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Fermentation Plant Proposal

Corner Brook, Newfoundland and Labrador

Group 1

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Group 1: Fermentation Plant Proposal

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Introduction

Corner Brook, Newfoundland, is a mid-sized coastal community with a population of 19,333. The local economy relies on forestry, fishing, and pulp and paper manufacturing, generating significant amounts of wood waste and biomass residues[15]. Recognizing the potential of these resources, our proposal, Bay Side Biorefinery (BSB), aims to expand renewable energy use while prioritizing sustainability and ecological responsibility. Utilizing forestry by-products will reduce waste, displace fossil fuel reliance, and enhance energy security.

Corner Brook's long winters bring heavy snowfall, strong winds, and high heating demands, making energy reliability essential. While hydroelectric power supplies most of the region's energy, reliance on a single source poses risks[25]. The Deer Lake Power facility, which powers the local pulp and paper mill, also faces legal and environmental challenges due to residential flooding[18]. Introducing a secondary sustainable energy source would enhance energy security and reduce regional vulnerability.

Fermentation-based bioenergy is a renewable and stable energy source. This biological process uses microorganisms to convert organic material into energy-rich compounds. In biofuel production, bacteria and yeast break down cellulose and hemicellulose into simple sugars, which are then metabolized into bioethanol, biogas, or hydrogen. Unlike combustion, which directly emits CO_2, fermentation operates within a closed carbon cycle, where released carbon is reabsorbed by growing plants[39]. When combined with carbon capture technology, fermentation-based bioenergy can potentially achieve net-negative emissions.

The BSB will strengthen Corner Brook's energy supply by fermenting forestry residues and paper sludge waste from the mill to reduce reliance on hydroelectric power. This bioenergy system will generate enough power to support the city's current population, enabling off-grid energy independence. Over time, BSB can expand to include additional organic waste sources, such as agricultural and fishery waste, which currently produce substantial amounts annually[12]. By integrating multiple waste streams, BSB will not only enhance energy security for Corner Brook but also contribute to the broader regional energy grid, reducing Newfoundland's dependence on external power sources.

Newfoundland's forests and the Corner Brook Pulp & Paper (CBPP) mill provide a steady biomass supply, with additional feedstock available from Nova Scotia, Quebec, and New Brunswick. Demolition wood, sawmill residues, paper sludge, and post-consumer wood waste can supplement production, maximizing resource efficiency. Advances in enzyme treatments and fermentation continue to improve biofuel yields, enhancing viability. BSB will strengthen energy security, reduce industrial waste, and most importantly create jobs, positioning Corner Brook as a leader in sustainable energy. Government incentives for biofuel research and waste reduction further support the initiative, helping to revitalize the local economy and attract the working population.

Production Overview

Global interest in biorefineries has grown as lignocellulosic biomass (LCB) gains recognition as a renewable resource for producing biofuels, biochemicals, and other valuable by-products. This shift not only reduces reliance on fossil fuels but also helps mitigate environmental impacts.

Figure 1 illustrates the overall process illustrating the key steps of biomass conversion, from feedstock supply to final energy production.

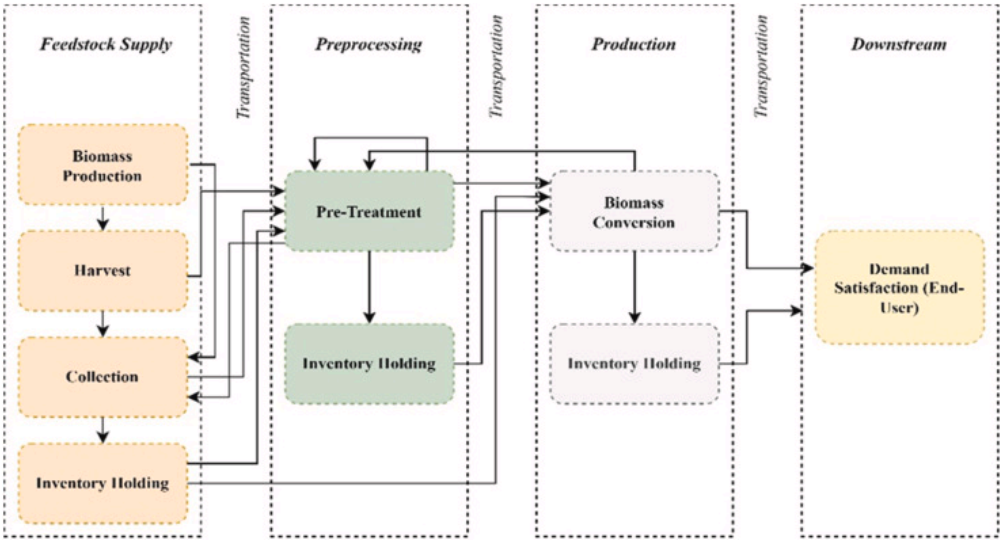

Figure 1: *A schematic representation of the biomass conversion process, detailing the stages from feedstock supply to end-user demand satisfaction. The process begins with biomass production, harvesting, and collection, followed by preprocessing through pre-treatment and inventory holding. Biomass conversion then takes place in the production phase, along with a secondary inventory holding, before transportation to consumers. The diagram highlights key transportation links between stages, using arrows to show the flow of materials*[69].

Production

LCB is composed of 40%–50% cellulose, 25%–30% hemicellulose, and 7%–20% lignin[60]. Cellulose, a homopolysaccharide of β-D-glucose, forms long, linear chains linked by β(1→4) glycosidic bonds, which aggregate into fibrils stabilized by hydrogen bonding[51]. Hemicellulose, a heteropolymer, consists of glucomannans (glucose/mannose) and xylans (xylose), forming a more branched and complex structure[44]. Lignin, a cross-linked, three-dimensional polymer provides structural integrity to plant cell walls. It is composed of phenylpropanoid-derived benzene rings with hydroxyl and methoxy groups[22 35]. Together, these polymers create LCB's

structural resilience, necessitating multi-step bioconversion processes for effective utilization (Figure 2).

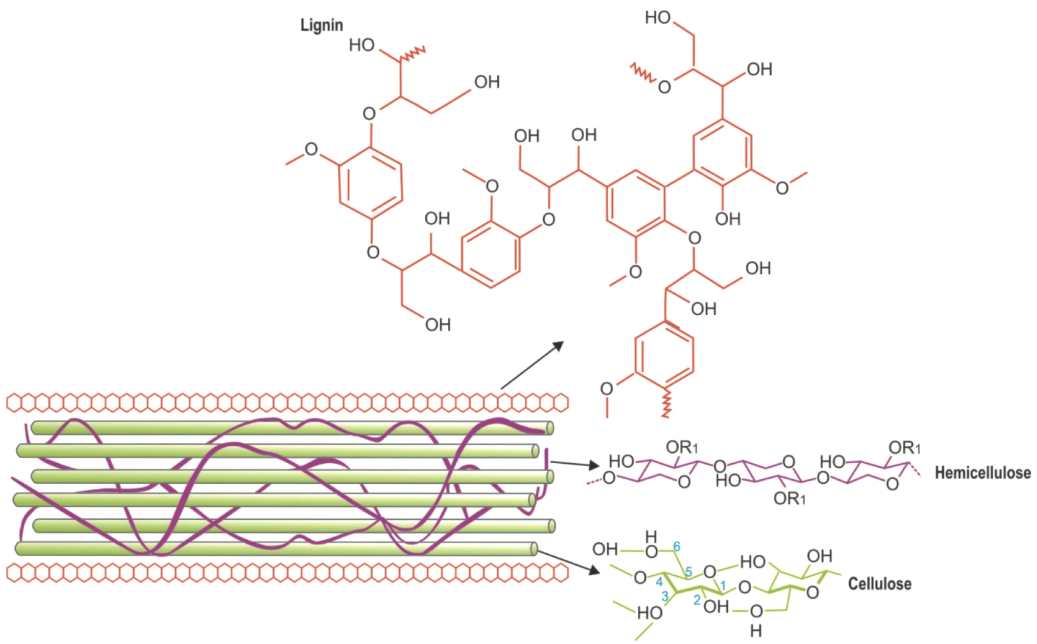

Figure 2: *Diagram depicting plant cell wall components, including cellulose (green), hemicellulose (purple), and lignin (red). The structure highlights the interlinked biopolymers, where cellulose microfibrils form a rigid backbone, hemicellulose acts as a cross-linking matrix, and lignin provides structural integrity and resistance to degradation*[49].

To convert LCB into biofuels, chemical reactions and catalytic processes break down structural polymers into fermentable sugars (Figure 3). Hydrolysis, which cleaves glycosidic bonds, is achieved through acid or enzyme catalysis[3].

Lignin, a cross-linked polymer of aromatic monomers, resists hydrolysis due to its irregular structure and strong ether bonds, requiring pretreatment methods like steam explosions to disrupt its polymer network[8]. In fermentation, oxidation-reduction reactions convert pyruvate, a

glycolysis product, into ethanol through NADH-mediated electron transfer, regenerating NAD^+ for sustained microbial metabolism. The fermentation rate follows reaction kinetics, with microbial growth adhering to a logistic model, where ethanol production peaks as substrate availability declines[70].

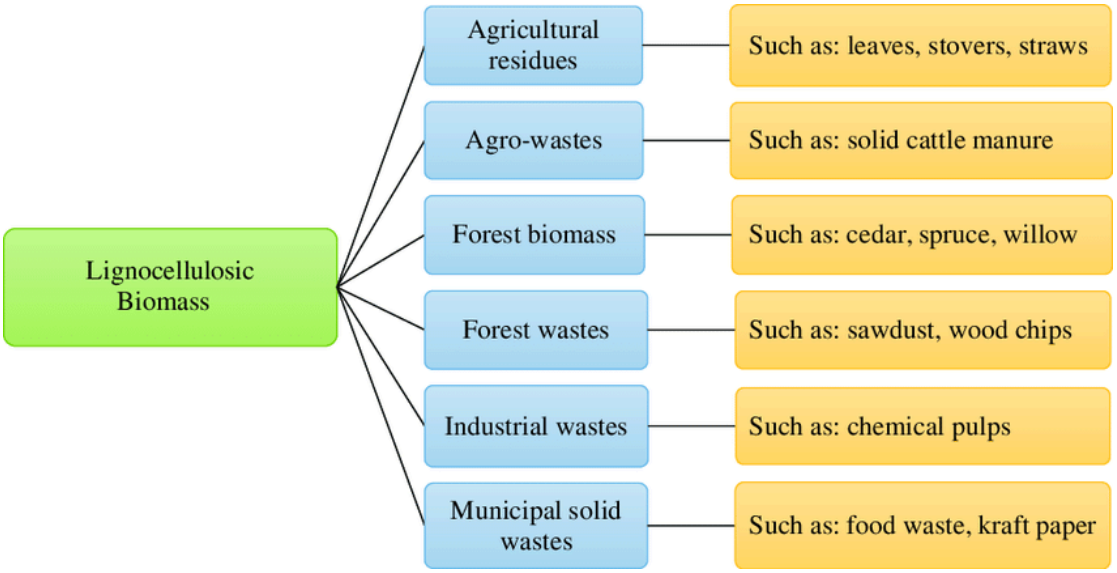

Figure 3: *Classification of LCB. Examples of each category are provided, highlighting diverse biomass feedstocks, which can be utilized for bioethanol and biogas production [2].*

Sourcing

Given the structural complexity of LCB, sourcing appropriate feedstocks is critical for maintaining consistent chemical composition and optimizing biofuel yields. Currently, the CBPP mill processes 450,000 cubic metres of balsam fir and black spruce round wood annually while incorporating waste biomass from local sawmills, including pulp chips and processing residues[30]. BSB will source biomass from CBPP's by-products, such as spent pulping liquor, wood fibre sludge, and lignin-rich residues, ensuring a centralized supply without additional handling.

Supplementary feedstocks, such as agricultural residues, municipal waste, and industrial waste, are also available.

Pretreatment

To efficiently convert LCB into useful products, the biomass must be pretreated to separate the lignin from the cellulose and hemicellulose present in the complex structure. The overarching aim of pretreatment is to reduce the size of the biomass particles, thus increasing their surface area and porosity, enhancing enzyme accessibility downstream[42]. As Corner Brook's biomass sources are mainly wood-based, pretreatment will use steam explosion (SE) to separate individual polymers.

SE is one of the most efficient pretreatment methods for wood and pulp biomass, disrupting lignin and hemicellulose structures with minimal chemical use in just minutes[75]. The process uses saturated steam, which holds the maximum heat at a given pressure, making it ideal for heat-based industrial applications[73]. High-pressure steam (160-270°C, 10-44 bar) is injected into a reactor containing LCB, softening its structure and weakening bonds[63]. When pressure rapidly drops, steam expansion fractures the material, breaking connections between cellulose, hemicellulose, and lignin for easier enzymatic breakdown[73]. Pretreatment loosens lignin, forming smaller compounds that can be removed, while heat and moisture convert hemicellulose into sugars like xylose and mannose. Rapid decompression separates cellulose, making it more accessible for enzymatic hydrolysis (EH)(Figure 4)[75].

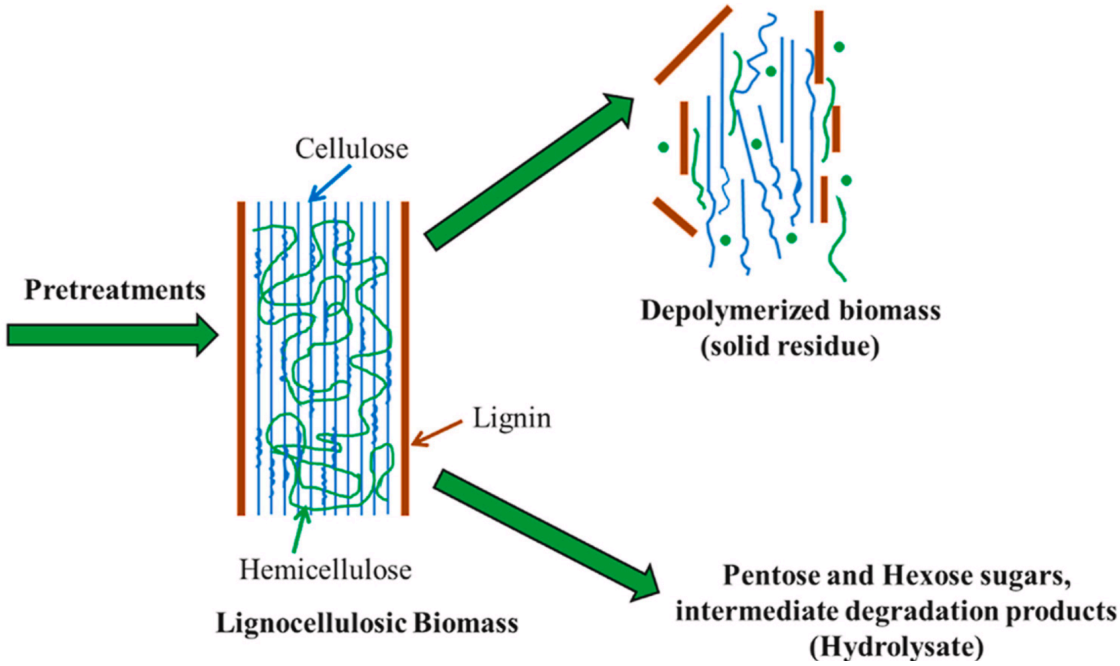

Figure 4: *LCB pretreatment methods and its effects on the overall structure. This process results in depolymerized biomass (solid residue) and the release of pentose and hexose sugars, along with intermediate degradation products, facilitating further bioconversion into bioethanol or biogas*[58].

Thermodynamics and Mechanics of Biomass Conversion

The conversion of LCB into bioethanol and biogas relies on heat transfer, pressure differentials, and fluid dynamics. In SE pretreatment, high-pressure steam injects thermal energy, increasing molecular vibrations and disrupting lignin's rigid structure[75]. When pressure rapidly drops, steam expansion generates mechanical forces that fracture polymer bonds, following the first law of thermodynamics[73].

EH and fermentation follow reaction kinetics, governed by the Arrhenius equation where k is the rate constant, A is the Arrhenius constant, E_a is the activation energy, R is the gas constant and T is the temperature (Equation 1).

Reaction rates increase with temperature until enzymes denature[57].

$$k = Ae^{\frac{-E_a}{RT}} \tag{1}$$

Detoxification

After SE pretreatment, toxic by-products can inhibit EH and fermentation, meaning an intermediate detoxification step, to enhance sugar conversion and maximize yield, is needed. The optimal detoxification process for bioethanol production combines overliming, sulfite treatment, and enzymatic detoxification, all of which use pH modulation to neutralize inhibitors and improve microbial fermentation[20 29]. Strong acids can degrade sugars into inhibitory by-products, requiring pH control with bases like $Ca(OH)_2$. These methods are scalable and can be combined for greater efficiency.

Enzymatic Hydrolysis

Following detoxification, raw materials undergo EH to obtain fermentable sugars. EH is a more environmentally friendly alternative to chemical hydrolysis, requiring less energy and operating under milder, non-corrosive conditions[9]. The process relies on cellulases and hemicellulases, which are enzyme complexes primarily produced by fungi and bacteria, to hydrolyze LCB[32].

Cellulolytic enzymes act synergistically to break down cellulose, with endo-1,4-β-D-glucanase, exo-1,4-β-D-glucanase, and β-glucosidase playing key roles in glucose release[9]. Hemicellulose, comprising 20 to 30% of LCB, is easier to hydrolyze but requires a diverse enzyme mix. Core enzymes like xylanases and mannanases degrade the polymer and work with accessory enzymes to enhance sugar release[71]. The hydrolysis of hemicellulose primarily yields pentoses, including xylose and arabinose. EH follows Michaelis-Menten kinetics, where reaction rates depend on

substrate concentration and enzyme activity, making temperature and pH optimization crucial[70]. Since enzymes operate within a narrow pH range, buffer solutions (phosphate or acetate-based) maintain conditions for cellulase and hemicellulase activity. Extreme pH variations denature enzymes, reducing efficiency[9]. Fermentation is similarly pH-sensitive, with industrial yeast strains achieving peak ethanol yield at pH 4.5–5.5.

EH optimization is crucial for cost-effective bioethanol production, as it accounts for 20 to 30% of production costs, making it a key component in the process.

Fermentation

Microbial fermentation is the final step in converting LCB into bioethanol. For hexose fermentation, industrial strains of *Zymomonas mobilis* and *Saccharomyces cerevisiae* are used for their high ethanol yield and inhibitor tolerance, converting glucose into ethanol via glycolysis[9]. Pentose fermentation, primarily xylose, and arabinose, utilizes *Candida shehatae* and *Pachysolen tannophilus* to enhance ethanol yield from hemicellulose-derived sugars[56]. As ethanol concentration rises, it must be monitored to prevent reduced efficiency due to microbial inhibition. Fermentation lasts 24 to 72 hours, after which residual biomass is separated by filtration and centrifugation[40].

The solid fraction, mainly lignin, undegraded sugars, and microbial cells, retains high energy content and can be processed into bioenergy[6]. By-products are burned in boilers for heat and steam or undergo anaerobic digestion by methanogenic bacteria to produce biogas for electricity or heating[1].

Bioethanol and biogas store chemical energy in molecular bonds, releasing heat upon combustion. This heat generates steam to drive a turbine, converting mechanical energy into electricity through electromagnetic induction (Faraday's Law). Unlike wind and solar, which fluctuate with environmental conditions, bioenergy provides a stable and continuous power supply, with efficiency depending on turbine design, steam pressure, and temperature[55 67].

Required Inputs and Infrastructure

Establishing a fermentation-based bioenergy system in Corner Brook requires appropriate infrastructure and inputs. The BSB will focus on producing biogas and bioethanol from local waste streams, utilizing fermentation as a renewable energy process[11].

Biomass collection centres and storage facilities are essential for sorting and storing municipal, agricultural, and wood waste. At collection centres, waste is sorted by type and transported via conveyor systems. Storage facilities include covered warehouses for dry biomass (wood chips, straw), silos for grains and loose materials, and anaerobic tanks for wet organic waste (food, manure). These facilities streamline feedstock management, ensuring efficient processing for bioenergy production.

Before EH and fermentation, LCB undergoes pretreatment in a facility with industrial grinders for mechanical processing and corrosion-resistant tanks for chemical treatments[42]. Fermentation can follow Separate Hydrolysis and Fermentation (SHF) or Simultaneous Saccharification and Fermentation (SSF)[21 62]. We are using SSF because it reduces enzyme inhibition, shortens processing time, and lowers costs by minimizing contamination risks[53].

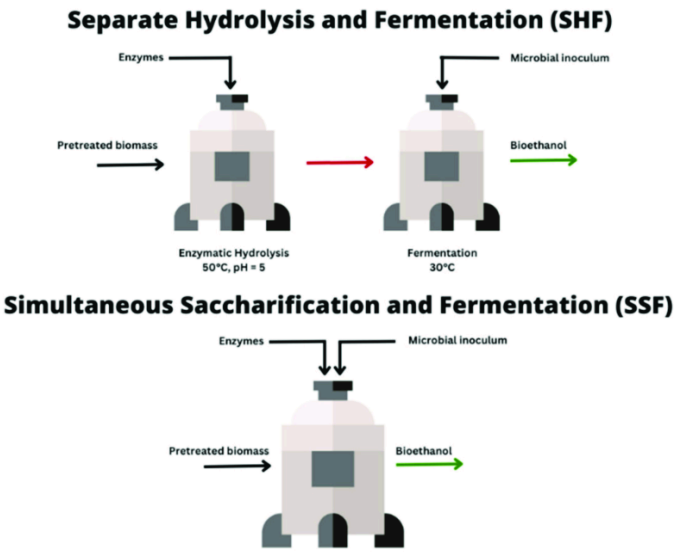

Figure 5: *In SHF (top), pretreated biomass is broken down into simple sugars at the optimal conditions of 50°C and pH 5, then fermented separately at 30°C using microorganisms to produce bioethanol. In SSF (bottom), both sugar breakdown and fermentation happen together in one reactor, making the process faster and more efficient*[21].

BSB will use a continuous SSF plant, integrating EH and fermentation in one system[34]. While SSF operates at a single temperature, which limits the ability to optimize conditions separately for EH and fermentation, its efficiency and cost benefits outweigh this limitation. Functioning like a Continuous Stirred-Tank Fermentation Reactor (Figure 6), it streamlines ethanol production by continuously adding biomass and removing ethanol. A stirrer ensures uniform mixing, and ethanol is isolated through distillation and purification[45 50].

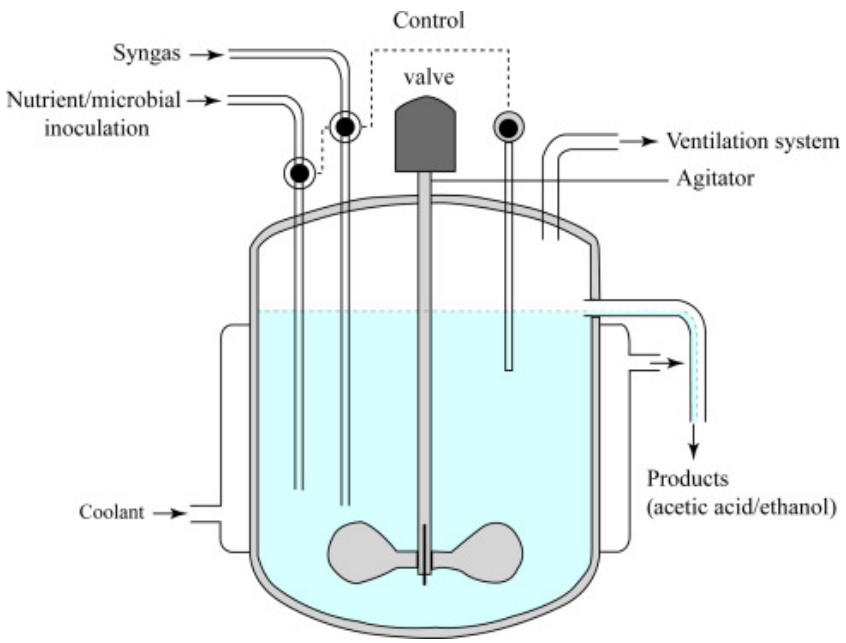

Figure 6: *A schematic representation of a Continuous Stirred-Tank Bioreactor used for syngas fermentation to produce ethanol. Syngas and nutrient/microbial inoculum are introduced into the reactor, where an agitator ensures proper mixing. The system includes a ventilation mechanism for gas exchange, a cooling system to maintain optimal temperatures and a control valve for process regulation. The final products, acetic acid, and ethanol, are collected from the output stream. This is an example of what our Continuous SSF Plant will look like, however, ours will also incorporate EH to streamline the efficiency*[45].

The process begins with extractive distillation, where the fermented liquid is heated in a boiling kettle, separating ethanol based on its boiling point[65]. The rectification column then purifies ethanol to ~95% by removing water and impurities through vapour-liquid equilibrium[4 16 23]. A dehydrator then eliminates any remaining water to produce fuel-grade ethanol. Finally, purification and filtration remove by-products like oils, aldehydes, and organic acids before storage in specialized tanks[4].

After ethanol extraction, the lignin-rich biomass is pre-treated and fed into a continuous anaerobic digester design for biogas production[68]. The biogas is transported via pipelines to collection centres. Additional infrastructure includes on-site labs for quality control, research, and transportation facilities for feedstock delivery and product distribution.

Environmental Considerations

The site for BSB considers geological stability, climate, and resource availability to minimize environmental impact. Corner Brook's heavy precipitation increases the risk of land movement, particularly in areas with porous sedimentary rock[26]. The proposed site, primarily bedrock, provides structural stability, reducing landslide risks (Figure 7)[26]. Western Corner Brook consists of island arc volcanic and volcaniclastic rocks, while the east contains high-grade metamorphic rock[26]. Marine clastic sedimentary rock, with high permeability and porosity, may impact drainage and erosion. To mitigate risks, BSB will assess elevation and slope and implement drainage systems for effective water management[27 59 66].

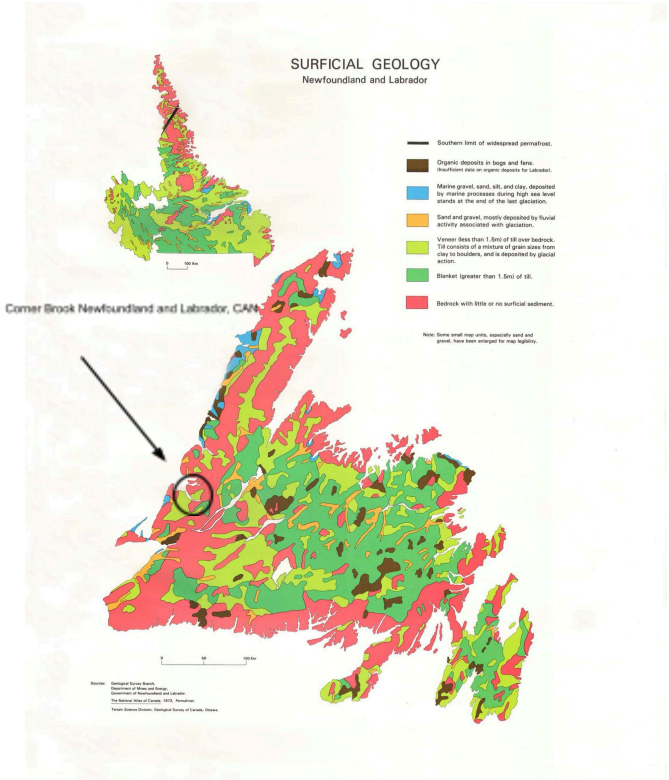

Figure 7: *A map of the main geology of different regions in Newfoundland and Labrador with the city of Corner Brook circled in black with an indicative arrow. This figure shows that the main geological composition of Corner Brook is bedrock, which consists of different sedimentary rocks. Although the circle encompasses an overall area of Corner Brook, the area that includes the proposed plant location is geologically identified as pure bedrock*[26].

High precipitation and porous sedimentary rock in the area increase the risk of mudslides and landslides. Careful placement of the facility and additional drainage systems will mitigate such potential issues (Figure 8).

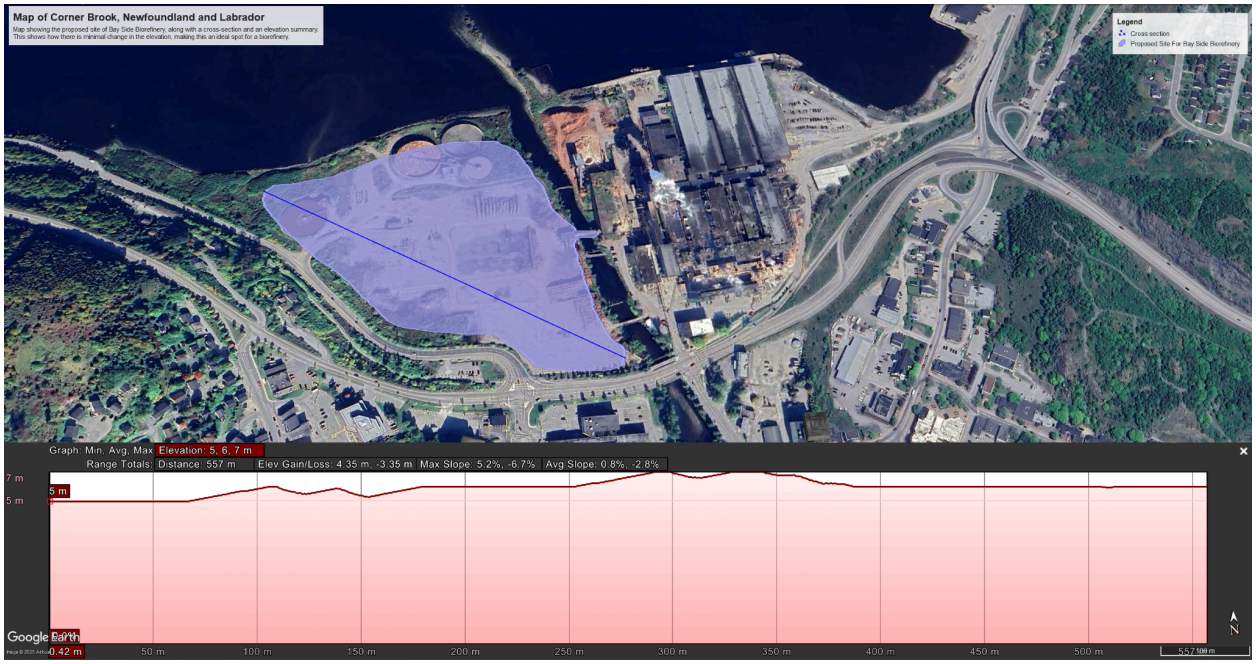

Figure 8: *A cross-section of the proposed location for BSB supported with elevation data regarding the cross-section. This data ensures a stable and consistent elevation with minimal change in the slope throughout the area. This concludes that the proposed site is not directly at risk of land movement from inclined slopes*[24].

Sustainable land use is essential for soil health and long-term biomass availability. BSB will prioritize forestry residues, pulp mill by-products, and municipal waste over energy crops, following sustainable forestry practices to prevent nutrient depletion. Fermentation wastewater, if untreated, can cause eutrophication (oxygen-depleting algal blooms) and high chemical oxygen demand (COD) levels, straining water ecosystems. To prevent this, BSB will treat wastewater through anaerobic digestion, microbial bioreactors, and membrane filtration, enabling water reuse. Solid by-products (digestate) will serve as organic fertilizer, reducing reliance on synthetic inputs and improving soil health.

Bioethanol production results in ethanol as the primary fuel product, with CO_2 as a secondary by-product. Unlike fossil fuels, bioethanol operates within a short-term carbon cycle, where emitted CO_2 is reabsorbed by biomass regrowth. Studies indicate that bioethanol production releases up to 10 times less CO_2 than traditional fossil fuel combustion[61]. To further reduce net emissions, BSB will implement CO_2 capture technologies, repurposing captured carbon for industrial applications[52].

Around 200 U.S. bioethanol facilities generate 40 million tonnes of CO_2 annually from fermenting 53 billion litres of ethanol, a small fraction of the 36.4 billion tonnes emitted globally by fossil fuels in 2019[43]. Unlike fossil fuels, which release ancient carbon, bioethanol comes from plants that recently absorbed CO_2, keeping emissions within a short-term natural cycle. To further cut emissions, BSB will capture CO_2 from fermentation for industrial use. Integrating bioethanol into Corner Brook's energy system will provide a cleaner, renewable fuel, reducing overall emissions and supporting a sustainable, circular economy (Figure 8).

Ecological and Societal Impacts

Sustainability and Environmental Benefits

Sustainability is a balance between economic, environmental, and social dimensions (Solarte-Toro & Cardona Alzate, 2023). The implementation of fermentation at BSB will increase Corner Brook's sustainability by reducing fossil fuel dependence, lowering CO_2 emissions, and repurposing waste biomass. While fermentation does emit CO_2, the emissions are significantly lower than those from fossil fuels, and research has demonstrated that CO_2 from bioethanol production can be captured and valorized, minimizing the carbon footprint[64].

Additionally, biomass does not contribute to long-term carbon accumulation in the atmosphere, unlike fossil fuels, which release sequestered carbon and increase net emissions. This prevents emissions and minimizes ecosystem disruption. The fermentation process mimics natural biological pathways, efficiently converting biomass while preventing nutrient overloading in ecosystems. Additionally, digestate, a fermentation by-product, can be repurposed as fertilizer, enhancing soil quality without synthetic inputs.

Minimizing Ecological Disruption

Bioenergy production can alter ecosystem interactions by affecting decomposers and detritivores reliant on organic material. To minimize disruption, BSB will use only waste materials that would otherwise be discarded, ensuring minimal impact on food webs. This supports nutrient cycling, preserves biodiversity, and enhances resource efficiency. By utilizing fishery by-products and forestry residues, BSB avoids extracting new resources, aligning with circular economy principles. Repurposing organic waste prevents uncontrolled decomposition and produces emissions, reducing nutrient overloading in terrestrial and aquatic ecosystems while contributing to sustainable energy production.

Social and Economic Benefits

BSB will generate stable, local employment in bioenergy production, feedstock processing, and infrastructure development. Studies show that economic benefits are most substantial in areas where employment is low[37]. Since Corner Brook has a smaller job market, creating new jobs through BSB can significantly improve economic stability and reduce poverty in the community.

As a mid-sized city, Corner Brook will benefit from the additional jobs, providing long-term economic stability while reducing dependence on external energy markets.

Biofuels also offer significant safety advantages over fossil fuels. Unlike petroleum-based fuels, bioethanol is non-toxic, biodegradable, and safer to handle[38]. Additionally, bioenergy production improves energy security by reducing reliance on imported fuels, ensuring a more self-sufficient energy system for Newfoundland.

Addressing Potential Challenges

Although BSB primarily relies on residual biomass from the pulp and paper industry, concerns exist about the broader impacts of biofuel production on forestry management. Increased demand for biomass could indirectly incentivize additional logging, even if BSB itself does not extract new biomass. To mitigate this risk, BSB will prioritize waste-stream utilization, incorporating municipal and agricultural residues to diversify feedstocks and reduce dependence on forestry-derived biomass. Deforestation can reduce urban green space, which has been linked to lower public health outcomes, including increased stress and reduced opportunities for social connections and physical activity[48]. To counteract this impact, BSB will expand its feedstock to include municipal and agricultural waste, further reducing landfill contributions while maintaining an environmentally responsible approach. By utilizing this resource we are also impacting the ecology of the area. Additionally, biomass removal alters local ecosystems by reducing available resources for organisms, potentially impacting their realized niches and metapopulations. With fewer accessible resources, species may experience shifts in their ecological roles, which can disrupt population dynamics. Given Corner Brook's geographic isolation, as Newfoundland is not connected to mainland Canada, species migration is limited.

This raises concerns about local extinctions, as reduced resource availability could lead to population declines, ultimately decreasing biodiversity in the region[13].

The introduction of bioenergy production also affects competitive interactions by altering the availability of organic material used by decomposers and detritivores, potentially impacting trophic dynamics. To prevent disruptions, BSB will use residual products rather than removing key organic inputs from the ecosystem, ensuring minimal ecological influence.

There may also be social resistance to adopting new energy technologies. People often become dependent on existing socio-technological systems, making transitions to new energy sources challenging[14]. However, BSB's integration with existing industrial infrastructure will minimize disruption while demonstrating bioenergy's feasibility as a sustainable and community-driven solution.

A Feasible and Sustainable Solution

By integrating bioenergy production with existing infrastructure and prioritizing waste reduction, ecological balance, and economic sustainability, BSB provides a scalable and low-impact energy solution. Unlike fossil fuels, bioenergy production maintains carbon neutrality by cycling CO_2 through biomass regrowth. This ensures that the energy produced aligns with Canada's climate goals and promotes regional energy security. As the most feasible and sustainable transition for Corner Brook, BSB will support a resilient, self-sufficient energy future through waste repurposing, carbon valorization, and ecosystem-conscious development.

Sustainable Bioenergy Implementation: Energy Potential, Efficiency, and Impact

Sustainable Bioenergy for Corner Brook

The BSB will utilize forestry residues, paper mill by-products, and municipal organic waste to produce bioethanol and biogas, reducing fossil fuel reliance while enhancing energy security. With over 400,000 tonnes of biomass available annually, this project ensures long-term sustainability. The CBPP mill provides a centralized facility, minimizing additional land use while optimizing waste streams. By converting paper sludge, municipal organic waste, and forestry by-products into energy, the facility reduces greenhouse gas emissions and aligns with Newfoundland's climate action goals.

Bioethanol Production and Energy Output

Estimated bioethanol production is 16.15 million litres annually, with an energy output of 124,111 megawatt-hours per year. This estimate accounts for biomass composition, sugar yield, fermentation efficiency, and ethanol energy content[5 10 46]. Bioethanol has an energy return on investment (EROI) of 20 to 37, factoring in harvesting (3.5 MJ per tonne), transportation (2.8 MJ per tonne), and processing[17]. Despite these inputs, bioethanol remains a competitive, stable, and locally-sourced renewable energy alternative. A similar bioethanol-producing plant costs approximately 6 million USD[19]. Since our plant will likely be of similar size and would have comparable features, its cost would fall within the same order of magnitude. This project also strengthens the economy by diversifying the forestry sector, creating jobs, and ensuring energy affordability, particularly during winter heating demands. Additionally, it reduces landfill waste

and methane emissions from organic decomposition, improving environmental and public health outcomes.

Unlike fossil fuels, which release carbon stored over millions of years, bioethanol operates within a short-term carbon cycle. The CO_2 released during combustion is offset by the CO_2 absorbed by plants during biomass growth, maintaining a balanced carbon exchange. Additionally, CO_2 from fermentation can be captured and repurposed for industrial applications, further enhancing sustainability.

Technological Advancements and Efficiency

Advancements in enzyme technology enhance bioethanol production efficiency. High-activity recombinant cellulases improve LCB breakdown, increasing sugar conversion and ethanol yields. A study on *Bacillus subtilis*-derived cellulase reported a K_m value of 0.996 mM and a V_{max} of 1.647 U/mL, indicating high substrate affinity and rapid catalytic activity[41]. Genetically modified cellulases further reduce processing time and energy costs, making bioethanol production more efficient.

Ethanol production dynamics can be modelled using the Modified Gompertz Function, which predicts ethanol accumulation over time, allowing real-time yield prediction, process control, and optimization of fermentation efficiency[57]. Parameters for this equation include maximum concentration of ethanol (P_m), maximum rate of ethanol production (R_m), and lag time (L). A value of 52.47 g/L was used for P_m, 0.52 g/Lh for R_m, and 6.31 h for L, values based on studies conducted under similar conditions[74 54]. Ethanol concentration *P* (g/L) was modelled as a function of fermentation time *t* (h) using the Modified Gompertz Equation (Equation 2). This

model predicts ethanol accumulation over time, facilitating real-time monitoring and fermentation optimization. Python-generated simulations confirm ethanol production trends, supporting adaptive process management in the biorefinery.

$$P = 52.47 \exp\left\{-\exp\left[\frac{0.52e}{52.47} \cdot (6.31 - t) + 1\right]\right\} \tag{2}$$

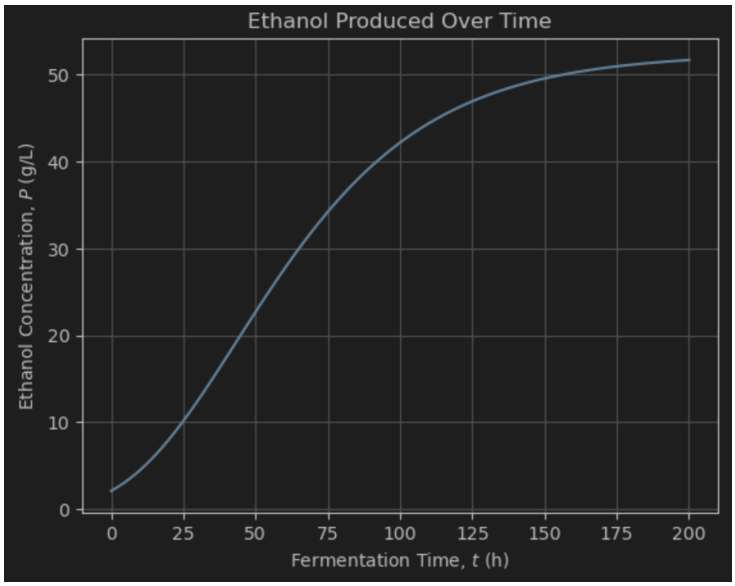

Figure 9: *Modeled ethanol concentration (g/L) as a function of fermentation time (h) using the Modified Gompertz Equation. This model predicts ethanol accumulation over time, aiding in real-time monitoring and optimization of fermentation efficiency.*

Projected Impact on Fuel Savings

Replacing gasoline with bioethanol at 5% and 10% blending rates could achieve up to 1,443.38 GJ of gasoline energy savings in the final year of a 20-year period[31]. Increasing bioethanol blending significantly reduces fossil fuel dependence, carbon emissions, and energy costs while improving regional energy security.

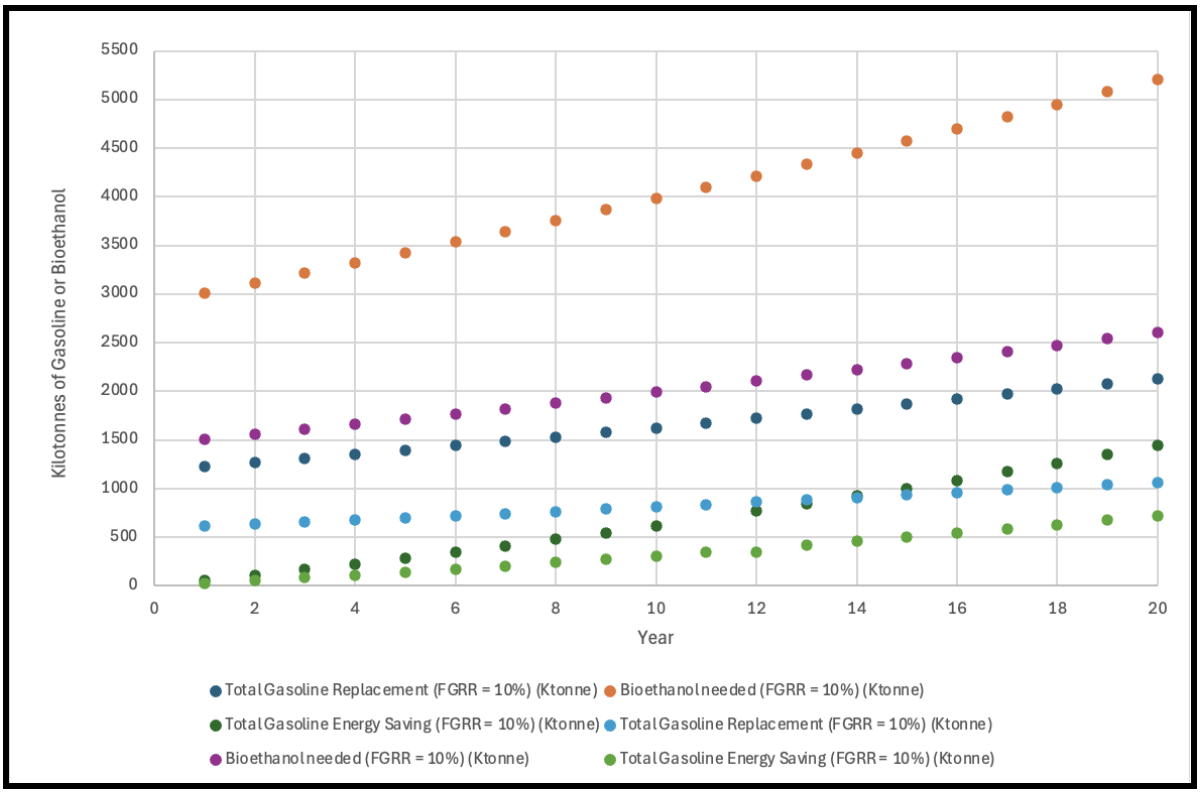

Figure 10: *Projected Fuel Savings from Gasoline Substitution with Bioethanol*[31].

Meeting Corner Brook's Energy Needs

BSB will produce sufficient bioethanol and biogas to meet the energy demands of Corner Brook's 19,333 residents. The average household electricity consumption in Newfoundland is approximately 1,278 kWh of electricity per month, or 15,336 kWh annually[47]. With an estimated 8,155 households in the city, the total residential electricity demand amounts to approximately 125 GWh per year, which is close to how much energy our fermentation plant could ideally produce from forestry waste and paper sludge as mentioned previously. Expanding feedstock sources to include additional organic waste streams will further enhance sustainability and energy security.

Summary and Justification

BSB offers the most feasible and sustainable energy solution for Corner Brook by utilizing existing CBPP infrastructure to produce bioethanol and biogas. With an annual biomass supply of over 400,000 tonnes, this project ensures long-term viability. The centralized facility minimizes additional land use while optimizing waste management, contributing to an estimated annual energy generation of 124,211 MWh.

Fermentation converts complex organic polymers into bioethanol and biogas through microbial metabolism. The energy stored in chemical bonds is released when these biofuels are combusted, converting chemical energy into thermal energy[72]. This heat generates steam, which expands to drive a turbine connected to a generator, converting thermal energy into mechanical energy and then into electrical energy via electromagnetic induction. Unlike intermittent renewable sources, this process provides continuous and stable power output, ensuring energy security for Corner Brook.

Through the fermentation of forestry residues and paper sludge waste from the mill, BSB will reduce Corner Brook's reliance on hydroelectric power, which has contributed to issues such as flooding. This bioenergy system will generate enough power to support the city's current population, enabling off-grid energy independence. In the future, the system can be expanded to incorporate additional organic waste sources, such as agricultural and fishery waste. This expansion will allow the biorefinery to contribute sustainable energy to the broader region, strengthening Newfoundland's energy security and reducing dependence on external power sources.

Bioethanol and biogas combustion are carbon-neutral, as emissions are reabsorbed through sustainable forestry practices, while methane emission reduction further lowers the city's carbon footprint. Economically, BSB strengthens the local job market, diversifies the forestry sector, and ensures long-term energy affordability. Production costs remain competitive with fossil fuels, maintaining energy security even in winter months when consumption peaks. By reducing landfill waste and air pollution, the project also supports environmental and public health objectives.

Compared to hydro, wind, and solar, bioenergy is the most reliable energy source for Corner Brook due to its stable energy conversion process. Hydroelectricity depends on gravitational potential energy stored in water reservoirs, but seasonal fluctuations and legal constraints, such as flooding risks in Deer Lake, limit its feasibility[7 33]. Wind power relies on kinetic energy transfer from moving air to turbine blades[36]. Solar energy converts photon energy into electrical energy via the photoelectric effect, yet Newfoundland's short daylight hours, frequent cloud cover, and snow accumulation restrict its output[28].

In contrast, bioenergy ensures a consistent year-round power supply by leveraging biochemical energy stored in organic matter. During fermentation, microbial metabolism breaks down cellulose and hemicellulose, converting stored chemical bonds into ethanol and biogas. When combusted, these fuels release thermal energy, which generates steam to drive turbines, converting mechanical energy into electrical energy through electromagnetic induction. Unlike wind and solar, which fluctuate with environmental conditions, bioenergy operates independently of weather, making it a more stable and predictable energy source for Corner Brook.

BSB boosts the local economy by creating jobs, diversifying the forestry sector, and reducing landfill waste. It also improves public health by cutting emissions from decomposing organic matter, which is 25 times more potent than CO_2. Through advanced biogas technology and diversified feedstocks, BSB supports Newfoundland's climate goals while ensuring long-term energy security and economic growth.

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Appendix

The forestry excess available for bioethanol production is 41,211 tonnes per year, which is equivalent to 41,211,000 kg. This biomass contains 45% cellulose and 27.5% hemicellulose, which can be converted into fermentable sugars. The cellulose component undergoes hydrolysis to produce glucose at a conversion rate of 1.1 kg of glucose per kg of cellulose, while hemicellulose yields sugars at a rate of 1.14 kg per kg of hemicellulose. After conversion, the glucose and hemicellulose-derived sugars are fermented to ethanol, with a yield of 0.51 kg of ethanol per kg of sugar. The resulting ethanol is then converted into its volume using the density of ethanol (0.789 kg/L). After adjusting for a process efficiency of 75%, the final ethanol yield is approximately 16.15 million litres per year, corresponding to an annual energy output of 340.82 million MJ.

For bioethanol production from paper sludge, the available biomass is 47,500 Mg (megagrams), of which 50% is assumed to be usable for fermentation. This results in 23,750 Mg of usable material. Assuming that 70% of this mass is converted into fermentable sugars and that each kg of sugar yields 0.51 kg of ethanol, the total ethanol production is estimated at 8,487.75 Mg. Converting this to volume using the density of ethanol (0.789 kg/L), the total ethanol volume is

approximately 6.7 million litres. After applying a process efficiency of 75%, the effective ethanol yield is 5.02 million litres. The final energy output, calculated using an energy density of 21.1 MJ/L, amounts to 105.98 million MJ annually.

$$\text{Glucose from cellulose} = 41,211,000 \times 0.45 \times 1.1 = 20,399,445 \text{ kg}$$
$$\text{Sugars from hemicellulose} = 41,211,000 \times 0.275 \times 1.14 = 12,919,648.5 \text{ kg}$$
$$\text{Total ethanol yield} = (20,399,445 + 12,919,648.5) \times 0.51 = 16,992,737.68 \text{ kg}$$
$$\text{Total ethanol volume} = \frac{16,992,737.68}{0.789} = 21,537,056.63 \text{ L}$$
$$\text{Effective ethanol output} = 21,537,056.63 \times 0.75 = 16,152,792.47 \text{ L}$$
$$\text{Total energy output} = 16,152,792.47 \times 21.1 = 340,823,921.1 \text{ MJ per year}$$
$$\text{Total biomass} = 47,500 \text{ Mg} \times 50\% = 23,750 \text{ Mg}$$
$$\text{Ethanol production} = 23,750 \times 0.70 \times 0.51 = 8,487.75 \text{ Mg ethanol}$$
$$\text{Total ethanol volume} = \frac{8,487.75 \times 1000}{0.789} = 6,696,834.75 \text{ L ethanol}$$
$$\text{Effective ethanol output} = 6,696,834.75 \times 0.75 = 5,022,626.063 \text{ L ethanol}$$
$$\text{Total energy output} = 5,022,626.063 \times 21.1 = 105,977,409.9 \text{ MJ}$$
$$\text{Forestry:}340,823,921.1 \text{ MJ per year} \rightarrow 94,673.31142 \text{ MWh per year}$$
$$\text{Paper sludge:}105,977,409.9 \text{ MJ per year} \rightarrow 29,438.16942 \text{ MWh per year}$$
$$94,673.31142 \text{ MWh} + 29,438.16942 \text{ MWh} = 124,111.4808 \text{ MWh per year}$$