Assessment of Energy Demand-based GHG Mitigation Options for the Pulp and Paper Sector

by

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Abstract

The pulp and paper industry plays a vital role in Canada's economy, and Alberta's pulp and paper industry has a 10% production share in Canada. Alberta's pulp and paper industry is the third largest energy consumer in the province's industrial sector, and there is significant potential to reduce energy demand and associated greenhouse gas (GHG) emissions. In this research, a bottom-up energy demand tree is developed for Alberta's pulp and paper industry to understand the energy intensities of various types of equipment associated with different end uses. This demand tree is further used to simulate an integrated resource planning model, the Long-range Energy Alternative Planning (LEAP) system model. Based on expected growth in the pulp and paper industry, a business-as-usual (BAU) scenario is developed for the years 2010 to 2050 to project the energy demand and GHG emissions of Alberta's pulp and paper mills. Twenty-eight GHG mitigation scenarios are developed for Alberta's pulp and paper mills, and energy and emissions reductions are estimated with respect to the BAU scenario. The scenarios are also analyzed in terms of the cost-benefit aspects by developing a GHG abatement cost curve. The GHG abatement cost curves compare the scenarios in terms of net GHG mitigation achievable in each scenario and GHG abatement cost (\$/tonne of CO_2 equivalent mitigation) compared to the business-as-usual case. The energy demand (electricity and natural gas) of Alberta's pulp and paper mills is expected to decrease from 20.37 PJ in 2010 to 19.46 PJ in 2050 in the BAU scenario. Twenty-eight scenarios were evaluated with the aim of reducing energy demand and mitigating emissions. These scenarios were developed for planning horizons of 2010-2030 and 2010-2050. Implementing the integrated scenarios can reduce emissions by 8.26 MT of CO_2 eq. collectively for the years 2010-2050 compared to the BAU scenario.

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List of Abbreviations

ADMT	Air Dried Metric Tonnes
Alpac	Alberta Pacific Forest Industries Inc.
ANC	Alberta Newsprint Company
BAU	Business-as-Usual
BCTMP	Bleached Chemi-Thermo Mechanical Pulping
CDN	Canadian dollar
CO_2	Carbon dioxide
CRF	Capital recovery factor
CSE	Cost of saved energy
DMI	Daishowa-Marubeni International Ltd.
DOE	Department of Energy
EIA	Energy Information Administration
EJ	Exajoules
ENPAC	Energy Price and Carbon Balance Scenarios tool
eq.	Equivalent
GDP	Gross domestic product
GHG	Greenhouse gas
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
Kg	Kilogram
KJ	Kilojoules
KW	Kilowatt
KWh	Kilowatt hour
LEAP	Long-rang Energy Alternatives Planning
M	Million
MJ	Megajoules
MT	Million tonne
MTOE	Million tonnes of oil equivalent
Mcf	Thousand cubic feet
NBSK	Northern Bleached Softwood Kraft
NPV	Net present value
NRC	Natural Resources Canada
O&M	Operating and Maintenance
OA	Oxalic Acid
PJ	Petajoules

T	Tonne
TED	Technology and environmental database
TMP	Thermo-mechanical pulping
US	United States
WEAP	Water Evaluation and Planning

1 Introduction

1.1 Background

The world population has grown exponentially from 4 billion in 1970 to over 7 billion in 2011 [1]. To meet the growing energy demand, the energy and industrial sector has expanded accordingly to provide for basic needs as well as changing lifestyles [2]. As a result, between 1970 and 2011, the primary energy supply doubled from 6,106 metric tonnes of oil equivalent (Mtoe) to 13,371 Mtoe, reflecting the trend of increasing per capita energy consumption [3]. One of the main impacts of increased energy consumption is greenhouse gas emissions (GHG), which increases global temperatures. From the start of industrial era around 1880 to 2015, due to high concentrations of CO_2 in the atmosphere, the earth's temperature has increased by 0.85°C, which is ten times more that the temperature increase in the previous 500 years [1, 4]. The increasing global temperature is a significant concern for the earth's future and thus a number of initiatives are underway to mitigate GHG emissions globally.

The widely accepted 2°C scenario, developed by the European Commission, aims to limit the global temperature increase to 2°C from 1880 level [5-7]. This target can only be achieved by reducing the GHG emissions in the atmosphere, and this can be done by reducing fossil fuel consumption and improving energy efficiency. One-third of the world's energy, or 127 exajoules (EJ), is consumed by manufacturing industries and results in 36% of global GHG emissions [8]. Two-thirds of this is from large materials manufacturing industries (pulp and paper, chemical, petrochemicals, iron and steel, cement, and other minerals) [8]. According to the United Nations Industry Development Organization, 31 EJ (approximately 26%) of global industrial energy demand can be reduced by improving process efficiency as well as implementing new technologies with low energy concentration [8]. The pulp and paper industry is responsible for 5.7% of global industrial final energy use and can play a significant role in reducing GHG emissions by reducing process energy consumption and increasing biomass energy shares [9].

1.2 Energy and emissions profile: Canada

Canada is the fifth largest energy consumer in the world and ranks ninth in global emissions [10]. Energy consumption has steadily increased between 1980 and 2009, although energy consumption per person has decreased from 335.1 GJ to 325.1 GJ [11]. Net energy consumption in Canada in 2013 was 8,924 PJ with the industrial sector consuming 40% of the energy [12]. Fossil fuels are the main source of energy production and crude oil is largest source, with a 41.4% share. Natural gas and coal represent 36.5% and 9.2% of primary energy production, respectively, while hydroelectricity and biomass represent only 7.5% and 3.5%, respectively, in the overall energy mix [13]. Energy consumption in Canada by sector is shown in Figure 1.

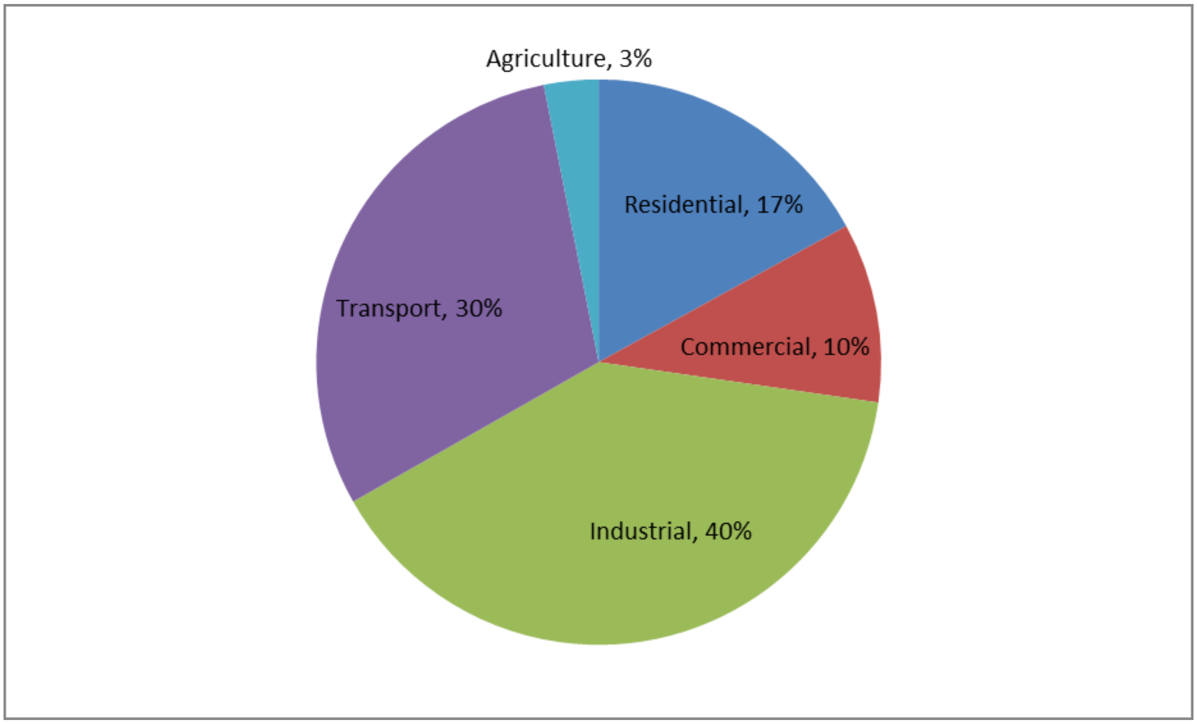


Figure 1: Canada's energy consumption profile, 2013 (PJ), from [12]

Canada's net GHG emissions as of 2013 are 726 MT CO_2 eq., a 13% increase over 1990 levels [14]. Figure 2 shows Canada's share of energy-based GHG emissions, which total 487 MT of CO_2 eq. [12]. The transport sector has the highest emissions share, followed by the industrial sector. The transport sector's high GHG emissions highlight the low efficiency of energy use of that sector.

Of the industrial sectors in Canada, the pulp and paper sector is responsible for 16.4% energy consumption with 6% emissions contribution [12]. Forestry is one of Canada's major economic sectors and contributed 1.25% to the nominal gross domestic product (GDP) in 2015, of which the pulp and paper industry holds a 36% share [15]. Canada is the world's third largest exporter of pulp and paper and has the largest production capacity of Northern Bleached Kraft (NBSK) pulp and newsprint paper [16, 17]. Hence the pulp and paper industry is of prime importance in Canada. Paper consumption has an increasing trend globally but is decreasing in North America due to a number of factors including increased use of electronic media and the 2007 financial crisis that forced companies to examine paper use and adopt efficient processes [17]. Paper consumption in North America dropped by 24% between 2006 and 2009 [18].

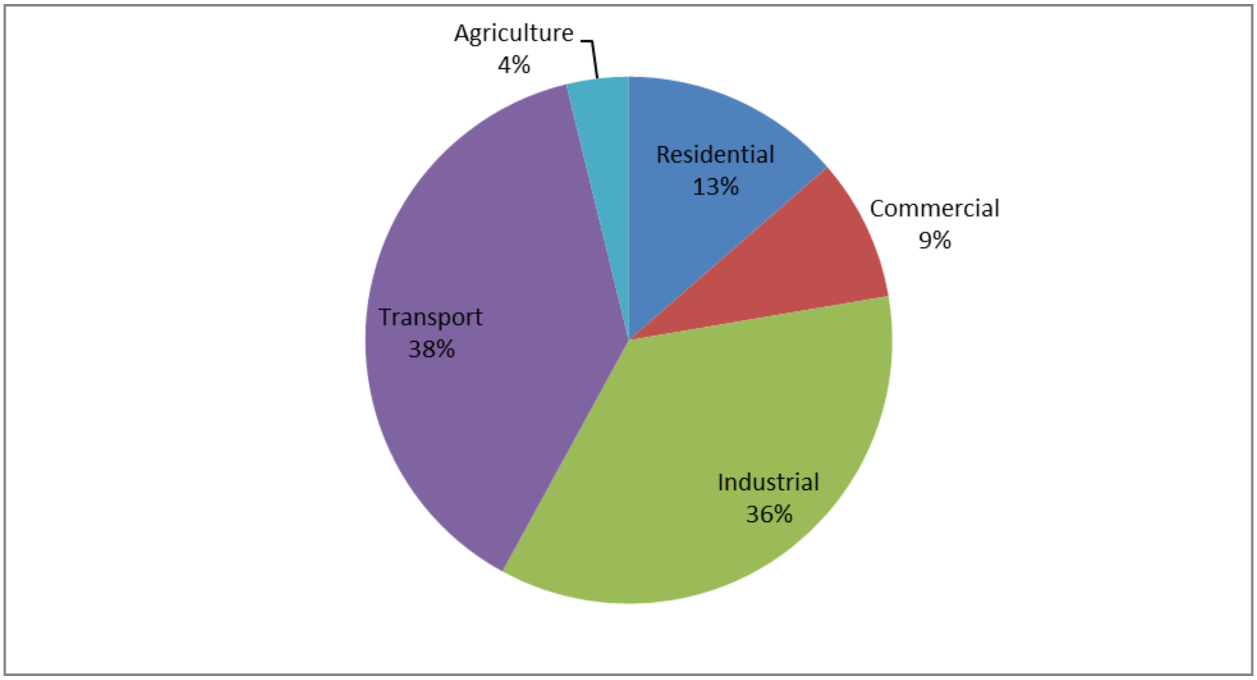


Figure 2: Canada's energy-related GHG emissions, 2013

1.3 Energy and emissions profile: Alberta

Of the Canadian provinces, Alberta has the second largest energy demand after Ontario with a 19.8% share [11]. In terms of GHG emissions, in 2013 Alberta emitted 267.2 MT of CO_2 eq., which are not only the highest in Canada but also 53% higher than the province's 1990 level. This significant increase is due to increased petroleum products' export and the use of coal for a major portion of electricity production [14]. Alberta's secondary energy consumption profile by energy sector is shown in Table 1. The industrial sector is the largest energy consumer with a 60% share (1383.6 PJ) of net provincial secondary energy use. The transportation and residential sectors are the second and third largest energy consumers with 33.6 PJ and 8.8 PJ of secondary energy use, respectively. A similar trend can be seen in the emissions from these sectors, as shown in Table 1.

Table 1: Alberta energy sector profile (2013) from [12]

Energy sector	Secondary energy use (PJ)	Percentage share (%)	GHG emissions excluding electricity (MT of CO_2 eq.)	Percentage share (%)
Industrial	1383.6	59.8	72.1	58.0
Transport	479.8	20.7	33.6	27.0
Residential	219.3	9.5	8.8	7.1
Commercial	173.2	7.5	6.1	4.9
Agriculture	58.3	2.5	3.7	3.0
Total	**2314.2**		**124.3**	

Of Alberta's several industrial sectors, the largest energy consuming sector is the mining sector. The pulp and paper sector comes third after the chemical sector. An overview of Alberta's industrial sector energy consumption is shown in Table 2 [12]. The pulp and paper sector consumes 86.4 PJ of secondary energy, accounting for 6.2% of the energy consumption from all of Alberta's industrial sectors. The main fuels consumed by the pulp and paper mills in Alberta are electricity, natural gas, and black liquor. A small amount of fuel oils is also used with a negligible share of overall energy consumption. Natural gas is primarily used to generate process steam for the pulp mill; however, depending on the plant location and fuel price, petroleum oils or coal can be used in place of natural gas. In Alberta, natural gas is cheap (C$1.89/Mcf which is C$1.67 lower than natural gas prices in US), easily available, and its combustion has a low GHG footprint compared to coal and oil and so it is used in all pulp and paper mills [19].

An overview of GHG emissions by industrial sector is provided in Table 2. Pulp and paper mills emitted 0.6 MT of CO_2 eq. in 2013. The pulp and paper sector has a low (0.8%) share of industrial sector GHG emissions, despite its high energy consumption. The main source of GHG emissions in the pulp and paper industry is from the burning of natural gas to generate steam.

Comparing the overall GHG emissions from pulp and paper mills with energy consumption, the GHG emissions share is fairly low (a 6.2% energy consumption share compared with a 0.8% GHG emissions share). The low share is due to the use of large amounts of biomass such as black liquor and wood waste to produce steam and electricity for mill use. Energy production from these sources is considered carbon neutral in GHG emissions calculations and thus the low share of 0.8% is reported.

Table 2: Alberta's industrial sector energy and emissions profile (2013) [12]

Industry sector	**Secondary energy use (PJ)**	**Percentage share (%)**	**GHG emissions excluding electricity (MT of CO_2 eq.)**	**Percentage share (%)**
Construction	12.9	0.9	0.8	1.2
Pulp and Paper	86.4	6.2	0.6	0.8
Smelting and Refining	0.3	0.0	0.0	0.0
Petroleum Refining	77.4	5.6	4.1	5.7
Cement	10.4	0.8	0.6	0.9
Chemicals	165.2	11.9	7.1	9.9
Iron and Steel	2.5	0.2	0.1	0.1
Other Manufacturing	79.6	5.8	2.4	3.3
Forestry	0.9	0.1	0.1	0.1
Mining	947.9	68.5	56.3	78.1
Total	**1383.6**		**72.1**	

1.3.1 Alberta's pulp and paper industry – an introduction

In 2010, Canada's pulp and paper production was 27.24 million tonnes (MT), of which Alberta holds a 10% share [20]. Alberta has 7 pulp and paper mills and they use both chemical and mechanical processes. The primary input in the pulp mills is wood chips, which undergo fiber separation and lignin removal followed by bleaching for coloring agent removal. The product is dried and sent for packing or to a paper mill for paper production. Electricity and natural gas are the primary energy inputs for pulp and paper mills. Some mills use biomass as an energy source, in the kraft pulp mills. Pulp and paper mills are usually located near sawmills to reduce wood chip transport costs.

The seven mills in Alberta are producing pulp and newsprint paper using the following three technologies:

(i) Mechanical: thermo-mechanical pulping (TMP) [21]

(ii) Chemical: kraft pulping [22-25]

(iii) Semi-chemical: bleached chemi-thermo mechanical pulping (BCTMP) [26, 27]

The detailed process description of these pulping technologies is provided in Chapter 2. Table 3 provides key information about these mills (i.e., name, type, location, and production capacities). The share of pulping technologies used in Alberta based on mill production capacity is shown in Figure 3.

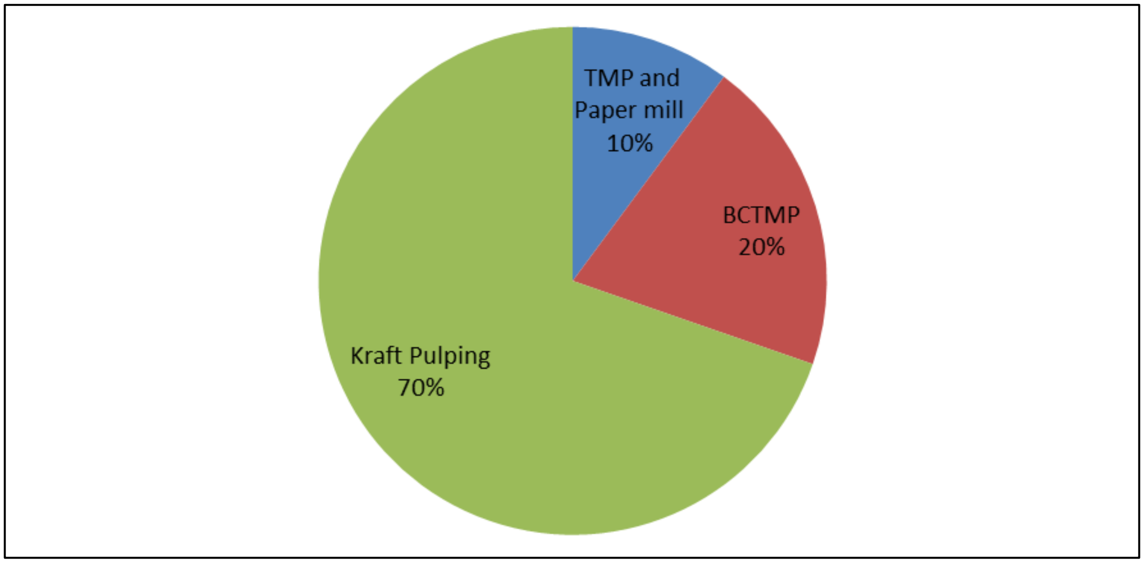


Figure 3: Technology share for pulp production in Alberta (based on Table 3)

Table 3: Alberta’s Pulp and Paper Companies

Company	Startup date	Mill location (AB, CA)	Mill type	Annual Production capacity (ADMT)	Pulp end-use	Ref.
Alberta Newsprint Company	1990	Whitecourt	TMP and Paper mill	270,000	43, 45 and 48.8 gram/square meter paper	[21, 28, 29]
Millar Western Forest Products Ltd.	1988	Whitecourt	BCTMP	315,000	Papers, tissues, packaging material and paper towels	[27, 29, 30]
West Fraser Timber Co. Ltd.	1991	Slave lake	BCTMP	222,000	Coated board grades, writing and printing paper	[26, 29, 31]
	1957*	Hinton	Kraft pulping	370000	Different varieties of paper (excellent tensile properties), specialty grades of tissues	[22, 29, 32, 33]
Weyerhaeuser Company	1973	Grand Prairie	Kraft pulping	390,000	Various paper-grade and specialty products (excellent tensile properties, superior sheet smoothness)	[23, 29, 34, 35]
Alberta Pacific (ALPAC) Forest Products Inc.	1993	Boyle	Kraft pulping	650,000	Medical surgical drapes, tea bags, absorbents in shoes etc.	[25, 29]
Daishowa-Marubeni International (DMI) Ltd.	1990	Peace River	Kraft pulping	475,000	Various paper-grade and specialty products	[24, 29]

* Acquired by West Fraser in 2004 [29]

1.4 Research rationale

The pulp and paper industry consumes 5.7% of global industrial sector energy [9]. A number of studies have evaluated the feasibility of efficiency improvements, energy savings, and GHG emissions reduction through retrofitting, process variation, and the introduction of new technologies [36-54]. However, they are limited in providing the full scope of these technologies, i.e., technology penetration rate, effect on overall energy consumption, and associated costs of new technologies during the lifetime of the technology. Several studies [36-48] provide a detailed analysis of energy saving potential along with associated costs in pulp and paper mills. The options include existing equipment upgrades as well as introducing emerging technologies in the pulp mill to significantly reduce energy consumption and GHG emissions. However, most of these studies provide generic savings potential in terms of per tonne of unit production and do not explore the long-term potential of implementing these measures [36, 37, 39-42]. Also, none of these studies assess the impacts on the provincial or country level.

A few studies provide bottom-up analyses of pulp and paper mills and corresponding future energy outlook when new technologies are implemented; however, these studies are focused on specific regions, i.e., China, the United States, Brazil, and Germany [38, 49-51]. A bottom-up analysis approach provides an extensive outlook on overall energy efficiency improvement and GHG mitigation in pulp and paper mills of a defined region during the lifetime of a technology. Such an analysis allows us to evaluate a feasible penetration rate that maximizes cost savings benefits. There are few studies that focus on energy efficiency improvement and GHG mitigation in Canada's pulp and paper industry, let alone Alberta's. A few benchmark reports have been produced by Natural Resources Canada and Canadian Manufacturers & Exporters (CME) [52-54] that explore current energy efficiency and best achievable efficiency in Canada's pulp and paper industry; however, these studies provide very limited equipment-level energy consumption details. There is no technical assessment or economic analysis provided that can be used to approach a high level of efficiency through process modification, retrofitting, and adopting new technologies.

Moreover, there is no comprehensive energy consumption demand tree available in the public domain for pulp and paper industry. The bottom-up approach in the demand tree provides details of mill equipment energy consumption, which enables us to assess energy efficiency improvement potential at the equipment level. Without such information, the true potential of new technology penetration in a jurisdiction's pulp and paper industry cannot be assessed in terms of both energy savings and economic suitability. This study proposes to fill this information gap in pulp and paper industry by developing a detailed demand tree to streamline the process of analyzing energy efficiency improvement and GHG mitigation options and propose the most technically and economically feasible solutions.

1.5 Energy modeling tools

To develop the energy demand tree and conduct long-term energy planning, a modeling tool is required, preferably one that can build an energy demand tree based on unit energy consumption and analyze multiple energy saving and GHG mitigation scenarios. The model also needs to incorporate a cost analysis module to evaluate the economic suitability of various scenarios. Energy modeling of the pulp and paper sector has been done with several static mathematical and software modeling tools in the past and are mostly specific to the types of the mills. Mathematical models calculate costs of conserved energy [55] and use horizontal comparisons of pulp and paper process energy efficiencies in different regions [56], a systems-based approach to include the impact of changes at the mill and industry level [57], energy, exergy and market demand allocation methods for fuel costs and CO_2 emissions [58], and the CADSIM model along with mass and heat balance calculations for water and energy saving [44]. These methods provide analysis of current energy consumption levels and GHG emissions in pulp and paper mills along with improvement potential in energy consumption and emissions. However, these models do not forecast the long-term energy consumption over a planning horizon. These studies also do not assess the impact of mitigation scenarios compared to the baseline energy consumption and emission levels during the lifetime of a technology. This study is an effort to address these gaps.

More detailed modeling tools that have been used in the past are US DOE energy footprints models [59], IS Industry [38], stochastic programming models, and the Energy Price and Carbon Balances Scenarios tool (ENPAC) [60]. An energy footprint model is Excel-based and can track up to 20 types of energy inputs with 20 dependent variables and produce charts that show energy consumption trends [61]. However, such models cannot forecast energy consumption and thus, cannot be used for long-term scenario analysis. The stochastic programming model and ENPAC focus on investment uncertainty analysis with respect to new technology penetration or measures in complex energy intensive industries [62]. The IS Industry model provides a bottom-up analysis of the pulp and paper industry and can forecast energy consumption patterns. This model allows the user to develop scenarios with varying diffusion of new measures and technologies that reduce energy consumption and also perform a cost analysis. The model is based on equations and analyzes a large number of scenarios. However, this model has very limited capability in assessing the long terms impacts of various energy efficiency improvement scenarios. This research is aimed at addressing these gaps.

For the current study, the Long-range Energy Alternative Planning (LEAP) system model is used and it provides a graphical interface to develop a bottom-up demand tree and a reference scenario in order to forecast energy consumption patterns and evaluate efficiency improvement and mitigation scenarios [63]. The LEAP model was selected as it combines all the desired properties discussed in the above-mentioned models with the ability to present results in a wide array of combinations. A number of studies have utilized the LEAP model to perform energy and emission analysis [64-73] however, none of these studies focus on developing abatement cost curves for the pulp and paper sector. The LEAP model also allows us to perform extensive cost analyses and provides results in various forms.

1.6 Research objective

The overall objective of this research is to identify energy end use in pulp and paper industrial sector and analyze GHG mitigation scenarios in terms of reduction in energy consumption, GHG mitigation, and associated costs to implement these scenarios. The Long-range Energy Alternative Planning (LEAP) model is used to simulate energy demand and analyze scenarios for Alberta's pulp and paper mills. The specific objectives of this research work are to:

i. Identify energy end uses along with end-use energy intensities to develop an energy demand tree for a bottom-up representation of energy consumption in pulp and paper industry.
ii. Develop a business-as-usual scenario for the years 2010 to 2050 based on expected production from pulp and paper mills to identify future energy consumption and GHG emissions patterns.
iii. Identify energy efficiency improvement and GHG mitigation options for pulp and paper industry.

iv. Simulate scenarios in the LEAP model to calculate energy savings and GHG mitigation potential compared to the business-as-usual scenario.
v. Assess the energy saving and GHG mitigation scenarios for cost effectiveness in pulp and paper industry.
vi. Develop a cost curve for pulp and paper industry to provide a comprehensive comparison of scenarios in terms of net GHG mitigation potential and GHG abatement costs during the study period.
vii. Conduct a case study for Alberta.

1.7 Organization of thesis

The thesis consists of five chapters, a table of contents, a list of tables and figures, a list of abbreviations, a bibliography, and appendices.

Chapter 1 introduces this research and includes the background, objectives, methodology, and scope.

Chapter 2 describes the LEAP model structure that is used in this study, the demand tree development and validation for Alberta's pulp and paper mills, and the development of the business-as-usual scenario. The chapter concludes with energy and GHG emissions-related results for the base year and BAU scenario.

Chapter 3 discusses the method used to develop scenarios in LEAP and describes the scenarios selected for Alberta's pulp and paper mills including the input parameters for energy and cost analyses in the LEAP model.

Chapter 4 discusses the results obtained from the LEAP model when we ran the scenarios described in chapter 3 in terms energy saving, emissions mitigation, and economic implications.

The results are discussed individually, category-wise, and overall to provide an extensive comparison of various scenarios. The results are also presented in the form of a cost curve as well as an integrated cost curve for comprehensive comparison of scenarios based on net GHG mitigation potential and GHG abatement costs.

Chapter 5 concludes the research and includes recommendations for future work.

Appendix provide detailed mill process description and the calculations for the costs of saved energy developed in an Excel-based model to be used in the LEAP model for the GHG abatement cost calculation.

2 Energy Demand Modeling for Pulp and Paper Sector using the LEAP Model

2.1 Introduction

Alberta has the second largest energy demand in Canada with 2,314 PJ of energy consumption [12] and a detailed energy demand tree is being developed to track the provincial energy end-use level. The Figure 4 shows the breakdown of Alberta's economic sectors for which the LEAP model is planned to be completed. Currently, a LEAP model for Alberta's residential, commercial, transport [74] and agriculture [64] sector has been developed whereas the current focus is on the industrial sector which is the largest energy consumer in Alberta. In industrial sector, the mining industry model is completed in an earlier study [75] whereas the other remaining industry models are under development. In this study, the LEAP model for pulp and paper industry is developed as a step forward for completing the Alberta's energy demand tree.

2.2 Methodology

The LEAP model for Alberta's pulp and paper industry requires process-level energy intensities as well as annual mill production, energy, and cost data as input to run scenarios in order to obtain results required for cost curve development. An extensive literature review is done to identify pulp and paper mills unit processes and process-level energy consumption to develop the demand tree. The energy demand tree is validated by calculating annual energy consumption through the LEAP model and comparing it with energy consumption reported by federal agencies over the last 7 years. Once validated, the business-as-usual scenario is developed by analyzing the market trend of pulp and paper industries in Canada and projecting future mill production.

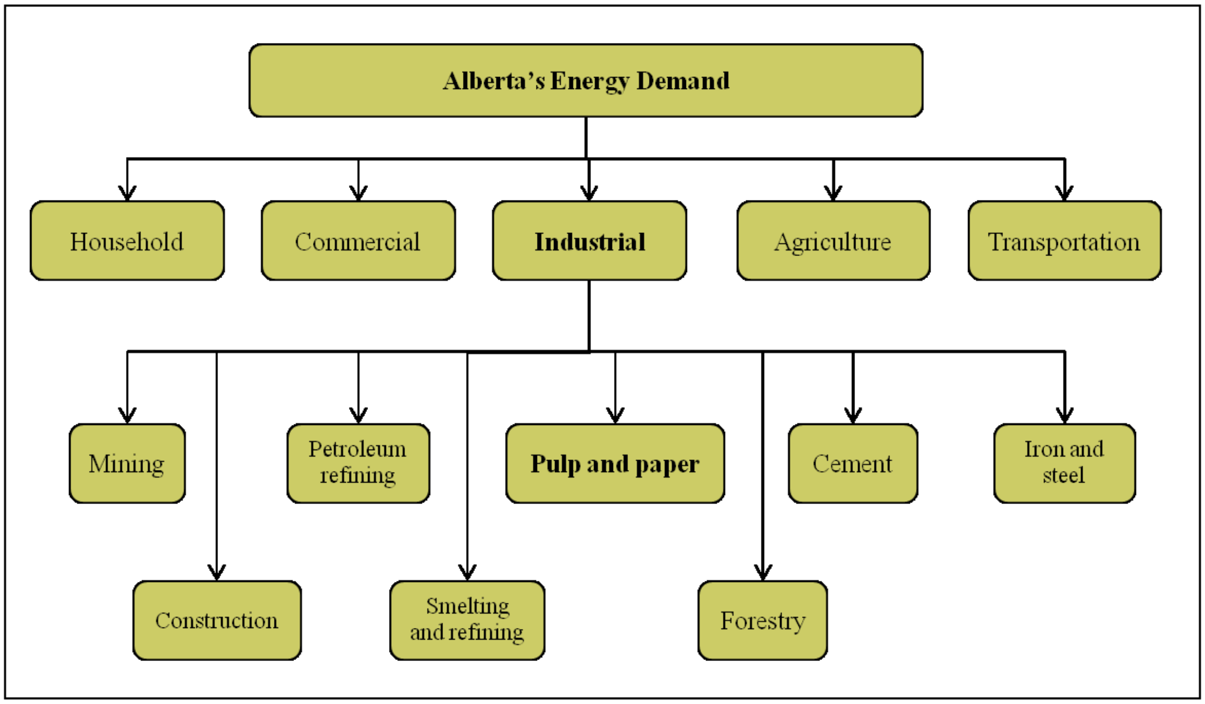


Figure 4: LEAP model development for Alberta's energy demand end-use analysis

The energy saving and GHG mitigation scenarios were extracted from literature reviews based on the applicability of the technology in Alberta, energy level and cost data, and reliability of the information source. Based on these data, fast and slow penetration scenarios were developed in the LEAP model for Alberta's pulp and paper mills with the BAU scenario as the reference. The penetration rates were selected based on technology maturity, current penetration in other jurisdictions, and economical attractiveness. Based on the inputs, the LEAP model calculated the net GHG mitigation potential for each scenario as well as the GHG abatement costs.

The output from the LEAP model is used to develop a cost curve that compares all the scenarios in terms of GHG mitigation potential and associated costs. All the scenarios developed in the LEAP model are not applicable in the pulp and paper mills simultaneously. Therefore, an integrated cost curve is developed to include scenarios that can be implemented together. The scenarios are selected based on their mitigation potential and economic suitability compared to their alternatives.

2.3 LEAP software – A modeling tool

The LEAP model is an energy policy analysis and GHG mitigation assessment framework developed by the Stockholm Environment Institute based in Sweden. It is an integrated planning tool that can be used to track the energy consumption, production, and extraction of resources in all economic sectors. The scenarios can be developed for medium- to long-term planning with an easy-to-use interface, and results can be developed at different point of time. The LEAP model has been extensively used for energy modeling by a number of organizations including the United Nations Framework Convention on Climate Change (UNFCCC) [76], the United Nations Development Programme (UNDP) [61], the Asia-Pacific Economic Cooperation (APEC) [77], and a number of governmental organizations [78].

The LEAP model contains various modules that are developed step by step to attain results (Figure 5). A detailed description of LEAP module development and operation is discussed elsewhere [64-66]; only a brief overview of LEAP modules is provided here.

2.3.1 Key assumptions

The key assumptions module allows us to enter macroeconomic parameters such as population, household income, unit consumption of a particular product, gross domestic product (GDP), etc. These parameters are used as variables to forecast the demand of a product which in current study is pulp.

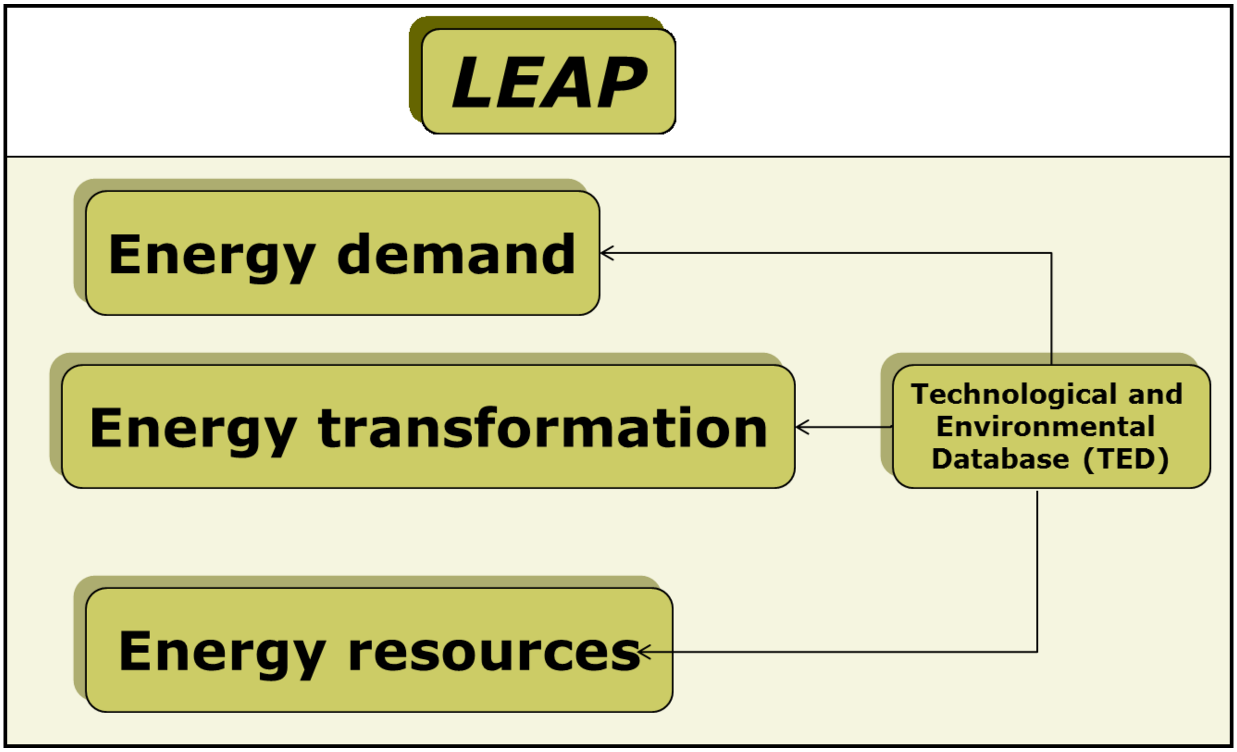


Figure 5: LEAP software modules

2.3.2 Energy demand module

The energy demand module is the backbone of the model wherein the energy demand sector (e.g. residential, commercial, industrial, transportation) is developed based on a bottom-up energy consumption approach. The sector is divided into various subsectors or end-uses (e.g. residential sector can have end-uses as cooking, lighting, space heating and others) that are further broken down to the lowest unit energy consumption level (equipment level) (e.g. furnaces, pumps, bulbs) with units of energy consumption per unit production output. The net energy consumption is a function of annual production and unit energy consumption where annual production can be entered manually or calculated from key assumptions.

2.3.3 Energy transformation module

The energy demand module calculates the net energy required by the sector under study in the form of fuels or electricity. To meet this demand, a transformation module is developed that, as the name indicates, transforms the primary energy to secondary energy to meet the energy demand. The transformation module includes characteristics of fuel refining, electricity generation, and transmission and distribution losses. The transformation module can have other sub-sectors depending on the characteristics of a jurisdiction.

2.3.4 Energy resource module

The energy resource module serves as the input to the transformation module and has the information on primary resources available for domestic use. The resources can be specified to be available locally or imported. This module includes the characteristics of the resource availability of a jurisdiction.

2.3.5 Technological and Environmental database (TED)

The LEAP model has a built-in technology and environment database that can be used to allocate the emissions related to all operations (e.g. combustion, extraction) in the demand and supply modules. TED contains emission factors related to a wide range of energy technologies reported by recognized institutions such as the Intergovernmental Panel on Climate Change (IPCC), the US Department of Energy (US DOE), and the International Energy Agency (IEA). The emissions can be easily allocated to demand and transformation modules sub-branches with the option to edit the factors based on local variations.

2.3.6 Scenario analysis

The demand and supply modules are initially developed for a base year, which is selected based on available data for the demand tree and transformation module. A business-as-usual scenario is developed starting from the base year up to the end of the study period. Once the BAU scenario is developed, a number of efficiency improvement and new technology penetration scenarios is developed with the BAU scenario as reference, which gives a clear picture of the implementation of each new scenario on the overall energy and emissions profile of the economic sector under study. The penetration rate of technologies is entered manually based on the maturity and acceptance behavior of the technology, which provides a more realistic approach as the adoption of new technology takes time.

2.3.7 Cost-benefit analysis

The LEAP model provides an extensive cost-benefit analysis option with various ways to enter the cost data. The costs can be entered as incremental between two scenarios (commonly with the BAU as the base scenario) in the form of activity cost or as net cost (capital, maintenance and operating) or in the form of cost of saved energy in the demand module. The transformation sector includes the cost of various conversion units with their characteristics. This is used in calculating the costs. The methodology to develop cost curve in this study is presented in Figure 6.

Developing scenarios with cost data helps in evaluating each measure from both economic and energy/emissions point of view. With the net emissions reduction potential and associated costs, a cost curve is developed to compare each scenario in a comprehensive manner in order to provide a clear picture to decision makers. The cost curve is explained in detail in chapter 4.

More details on the LEAP model use for energy modeling can be found in earlier published studies [64, 65, 74, 79-82].

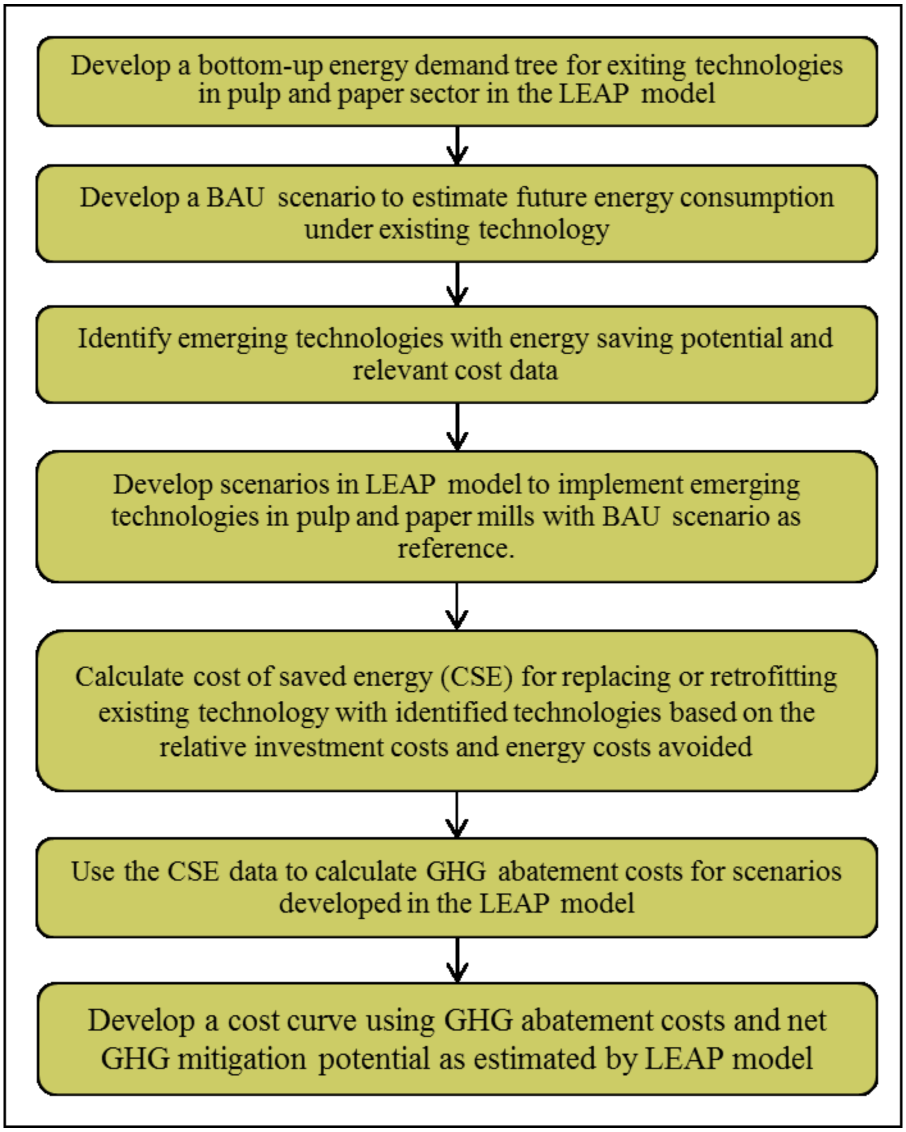


Figure 6: Methodology to develop cost curves using LEAP model

2.4 Alberta's pulp and paper – LEAP framework development

Alberta's pulp and paper sector has seven mills, which are discussed in detail in section 1.3. Electricity and natural gas are the main fuels consumed by this sector, and energy consumption varies based on annual production. However, the data reported by the Natural Resources Canada (NRCan) is limited to net fuel consumed only by the whole sector and does not provide any breakdown of energy use in the industry as shown in Figure 7. The ten-year energy consumption pattern for the industry excluding biomass is shown in Figure 8 [12].

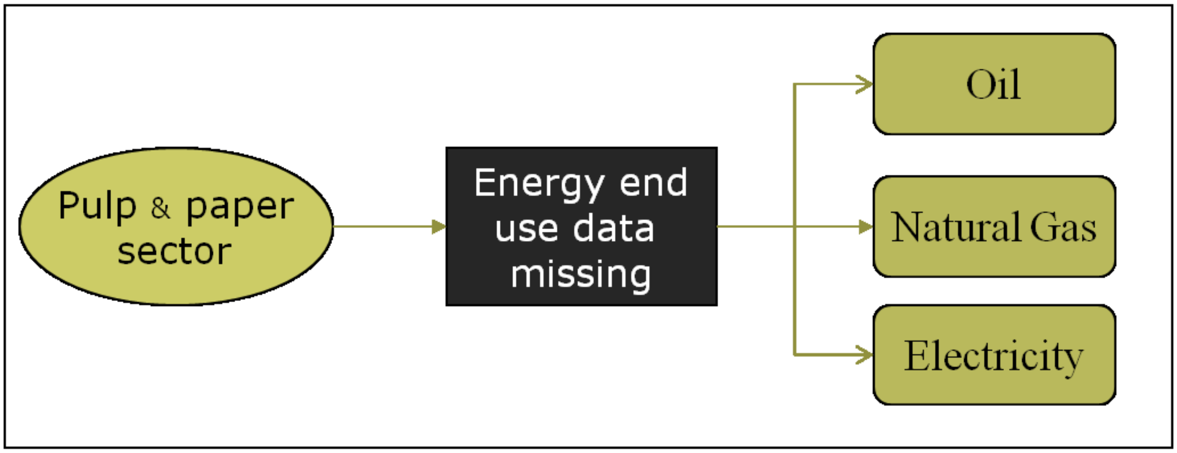


Figure 7: Energy consumption data breakdown level as reported by Natural Resource Canada

Some data not reported in NRCan are taken from Statistics Canada reports of energy supply and demand [83]. Overall energy consumption is decreasing as a result of inherent efficiency improvement as well as annual production variations.

To understand the energy end use in pulp and paper mills, the energy demand tree is developed and simulated in the LEAP model. The LEAP requires process-level energy intensities as well as annual mill production to calculate annual energy use in the mills. An extensive literature review is done to identify pulp and paper mills unit processes energy consumption. The model is verified against reported energy consumption in recent years to assure the accuracy of the LEAP model output. Once validated, the business-as-usual scenario is developed by analyzing the market trend of pulp and paper industries in Canada and projecting future mill production. The energy demand tree development is discussed in detail in section 2.4.1.

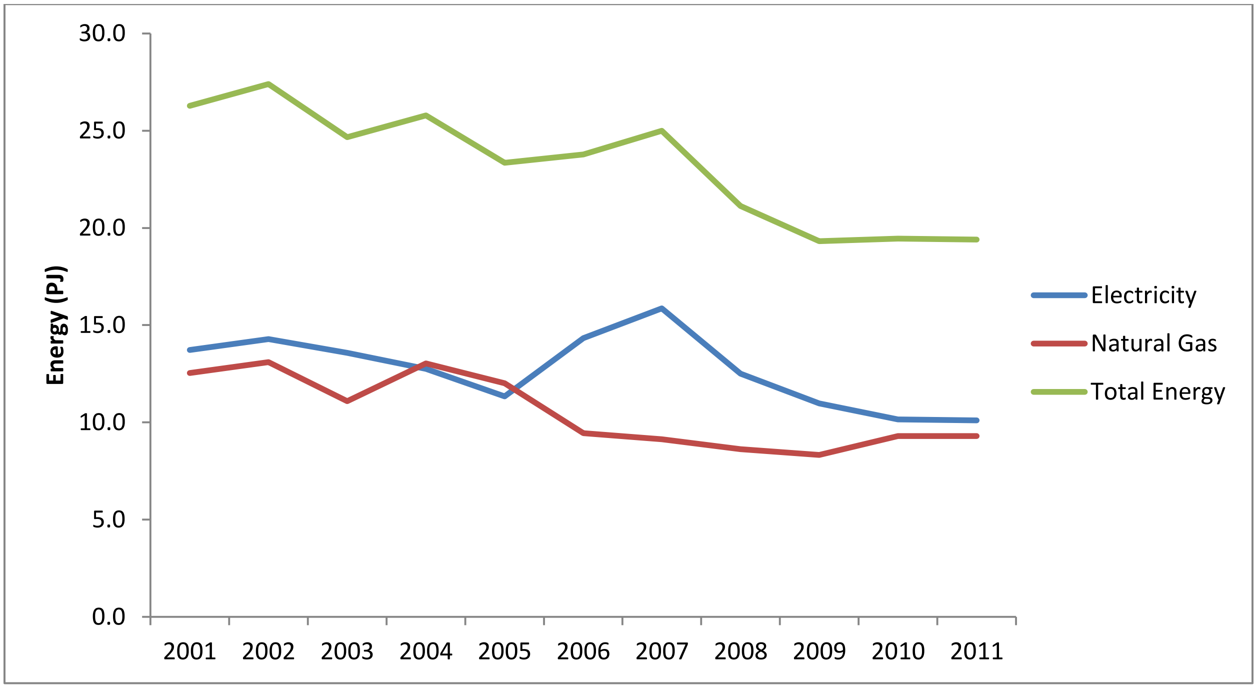


Figure 8: Ten-year energy consumption trend of Alberta's pulp and paper industry

2.4.1 Energy demand module - base case scenario

To assess the various energy efficiency improvement scenarios in pulp and paper sector, the first step was to develop a detailed bottom-up demand tree for the pulp and paper sector. The demand tree was categorized by technology (see Figure 9). The mills use three processes for pulp production: Kraft, BCTMP, and TMP. Process differences in mills of similar type are not significant enough to have a major impact on final energy consumption. The energy intensities for various end-use equipment were collected from several studies, with preference given to Canadian studies as they reflect actual environmental impacts on the processes. In addition, the studies from around the world were also reviewed for further validation. Also, the model results as a whole are verified by comparing the net energy consumption calculated by the model with the numbers reported by federal and provincial agencies.

The base year is selected based on the most recent energy consumption data available for all economic sectors in Alberta. Year 2010 was selected as the base year due to availability of complete actual energy consumption data [64, 65]. The demand tree for each sub-sector is developed based on detailed study of the process and unit energy data collection from various sources as explained in the following sections.

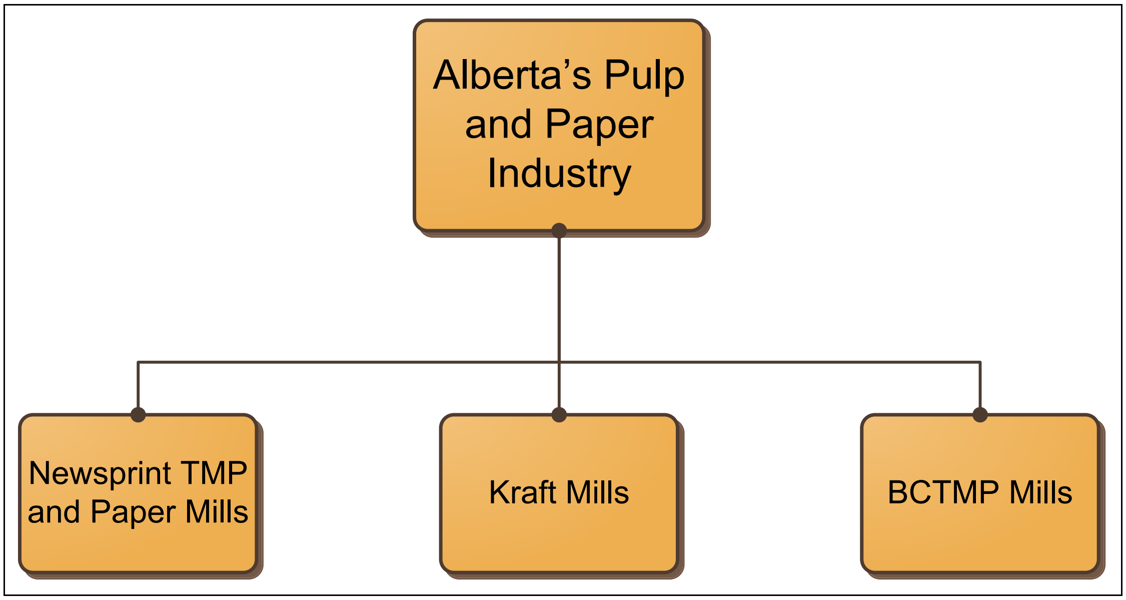


Figure 9: Alberta's pulp and paper sector demand tree

2.4.1.1 Demand tree development - TMP and paper mill

Thermo-mechanical pulping is an old process that uses mechanical force to convert wood chips into pulp [36, 37, 40, 52, 53, 84]. In Alberta, only one mill uses this process in integration with paper production facility due to which both processes are discussed together.

In the mechanical pulping process, wood fibers are separated mechanically. The bond between the wood fibers breaks under force and the fibers separate in the form of single fibers and fragments. The adhesive, lignin, stays in the final product, contributing to a high pulp yield of 95% or more compared to other pulping processes [40]. Due to the presence of lignin, the useful life of the product made from such pulp is low, thus TMP pulp is predominately used for low-grade paper such as newsprint, print magazines, catalogues, etc. [37]. A typical process flow diagram for TMP and paper making is shown in Figure 10.

Paper production involves the simple processes of stock preparation, forming, pressing, and drying/finishing operations. Bleaching is an optional process that may be required based on the application of the pulp produced. For newspaper production, bleaching is typically not required.

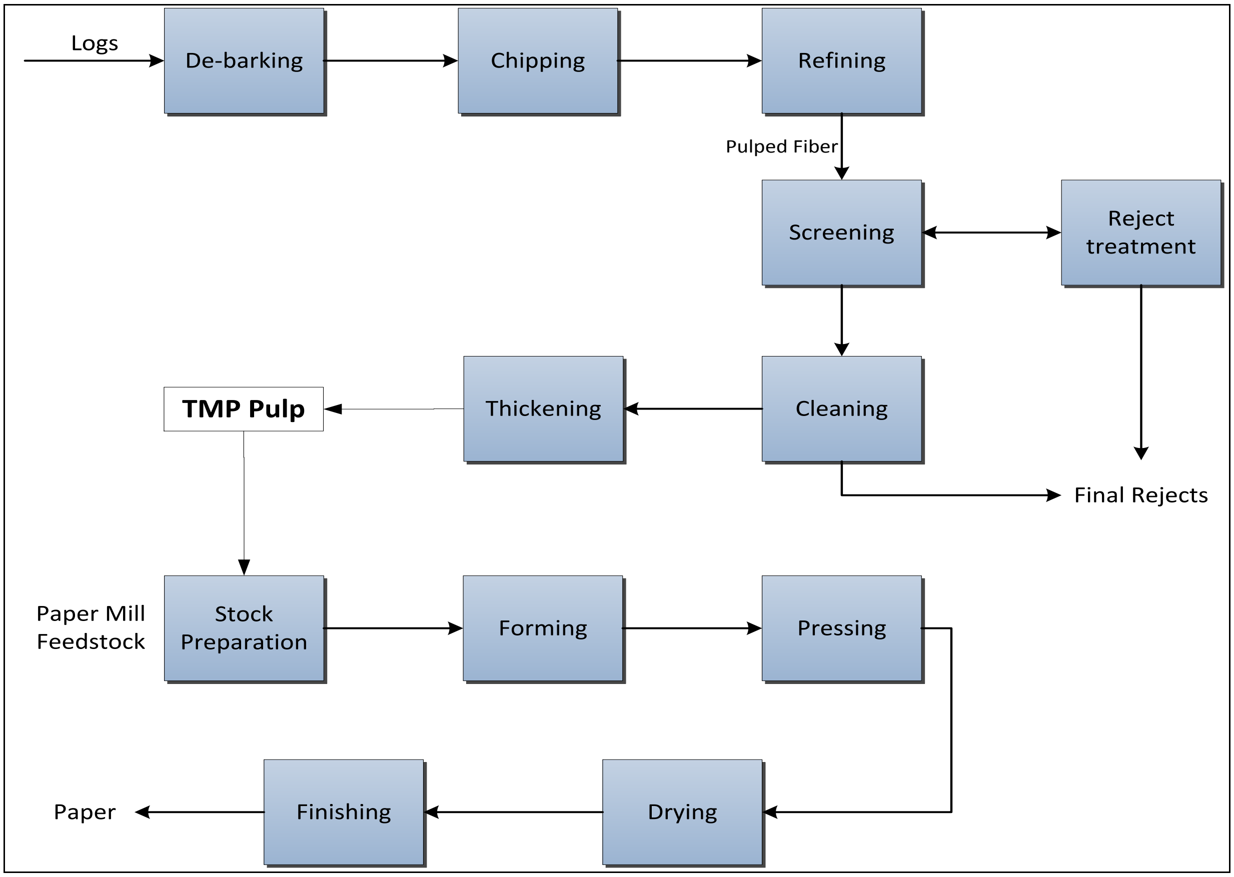


Figure 10: Process flow diagram TMP mill

A detailed description of various processes involved in thermo-mechanical pulping and paper making collected is discussed in detail in Appendix A. The structure of demand tree developed in the LEAP model for TMP and pulp mills is shown in Figure 11. In LEAP the TMP and paper mill processes are categorized under same branch as both mills are integrated to generate one final product. The energy intensities of the various processes in TMP and paper mill shown in Figure 10 are collected from multiple reports as discussed in Appendix A and are summarized in Tables 4 and 5 [36, 37, 40, 52, 53, 84].

Table 4: Energy intensities for a TMP mill [36, 37, 40, 52, 53, 84]

TMP mill*	**Electricity (kWh/ADMT)**
Wood chip handling and conveying	40
Refiner	2160
Screening/Cleaning/Thickening/Auxiliaries	240
Heat recovery	10
Effluent treatment	60
Total	**2510**

* The steam consumption in TMP mills is met by the heat recovered from the paper mill, thus no steam consumption is reported here.

Table 5: Energy intensities for an integrated paper mill [36, 37, 40, 52, 53, 84]

Paper mill	**Electricity (kWh/ADMT)**	**Steam (GJ/ADMT)**
Stock preparation	100	0.7
Forming, pressing	140	0.3
Drying, finishing, auxiliary systems	90	3.4
Total	**330**	**4.4**

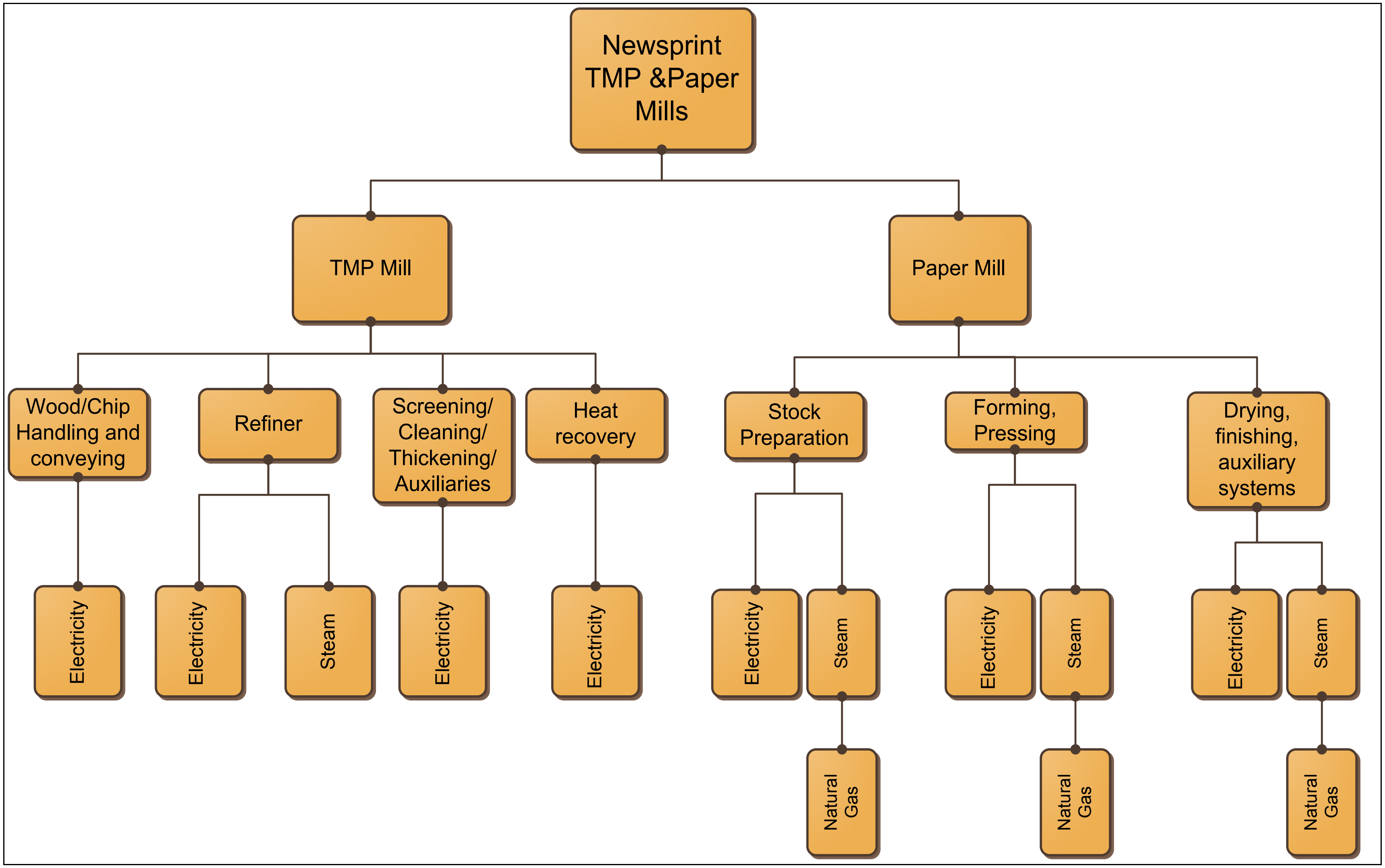


Figure 11: Energy demand tree for TMP and paper mills

2.4.1.2 Demand tree development - BCTMP mill

The bleached chemi-thermo mechanical pulping (BCTMP) is a modified version of the TMP process in which the chips are impregnated with chemicals before the refining stage. The mild chemical digestion process softens the wood, which leads to less energy consumption in refiner than for the TMP process. In 2005, Millar Western BCTMP mill reported a value of 1295 kWh/ADMT [85], which is significantly lower than refiner energy consumption in TMP mills (2160 kWh/ADMT) [52, 53]. In 2012, as part of an energy-saving project, the refiner plates were redesigned in Millar Western mill to reduce refiner energy consumption to 917 kWh/ADMT [85]. However, other mills might not have adopted this refiner design improvement. Therefore, the value of 1295 kWh/ADMT has been used for the base case energy model with improvements in technology considered in developing the business-as-usual scenario.

The BCTMP process has a higher yield than the kraft pulping and lower than mechanical pulping [36]. A comparison of yields and applications of pulp produced through different processes is shown in Table 9. The pulp produced through BCTMP has sufficient strength to be used as printing paper, packaging board, and hygienic paper products [40]. BCTMP is similar to TMP except that BCTMP includes chemical pretreatment, pulp drying (for a non-integrated mill), and washing stages (due to the chemicals in the wood chips). The BCTMP mill processes and their related energy intensities are discussed in detail in Appendix A and the process flow diagram for a typical BCTMP mill is shown in Figure 12.

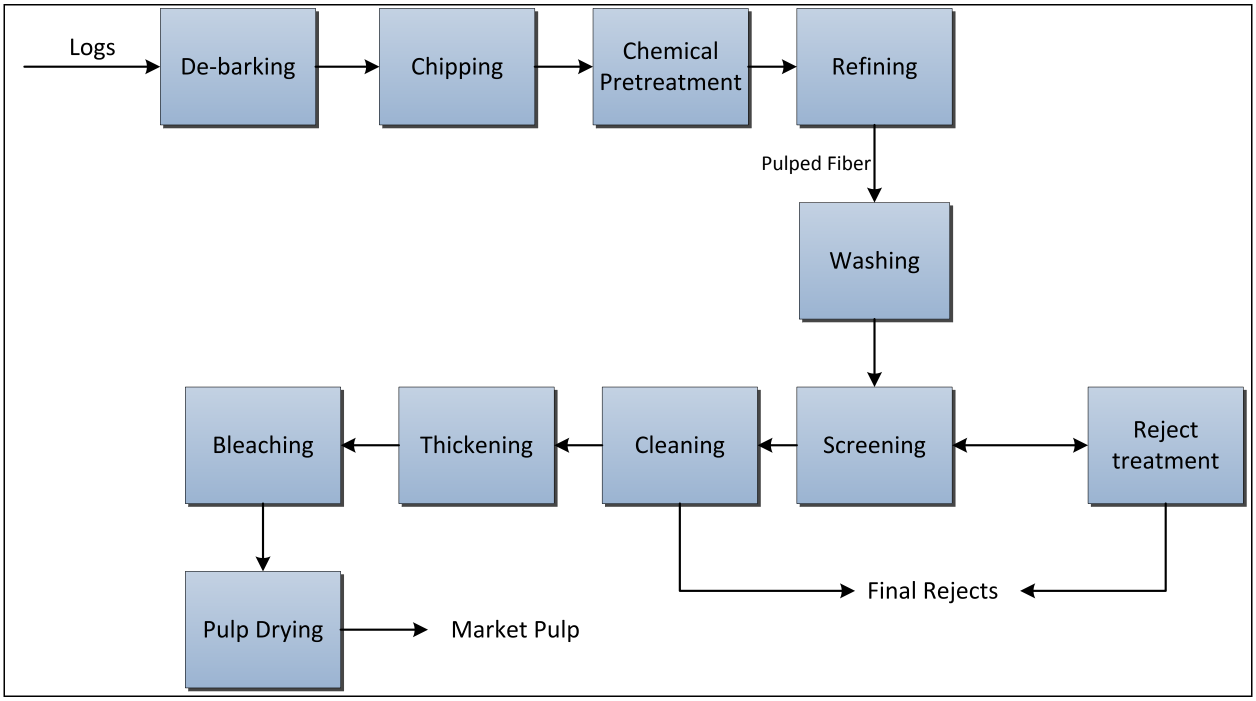
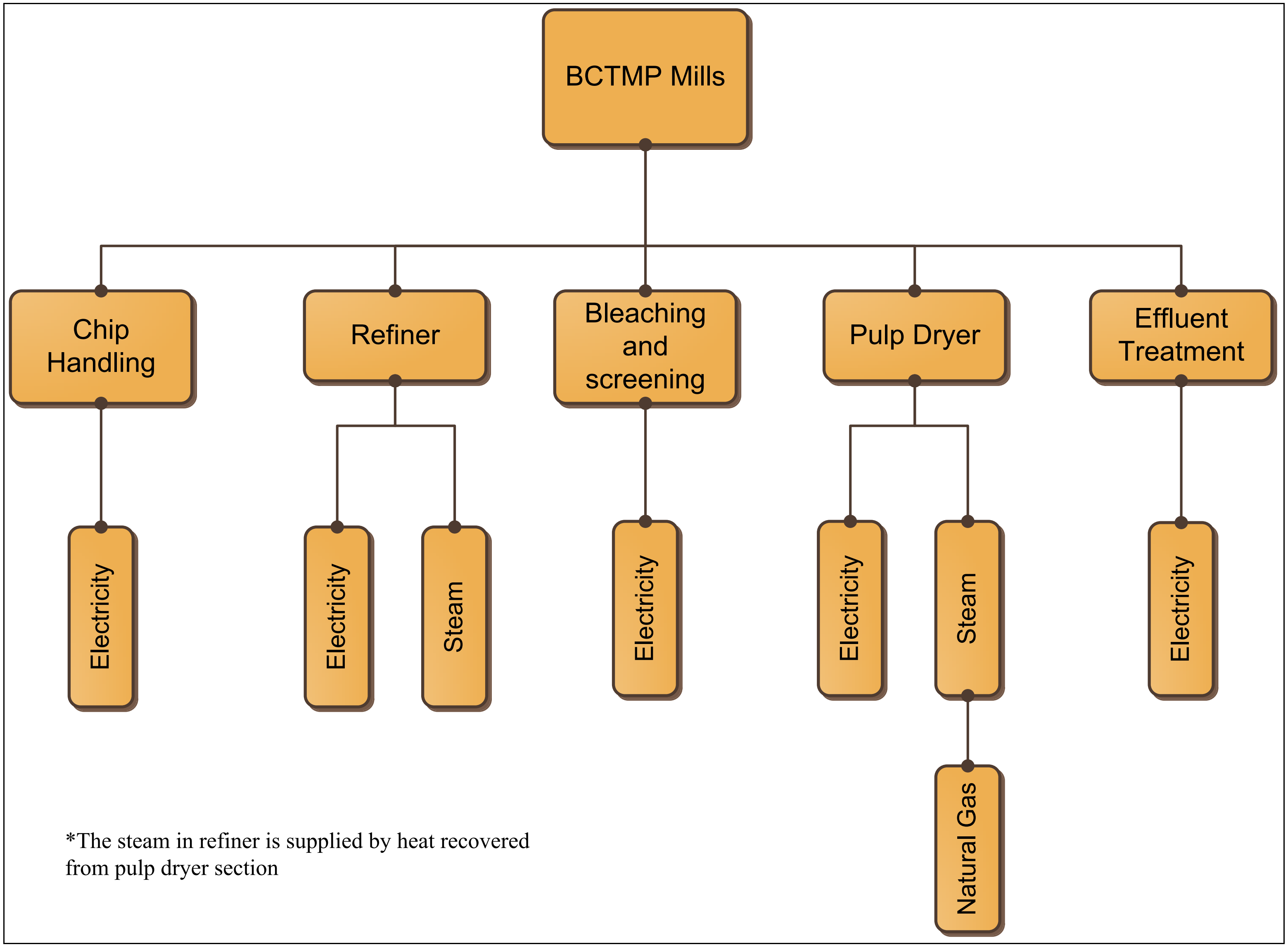


Figure 12: Process flow diagram BCTMP mill

The energy intensities for various processes in the BCTMP mill are provided in Table 6 [36, 37, 40, 52, 84, 86, 87] with specific intensity selection details provided in Appendix A. The Figure 13 shows the demand tree flow chart that is followed to develop the LEAP model for BCTMP mill.

Table 6: Energy intensities for the BCTMP mill [36, 37, 40, 52, 84, 86, 87]

BCTMP mill	**Electricity KWH/ADMT**	**Steam GJ/ADMT**
Chip handling	40	0.00
Refiners	1295	0.00
Bleaching and screening	500	0.00
Pulp dryer	150	3.37
Effluent treatment	60	0.00
Total	2045	3.37



*The steam in refiner is supplied by heat recovered from pulp dryer section

Figure 13: Energy demand tree BCTMP mill

2.4.1.3 Demand tree development - Kraft mill

Kraft mills use chemical pulping and so, instead of converting wood chips to pulp with mechanical energy, a chemical solution is used, thereby greatly reducing the energy consumption. 80% of the world's pulp is produced this way [40]. This process produces pulp with strong and stable fibers suitable for high -quality products like office paper, linerboards, etc. However, the yield is low as the lignin content and some hemicelluloses present in the wood are absorbed by the chemicals and separated from the pulp produced resulting in around 50% yield. Lignin typically makes up 25-35% of the wood [88].

Kraft pulping is similar to mechanical pulping but for the replacement of refining with digestion. The digestion process has additional steps related to chemical recovery as well as the oxygen delignification of pulp. The process flow chart is shown in Figure 14 and the individual processes are explained in detail in Appendix A.

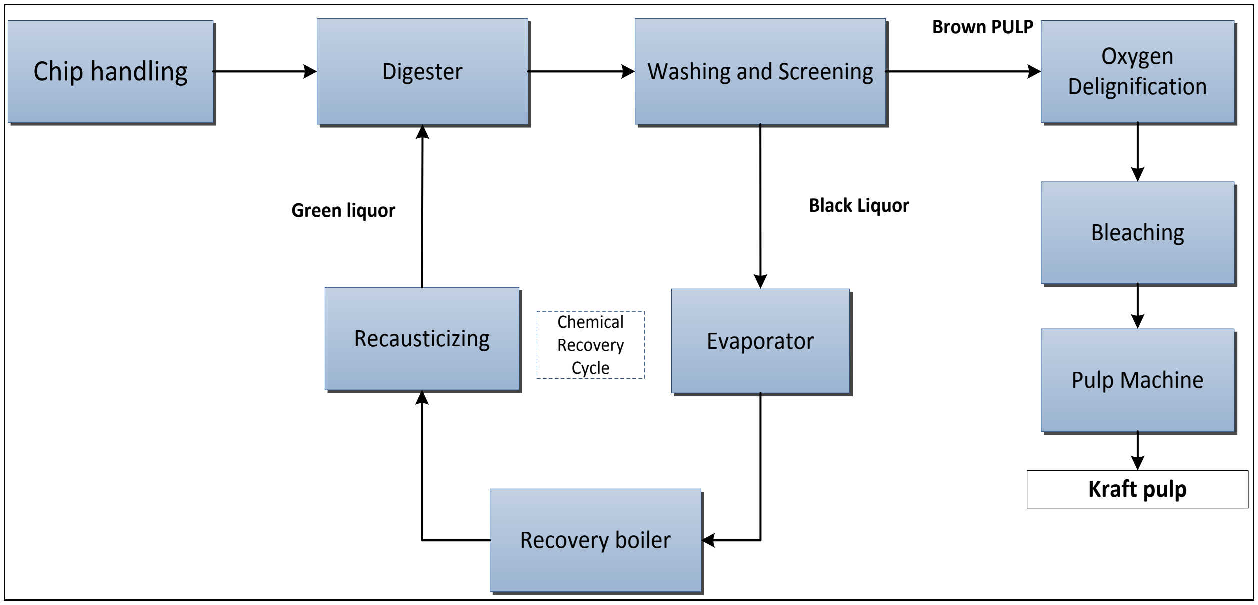


Figure 14: Kraft pulp process flow diagram

The Table 7 shows the of kraft mill process level electricity and natural gas consumption intensity as collected from multiple sources with respective references in the top column.

Table 7: Kraft mill energy intensities comparison from previous studies

Kraft pulping Processes	**Electricity Consumption (kWh/ADMT)**					**Thermal Energy Consumption (GJ/ADMT)**				
Data source	**[53]**	**[89]**	**[86]**	**[52]**	**[84]**	**[53]**	**[89]**	**[86]**	**[52]**	**[84]**
Chip conveying	20	45	55	31.60	90		0.14	0.15		0.26
Digester	40	44	65	221.3	80	1.7	2.57	2.05	3.81	2.43
Washing and screening	30	90	55		60			0.00		
Oxygen delignification	75	80	45		129	0.5	0.18	0.40		2
Bleaching	100	100	129	240.7		2.3	0.35	0.57	4.65	
Pulp machine	141		105	191.30		2.3	7.79	2.85	5.26	
Black liquor evaporators	30	30	30	30.60	40	3.1	4.45	4.10	7.06	3.69
Power plant	60		90			2.3		0.61		
Kiln and re-causticizing	50	30	30	47.90	36		0.59	1.50	2.34	2.74
Hot water supply	32	22					0.37			
Waste-water treatment	30	30	20	54.60	82					0.95
Miscellaneous	30	35	136	55.00			0.66	2.17		
Total:	**638**	**506**	**760**	**873**	**517**	**12.2**	**17.10**	**14.40**	**23.12**	**12.1**

* The merged columns represent that only net numbers are reported for respective processes in referred data source.

To develop the LEAP model, the energy intensities for the kraft mills were selected predominantly from Canadian studies not only because the data are local but the energy breakdown is detailed. This helps in more accurately analyzing energy efficiency improvement at the equipment level with subsector details. The energy intensities used in modeling kraft mills in the LEAP model are summarized in Table 8 and the demand tree structure is shown in Figure 15.

Table 8: Energy intensities for kraft Mill

Kraft Mill	**Electricity KWH/ADMT**	**Steam GJ/ADMT**
Chip conveying	20	0
Digester	40	1.7
Washing and screening	30	0
Oxygen delignification	75	0.5
Bleaching	100	2.3
Pulp machine	141	2.3
Black liquor evaporators	30	3.1
Power plant	60	2.3
Kiln and re-causticizing	50	1.5
Hot water supply	32	0
Waste-water treatment	30	0
Miscellaneous	30	0
Total:	638	13.70

It is important to note that the black liquor generates enough heat to meet the mill steam demand in most cases. However, it is not a consistent source and a continuous supply of natural gas is needed to meet mill steam demands [90]. Also, the kiln process requires direct burning of natural gas, which cannot be provided with black liquor. To accommodate for the energy balance uncertainty in this study, it is assumed that 10% of the steam is supplied by the natural gas burning and 90% is generated from black liquor. The efficiency of the natural gas boiler is considered to be 75% and the black liquor boiler is considered to have an 80% heat-to-steam efficiency [90, 91].

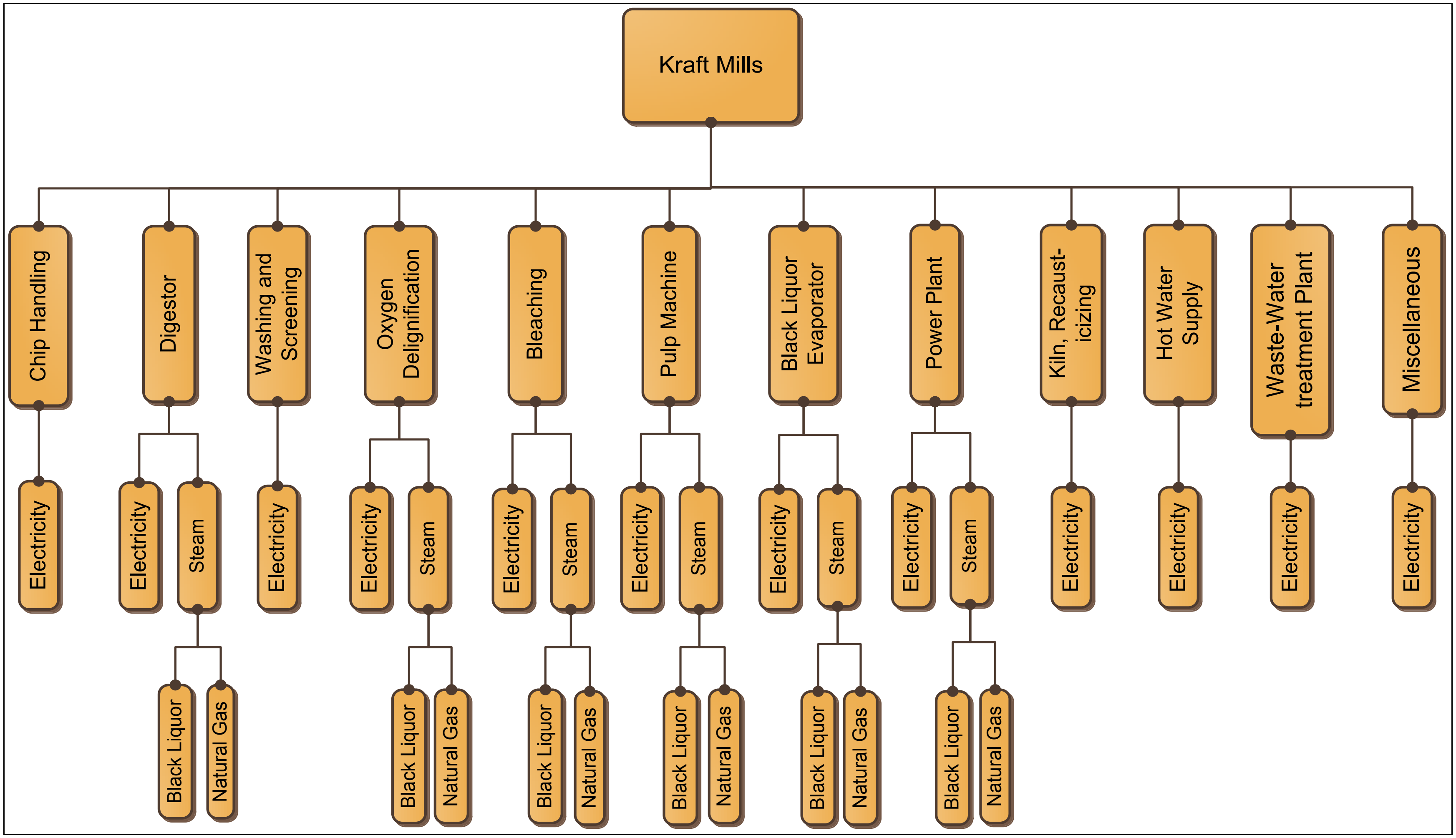


Figure 15: Energy demand tree kraft mill

The TMP, BCTMP and kraft mills produce different qualities of pulp as they use different approaches to convert wood chips to pulp as discussed above. A comparison of pulp yield, properties and its application under different processes is shown in Table 9 along with typical energy consumption for unit pulp production [37, 40, 92].

Table 9: Comparison of pulping processes

Technology	**Typical electricity intensity (kWh/ADMT)**	**Typical steam intensity (GJ/ADMT)**	**Pulp yield**	**Pulp properties**	**Typical application**
Thermo-mechanical pulping	2510	4.4*	87% - 97.5%	Short, weak, good printing quality	Newsprint, magazines, container board
Bleached chemi-thermo mechanical pulping	2350	3.37	90% - 94%	Intermediate properties compared to TMP and kraft pulp	Printing & writing paper, tissue, corrugated and packaging boards
Kraft (chemical) pulping	638	13.7	45%-50%	Long, strong and stable fibers	Bags, wrapping, linerboard, newsprint, specialty paper

* 4.4 GJ/ADMT represent the steam consumption in an integrated TMP and paper mill.

2.4.1.4 Alberta's pulp and paper sector LEAP model validation

Model validation is an important step to verify accuracy. The LEAP model uses bottom-up energy intensities to calculate annual mill energy consumption, thus it requires the annual mill production as input. Annual pulp production data from Alberta's seven mills are found in the company's annual financial reports, energy project reports, and in some cases from direct communication with mill engineers. The mill production levels from 2005-12 are shown in Table 10. Annual net energy consumption in Alberta's pulp and paper mills as reported by federal agencies for the years 2005-11 is shown in Table 11 [12, 83]. The actual energy consumption reported by these agencies are used for model validation.

Table 10: Alberta's pulp and paper mills' annual production

Years	Alberta Newsprint Company* (ADMT/Year)	West Fraser BCTMP Mill (ADMT/Year)	West Fraser kraft Mill (ADMT/Year)	Weyerhaeuser + Alpac + DMI+ Millar Western** (ADMT/Year)	Total (ADMT/Year)
2005	257,100	218,000	420,000	1,781,665	2,676,765
2006	248,153	218,000	381,000	1,754,017	2,601,170
2007	247,015	217,000	302,000	1,757,673	2,523,688
2008	247,643	205,000	325,000	1,717,886	2,495,529
2009	222,000	203,000	361,000	1,697,092	2,483,092
2010	262,000	249,000	354,000	1,728,291	2,593,291
2011	244,000	231,000	337,000	1,731,292	2,543,292
2012	256,000	222,000	370,000	1,789,358	2,637,358

*Newspaper mill production data were collected from the Alberta Newsprint Company natural gas reduction project report for the years 2005-2008 [28]. For the years 2009 to 2012, the data were obtained from West Fraser annual reports as West Fraser are 50% owners of Alberta Newsprint Company. These annual reports also provide the annual production from West Fraser BCTMP kraft mills [93].

**The production data for these mills are not publicly available and have been obtained directly from mill personnel [90, 94-96]. The values for these mills are presented as summations to maintain data confidentiality.

Based on pulp and paper mills' annual production shown in Table 10 and the energy demand tree developed in the LEAP model, the net annual energy consumption based on a bottom-up energy demand is calculated by the LEAP model. This is shown in Table 11. The comparison of the LEAP model results and energy consumption reported by federal agencies: NRCan [12], Statistics Canada [83] are shown in Figure 16.

Table 11: Alberta's pulp and paper mills annual energy consumption comparison

		2005	2006	2007	2008	2009	2010	2011
Natural Resources Canada (NRCan)	Electricity (PJ)	11.3	14.3	15.9	12.5	11.0	10.2	10.1
	Natural gas (PJ)	12.0	9.5	9.1	8.6	8.3	**9.4**	**9.4**
Statistics Canada	Electricity (PJ)	11.8	8.7	7.1	6.1	6	**10.2**	10.1
	Natural gas (PJ)	9.314	9.64	9.7	9.6	9.6	**9.4**	9.4
LEAP model	Electricity (PJ)	10.8	10.5	10.4	10.2	9.9	10.8	10.6
	Natural gas (PJ)	11.1	10.4	9.8	9.2	8.6	8.9	7.9

* Bold numbers are extracted from alternate report as they are not reported by respective source i.e. data missing in NRCan is taken from Statistics Canada and vice versa.

Figure 16 indicates that the LEAP model closely follows the energy consumption patterns reported by NRC and Statistics Canada. However, there are some variations in the absolute values. The assumptions in developing the validation model and possible causes of variations in results are explained as follows:

- The LEAP model requires the actual production by mills to calculate net energy consumption of previous years. The earliest production data that could be acquired for some mills were from the year 2005. Further, federal agencies provide complete pulp and paper mill data only up to the year 2011. Therefore, the model validation is done for the years 2005 to 2011.
- The data collected from Statistics Canada are from available energy supply and demand annual reports. No report is available for the year 2010, thus the values for that year are taken from NRCan. The NRCan does not report natural gas consumption in 2011 and thus the NG value is taken from Statistics Canada report on energy supply and demand.
- The LEAP model reflects average energy consumption irrespective of feedstock type. The feedstock wood can be either hardwood or softwood, and softwood consumes more

energy [89]. However, the data on feedstock type used in Alberta's pulp and paper mills are limited, which makes it difficult to produce exact energy consumption numbers, as federal agencies do.

- The steam used in kraft mills for process use and electricity generation can be produced using black liquor, natural gas, and wood bark. Natural gas consumption varies significantly depending on various economic parameters and mill operational status. Based on energy data received from DMI pulp mill [90], the natural gas share for steam production can vary from 0% to ~30% daily depending on the price of electricity (for export) and natural gas and the availability of wood bark and black liquor; most days the NG share is less than 10%. A typical kraft mill is expected to generate 80% of energy from black liquor [97] however actual values can vary significantly as discussed above. This huge variation makes it difficult to reflect exact energy consumption by pulp mills in the LEAP model. For validation purposes, it is assumed in the model that the natural gas consumption share decreasing from 80% to 90% as the black liquor and wood bark supply become more reliable. The actual natural gas consumption for steam production cannot be tracked, which leads to differences in the results.
- The boundary for pulp and paper mill energy consumption is not defined in the reference reports. Kraft mills generate electricity on site, which means that all processes related to electricity production can potentially be excluded from pulp and paper mill energy consumption. This will result in lower energy consumption reporting from pulp and paper mills, as can be seen in Statistics Canada's reported numbers. From 2010 onwards, Statistics Canada and NRCan started using same data source for reporting purposes, which makes their data similar.

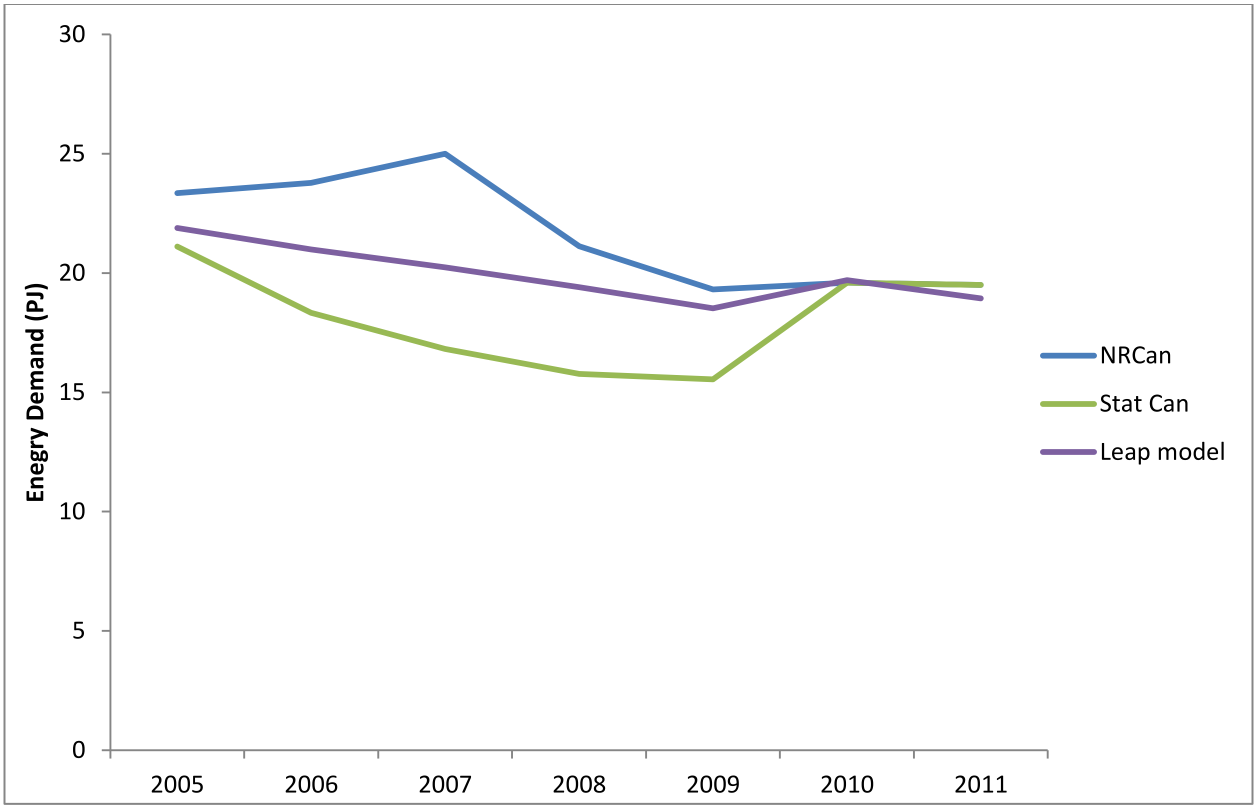


Figure 16: LEAP model validation

Based on the above discussion and the comparison shown in Figure 16, it can be justified that the LEAP model developed using a bottom-up energy consumption approach can closely reflect the energy consumption pattern of pulp and paper industries in Alberta.

2.4.2 Energy demand module - business-as-usual case scenario

The LEAP model has been validated and thus can be used to forecast energy consumption in pulp and paper mills depending on their expected annual productions. Using the base case, we developed a business-as-usual (BAU) case in the LEAP model to understand future energy consumption in Alberta's pulp and paper mills from 2010 to 2050. The BAU scenario is developed based on projected mill production as well as expected energy intensity improvements in the mills. The BAU scenario serves as a baseline for investigating various energy efficiency improvement and GHG mitigation options as it provides information on net energy consumption on sub-process levels when mills continue to work without any significant process modification and inherent energy efficiency improvement practices. The net annual energy consumption results are calculated by the LEAP model using a bottom-up demand tree based on equation 1.

Equation 1: Annual energy consumption based on a bottom-up demand tree

$$\begin{aligned}&\boldsymbol{Pulp\ and\ Paper\ mills\ Energy\ Consumption_i}\\&= \sum_{\boldsymbol{i=0}}^{\boldsymbol{n}} \boldsymbol{Production\ Capacity_i * Electricity\ Intensity_i}\\&+ \sum_{\boldsymbol{i=0}}^{\boldsymbol{n}} \boldsymbol{Production\ Capacity_i * Natural\ Gas\ \mathrm{I}ntensity_i}\end{aligned}$$

Equation 1 represents the LEAP model methodology to calculate net energy consumption in Alberta's pulp and paper mills in any year "i." "i" refers to the year with 0 as the base year, 2010 in our case. The model multiplies the energy intensities of the processes for a given year with the net production expected from the mills in that year. The following sections explain mill production projections from the base year of 2010 through to 2050 and the change in energy intensities of sub-processes in pulp and paper mills from the BAU scenario.

2.4.2.1 Projecting mill production in Alberta

Mill production levels can be evaluated in a number of ways including social and economic parameters. Social parameters include population growth, income growth, consumption per capita, etc., which can be used to calculate local pulp and paper products demand. However, social parameters are accurate when most of the products are consumed locally with only a minor portion exported. For Canada's pulp and paper industry, production is largely export-driven as Canada is major exporter of pulp and paper products [16, 17, 20]. Therefore, the local social parameters cannot accurately reflect the expected production from Alberta's pulp and paper mills.

Economic parameters include gross domestic product contribution, which can be extrapolated based on historical trends and used to calculate pulp and paper production based on expected sale price of pulp. However, the demand for pulp and paper products has fallen significantly in recent years as discussed in section 1.2. This downturn has led to the closure of some pulp and paper mills all across Canada, which makes it difficult to extrapolate production based on historical economic performance. The closure of these mills paved the way for the remaining mills to have a relatively stable market, as the supply reduced to adjust with the demand [98, 99].

For this study, it is assumed that no new mills will start up in the future and existing mills will remain operational as they adapt to changing global demands. Since social and economic parameters cannot accurately represent future pulp and paper production, each mill is expected to reach its maximum production capacity by the end of the study period (2050). There is an increase in softwood pulp production as hardwood pulp is predominantly used for paper, for which demand is declining. Softwood pulp has a lower yield than hardwood pulp [89] and thus production is not expected to reach maximum capacity levels of the mills in the future. The mill production values assumed to develop BAU are shown in Table 12.

Table 12: Pulp and paper mills expected annual production for BAU scenario

Pulp mill	Expected annual production in 2050 (ADMT)	Discussion
Alberta Newsprint mill	264,000	The Alberta Newsprint company annual production between 2005 and 2012 averaged 250,000 ADMT (see Table 10). The maximum annual production was 264,000 ADMT in 2014 and thus, this figure is considered the maximum value achievable by 2050 [31].
Millar Western BCTMP mill	318,000	The Millar Western BCTMP mill has an annual production capacity of 320,000 ADMT with an average annual production of 300,000 ADMT between 2005-2012. The maximum actual production was reported to be near production capacity in recent years 2010-2012. The 8-year average is low since the plant capacity was recently increased to 320,000 ADMT as part of an upgrade. Taking downtime into account, annual average production is expected to reach 318,000 ADMT by 2050.
West Fraser BCTMP mill	249,000	The West Fraser BCTMP mill has a plant capacity of 250,000 ADMT per annum and approached annual production of 249,000 ADMT in 2010 (see Table 10). Therefore, for the BAU scenario the plant production is expected to reach 249,000 ADMT per annum by the end of the study period.
West Fraser kraft mill	360,000	West Fraser kraft mill’s production has varied significantly over the past 8 years as shown in Table 10. The variation is reported to be caused by maintenance issues that stopped production [31]. Considering a maximum production capacity of 380,000 ADMT per annum and the trend over the 8 years (Table 10), an annual production level of 360,000 ADMT by 2050 was selected from the base year value of 354,000 ADMT to account for maintenance issues and variations between hardwood and softwood.

Pulp mill	Expected annual production in 2050 (ADMT)	Discussion
Weyerhaeuser kraft mill	390,000	The Weyerhaeuser kraft mill has an annual production capacity of 395,000 ADMT with maximum annual production reported to be 380,000 ADMT between 2005-2012 (Table 10). For the BAU scenario in the LEAP model, annual production is expected to reach 390,000 ADMT by 2050.
Alpac kraft mill	630,000	At 650,000 ADMT, the Alpac kraft mill has the largest annual production capacity among Alberta's pulp mills with an average annual production of 600,000 ADMT and a maximum production around 630,000 ADMT reported between 2005-2012. For BAU scenario, it is expected that the mill will reach 630,000 ADMT by the end of the study period to accommodate for feedstock variation.
DMI kraft mill	475,000	The DMI kraft mill has a maximum annual production capacity of 475,000 ADMT with an average of 470,000 ADMT between 2005-2012 (Table 10). By the end of the study period, annual production is expected to be close to 475,000 ADMT due to planned upgrades in the plant in near future [90].

2.4.2.2 Energy intensity trends in the BAU scenario

The energy intensities for various processes involved in mills were discussed in detail in section 2.4.1. For the current study the energy intensities are assumed to remain fairly constant during the BAU scenario except in some of the mills where efficiency improvements are expected to take place under regular maintenance and upgrading plans. The two major efficiency improvements expected are:

a) Boiler efficiency improvement

The efficiency of the boiler in converting natural gas to steam is considered to be 75% in the base year energy demand tree based on the data provided by DMI kraft mill [90]. Depending on the continuous maintenance and retrofitting projects, 85% efficiency is anticipated [91]. This efficiency improvement has been considered in developing the BAU scenario as an inherent industrial improvement procedure. The boilers are expected to reach 85% efficiency by the end of the study period in 2050.

b) Refiner efficiency improvement

The refiner used in BCTMP mills consumes 1295 kWh/ADMT electricity. However, one mill in Alberta reduced its energy consumption to 915 kWh/ADMT as part of an efficiency improvement initiative and it is expected that other mills will follow up with this design improvement in near future [85]. Therefore, in the BAU scenario it is assumed that all BCTMP mills in Alberta will adopt the efficient refiner design by 2020, thus reducing energy consumption by 30% from the base year value.

Based on above-discussed efficiency improvement measures, the BAU scenario was developed in the LEAP model for Alberta's pulp and paper industry and the results are discussed in detail in section 2.4.

2.4.3 Transformation Module

In the LEAP model for Alberta's pulp and paper industry, the transformation module is borrowed from an earlier study that developed this module in detail [65]. In Alberta, the major electricity generation sources are coal and natural gas with small amounts of hydro, wind, and biomass. Oil extraction and refining play a vital role in the transformation sector, and most of the oil is exported.

2.4.4 Resource module

The primary resources in Alberta's pulp and paper LEAP model are natural gas, crude oil, coal, wood, wind, hydro, etc., details of which are extracted by the LEAP from the transformation module [100]. The major secondary fuels are electricity and natural gas, based on demand energy requirement.

2.4.5 Environmental analysis - emission factors

In the LEAP model for the pulp and paper sector, only two forms of energy that result in environmental emissions are included. Emissions related to electricity use in pulp and paper mills are not calculated or assigned in the demand module as these emissions depend on the source fuel for electricity generation. Electricity-related emissions are calculated in the transformation module and then allocated to the demand side. The other fuel used in pulp and paper mills is the natural gas that is burned in the boiler to generate steam. The emissions related to burning natural gas in the boiler are assigned from IPCC Tier 1 default emissions factors built into TED.

The transformation sector generates high emissions due to extensive burning of fossil fuels such as coal and natural gas as well as other processes related to oil extraction and refining. The emissions factors related to the transformation sector are manually entered in the LEAP model to give accurate supply side emission levels in Alberta. The emissions factors database, along with a complete transformation module, was extracted from an earlier study [65].

2.5 Results and Discussion

The energy demand tree for Alberta’s pulp and paper industry was developed in the LEAP model with process-level energy intensity information as discussed in section 2.4.1. The demand tree is used to calculate the base year energy consumption and GHG emissions on which the BAU scenario was developed for the years 2010-2050. In this section, the LEAP model results are discussed covering base year energy consumption and GHG emissions in detail as well as the BAU scenario energy consumption and GHG emissions. The emissions are presented for both demand and transformation modules to discuss the electricity and energy transportation related emissions.

2.5.1 Energy consumption

Based on the analysis and data collection explained in this chapter, the LEAP model can run the simulation to provide information on Alberta’s pulp and paper mills energy consumption in the base year as well as forecast it up to 2050. The model can also provide us detailed GHG emissions expected from the pulp and paper mills during the study period. The following sections explain the energy demand and emissions from Alberta’s pulp and paper mills as calculated by the LEAP model.

2.5.1.1 Base year energy demand

The base year serves as a reference point in the model from which the data can be projected in to future years in the BAU scenario. 2010 is chosen as the base year as this is the year for which the most recent and complete energy consumption data are available in the public domain. Energy data are collected based on units of energy required to produce one tonne of pulp, thus to find the mill’s net annual energy consumption in the base year, the mill’s actual production in 2010 is required. Alberta has seven mills, and their production levels in 2010 are shown in Table 10.

With 2010 production levels and pulp and paper mills' energy intensities, the LEAP model calculated the net energy consumption for the base year to be 20.37 PJ. Energy consumption for the pulp and paper mills based on different technologies and energy types is shown in Figure 17 for the base year 2010. It is important to note that the base year energy consumption discussed here is different from energy consumption values calculated for the year 2010 in the validation model. The difference is due to the assumption that natural gas will provide 10% of mill steam in the base year; the validation model takes into account the varying nature of natural gas consumption, as described in section 2.3.1.4. Also, the pulp and paper mills energy consumption reported by this model only covers electricity and natural gas as they are responsible for GHG emissions in the mills. The energy consumed in form of black liquor is not reported here as it is considered carbon neutral due to which the net energy consumption reported by the LEAP model is lower as compared to data reported by federal agencies presented in Table 2.

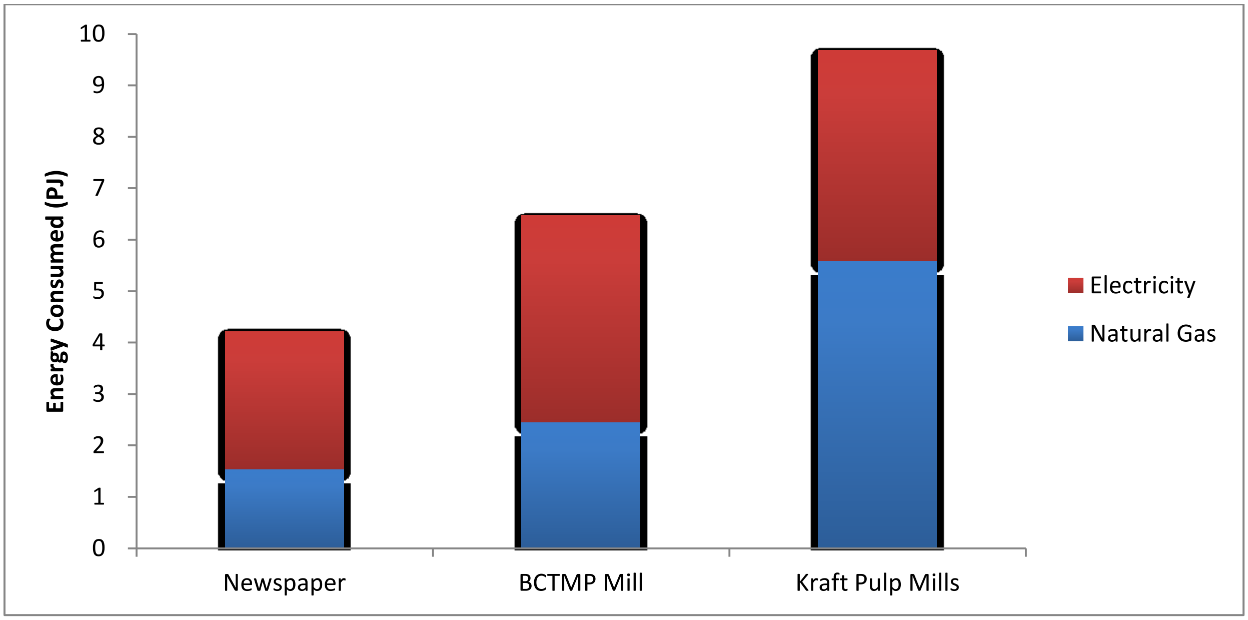


Figure 17: Base year (2010) energy consumption as calculated by the LEAP model

Energy consumption can be tracked to the sub-process level in LEAP and shares of electricity and natural gas can be distinguished. Table 13 shows the energy consumption breakdown in different mill types at the process level, and this breakdown can be used to identify the most energy intensive equipment in the pulp and paper industries.

a) Kraft mills

At 9.68 PJ of net energy consumption, kraft mills consumed the most energy of all the pulp and paper mills in Alberta as estimated by the LEAP model. This high energy consumption is due to kraft mills' high production rather than high energy intensity. Kraft mills produce almost 70% of net pulp among all of Alberta's mills (see Figure 3), thus they consume a large amount of energy. The pulp machine in kraft mills is the largest electricity-consuming device, and the kiln and re-cauticizer consume the highest amount of natural gas of all processes in kraft mill.

b) BCTMP mills

BCTMP mills consumed the second largest amount of energy in base year (6.47 PJ) after kraft mills and have a 21% share in net pulp production (see Figure 3). Despite big differences in production levels, the electricity consumption in kraft and BCTMP mills are very close, 4.10 PJ and 4.02 PJ, respectively. The BCTMP, a mechanical process-based mill, is highly energy intensive and consumes large amounts of electricity to produce a small quantity of pulp compared to kraft mills. The most energy-consuming processes in BCTMP mills are the refiner and pulp dryer.

c) Newspaper mills

The newspaper mill consumed 4.21 PJ of energy in 2010 as estimated by the LEAP model and have 9% share in the province's net pulp production. The majority of the processes are similar to BCTMP with the exception of including paper production-related processes. The energy consumption in newspaper mills is highest among all mills when the same production quantity is considered. The refining and paper drying processes are most energy intensive in the newspaper mills.

Table 13: Base year energy consumption in Alberta's pulp and paper mills as estimated by the LEAP model

Sectors/subsectors	Electricity (PJ)	Natural Gas (PJ)
Kraft mills		
Chip conveying	0.13	-
Digester	0.26	0.40
Washing and screening	0.19	-
Oxygen delignification	0.48	0.12
Bleaching	0.64	0.55
Pulp machine	0.91	0.55
Black liquor evaporators	0.19	0.74
Power plant	0.39	0.55
Kiln and recausticizing	0.32	2.68
Hot water supply	0.21	-
Waste-water treatment	0.19	-
Miscellaneous	0.19	-
BCTMP mills		
Chip handling	0.08	-
Refiners	2.55	-
Bleaching and screening	0.98	-
Pulp dryer	0.29	2.45
Effluent treatment	0.12	-
Newspaper mills		
Wood chip handling and conveying	0.04	-
Refiner	2.04	-
Screening/Cleaning/Thickening/Auxiliaries	0.01	-

Sectors/subsectors	Electricity (PJ)	Natural Gas (PJ)
Heat recovery	0.06	-
Effluent treatment	0.23	-
Stock preparation	0.09	0.24
Forming, pressing	0.13	0.10
Drying, finishing, auxiliary systems	0.08	1.19
Total	**10.8**	**9.57**

2.5.1.2 BAU scenario energy demand for the planning horizon of 2010-2050

The BAU scenario is developed based on the assumptions discussed in section 2.4.2. The mills' production was extrapolated and some inherent energy efficiency improvement measures were implemented in developing the BAU scenario. Table 14 shows the expected energy consumption from 2010 to 2050 in the business-as-usual scenario, and the energy consumption trend can be tracked to the sub process level. Energy consumption is expected to decrease from the base year value of 20.37 PJ to 19.46 PJ in 2050. Although production in the mills is increasing, efficiency improvement measures in kraft, BCTMP, and newspaper mills are reducing the overall energy consumption in BAU scenario by 4.4%. These reductions are expected to take place without any changes in mill continuous process or maintenance practices.

Through increases in production, the kraft mills are expected to increase net energy consumption from 9.68 PJ in 2010 to 9.74 PJ in 2050, even with efficiency improvements. The BCTMP mill shows a significant drop in energy consumption, from 6.47 PJ in 2010 to 5.65 PJ in 2050, predominantly due to significant improvements expected in refiner design, which would reduce electricity consumption. The newspaper mill also shows a reduction in energy consumption from 4.21 PJ to 4.06 PJ; the production stays almost constant with boiler efficiency improvement in BAU scenario.

Table 14: BAU scenario energy consumption in Alberta's pulp and paper mills (PJ) as estimated by the LEAP model

Sectors/Subsectors	2010	2020	2030	2040	2050
Kraft mills					
Chip conveying	0.13	0.13	0.13	0.13	0.13
Digester	0.66	0.66	0.65	0.65	0.64
Washing and screening	0.19	0.19	0.20	0.20	0.20
Oxygen delignification	0.60	0.60	0.61	0.61	0.61
Bleaching	1.19	1.19	1.18	1.18	1.17
Pulp machine	1.45	1.45	1.45	1.45	1.45
Black liquor evaporators	0.93	0.92	0.91	0.89	0.88
Power plant	0.93	0.93	0.92	0.91	0.91
Kiln and recausticizing	3.00	3.03	3.06	3.10	3.13
Hot water supply	0.21	0.21	0.21	0.21	0.21
Waste-water treatment	0.19	0.19	0.20	0.20	0.20
Miscellaneous	0.19	0.19	0.20	0.20	0.20
BCTMP mills					
Chip handling	0.08	0.08	0.08	0.08	0.08
Refiners	2.55	1.82	1.84	1.85	1.87
Bleaching and screening	0.98	0.99	1.00	1.01	1.02
Pulp dryer	2.75	2.70	2.65	2.61	2.55
Effluent treatment	0.12	0.12	0.12	0.12	0.12
Newspaper mills					
Wood chip handling and conveying	0.04	0.04	0.04	0.04	0.04
Refiner	2.04	2.04	2.04	2.05	2.05
Screening/Cleaning/Thickening/Auxiliaries	0.01	0.01	0.01	0.01	0.01
Heat recovery	0.06	0.06	0.06	0.06	0.06
Effluent treatment	0.23	0.23	0.23	0.23	0.23
Stock preparation	0.34	0.33	0.33	0.32	0.31
Forming, pressing	0.24	0.23	0.23	0.23	0.23
Drying, finishing, auxiliary systems	1.27	1.24	1.21	1.17	1.14
Total	**20.37**	**19.59**	**19.55**	**19.51**	**19.46**

2.5.2 Net GHG emissions

The LEAP model simulates the GHG emissions based on the emission factor allocated to fuel use and the fuel used in energy production as well as through meeting demand. The emissions produced from Alberta's transformation sector as well as pulp and paper mills in the base year and BAU scenarios are discussed in the following sections.

2.5.2.1 GHG emissions in Alberta's pulp and paper mills

The major fuels consumed in pulp and paper mills in Alberta are electricity and natural gas, and these are responsible for GHG emissions. The GHG emissions related to electricity generation are produced in the transformation sector as the fuels are burned in the electricity generation plants. This is discussed in next section. The GHG emissions related to natural gas consumption in the base year of 2010 and the BAU scenario are shown in Table 15.

Table 15: Base year and BAU scenario GHG emissions for Alberta's pulp and paper mills excluding electricity as estimated by the LEAP model

Sectors/Subsectors (kT CO_2 eq.)	2010	2020	2030	2040	2050
Kraft mills					
Digester	22.63	22.20	21.75	21.29	20.82
Oxygen delignification	6.65	6.53	6.40	6.26	6.12
Bleaching	30.61	30.03	29.43	28.81	28.17
Pulp machine	30.61	30.03	29.43	28.81	28.17
Black liquor evaporators	41.26	40.48	39.67	38.83	37.97
Power plant	30.61	30.03	29.43	28.81	28.17
Kiln and recausticizing	149.74	151.34	152.94	154.55	156.16
BCTMP mills					
Pulp dryer	137.22	134.46	131.63	128.72	125.72
Newspaper mills					
Stock preparation	13.67	13.30	12.92	12.54	12.15
Forming, pressing	5.86	5.70	5.54	5.37	5.21
Drying, finishing, auxiliary systems	66.39	64.58	62.74	60.89	59.03
Total	**535.26**	**528.66**	**521.87**	**514.88**	**507.70**

Kraft mills hold the highest share of emissions due to their larger production size compared to other mills. Emissions are expected to drop from 535.26 to 507.07 kT of CO_2 eq., largely due to improvements in natural gas boiler efficiency. Kiln and re-causticizing processes in kraft mills emit the most GHGs closely followed by pulp drying in BCTMP mills. A comparison of mill emissions' shares in the base year as well as the BAU scenario is shown in Figure 18.

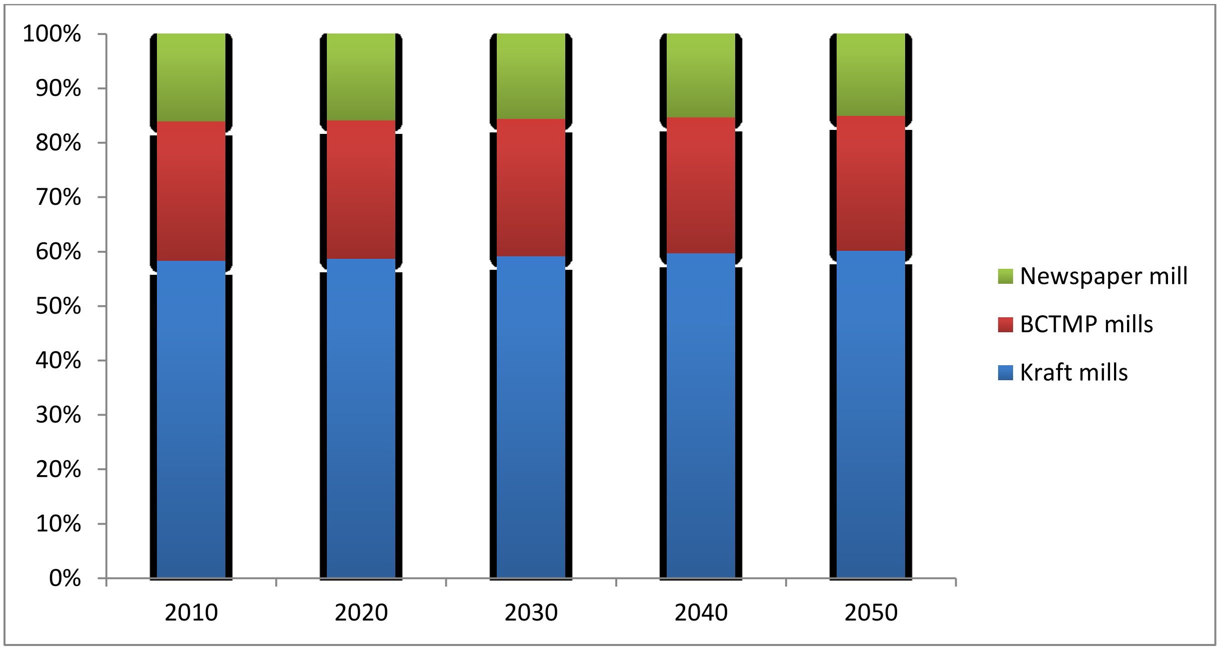


Figure 18: Mill GHG emissions' shares in BAU scenario as estimated by the LEAP model

2.5.2.2 GHG emissions in the transformation sector

The transformation sector in Alberta consists of primary resource extraction, refining, and energy conversion practices and is responsible for a significant amount of emissions. The transformation sector scenario developed in the LEAP model uses the emission factors from TED, and the model calculates the net GHG emissions (see Table 16). GHG emissions are expected to increase due to increases in oil-sands-related production. The scenarios where increases are found are discussed in detail in an earlier study from which the transformation sector scenario is adopted [65].

Table 16: GHG emissions from the transformation sector for Alberta's pulp and paper sector as developed by the LEAP model

Transformation Sector (MT CO2 eq.)	2010	2020	2030	2040	2050
Electricity generation	3.19	5.23	5	5.01	5.02
Natural gas and coal bed methane extraction	2.55	2.04	1.63	1.29	1.01
Alberta oil refining	4.26	4.27	4.27	4.27	4.27
Synthetic crude oil production	3.00	13.18	13.18	13.18	13.18
Crude bitumen production	13.27	44.95	44.95	44.95	44.95
Total	**26.28**	**69.68**	**69.03**	**68.70**	**68.44**

2.5.2.3 Net GHG emissions as estimated by the LEAP model

The overall GHG emissions from the energy demand for pulp and paper mills and Alberta's transformation sector are shown in Table 17. The pulp and paper industry contributes a small portion of emissions excluding electricity-related emissions. The net GHG emissions in Alberta are expected to double from the BAU scenario by the end of 2050.

Table 17: Overall GHG emissions for Alberta's pulp and paper mills as developed by LEAP model

Sectors (MT CO_2 eq.)	2010	2020	2030	2040	2050
Demand	0.54	0.53	0.52	0.51	0.51
Transformation	26.28	69.68	69.03	68.70	68.44
Total	**26.82**	**70.20**	**69.55**	**69.22**	**68.94**

2.6 Summary

Chapter 2 discussed the LEAP model structure, modeling methodology, and the energy demand tree development. The energy demand tree was developed by collecting data from various sources and the data were validated through federal agency reports. Based on the validated model, a BAU scenario was developed to simulate the expected energy consumption by

Alberta’s pulp and paper mills from the base year of 2010 to the end of the study period (2050). The results were presented at the subsector level to identify energy and GHG emissions-intensive operations and compare pulping technologies. In the next chapter, several energy efficiency improvement and GHG mitigation scenarios are developed using the energy demand tree discussed in this chapter to identify potential options to reduce GHG emissions in Alberta’s pulp and paper industry.

3 The use of the LEAP model to assess GHG mitigation scenarios in Alberta's pulp and paper industry

Chapter 2 provided the ground work required to develop GHG mitigation scenarios in Alberta's pulp and paper industry. The base year energy demand tree and development of BAU scenario provided an overview of future energy consumption patterns at the sub process level. With this information, we can evaluate the impact of implementing new technologies in these processes in detail with the results providing actual information on energy saving and GHG mitigation potential. The previous studies that have identified the energy saving potential in Canada's pulp and paper mills are either benchmarking studies [52, 53] or a top-down analysis [101]. A top-down approach considers changes in macroeconomic parameters to reduce GHG emissions, i.e., GPD, income growth, and energy consumption or production patterns. The top-down approach cannot accurately reflect technological changes throughout the study period as it assumes the market is using efficient systems. However, in this study, we use a bottom-up approach, in which a new technology or retrofitting option based on relative economic costs to achieve unit GHG mitigation is evaluated. To perform such an analysis, a framework or model is required that serves as the base of the GHG mitigation analysis. The bottom-up approach evaluates the mitigation potential based on microeconomic factors and the assumption that there are inefficiencies in the market [63, 102, 103].

We developed 28 scenarios in the LEAP model for Alberta's pulp and paper industry and analyzed the outcomes. The first few sections of this chapter explain the various parameters involved in scenario selection, followed by a detailed description of scenarios.

3.1 Method for scenario selection

The mitigation scenarios were selected based on energy savings potential, GHG mitigation potential, and applicability in Alberta's pulp and paper mills. There are a number of efficiency options available that can significantly reduce mill energy consumption; however, some of these options are only at the conceptual or laboratory stage. Also, the lack of cost data hinders the understanding of the true potential of emerging technologies. Only those scenarios that are in the pilot phase of development (or beyond) and those with available implementation cost data are developed here. Only reliable sources have been used in developing scenarios; these include public research institutes with a focus on energy efficiency improvement, government-funded research projects, and research work published in peer-reviewed journals.

3.2 Scenario development in LEAP

To develop scenarios in the LEAP model, the BAU scenario is set as reference scenario and a number of parameters are used to simulate the new technology scenario. The LEAP model provides the option of adding new technologies and expected technology adoption rate as well as related costs. This flexibility allows for a realistic evaluation of the potential for new technologies in the market. Parameters used to develop these scenarios are discussed in following sections.

3.2.1 Penetration rates of technologies

The penetration rate or activity level describes the rate of implementation of a new technology or retrofitting option. New technologies introduced in the market usually follow four stages: innovation stage, early and slow adoption stage, high adoption stage, and finally market saturation stage. These stages are commonly referred as sigmoid or s-curve technology diffusion as the cumulative adoption in these stages makes an "s" form, as shown in Figure 19.

Initially, a new technology has a low adoption due to high uncertainty in technology performance and economic parameters. With time, as the technology shows promising results, more industries adopt it until the majority of industries implement it and eventually the market is saturated. The adoption rate starts decreasing at this stage, with the highest level of cumulative adoption. The last stage of a technology is typically the introductory stage of a newer technology and the cycle goes on [104-106].

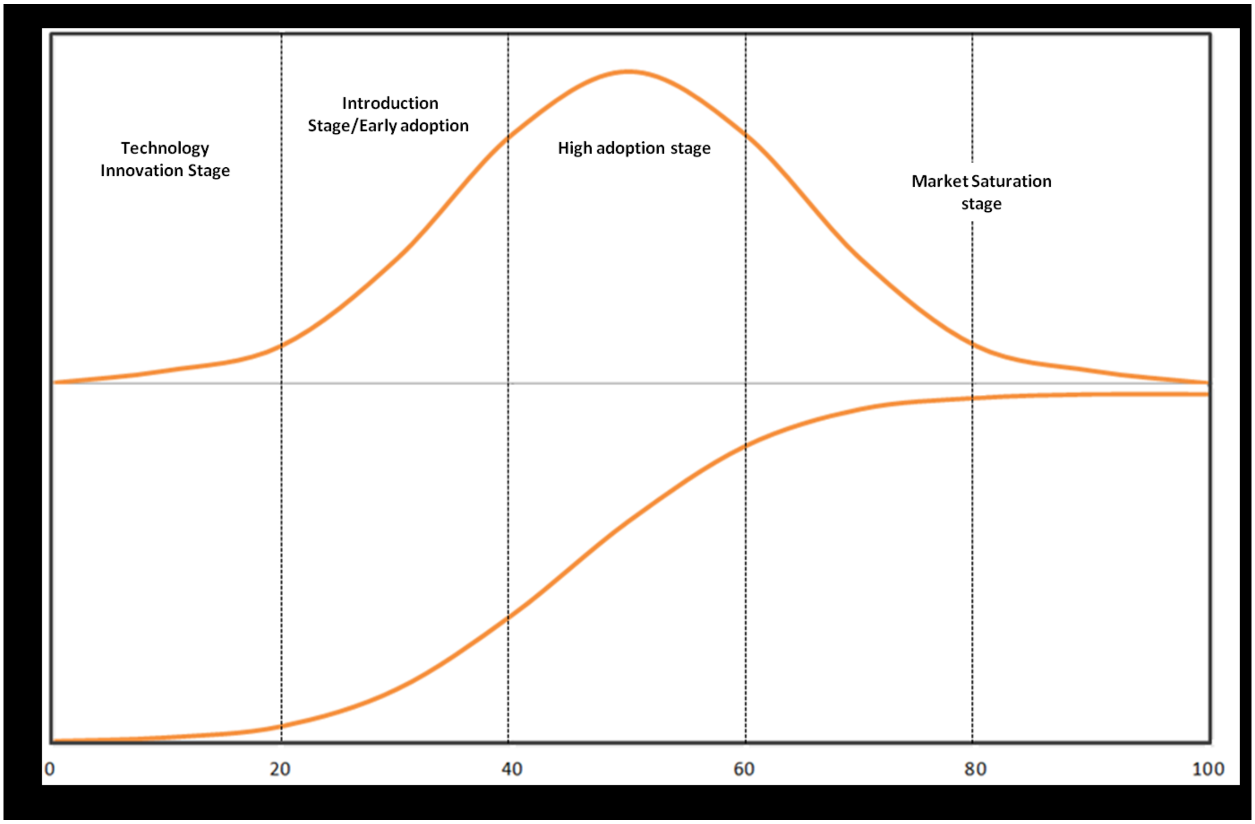
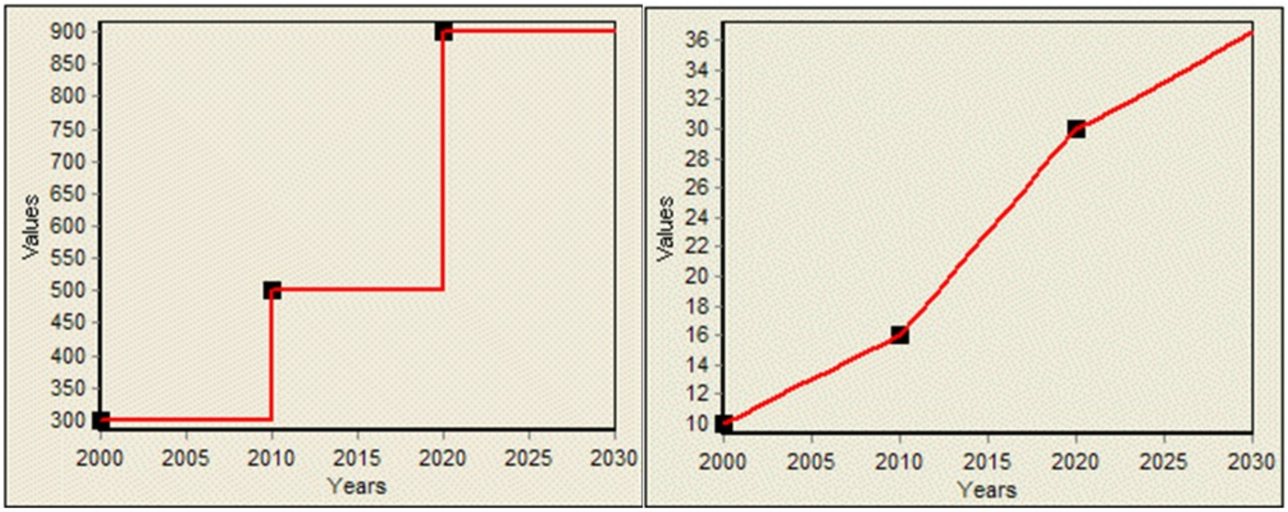


Figure 19: Technology adoption rate in market in S-curve pattern (derived from [104-106])

The LEAP model requires data on technology adoption rate in the form of the technology's activity level; this can range from 0 to 100% in a given year. As shown in Figure 19, technology adoption is not linear. The pulp and paper mills in Alberta share 10% of Canada's pulp and paper related production, therefore, technology adoption in these mills is assumed to take place in a limited timeframe and in a nearly linear fashion. The penetration rates for technologies are extracted from the literature and the technologies with limited data are expected to have 100% penetration by 2030 or 2050. The penetration rates for each scenario are discussed in detail and rates are adopted on case by case conditions.

The penetration rate can be entered in the form of fixed values in certain years (LEAP step function) where the penetration rate remains constant between two data points and rises to the next level in the given year. Such a pattern does not reflect realistic penetration rates as the technology adoption normally increases every year. Another way to enter data in the LEAP model is through the interpolation function in which the data points at certain times are provided and values are linearly interpolated between any two data points. This provides a smoother technology adoption rate and practical results. A visual representation of these functions is provided in Figure 20 [63]. In this study, the interpolation function is used to provide penetration rates for various scenarios discussed in upcoming sections.



Step Function

Interpolation Function

Figure 20: LEAP model data entry functions: Step and Interpolation [63]

3.2.2 Energy intensity

Energy consumption reduction and GHG emission mitigation scenarios, based on new technology implementation, are developed in the LEAP model. The new technologies are either more efficient than existing ones or completely change the fuel type required in order to provide same or better output. In both cases, less energy is consumed or fewer GHGs are emitted than the existing technologies. After entering the penetration rate of a scenario in the LEAP model, the energy intensity is entered in similar units as used in BAU scenario, which allows an accurate comparison of new measures with existing ones.

3.2.3 Scenario cost analysis

The scenarios developed in the LEAP model to assess GHG mitigation and energy saving potential are also evaluated for their economic suitability. The cost analysis is a vital part of this study as new technologies might not be economically feasible from a business point of view. Therefore, GHG abatement costs for each scenario are developed to investigate technology implementation from both the extent of GHG mitigation and from the perspective of cost saving compared to the baseline scenario. The analysis provides a detailed energy cost saving potential for a technology throughout study period and presented as net present value. There are different costs involved in technology implementation, and the results are calculated using various financial techniques. In this chapter, all the cost data relevant to a scenario is provided under respective scenario descriptions. The common terms and data related to the cost analysis as well as the cost conversion factors used are discussed in the subsequent sections. It should be noted that all the costs provided in this document are in Canadian dollars in the base year 2015 unless specified. The structure of section 3.2.3 is described as follows:

The cost data for the implementation of a technology is provided in the form of capital and operating and maintenance costs; these are defined in section 3.2.3.1. There are three different ways to input these costs in the LEAP model, and these are discussed in section 3.2.3.2. Defining all the terms involved in development of the cost analysis and constant values used in for every scenario, are provided in section 3.2.3.3. At the end, the method used to perform an economic evaluation is discussed in detail using the various parameters defined in previous sections.

3.2.3.1 Technology implementation costs

The scenarios developed for Alberta's pulp and paper mills to reduce GHG emissions involve different technology implementation costs and keep the technologies functional throughout the study period. These costs can be categorized as follows:

a) Capital costs

Capital costs are one-time expenses for designing, constructing, shipping, implementing, and starting up. This cost is normally reported as the net project cost with respect to design production capacity of the equipment. The capital cost decreases with time as the technology matures and is adopted more widely.

b) Operating costs

Operating costs are the expenses to keep equipment running. These costs typically include fuel and machine operator-related costs and are reported in terms of cost per unit production.

c) Maintenance costs

Maintenance costs are those related to the regular replacement of machinery parts, machine repair, and associated labor costs. These costs are also reported as cost per unit production and usually combined with operating costs.

3.2.3.2 Cost data in LEAP

There are different ways to enter cost data in the LEAP model, which give the flexibility in evaluating scenarios. For industry-related studies, the costs can be entered in the LEAP model as total cost, cost per activity, or cost of saved energy (CSE) [63]. These terms are explained as follows:

a) Total cost

In the LEAP model, the total cost can be entered as the annual cost of an activity without the production level or equipment activity level. This option is useful when only the annual cost of performing an activity is known without any cost breakdown [107].

b) Cost per activity

This is a default option in the LEAP model and requires cost data per unit activity level. This method is predominantly used to specify non-fuel costs per unit activity such as cost per residential household or cost per passenger-km for transportation related studies. The LEAP model uses the following formula to calculate net activity cost:

Equation 2: Cost calculation for cost per activity in LEAP

$$\boldsymbol{Cost_{s,t} = Costperactivity_{s,t} \times Activitylevel_{s,t}}$$

where “s” represents the current scenario and “t” represents the year

c) Cost of saved energy (CSE)

The cost of saved energy value provides the comparative cost of a new option with respect to a base option. The CSE is an incremental cost of energy saving with respect to the base technology and very effective when comparing the efficiency improvement options of a particular device. The CSE is used only when the scenario evaluates the modification of a particular sub process in a system rather than switching to a completely different technology at the industry level. The CSEs are calculated relative to a certain scenario which, in this study, is the BAU scenario. This allows us to economically evaluate a scenario without the need for the cost data of existing technologies in the BAU scenario. The CSE is typically calculated by dividing the net cost of efficiency improvement to annual energy savings. The units are $/GJ or $/kWh, depending upon the fuel type in a particular scenario.

The CSE is calculated outside the LEAP model through the development of a techno-economic model. The CSE data are entered in the LEAP model, which uses equation 3 to calculate the net cost of implementing the scenario in the case study.

Equation 3: Cost calculation for CSE data in LEAP

$$Cost_{s,t} = CSE_{s,t} \times Activity\ level_{s,t} \times (Energy\ Intensity_{BL,t} - Energy\ Intensity_{s,t})$$

where "s" represents the current scenario, "BL" represents baseline scenario (BAU), and "t" represents the year.

3.2.3.3 Common cost-related factors

Several common values are used to perform the cost analysis, i.e., energy price, conversion rate, inflation rate, and discount factor. These values remain constant throughout the analysis and serve as the basis for calculations for most scenarios. The base case assumptions related to these factors are discussed in this section and will be used during the techno-economic analysis discussed in the subsequent sections.

a) Energy price

The energy price forecast is vital for an accurate techno-economic analysis to calculate the CSE. As discussed in chapter 2, the main forms of energy being used in pulp and paper mills are electricity and natural gas. To calculate the CSE, the energy price forecast for these energy sources in Alberta is required. The National Energy Board (NEB) releases regular energy outlook reports in Canada and the provinces 20 years into the future that serve as the major source of energy prices for this study. Based on the NEB report, average electricity and natural gas prices have been assumed for 2010 to 2050 with 10-year interval averages and are shown in Table 18 [108]. The values are available till 2035, therefore the average value for the decade 2040-2050 is taken by assuming the same price change as in the previous two decades.

Table 18: Energy price forecasts

Energy price forecast	2011-2020	2021-2030	2031-2040	2041-2050
Electricity unit price ($/kWh)	0.11	0.16	0.17	0.18
Natural gas unit price ($/GJ)	4.20	6.03	6.61	7.19

b) Currency conversion factors

Cost data were collected from studies done globally and the calculations for cost analysis were performed in 2015 Canadian dollars. The values were first converted from the base currency to the Canadian currency for that same year (e.g., 2005 US dollar to 2005 Canadian dollar) and then corrected for inflation to the year 2015. The Bank of Canada rates are used for currency conversion and inflation corrections [109, 110]. The cost data provided in the scenario descriptions are converted to the 2015 currency level.

c) Discount rate

The discount rate to calculate the CSEs is considered to be 5%; this is on par with many similar recent studies [64, 65].

3.2.3.4 Cost analysis method

The cost analysis is done by calculating the cost of saved energy (CSE) using a techno-economic model, which acts as input in the LEAP model to calculate the costs associated with respective scenarios. The CSE is calculated considering the BAU scenario as the base case, which allows us to perform an incremental cost analysis considering the costs associated with efficiency improvement measures only [100]. To calculate the CSE, costs related to scenario implementation in the industry as well as annual energy saving expected are required. The costs and related data are extracted from a literature review, as provided in the scenario description section, and consist of capital, operating, and maintenance costs as well as technology lifetime. The operating costs and maintenance costs are provided on an annual basis; however, the capital cost is a one-time initial cost.

The capital cost is calculated by multiplying the dollar amount required per unit production capacity with the present mill capacities in Alberta. The capital cost is then annualized based on the lifetime of the technology using the capital recovery factor (CRF) [9]. The CRF is calculated as follow:

Equation 4: Capital recovery factor equation

$$\boldsymbol{CRF = \frac{i(1+i)^n}{(1+i)^n - 1}}$$

where

i = discount rate

n= life of the equipment

The annualized capital cost is calculated by multiplying the CRF with the capital cost of the equipment as shown in equation 5. This annualized capital cost can be added to the annual operating and maintenance cost to achieve the net implementation cost of a technology in Alberta’s pulp and paper mills.

Equation 5: Annualized capital recovery factor calculator

$$\boldsymbol{Annualized\ capital\ cost\ (ACC) = Capital\ cost * CRF}$$

To calculate the CSE, the costs saved due to reduced energy consumption and amount of energy saved are required. The energy savings from the scenarios can be calculated from expected energy reduction multiplied by the average annual mill production. The results of these energy savings are discussed in chapter 4. The annualized costs of the scenario implementation are divided by the energy saving potential to achieve the CSE, as shown in equation 6 [9]. Since the fuel cost is averaged for 10 years as discussed in section 3.2.3.3, the CSE is also calculated once for every ten-year interval by taking the average of all the parameters involved during those ten years.

Equation 6: Calculating the cost of saved energy

$$Cost\ of\ Saved\ Energy\ (CSE) = \frac{AAC + OC + MC - CS}{Annual\ Energy\ Savings}$$

where

AAC= Annualized capital cost

OC = Operating cost

MC = Maintenance cost

CS = Cost saved by energy reduction compared to BAU scenario

The CSE values act as input in the LEAP and the model calculates the costs associated with each scenario with respect to the BAU scenario. The results obtained from the LEAP model are further used to provide a comprehensive scenario analysis through cost curves, which are discussed in detail in chapter 4.

3.3 Mitigation scenarios for Alberta's pulp and paper industry

Canada is leading the efforts to reduce GHG emissions by introducing GHG mitigation-related policies, investments, and targets in the public and private sectors [111, 112]. At the United Nations conference on Climate Change (COP21), Canada signed the Paris Agreement to improve efforts to keep global temperature increase well below 2°C and limit the temperature rise to 1.5°C from pre-industrial levels [113]. A step forward related to this agreement is the Alberta Climate Leadership Plan, which implements a carbon tax and introduces other emissions reduction measures in Alberta, thereby putting Canada on the road towards a sustainable future [114]. All such measures aim to achieve GHG emissions reduction by adopting efficient equipment, low energy intensive technologies, and fuel switching to reduce emissions. This study provides a detailed analysis on assessment of energy efficient options in the pulp and paper industry. Twenty-eight emissions reduction scenarios for Alberta were developed and evaluated.

The scenarios are developed in three broad categories including pretreatment technologies, efficient drying technologies, and process improvements. The scenarios are discussed through scenario description, energy saving potential, penetration rate, and cost analysis data along with a summary table showing the major input parameters used in developing the LEAP model.

3.3.1 Pretreatment technologies scenarios

In the pulp and paper industry, pretreatment technologies modify wood chip structure and convert the chips to pulp with less energy and thereby fewer GHG emissions than otherwise. Several chemical pretreatment technologies are in use in kraft and BCTMP mills; however, these technologies lead to yield losses and environmental concerns. The use of sodium hydroxide and sodium sulfide reduces pulp yield significantly due to carbohydrate instability and degradation [115]. Some of the products achieved in chemical pulping are chlorinated and therefore toxic and harmful to the biological systems [116]. Several pretreatment technologies that are not only environmentally safe but also increase yield and reduce energy consumption are discussed below.

3.3.1.1 Scenario 1: Microwave pretreatment

a) Description

In the current chemical pulping process, the reactions that split the covalent bonds between wood fibers are helped by energy and chemicals. Microwave pretreatment technology modifies the cellular microstructure to enhance the permeability of the chemicals in the wood chips, thereby reducing the amount of energy and the chemicals required to reach center of wood chips. Larger wood chips have to be screened out before conventional chemical pulping because of the higher energy and time required to penetrate the center of the chips; however, microwave pretreatment opens up the cellular microstructure of the wood chips and so the larger chips can be used without any loss of energy. The reduction in chemical consumption significantly reduces the natural gas required in the lime kiln process that is used to recover the spent chemicals and provides a pulp of acceptable quality with a low H-factor. The H-factor determines the time required for digester operation; thus, a lower H factor provides improves the process.

The microwave drying technology is currently tested to work in kraft mills and can be adapted to be used in CTMP and TMP processes. However, there are some disadvantages to this pretreatment. Although the natural gas savings are greater in comparison, the microwaves will increase mill electricity consumption. There is a potential to damage pulp fibers (bursts and tears) as well as lower paper tensile strength due to the reduction in hemicellulose content in the final product [36, 117-119].

b) Energy savings potential

The microwave pretreatment increases the penetration of pulping chemicals towards the center of the wood chips, thereby reducing the amount of chemicals required. This reduces natural gas required in the lime kiln for chemical recovery, and natural gas savings of up to 40% are expected for the same level of pulp production. The yield is also expected to increase with the option to use larger chips and the lower H-factor of the digester, which also reduces the energy consumption indirectly; however, these savings are not quantified [118].

c) Penetration rate

The technology is designed to be implemented in kraft mills with potential applications in BCTMP and TMP mills in the future. In the US, it is expected that 75% of the kraft mills will adopt this technology retrofit [117]. This technology is not applicable in all mills, as for some specialized products, the pulp requires specific qualities that might not be possible with microwave pretreatment. In Canada, 75% of kraft mill production is expected to be through microwave pretreatment by the end of 2030 in fast penetration scenario and by 2050 in slow penetration scenario (up from the current level of 0%). The technology has been adopted by the sugar industry for enhanced sugar extraction by pretreatment of bagasse [120]. Since there are only four kraft mills in Alberta, the technology penetration is considered to be linear with an average of one mill adopting this technology every 10 years in slow penetration scenario.

d) Cost analysis data

The microwave pretreatment technology is expected to cost approximately $33.08 million for a 1000 ADMT mill [118]. The operating and maintenance costs are expected to be minimal as there are no moving parts and no direct contact of the product with equipment.

The summary of microwave pretreatment scenario parameters used in the LEAP model for Alberta's pulp and paper mills is provided in Table 19.

Table 19: Scenario 1 input parameters (Microwave pretreatment)

Scenario	Microwave pretreatment technology					
Application	Kraft mills					
Technology status	Pilot stage					[120]
Energy saving potential	Reduces the natural gas consumption in a lime kiln by 40%. Energy intensity reduction in lime kiln process from 1.5 GJ/ADMT to 0.9 GJ/ADMT					[118]
Penetration rates	2010	2020	2030	2040	2050	
Slow scenario	0	10.7%	32.1%	53.6%	75%	[117]
Fast scenario	0	25%	75%			
Cost data	Capital cost: $38.8 million dollars for 1000 ADMT/d mill capacity Lifetime = 15 years					[118]

3.3.1.2 Scenarios 2, 3, 4: Enzymatic pretreatment (xylanase, cellulase, pectinase)

a) Description

The TMP and BCTMP processes use mechanical energy to convert wood chips into fibers in a refiner. The refiner is the most energy intensive component of mechanical pulping and consumes 1295-2160 kWh/ADMT of electricity. Enzyme pretreatment of wood chips modifies the cellular structure, softening the chips, which makes it easier to convert them to fibers. Though refiner energy is significantly reduced following this pretreatment, pulp quality is maintained [121]. Wood chip pretreatment also improves refiner equipment life, as less mechanical energy is applied on the chips and thus less wear and tear of the equipment. However, enzymatic pretreatment reduces fiber length, which can weaken the final product in certain cases [36, 122].

Enzymatic pretreatment is done with a number of different enzymes such as lipase, esterase, cellulase, xylanase, pectinase, hemicellulase, and laccase, which provide different energy saving potential and product quality [123]. Of these enzymes, xylanase, pectinase, and cellulase have been analyzed under the ECOTARGET program and showed significant energy savings potential in the European pulp and paper industry [42]. In this study, three scenarios are developed for enzymatic pretreatment based on enzymes energy saving potential.

b) Energy savings potential

Enzymatic pretreatment reduces refiner energy consumption significantly; the amount varies depending on the enzyme. Xylanase showed the highest energy saving potential (25%) and cellulase showed a reduction of 20% under similar pretreatment conditions. Of the three enzymes, pectinase showed the lowest energy saving potential (10%) [42]. The pulp quality varies with the enzyme type, as shown by Mårtensson in his study of enzymes' impact on pulp production [124]. However, in this study of GHG mitigation planning for pulp and paper mills, the qualitative aspect of the product cannot be quantified due to varying product end use. Since the selection of enzymes will depend on energy savings potential as well as pulp quality, all three enzymes were evaluated in the model for respective energy savings potential.

c) Penetration rate

The enzymatic pretreatment technology is currently in the pilot stage and research is being done for the process optimization to reduce fiber length losses. This pretreatment measure is expected to be in the commercial stage by 2020 and penetrate up to 17% of pulp and paper mills in Germany by 2035 [38]. All enzymatic pretreatment technologies are expected to penetrate Alberta's pulp and paper mills that currently use mechanical pulping by 25% both in slow and fast penetration scenarios.

d) Cost analysis data

A study done earlier for German pulp and paper mills provides detailed cost data on the implementation of enzymatic pretreatment technology in mechanical mills [38]. Enzyme costs vary locally, but operating costs are a small portion of overall costs; hence the cost data are adopted from the study by Fletcher et al. [38] and converted to current Canadian currency levels, as discussed in section 3.2.3. The capital cost of implementing this technology is \$761.24 per ADMT of pulp with a 1.6% annual reduction expected as the technology matures and becomes more widely known. Annual operational and maintenance (O&M) costs of \$4.92/ADMT are expected with a 10–year equipment lifetime.

The summary of parameters used in the LEAP model for energy modeling and GHG mitigation of scenario 2 is provided in Table 20.

Table 20: Scenarios 2, 3, 4 input parameters (enzymatic pretreatment)

Scenario	Enzymatic pretreatment					
Application	Mechanical mills					
Technology status	Pilot stage					[36]
Energy saving potential	Scenario 2: Xylanase pretreatment reduces refiner electricity consumption by 25% Scenario 3: Cellulase pretreatment reduces refiner electricity consumption by 20% Scenario 4: Pectinase pretreatment reduces refiner electricity consumption by 10%					[42]
Penetration rates	2010	2020	2030	2040	2050	
Slow scenario	0	0	8.3%	16.7%	25%	[38]
Fast scenario	0	0	25%			
Cost data	Capital cost: $761.24/ADMT O&M cost: $4.92/ADMT/year Lifetime: 10 years Annual reduction in capital cost: 1.6%					[38]

3.3.1.3 Scenario 5: Fungal pretreatment

a) Description

Fungal pretreatment follows same basic principle as enzymatic pretreatment to reduce refiner energy consumption by modifying the wood structure. The microscopic action of the fungi weakens the internal bonding of the wood fibers, thereby reducing the energy required to mechanically separate the fibers. The process has been evaluated at the laboratory scale, and semi-commercial stage plants have been developed to study the large-scale implementation of this technology [125]. Fungal pretreatment has been shown to reduce refiner energy consumption by 25-40% without significant drop in pulp quality [36, 125, 126]. The economic analysis has shown promising results with some loss in pulp brightness that can be recovered by using extra bleaching chemicals. Added benefits of using fungal pretreatment are strength improvement, pitch reduction. and improved uniform properties imparted to wood chips [125].

b) Energy savings potential

The energy saving potential of fungal pretreatment is higher than enzymatic pretreatment. Though an earlier study reported fungal pretreatment energy savings potential in the range of 25% to 40% [126], a more recent study at a semi-commercial level reported savings of 33% [125]. For the purpose of this study, refiner energy savings are considered to be 33% in terms of electricity, which reduces the refiner energy intensity from 2160 kWh/ADMT to 1447 kWh/ADMT.

c) Penetration rate

Fungal pretreatment has been evaluated for TMP mills with promising results. Since there is only one TMP mill in Alberta, the technology adoption rate is expected to be 100% at the end of study period 2030 or 2050, up from the current level of 0%. It is assumed that the technology will be available commercially by 2020.

d) Cost analysis data

Cost data for the application of fungal pretreatment were adopted from pilot plants developed to study the impacts of this pretreatment [126]. 2.5 million US dollars were invested in a 200 ADMT/day TMP production plant that integrated fungal pretreatment technology; this cost provides a reference for the capital cost required for large capacity plants and was converted to $67.39 per ADMT of mill capacity in current Canadian currency [126]. An operating and maintenance cost of $28.84 per ADMT is expected for biological pretreatment with an additional $15.38 per ADMT due to increased chemical use in bleaching and other dependent processes [125]. The fungal pretreatment process is similar to enzymatic pretreatment and it is expected that with maturity of the technology the investment cost will be reduced by 1.6% annually [38].

The summary of parameters used in the LEAP model for energy modeling and GHG mitigation in fungal pretreatment scenarios is provided in Table 21.

Table 21: Scenario 5 input parameters (Fungal pretreatment)

Scenario	Fungal pretreatment					
Application	Mechanical mills					
Technology status	Semi-commercial stage					[36]
Energy saving potential	Fungal pretreatment reduces refiner electricity consumption by 33%					[125, 126]
Penetration rates	2010	2020	2030	2040	2050	
Slow scenario	0	0	33.3%	66.7%	100%	
Fast scenario	0	0	100%			
Cost data	Capital cost: \$67.93/ADMT O&M cost: \$44.23/ADMT/year Lifetime: 10 years Annual reduction in capital cost: 1.6%					[38, 125, 126]

3.3.1.4 Scenario 6: Chemical pretreatment

a) Description

The chemical modification of fibers is a technique used in the TMP process before mechanical refining. This modification converts TMP mills in to CTMP mills and reduces energy in refiners while developing a pulp suitable for papermaking. The chemical modification of wood chips acts on the binding forces between fibers including hydrogen bonding and produces stronger paper. This partial replacement of mechanical refining with chemicals reduces water retention, thereby reducing the energy required for water removal [127]. Typically, alkaline solutions such as sodium sulfate and alkaline peroxide are used, depending on wood chip type. Refiner energy savings are reported to be up to 40% and the press section can reduce electricity by 15% due to the lower water content in the pulp. The technology is already mature and TMP mills can be converted to CTMP mills depending on the paper grade and quality required [38].

b) Energy savings potential

The chemical pretreatment of wood chips significantly reduces TMP mill energy use. The refiner is the most electricity intensive equipment in the TMP mill, and chemical pretreatment of wood chips reduces refiner electricity by 40%. In the LEAP model the chemical pretreatment scenario is set to reduce refiner energy consumption from 2160 kWh/ADMT to 1296 kWh/ADMT. Additional savings are achieved in the pressing and drying sections, where less energy is consumed due to lower water retention; net electricity consumption can be reduced by 15%. In the development of this scenario in the LEAP model, an energy reduction of 90 kWh/ADMT to 76.50 kWh/ADMT was assumed in pressing and drying [38, 127]. Some savings are also expected through reduction in natural gas demand during the drying process; however, to account for increased energy consumption due to chemical pretreatment equipment, this saving is neglected.

c) Penetration rate

The chemical pretreatment technology is already in use in BCTMP mills and can be implemented in a TMP mill depending on the quality of the paper required. To assess the energy savings and GHG mitigation potential of this technology, it is assumed in the chemical pretreatment scenario that this technology will be fully integrated in Alberta's one paper mill by 2030 in fast penetration scenario and by 2050 in slow penetration scenario. To study the impact of fuel pricing, the penetration is set up as linear interpolation in the LEAP model for Alberta's pulp and paper mills.

d) Cost analysis data

The implementation of a chemical pretreatment system in a TMP mill requires an initial investment of $7.21 per ADMT. The capital cost is expected to reduce annually by 1% as the technology matures and enhanced understanding of equipment requirements. The operating and maintenance costs are expected to be $5.27 per ADMT per year [38].

The summary of parameters used in the LEAP model for energy modeling and GHG mitigation in chemical pretreatment scenarios is provided in Table 22.

Table 22: Scenario 6 input parameters (chemical pretreatment)

Scenario	Chemical pretreatment					
Application	Mechanical mills					
Technology status	Commercial stage					[38]
Energy savings potential	Chemical pretreatment reduces refiner electricity consumption by 40% and pressing electricity consumption by 15%.					[38, 127]
Penetration rates	2010	2020	2030	2040	2050	
Slow scenario	0	14.3%	42.9%	71.4%	100%	
Fast scenario	0	33.3%	100%			
Cost data	Capital cost: $7.21/ADMT O&M cost: $5.27/ADMT/year Lifetime: 10 years Annual reduction in capital cost: 1 %					[38]

3.3.1.5 Scenario 7: Oxalic acid pretreatment

a) Description

Oxalic acid (OA) pretreatment is used in mechanical pulping to reduce the energy required to separate wood fibers in chips while maintaining pulp quality. As of 2003, 25% of the pulp produced globally undergoes mechanical pulping process and if this pulp undergoes OA pretreatment, significant energy savings can be realized without compromising pulp quality. The involvement of oxalic acids in bio-pulping was observed during fungal pretreatment trials when calcium oxalate deposits were found on the surface of and inside wood chips after fungal pretreatment [128]. A pilot-scale evaluation of OA pretreatment at the Andritz pilot plant in Springfield (US) showed significant energy savings of 25% in refiner energy with improved paper strength, reduced pitch content, and improved dewatering properties compared to regular refining operation [41].

Additional benefits of OA pretreatment include lower shive production and improved uniformity of the pulp with lower fine impacts on the water loop. Although this pretreatment incurs extra costs such as buying the chemicals, ~3.5% wood yield loss and increased energy use, the overall quantified results of the technology provide a net benefit to the mill.

The studies referred focus on TMP mills, yet CTMP mills follow the same basic principle and can benefit from this technology. However, because there is no pilot scale testing in BCTMP mills, the scenario is only considered for the paper mill. The energy savings potential, technology penetration rate, and the cost parameters used for the LEAP model are discussed in the next sections.

b) Energy savings potential

ECOTARGET is the largest research project in the European pulp and paper industry funded by European Commission [36]. Oxalic acid pretreatment savings were analyzed in detail under this project. The energy savings are reported to be a reduction in refiner electricity consumption by 25%-30% while producing same quantity and improved quality of pulp [128, 129]. In the LEAP model, refiner energy consumption in a TMP mill drops from the current level of 2160 kWh/ADMT to 1512 kWh/ADMT after a 30% electricity reduction.

c) Penetration rate

The OA pretreatment has been tested at the pilot scale and is expected to be commercially available in the near future. Since there is only one mill that uses the TMP process, the technology penetrate rate is expected to be 100% by the end of the study period. It is assumed for the reference purpose that the technology will be available commercially by 2020.

d) Cost analysis data

The OA pretreatment technology requires the implementation of equipment needed to transport chips and a treating chamber with accessories. The capital costs of implementing OA pretreatment technology is not provided in the literature; therefore, due to the similarity of the process with the chemical modification of fibers in a TMP mill (as discussed in scenario 4), the capital is assumed to be the same, i.e., $7.21 per ADMT with a 1% annual reduction [38]. The operating and maintenance cost is adopted from the study done on an OA pretreatment pilot plant that gives an average value of $17.31 per ADMT. The O&M costs include chemical supply, utilities, incremental water treatment, labor, and maintenance-related expenses [128]. The lifetime of the equipment is assumed to be 10 years, the same as for scenarios 2, 3 and 4 due to process similarity.

The summary of the parameters used in the LEAP model for energy modeling and GHG mitigation of OA pretreatment scenario is provided in Table 23.

Table 23: Scenario 7 input parameters (Oxalic acid pretreatment)

Scenario	Oxalic acid pretreatment					
Application	Mechanical mills					
Technology status	Pilot stage					[41]
Energy savings potential	Oxalic acid pretreatment reduces refiner electricity consumption by 30%					[128, 129]
Penetration rates	2010	2020	2030	2040	2050	
Slow scenario	0	0	33.3%	66.7%	100%	
Fast scenario	0	0	100%			
Cost data	Capital cost: $7.21/ADMT O&M cost: $17.31/ton of pulp production Lifetime: 10 years Annual reduction in capital cost: 1%					[38, 128]

3.3.2 Efficient drying technologies scenarios

The production of pulp through chemical or mechanical pulping requires water mixed with wood chips at different stages to produce good quality pulp. This water has to be removed from pulp to prepare it for shipping or other uses. The pulp is shipped in units of air dried metric tonnes that are 90% pulp and 10% moisture as discussed in chapter 2. The wet slurry containing wood pulp that is produced after the digester or refining process has up to 80% water, which is removed in a number of steps. In a paper mill, the pulp is dried to achieve a fine quality paper with a moisture content of 5-10%; this is achieved by passing the slurry through pressing and drying sections. These processes have been explained in detail in chapter 2 with the information on energy intensity levels. Typical amounts of 140 kWh/ADMT and 0.3 GJ/ADMT are required for forming and pressing and the drying section consumes 90 kWh/ADMT of electricity with 3.4 GJ/ADMT of natural gas. Several techniques have been proposed to reduce the most energy intensive operations in the paper mill such as replacing or retrofitting conventional steam-heated drums with new technologies. Three such technologies were considered in this study based on data availability and are explained in scenarios 8, 9, and 10.

3.3.2.1 Scenario 8: Microwave drying technology

a) Description

Microwave drying can remove water from pulp web during paper production and level out the moisture profile across the wet sample [130]. A microwave dryer is added as a retrofit and reduces dryer energy consumption. The microwave can also replace some of the steam drums to achieve similar results but with higher energy efficiency. Microwave drying has been investigated since the 1960s as a means of achieving an energy efficient drying system that produces good quality paper. Initial studies showed favorable economics with no significant damage to the paper produced. However, achieving paper uniformity was an issue until Industrial Microwave Systems (IMS) improved the process. Their improvement was a milestone in large-scale and efficient uniform paper production [131].

The microwave heating system consists of a power generating system, an applicator, and a control unit. The applicator generates the microwaves that are absorbed by the moist planar material (the pulp); the amount and composition of the pulp web are controlling factors. The applicator can be oriented in two configurations: cross-machine direction (CD) oriented and machine direction (MD) oriented. The microwave drying system can be placed before the last pressing nip or before the drying section (after the pressing section) based on the properties required in the final product. Fredrick W. Ahrens and other partners [132] analyzed in detail the microwave drying technology in various configurations. According on their evaluation, the MD configuration applicator dried more efficiently than the CD applicator and the post press was an easier retrofitting option from an engineering point of view.

The benefits of microwave drying technology include reduced water load on the dryer, lower capital costs in the dryer section by reducing the number of steam drums required, and high temperatures in the dryer that increase the efficiency of steam drums. The paper machine speed significantly increases, thereby increasing mill productivity with an investment that has lower capital costs than adding steam drums to achieve the same results [36, 132].

b) Energy savings potential

The energy savings potential can range from 12% to 20% in the dryer section of the paper mill. There are additional savings expected due to increased paper machine speed, which is usually a limiting factor in mill paper production overall, as well as increased dryer efficiency due to the higher temperatures of the paper going into dryer. These additional benefits are not quantified and therefore the upper range of the energy savings potential was considered for this study. Furthermore, additional electricity will be required to run the microwave, but overall energy consumption will decrease due to the improved energy efficiency of the system, and the energy savings potential is reported after considering electricity requirements [132].

c) Penetration rate

Microwave drying was tested at the laboratory scale in 2003 and was expected to be commercialized sometimes in the last 10 years [131]. However, microwave drying requires a high initial investment and specialized system design for each mill, both of which have hindered commercialization. In this analysis of energy savings and GHG mitigation potential for the paper mill in Alberta, the technology is expected to be fully implemented by the end of the study period depending on (fast and slow penetration scenarios) with initial testing starting in 2020.

d) Cost analysis data

Microwave generator costs have dropped significantly in the last 4 decades. The capital cost of an industrial-scale microwave has reduced by a factor of 4 (with 1985 as base year), and the maintenance cost has reduced by a factor of 10 due to increased understanding of the technology. The life expectancy has accordingly increased, which has made this option economically attractive for the paper production industry [132]. A number of case studies have been presented in a report by Fredrick [132] with detailed cost data for the capital and O&M costs of implementing microwave drying. The following cost data for developing this scenario in the LEAP model were extracted from Fredrick's report:

a) The paper produced in Alberta Newsprint Company has mass bases of 43, 45, and 48.8 grams per meter square [31]. In the reference report, the cost of microwave equipment required to process 50 grams per meter square quality newsprint is provided and is used to perform cost analysis in this scenario.
b) The microwave equipment can be installed before or after the pressing section. Post-press requires minimal process modification from an engineering and construction perspective, and thus cost data were taken assuming a post-press configuration.

Based on the above assumptions, the capital cost is expected to be $12.43 million dollars along with the fixed maintenance cost of $0.63 million dollars. The operating cost is calculated based on equipment electricity consumption and average electricity price. The equipment life is taken to be 20 years as it is in the referenced study [132].

The summary of the parameters used in the LEAP model for energy modeling and GHG mitigation for the microwave drying scenario is provided in Table 24.

Table 24: Scenario 8 input parameters (microwave drying)

Scenario	Microwave drying technology					
Application	Paper mills					
Technology status	Development stage					[36, 131]
Energy savings potential	20% reduction in steam intensity in drying section of the paper mill					[132]
Penetration rates	2010	2020	2030	2040	2050	
Slow scenario	0	0	33.3%	66.6%	100%	
Fast scenario	0	0	100%			
Cost data	Capital cost: $12.43 million O&M cost: $0.63 million Lifetime: 20 years					[132]

3.3.2.2 Scenario 9: Shoe press drying technology

a) Description

Shoe press drying technology is incorporated in the press section where the pulp is pressed between two surfaces to remove water. A typical pressing system consists of two rotating rollers set up close to each other with a small clearance through which the pulp sheet is passed. A belt known as felt also passes through same clearance beneath the pulp to collect the water extracted from the pulp web. As the point of contact between rollers is very small the residence time of the pulp in the pressing section is short. These factors limit the pressing speed, as increasing speed reduces the residence time further and thus less water is removed. The pressure cannot be increased beyond a certain level without damaging the paper sheet.

To resolve these issues, the shoe press was designed to increase the pulp web residence time in the pressing section, which will allow for a higher press speed as well as increased water removal. The shoe press replaces the bottom roller in a conventional presser with a concave-shaped shoe that is longer than the single contact point between two rollers. A detailed description of this technology from concept to commercial level is provided by Esther and Kornelis [133]. The benefits of using shoe press drying include 5-7% more water removal and increased wet tensile strength. The plant capacity is also expected to increase by 25% if the plant is limited in production due to dryer size [37, 50].

b) Energy savings potential

The shoe press removes extra water from the pulp web through pressure, which reduces the amount of heat required in the drying section. Since the dryer section uses steam drums, the net steam requirement reduces by 12-15% on average when a shoe press is used [37, 38]. The shoe press requires electrical energy for operation; however; it is used instead of a conventional roller, thus the net energy requirement is expected to remain constant. In the LEAP model for Alberta's pulp and paper mills, the scenario is assessed by reducing the steam energy requirement in the drying section by 15% when the shoe press is used in the paper mill.

c) Penetration rate

The technology is fully developed and now being used at a commercial scale and can be implemented in a paper mill's pressing section [38, 133]. Since there is no evidence in publicly available data that this technology is being used at Alberta Newsprint Company, the shoe press drying is expected to be implemented in the paper mill by 2050 in slow penetration scenario and by 2030 in fast penetration scenario. Detailed penetration rates of this technology are provided in Table 24.

d) Cost analysis data

The shoe press drying technology is a retrofitting or a replacement option depending on the status and age of the existing press section in a paper mill. The capital cost has been reported by De Beer et al. [134] to be 38 US dollars per tonne (~$78 CAD per ADMT); however, an updated estimate has reported to it to be 28.9 Euros per ADMT ($50.81 CAD per ADMT) [38]. The operating costs of implementing this technology are neglected as it is assumed to be a replacement in the press section and the resulting in net energy consumption to be constant. Even if the system is considered an addition, the other benefits of this technology as discussed above are not quantified in this study and can be considered to balance the operating costs. The economic life of the technology is 10 years with a 1% per annum reduction in capital costs [38].

The summary of the parameters used in the LEAP model for energy modeling and GHG mitigation of the shoe press drying scenario is provided in Table 25.

Table 25: Scenario 9 input parameters (shoe press drying)

Scenario	Shoe press drying					
Application	Paper mill					
Technology status	Operational					[38, 133]
Energy savings potential	15% reduction in steam intensity in paper mill dryer section					[37, 38]
Penetration rates	2010	2020	2030	2040	2050	
Slow scenario	0	14.3%	42.9%	71.4%	100%	
Fast scenario	0	33.3%	100%			
Cost data	Capital cost: $50.81/ADMT of pulp production capacity Lifetime: 10 years Annual reduction in capital cost: 1%					[38]

3.3.2.3 Scenario 10: Condebelt drying technology

a) Description

The drying section in a paper mill consumes highest amount of steam to dry the paper sheet to the desired moisture level. Drying is carried out by steam-heated rolling drums and the paper is pressed against the surface of the drums to evaporate the water. To reduce the steam consumption and increase the water removal speed, the Condebelt drying system was developed. In a Condebelt drying system, the paper is pressed against a continuous hot steel band that can be heated directly by steam or gas. The other side of the paper is under three layers: a wire gauze layer, a coarse gauze layer, and a cold steel band layer. The heated steel band evaporates the water, which then passes through the wire gauzes and condenses on the cold steel band. The water is removed under pressure, which can reach up to 10 bars. The Condebelt drying system dries 5-15 times faster than conventional steam drums due to the lower thermal resistance of the steel band as well as better contact between surface and paper. The process is carried out in the absence of air, which lowers the thermal and diffusion resistance in the paper [135].

The benefits of using Condebelt drying include faster drying rates, lower energy consumption, smaller space requirement for similar load, and significant increase in product strength [37, 86, 135]. The technology has been commercially installed in few mills; however, it is not commonly applied due to the custom design requirements [39].

b) Energy savings potential

The Condebelt drying system can replace the entire drying section of a paper mill. It can also be installed as a partial replacement but the conventional drying system can limit the speed of the paper machine, undermining the benefits of the Condebelt system. As a standalone system in a paper mill, Condebelt drying is expected to consume the same amount of electricity as conventional drying with a 10-20% reduction in steam consumption [36, 37, 39]. In the LEAP model for Alberta's pulp and paper mills, the scenario is developed on assumed steam reduction by 20% when the Condebelt drying system is installed in the paper mill as a replacement for conventional steam drums drying.

c) Penetration rate

The Condebelt drying system has been implemented successfully in two mills and expected to be fully commercialized soon. However, high initial investment costs and the need for customized equipment has reduced the technology penetration [39]. For the purpose of this study, it is expected that this technology will be fully adopted by the end of 2030 or 2050 in the paper mill through a step-by-step replacement of the conventional drying system. The penetration rates used in the LEAP model are shown in Table 25.

d) Cost analysis data

Condebelt drying replaces conventional steam drying and can also be installed as a standalone drying system. There is limited data available publicly on the cost to implement this technology. The first Condebelt drying system began to operate in Finland in 1996 with a capital investment of 24.6 million CAD dollars [135]. Estimates of $110/t [50] and $260/t [39] (US currency) are reported for a full replacement of the conventional drying system. No additional O&M costs are expected compared to the conventional drying system; hence these are neglected for the comparative analysis performed in this study. The average estimated life of the system is 20 years [39].

The summary of the parameters used in the LEAP model for energy modeling and GHG mitigation of the Condebelt drying scenario is provided in Table 26.

Table 26: Scenario 10 input parameters (Condebelt drying system)

Scenario	Condebelt drying system					
Application	Paper mills					
Technology status	Semi-commercial stage					[39]
Energy savings potential	20% reduction in steam in the drying section of paper mill					[36, 37, 39]
Penetration rates	2010	2020	2030	2040	2050	
Slow scenario	0	0	33.3%	66.7%	100%	
Fast scenario	0	0	100%			
Cost data	Capital cost: $327/ton of paper production capacity Lifetime: 20 years					[39]

3.3.3 Process improvement scenarios in Alberta's pulp and paper mills

The process improvement scenarios include efficiency improvement, process optimization, heat recovery, and enhanced integration of systems. These processes often require lower investment compared to implementing new equipment and result in considerable energy savings. The scenarios discussed in the next section are fibrous fillers, efficient heat recovery systems, idle time optimization, and high-consistency paper making. The fibrous fillers scenario provides an opportunity to reduce the amount of feedstock required to produce same quantity of pulp with a cheaper alternative. The efficient heat recovery system, idle time optimization, and high-consistency paper making improve the net mill energy efficiency by reducing waste energy and varying the operational parameters for an optimal process from an energy point of view. The details of these scenarios are discussed as follows:

3.3.3.1 Scenario 11: Fibrous fillers

a) Description

Fibrous fillers are substitute minerals that can be substituted with wood pulp to produce paper or other products. Conventionally TiO_2 and Silica can be used as fillers; they are expensive and are limited to a 15-20% replacement ratio to maintain product quality. The use of these fillers reduces the wood chip quantity and energy required to produce the same level of pulp. Recently, GR International tested the feasibility of calcium- and silica-based fillers that can replace up to 40% of the pulp while maintaining the critical properties of the final product [136]. The benefits of using calcium- and silica-based fillers include up to 25% energy savings, lighter weight paper, and improved water use efficiency in the mill [36, 41, 137].

GR International's detailed analysis of various forms of silica- and calcium-based fillers by [136] includes the performance of the fillers as well as the economical aspects of using them on a commercial scale. These fillers are expected to be used in paper manufacturing as well as for other product; therefore, the fillers are assumed to be added to the final products made in mechanical mills in Alberta as well as in kraft mills, as discussed in the penetration rate section of this scenario.

b) Energy savings potential

The use of fibrous fillers can replace up to 40% of the pulp in the final product, thereby reducing the energy required to produce 40% of a mill's pulp. Due to process-inherent energy requirements, it is expected that energy reduction can reach 25% when up to 40% fibrous fillers are added in the pulp [36, 137]. In the LEAP model it is assumed for same level of pulp production the energy intensity will reduce by 25% mill wide. The fillers are assumed to be produced externally and their impact is assumed in the form of external cost that is discussed further in the cost analysis data.

c) Penetration rate

The addition of fibrous fillers in the pulp modifies the properties of the net mixture, making the pulp suitable for limited products such as newspaper or similar sheets. Certain products such as specialized papers or cardboard can only accept limited filler material, thus limiting the potential use this technique [136]. To accommodate for the limitations, it is assumed that among the mechanical mills, only the newspaper mill will adopt this technology fully by 2030 or 2050, and in chemical mills only 50% of the production will use the fillers in the final product in same time frame. The penetration rate of fibrous fillers in mechanical and chemical mills is shown in Table 26.

d) Cost analysis data

The cost data to produce fibrous fillers is limited due to the low use of this technology to date. The technology is still in the pilot stage. GR International, which has used this technology, compared the costs of producing one ton of pulp and one ton of filler material to be added in the final product [136]. On average, based on GR International's data, the production of one ton of pulp costs $600 and the nano material costs $450 per ton of filler material (2009 US dollars) [138]. The CSE was calculated with this data for mechanical and chemical mills and is discussed in detail in the results section of scenario 9. The costs for this scenario are shown in Table 27.

The summary of the parameters used in the LEAP model for energy modeling and GHG mitigation of fibrous fillers scenario is provided in Table 27.

Table 27: Scenario 11 input parameters (fibrous fillers)

Scenario	Fibrous fillers					
Application	Mechanical and chemical mills					
Technology status	Pilot stage					[36]
Energy savings potential	Mill-wide energy reduction by 25%					[36, 137]
Penetration rate (paper mill)	2010	2020	2030	2040	2050	
Slow scenario	0	0	33.3%	66.7%	100%	
Fast scenario	0	0	100%			
Penetration rate (kraft mills)	2010	2020	2030	2040	2050	
Slow scenario	0	0	16.7%	33.3%	50%	
Fast scenario	0	0	50%			
Cost data	Pulp production cost: $767.89/ADMT Filler production cost: $575.92/ton of fibrous filler					[138]

3.3.3.2 Scenario 12: Efficient heat recovery system

a) Description

The refiners in mechanical mills have relatively poor process energy efficiency, especially in old plants, considering the waste thermal energy. Refiners use electrical energy to drive mechanical components that convert the wood chips in to pulp. The process involves considerable friction and generates heat. Thus, a portion of the electricity consumed in a refiner can be recovered as high pressure steam as well as low pressure steam from blowback steam and in some cases as heated water [40]. In a typical mill, 20-40% of the electricity consumed in a refiner can be recovered in the form of steam and a further 20-30% can be recovered in the form of hot water [38]. Other areas of efficient heat use and recovery include bleaching plant effluent water heat recovery, drying bark and sludge before using them as fuel, and mill-wide pinch analyses to identify areas of heat recovery [37, 40, 139].

b) Energy savings potential

Efficient heat recovery systems can result in significant energy savings as pulp production is a steam-intensive process. The heat can be used in subsequent processes and energy savings of up to 38% can be achieved in fuel consumption by following the heat recovery measures discussed in the previous section [38]. The savings are more prominent in a standalone mill than integrated paper plants; therefore, the heat recovery potential is only assessed for BCTMP mills in Alberta.

c) Penetration rate

There is great potential for improving the efficiency of heat recovery in old pulp mills; new plants include such efficiency in the plant design. Efficient heat recovery systems are standard practice in industry and currently in Alberta the penetration of such systems is 16%

[54]. In the current study, it is assumed that the penetration of efficient heat recovery systems will reach 100% by 2030 or 2050.

d) Cost analysis data

Efficient heat recovery systems can be implemented in various types of equipment in pulp mills and the cost is expected to be different from case to case. However, costs are expected to stay low overall as these new systems do not require significant amounts of energy, and thus the operational and maintenance costs will be low. On average, efficient heat recovery systems are expected to cost $62.96 per ADMT as a capital investment with lifetime of 10 years [38].

The summary of the parameters used in the LEAP model for energy modeling and GHG mitigation for the efficient heat recovery scenario is provided in Table 28.

Table 28: Scenario 12 input parameters (efficient heat recovery systems)

Scenario	Efficient heat recovery system					
Application	BCTMP mills					
Technology status	Operational					[40]
Energy savings potential	Steam reduction by 38% in the drying section of a BCTMP mill					[38]
Penetration rate	2010	2020	2030	2040	2050	
Slow scenario	0	28%	52%	76%	100%	
Fast scenario	0	44%	100%			
Cost data	Capital cost: $62.96/ADMT of pulp production capacity Lifetime: 10 years					[38]

3.3.3.3 Scenario 13: Idle time optimization

a) Description

The refiner is the most energy intensive equipment in mechanical mills and is responsible for almost 70% of a mill's electricity consumption. The refiners consume significant amounts of energy even under no load conditions, which occur due to constraints of other connected equipment in the mill (i.e., limited feed pump capacity, insufficient storage chests, etc.). The no-load energy consumption can be up to 40% of the refiner's net power consumption, and optimizing the process to ensure lower no-load energy consumption as well as reducing the no-load time can reduce net energy consumption by 12-18% [40]. The modification of refining equipment such as using cylindrical refiners that separate the refining process from the fiber transportation line can also result in similar savings through reduced idle time [38]. The energy savings potential has been evaluated for TMP mills, and while BCTMP mills are expected to have similar consumption patterns, the exact energy savings potential is not reported in the literature and thus in this study this optimization process is considered to be effective only in TMP mills.

b) Energy savings potential

Optimizing refiner equipment idle time can significant reduce electricity consumption. The savings can vary significantly based on the mill design, with large potential in mills with refiner production capacity limited by other equipment. A typical energy savings of 12-18% is achievable with idle time optimization [40], and for the purpose of this study a 16% electricity saving is considered when idle time optimization measures are implemented [38]. The optimization of refining operations will reduce electricity intensity from 2160 kWh/ADMT to 1814.4 kWh/ADMT in the paper mill.

c) Penetration rate

The idle time optimization process in the refiner is a step-by-step improvement that requires synchronizing the equipment connected to the refiner. Process optimization is usually a long-term process that improves with better understanding of equipment interdependencies. Therefore, it is assumed in this study that 16% energy savings will be realised by 2030 or 2050, up from the current level of 0%.

d) Cost analysis data

Idle time optimization for the refining process is the general modification of operating parameters with minor modifications in the control systems. The initial investment cost is expected to be $1.06 per ADMT with no extra operational or maintenance costs. The economic lifetime of this measure is 10 years, which refers to the reinvestment period to continue using the optimized process [38].

The summary of the parameters used in the LEAP model for energy modeling and GHG mitigation for the idle time optimization scenario is provided in Table 29.

Table 29: Scenario 13 input parameters (idle time optimization)

Scenario	Idle time optimization					
Application	Paper mills					
Technology status	Commercial stage					[40]
Energy savings potential	16% reduction in refiner electricity consumption					[38, 40]
Penetration rate	2010	2020	2030	2040	2050	
Slow scenario	0	14.3%	42.9%	71.4%	100%	
Fast scenario	0	33.3%	100%			
Cost data	Capital cost: $1.06/ADMT of pulp production capacity Lifetime: 10 years					[38]

3.3.3.4 Scenario 14: High-consistency paper making

a) Description

During the paper making process, the pulp stock is in the form of a 0.1-0.5% consistent slurry of water, fibers, and chemicals. The slurry is passed through a headbox that creates turbulent flow conditions to produce a homogeneous mixture and thus uniformly distribute fibers. When the consistency is low, considerable energy is consumed at later stages to remove the high amounts of water and chemicals. Increasing the consistency of the slurry can significantly reduce the drying energy consumption and produce same quantity of paper. This measure can be implemented in existing mills with minor modifications [140].

Producing high-consistency paper with has been attempted as early as 1980 but resulted in unacceptable sheet quality due to low slurry homogeneity. High-consistency slurry is challenging, especially achieving sufficient turbulence in the headbox, controlling fluidization, and screening high quantity stock. Innovative head design, shorter circulation systems, and screening mechanisms are required for high consistency pulping and to save energy in paper mills [40]. New headbox designs with high (4-20%) [141] and (5-12%) [142] consistencies can reduce stock storage, pump, and forming section sizes and increase process speed [36].

b) Energy savings potential

The papermaking process using high-consistency suspension can result in significant energy savings in stock preparation, forming, vacuum systems, and slurry transport. The net energy intensity of the paper mill is expected to reduce by 30% when the high-consistency suspension method is utilized [40]. The technology saves energy in paper mill-related operations only, and 30% saving is evenly distributed among all processes considered for the paper mill.

c) Penetration rate

High-consistency paper making technology is at the pilot stage and work is being carried out to optimize the screening and turbulent mixing process to achieve good quality paper. For this scenario, it is assumed that the high-consistency paper production method will be commercially available by 2020 and fully adopted by 2030 or 2050 in the paper mill existing in Alberta. The detailed penetration rates of scenario 14 are shown in Table 30.

d) Cost analysis data

The high-consistency paper making technique can be implemented in existing mills as a retrofit and will produce the desired quality of the paper once the process operating parameters are optimized for the new system [40]. The system is expected to have a capital cost of \$137.3 per ton with operating and maintenance costs of \$1.41 per ton of paper produced [36]. The economic life of the equipment is assumed to be 15 years for the purpose of this analysis.

Table 30: Scenario 14 input parameters (high-consistency paper making)

Scenario	High-consistency paper making					
Application	Paper mill					
Technology status	Pilot stage					[36]
Energy savings potential	Paper mill net energy reduction by 30%					[40]
Penetration rate	2010	2020	2030	2040	2050	
Slow scenario	0	0	33.3%	66.7%	100%	
Fast scenario	0	0	100%			
Cost data	Capital cost: \$137.3 per ton of production capacity O&M costs: \$1.41 per ton of production Lifetime: 15 years					[36]

These twenty-eight scenarios were developed in the LEAP model based on the input parameters discussed above. Table 31 provides these scenarios' descriptions, energy savings potential, and GHG emissions reduction.

Table 31: Summary of GHG mitigation scenarios for Alberta's pulp and paper mills

Scenario number	**Scenario name**	**Scenario details**	**Input data for energy intensity and penetration**
Scenario 1	Microwave pretreatment	Microwave pretreatment technology modifies the cellular microstructure to allow enhanced permeability of chemicals in wood chips, which reduces the amount of energy and chemicals required to reach the center of the wood chips.	Reduces the natural gas consumption in a kraft mill lime kiln by 40%. 75% penetration by 2030 or 2050.
Scenario 2	Xylanase enzymatic pretreatment	Xylanase pretreatment modifies the cellular structure of the wood chips, which softens them and makes it easier to convert them into fibers. The refiner energy is significantly reduced in the process.	Xylanase pretreatment reduces refiner electricity consumption by 25%. Penetration level of 25% expected by 2030 or 2050.
Scenario 3	Cellulase enzymatic pretreatment	Cellulase pretreatment modifies the cellular structure of the wood chips, which softens them and makes it easier to convert them into fibers. The refiner energy is significantly reduced in the process.	Cellulase pretreatment reduces refiner electricity consumption by 20%. Penetration of 25% expected by 2050
Scenario 4	Pectinase enzymatic pretreatment	Pectinase pretreatment modifies the cellular structure of the woodchips, which softens them and makes it easier to convert them into fibers. The refiner energy is significantly reduced in the process.	Pectinase pretreatment reduces refiner electricity consumption by 10%. Penetration of 25% expected by 2030 or 2050

Scenario 5	Fungal pretreatment	A biological pretreatment process in which the microscopic action of fungi weakens the internal bonding of the wood fibers, thereby reducing the energy required to mechanically separate the fibers.	Fungal pretreatment reduces refiner electricity consumption by 33%. Penetration of 100% expected by 2030 or 2050 in mechanical mills.
Scenario 6	Chemical pretreatment	The chemical modification of woodchips influences the binding forces between fibers and strengthens the paper. This partial replacement of mechanical refining with chemicals uses less refiner energy and the pulp retains less water, which further reduces the energy required.	Chemical pretreatment reduces refiner electricity consumption by 40% and pressing electricity consumption by 15%. Penetration of 100% expected by 2030 or 2050 in mechanical mills.
Scenario 7	Oxalic acid pretreatment	Oxalate was observed to be the main agent softening the wood chips in the trials of fungal pretreatment. Direct use of oxalic acid can significantly reduce refiner energy consumption	Oxalic acid pretreatment reduces refiner electricity consumption by 30%. Penetration rate of 100% expected by 2050 in mechanical mills.
Scenario 8	Microwave drying technology	Microwave drying can remove water from the pulp web during paper production and level out the moisture profile across the wet sample. The microwave can reduce drying energy use in conventional steam-heated drum drying systems.	Steam intensity reduction by 20% in drying section of the paper mill. Penetration of 100% expected by 2030 or 2050.
Scenario 9	Shoe press drying technology	Shoe pressing was designed to increase the residence time of the pulp web in the pressing section. The shoe press replaces the bottom roller in a conventional presser with a concave-shaped shoe that is longer than the single contact point between two rollers and more easily remove water.	Steam intensity reduction by 15% in paper mill dryer section. 100% penetration expected by 2030 or 2050.

Scenario 10	Condebelt drying technology	In the Condebelt drying system, the paper is pressed against a continuous hot steel layer and the other side of the paper is under 3 layers: a wire gauze, a coarse gauze and a cold steel band. The heated steel band evaporated the water, which passes through the wire gauzes and condenses on the cold steel band. Condebelts use energy efficiently compared to conventional steam drum drying systems.	Steam reduction by 20% in drying section of paper mill. Penetration of 100% expected by 2030 or 2050.
Scenario 11	Fibrous fillers	Fibrous fillers are substitute minerals that can be added to the pulp before processing it further to produce paper or other products. Calcium- and silica-based fillers can replace up to 40% of the pulp while maintaining the critical properties of the final product, thereby reducing mill-wide energy use by 25%.	Mill-wide energy reduction by 25%. 100% penetration expected in mechanical mills and 50% in kraft mills.
Scenario 12	Efficient heat recovery system	The refiners in mechanical mills use electrical energy to drive the mechanical components that convert the wood chips into pulp. The process involves considerable friction and generates heat that can be recovered in the form of high and low pressure steam to be reused.	Steam reduction by 38% in drying section of BCTMP mill. 100% penetration expected by 2030 or 2050 in mechanical mills.
Scenario 13	Idle time optimization	The refiners consume significant amounts of energy (even under no-load conditions), up to 40% of refiner net power consumption. Optimizing the process to ensure lower energy consumption at no-load as well as reducing the no-load time can result in significant energy savings.	Optimizing the process can result in reduction of refiner electricity consumption by 16%

Scenario 14	High-consistency paper making	Pulp stock is used in a water, fiber, and chemical slurry that has a 0.5-1.0% consistency. This low consistency requires the removal of high quantities of water and chemicals, which later consumes energy in to dry the paper. Increasing the consistency of the slurry can significantly reduce energy consumption due to reduced drying requirements.	Paper mill net energy reduction by 30% when high consistency pulp slurry is used. Penetration of 100% expected by 2030 or 2050 in the paper mill.

4 Results and discussion

Alberta’s pulp and paper sector consists of seven mills whose major energy sources are electricity and natural gas. Chapter 2 discusses the main processes involved in producing pulp from mechanical and chemical mills with detailed information on the energy required in each process. Chapter 3 discusses twenty-eight scenarios that can be implemented in Alberta’s pulp and paper mills with information on energy savings potential, technology penetration rates, and technology implementation costs. These scenarios were developed in the LEAP model to assess energy savings and GHG mitigation potential as well as to analyze the cost to implement them.

In this chapter, the results from energy modeling and implementation of mitigation scenarios are discussed in detail. This chapter has two major sections. In the first section, the energy savings and GHG mitigation potential for each scenario, as developed in the LEAP model, are discussed along with assessment of the cost of saved energy for each scenario. The results are discussed for scenarios initially and then followed by category-based results. The three categories, as defined in chapter 3 based on their application in pulp and paper mills, help provide a comparative analysis of the scenarios in terms of energy savings and GHG mitigation potential. The section closes with a summary result of all scenarios developed in this study for Alberta’s pulp and paper mills. The second section of chapter 4 provides a cost comparison of all scenarios in the form of a cost curve that helps understand the mitigation potential of scenarios with respect to the associated costs. This section also discusses the method to develop cost curve, cost curves for all scenarios, and a cost curve for the integrated scenarios for Alberta’s pulp and paper mills.

4.1 LEAP model results: Energy and emissions reduction with cost assessment

4.1.1 Scenario-based results

4.1.1.1 Scenario 1 results: Microwave pretreatment

a) Energy savings and GHG mitigation potential

Microwave pretreatment used in kraft mills reduces energy. The implementation of this pretreatment is expected to result in net natural gas savings of 14.9 PJ which will reduce the GHG emissions by 843.86 kT CO_2 eq. in the slow penetration scenario. In the fast penetration scenario, 6.53 PJ of energy savings is achievable resulting in 369.8 kT CO_2 eq. of GHG mitigation. Table 32 provides the detailed energy reduction and GHG mitigation potential under slow and fast penetration scenarios when microwave pretreatment is implemented in Alberta's pulp and paper industry.

b) Cost assessment

The techno-economic model is used to assess the cost of saved energy and shows positive costs for all years, as shown in Table 32. When these CSEs are input in the LEAP model, the NPV for the slow penetration scenario is 48.2 million dollars whereas NPV is 41 million dollars for fast penetration scenario. Positive NPV indicates that even after considering the energy-related cost savings, implementing microwave pretreatment in Alberta mills will incur extra costs. The techno-economic model results for CSEs of this scenario are shown in Appendix B, Table 50.

c) GHG abatement cost

This scenario's GHG abatement potential is 843.85 kT CO_2 eq. in slow penetration scenario with a 48.2 million incremental cost, or a cost per unit GHG mitigation of \$57.2/tonne CO_2

eq. Accordingly, the fast penetration scenario results in GHG abatement cost of \$110.8/tonne CO_2 eq. when microwave pretreatment technology is installed in Alberta's pulp and paper mills. Table 32 shows the microwave pretreatment potential in Alberta's pulp and paper industry.

Table 32: Scenario 1 results (microwave pretreatment)

	2010-2020	**2021-2030**	**2031-2040**	**2041-2050**	**Total**
Slow penetration scenario					
Energy reduction (PJ)	0.35	2.45	4.84	7.27	14.90
GHG mitigation (kT CO_2 eq.)	19.67	138.83	273.79	411.55	843.85
Cost of saved energy (\$/GJ)	11.14	9.14	8.40	7.67	--
Incremental NPV of scenario implementation	48.2 million dollars				
Cost per unit GHG mitigation	57.2 \$/tonne of CO_2 eq.				
Fast penetration scenario					
Energy reduction (PJ)	0.81	5.72	--	--	6.53
GHG mitigation (kT CO_2 eq.)	45.9	323.9	--	--	369.8
Cost of saved energy (\$/GJ)	11.14	9.14	--	--	--
Incremental NPV of scenario implementation	41 million dollars				
Cost per unit GHG mitigation	110.8 \$/tonne of CO_2 eq.				

*As developed by the LEAP model

4.1.1.2 Scenario 2, 3, 4 results: Enzymatic pretreatment

a) Energy savings and GHG mitigation potential

In the enzymatic pretreatment scenarios, we evaluate the use of 3 different enzymes in mechanical mills and analyze their energy savings potential in Alberta's pulp and paper sector. The xylanase pretreatment shows the most promising results, with 3.78 PJ of net energy savings potential, and cellulase and pectinase show energy savings potential of 3.03 PJ and 1.51 PJ, respectively, in the slow penetration scenario based on the parameters shown in Table 20. Accordingly, the xylanase pretreatment results in 510.91 kT CO_2 eq. net emissions reduction followed by cellulase and pectinase with 408.73 and 204.36 kT CO_2 eq., respectively. The energy reduction and GHG mitigation potential under slow and fast penetration scenarios of implementing enzymatic pretreatment are presented in Tables 33, 34, and 35 for xylanase, cellulase and pectinase, respectively.

Table 33: Scenario 2 results (xylanase enzymatic pretreatment)

	2010-2020	2021-2030	2031-2040	2041-2050	Total
Slow penetration scenario					
Energy reduction (PJ)	0.00	0.44	1.26	2.08	3.78
GHG mitigation (kT CO_2 eq.)	0	61.97	169.17	279.77	510.91
CSE BCTMP mill ($/kWh)	0.29	0.20	0.13	0.08	--
CSE TMP mill ($/kWh)	0.06	-0.01	-0.04	-0.07	--
Incremental NPV of scenario implementation	10 million dollars				
Cost per unit GHG mitigation	19.5 $/tonne of CO_2 eq.				

	2010-2020	2021-2030	2031-2040	2041-2050	Total
Fast penetration scenario					
Energy reduction (PJ)	0	1.33	--	--	1.33
GHG mitigation (kT CO_2 eq.)	0	185.9	--	--	185.9
CSE BCTMP mill ($/kWh)	0.29	0.20	--	--	--
CSE TMP mill ($/kWh)	0.06	-0.01	--	--	--
Incremental NPV of scenario implementation	25 million dollars				
Cost per unit GHG mitigation	134.6 $/tonne of CO_2 eq.				

*As developed by the LEAP model

b) Cost assessment

The pretreatment of wood chips with enzymes was evaluated for economical suitability and the cost of saved energy was calculated through development of techno-economic models. All enzymes show positive CSEs except for some time periods in the TMP mill. The CSEs for implementing enzymatic pretreatment in TMP and BCTMP mills are presented in Tables 33, 34, and 35.

The incremental net present value of implementing xylanase pretreatment is calculated by the LEAP model to be 10 million dollars with a 5% discount rate in slow penetration scenario, which is lowest of the three enzymes considered for this study (51.5 million dollars for cellulase and 280.7 million dollars for pectinase). A similar trend is followed in the fast penetration scenario as shown in Tables 33, 34 and 35. The results from the techno-economic model used to calculate the CSEs are shown in Appendix B, Tables 51 to 56.

Table 34: Scenario 3 results (cellulase enzymatic pretreatment)

	2010-2020	2021-2030	2031-2040	2041-2050	Total
Slow penetration scenario					
Energy reduction (PJ)	0.00	0.36	1.01	1.66	3.03
GHG mitigation (kT CO_2 eq.)	0	49.58	135.34	223.81	408.73
CSE BCTMP mill ($/kWh)	0.40	0.29	0.21	0.14	--
CSE TMP mill ($/kWh)	0.10	0.03	-0.01	-0.04	--
Incremental NPV of scenario implementation	51.5 million dollars				
Cost per unit GHG mitigation	126.1 $/tonne of CO_2 eq.				
Fast penetration scenario					
Energy reduction (PJ)	0	1.07	--	--	1.07
GHG mitigation (kT CO_2 eq.)	0	148.7	--	--	148.7
CSE BCTMP mill ($/kWh)	0.40	0.29	--	--	--
CSE TMP mill ($/kWh)	0.10	0.03	--	--	--
Incremental NPV of scenario implementation	57.2 million dollars				
Cost per unit GHG mitigation	384.8 $/tonne of CO_2 eq.				

*As developed by the LEAP model

c) GHG abatement costs

The GHG abatement cost is the cost to reduce GHG emissions through enzymatic pretreatment. In slow penetration scenario, the abatement cost for reducing one tonne of CO_2 eq. is $19.5 when using xylanase pretreatment whereas when cellulase and pectinase are used, the costs are \$126.1 and \$1373.8, respectively. In fast penetration scenario, the costs increase to \$134.6, \$384.8 and \$3051 per tonne GHG mitigation for xylanase, pectinase and cellulose respectively due to accelerated installation of these technologies.

Energy savings, GHG mitigation, and cost assessment results are shown in Tables 33, 34 and 35 for xylanase, cellulase, and pectinase enzymes, respectively.

Table 35: Scenario 4 results (pectinase enzymatic pretreatment)

	2010-2020	2021-2030	2031-2040	2041-2050	Total
Slow penetration scenario					
Energy reduction (PJ)	0.00	0.18	0.50	0.83	1.51
GHG mitigation (kT CO_2 eq.)	0	24.79	67.67	111.91	204.36
CSE BCTMP mill ($/kWh)	0.90	0.73	0.59	0.47	--
CSE TMP mill ($/kWh)	0.31	0.21	0.15	0.09	--
Incremental NPV of scenario implementation	280.7 million dollars				
Cost per unit GHG mitigation	1373.8 \$/tonne of CO_2 eq.				
Fast penetration scenario					
Energy reduction (PJ)	0	0.53	--	--	0.53
GHG mitigation (kT CO_2 eq.)	0	74.36	--	--	74.36
CSE BCTMP mill ($/kWh)	0.90	0.73	--	--	--
CSE TMP mill ($/kWh)	0.31	0.21	--	--	--
Incremental NPV of scenario implementation	226.9 million dollars				
Cost per unit GHG mitigation	3051 \$/tonne of CO_2 eq.				

*As developed by the LEAP model

4.1.1.3 Scenario 5 results: Fungal pretreatment

a) Energy savings and GHG mitigation potential

Fungal pretreatment is expected to reduce mechanical mill refiner's energy consumption by 33% and, based on the expected penetration rate in Alberta's pulp and paper mills, will result in 10.48 PJ and 3.71 PJ of net energy reduction in slow and fast penetration scenarios while collectively reducing 1415.60 and 517.6 kT of CO_2 eq., respectively. Expected reductions in energy consumption and GHG emissions are presented in Table 36 for different phases of the study period.

b) Cost assessment

The cost of saved energy for fungal pretreatment is estimated to be -$0.04/kWh in 2010-2020 and drops to -$0.11/kWh in 2041-2050. The negative costs indicate that this pretreatment measure is cost effective. In slow penetration scenario, the LEAP model estimates net savings of 165.3 million dollars (in present value), which shows that the energy savings costs are significantly higher than the costs associated with implementing this pretreatment measure. The NPV reduces to -97.6 million dollars under fast penetration scenario for fungal pretreatment in the TMP mill. The CSEs for different phases of study period are shown in Table 36, with detailed calculations presented in Appendix B, Table 57.

c) GHG abatement cost

The fungal pretreatment scenario can significantly lower emissions through reduced mill energy consumption. The average cost to reduce one tonne of CO_2 eq. emissions is -$116.8 and -$188.5 during slow and fast penetration scenarios, respectively, which shows that fast penetration of fungal pretreatment is more economical GHG mitigation option.

Table 36 shows energy reduction, GHG mitigation, and cost assessment results for the fungal pretreatment scenario.

Table 36: Scenario 5 results (fungal pretreatment)

	2010-2020	2021-2030	2031-2040	2041-2050	Total
Slow penetration scenario					
Energy reduction (PJ)	0.00	1.24	3.49	5.75	10.48
GHG mitigation (kT CO_2eq.)	0	172.53	469.45	773.62	1415.60
Cost of saved energy ($/kWh)	-0.04	-0.09	-0.10	-0.11	--
Incremental NPV of scenario implementation	-165.3 million dollars				
Cost per unit GHG mitigation	-116.8 $/tonne of CO_2 eq.				
Fast penetration scenario					
Energy reduction (PJ)	0.0	3.71	--	--	3.71
GHG mitigation (kT CO_2eq.)	0	517.6	--	--	517.6
Cost of saved energy ($/kWh)	-0.04	-0.09	--	--	--
Incremental NPV of scenario implementation	-97.6 million dollars				
Cost per unit GHG mitigation	-188.5 $/tonne of CO_2 eq.				

*As developed by the LEAP model

4.1.1.4 Scenario 6 results: Chemical pretreatment

a) Energy savings and GHG mitigation potential

The chemical pretreatment technology has applications in the paper mill in Alberta and can reduce refiner and pressing section energy consumption. Based on the parameters discussed in chapter 3, it is calculated that 15.10 PJ of energy can be reduced collectively by 2050 compared to BAU scenario in the slow penetration scenario. Alternatively, 6.64 PJ of energy savings can be realized if chemical pretreatment technology is adopted by 2030 under fast penetration scenario. The net GHG emissions will be reduced by 2058.9 and 955.7 kT CO_2 eq. with this pretreatment measure in slow and fast penetration scenarios, respectively.

b) Cost assessment

Based on capital cost, O&M costs, and saved energy reduction costs, the CSE was calculated to be -\$0.10/kWh in the 2010-2020 timeline and is expected to drop to -\$0.17/kWh by 2041-2050. Based on the CSE, the model estimated the incremental NPV for this scenario to be -\$318.4 million in slow penetration scenario and -\$228.8 million in the fast penetration case, which shows overall cost savings. The results from the techno-economic model used for CSE calculations in the chemical pretreatment scenario are shown in Appendix B, Table 58.

c) GHG abatement cost

The GHG emissions abatement costs are obtained using the net GHG mitigation potential and the incremental NPV. With chemical pretreatment, one tonne of CO_2 eq. emissions can be reduced with a negative cost of \$154.6 in slow penetration scenario. The abatement cost reduces further in fast penetration scenario for chemical pretreatment case to -\$239.4/tonne of CO_2 eq. showing the benefits of early adoption of this technology. The scenario is economically viable for Alberta's pulp and paper industry in both short and long-term and can significantly reduce emissions.

Table 37 shows energy reduction, GHG mitigation, and cost assessment results for the chemical pretreatment scenario in Alberta's pulp and paper industry.

Table 37: Scenario 6 results (chemical pretreatment)

	2010-2020	2021-2030	2031-2040	2041-2050	Total
Slow penetration scenario					
Energy reduction (PJ)	0.36	2.54	4.92	7.28	15.10
GHG mitigation (kT CO_2 eq.)	59.20	358.8	662.3	978.6	2058.9
Cost of saved energy ($/kWh)	-0.10	-0.15	-0.16	-0.17	--
Incremental NPV of scenario implementation	-318.4 million dollars				
Cost per unit GHG mitigation	-154.6 $/tonne of CO_2 eq.				
Fast penetration scenario					
Energy reduction (PJ)	0.83	5.81	--	--	6.64
GHG mitigation (kT CO_2eq.)	135.4	820.4	--	--	955.7
Cost of saved energy ($/kWh)	-0.10	-0.15	--	--	--
Incremental NPV of scenario implementation	-228.8 million dollars				
Cost per unit GHG mitigation	-239.4 $/tonne of CO_2 eq.				

*As developed by the LEAP model

4.1.1.5 Scenario 7 results: Oxalic acid pretreatment

a) Energy savings sand GHG mitigation potential

The oxalic acid pretreatment technology scenario was developed in the LEAP model for Alberta's pulp and paper industry with the parameters discussed in chapter 3 section 3. Compared to BAU scenario, the model estimated a 9.53 PJ of reduction in electric energy by the end of 2050 in slow penetration and 3.37 PJ reduction by end of 2030 in fast penetration scenario. These energy reductions will result in a net GHG mitigation of 1286.91 and 470.5 kT CO_2 eq. under slow and fast penetration scenarios, respectively. The results are shown in detail in Table 38.

b) Cost assessment

The CSE for this scenario are negative during the study period and ranges from -\$0.08/kWh to -\$0.15/kWh as shown in Table 38. The negative CSE costs result in an incremental NPV of -228.7 million dollars in slow penetration scenario and -137.8 million dollars in the fast penetration scenario, which shows that oxalic acid pretreatment is a cost-effective measure. The results from the techno-economic model used for CSE calculations of oxalic acid pretreatment scenario are shown in Appendix B, Table 59.

c) GHG abatement cost

Oxalic acid pretreatment reduces mill energy consumption which in turn reduces GHG emissions in relation to the BAU scenario. The GHG abatement cost is calculated to be -\$177/tonne CO_2 eq. in the slow penetration case and -\$292.9/tonne of CO_2 eq. in the fast penetration case which shows that this pretreatment can reduce the emissions without cost constraints over both short and long-terms.

Energy savings, GHG mitigation, and cost assessment results are given in Table 38.

Table 38: Scenario 7 results (oxalic acid pretreatment)

	2010-2020	2021-2030	2031-2040	2041-2050	Total
Slow penetration scenario					
Energy reduction (PJ)	0.00	1.12	3.17	5.23	9.53
GHG mitigation (kT CO_2 eq.)	0	156.84	426.77	703.29	1286.91
Cost of saved energy ($/kWh)	-0.08	-0.13	-0.14	-0.15	--
Incremental NPV of scenario implementation	-228.7 million dollars				
Cost per unit GHG mitigation	-177.7 $/tonne of CO_2 eq.				
Fast penetration scenario					
Energy reduction (PJ)	0.0	3.37	--	--	3.37
GHG mitigation (kT CO_2eq.)	0.0	470.5	--	--	470.5
Cost of saved energy ($/kWh)	-0.08	-0.13	--	--	--
Incremental NPV of scenario implementation	-137.8 million dollars				
Cost per unit GHG mitigation	-292.9 $/tonne of CO_2 eq.				

*As developed by the LEAP model

4.1.1.6 Scenario 8 results: Microwave drying technology

a) Energy savings and GHG mitigation potential

Microwave drying technology would replace the conventional steam drying section in paper mills and significantly reduce energy, as discussed in chapter 3. The implementation of microwave drying in Alberta's pulp and paper industrial sector will result in energy savings of 2.05 PJ collectively if implemented under slow penetration scenario. The main energy source is natural gas; its reduced use will mitigate GHGs by 116.09 kT CO_2 eq. In fast penetration scenario, 0.98 PJ of energy savings are achievable between 2010 and 2030 with GHG mitigation of 55.7 kT CO_2 eq. The energy reduction and GHG mitigation pattern is presented in Table 39 for different phases of the study period.

b) Cost assessment

Microwave drying will require significant capital cost investment with regular operational and maintenance costs during its lifetime. Based on the energy reduction potential and relative energy costs savings, the CSE is calculated to be \$0.20/GJ in the 2010-2020 timeframe. The CSE will continue to drop over time due to changing energy costs in the future, as shown in Table 39. With the CSE data in the model, the incremental NPV of microwave drying technology is calculated to be -8.8 million dollars in slow penetration scenario and -4.4 million dollars in fast penetration scenario, which shows that this measure is cost effective in all cases. The results from the techno-economic model used for CSE calculations of microwave drying technology scenario are shown in Appendix B, Table 60.

c) **GHG abatement cost**

The microwave drying technology is a cost-effective measure to reduce energy consumption in the paper mill and results in a GHG abatement cost of -76.1 \$/tonne of CO_2 eq. in slow penetration scenario and -79.8 \$/tonne of CO_2 eq. in the fast penetration scenario, which indicates that this technology is a cost-effective way of reducing GHGs in Alberta's pulp and paper industry sector.

Table 39 gives the results for the microwave drying scenario in Alberta's pulp and paper industry.

Table 39: Scenario 8 results (microwave drying technology)

	2010-2020	2021-2030	2031-2040	2041-2050	Total
Slow penetration scenario					
Energy reduction (PJ)	0.00	0.33	0.76	0.96	2.05
GHG mitigation (kT CO_2 eq.)	0	18.55	43.09	54.45	116.09
Cost of saved energy (\$/GJ)	0.20	-1.64	-2.23	-2.82	--
Incremental NPV of scenario implementation			-8.8 million dollar		
Cost per unit GHG mitigation			-76.1 \$/tonne of CO_2 eq.		
Fast penetration scenario					
Energy reduction (PJ)	0.00	0.98	--	--	0.98
GHG mitigation (kT CO_2 eq.)	0	55.7	--	--	55.7
Cost of saved energy (\$/GJ)	0.20	-1.64	--	--	--
Incremental NPV of scenario implementation			-4.4 million dollar		
Cost per unit GHG mitigation			-79.8 \$/tonne of CO_2 eq.		

*As developed by the LEAP model

4.1.1.7 Scenario 9 results: Shoe press drying

a) Energy savings and GHG mitigation potential

The shoe press drying technology increases the contact time of the pulp film with the pressing surface, thereby increasing the amount of water removed in the press section and reducing the natural gas requirement in dryer section. Implementing shoe press drying in a paper mill is expected to result in a net energy savings of 1.41 PJ in the slow penetration scenario and 1 PJ in fast penetration scenario. The emissions reduction potential is calculated to be 79.8 and 56.6 kT CO_2 eq. compared to BAU scenario, respectively. The energy and GHG emissions reduction pattern under slow and fast penetration scenarios are presented in Table 40.

b) Cost assessment

Shoe press drying can be retrofitted in existing mills, which requires a capital investment. Based on the associated costs of implementing shoe press drying in a paper mill and costs saved due to reduced energy, the CSEs have been calculated to be \$4.92 (2010-2020), \$2.38 (2021-2030), \$0.98 (2031-2040), and -\$0.34 (2041-2050) per GJ. With these data in the LEAP model, the cost of implementing this technology is calculated to be 3.2 million dollars in slow penetration scenario and 7.2 million dollars in fast penetration scenario. The positive cost to implement this scenario indicates that it will not result in net cost savings during the study period. The results from the techno-economic assessment of the shoe press drying technology scenario are shown in Appendix B, Table 61.

c) GHG abatement cost

With the incremental NPV of the implementing shoe press drying technology and net GHG mitigation potential, the GHG abatement cost is calculated to be 40.3 \$/tonne CO_2 eq. in slow penetration scenario and 128 \$/tonne CO_2 eq. in the fast penetration scenario. The positive GHG abatement costs indicate that to mitigate GHGs with this technology, an investment will be required with no significant cost savings.

Table 40 shows the results for shoe press drying technology implementation in Alberta's pulp and paper industry during various phases of the study period.

Table 40: Scenario 9 results (shoe press drying)

	2010-2020	2021-2030	2031-2040	2041-2050	Total
Slow penetration scenario					
Energy reduction (PJ)	0.06	0.36	0.52	0.47	1.41
GHG mitigation (kT CO_2 eq.)	3.59	20.66	29.2	26.4	79.8
Cost of saved energy (\$/GJ)	4.92	2.38	0.98	-0.34	--
Incremental NPV of scenario implementation	3.2 million dollars				
Cost per unit GHG mitigation	40.3 \$/tonne of CO_2 eq.				
Fast penetration scenario					
Energy reduction (PJ)	0.15	0.85	--	--	1
GHG mitigation (kT CO_2 eq.)	8.4	48.2	--	--	56.6
Cost of saved energy	0.20	-1.64	--	--	--

($/GJ)	
Incremental NPV of scenario implementation	7.2 million dollars
Cost per unit GHG mitigation	128 $/tonne of CO_2 eq.

*As developed by the LEAP model

4.1.1.8 Scenario 10 results: Condebelt drying technology

a) Energy savings and GHG mitigation potential

Condebelt drying technology uses the temperature and pressure differential to drive water out of the pulp slurry in the paper mill drying section. This technology can replace conventional steam drum drying technology to achieve similar results with lower energy consumption. Implementing Condebelt drying in Alberta's pulp and paper industry sector can reduce energy by 2.05 PJ in relation to the BAU scenario in the slow penetration scenario. This energy savings will result in net GHGs mitigation by 119.06 kT CO_2 eq. between 2010 and 2050. The energy reduction and GHG reduction pattern for both slow and fast penetration scenarios are shown in Table 41 for the Condebelt drying technology.

b) Cost assessment

The CSEs is calculated to be 25.88 $/GJ in 2010-2020 and 22.72 $/GJ by 2050, as shown in Table 41. With the CSE, the model estimated the incremental NPV of Condebelt drying scenario implementation to be 80.9 million dollars in the slow penetration scenario and 53.1 million dollars in the fast penetration scenarios, which indicates that this scenario will not result in net cost savings. The results from the techno-economic model used for CSE calculations for the Condebelt drying technology scenario are shown in Appendix B, Table 62.

c) GHG abatement cost

With the incremental NPV of Condebelt drying and net GHG mitigation potential, the GHG abatement cost is calculated to be 696.6 \$/tonne CO_2 eq. in slow penetration scenario and 954.5 \$/tonne CO_2 eq. in fast penetration scenario. To reduce emissions with Condebelt drying system, an investment will be required in both slow and fast penetration scenarios.

Table 41 provides the results for the Condebelt drying system as calculated by the LEAP model and the techno-economic model for the years 2010-2050.

Table 41: Scenario 10 results (Condebelt drying technology)

	2010-2020	2021-2030	2031-2040	2041-2050	Total
Slow penetration scenario					
Energy reduction (PJ)	0.00	0.33	0.76	0.96	2.05
GHG mitigation (kT CO_2 eq.)	0	18.55	43.09	54.45	116.09
Cost of saved energy (\$/GJ)	25.88	23.99	23.35	22.72	--
Incremental NPV of scenario implementation			80.9 million dollars		
Cost per unit GHG mitigation			696.6 \$/tonne of CO_2 eq.		
Fast penetration scenario					
Energy reduction (PJ)	0	0.98	--	--	0.98
GHG mitigation (kT CO_2 eq.)	0	55.6	--	--	55.6
Cost of saved energy (\$/GJ)	25.88	23.99	--	--	--
Incremental NPV of scenario implementation			53.1 million dollars		

Cost per unit GHG mitigation	954.5 \$/tonne of CO_2 eq.

*As developed by the LEAP model

4.1.1.9 Scenario 11 results: Fibrous fillers

a) Energy savings and GHG mitigation potential

Fibrous fillers are artificial materials that can be added in pulp without affecting the quality of final product. The addition of fibrous fillers can reduce energy by 31.44 PJ during 2010-2050 in the slow penetration scenario. The energy reduction is in both electricity and natural gas, and can collectively reduce 3242.64 kT CO_2 eq. compared to BAU scenario. In fast penetration scenario, 11.7 PJ of energy demand reduction is expected with GHG mitigation of 1207.4 kT CO_2 eq. The details of energy reduction and GHG mitigation pattern are shown in Table 42 for different phases of study period.

b) Cost assessment

The CSE is calculated separately for kraft mills and the paper mill due to differences in energy savings when using fibrous fillers. The CSE calculated with techno-economic model results in negative values for timeframes of the study period. For kraft mills the value ranges from -\$0.0787/kWh (2010-2020) to -\$0.3105/kWh (2041-2050), whereas for TMP mills the value ranges from -\$0.0790/kWh (2010-2020) to -\$0.3115/kWh (2041-2050). The CSEs were used in the LEAP model to assess the incremental net present value of the current scenario, which is calculated to be -1300.5 million dollars in slow penetration scenario. In fast penetration scenario, -515.5 million dollars of NPV is calculated to adopt fibrous fillers technology. The negative NPV of this scenario makes it suitable for implementation in

Alberta's pulp and paper mills with net cost savings. The techno-economic model results for CSEs of fibrous fillers scenario are shown in Appendix B, Tables 63 and 64.

c) GHG abatement cost

The GHG abatement cost is calculated to be -401.1 \$/tonne of CO_2 eq., in slow penetration scenario and -426.9 \$/tonne of CO_2 eq. in fast penetration scenario based on respective incremental NPV and net GHG mitigation achievable. Negative abatement costs allow for a reduction in GHG emissions without the need for extra investment.

Table 42 shows the results for using fibrous fillers in Alberta's pulp and paper industry during various phases of the study period.

Table 42: Scenario 11 results (fibrous fillers)

	2010-2020	2021-2030	2031-2040	2041-2050	Total
Slow penetration scenario					
Energy reduction (PJ)	0.0	3.90	10.65	16.88	31.44
GHG mitigation (kT CO_2 eq.)	0	402.46	1085.72	1754.45	3242.64
CSE kraft mill (\$/kWh)	-0.0787	-0.1077	-0.1906	-0.3105	--
CSE TMP mill (\$/kWh)	-0.0790	-0.1081	-0.1913	-0.3115	--
Incremental NPV of scenario implementation	-1300.5 million dollars				
Cost per unit GHG mitigation	-401.1 \$/tonne of CO_2 eq.				
Fast penetration scenario					
Energy reduction (PJ)	0.0	11.7	--	--	11.7
GHG mitigation (kT CO_2	0	1207.4	--	--	1207.4

	2010-2020	2021-2030	2031-2040	2041-2050	Total
eq.)					
CSE kraft mill ($/kWh)	-0.0787	-0.1077	--	--	--
CSE TMP mill ($/kWh)	-0.0790	-0.1081	--	--	--
Incremental NPV of scenario implementation	-515.5 million dollars				
Cost per unit GHG mitigation	-426.9 \$/tonne of CO_2 eq.				

*As developed by the LEAP model

4.1.1.10 Scenario 12 results: Efficient heat recovery system

a) Energy savings and GHG mitigation potential

The efficient heat recovery system improves mill energy efficiency by recovering the maximum amount of energy from energy-intensive processes and using this energy in other processes. This recovery can significantly reduce energy use. Based on the LEAP scenario analysis, efficient heat recovery will result in a cumulative 16.09 PJ of energy savings in the slow penetration scenario and 8.08 PJ in the fast penetration scenario. This reduction is in the form of natural gas reduction, which results in reduction of 910.71 kT of CO_2 eq. emissions collectively in the slow penetration scenario and 457.3 kT of CO_2 eq. emissions in the fast penetration scenario. The detailed savings potential and GHG mitigation results are presented in Table 43.

b) Cost assessment

The CSEs of efficient heat recovery system were calculated to be \$0.78 (2010-2020), -\$1.10 (2021-2030), -\$1.72 (2031-2040), and -\$2.35 (2041-2050) per GJ of energy used. With the CSE data, the model estimated the incremental net present value of implementing an efficient heat recovery system to be -16 million dollars in slow penetration scenario and -8.2 million dollars in the fast penetration scenario. The techno-economic model results for efficient heat recovery system scenario CSEs are shown in Appendix B, Table 65.

c) GHG abatement cost

In slow penetration scenario, the GHG abatement cost is estimated to be -17.5 \$/tonne CO_2 eq. whereas it is -17.8 \$/ tonne CO_2 eq. in the fast penetration scenario for installation of an efficient heat recovery system in Alberta's pulp and paper industrial sector.

Table 43 provides the results for the efficient heat recovery system scenario as calculated by the LEAP model and the techno-economic model for the years 2010 to 2050.

Table 43: Scenario 12 results (efficient heat recovery system)

	2010-2020	**2021-2030**	**2031-2040**	**2041-2050**	**Total**
Slow penetration scenario					
Energy reduction (PJ)	1.46	3.42	4.99	6.22	16.09
GHG mitigation (kT CO_2 eq.)	82.51	193.53	282.28	352.39	910.71
Cost of saved energy (\$/GJ)	0.78	-1.10	-1.72	-2.35	--
Incremental NPV of scenario implementation	-16 million dollars				
Cost per unit GHG mitigation	-17.5 \$/tonne of CO_2 eq.				
Fast penetration scenario					
Energy reduction (PJ)	1.88	6.2	--	--	8.08
GHG mitigation (kT CO_2 eq.)	106.4	350.9	--	--	457.3

	2010-2020	2021-2030	2031-2040	2041-2050	Total
Cost of saved energy ($/GJ)	0.78	-1.10	--	--	--
Incremental NPV of scenario implementation	-8.2 million dollars				
Cost per unit GHG mitigation	-17.8 \$/tonne of CO_2 eq.				

*As developed by the LEAP model

4.1.1.11 Scenario 13 results: Idle time optimization

a) Energy savings and GHG mitigation potential

Idle time optimization in a paper mill involves advanced synchronization of the processes to assure reduced equipment idling time and can result in significant energy savings, as discussed in section 3.3. The implementation of this measure in a paper mill is expected to reduce net energy consumption by 5.9 PJ and 2.9 PJ respectively in the 2050 and 2030 scenarios compared to the BAU scenario. The improved energy consumption of the mill will result in a net emissions reduction of 803.89 kT CO_2 eq. in 2050 scenario and 376.4 kT CO_2 eq. in the 2030 scenario. Table 44 provides detailed energy and emissions reduction potential in Alberta's pulp and paper industry sector for this scenario

b) Cost assessment

The CSE for idle time optimization is calculated through the techno-economic model which uses retrofitting costs and considers reduced energy. The CSEs for this scenario range from -\$0.11/kWh to -\$0.18/kWh between 2010 and 2050. With the CSE, the model estimated an investment of -401 million dollars (incremental net present value) in the 2050 scenario and -

299.3 million dollars in the 2030 scenario, which makes idle time optimization economically suitable. The results from the techno-economic model used for CSE calculations for this scenario are shown in Appendix B, Table 66.

c) GHG abatement costs

With the high GHG mitigation potential and negative incremental NPV for this scenario, the GHG abatement cost is calculated to be -\$498.8/tonne CO_2 eq. in 2050 scenario and -\$795/tonne CO_2 eq. The negative abatement cost makes this scenario attractive in terms of energy savings and GHG mitigation in both slow and fast penetration scenarios.

Table 44 provides the results for the idle time optimization scenario in Alberta's pulp and paper industrial sector as calculated by the LEAP model and the techno-economic model for the years 2010 to 2050.

Table 44: Scenario 13 results (idle time optimization)

	2010-2020	2021-2030	2031-2040	2041-2050	Total
Slow penetration scenario					
Energy reduction (PJ)	0.14	0.98	1.92	2.86	5.90
GHG mitigation (kT CO_2 eq.)	22.85	138.47	258.03	384.54	803.89
Cost of saved energy (\$/kWh)	-0.11	-0.16	-0.17	-0.18	--
Incremental NPV of scenario implementation	-401 million dollars				
Cost per unit GHG mitigation	-498.8 \$/tonne of CO_2 eq.				

	2010-2020	2021-2030	2031-2040	2041-2050	Total
Fast penetration scenario					
Energy reduction (PJ)	0.33	2.29	--	--	2.62
GHG mitigation (kT CO_2 eq.)	53.3	323.1	--	--	376.4
Cost of saved energy ($/kWh)	-0.11	-0.16	--	--	--
Incremental NPV of scenario implementation	-299.3 million dollars				
Cost per unit GHG mitigation	-795 $/tonne of CO_2 eq.				

*As developed by the LEAP model

4.1.1.12 Scenario 14 results: High-consistency paper making

a) Energy savings and GHG mitigation potential

The high-consistency paper making measure focuses on reducing the water content in the pulp during all stages of the pulp and paper making process, which reduces the amount of energy required to handle the pulp. Reducing the water content can significantly reduce energy. Based on the LEAP model assessment, 1.46 PJ of energy can be reduced collectively in slow penetration scenario compared to BAU scenario whereas 0.52 PJ is expected to be reduced in fast penetration scenario. Accordingly, the 2050 scenario can result in net GHG mitigation of 196.6 kT CO_2 eq. whereas the 2030 scenario can mitigate 71.9 kT CO_2 eq.

b) Cost assessment

The CSEs for high consistency paper making were calculated to be \$0.04 (2010-2020), -\$0.01 (2021-2030), -\$0.02 (2031-2040), and -\$0.03 (2041-2050) per kWh of energy used. The techno-economic model estimated an incremental net present value of -8.1 million dollars in the slow penetration scenario and -3.9 million dollars in the fast penetration scenario, which indicate that the high-consistency paper making can potentially be profitable. The CSE calculations for high-consistency paper making scenario is shown in Appendix B, Table 67.

c) GHG abatement cost

The GHG abatement cost for high-consistency paper making is calculated to be -\$41.3/tonne CO_2 eq. in the slow penetration scenario and -\$53.9/tonne of CO_2 eq. based on the incremental NPV and net GHG mitigation potential in both cases. The negative abatement cost makes this scenario an attractive means of reducing GHG emissions with net cost savings.

Table 45 provides the results for high-consistency paper making scenario implementation in Alberta's pulp and paper industrial sector.

Table 45: Scenario 14 results (high consistency paper making)

	2010-2020	2021-2030	2031-2040	2041-2050	Total
Slow penetration scenario					
Energy reduction (PJ)	0	0.17	0.48	0.80	1.46
GHG mitigation (kT CO_2 eq.)	0	23.96	65.20	107.45	196.6
Cost of saved energy (\$/kWh)	0.04	-0.01	-0.02	-0.03	--
Incremental NPV of scenario implementation			-8.1 million dollars		
Cost per unit GHG mitigation			-41.3 \$/tonne of CO_2 eq.		

	2010-2020	2021-2030	2031-2040	2041-2050	Total
Fast penetration scenario					
Energy reduction (PJ)	0.0	0.52	--	--	0.52
GHG mitigation (kT CO_2 eq.)	0.0	71.88	--	--	71.9
Cost of saved energy ($/kWh)	0.04	-0.01	--	--	--
Incremental NPV of scenario implementation	-3.9 million dollars				
Cost per unit GHG mitigation	-53.9 $/tonne of CO_2 eq.				

*As developed by the LEAP model

4.1.2 Discussion

Alberta's pulp and paper industry LEAP model was used to evaluate 14 scenarios under slow and fast penetration cases that show different energy savings and GHG mitigation results, as discussed in previous section. These scenarios have been categorized into three types, depending on the measure, which makes it easier to compare scenarios of similar nature. The three categories were defined in chapter 3, and the scenarios results within these categories will be discussed below.

4.1.2.1 Category 1: Pretreatment technologies scenarios

The pretreatment technologies focus on modifying the wood chips before sending them to the refiner to convert them in to wood chips. The modification in wood chip structure depends on the technology used and can impact the quality of pulp produced. The pretreatment technologies are used in mechanical and chemical mills, and in this study, seven such technologies have been evaluated.

Figure 21 shows the comparison, estimated by the LEAP model, of energy reduction potential by pretreatment scenario compared to the BAU scenario when technologies are adopted under slow penetration scenario. The chemical pretreatment scenario will result in the largest collective energy savings of 15.10 PJ compared to other pretreatment technologies. Microwave pretreatment and fungal pretreatment scenarios result in the second and third largest cumulative energy savings of 14.90 and 10.48 PJ respectively in slow penetration scenario. The oxalic acid pretreatment closely follows the fungal pretreatment whereas the enzymatic pretreatment scenarios are among the lowest energy-reducing scenarios in this category. A similar trend can be seen in the fast penetration scenario case as shown in Figure 22, where chemical pretreatment results in largest energy saving potential of 6.67 PJ in this category closely followed by microwave pretreatment technology with 6.53 PJ of total energy reduction.

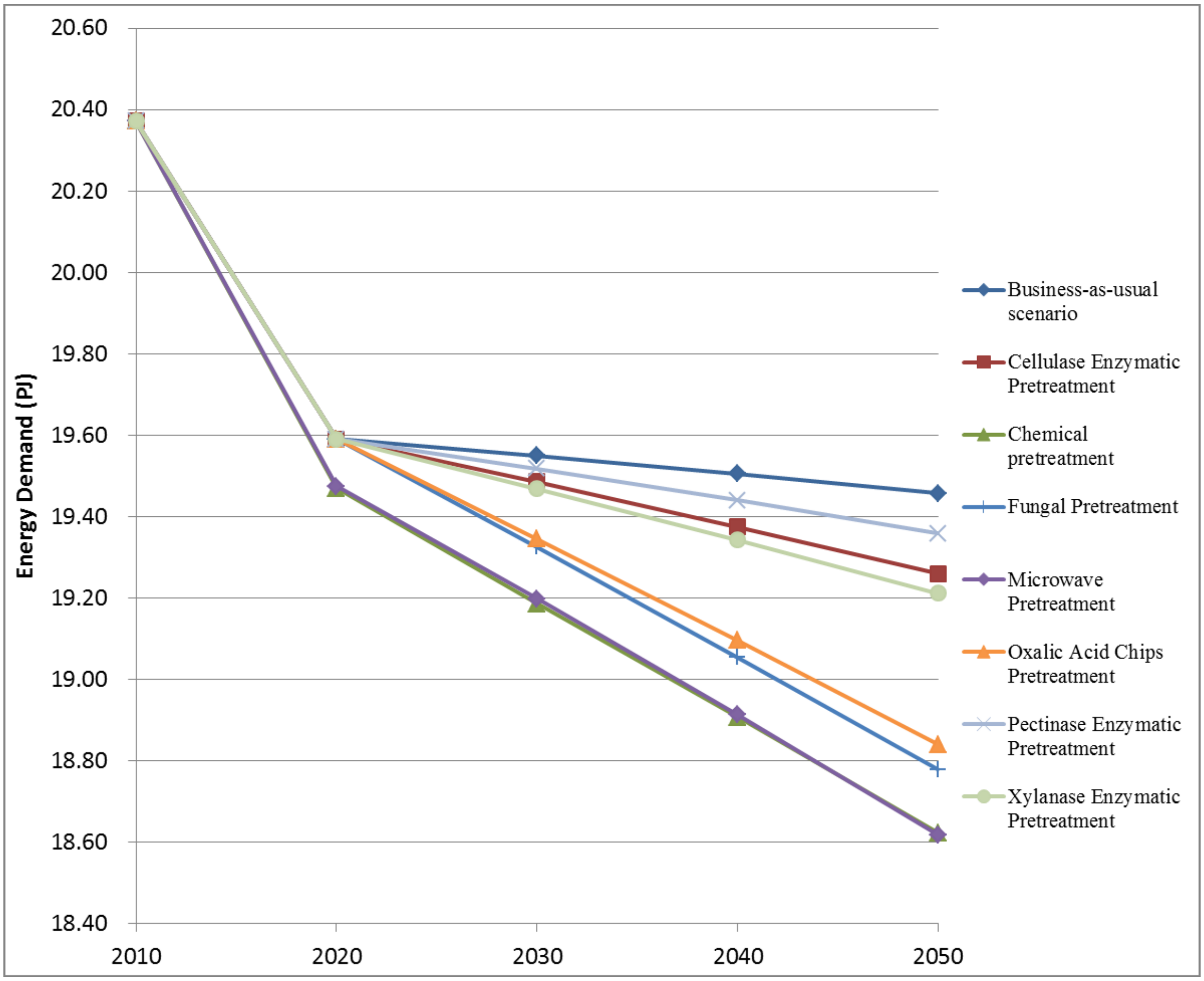


Figure 21: Energy demand reduction by slow penetration of pretreatment technologies in Alberta's pulp and paper mills as estimated by the LEAP model

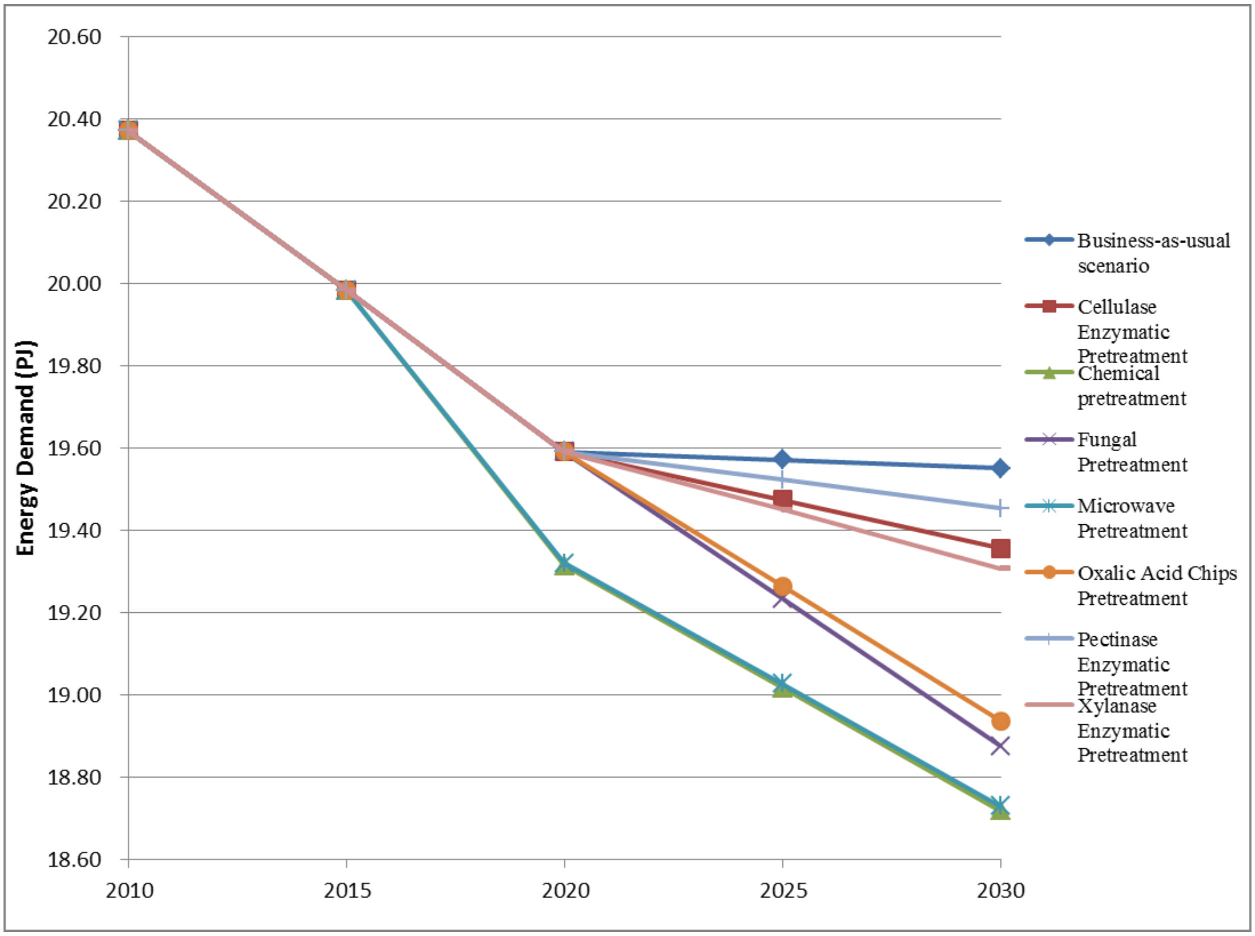


Figure 22: Energy demand reduction by fast penetration of pretreatment technology in Alberta's pulp and paper mills as estimated by the LEAP model

Figure 23 and 24 shows the comparison of the GHG emissions reduction potential of various pretreatment options under the slow and fast penetration scenarios, respectively. The results are provided as a difference in emissions with respect to the BAU scenario, hence the BAU scenario emissions are shown as 0 and the others are negative. The negative emission values show that the emissions are reduced by pretreatment and, as shown in the Figures 23 and 24, the chemical pretreatment scenario shows the largest cumulative GHG emissions reduction during the respective modeling study period. Unlike the energy reduction potential results, the microwave pretreatment shows lower GHG mitigation compared to fungal pretreatment due to differences in the type of energy reduced and application in the mill. Microwave pretreatment reduces natural gas consumption whereas fungal pretreatment reduces electricity consumption in the mills. The electricity emissions are reduced based on the transformation sector supply reduction whereas the natural gas emissions are reduced based on site burning of natural gas for steam generation. The fungal pretreatment and oxalic acid pretreatment are the second and third largest emissions-reducing scenarios in this category with respect to the BAU scenario in both slow and penetration scenarios.

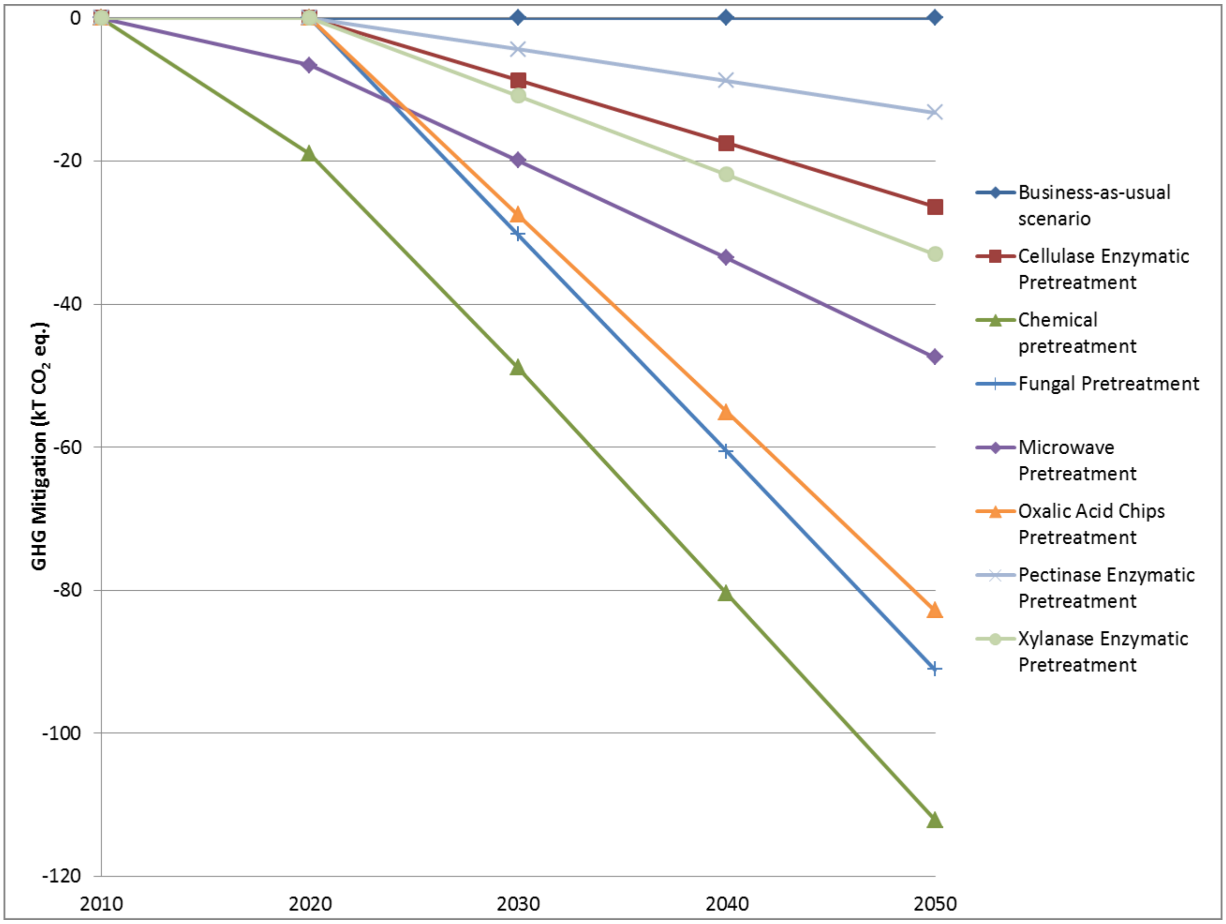


Figure 23: GHG emissions reduction by slow penetration of pretreatment scenario with BAU emissions as the baseline

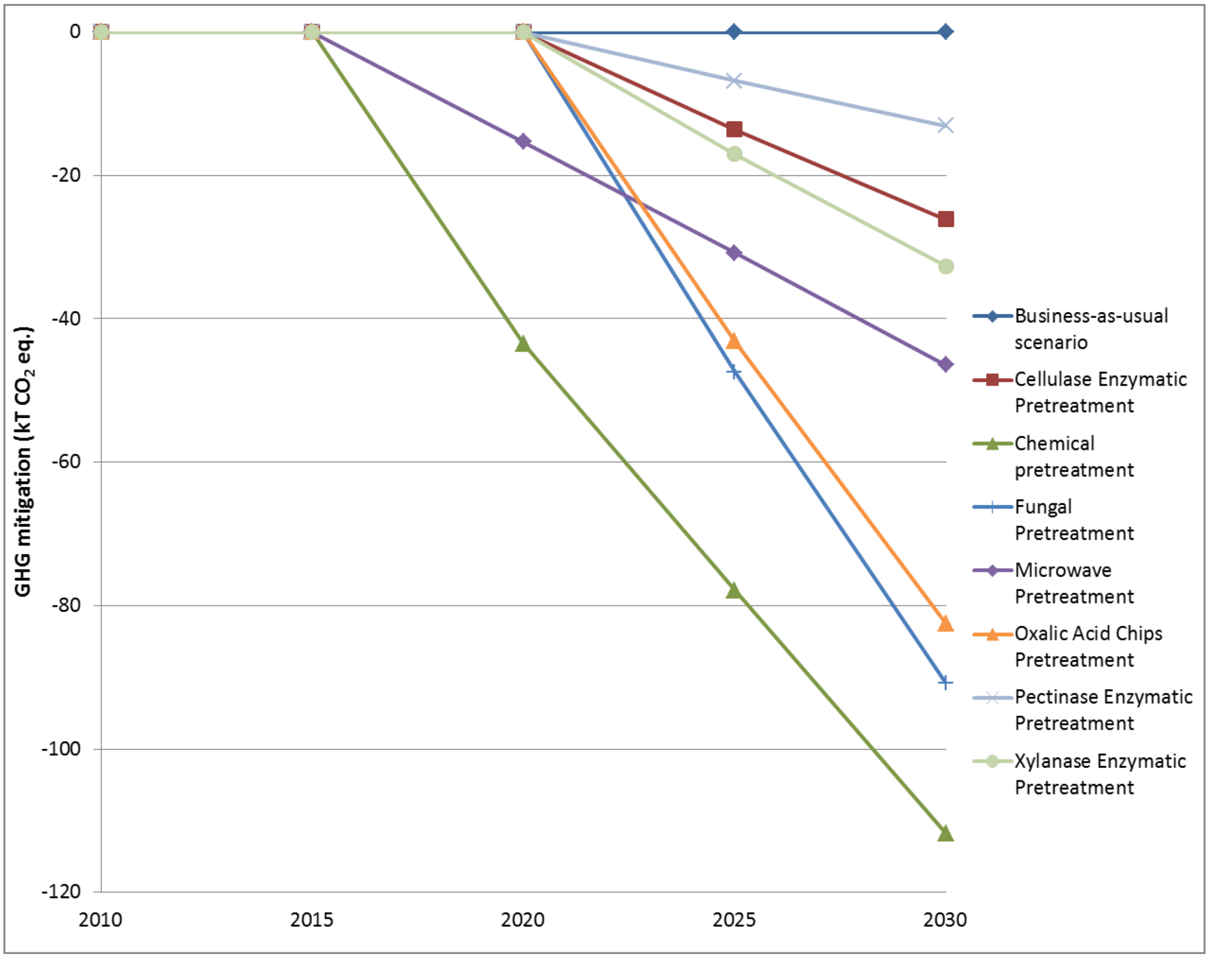


Figure 24: GHG emissions reduction by fast penetration of pretreatment scenario with BAU emissions as the baseline

4.1.2.2 Category 2: Efficient drying technologies scenarios

Efficient drying technologies replace or retrofit conventional water removal techniques from pulp slurries to give the pulp its final form of paper with a 90% or greater dryness factor. Conventionally, rollers and steam-heated drums are used to remove water in the pressing and drying sections of the paper mill, and these are energy-intensive processes. Three of technologies were evaluated in chapter 3, and individual results were discussed in the previous section. The three scenarios in efficient the drying technology category are microwave, shoe press, and Condebelt drying.

The energy demand of Alberta's pulp and paper industry shown in Figures 25 and 26 provide a comparison of drying technologies penetration in the mills under slow and fast penetration scenarios, respectively. All drying technology scenarios result in energy reduction in a close range to each other. In the fast penetration cases, the Condebelt and microwave drying technologies have similar energy reduction potential as both measures have similar penetration rates as well as energy efficiency improvement potential. The deciding factor between these two scenarios is the economical suitability, which will be compared below. Shoe press drying results in higher cumulative energy savings in the fast penetration scenario (1 PJ of energy reduction as compared to 0.98 PJ in case of Condebelt and microwave drying) whereas its energy reduction potential is lower compared to other two in case of slow penetration scenario. Shoe press drying is retrofitted in the press section and the microwave can be added to the drying section and replace some of the steam-heated drums. The Condebelt drying technology can fully replace the drying section of the paper mill.

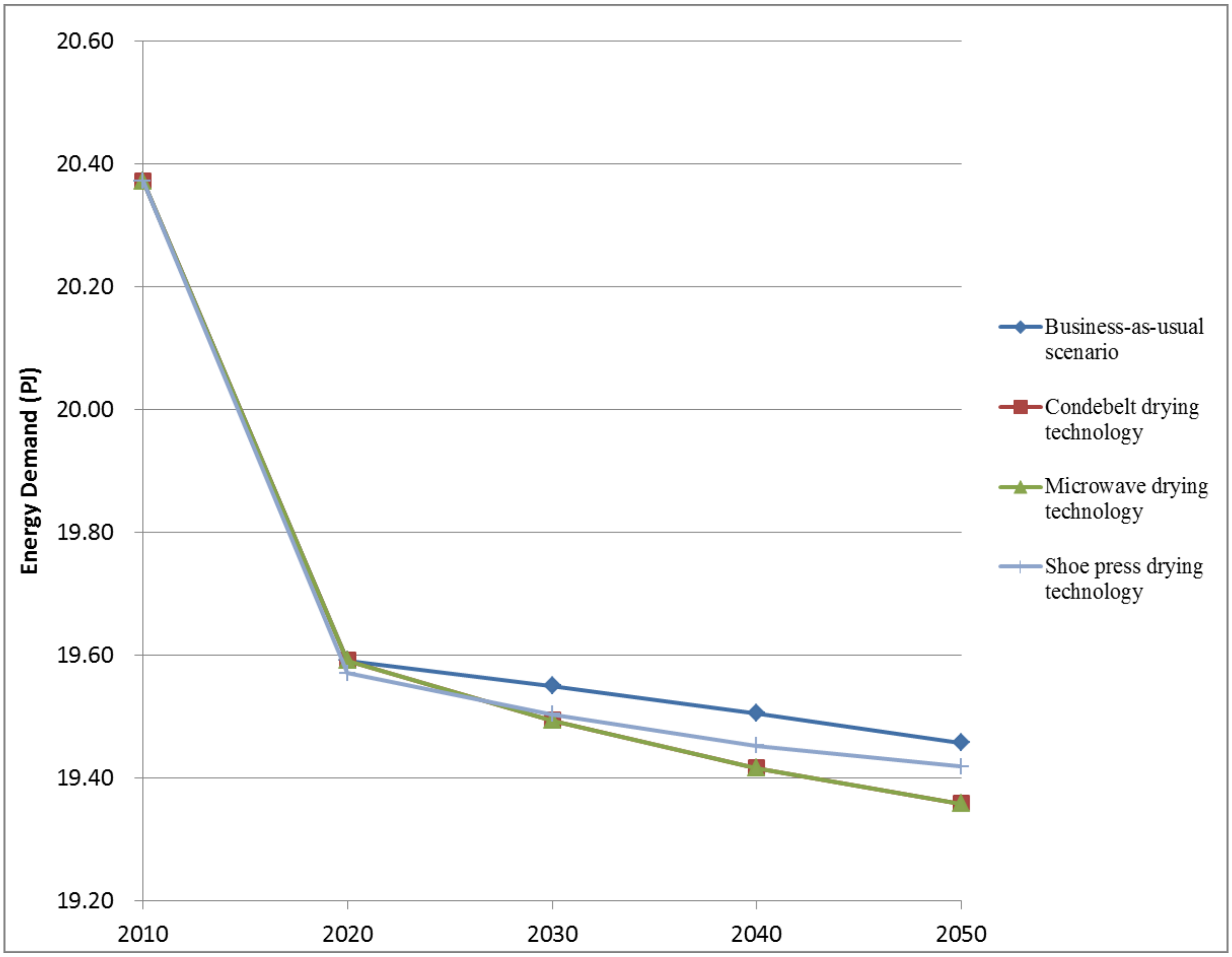


Figure 25: Energy demand reduction by slow penetration of efficient drying technologies in Alberta’s pulp and paper mills as estimated by the LEAP model

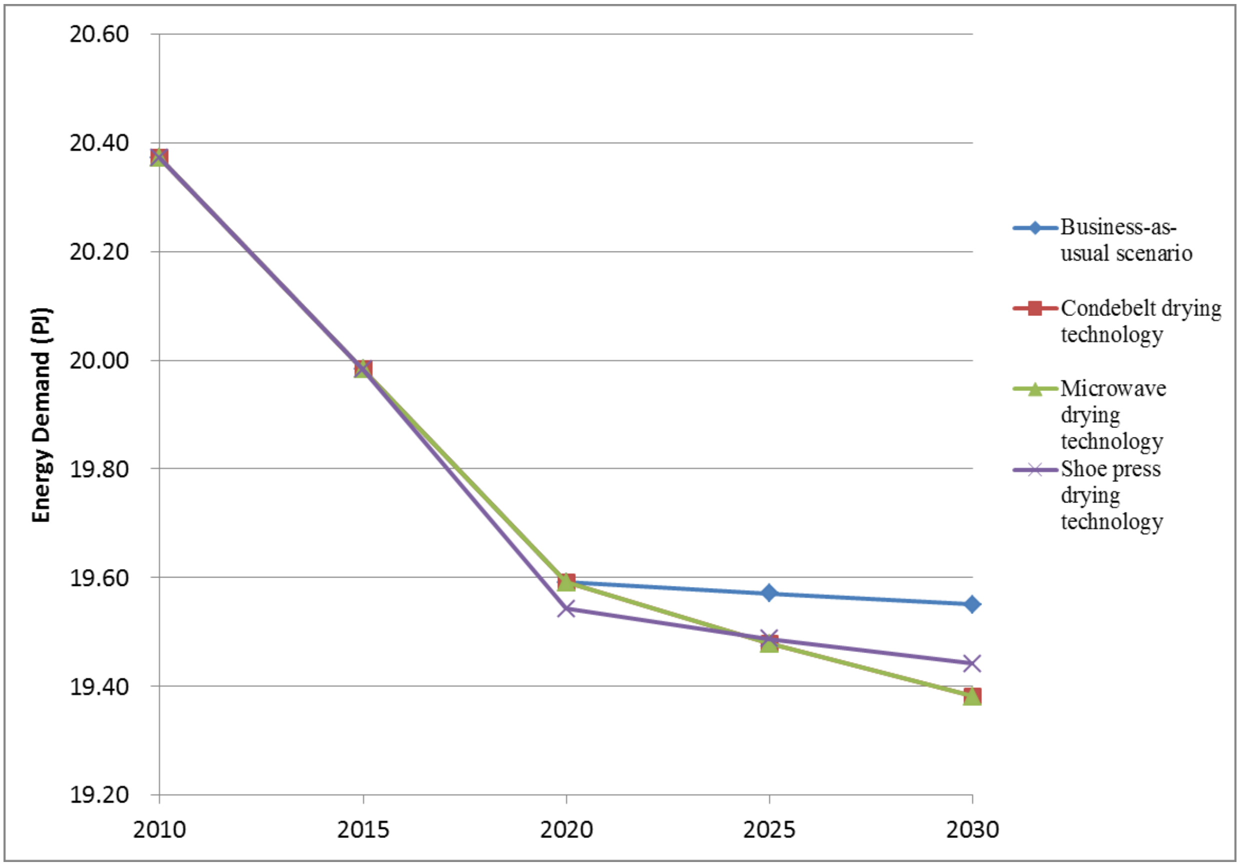


Figure 26: Energy demand reduction by fast penetration of efficient drying technologies in Alberta's pulp and paper mills as estimated by the LEAP model

Figures 27 and 28 show the emissions reduction potential of efficient drying technologies in Alberta's pulp and paper mills as evaluated by the LEAP model under the slow and fast penetration scenarios respectively. In both scenarios, Condebelt drying and microwave pretreatment result in similar emissions reduction as both reduce natural gas consumption of the paper mill by the same amount. The selection criteria in such scenarios will be the cost investment required to mitigate the same quantity of emissions; this is discussed below. The GHG mitigation from the shoe press drying technology installation in the mills shows a reducing trend after 2035 in the slow penetration scenario as shown in Figure 27. This reducing trend is the result of high GHG mitigation rate in BAU scenario (due to inherent efficiency improvements) as compared to shoe press drying. The results are shown with BAU scenario emissions as reference to provide a comparative analysis. The LEAP model allows thorough scenario investigation so that we can realistically implement technologies.

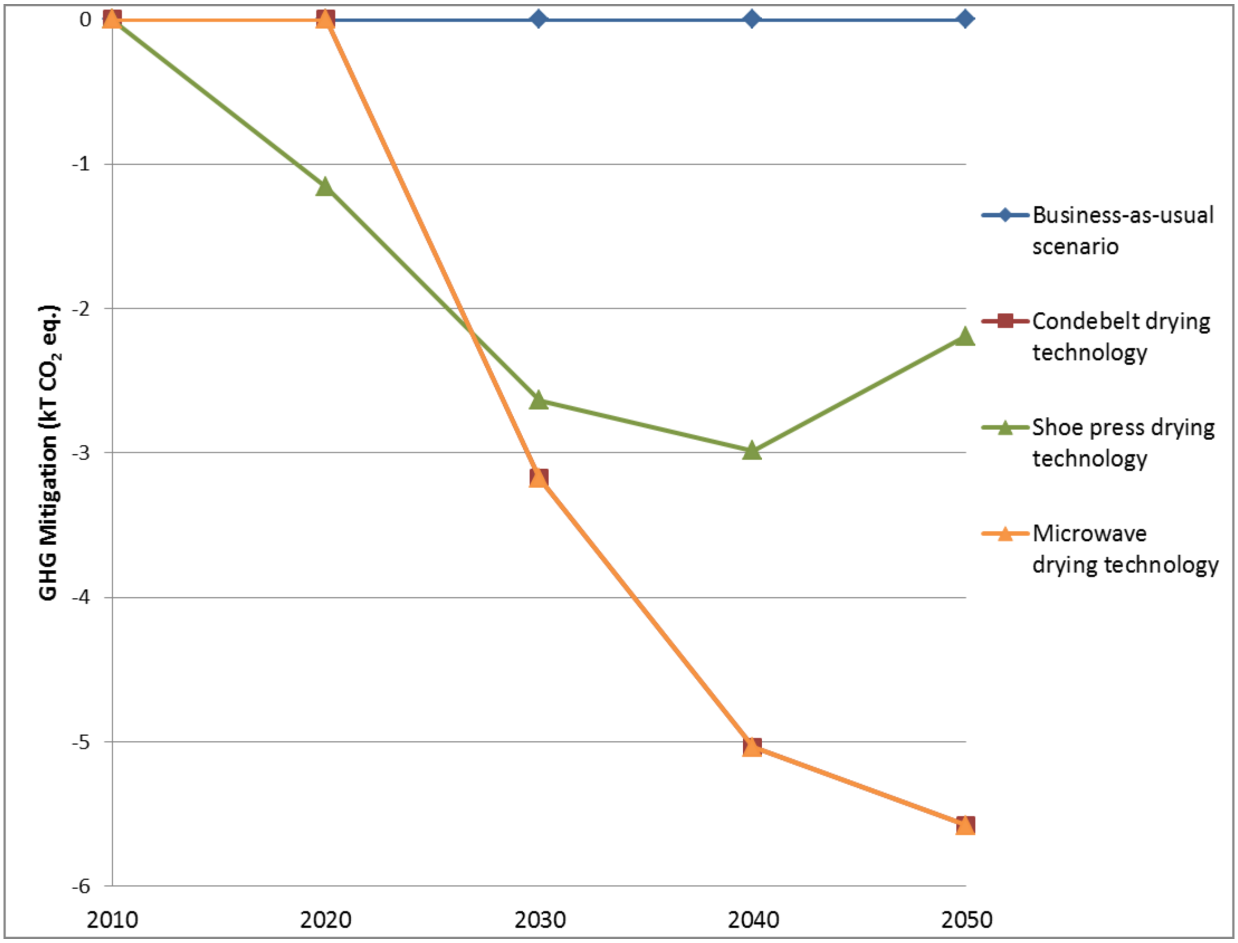


Figure 27: GHG emissions reduction by slow penetration of efficient drying technologies with BAU emissions as the baseline

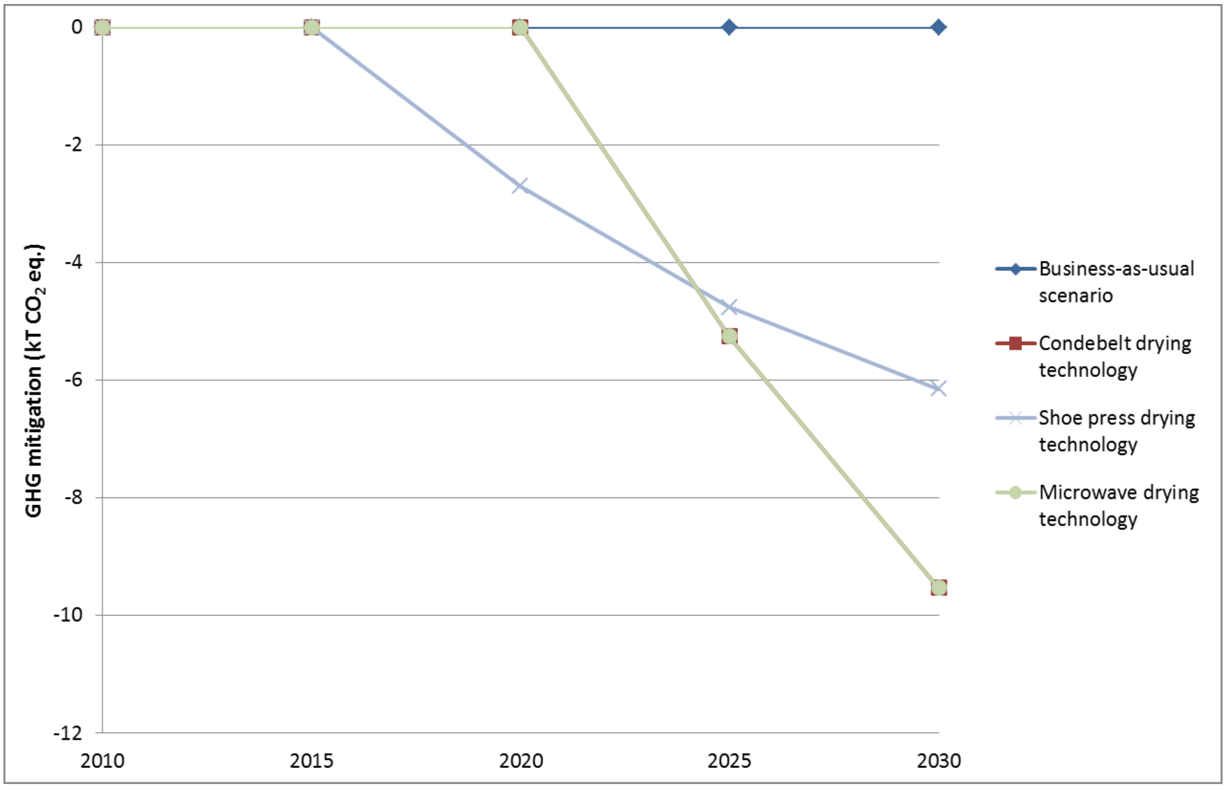


Figure 28: GHG emissions reduction by fast penetration of efficient drying technologies with BAU emissions as the baseline

4.1.2.3 Category 3: Process improvement scenarios

Category 3 is made up of scenarios that improve processes by integrating mill operations or reduce the feedstock required without changing mill production quality and quantity. The scenarios in this category are fibrous fillers, efficient heat recovery, idle time optimization, and high-consistency paper making. Figures 29-32 show a comparison of energy demand reduction and GHG reduction potential when these scenarios are implemented in Alberta's pulp and paper mills, as evaluated by the LEAP model.

Energy demand reduction compared to the BAU scenario is highest with the use of fibrous fillers, as shown in Figures 29 and 30, simply because fillers can be used in both chemical and mechanical mills, unlike the other options in this section category, which are suitable for one type of mill only. That said, efficient heat recovery significantly reduces energy consumption, and idle time optimization and high-consistency paper making result in relatively lower energy savings in both slow and fast penetration scenarios.

GHG emissions reduction potential trend through process improvements measure is similar to that of energy demand reduction. Fibrous fillers show the highest GHG emissions reduction, as they reduce energy consumption mill-wide, whereas efficient heat recovery, idle time optimization, and high-consistency paper show comparatively lower emissions reduction in both slow and fast penetration scenarios.

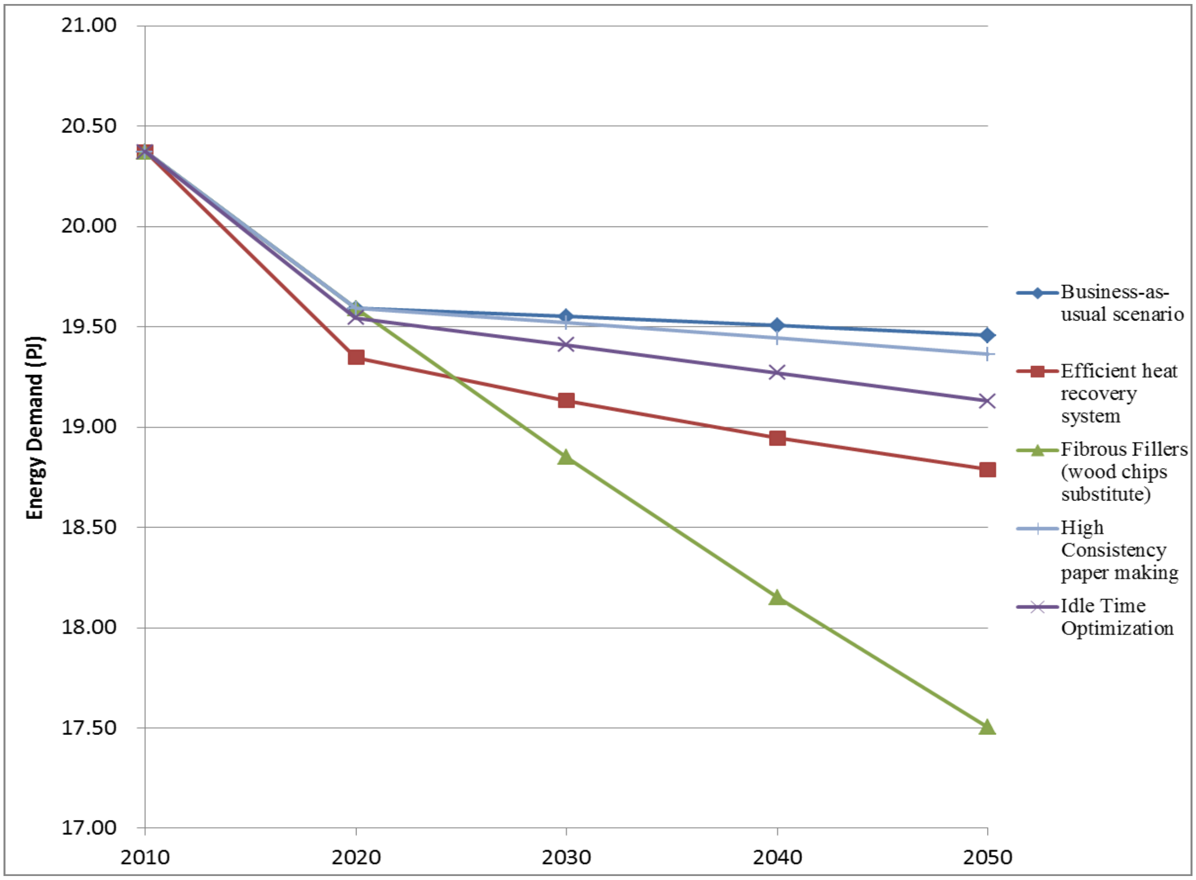


Figure 29: Energy demand reduction through slow penetration of process improvement scenarios in Alberta's pulp and paper mills as estimated by the LEAP model

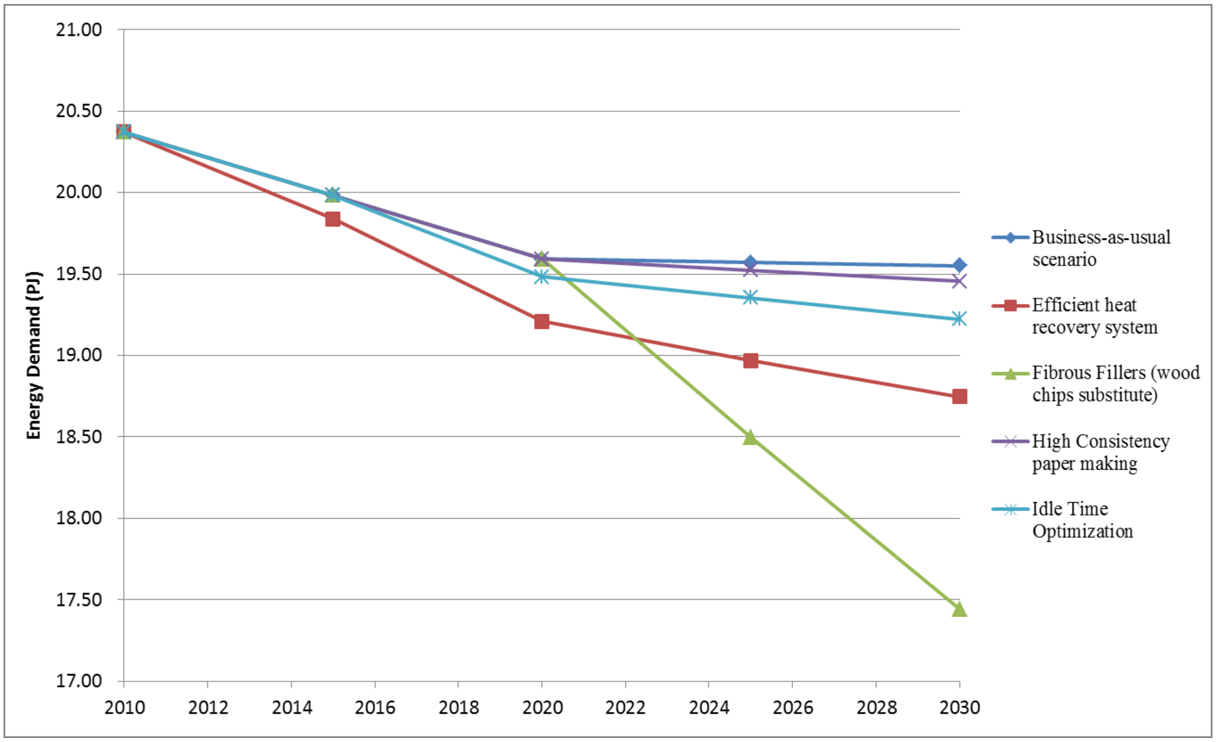


Figure 30: Energy demand reduction through fast penetration of process improvement scenarios in Alberta's pulp and paper mills as estimated by the LEAP model

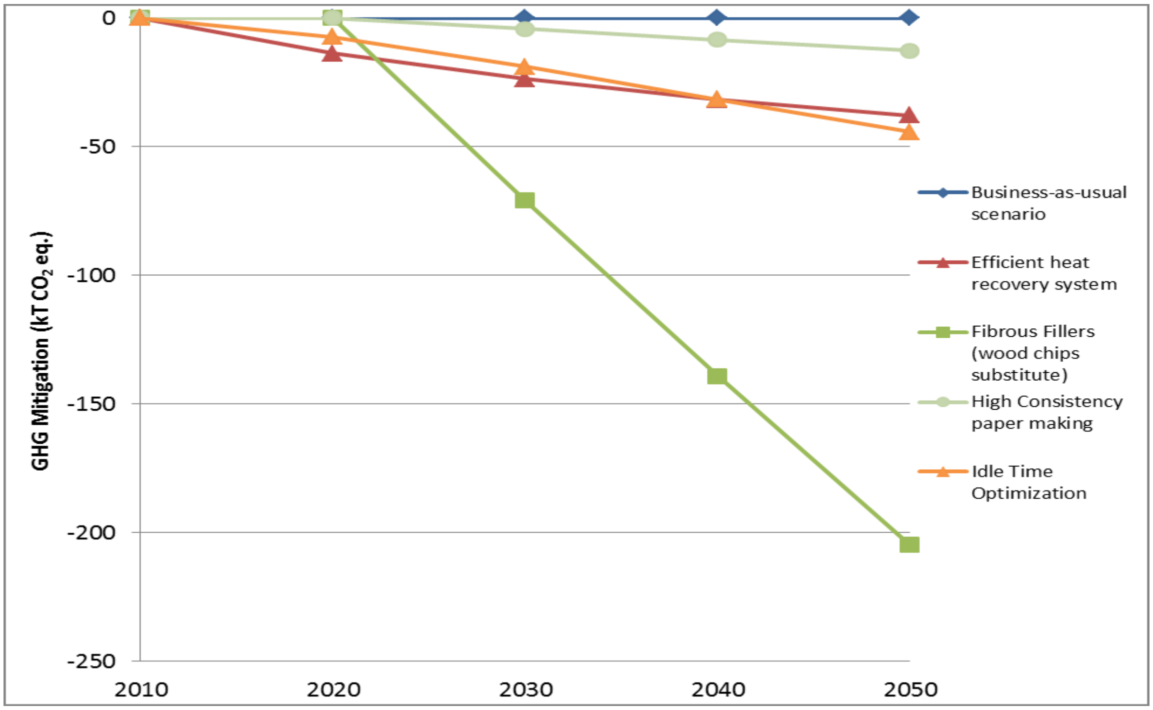


Figure 31: GHG emissions reduction by slow penetration of process improvement scenarios with BAU emissions as the baseline

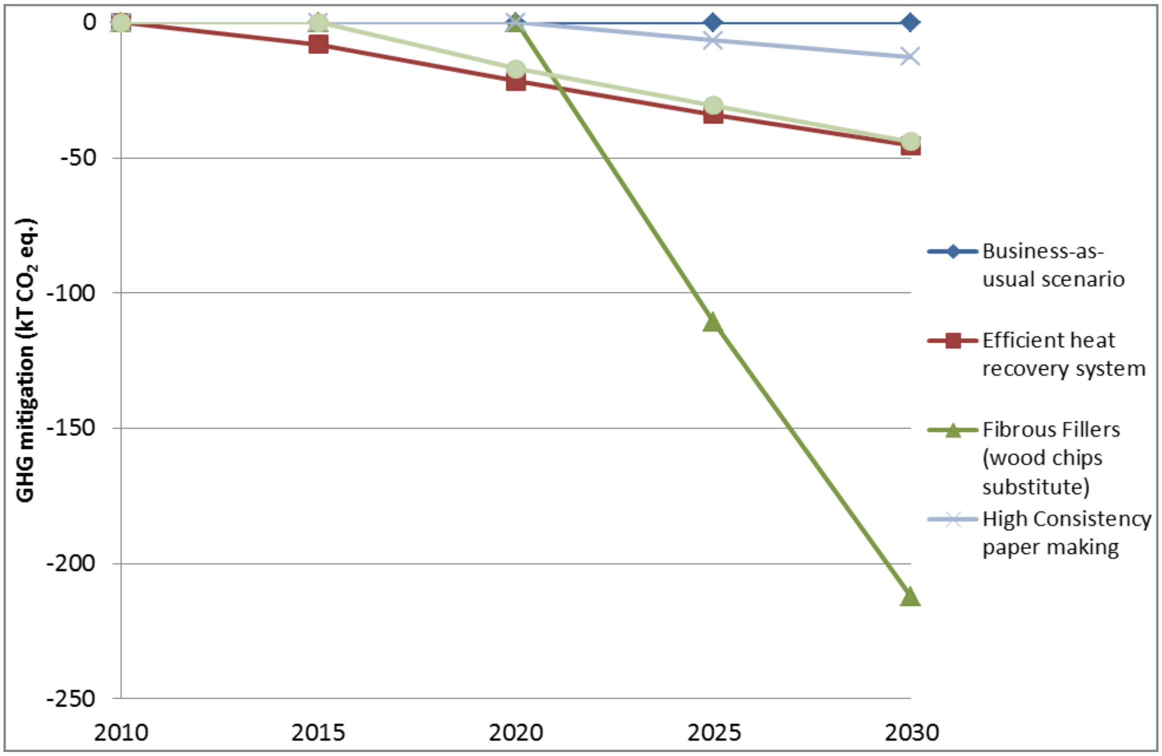


Figure 32: GHG emissions reduction by fast penetration of process improvement scenarios with BAU emissions as the baseline

The Appendix C Tables 68-69 provide the annual energy demand of the Alberta's pulp and paper industry in terms of electricity and natural gas when all identified technologies are implemented under the slow and fast penetration scenarios. Based on these tables, a graphical comparison of net energy demand change and GHG mitigation under the slow penetration of all scenarios is shown in Figure 33 and 34 for an overall overview of the results. The fibrous fillers scenario results in largest energy saving and GHG mitigation potential among all scenarios in both slow and fast penetration cases. The chemical pretreatment scenario results in second largest GHG mitigation whereas the efficient heat recovery system results in second largest energy reduction after the fibrous fillers in both slow and fast penetration cases.

An extensive comparison of scenario implementation in Alberta's pulp and paper industry has been discussed in section 4.1. However, up till this point the scenarios are compared only in terms of energy savings and GHG mitigation potential. Moreover, the scenario analysis has been assessed individually, i.e., one scenario is assessed at a time and compared with BAU scenario. To make an informed decision and evaluate the potential of implementing multiple scenarios simultaneously, the scenarios have to be compared in terms of costs associated with the GHG mitigation. A comprehensive analysis comparing the costs and emissions mitigation potential of the scenarios developed in this study can be presented in the form of a GHG abatement cost curve.

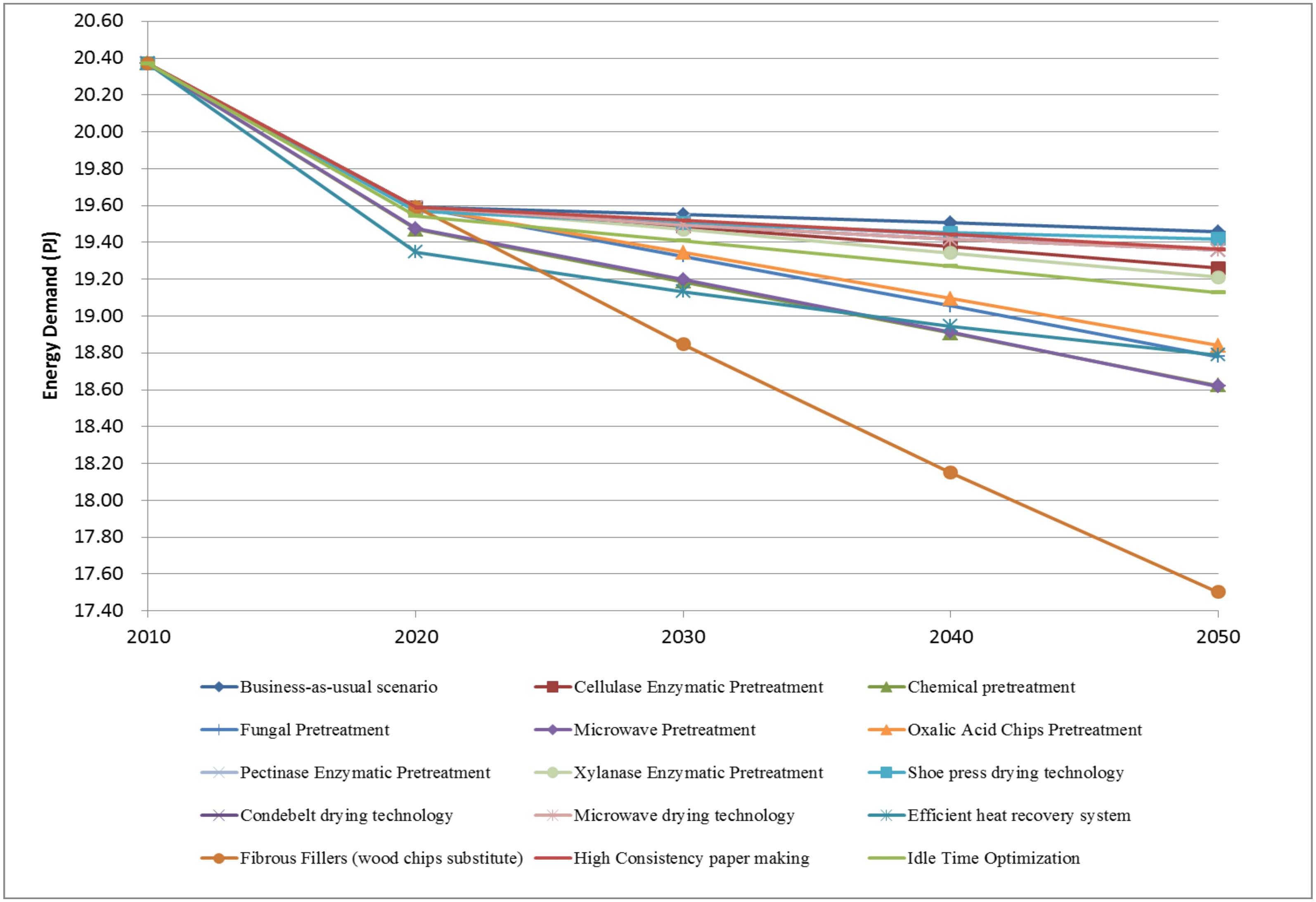


Figure 33: Energy demand for Alberta's pulp and paper industry under slow penetration of mitigation scenarios as estimated by the LEAP model

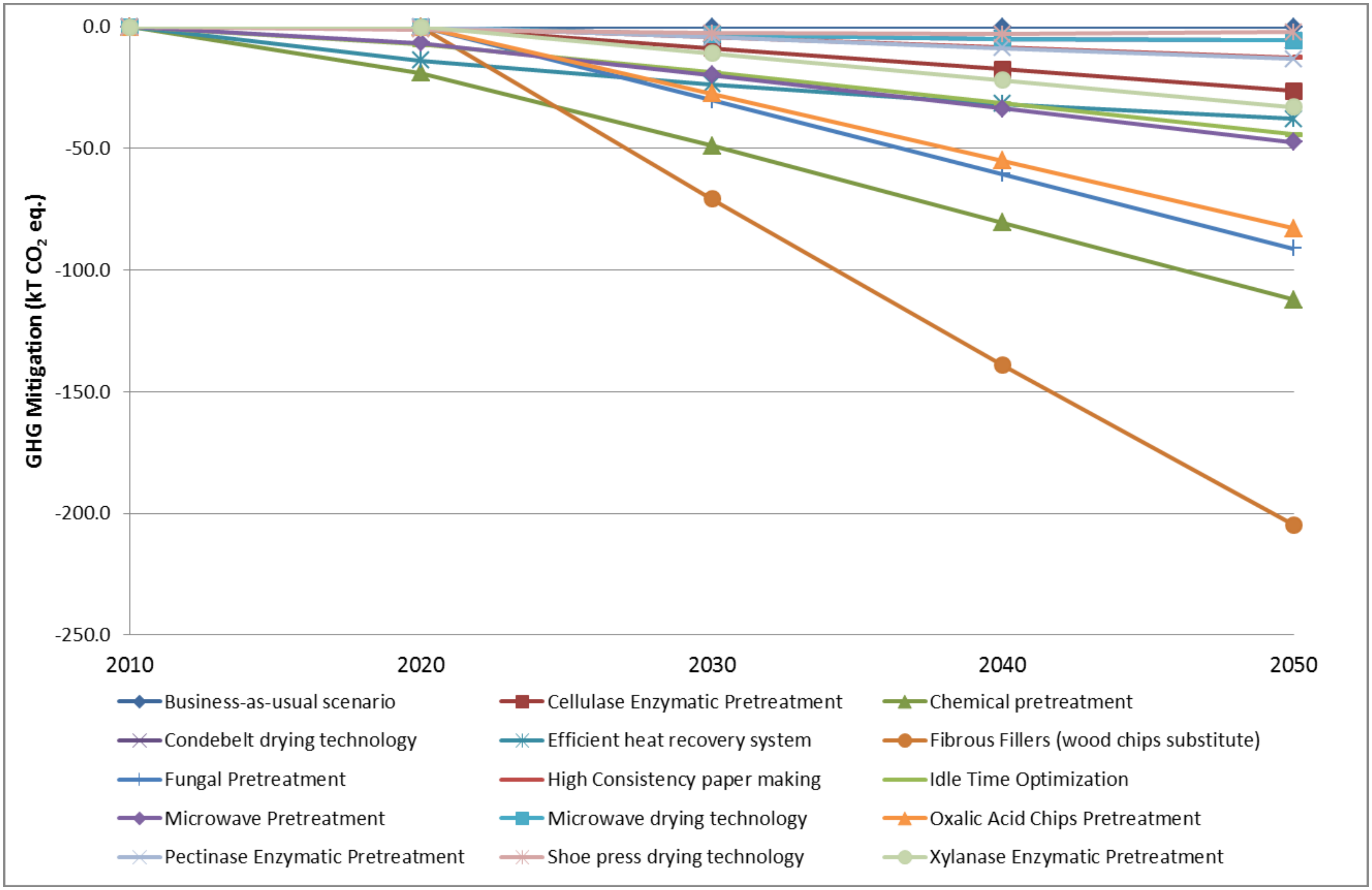


Figure 34: Comparison of GHG mitigation pattern by slow penetration of scenarios, as estimated by the LEAP model for Alberta's pulp and paper industry

4.2 Cost curve analysis

In the previous sections, the scenarios developed for Alberta's pulp and paper industry were compared in terms of energy reduction, GHG mitigation, and cost of mitigation. However, to understand the impact of all of these scenarios in relation to each other from both an emission mitigation and a cost perspective, GHG abatement cost curves have been developed. A cost curve can provide a comprehensive comparison of scenarios on how much GHG emissions will be mitigated during the study period as well as the cost to mitigate one tonne of GHGs. A number of studies have used GHG abatement cost curves to present scenario analysis in various economic sectors as well as country-wide and globally [9, 64, 65, 143-149].

A sample GHG abatement cost curve is shown in Figure 35 with the comparison of 6 imaginary scenarios. The data required to develop a GHG abatement cost curve consist of the estimate of net GHG mitigation achievable when a scenario is implemented and the cost to reduce one tonne of GHG emissions in that scenario. Figure 35 is a GHG abatement cost curve that shows mitigation results (block width) and unit mitigation cost (block height). The block height can be above or below the axis, which indicates economic implications of implementing a scenario. The 6 sample scenarios shown in this figure can be compared with each other for mitigation potential and economic suitability using a cost curve.

In this manner, a GHG abatement cost curve is developed for the scenarios developed for Alberta's pulp and paper industry with the results from both the LEAP scenario analysis and the techno-economic model.

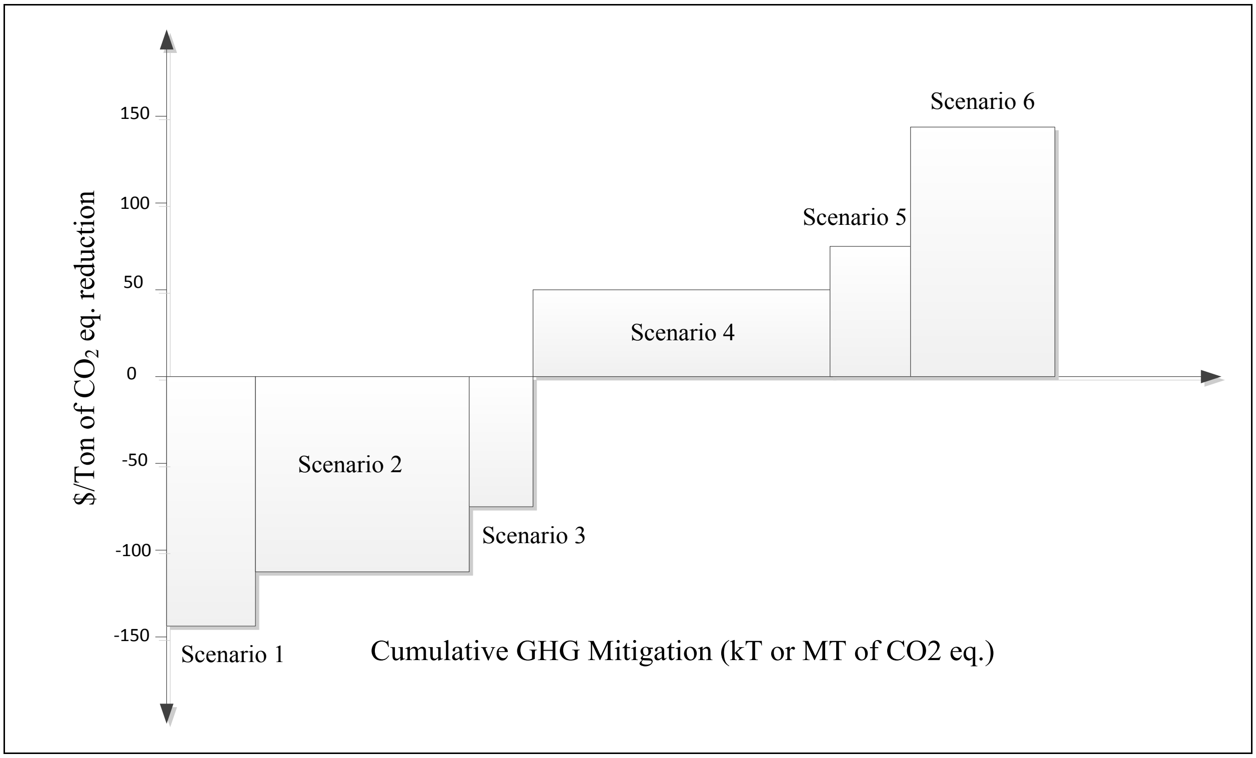


Figure 35: Sample GHG abatement cost curve

4.2.1 GHG abatement cost curve for Alberta's pulp and paper industry

The GHG abatement cost curve developed for Alberta's pulp and paper industry is shown in Figures 36 and 37 for slow and fast penetration scenarios respectively. The input data for the cost curve were calculated in the LEAP model and have been discussed in detail in section 4.1. The net GHG mitigation achievable by implementation of each scenario independently is provided in Appendix C Tables 70 and 71. The GHG mitigation data is used to scale the block width. For the block height, the cost per unit GHG mitigation is required that is estimated in section 4.1 as estimated by the LEAP model. A detailed discussion on GHG abatement cost curves developed is provided for slow and fast penetration scenario cases in following sections.

4.2.1.1 Slow penetration scenario

The GHG abatement cost curve in Figure 36 shows that eight out of the fourteen scenarios are below the x-axis, indicating that these options are cost effective in reducing GHG emissions. The highest cost savings potential is through idle time optimization in paper mills, with an estimated cost savings of \$500/tonne CO_2 eq., resulting in 0.8 MT CO_2 eq. mitigation compared to the baseline scenario. The pectinase enzymatic pretreatment will require the highest investment and reduce emissions by 0.2 MT CO_2 eq. for an average cost of \$1373/tonne of CO_2 eq. The highest GHG mitigation potential can be achieved with fibrous fillers and chemical pretreatment; these can reduce GHG emissions by 3.24 MT and 2.06 MT CO_2 eq. collectively during the study period of 2010-2050, with fibrous fillers showing relatively higher cost savings. The use of fibrous fillers will save \$401/tonne CO_2 eq. whereas the chemical pretreatment will save \$155/tonne CO_2 eq.

Of the seven pretreatment options, only three show net cost savings: oxalic acid (-\$177/tonne of CO_2 eq.), chemical (-\$155/tonne of CO_2 eq.), and fungal (-\$116/tonne of CO_2 eq.) pretreatment, which can result in 4.76 MT of CO_2 eq. GHG mitigation collectively compared to the baseline scenario. The microwave, xylanase, cellulase, and pectinase (enzymatic) pretreatment options have GHG abatement costs of \$57, \$19.5, \$126, and \$1373/ tonne CO_2 eq. to achieve net a GHG mitigation of 0.84 MT, 0.51 MT, 0.41 MT, and 0.2 MT CO_2 eq., respectively. The drying technologies can result in significant mitigation; however, only microwave drying shows potential net cost savings. The Condebelt and microwave drying scenarios result in the same emission reductions of 0.12 MT CO_2 eq.; however, the microwave drying shows a GHG abatement of \$76/tonne CO_2 eq. mitigated whereas the Condebelt drying system has a GHG abatement cost of \$696/tonne CO_2 eq. mitigated. The shoe press dryer will result in lower emissions mitigation (0.08 MT of CO_2 eq.) but has a lower GHG abatement cost of \$40.3/tonne of CO_2 eq. compared to the Condebelt drying.

All scenarios related to process improvement are expected to result in net cost savings while significantly reducing emissions in Alberta's pulp and paper mills. The idle time optimization, fibrous fillers, high-consistency paper making, and efficient heat recovery systems will result in cost savings of \$498, \$401, \$41, and \$17/tonne CO_2 eq. mitigation with net GHG mitigation potential of 0.8, 3.24, 0.20, and 0.9 MT of CO_2 eq., respectively.

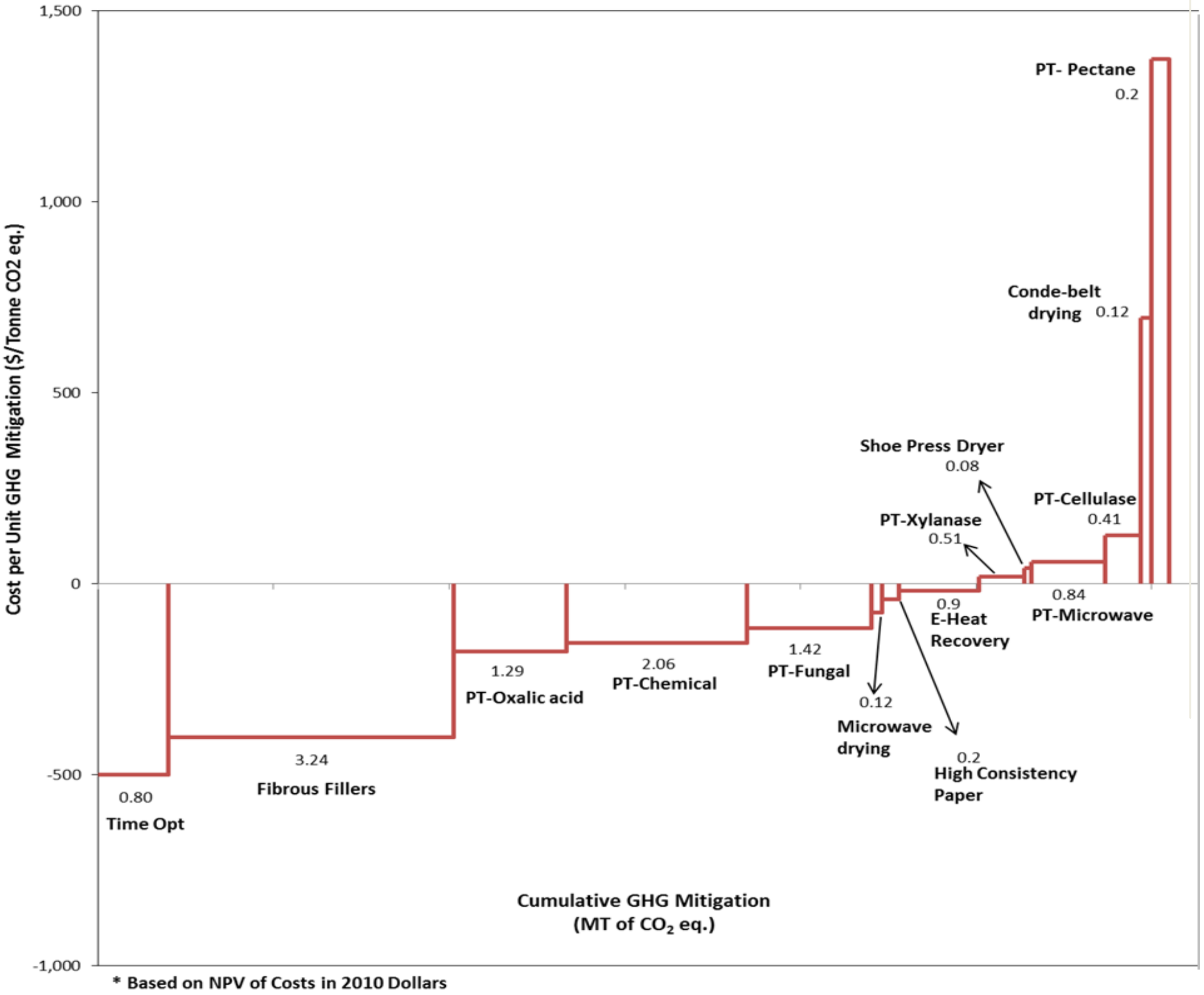
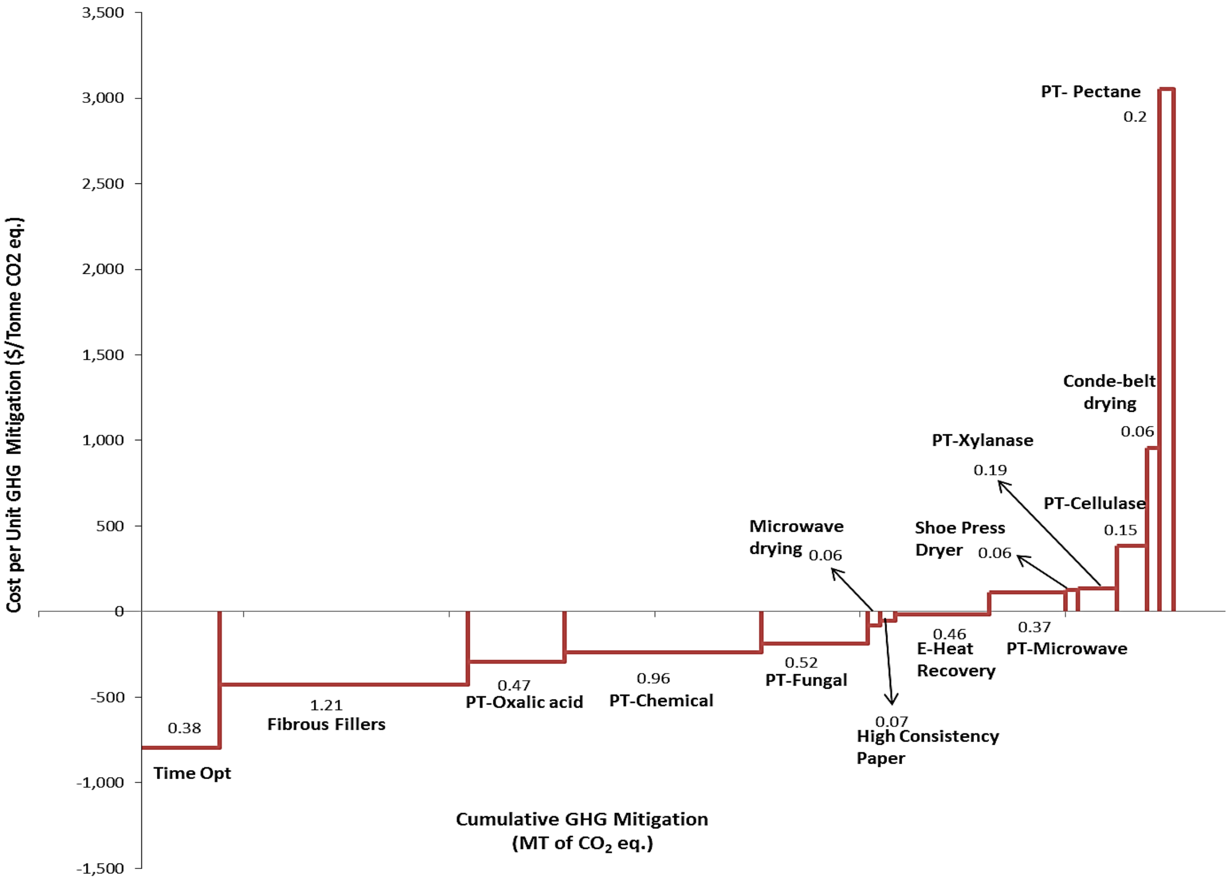


Figure 36: GHG abatement cost curve for Alberta's pulp and paper industry under slow penetration scenario

4.2.1.2 Fast penetration scenario

The cost curve for the fast penetration of GHG mitigation scenarios is shown in Figure 37. The fast penetration scenario cost curve follows the same trend as was in the slow penetration case, however the GHG abatement costs and mitigation potential is different. The idle time optimization results in lowest GHG abatement cost of -$795/tonne CO_2 eq. mitigation whereas the pectinase pretreatment scenario requires highest GHG abatement of $3051/tonne CO_2 eq. among all developed scenarios. The fibrous fillers scenario results in highest GHG mitigation of 1.21 MT of CO_2 eq. in fast penetration of all scenarios followed by chemical pretreatment scenario with mitigation potential of 0.96 MT of CO_2 eq.



*** Based on NPV of Costs in 2010 Dollars**

Figure 37: GHG abatement cost curve for Alberta's pulp and paper industry under fast penetration scenario

The collective GHG mitigation of all scenarios sums up to 12.2 MT of CO_2 eq. in the slow penetration scenario and 5.03 MT of CO_2 eq. in the fast penetration case. However, all the scenarios shown in the GHG abatement cost curves cannot be implemented at the same time, and to understand the maximum GHG mitigation potential achievable based on implementing the scenarios simultaneously, an integrated cost curve is developed and discussed in the next section.

4.2.2 Integrated scenarios cost curve for Alberta's pulp and paper industry

To understand the maximum potential for GHG emissions reduction in Alberta's pulp and paper industry, an integrated GHG abatement cost curve has to be developed. The integrated GHG abatement cost curve will contain scenarios that can be implemented simultaneously in Alberta's pulp and paper mills. The scenarios are selected based on highest mitigation potential during the study period in both fast and slow penetration cases.

4.2.2.1 Scenario selection for integrated cost curve

a) Category 1 scenarios: Pretreatment technologies

The pretreatment technology category has seven scenarios, some of which can be implemented at same time based on their application location. The microwave pretreatment technology can only be implemented in kraft mills, whereas all other pretreatment technologies can be only implemented in mechanical mills. Therefore, the microwave pretreatment technology is considered for the integrated GHG abatement cost curve.

The enzymatic, fungal, chemical and oxalic acid pretreatment technologies can be implemented in mechanical mills. However, only one can be implemented at a time, and the most suitable technology has to be selected for the integrated GHG abatement cost curve. As shown in Table 46, the chemical pretreatment technology has highest net GHG mitigation potential of 2.06 MT of CO_2 eq. with negative GHG abatement cost due to which it is selected for the integrated GHG abatement cost curve.

The comparison of mitigation potential and GHG abatement costs for category 1 scenarios is shown in Table 46, with indication of selected scenarios for integrated cost curve.

Table 46: Category 1 scenario comparison for the development of the integrated cost curve

Scenario name	**Slow penetration scenario**		**Fast penetration scenario**		**Selected for integrated cost curve**
	Net GHG mitigation (MT of CO_2 eq.)	**GHG abatement cost (\$/tonne of CO_2 eq.)**	**Net GHG mitigation (MT of CO_2 eq.)**	**GHG abatement cost (\$/tonne of CO_2 eq.)**	
Microwave pretreatment	0.84	57.2	0.37	110.8	●
Xylanase enzymatic pretreatment	0.51	19.5	0.19	134.6	
Cellulase enzymatic pretreatment	0.41	126.1	0.15	384.8	
Pectinase enzymatic pretreatment	0.20	1373.8	0.07	3051	
Fungal pretreatment	1.42	-116.8	0.52	-188.5	
Chemical pretreatment	2.06	-154.6	0.96	-239.4	●
Oxalic acid pretreatment	1.29	-177.7	0.47	-292.9	

b) Category 2 scenarios: Efficient drying technologies

Category 2 has three scenarios: microwave drying, shoe press drying, and Condebelt drying, all of which can only be implemented in Alberta's single paper mill. Shoe press drying is a retrofit and the microwave and Condebelt drying can replace a conventional steam drum drying system. Therefore, the shoe press drying scenario is included in integrated GHG abatement cost curve as it does not overlap with microwave or Condebelt drying. Only one in microwave and the Condebelt drying will be chosen.

Microwave and Condebelt drying show equal GHG mitigation of 0.12 MT CO_2 eq. but abatement costs differ significantly. The microwave drying results in net cost savings of \$76.1/tonne of CO_2 eq. and the Condebelt drying requires an investment of \$696.6/tonne CO_2 equivalent in the slow penetration scenario. Since the mitigation potential is similar, the microwave drying scenario has been selected for the integrated scenario. Table 47 shows the comparative analysis of scenarios in category 2 for integrated cost curve selection purposes.

Table 47: Category 2 scenarios comparison for the integrated cost curve

Scenario name	**Slow penetration scenario**		**Fast penetration scenario**		**Selected for integrated cost curve**
	Net GHG mitigation (MT of CO_2 eq.)	**GHG abatement cost (\$/tonne of CO_2 eq.)**	**Net GHG mitigation (MT of CO_2 eq.)**	**GHG abatement cost (\$/tonne of CO_2 eq.)**	
Microwave drying technology	0.12	-76.1	0.06	-79.8	●
Shoe press drying	0.08	40.3	0.06	128	●

technology				
Condebelt drying technology	0.12	696.6	0.06	954.5

c) Category 3 scenarios: Process improvement

The process improvement scenarios are the use of fibrous fillers, efficient heat recovery system, idle time optimization, and high-consistency paper making. Fibrous fillers can be used in any mill without disturbing mill processes as they replace the raw material rather than modifying any process technology. Moreover, fibrous fillers have high GHG mitigation potential of 3.24 MT with a GHG abatement cost of \$401/tonne CO_2 mitigation in the slow penetration scenario. The filler material can be used without conflicting with any technology considered in other scenarios. A similar trend can be seen in fast penetration scenario as shown in Table 48 therefore, this scenario has been considered for the integrated GHG abatement cost curve.

The efficient heat recovery system, idle time optimization and high consistency paper making can be implemented in mechanical pulp mill without creating any technical limitations for other scenario technologies considered in this study. These scenarios focus on process operational parameter improvement rather than modifying a technology in the paper mill. All scenarios in this category are applicable in Alberta’s paper mill due to their independent nature. All process improvement scenarios are selected for the integrated GHG abatement cost curve. Table 48 shows the scenarios in terms of mitigation potential and abatement for selection purposes in the integrated GHG abatement cost curve.

Table 48: Category 3 scenarios comparison for integrated cost curve

Scenario name	Slow penetration scenario		Fast penetration scenario		Selected for integrated cost curve
	Net GHG mitigation (MT of CO_2 eq.)	GHG abatement cost ($/tonne of CO_2 eq.)	Net GHG mitigation (MT of CO_2 eq.)	GHG abatement cost ($/tonne of CO_2 eq.)	
Fibrous fillers	3.24	-401.1	1.21	-426.9	●
Efficient heat recovery system	0.91	-17.5	0.46	-17.8	●
Idle time optimization	0.80	-498.8	0.38	-795.1	●
High consistency paper making	0.20	-41.3	0.07	-53.9	●

4.2.2.2 Integrated GHG abatement cost curve for Alberta's pulp and paper industry

Based on the above discussion, the GHG abatement cost curve for Alberta's pulp and paper was modified to include only those scenarios that can be implemented at the same time due to their independent nature. The integrated GHG abatement cost curve includes eight scenarios with the remaining 6 scenarios showing lower potential in terms of costs and emissions compared to alternate available options. Two integrated cost curves were developed based on the slow penetration and fast penetration scenarios as shown in Figures 38 and 39, respectively.

In the slow penetration of integrated scenarios, the collective GHG mitigation achievable is 8.26 MT CO_2 eq. with a net GHG abatement cost of -$1092/tonne CO_2 mitigation. The actual GHG abatement costs for the scenarios used in this cost curve are in both the positive and the negative range. The net GHG abatement cost of -$1097/tonne CO_2 eq. is provided for comparison purposes only. In the fast penetration case, the net GHG mitigation potential is 3.57 MT CO_2 eq. with a net GHG abatement cost of -$1374/tonne of CO_2 eq. which shows more GHG abatement cost than slow penetration of scenarios but with lower overall GHG mitigation.

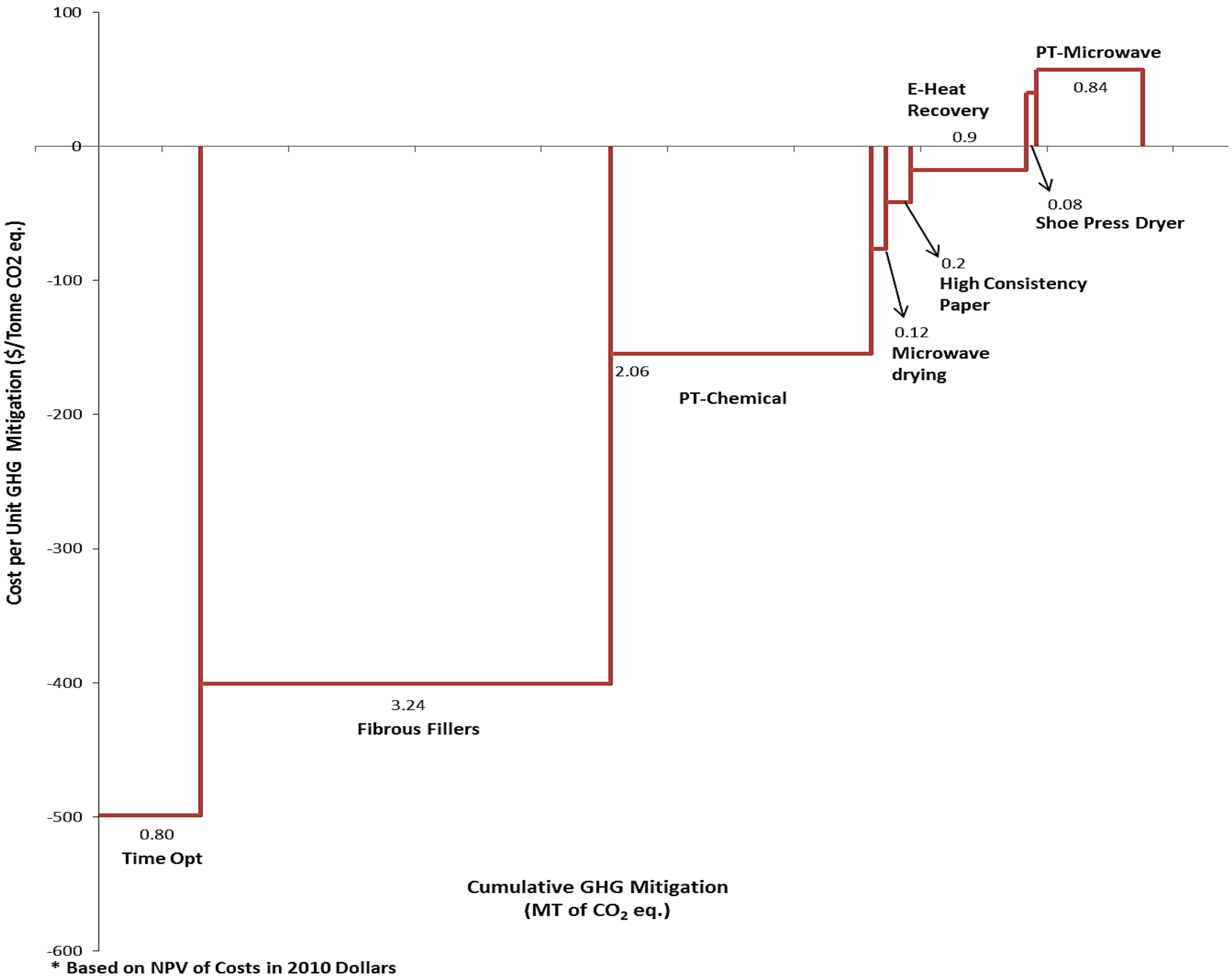


Figure 38: Integrated GHG abatement cost curve for Alberta's pulp and paper industry under slow penetration scenario

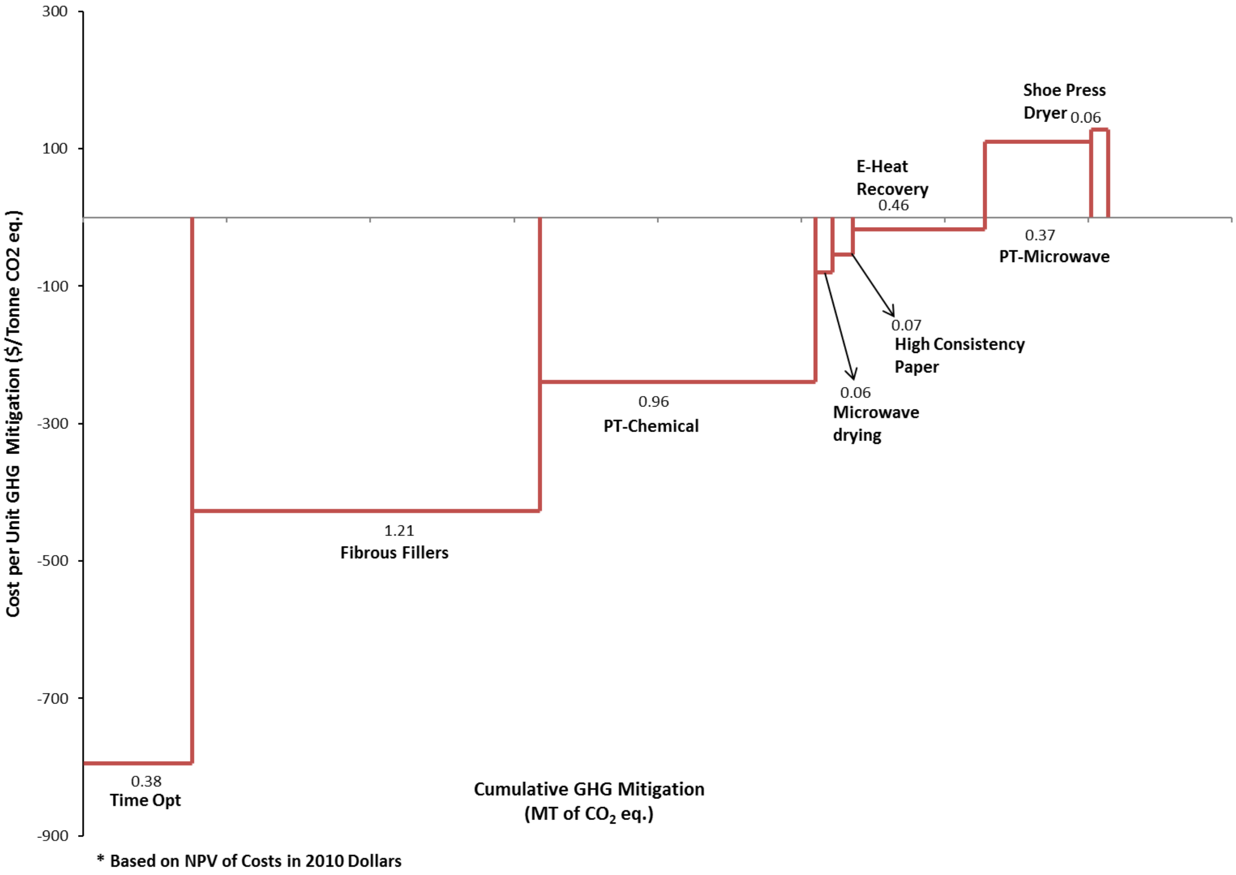


Figure 39: Integrated GHG abatement cost curve for Alberta's pulp and paper industry under fast penetration scenario

5 Conclusion and recommendations for future work

5.1 Conclusion

Canada is the fifth largest energy consumer in the world and consumed 8924 PJ of energy in 2013. The industrial sector in Canada consumes 40% of this energy, and the pulp and paper sector is responsible for 16.4% of this consumption. Alberta's pulp and paper industry is responsible for 10% of pulp and paper related production in Canada, with 86.4 PJ of energy consumption in 2013. There are seven pulp and paper mills in Alberta that are using three different technologies. Due to the lack of process level information, a detailed energy demand tree is required to understand the energy consumption patterns of the industry that will in turn allow us to accurately analyze GHG mitigation potential through the implementation of efficient and emerging technologies. The objective of this research was to develop a detailed energy demand tree for the pulp and paper mills that can be used to develop a business-as-usual (BAU) scenario. The BAU scenario provided a baseline against which energy efficient technologies are assessed in terms of potential reduction in GHG emissions as well as the cost of implementing these technologies as a GHG mitigation option.

The Long-range Energy Alternatives Planning (LEAP) software was used in this study to develop the energy demand tree and simulate a business-as-usual scenario (BAU) for Alberta's pulp and paper industry. An energy transformation sector, consisting of Alberta's natural resource extraction and refining as well as electricity generation, was developed to account for emissions and losses associated with energy generation and transmission to the mills. The built-in technology and environmental database (TED) in LEAP was used to assign emission factors to different forms of energy generation and consumption in the transformation sector as well as the pulp and paper mills energy demand tree. Using the BAU scenario as reference, the mitigation scenarios were developed in LEAP to perform a comparative analysis of energy and emissions reduction from the reference case.

The demand tree was developed by collecting energy consumption data from pulp and paper mills at the process level with units of energy (kWh or GJ) per air dried metric tonnes (ADMT) of pulp production. The demand tree was validated by comparing the LEAP model results with annual energy consumptions reported by federal agencies (Natural Resource Canada and Statistics Canada) as shown in Figure 40.

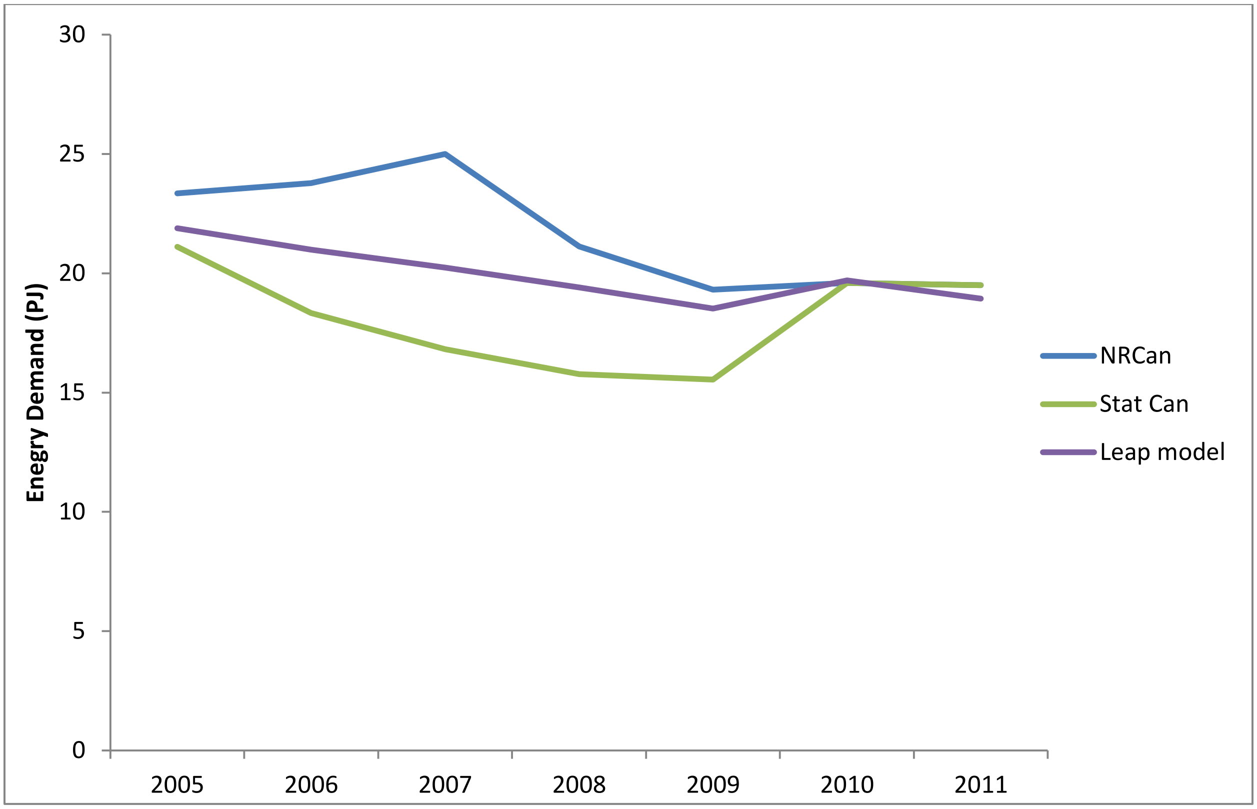


Figure 40: Alberta's pulp and paper sector LEAP model validation

The BAU scenario was developed based on a projection of existing mill production to 2050 as no new mills are expected to start up in Alberta in the future. The energy consumption and GHG emissions in the BAU scenario are shown in Table 49. Energy consumption is expected to decrease from 20.37 PJ to 19.46 PJ between 2010 and 2050, although the mill production is expected to increase in the BAU scenario. The reason for the decrease in energy consumption is the expected improvement in process efficiencies inherently. Emissions will increase by 2020 due to changes in Alberta's transformation sector discussed in detail in an earlier study [65].

Table 49: Alberta's pulp and paper mills energy and emissions profile in the BAU scenario

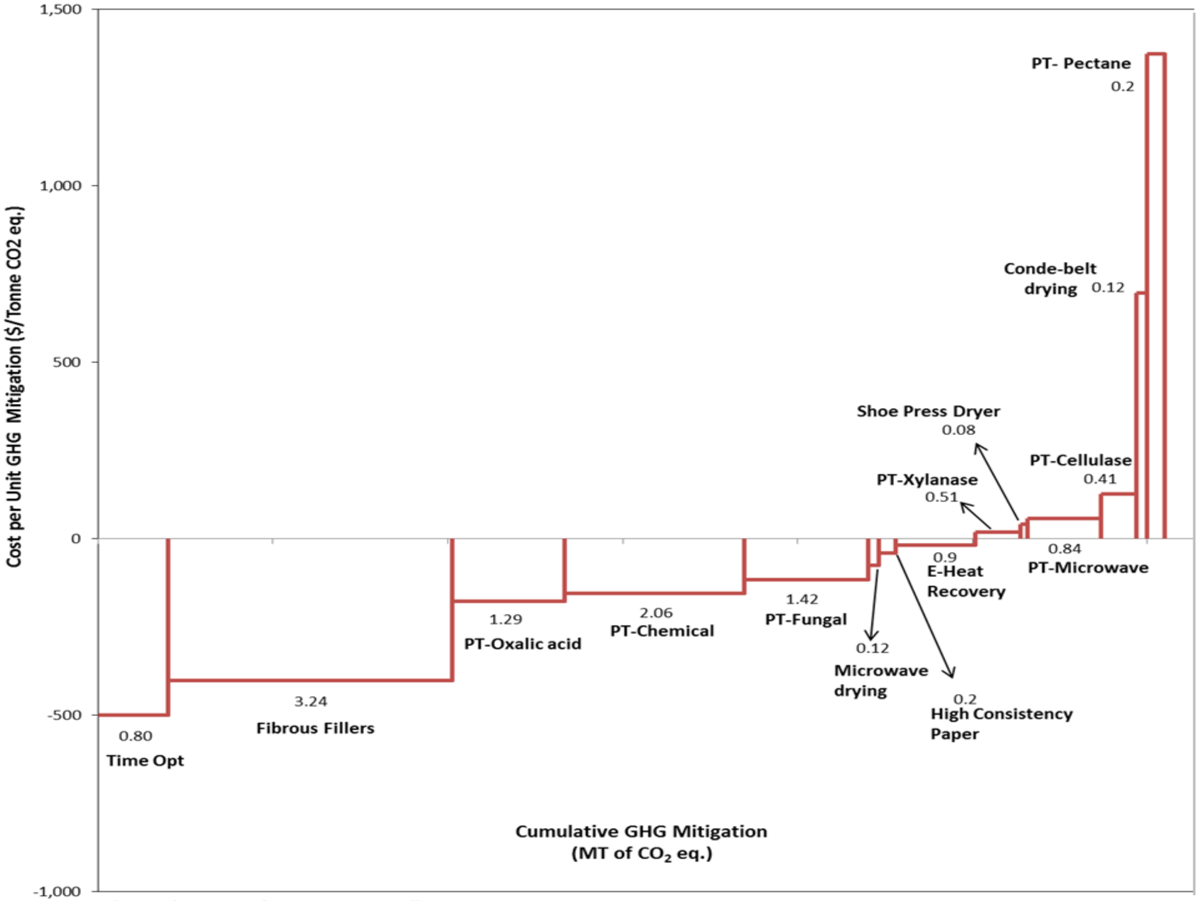
Energy and emissions	2010	2020	2030	2040	2050
Net energy demand (PJ)*	20.37	19.59	19.55	19.51	19.46
Net GHG emissions (MT of CO_2 eq.)**	26.82	70.20	69.55	69.22	68.94

* Includes electricity and natural gas demand by Alberta's pulp and paper mills as developed by the LEAP model

** Includes pulp and paper and transformation sector-related emissions

Twenty-eight GHG mitigation scenarios were developed for Alberta's pulp and paper industry considering slow penetration of technologies between 2010 and 2050 as well as fast penetration between 2010 and 2030. The scenarios were compared in three categories: pretreatment technologies, efficient drying technologies, and process improvement-related scenarios. Variations in energy demand through the use of energy efficient technologies reduce the overall energy demand in the pulp and paper mills which is shown in Appendix C Table 68 and 69. When the GHG mitigation scenarios are implemented, the resulting energy reduction inherently reduces the emissions (Appendix C Table 70, 71).

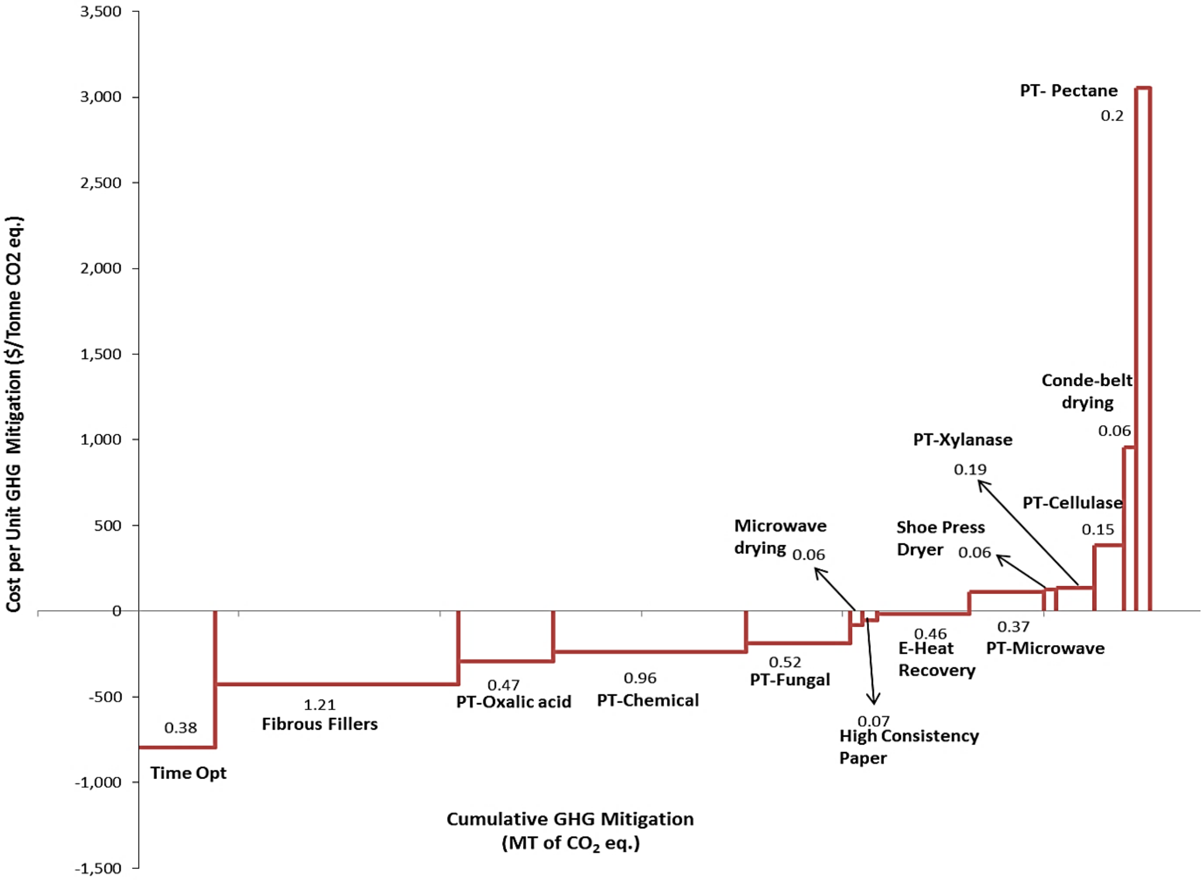
The scenarios were evaluated from a cost perspective by calculating the cost of saved energy and using it to calculate the GHG abatement cost in the form of dollars per unit GHG mitigation. The net mitigation potential and GHG abatement costs were used to develop a cost curve to provide a comprehensive comparison of mitigation scenarios. The GHG abatement cost curve for slow penetration scenarios, given in Figure 41, shows that the fibrous fillers scenario has the highest GHG mitigation potential (3.24 MT CO_2 eq.) and the idle time optimization scenario has the lowest GHG abatement cost (-\$498/tonne CO_2 eq. mitigation). The pectinase pretreatment and Condebelt drying scenarios show low GHG mitigation potential with high GHG abatement costs of \$1373 and \$696/tonne of CO_2 eq., making them the least attractive options. Scenarios such as chemical pretreatment, oxalic acid pretreatment, and fungal pretreatment offer a high level of GHG mitigation and negative abatement costs.



* Based on NPV of Costs in 2010 Dollars

Figure 41: GHG abatement cost curve for Alberta's pulp and paper industry under slow penetration scenario

In fast penetration scenarios, a trend similar to slow penetration case can be observed as shown in Figure 42. The idle time optimization results in lowest GHG abatement cost of -\$795/tonne CO_2 eq. mitigation whereas the pectinase pretreatment scenario requires highest GHG abatement of \$3051/tonne CO_2 eq. among all developed scenarios. The fibrous fillers scenario results in highest GHG mitigation of 1.21 MT of CO_2 eq. in fast penetration of all scenarios followed by chemical pretreatment scenario with mitigation potential of 0.96 MT of CO_2 eq.



* Based on NPV of Costs in 2010 Dollars

Figure 42: Cost curve for Alberta's pulp and paper industry under fast penetration scenario

The GHG abatement cost curves shown in Figures 41 and 42 represent outcomes when each scenario is implemented at a time and reflects the fact that the scenarios may not be implemented simultaneously. To develop a GHG abatement cost curve with those scenarios that can all be implemented simultaneously, an integrated GHG abatement cost curve is developed. This curve was developed based on the scenarios that can be implemented simultaneously and shows highest GHG mitigation during the study periods.

The integrated GHG abatement cost curve includes eight scenarios with the remaining 6 scenarios excluded as these showed lower potential in terms of costs and emissions. Two integrated GHG abatement cost curves were developed based on the slow penetration and fast penetration scenarios as shown in Figures 43 and 44, respectively. In the slow penetration of integrated scenarios, the collective GHG mitigation achievable can reach 8.26 MT CO_2 eq. with a net abatement cost of -$1092/tonne CO_2 mitigation. In the fast penetration case, the net GHG mitigation potential is 3.57 MT CO_2 eq. with a net abatement cost of -$1374/tonne of CO_2 eq. which shows more cost saving potential than slow penetration of scenarios but with lower overall GHG mitigation.

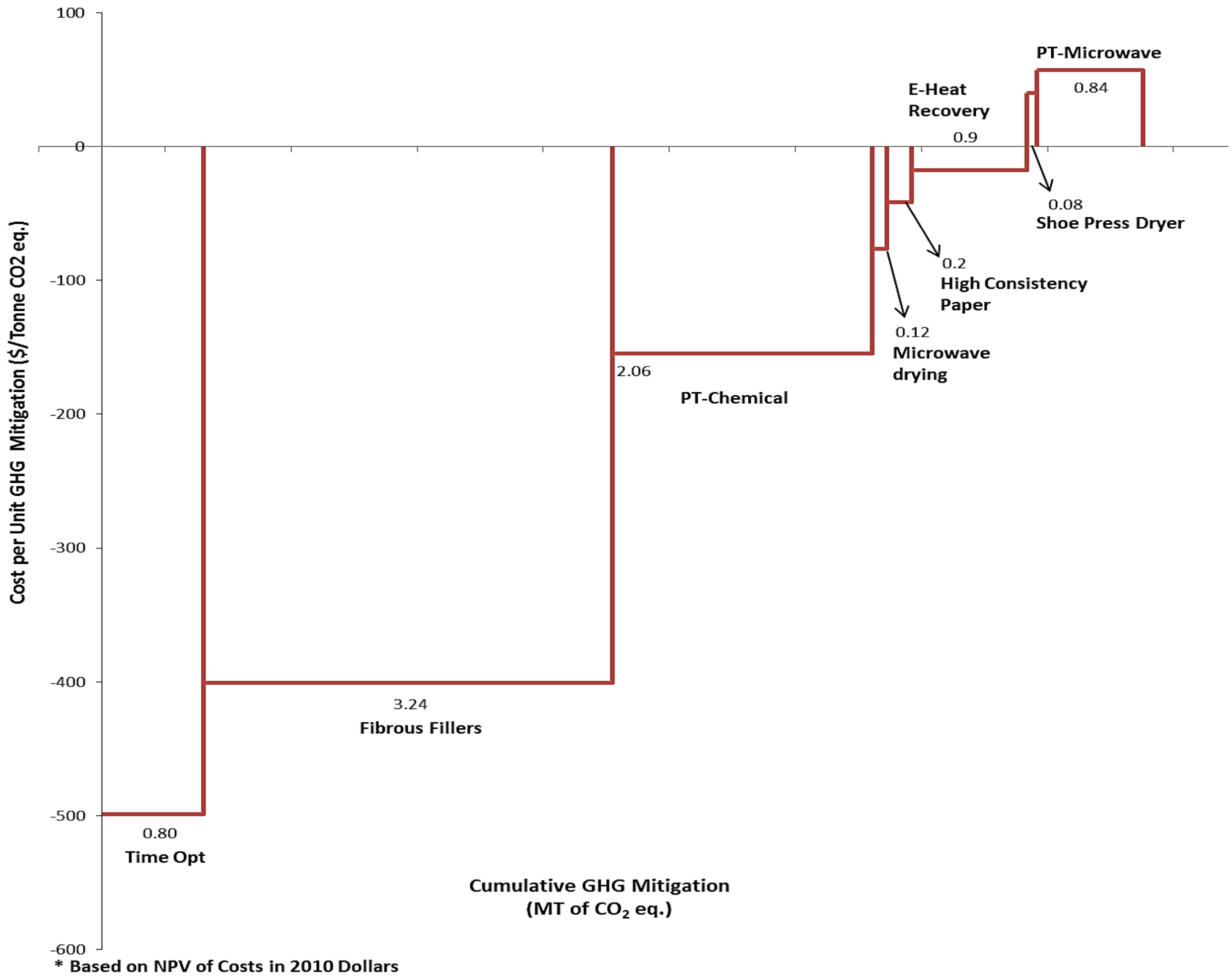


Figure 43: Integrated GHG abatement cost curve for Alberta's pulp and paper industry under slow penetration scenario

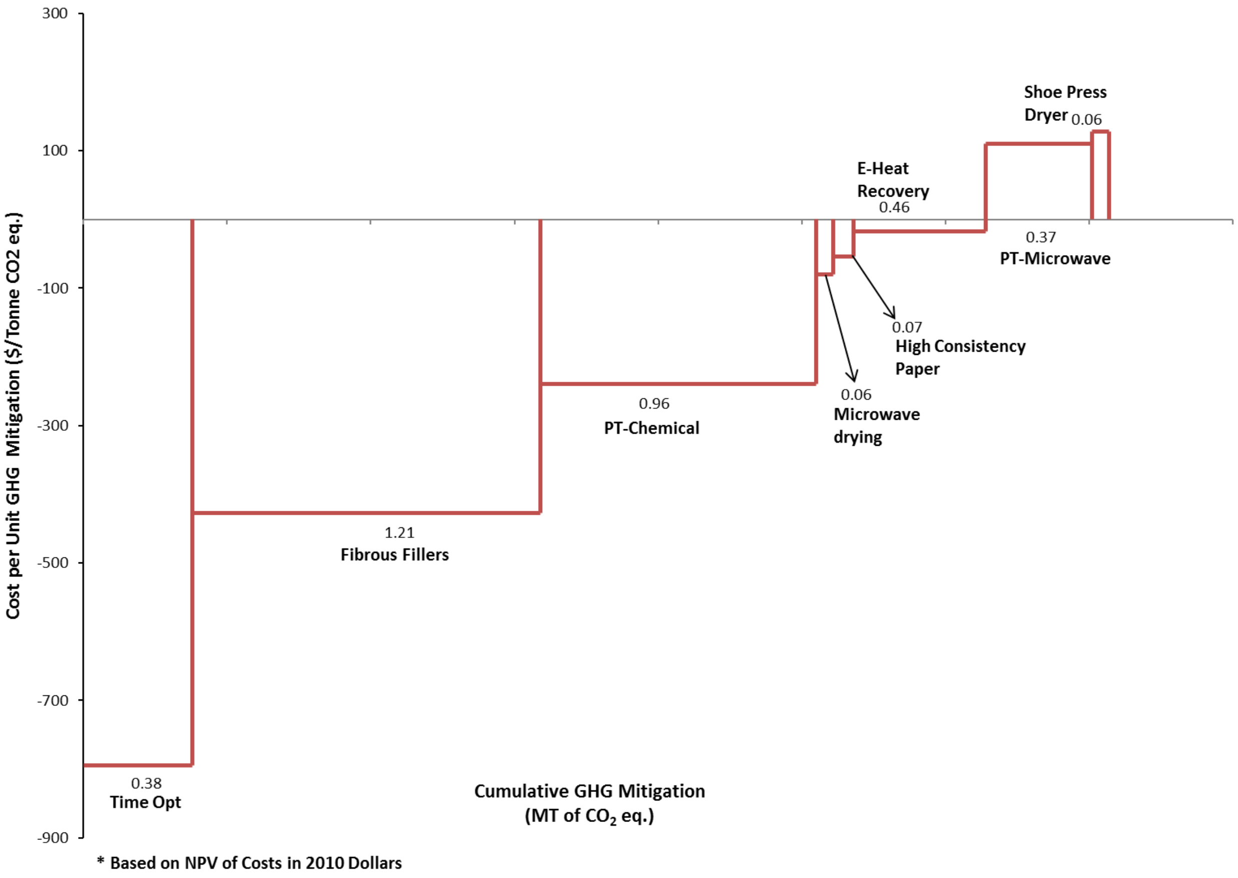


Figure 44: Integrated GHG abatement cost curve for Alberta's pulp and paper industry under fast penetration scenario

5.2 Future recommendations

This research work developed GHG mitigation options for Alberta's pulp and paper industry by developing an energy demand tree and evaluating twenty-eight scenarios. Some of the recommendations to extend this work are:

i. Daily kraft mill natural and black liquor consumption varies significantly due to electricity and natural gas price variations and plant operational status. In this study, the natural gas share is assumed to be constant at 10% of net steam production. A model can be developed to calculate mill natural gas consumption based on market parameters to accurately reflect achievable GHG mitigation potential.

ii. Pulp and paper mills consume significant amounts of water, which can be studied through the Water Evaluation and Planning System (WEAP) model and the results integrated with the current LEAP model to study pulp and paper sector energy and water use in detail and run combined scenarios.

iii. The current study only covers energy-related emissions; however, a large quantity of chemicals are used in mills and can cause environmental emissions. The study can be expanded to include chemical-related emissions and environmental concerns.

iv. Mills gather significant amounts of biomass for process use. In light of the new Alberta Government policy of phasing out of coal plants and increasing the renewable electricity share, a feasible study of replacing or integrating electricity plants in existing pulp and paper mills can be performed to assess the environmental and economic implications.

v. This study can further be extended to the pulp and paper sector in Canada to assess the various options of GHG mitigation.

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Appendix A

Pulp and paper mills process description

(i) TMP and paper mill

A detailed description of various processes involved in thermo-mechanical pulping (a-e) and paper making (f-h) collected from [36, 37, 40, 52, 53, 84] is discussed as below.

a) Chips handling

The feedstock required for the pulp mill is wood chips; these can be produced on site from logs or purchased from saw mills in the form of chips. In this study, it is assumed all mills purchase wood chips, as most of the pulp mills in Alberta are located near saw mills.

The wood chips are initially screened to remove debris such as small stones, grains of sand, pieces of metal, etc., that can harm the pulping equipment. The screened chips are subjected to the steam preheating process to soften them before refining, a process that increases the quality of pulp compared to directly refined chips that are not preheated. The chip handling process includes screening, steaming, and conveying [36, 52, 84] and consumes around 40 kWh/ADMT electricity produced with steam recovered from other processes.

b) Refiner

Refining is the main process in the TMP mill. During refining, wood fibers are separated by mechanical force i.e. the chips are ground between two grooved discs to soften the lignin and separate the fibers. The process is highly electricity intensive and the energy is converted to heat during grounding due to friction. The water present in wood chips converts into steam, which increases the pressure of the overall process. A significant amount of heat can be recovered from this process and used in other processes.

The refiner consumes the highest amount of electricity in the TMP mill. A wide range (1000-4300 kWh/ADMT) of energy consumption has been reported [36, 40, 52, 53, 84]. Based on data from two Canadian studies [52, 53], 2160 kWh/ADMT is selected as the energy intensity for the refiner process.

c) Screening/cleaning/thickening/auxiliaries

The pulp obtained from refining processes can contain unrefined products such as shavings or coarse fibers. They are removed in the screening (using hydro cyclones) and cleaning processes, and rejects are sent back to the refiner. The pulp goes through a thickening process to achieve the desired pulp quality based on the application.

The processes are combined as one energy-consuming sub-unit due to limited data for each process. Collective numbers for these processes have been reported to be 190 - 240 kWh/ADMT [40, 53], and a value of 240 kWh/ADMT has been considered as it is reported in a Canadian study on pulp and paper mills.

d) Heat recovery

The heat recovery system is used in the refiner to recover process heat in the form of steam that can be used in other processes. The system consumes 10 kWh/ADMT of electricity in order to operate [53].

e) Effluent treatment

The mill uses a considerable amount of water for washing and cleaning, and this water has to be treated before it is sent back into the main water stream or reused internally. The clarification and activated sludge treatment process consumes electricity between 30 and 70 kWh/ADMT [40, 52, 53], and the value of 60 kWh/ADMT is selected for this study as it is given in benchmark reports for Canadian mills.

f) Paper mill stock preparation

In an integrated mill, pulp is supplied in suspended form and has to be prepared in order to produce the desired quality of the paper. The stock preparation involves a number of steps such as fiber disintegration and de-clustering, addition of chemical additives, containment screening, cleaning, and optimal mixing. The required pulp slurry consistency is produced at the end of this process. The stock preparation energy consumption varies depending on the paper type being produced and pulp feedstock properties and has been reported to be in range of 90-300 kWh/ADMT [40, 53, 84]. The value of 100 kWh/ADMT as well as the steam requirement of 0.7 GJ/ADMT are selected here [53].

g) Forming and pressing

The forming and pressing sections are the parts of the paper machine where pulp is given the shape of the paper. A wet pulp slurry with 0.2 to 1.5% consistency is fed into the paper machine, where it passes through a forming section, known as the wet end of the paper machine. The pulp slurry is spread evenly on a moving fabric mesh using the headbox. The uniform layer covers the width of the paper machine, and a large amount of water is removed by gravity assisted drainage and vacuum pressure. The wet sheet produced in forming is up to 80% water.

The 20% concentrated paper web goes through the pressing section where it passes through a number of rollers, press fabrics, and vacuum sections to reach up to 50% dryness without any application of heat. The water removal promotes bonding between the fibers, thus giving the pulp the shape of the paper. Achieving high dryness at this stage can save a significant amount of energy in the steam assisted drying process.

The conventional energy consumption for the forming, pressing, and drying sections is usually reported together; however the reference [53] subcategorizes, it is divided into 2 sub-sectors, "forming and pressing" and "drying", which provide greater flexibility in scenario analysis. The energy intensity for the forming and pressing sections is considered to be 140 kWh/ADMT along with 0.3 GJ/ADMT steam requirement.

h) Drying and finishing

The 50% dry concentration paper from the press section is sent to the dry end of the paper machine where it is further dried to achieve a 5-10% water concentration in the final product. The dryer section is highly energy intensive and uses steam as a heat source to evaporate the water in the paper web. The steam is typically used to heat rotating drums, which are in contact with the paper web and cause the water in the paper to evaporate. Once dried, the paper is sent to the finishing section where it is cut or wrapped and prepared for shipping.

The typical energy required for this process is 90 kWh/ADMT of electricity with 3.4 GJ/ADMT of steam to achieve up to 90% dryness [53]. The energy requirement reported by other sources ranges from 3-6 GJ/ADMT [36, 40, 52, 84]; hence a value of 3.4 GJ/ADMT is selected as the average energy consumption.

(ii) BCTMP mill

BCTMP is similar to TMP except that BCTMP includes chemical pretreatment, pulp drying (for a non-integrated mill), and washing stages (due to the chemicals in the wood chips). These three processes will be discussed in detail here; the other processes are explained in TMP mill process description and no change is expected in the energy intensities.

a) Chemical pretreatment

After chip debarking and cleaning, the chips are chemically treated and then sent to the refiner. The chemicals typically used are alkaline solutions such as sodium sulfate and alkaline peroxide depending on the type of wood chips. Following this short chemical treatment, the wood chips are softened sufficiently that they can be easily refined with low energy consumption. The process does not absorb the lignin in the wood chips and thus the yield is high (~90%), especially compared to the kraft process, in which lignin is absorbed during chemical treatment, resulting in a yield of only~50%. [40].

b) Bleaching

For bright paper/board, mechanically produced pulp must be bleached. In the BCTMP process, the bleaching has to take into account the pulp lignin content, which makes it different from the low lignin in chemically produced pulp. The lignin content has to be targeted to convert chromophoric groups of lignin polymers into a colorless form. However, the effect is not long lasting, and the product turns yellow over time. The most common chemicals used for bleaching are hydrogen peroxide and sodium dithionite/hydrosulfite [36, 40].

The process is highly energy intensive with the major energy portion being thermal energy. However, the thermal energy demand can be met by the heat recovered from the pulp dryer and the refining process. The electricity demand is reported to be in the range of 185 to 500 kWh/ADMT, with lower values representing the integrated mills [36, 86, 87]. The value of 500 kWh/ADMT is reported for a non-integrated mill, which corresponds to Alberta's BCTMP mills; therefore, this value is used in this study.

c) Pulp dryer

In a standalone pulp mill, the final product has to be shipped in the form of pulp. To maintain the pulp properties while minimizing shipping costs, the pulp moisture level has to be optimized. A standard practice is to produce market pulp in units of air-dried metric tonnes (ADMT). Each ADMT is 90% dry pulp with 10% moisture [150]. The pulp is dried with thermal and electrical energy in steam drums or air floatation dryers. 2.11-5.6 GJ/ADMT thermal energy and 150-191 kWh/ADMT electricity is required, as reported in literature [36, 37, 40, 52, 84]. A value of 150 kWh/ADMT is used in the LEAP model for electricity consumption, as this is the most recent figure. The thermal energy value of 3.37 GJ/ADMT is used that is close to the average of the ranges given above.

(iii) Kraft mill

Kraft pulping is similar to mechanical pulping but for the replacement of refining with digestion. The digestion process has additional steps related to chemical recovery as well as the oxygen delignification of pulp. The process flow chart is shown in Figure 14 and the processes involved are explained below.

d) Chip handling

The chips can be produced on site from logs or bought from saw mills. In Alberta, most pulp mills are located near saw mills and wood chips are bought from saw mills. The chips are conveyed to the pulping section as preheated chips. Heat is recovered from black liquor burning; therefore, energy is required only to run the conveyers.

The energy required varies based on the distance travelled as well as the status of the feedstock. An electricity requirement of 20-90 kWh/ADMT has been reported in many studies (see Table 7) [52, 53, 84, 86, 89]. The value of 20 kWh/ADMT has been selected for this study as kraft mills in Alberta are expected to receive pre-screened woods chips for direct use.

e) Digester

The wood is composed of cellulose, lignin, and hemicelluloses with small quantities of other extractives. In the chemical pulping process, the lignin content that is responsible for binding the fibers together is absorbed by a chemical mixture of sodium hydroxide and sodium sulphide, allowing the fibers to separate and convert to pulp. The lignin is removed from the fiber walls as well as the middle lamina to allow maximum separation of the fibers without breaking them, thereby producing high quality pulp. The chemical used for cooking is known as “white liquor” and contains sodium hydroxide and sodium sulfide. The chemical absorbs the lignin and some of the hemicelluloses during digestion; this mixture turns black and is commonly referred to as “black liquor.” Air in the wood chips hinders the uniform mixing of chips and pulping chemicals, thus the chips are steamed to remove any trapped air [40].

The digestion process can take place in batches or in a continuous process. The batch digestion process mixes the wood chips and chemicals in a batch digester where the chips stay in the chemicals until sufficient lignin is absorbed. The contents are then removed, separated, and sent for further processing while a new batch of wood chips and chemicals is added to the digester. In the continuous process, the wood chips are mixed with chemicals at a high temperature, which reduces the lignin absorption time. The system temperature and the retention time determine the amount of lignin absorbed during the continuous process [37].

The energy required for digestion varies based on process type (batch or continuous) and the wood chip. A wide range of values has been reported (see Table 7); however, the system boundaries in reports also vary widely. Electricity consumption for the digestion process in our model is assumed to be 40 kWh/ADMT with 0.17 GJ/ADMT of steam; these values are taken from a study that used a clearly defined digestion process boundary [53].

f) Washing and screening

Washing separates the pulp from the mixture obtained from the digester. The mixture, known as black liquor, contains pulping chemicals in which over 50% of the wood components are absorbed. The black liquor is washed away from the cellulose fibers using water in drums and diffusers. High efficiency chemical removal is desired at this stage to reduce the chemical and energy use in later stages such as the bleaching process. However, using large amounts of water in the washing process to remove the maximum amount of black liquor will require more steam in the evaporation stage to dry the pulp. The chemical removal and amount of water used are optimized to achieve minimal energy use while maintaining pulp quality.

The separated pulp is screened to remove undesired fibers such as knots and bundles of fibers. Screening is done in a number of ways such as through pressure screens, centricleaners, and vibrating equipment. The knots are re-cooked for pulping and the rejects are burned in a boiler, where they generate steam. The washed and screened pulp is dark brown and can be used to make cardboard products or grocery bags. To make a white product, the pulp is bleached [37, 40, 89].

The washing and screening processes are reported together in terms of unit energy consumption in most studies (see Table 7). The value of 30 kWh/ADMT is used for the current study as it represents the case in Canada and local wood species.

g) Oxygen delignification

The pulp obtained from the digester is brown due to the lignin content. Bleaching whitens the pulp, however, the oxygen-assisted delignification process is done first to further reduce the lignin content. Oxygen delignification significantly reduces the energy and chemicals required in the bleaching process. The process takes place in an alkaline environment with oxygen generated on site or directly purchased. Two washing stages are required after delignification to recover the dissolved fibers and remove the chemicals [40, 53, 89].

The oxygen is less soluble in alkaline and thus the reactor has to be pressurized at an elevated temperature. The process requires 75 kWh/ADMT of electricity with 0.5 GJ/ADMT of steam on average based on values taken from the literature and presented in Table 7.

h) Bleaching

Bleaching chemically produced pulp removes lignin, unlike the bleaching process of mechanical pulping, which involves de-colorizing the lignin present in the pulp. The chemical pulp is bleached in several stages alternating with washing stages. A modern mill typically uses a four-stage elemental chlorine-free process. There are different sequences available to bleach the pulp depending on the desired quality with a typical brightness level of 90% ISO. Chlorine dioxide and sodium hydroxide are commonly used chemicals that can be produced on site or purchased directly [40, 53, 89].

Bleaching is highly energy intensive and requires 2.1 GJ/ADMT of steam and 100 kWh/ADMT of electricity. The values reported in several sources are presented in Table 7.

i) Pulp machine

In integrated mills, the pulp is transported to the paper making section directly from the bleaching process output. However, in non-integrated mills such as kraft mills in Alberta, the pulp has to be dried to achieve 10% moisture content for packaging and shipping. The pulp machine distributes the pulp evenly, removes the moisture by double wire press, and finally dries the pulp using steam drum dryers [40, 52, 53].

The typical energy consumption in a pulp machine is shown in Table 7. Values of 141 kWh/ADMT and 2.3 GJ/ADMT are used for the current study.

j) Black liquor evaporators

The black liquor separated in the kraft pulping washing stage is treated further for recycling purposes. The liquor is typically at 15% solids concentration when received from the washing stage and referred to as weak black liquor. The solids components in liquor are absorbed lignin and hemicelluloses from the wood chips and can be burned to generate heat. Burning the black liquor can provide significant amounts of energy along with recovering the pulping chemicals to be reused in digester.

To generate energy from black liquor, the solution is first concentrated to 75%-80% solids concentration by removing water in the evaporators. The evaporators can be of different configurations, though multiple-stage evaporators are most common. The black liquor evaporator is the most energy intensive process in kraft mills due to its steam consumption. Typical values of 3.1 GJ/ADMT of steam and 30 kWh/ADMT of electricity are used for the current model [40, 52, 89].

k) Power plant

The power plant area consists of boilers and steam and gas turbines that generate steam and electricity for mill process use. The concentrated black liquor is burned in a recovery boiler with 75-80% heat-to-steam efficiency. The steam produced is enough to meet mill heat and electricity demands depending on overall process efficiency. When more energy is needed, residual biomass (bark, hog fuel, etc.) and natural gas are burned.

The Tomlinson recovery boiler burns the organic components in the black liquor and leaves the inorganic components as smelt [40]. The smelt is dissolved in water or weak white liquor to form green liquor, which is sent for recausticizing, where it is further processed. The typical energy consumption in the power plant area is shown in Table 7 as gathered from various sources. The intensity of 2.3 GJ/ADMT natural gas with 60 kWh/ADMT of electricity consumption is considered for the LEAP model in this study [40, 53, 84].

l) Kiln and recausticizing

The smelt obtained from recovery boiler is mixed with weak white liquor to form a solution known as green liquor. The green liquor consists of sodium carbonate and sodium sulfide, which are recausticized to sodium hydroxide and calcium carbonate by adding calcium hydroxide. The calcium carbonate is in precipitate form and removed from the solution leaving behind sodium hydroxide and sodium sulfide which is recycled to be used as white liquor. The calcium carbonate is heated in a kiln to produce calcium oxide (lime) and carbon dioxide. The lime is mixed with water to retrieve calcium hydroxide, which is sent back to the causticizing process [37, 40, 53, 84].

The lime kiln and re-causticizing process consume 50 kWh/ADMT of electricity with 1.5 GJ/ADMT of natural gas to convert green liquor to white liquor. Table 7 shows the unit energy consumption from several reports.

m) Hot water supply

Low temperature heat recovery is possible from several areas of kraft pulping such as the digester, evaporators, recovery boilers, etc., to heat water to 60°C. The water supply and transport system consumes significant amounts of energy in the mill, to a total average of 32 kWh/ADMT [53, 89].

n) Waste water treatment

The effluent produced in the mill has to be treated before reuse or discharge. The treatment is done in the primary clarifier to remove fiber sludge and sent to the secondary activated sludge basin for low bio-sledge production and nutrient discharge. The heat removal process takes place in a cooling tower. The typical energy required for this treatment is 30 kWh/ADMT [53, 89].

o) Miscellaneous:

Miscellaneous energy use includes heating, ventilation, air conditioning, lighting, office equipment, and maintenance facilities, etc., that are part of a running plant. 30 kWh/ADMT of electricity consumption are allocated to miscellaneous energy consumption [53, 89].

Appendix B

Scenario 1: Microwave pretreatment

Capital cost	$91/ADMT
O&M costs	Nil
Energy savings potential	0.6 GJ/ADMT
CRF	0.096

Table 50: Microwave pretreatment scenario cost of saved energy (CSE) calculations

	Cost of equipment ($)	Incremental annualized cost ($)	Saved energy (GJ/yr.)	CSE ($/GJ)
2010-2020				**11.14**
Capital cost	171455561.4	16518421	1076858.81	
Incremental O&M costs	-4527114.44	-4527114.44		
2020-2030				**9.14**
Capital cost	171455561.4	16518421	1088898.865	
Incremental O&M costs	-6564971.26	-6564971.26		
2030-2040				**8.40**
Capital	171455561.4	16518421	1100388.725	
Incremental O&M costs	-7273569.47	-7273569.47		
2040-2050				**7.67**
Capital cost	171455561.4	16518421	1111900.977	
Incremental O&M costs	-7995679.92	-7995679.92		

Scenario 2: Xylanase enzymatic pretreatment

Capital cost	$761.24/ADMT (1.6% cost reduction considered annually for CSE calculations)
O&M costs	$4.92/ADMT/year
Energy savings potential	229.25kWh/ADMT (BCTMP mill) 540kWh/ADMT (Paper mill)
CRF	0.130

Table 51: Xylanase pretreatment cost of saved energy (CSE) calculations (BCTMP mill)

	Cost of equipment ($)	Incremental annualized cost ($)	Saved energy (kWh/yr.)	CSE ($/kWh)
2010-2020				**0.29**
Capital cost	372404266	48228056.18	125804854.3	
Incremental O&M costs	-11177186.47	-11177186.47		
2020-2030				**0.20**
Capital cost	327549272	42419129.25	127066188.3	
Incremental O&M costs	-17398289.56	-17398289.56		
2030-2040				**0.13**
Capital cost	278758181.6	36100459.83	128267458.7	
Incremental O&M costs	-19013618.43	-19013618.43		
2040-2050				**0.08**
Capital cost	237234915.3	30723006.87	129468729.1	
Incremental O&M costs	-20525805.71	-20525805.71		

Table 52: Xylanase pretreatment cost of saved energy (CSE) calculations (paper mill)

	Cost of equipment ($)	Incremental annualized cost ($)	Saved energy (kWh/yr.)	CSE ($/kWh)
2010-2020				**0.06**
Capital cost	172481976	22337205	141587935.8	
Incremental O&M costs	-14328077.03	-14328077.03		
2020-2030				**-0.01**
Capital cost	151707031	19646755	141888502.01	
Incremental O&M costs	-21180153.83	-21180153.83		
2030-2040				**-0.04**
Capital cost	129109052.5	16720213	142153929.86	
Incremental O&M costs	-22827693.77	-22827693.77		
2040-2050				**-0.07**
Capital cost	109877224	14229603	142399203.9	
Incremental O&M costs	-24334441.73	-24334441.73		

Scenario 3: Cellulase enzymatic pretreatment

Capital cost	$761.24/ADMT (1.6% cost reduction considered annually for CSE calculations)
O&M costs	$4.92/ADMT/year
Energy savings potential	183.4kWh/ADMT (BCTMP mill) 432kWh/ADMT (Paper mill)
CRF	0.130

Table 53: Cellulase pretreatment cost of saved energy (CSE) calculations (BCTMP mill)

	Cost of equipment ($)	Incremental annualized cost ($)	Saved energy (kWh/yr.)	CSE ($/kWh)
2010-2020				**0.40**
Capital cost	372404266.2	48228056.21	100643883.5	
Incremental O&M costs	-8401762.37	-8401762.37		
2020-2030				**0.29**
Capital cost	327549272.2	42419129.28	101652950.6	
Incremental O&M costs	-13373230.86	-13373230.86		
2030-2040				**0.21**
Capital cost	278758181.8	36100459.85	102613966.9	
Incremental O&M costs	-14660337.8	-14660337.8		
2040-2050				**0.14**
Capital cost	237234915.5	30723006.89	103574983.3	
Incremental O&M costs	-15864931.46	-15864931.46		

Table 54: Cellulase pretreatment cost of saved energy (CSE) calculations (paper mill)

	Cost of equipment ($)	Incremental annualized cost ($)	Saved energy (kWh/yr.)	CSE ($/kWh)
2010-2020				**0.10**
Capital cost	172481976	22337205	113270348.7	
Incremental O&M costs	-11204456.94	-11204456.94		
2020-2030				**0.03**
Capital cost	151707031	19646755	113510801.61	
Incremental O&M costs	-16685570.69	-16685570.69		
2030-2040				**-0.01**
Capital cost	129109052.6	16720213	113723143.89	
Incremental O&M costs	-18003118.97	-18003118.97		
2040-2050				**-0.04**
Capital cost	109877224	14229603	113919363.1	
Incremental O&M costs	-19208070.39	-19208070.39		

Scenario 4: Pectinase Enzymatic pretreatment

Capital cost	$761.24/ADMT (1.6% cost reduction considered annually for CSE calculations)
O&M costs	$4.92/ADMT/year
Energy savings potential	91.7kWh/ADMT (BCTMP mill) 216kWh/ADMT (Paper mill)
CRF	0.130

Table 55: Pectinase pretreatment cost of saved energy (CSE) calculations (BCTMP mill)

	Cost of equipment ($)	Incremental annualized cost ($)	Saved energy (kWh/yr.)	CSE ($/kWh)
2010-2020				**0.90**
Capital cost	372404266.2	48228056.21	50321941.74	
Incremental O&M costs	-2850914.15	-2850914.15		
2020-2030				**0.73**
Capital cost	327549272.2	42419129.28	50826475.31	
Incremental O&M costs	-5323113.48	-5323113.48		
2030-2040				**0.59**
Capital cost	278758181.8	36100459.85	51306983.47	
Incremental O&M costs	-5953776.54	-5953776.54		
2040-2050				**0.47**
Capital cost	237234915.5	30723006.89	51787491.64	
Incremental O&M costs	-6543182.97	-6543182.97		

Table 56: Pectinase pretreatment cost of saved energy (CSE) calculations (paper mill)

	Cost of equipment ($)	Incremental annualized cost ($)	Saved energy (kWh/yr.)	CSE ($/kWh)
2010-2020				**0.31**
Capital cost	172481976	22337205	56635174.34	
Incremental O&M costs	-4957216.76	-4957216.76		
2020-2030				**0.21**
Capital cost	151707031	19646755	56755400.80	
Incremental O&M costs	-7696404.39	-7696404.389		
2030-2040				**0.15**
Capital cost	129109052.6	16720213	56861571.94	
Incremental O&M costs	-8353969.36	-8353969.36		
2040-2050				**0.09**
Capital cost	109877224	14229603	56959681.54	
Incremental O&M costs	-8955327.71	-8955327.71		

Scenario 5: Fungal pretreatment

Capital cost	\$67.93/ADMT (1.6% cost reduction considered annually for CSE calculations)
O&M costs	\$44.23/ADMT/year
Energy savings potential	712.8kWh/ADMT
CRF	0.130

Table 57: Fungal pretreatment scenario cost of saved energy (CSE) calculations

	Cost of equipment (\$)	Incremental annualized cost (\$)	Saved energy (kWh/yr.)	CSE (\$/kWh)
2010-2020				**-0.04**
Capital cost	17231300	2231532.18	186896075.3	
Incremental O&M costs	-9018791.84	-9018791.84		
2020-2030				**-0.09**
Capital cost	15155840.81	1962750.72	187292822.7	
Incremental O&M costs	-18042529.44	-18042529.44		
2030-2040				**-0.10**
Capital cost	12898256.8	1670383.26	187643187.4	
Incremental O&M costs	-20198733.86	-20198733.86		
2040-2050				**-0.11**
Capital cost	10976958.03	1421566.28	187966949.1	
Incremental O&M costs	-22170501.23	-22170501.23		

Scenario 6: Chemical pretreatment

Capital cost	\$7.21/ADMT (1% cost reduction considered annually for CSE calculations)
O&M costs	\$5.27/ADMT/year
Energy savings potential	877.5kWh/ADMT
CRF	0.130

Table 58: Chemical pretreatment scenario cost of saved energy (CSE) calculations

	Cost of equipment (\$)	Incremental annualized cost (\$)	Saved energy (kWh/yr.)	CSE (\$/kWh)
2010-2020				**-0.10**
Capital cost	1730364.16	224090.08	230080395.7	
Incremental O&M costs	-23997619.85	-23997619.85		
2020-2030				**-0.15**
Capital cost	1597114.44	206833.63	230568815.8	
Incremental O&M costs	-35133761.40	-35133761.4		
2030-2040				**-0.16**
Capital cost	1444401.67	187056.62	231000136	
Incremental O&M costs	-37812353.23	-37812353.23		
2040-2050				**-0.17**
Capital cost	1306290.98	169170.66	231398706.3	
Incremental O&M costs	-40262056.38	-40262056.38		

Scenario 7: Oxalic acid pretreatment

Capital cost	$7.21/ADMT (1% cost reduction considered annually for CSE calculations)
O&M costs	$17.31/ADMT/year
Energy savings potential	648kWh/ADMT
CRF	0.130

Table 59: Oxalic acid pretreatment scenario cost of saved energy (CSE) calculations

	Cost of equipment ($)	Incremental annualized cost ($)	Saved energy (kWh/yr.)	CSE ($/kWh)
2010-2020				**-0.08**
Capital cost	1730364.16	224090.08	169905523	
Incremental O&M costs	-14203040.59	-14203040.59		
2020-2030				**-0.13**
Capital cost	1597114.44	206833.63	170266202.4	
Incremental O&M costs	-22419184.13	-22419184.13		
2030-2040				**-0.14**
Capital cost	1444401.67	187056.62	170584715.8	
Incremental O&M costs	-24390625.63	-24390625.63		
2040-2050				**-0.15**
Capital cost	1306290.98	169170.66	170879044.6	
Incremental O&M costs	-26193542.44	-26193542.44		

Scenario 8: Microwave drying technology

Capital cost	$12.43 million
O&M costs	$0.63 million (Lifetime)
Energy savings potential	0.9 GJ/ADMT
CRF	0.08

Table 60: Microwave drying technology scenario cost of saved energy (CSE) calculations

	Cost of equipment ($)	Incremental annualized cost ($)	Saved energy (GJ/yr.)	CSE ($/GJ)
2010-2020				**0.20**
Capital cost	12942000	1038499.563	235979.8931	
Incremental O&M costs	-992059.47	-992059.47		
2020-2030				**-1.64**
Capital cost	12942000	1038499.563	236480.8367	
Incremental O&M costs	-1425742.96	-1425742.96		
2030-2040				**-2.23**
Capital cost	12942000	1038499.563	236923.2164	
Incremental O&M costs	-1566062.46	-1566062.46		
2040-2050				**-2.82**
Capital cost	12942000	1038499.563	237332.0064	
Incremental O&M costs	-1706654.46	-1706654.46		

Scenario 9: Shoe press drying

Capital cost	\$50.81/ADMT (1% cost reduction considered annually for CSE calculations)
O&M costs	Nil
Energy savings potential	0.6 GJ/ADMT
CRF	0.130

Table 61: Shoe press drying technology scenario cost of saved energy (CSE) calculations

	Cost of equipment (\$)	Incremental annualized cost (\$)	Saved energy (GJ/yr.)	CSE (\$/GJ)
2010-2020				**4.92**
Capital cost	12194147.45	1579197.88	173051.92	
Incremental O&M costs	-727510.28	-727510.28		
2020-2030				**2.38**
Capital cost	11255115.77	1457588.98	173419.28	
Incremental O&M costs	-1045544.84	-1045544.84		
2030-2040				**0.98**
Capital cost	10178924.95	1318217.35	173743.69	
Incremental O&M costs	-1148445.80	-1148445.80		
2040-2050				**-0.34**
Capital cost	9205637.27	1192172.14	174043.47	
Incremental O&M costs	-1251546.60	-1251546.60		

Scenario 10: Condebelt drying technology

Capital cost	$327.62/ADMT
O&M costs	Nil
Energy savings potential	0.9 GJ/ADMT
CRF	0.08

Table 62: Condebelt drying technology scenario cost of saved energy (CSE) calculations

	Cost of equipment ($)	Incremental annualized cost ($)	Saved energy (GJ/yr.)	CSE ($/GJ)
2010-2020				**25.88**
Capital cost	86491680	6940316.17	230735.89	
Incremental O&M costs	-970013.70	-970013.70		
2020-2030				**23.99**
Capital cost	86491680	6940316.17	231225.70	
Incremental O&M costs	-1394059.78	-1394059.78		
2030-2040				**23.35**
Capital cost	86491680	6940316.17	231658.25	
Incremental O&M costs	-1531261.07	-1531261.07		
2040-2050				**22.72**
Capital cost	86491680	6940316.17	232057.96	
Incremental O&M costs	-1668728.80	-1668728.80		

Scenario 11: Fibrous fillers

For kraft mills

Pulp production cost in the base year: $767.89/ADMT

Filler production cost in the base year: $575.92/ton of fibrous filler

Net cost savings in 2015: $192.79/ADMT of pulp

Energy savings potential: 1111 kWh/ADMT (25% of net kraft mill energy reduction)

The costs are considered on an annual basis as O&M costs in the table. The future value of the production costs has been considered in the analysis for 2020 onwards to account for changes in the economy and fuel prices with discount rate of 5%.

For paper mills

Pulp production cost in the base year: $767.89/ADMT

Filler production cost in the base year: $575.92/ton of fibrous filler

Net cost savings in 2015: $192.79/ADMT of pulp

Energy savings potential: 1107 kWh/ADMT (25% of net paper mill energy reduction)

The costs are considered on an annual basis as O&M costs in the table. The future value of the production costs has been considered in the analysis for 2020 onwards to account for changes in the economy and fuel prices with discount rate of 5%.

Table 63: Fibrous fillers scenario cost of saved energy (CSE) calculations (kraft mills)

	Cost of equipment ($)	Incremental annualized cost ($)	Saved energy (kWh/yr.)	CSE ($/kWh)
2010-2020				**-0.0787**
Capital cost	0	0	1993768191	
Incremental O&M costs	-156903206.9	-156903206.9		
2020-2030				**-0.1077**
Capital cost	0	0	2016059953	
Incremental O&M costs	-217143132.3	-217143132.3		
2030-2040				**-0.1906**
Capital cost	0	0	2037333044	
Incremental O&M costs	-388307734.3	-388307734.3		
2040-2050				**-0.3105**
Capital cost	0	0	2058647595	
Incremental O&M costs	-639129718	-639129718		

Table 64: Fibrous fillers scenario cost of saved energy (CSE) calculations (Paper mills)

	Cost of equipment ($)	Incremental annualized cost ($)	Saved energy (kWh/yr.)	CSE ($/kWh)
2010-2020				**-0.0790**
Capital cost	0	0	290255268.5	
Incremental O&M costs	-22922226.29	-22922226.29		
2020-2030				**-0.1081**
Capital cost	0	0	290871429.1	
Incremental O&M costs	-31438603.55	-31438603.55		
2030-2040				**-0.1913**
Capital cost	0	0	291415556.2	
Incremental O&M costs	-55737344.03	-55737344.03		
2040-2050				**-0.3115**
Capital cost	0	0	291918367.9	
Incremental O&M costs	-90946910.75	-90946910.75		

Scenario 12: Efficient heat recovery system

Capital cost	$62.96/ADMT
O&M costs	Nil
Energy savings potential	1.7 GJ/ADMT
CRF	0.130

Table 65: Efficient heat recovery scenario cost of saved energy (CSE) calculations

	Cost of equipment ($)	Incremental annualized cost ($)	Saved energy (GJ/yr.)	CSE ($/GJ)
2010-2020				**0.78**
Capital cost	35888953.85	4647783.71	932904.05	
Incremental O&M costs	-3921928.61	-3921928.61		
2020-2030				**-1.10**
Capital cost	35888953.85	4647783.71	942257.45	
Incremental O&M costs	-5680870.16	-5680870.16		
2030-2040				**-1.72**
Capital cost	35888953.85	4647783.71	951165.45	
Incremental O&M costs	-6287203.63	-6287203.63		
2040-2050				**-2.35**
Capital cost	35888953.85	4647783.71	960073.45	
Incremental O&M costs	-6903888.21	-6903888.21		

Scenario 13: Idle time optimization

Capital cost	$1.06/ADMT
O&M costs	Nil
Energy savings potential	346kWh/ADMT
CRF	0.130

Table 66: Idle time optimization scenario cost of saved energy (CSE) calculations

	Cost of equipment ($)	Incremental annualized cost ($)	Saved energy (kWh/yr.)	CSE ($/kWh)
2010-2020				**-0.11**
Capital cost	279840	36240.56	90721158.89	
Incremental O&M costs	-10007153.25	-10007153.25		
2020-2030				**-0.16**
Capital cost	279840	36240.56	90913743.88	
Incremental O&M costs	-14399312.68	-14399312.68		
2030-2040				**-0.17**
Capital cost	279840	36240.56	91083814.32	
Incremental O&M costs	-15456508.17	-15456508.17		
2040-2050				**-0.18**
Capital cost	279840	36240.56	91240971.36	
Incremental O&M costs	-16423374.84	-16423374.84		

Scenario 14: High-consistency paper making

Capital cost	$137.33/ADMT
O&M costs	$1.41/ADMT/year
Energy savings potential	99kWh/ADMT
CRF	0.096

Table 67: High-consistency paper making scenario cost of saved energy (CSE) calculations

	Cost of equipment ($)	Incremental annualized cost ($)	Saved energy (kWh/yr.)	CSE ($/kWh)
2010-2020				**0.04**
Capital cost	36255120	3492901.20	25957788.24	
Incremental O&M costs	-2493616.583	-2493616.58		
2020-2030				**-0.01**
Capital cost	36255120	3492901.20	26012892.04	
Incremental O&M costs	-3749547.908	-3749547.91		
2030-2040				**-0.02**
Capital cost	36255120	3492901.20	26061553.81	
Incremental O&M costs	-4051347.198	-4051347.20		
2040-2050				**-0.03**
Capital cost	36255120	3492901.20	26106520.71	
Incremental O&M costs	-4327353.584	-4327353.58		

Appendix C

Table 68: Electricity and natural gas annual energy demand for Alberta's pulp and paper industry under slow penetration scenario as estimated by LEAP model

	Scenario name	Energy (PJ)	Slow penetration scenario				
			2010	**2020**	**2030**	**2040**	**2050**
0	Business-as-usual	Electricity	10.80	10.14	10.22	10.30	10.38
		Natural gas	9.57	9.45	9.33	9.21	9.08
1	Microwave pretreatment	Electricity	10.80	10.14	10.22	10.30	10.38
		Natural gas	9.57	9.34	8.98	8.62	8.24
2	Xylanase enzymatic pretreatment	Electricity	10.80	10.14	10.14	10.13	10.13
		Natural gas	9.57	9.45	9.33	9.21	9.08
3	Cellulase enzymatic pretreatment	Electricity	10.80	10.14	10.15	10.17	10.18
		Natural gas	9.57	9.45	9.33	9.21	9.08
4	Pectinase enzymatic pretreatment	Electricity	10.80	10.14	10.18	10.23	10.28
		Natural gas	9.57	9.45	9.33	9.21	9.08
5	Fungal pretreatment	Electricity	10.80	10.14	9.99	9.85	9.70
		Natural gas	9.57	9.45	9.33	9.21	9.08
6	Chemical pretreatment	Electricity	10.80	10.02	9.85	9.70	9.54
		Natural gas	9.57	9.45	9.33	9.21	9.08
7	Oxalic acid pretreatment	Electricity	10.80	10.14	10.01	9.89	9.76
		Natural gas	9.57	9.45	9.33	9.21	9.08
8	Microwave drying technology	Electricity	10.80	10.14	10.22	10.30	10.38
		Natural gas	9.57	9.45	9.28	9.12	8.98
9	Shoe press drying technology	Electricity	10.80	10.14	10.22	10.30	10.38
		Natural gas	9.57	9.43	9.29	9.16	9.04
10	Condebelt drying technology	Electricity	10.80	10.14	10.22	10.30	10.38
		Natural gas	9.57	9.45	9.28	9.12	8.98

11	Fibrous fillers	Electricity	10.80	10.14	9.82	9.50	9.17
		Natural gas	9.57	9.45	9.03	8.66	8.33
12	Efficient heat recovery system	Electricity	10.80	10.14	10.22	10.30	10.38
		Natural gas	9.57	9.21	8.92	8.65	8.41
13	Idle time optimization	Electricity	10.80	10.09	10.08	10.06	10.05
		Natural gas	9.57	9.45	9.33	9.21	9.08
14	High consistency paper making	Electricity	10.80	10.14	10.19	10.23	10.28
		Natural gas	9.57	9.45	9.33	9.21	9.08

Table 69: Electricity and natural gas annual energy demand for Alberta's pulp and paper industry under fast penetration scenario as estimated by LEAP model

	Scenario name	Energy (PJ)	Fast penetration scenario				
			2010	**2015**	**2020**	**2025**	**2030**
0	Business-as-usual	Electricity	10.80	10.47	10.14	10.18	10.22
		Natural gas	9.57	9.51	9.45	9.39	9.33
1	Microwave pretreatment	Electricity	10.80	10.47	10.14	10.18	10.22
		Natural gas	9.57	9.51	9.18	8.85	8.51
2	Xylanase enzymatic pretreatment	Electricity	10.80	10.47	10.14	10.06	9.97
		Natural gas	9.57	9.51	9.45	9.39	9.33
3	Cellulase enzymatic pretreatment	Electricity	10.80	10.47	10.14	10.08	10.02
		Natural gas	9.57	9.51	9.45	9.39	9.33
4	Pectinase enzymatic pretreatment	Electricity	10.80	10.47	10.14	10.13	10.12
		Natural gas	9.57	9.51	9.45	9.39	9.33
5	Fungal pretreatment	Electricity	10.80	10.47	10.14	9.84	9.54
		Natural gas	9.57	9.51	9.45	9.39	9.33
6	Chemical pretreatment	Electricity	10.80	10.47	9.86	9.62	9.39
		Natural gas	9.57	9.51	9.45	9.39	9.33
7	Oxalic acid pretreatment	Electricity	10.80	10.47	10.14	9.87	9.60
		Natural gas	9.57	9.51	9.45	9.39	9.33
8	Microwave drying technology	Electricity	10.80	10.47	10.14	10.18	10.22
		Natural gas	9.57	9.51	9.45	9.30	9.16
9	Shoe press drying technology	Electricity	10.80	10.47	10.14	10.18	10.22
		Natural gas	9.57	9.51	9.41	9.31	9.22
10	Condebelt drying technology	Electricity	10.80	10.47	10.14	10.18	10.22
		Natural gas	9.57	9.51	9.45	9.30	9.16
11	Fibrous fillers	Electricity	10.80	10.47	10.14	9.58	9.02
		Natural gas	9.57	9.51	9.45	8.92	8.42

12	Efficient heat recovery system	Electricity	10.80	10.47	10.14	10.18	10.22
		Natural gas	9.57	9.37	9.07	8.79	8.53
13	Idle time optimization	Electricity	10.80	10.47	10.03	9.96	9.89
		Natural gas	9.57	9.51	9.45	9.39	9.33
14	High consistency paper making	Electricity	10.80	10.47	10.14	10.13	10.12
		Natural gas	9.57	9.51	9.45	9.39	9.33

Table 70: Comparison of net GHG mitigation in slow penetration scenario, estimated by the LEAP model for Alberta's pulp and paper industry

No.	Scenario name	Carbon dioxide mitigation (kT of CO_2 eq.)	Methane mitigation (kT of CO_2 eq.)	Nitrous oxide mitigation (kT of CO_2 eq.)	Total emissions mitigation (kT of CO_2 eq.)
1	Microwave pretreatment	831.39	11.994	0.462	**843.85**
2	Xylanase enzymatic pretreatment	505.76	3.469	1.682	**510.91**
3	Cellulase enzymatic pretreatment	404.60	2.775	1.346	**408.73**
4	Pectinase enzymatic pretreatment	202.30	1.388	0.673	**204.36**
5	Fungal pretreatment	1401.33	9.612	4.660	**1415.60**
6	Chemical pretreatment	2038.24	13.769	6.851	**2058.86**
7	Oxalic acid pretreatment	1273.94	8.739	4.237	**1286.91**
8	Microwave drying technology	114.38	1.650	0.064	**116.09**
9	Shoe press drying technology	78.704	1.135	0.044	**79.88**
10	Condebelt drying technology	114.38	1.650	0.064	**116.09**
11	Fibrous fillers	3206.55	27.398	8.686	**3242.64**
12	Efficient heat recovery system	897.27	12.944	0.499	**910.71**
13	Idle time optimization	795.83	5.378	2.674	**803.89**
14	High-consistency paper making	194.63	1.335	0.647	**196.61**

Table 71: Comparison of net GHG mitigation in fast penetration scenario, estimated by the LEAP model for Alberta's pulp and paper industry

No.	Scenario name	Carbon dioxide mitigation (kT of CO_2 eq.)	Methane mitigation (kT of CO_2 eq.)	Nitrous oxide mitigation (kT of CO_2 eq.)	Total emissions mitigation (kT of CO_2 eq.)
1	Microwave pretreatment	364.38	5.257	0.202	**369.83**
2	Xylanase enzymatic pretreatment	184.07	1.199	0.633	**185.91**
3	Cellulase enzymatic pretreatment	147.26	0.959	0.506	**148.73**
4	Pectinase enzymatic pretreatment	73.63	0.480	0.253	**74.36**
5	Fungal pretreatment	512.48	3.339	1.762	**517.58**
6	Chemical pretreatment	946.52	5.831	3.371	**955.72**
7	Oxalic acid pretreatment	465.89	3.035	1.602	**470.53**
8	Microwave drying technology	54.83	0.791	0.030	**55.65**
9	Shoe press drying technology	55.76	0.804	0.031	**56.59**
10	Condebelt drying technology	54.83	0.791	0.030	**55.65**
11	Fibrous fillers	1,194.06	10.051	3.278	**1,207.39**
12	Efficient heat recovery system	450.58	6.500	0.250	**457.33**
13	Idle time optimization	372.78	2.296	1.328	**376.41**
14	High-consistency paper making	71.18	0.464	0.245	**71.89**