistorius T, Ravilious C, Steininger M, Winkel G. 2009. Global analysis of the protection status of the world's forests. *Biological Conservation* 142(10):2122-2130.
- Sharma AK. 2009. Experimental study on 75 kWth downdraft (biomass) gasifier system. *Renewable Energy* 34(7):1726-1733.
- Shieh JH, Fan LT. 1982. Estimation of energy (enthalpy) and exergy (availability) contents in structurally complicated materials. *Energy sources* 6(1 & 2):1-46.
- Syred C, Fick W, Griffiths AJ, Syred N. 2004. Cyclone gasifier and cyclone combustor for the use of biomass derived gas in the operation of a small gas turbine in cogeneration plants. *Fuel* 83(17-18):2381-2392.
- Szargut J, Morris DR, Steward FR. 1988. Exergy analysis of thermal, chemical, and metallurgical processes: Hemisphere publishing corporation.
- Tilman D, Socolow R, Foley JA, Hill J, Larson E, Lynd L, Pacala S, Reilly J, Searchinger T, Somerville C, Williams R. 2009. Beneficial Biofuels-The Food, Energy, and Environment Trilemma. *Science* 325:270.
- Vyarawalla F, Parikh PP, Dak HC, Jain BC. 1984. Utilisation of biomass for motive power generation -- gasifier engine system. *Biomass* 5(3):227-242.
- Wooley R, Ruth M, Sheehan J, Ibsen K, Majdeski H, Galvez A. 1999. Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis Current and Futuristic Scenarios. National Renewable Energy Laboratory.
- Zhang YHP. 2008. Reviving the carbohydrate economy via multi-product lignocellulose biorefineries. *J Ind Microbiol Biotechnol: BioEnergy- Special Issue* 35(5):367-375.