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Integration of Biomass Conversion Technologies and Geothermal Heat into a Model Wood Processing Cluster

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Due to the anticipated future demand for bio-derived fuels and chemicals it is important to identify which processes would benefit from integration with existing industrial clusters, especially those producing wood based products such as pulp and paper. Specific integration schemes need to be identified and benefits, both economic and environmental, quantified to assist the successful commercialisation and adoption of these new technologies. These synergies are examples of industrial symbiosis; the sharing of resources, including utilities and services between different co-located production facilities. Total site analysis is an important tool to accomplish this task. A model of a typical wood processing cluster including a thermo-mechanical pulp and paper mill, kraft pulp and paper mill, and saw mill have been used to evaluate the integration potential of possible new entrants into the cluster. A background/foreground analysis was used to assess any heat recovery potential between the cluster and the new entrant. Some of the processes considered had little or no integration potential due to having approximately the same pinch temperature as the cluster. Large potential was found to occur where the pinch temperatures were dissimilar and the shape of the grand composite curves complimentary. The integration of geothermal heat as a means of generating surplus black liquor as a feed to a biorefinery process was also examined.

1. Introduction

It is anticipated that demand for chemicals and fuel derived from sustainably grown bio-mass will increase in demand over the coming decades (Dornburg et al., 2008). To avoid using valuable food crops and high quality agricultural land, it is almost certain that lignocellulosic biomass (e.g. wood based biomass) will become the major feedstock for these products. To assist the economics and improve the sustainability of these emerging conversion technologies there is opportunity to integrate these processes into current industrial clusters; especially those that produce wood products such as pulp and paper. The wood processing sector is already highly integrated with high use of residues from primary wood processing (e.g. solid lumber) in secondary wood processing (i.e. pulp). These processing facilities are often co-located, due to improved logistics, and frequently utilise common infrastructure; therefore it makes sense that emerging conversion processes based on wood feedstock could also benefit from co-location and integration to improve the economics and environmental outcomes. This is the biorefinery concept.
A model of a typical wood processing cluster has been used to evaluate the integration potential of possible new entrants and biorefinery processes into the cluster. Total Site Integration (TSI) methods, including background/foreground analysis were used to determine the heat integration benefits of several potential new entrants into the model cluster.

1.1 Industrial Clusters and Total Site Integration

In recent years there is growing international interest in industrial clusters as a means of achieving industrial symbiosis and therefore improved economic and environmental outcomes (Yu et al., 2014). However to date much of the focus in the industrial symbiosis literature has been on non-technical issues such as social aspects and policy mechanisms, and is dominated by descriptive rather than technical analysis (Hiete et al., 2012). Process integration, in particular TSI methods, can be used to help achieve

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industrial symbiosis and adapted to overcome the limitations of current industrial symbiosis methods, which are generally conceptual by nature. One of the most promising developments is the integrated biorefinery concept where biomass is transformed into value-added products, in particular chemicals and fuels (Stuart and El-Halwagi, 2013). In order to be economic these processing facilities will require a higher degree of integration and industrial symbiosis to extract the full value of the biomass feedstock. Pulp and paper mills are examples of biorefineries, although it is anticipated that in the future they will produce a greater variety of products including fuels and chemicals.

2. Model Wood Processing Industrial Cluster

A model industrial cluster was used in this case study. The cluster was based around pulp/wood processing and included a thermo-mechanical pulp (TMP) mill with paper machine producing newsprint, a Kraft pulp mill with paper machine producing liner board, and a sawmill producing kiln dried structural lumber. Each plant at the cluster is assumed to have a separate utility system. The production rate, hot and cold utility targets, and pinch temperature for the plants in the existing cluster are given in Table 1.

Table 1: Details for existing processes and potential entrants into the cluster.

Process	Production Rate	Hot Utility [MW]	Cold Utility [MW]	Pinch Temp. [°C]	Reference
Existing Cluster					
TMP Mill	155 kt/y	20.4	5.4	65	Jönsson et al., 2010
Kraft Mill	300 kt/y	137.5	36.0	56	Bonhivers and Stuart, 2013
Kraft Paper Machine	300 kt/y	4.4	25.5	70	Author's Data
Saw Mill	350 km^3/y	19.0	0.0	69	Author's Data
Potential Entrants					
Urea[a]	360 kt/y	0.0	51.8	924	Spath et al., 2005; Picón-Núñez, 2013
Ethylene[b]	200 kt/y	74.0	147.7	96	Hackl and Harvey, 2013
Bioethanol	15.7 kt/y	17.0	0.0	20	Mora et al., 2011
Syngas	60 MW	0.0	26.5	897	Arvidsson et al., 2014
Milk Powder	210 kt/y	35.5	0.0	18	Author's Data

[a] Biomass gasification → NH_3 → urea

[b] Ethanol → ethanol dehydration → ethylene

The combined Grand Composite Curve (GCC) for the entire cluster is shown in Figure 1, including the utility systems. The GCC for the cluster was produced by adding the individual process GCC together. The combined utility system for the cluster has four steam levels: Very High Pressure (VHP) at 61 bar with superheat, High Pressure (HP) at 40 bar, Medium Pressure (MP) at 8 bar, and Low Pressure (LP) at 4.5 bar. The recovery boiler at the Kraft mill produces superheated VHP steam, which is let down to HP and MP steam through back pressure turbines that generate a total of 18.8 MW of power. The heat produced by burning black liquor in the kraft recovery boiler meets the heat demand for the kraft mill but not the paper machine at that mill, which is supplied with LP steam produced from wood waste. LP steam for process heat for the TMP mill and sawmill is also produced using waste wood/hog fuel boilers. Cold utility is available at all plants in the form of Cooling Water (CW) and Chilled Water (CL).

The GCC's for each process in the cluster were taken from literature or the author's data and are based on typical values of temperature and flowrate. The sum of the hot utility targets for the individual processes is equal to 181.3 MW; however if integration between the existing plants is considered this reduces to 162.4 MW as indicated on the GCC in Figure 1. The 18.9 MW of additional heat recovery potential is mostly from using waste heat below the pinch temperature from the TMP mill and paper machines to pre-heat kiln drying air for the saw mill. The overall pinch temperature of the cluster is 60 °C.

2.1 New Processes

Several processes of interest were examined to determine any potential benefits from heat integration with the cluster. The production rate, utility targets, and pinch temperature for each of the new entrants considered is given in Table 1. Each process used lignocellulosic biomass (except the milk powder plant) as the feedstock and it was assumed that sufficient additional feedstock was available to supply the new entrant. The heat demand (i.e. GCC) for each process was taken from literature or based on the author's data. The GCC's in the literature were scaled to better match the cluster size and realistic amounts of available feedstock. While the processes considered here are not a comprehensive list of potential biorefinery processes the procedure could easily be repeated for other processes. The information from the cluster GCC provides a good first set of criteria to quickly asses if there would be any heat recovery potential from having any new process join the cluster.

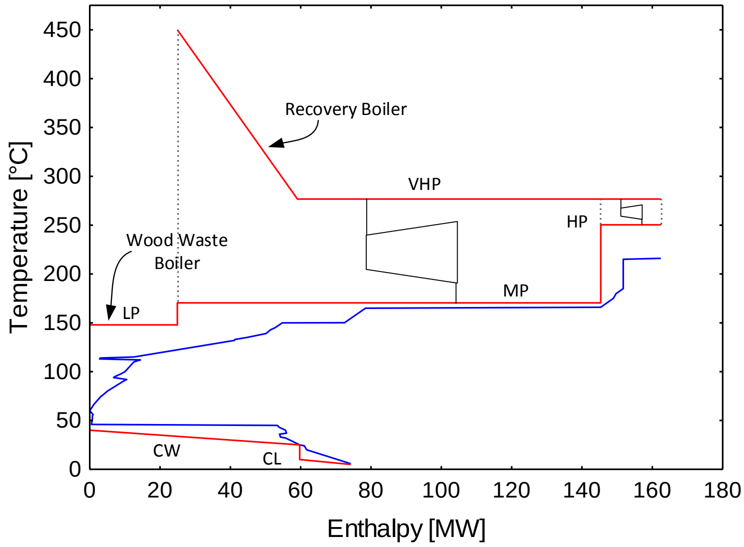

Figure 1: Grand Composite Curve including the utility system for the cluster.

The urea plant included gasification of biomass to produce sufficient hydrogen to meet the specified production rate of urea. The details for the gasification process is taken from Spath et al. (2005) while the urea synthesis from ammonia is taken from Picón-Núñez (2013). Ethylene is a major chemical feedstock and can be produced by dehydrating ethanol. The process considered here involves ethanol production via fermentation before dehydrating ethanol to form ethylene as described by Hackl and Harvey (2013). Direct steam injection required for the fermenters and ethylene reactor is not included. Bioethanol from woody biomass using near-neutral hemicellulose pre-extraction and fermentation is also considered and based on the process outlined by Mora et al. (2011). In this case a by-product, acetic acid, is also produced in roughly the same quantity as ethanol. Syngas from gasification of wood was based on the bio-SNG-LP scenario described in Arvidsson et al. (2014). Syngas could be used as a feed to synthesise fuels or chemicals. A milk powder was also considered because in New Zealand there is often close proximity between dairy factories and wood processing plant.

3. Integration Benefits of New Entrants in the Cluster

A simple background/foreground analysis was used to determine the integration potential of the new entrants. The existing steam pressures of the cluster were used unless an obvious improvement could be gained by introducing an additional steam header, as in the case of the urea process. The reduction in the hot and cold utility, and change in power generation from integration of each of the entrants is shown in Table 2. A decrease in hot utility of the cluster represents a decrease in the cold utility requirement of the new entrant, and a decrease in cold utility in the cluster is a decrease in the hot utility required for the new entrant.

Table 2: Effect of heat integration on the utilities of the cluster.

Process	Cluster Hot Utility Reduction [MW]	Cluster Cold Utility Reduction [MW]	Power Generation Change [MW]	Black Liquor Surplus [%]
Urea	35.8	0.0	+3.0	7.9
Ethylene	2.8	0.0	0.0	0.0
Bioethanol	1.8	3.8	0.0	0.0
Syngas	21.4	0.5	+5.6	0.0
Milk Powder	0.0	3.5	0.0	0.0

Both the pinch temperatures and the shapes of the GCC are important in determining the amount of potential integration. One of the limitations for integration is the near pinch of the cluster that occurs at 113 °C. Consequently processes with a pinch temperature between the cluster pinch (60 °C) and near pinch (113 °C) will have limited integration potential. A good example of this is illustrated on the left of Figure 2 where the ethylene plant is shown as the foreground GCC. The pinch of the ethylene plant occurs at 96 °C, which restricts how much heat recovery can occur, and in this case is only 2.8 MW.
The bioethanol plant as the foreground GCC is shown on the right in Figure 3 and due to the shape of the bioethanol GCC the cluster is able to slightly fit into the pocket and allow a slight amount of feasible heat recovery from both the bioethanol process and the cluster. The production rate of the new entrant can have an effect on the amount of heat recovery possible by typically not the temperature of the heat transferred. There will also be critical production rates that above this value produce no added heat recovery benefit due to the shape of the GCC. For example, in the case of the ethylene plant increasing the production rate above that specified in Table 1 yields no additional heat recovery benefit. For the bioethanol plant the production could be increased until the pocket becomes too large and pinch will occur with cluster.

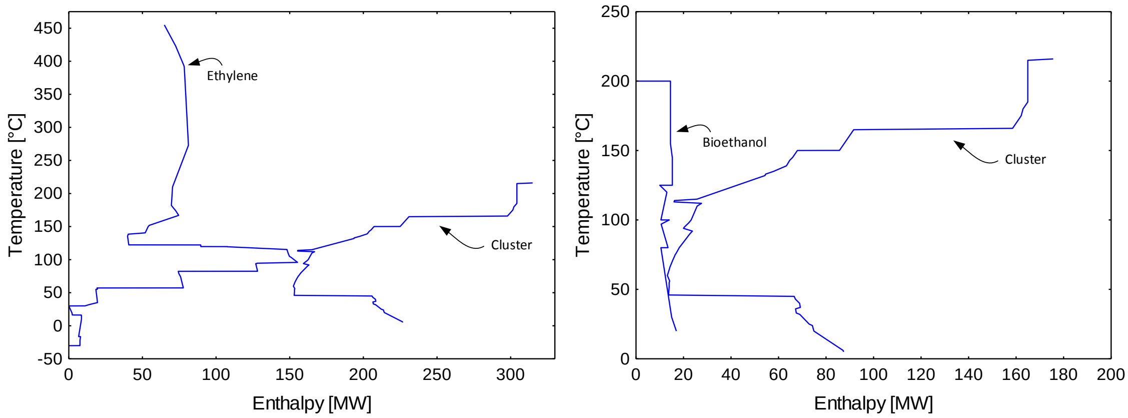

Figure 2: Background/foreground analysis of the ethylene process and the cluster (left) and the bioethanol plant and the cluster (right).

3.1 Urea Production

An interesting case is the production of urea from biomass. Traditionally the feedstock of urea is natural gas that is steam reformed to produce syngas followed by ammonia and finally urea. Biomass can also be used to produce syngas before being synthesised into urea (also via ammonia). A background/foreground analysis of the GCC's of the cluster (background) and the urea plant (foreground) is illustrated in Figure 3. To take full advantage of the available heat and power generation opportunity, an additional steam header at 12.5 bar is required. In this case, there is a reduction in the recovery boiler duty of 10.9 MW, with surplus black liquor being used to generate additional power (+2.6 MW_e) or as a feedstock to a further biorefinery process that uses lignin as a feed.

4. Surplus Black Liquor for Biorefinery Processes

A major opportunity for producing chemicals exists by utilising black liquor as the feedstock instead of burning it for process heat; however the challenge is to still provide the heat demand to the kraft mill despite the reduction in black liquor going to the recovery boiler. There are numerous possibilities for the utilisation of lignin and hemicellulose to produce chemical products (Azadi et al., 2013). Biomass gasification routes provide a significant amount of heat that could be used to supply a portion of the heat demand to the kraft mill allowing surplus black liquor to be used for other biorefinery processes. Alternatively black liquor can be gasified directly to provide heat to the kraft process and syngas as a feedstock for other processes, such as the urea plant (Eriksson and Harvey, 2004). Surplus black liquor produced for each of the options is shown in Table 2. Another option to produce surplus black liquor is to substitute heat from the recovery boiler with another heat source. This could be achieved by burning additional biomass or waste wood (if available) or geothermal energy (if available).

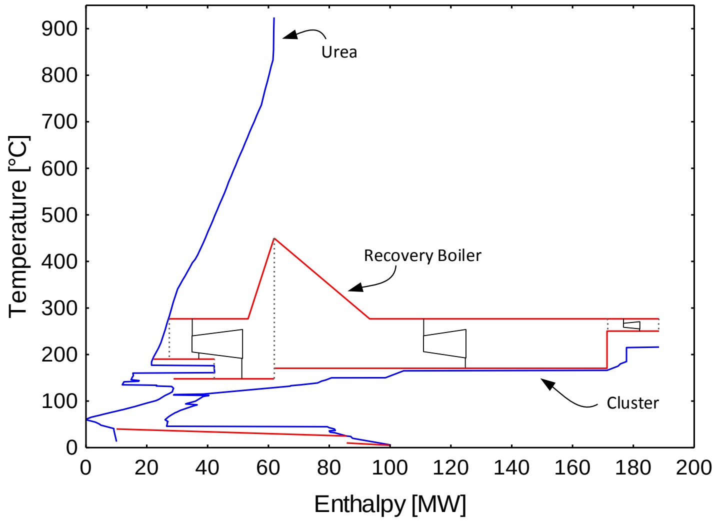

Figure 3: Background/foreground analysis of hydrogen/ammonia/urea production with the cluster.

4.1 Geothermal for Process Heat

In some locations geothermal energy is available in sufficient quantity and quality to provide process heat or generate power. As one of the few renewable forms of process heat it can be integrated either directly (i.e. using geothermal steam/fluid as utility stream) or indirectly (i.e. produce clean steam/hot water) to provide heat. For example, throughout parts of the Central North Island of New Zealand geothermal steam is used directly and indirectly for process heat in a number of industrial processes such as wood drying, pulp and paper production, and milk powder production. The main cost of geothermal is the drilling of the production and reinjection wells and any payment for the steam to the resource owner. In New Zealand geothermal is cost effective with both coal and natural gas where it is available. Where geothermal heat is economic, an additional degree of freedom is added to the potential utility system of an industrial cluster. A geothermal well can reasonably produce 10 – 40 MW of heat typically between 150 – 220 °C and is a two phase mixture of steam and liquid. Normally geothermal fluid is reinjected between 80 – 120 °C back to the geothermal field to maintain a sustainable system. Several wells may be needed to provide enough process heat to the plant.

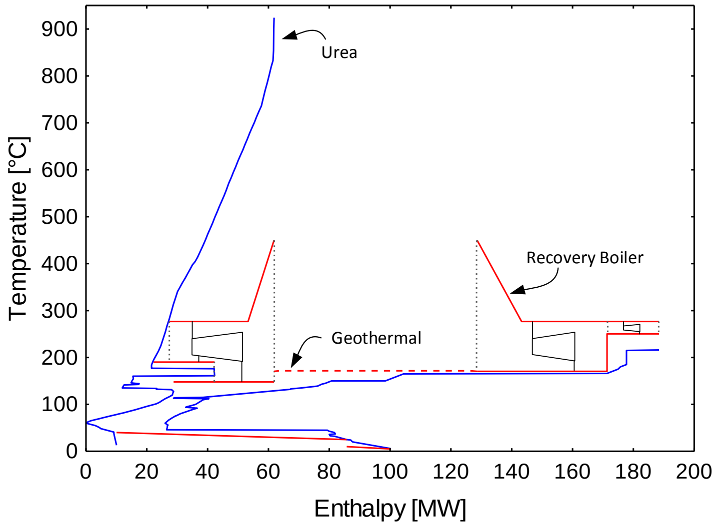

Figure 4: Integration of 78 MW of geothermal heat producing 56 % surplus black liquor to produce urea.

If 78 MW of geothermal heat was available at the cluster and used to supply clean steam to the MP header (8 bar, 170 °C sat. temp.) it could be beneficially integrated to produce enough surplus black liquor to supply the urea process. Two or three wells might reasonably be able to supply this amount of heat to the cluster. Power generation would be reduced by 11.9 MW. Figure 4 illustrates the above scenario on the cluster GCC.

5. Conclusions

The background/foreground analysis is a useful method to quickly assess the integration potential of new entrants into industrial clusters. As expected the amount of heat integration potential with the model wood processing cluster was very dependent on the GCC of the new entrant. In general there is a good opportunity to integrate gasification based processes, such as urea and syngas production, because they generate high quality heat in sufficient quantity to be of benefit to the cluster. Other processes with more modest pinch temperatures produced very little or no integration benefit due to the mismatch of pinch temperatures and GCC's. The relatively low pinch temperature of the cluster (60 °C) as well as the near pinch (130 °C) limits somewhat the suitable new entrants.

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