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Energy Efficiency – A Particular Challenge for the Cellulose-based Products Industries

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Wood-processing facilities, including pulp, paper, lumber, and engineered wood facilities, use large amounts of energy for such purposes as evaporative drying and the curing of adhesives. Much of that energy is already being supplied by the incineration of biomass, and there is opportunity to increase the proportion of renewable energy that is used. Specific changes can be made within such factories that allow them to come closer to what is thermodynamically possible in terms of avoiding the wastage of exergy, which can be defined as useful energy. Savings in exergy are often obtained by optimization of a network of heat exchangers within an integrated system. No steam should be allowed to leak to the atmosphere; rather the latent heat (due to phase transitions) and sensible heat (due to temperature changes) are recovered during the heating up of incoming air and water, ideally at a similar range of temperatures. Thus, by a combination of process integration and full utilization of cellulosic residues generated from the process, even bio-based industries can be made greener.

Keywords: Exergy; Process integration; Biomass energy; Residues; Hog fuel; Efficiency

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Energy-intensive Industries

Think about the cellulose-based products that you use every day, *i.e.* paper, solid wood, and various composites. All of them require substantial amounts of heating during their preparation (Perre *et al.* 2007). Most solid wood products that we use each day have been kiln-dried at temperatures in the range 40 to 132 °C (Oltean *et al.* 2007). Engineered wood products, such as particleboard and oriented strandboard, need further heating to cure adhesive resins. Evaporation of water from paper represents the largest component of energy during its manufacturing processes. The typical amount of energy used to dry a sheet of paper on a commercial paper machine is about 3000 GJ per air-dried metric ton of product (Stenström 2020). Representatives from the wood-products, pulp, and paper industries, myself included, are often quick to point out the environmental advantages of using photosynthetically renewable wood as the main raw material. But the flip side is that these industries are highly energy-intensive. There are further measures that could be taken to reduce the energy footprint of cellulose-based industries.

The principles of thermodynamics set some absolute limits on the degree to which it is possible to reduce the amount of energy required to achieve certain objectives, especially those that involve the removal of water from cellulosic materials. Fortunately, strategies have been developed that allow engineers to modify such processes so that the limits imposed by thermodynamics can be approached more closely. In addition, by applying some outside-of-the-box thinking, there are some opportunities to reduce the wastage of energy.

Process Integration

A key to minimizing the amount of energy required to heat, dry, or thermally process cellulosic materials is to take full advantage of integrating those unit operations with other processes that are already taking place within the same industrial facilities. For example, in a pulp and paper mill there may be a boiler that is incinerating lignin and converting the heat of combustion into high-pressure steam. Some of the steam may be used to generate electricity, and the medium-pressure steam left over is routinely used to dry the paper web. Hot condensate collected after the drying process can be run through a heat-exchanger so that the energy can be used to warm up incoming air and fresh water, as needed for various processing steps. Likewise, there is an option of using biomass residues available at sawmills as fuel for wood kilns or for hot-pressing operations.

When looking for further opportunities to apply such strategies in combined pulp and paper facilities, engineers use a graphical system called "pinch analysis". A simplified example is shown in Fig. 1, which is adapted from Atkins *et al.* (2012). To prepare a pinch graphic, two cumulative lists are prepared. One list includes all of the streams of material that need to be heated up, including fresh water, air, and cellulosic materials, *etc.* The other list includes all of the streams that will be cooling down, including steam, hot humid air, and condensate, *etc.* Some of the streams being cooled down may be an ideal source of energy to be used to heat up the incoming streams. In the example depicted in the figure, a large proportion of the heat required for the process was obtained from "heat recovery" (see top of figure). Only a relatively small proportion of refrigeration energy (see left side of figure) and "added heating" (see right side of figure) had been required in this hypothetical case. By looking at the plot prepared for a typical pinch analysis, the engineers envision ways in which the two plotted lines can be brought closer together, thus coming closer to the thermodynamic limits of potential energy savings. This is done by strategic placement of heat exchangers in optimum positions within the process.

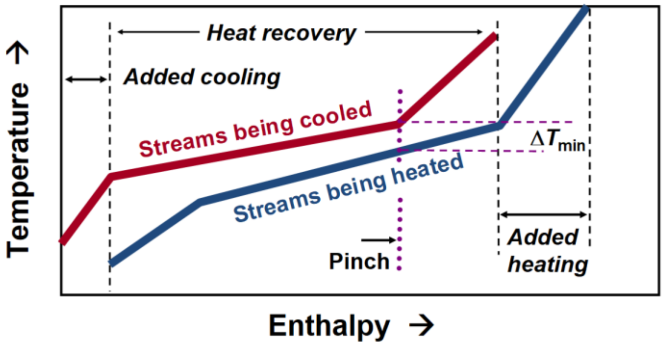

Fig. 1. Example of a basic plot prepared for pinch analysis

Considerable amounts of energy within biomass-processing facilities will be embodied in warm water or warm humid air, *etc.* Often it may appear that such energy no longer has a sufficiently high difference in temperature from the adjacent environment (*e.g.* typical outdoor air temperatures) so that there is no practical way to convert the heat into a useful form, such as electricity, pressurized air, or the turning of a shaft. To clarify such issues, engineers quantify the exergy content of each stream. Exergy is obtained by starting with the energy content of that stream and subtracting the energy corresponding to a selected temperature, which represents a typical value for the surrounding environment

(Dincer and Rosen 2021). In temperate climates there can be dramatic differences between summer and winter outdoor temperatures. Thus, pulp and paper facilities in Sweden routinely provide winter heating services for adjacent businesses or homes in their districts (Andersson *et al.* 2006). In such instances, pinch analysis has been used to guide pulp and paper companies to reconfigure their networks of heat exchangers within their facilities, depending on the season of the year (Persson and Bertsson 2009).

Underutilized Energy from Residues

The mill yards and initial unit operations of forest products industries can be generation points for various residues such a bark, sawdust, and trimmings. Environmental gains can be achieved when such residues are utilized as fuel, replacing the usage of fossil fuels and purchased electricity (which often is produced mainly from combustion of coal, petroleum, or natural gas). The biomass can be naturally replaced by photosynthesis, whereas the fossil fuels cannot. One option for the use of the biomass residues is to feed them into a so-called hog-fuel boiler (from a Scandinavian word meaning "chopped"). Another option is to compress the biomass into pellets, which converts the material into a denser format, which can be easily poured, transported, stored, and metered. Waste heat from flue gases (smokestacks) can be used to pre-dry the residues, which is especially important if they are about to be fed into a hog-fuel boiler. This is represented by the red dotted arrows at the top and upper left in this updated version of Fig. 2 (Nelson *et al.* 2018). By using low-grade, excess heat to evaporate water from the incoming biomass, the same amount of material, after it is drier, can be incinerated at a higher temperature. This provides a higher content of exergy, meaning that a higher proportion of the heat can be fully utilized in running the process as a whole. Caution is needed, however. Unintended fires can start when using flue gases for pre-drying, so careful automatic control of the process is needed. The circled numbers in Fig. 2 indicate operations to remove different contaminants from the flue gases.

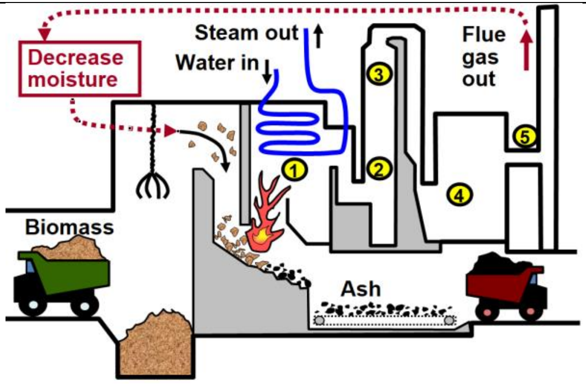

Fig. 2. Schematic of a system for generating energy from lignocellulosic residues. 1: Furnace and removal of nitrogen oxide gases; 2: Hg and dioxin removal; 3. Acid gas removal; 4. Particulate removal; 5. Pollution control testing

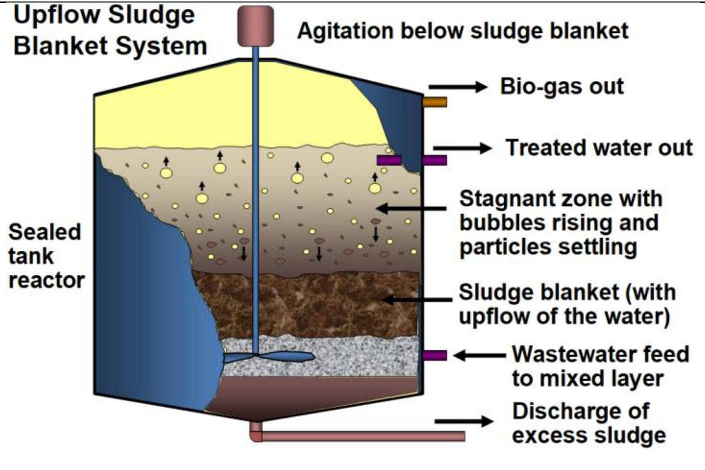

Fig. 3. Schematic of an upflow sludge-blanket anaerobic digester

The wastewater left over after the processing of biomass, as in the manufacture of pulp and paper, also can have big consequences for the overall energy balance of the facility. The sludge resulting from conventional aerobic biological treatment (*i.e.*

"activated sludge") is difficult to squeeze water out of, and there is a risk of release of the potent greenhouse gas methane if wet sludge is placed in a landfill. A better energy situation can be achieved if the mill constructs an enclosed reactor for anaerobic digestion of the organic content in wastewater. Figure 3 shows the type of reactor system that can be used (Hubbe *et al.* 2016). Such processing yields much less biological sludge compared to typical activated sludge processing, and the biological processes result in generation of methane gas, which can be collected and used as a fuel. Though the amount of methane produced may be only enough to compensate for the energy needed to run the wastewater treatment plant itself (Precci Lopes *et al.* 2018), the environmental benefits can be large. The point to keep in mind that process streams that are called "waste" often represent opportunities to improve the energy-efficiency of the plant and decrease the purchase of fossil fuels.

References Cited

Andersson, E., Harvey, S., and Berntsson, T. (2006). "Energy efficient upgrading of biofuel integrated with a pulp mill," *Energy* 31(10-11), 1384-1394. DOI: 10.1016/j.energy.2005.05.020

Atkins, M., Walmsley, M., Morrison, A., and Neale, J. (2012). "Process integration in pulp and paper mills for energy and water reduction - A review," *APPITA J.* 65(2), 170-177.

Dincer, I., and Rosen, M. A. (2021). *Exergy: Energy, Environments, and Sustainable Development*, 3rd Ed., Elsevier, Amsterdam. DOI: 10.1016/B978-0-12-824372-5.00004-X

Hubbe, M. A., Metts, J. R., Hermosilla, D., Blanco, M. A., Yerushalmi, L., Haghighat, F., Lindholm-Lehto, P., Khodaparast, Z., Kamali, M., and Elliott, A. (2016). "Wastewater treatment and reclamation: A review of pulp and paper industry practices and opportunities," *BioResources* 11(3), 7953-8091. DOI: 10.15376/biores.11.3.Hubbe

Nelson, L., Park, S., and Hubbe, M. A. (2018). "Thermal depolymerization of biomass with emphasis on gasifier design and best method for catalytic hot gas conditioning," *BioResources* 13(2), 4630-4727. DOI: 10.15376/biores.13.2.Nelson

Oltean, L., Teischinger, A., and Hansmann, C. (2007). "Influence of temperature on cracking and mechanical properties of wood during wood drying – A review," *BioResources* 2(4), 789-811.

Perre, P., Remond, R., and Aleon, D. (2007). "Energy saving in industrial wood drying addressed by a multiscale computational model: Board, stack, and kiln," *Drying Technol.* 25, 75-84. DOI: 10.1080/07373930601160841

Persson, J., and Bertsson, T. (2009). "Influence of seasonal variations on energy-saving opportunities in a pulp mill," *Energy* 34(10), 1705-1714. DOI: 10.1016/j.energy.2009.07.023

Precci Lopes, A. D., Silva, C. M., Rosa, A. P., and Rodrigues, F. D. (2018). "Biogas production from thermophilic anaerobic digestion of kraft pulp mill sludge," *Renew. Energy* 124, 40-49. DOI: 10.1016/j.renene.2017.08.044

Stenström, S. (2020). "Drying of paper: A review 2000-2018," *Drying Technol.* 38, 825-845. DOI: 10.1080/07373937.2019.1596949