The Role of Industrial Energy Efficiency and Fuel Switching as Pathways to Net-Zero Emissions in the Canadian Pulp and Paper Sector

by

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Abstract

Industrial decarbonization is a critical challenge along the pathway to reducing greenhouse gas (GHG) emissions at a sufficient scale and pace to avoid the worst impacts of climate change. The intrinsic energy- and emissions-intensive nature of heavy industry has led to the recognition that efforts to change the profile of industrial energy use could play a major role in meeting this challenge. This concept, defined broadly as industrial energy efficiency, encompasses a category of technology solutions such as process improvements, equipment upgrades, and fuel switching within sector boundaries. These and other efficiency technologies are notable for their potential to lower industrial emissions while improving (rather than reducing) competitiveness. Robust analysis of the costs and benefits of efficiency as a comprehensive technology suite can help to overcome known barriers to adoption including poor awareness of efficiency opportunities and perceptions of high risk for efficiency investments. Understanding the impacts of efficiency can also be beneficial to policymakers by identifying effective emissions reduction pathways. The overall objective of this thesis is to develop a novel method for fully characterizing the techno-economic potential of industrial energy efficiency and in-sector fuel switching as solutions for energy savings and emissions reductions. This thesis demonstrates application of the method to the case study of the Canadian pulp and paper sector.

To achieve the objective of this thesis, a technology-explicit energy and GHG emissions modelling and analysis framework was developed based on best practices for studies of energy efficiency and resource potential. The framework integrates a bottom-up sector energy model with a comprehensive database of energy efficiency technologies validated against data from actual projects in industry. Analysis of efficiency measures was linked to the sector energy model at the point of end-use secondary energy consumption, enabling more realistic representation of how efficiency technologies can impact final energy use. Technology-explicit applicability factors and iterative, cumulative analysis techniques were used to capture the expected impacts of measure overlap, interference, and diminishing returns so as to not overestimate the effects of all measures acting in parallel. Energy savings bandwidths and cost of saved energy curves were developed to characterize the energy savings potential associated with efficiency. Energy-driven GHG emissions abatement scenarios were then developed and analyzed within a Canada-wide energy and emissions model over a long-term planning horizon at both the sector and system level. Marginal GHG abatement cost curves were produced to provide insights into the most impactful and cost-effective technologies over the study period.

The key findings of this work demonstrate that natural gas, biomass, and net electricity consumption in the Canadian pulp and paper sector could be reduced by 95%, 1%, and 41%, respectively, via adoption of economically viable efficiency technologies at current energy prices. Achieving this potential would significantly improve sector competitiveness by bringing it into alignment with international energy intensity benchmarks and by dramatically reducing energy costs. At current production levels, efficiency in the pulp and paper sector could reduce net demand for natural gas and electricity by 71 PJ/year and 44 PJ/year, respectively. Energy efficiency was also found to have significant potential as a tool for reducing GHG emissions. The annual GHG emissions abatement associated with economical efficiency measures was estimated to be 3.6 MtCO2e (46%) by 2030 and 4.9 MtCO2e (66%) by 2050 relative to business as usual. Accounting for the technical potential of all measures increases the abatement potential to

6.2 MtCO2e in 2050. Over the study period, energy efficiency was found to reduce cumulative sector GHG emissions by 107.6 MtCO$_2$e (42%) through 2050 at a weighted average abatement cost of -\$162/tCO$_2$e. When considering system-level effects, the cumulative abatement rises by 44% to 155.6 MtCO$_2$e through 2050.

The results presented in this thesis provide a clear indication to industry and policymakers that energy efficiency could be the single most important technology solution to achieve emissions reduction targets at low or negative cost while enhancing pulp and paper sector competitiveness. The novel framework developed in this thesis can be adapted to any other jurisdiction or sector to produce similar insights. Further work is needed to determine how best to achieve the potential associated with industrial energy efficiency so that it can take a leading role in the transition to a prosperous low-carbon economy.

Preface

This thesis contains material from three studies that are attributed to myself as lead author alongside two coauthors.

Chapter 3 is planned to be submitted for publication in a peer-reviewed journal as “Development of technology-explicit energy saving bandwidths: a case study for the pulp and paper sector” by Christophe Owttrim, Matthew Davis, and Amit Kumar. To be submitted to *Energy Conversion and Management*.

Chapter 4 is planned to be submitted for publication in a peer-reviewed journal as “Energy efficiency as a critical resource to achieve carbon neutrality in the pulp and paper sector” by Christophe Owttrim, Matthew Davis, Hafiz Umar Shafique, and Amit Kumar. To be submitted to *Journal of Cleaner Production*.

Because of their pending publication status, Chapters 3 and 4 are presented in their entirety in the format in which they will be submitted. This results in some commonalities and overlap between Chapters 3 and 4 and the other content presented in this thesis, e.g.: literature reviews and policy discussions. The supplementary information documents to be submitted alongside Chapters 3 and 4 have been reorganized into the Appendices of this thesis for the sake of consistency and logical order.

Chapters 1, 2, and 5 contain content originally developed by me for an unpublished report submitted to Environment and Climate Change Canada, entitled “Efficiency Potential in the Canadian Pulp & Paper Sector” by Christophe Owttrim, Matthew Davis, and Amit Kumar. This content has been edited and reorganized to align with the structure of this thesis, and is indicated by footnotes at the beginning of the relevant sections. A version of Chapter 5 is expected to be submitted for publication following acceptance of this thesis.

I was responsible for program design, literature review, data collection & processing, methods development, formal analysis, modelling, analysis & interpretation of results, and writing for all material presented in this thesis. Matthew Davis provided input on research program design, method development, and modelling. He provided support for modelling activities related to implementation of the sector energy model and energy efficiency scenarios within LEAP-Canada, and led implementation of the upstream/system-level LEAP model described in Section 4.2.2.2. He also provided editorial input on all content in this thesis. Dr. Amit Kumar directed the conceptual study design, provided overall supervision and editorial input on all content in this thesis, coordinated funding of the work, provided inputs to designed scenarios and feedback on the results, and led engagement with key stakeholders from government, industry, and the chair programs.

Dedication

This thesis is dedicated to future generations whose lives and livelihoods will be dramatically impacted by the extent to which we act in the present day to achieve an energy transition to avert the most severe impacts of climate change.

"A letter to the future [generations]…. we know what is happening and what needs to be done. Only you know if we did it."

- Plaque written by Andri Snaer Magnason to commemorate the first Icelandic glacier wholly lost to climate change, August 2019[1]

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[1] Toby Luckhurst. Iceland's Okjokull glacier commemorated with plaque. 2019. BBC News. https://www.bbc.com/news/world-europe-49345912. [accessed: 6 September 2021]

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I wish to note my appreciation for my supervisors and colleagues at Emissions Reduction Alberta and Alberta Innovates Clean Resources for their mentorship and flexibility in enabling me to complete this thesis while continuing in my professional role.

Thanks to Nat for being with me throughout this journey and for always supporting me. Your encouragement, insight, and understanding mean more than you know, and I can’t wait to see what the future holds for us! To my siblings and friends, thanks for sticking with me even when I disappeared into the work. Lastly, I am immensely grateful for the support and inspiration provided by my parents, George Owttrim and Dana Chamot, throughout my academic and professional career. I could not ask for better role models, and I thank you for always encouraging my pursuit of knowledge and for fostering my desire to better the world.

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List of Abbreviations

ADMT	Air dry metric tonne
AF	Applicability factor
AR	Adoption rate
BAU	Business-as-usual
BCTMP	Bleached chemi-thermo-mechanical pulp(ing)
CAD	Canadian dollar
CAD	Canadian dollar
CHP	Combined heat and power
CP	Chemical (market) pulp
CSE	Cost of saved energy
CTMP	Chemi-thermomechanical pulp(ing)
DE	Device efficiency
ECCC	Environment and Climate Change Canada
EDT	Energy demand tree
EEM	Energy efficiency measure
EESB	Economic energy saving bandwidth
EI	Energy intensity
EITE	Emissions-Intensive, Trade-Exposed
GDP	Gross domestic product
GHG	Greenhouse gas
GJ	Gigajoule
GO	Gross output
IRR	Internal rate of return
kWh	Kilowatt-hour
LEAP	Low Emissions Analysis Platform
MAC	Marginal GHG emissions abatement cost
MDE	Marginal device efficiency
MP	Mechanical (market) pulp
MPE	Marginal process efficiency
Mt	Million metric tonne (megatonne)
NAICS	North American Industry Classification System
NEMA	National Electrical Equipment Manufacturers Association
NP	Newsprint
NPV	Net present value
NRCan	Natural Resources Canada
O&M	Operations and maintenance
P&P	Pulp and paper
PB	Paperboard
PCF	Pan-Canadian Framework (on Clean Growth and Climate Change)
PE	Process efficiency
PJ	Petajoule
PL	Penetration level

PP	Print paper
ROI	Return on investment
SEC	Specific energy consumption
SEM	Sector energy model
t	Metric tonne
tCO_2e	Metric tonnes carbon dioxide equivalent (100-year global warming potential)
TESB	Technical energy saving bandwidth
TIC	Total (annualized) implementation cost
TMP	Thermomechanical pulp(ing)
U.S.	United States of America
U.S. DOE	United States Department of Energy

1. Introduction

1.1. Motivation

In 2021, the year this thesis was completed, atmospheric concentrations of carbon dioxide approached 420 parts per million for the first time in recorded human history [1]. This milestone represents the culmination of centuries of unconstrained extraction and combustion of fossil fuels to support economic activities in the absence of appropriate valuation of their associated environmental impacts. If left unchecked, there is abundant evidence that ongoing greenhouse gas (GHG) emissions will drive global temperatures well outside the boundaries within which human civilization has developed, threatening the peace and prosperity of all future generations [2]. Recognition of this fact has led to the inexorable conclusion that anthropogenic GHG emissions must peak as soon as possible and must furthermore be reduced to net-zero by mid-century [3].

To meet this monumental challenge it will be necessary to consider all available options for emissions abatement [4]. We must also recognize, however, that the resources required to implement emissions abatement options—such as time, financing, effort, political capital, and social acceptance—are finite. Apportionment of such resources in the most effective manner possible requires a clear understanding of the overall emissions reduction potential and trade-offs associated with each abatement opportunity. It is in this context that engineering modelling and analysis of emissions abatement pathways can contribute to a more effective response to climate change. Such analysis can ensure that the right solutions are applied to the right economic sectors at the right time in order to achieve the required scale and rapidity of emissions abatement without imposing unnecessary costs or hardships.

Numerous technological solutions have been proposed to avoid emission of GHGs to the atmosphere or to remove previously-emitted GHGs. One broad technology category that applies to nearly any economic sector is the concept of improving energy efficiency, which, broadly construed, is the concept of reducing the quantity of energy input required to produce desired outputs. To explore the link between energy and emissions and to develop a rationale for defining and investigating energy efficiency, it is instructive to consider the identity presented in Equation 1, which has been attributed to Japanese economist Yoichi Kaya [5]:

$$Emissions = Population \times \frac{Economic\ Output}{Population} \times \frac{Energy}{Economic\ Output} \times \frac{Emissions}{Energy} \tag{1}$$

The Kaya identity highlights the role of key technoeconomic parameters on emissions and the limited levers available to combat emissions in an ethical and equitable manner. Clearly, the *population* parameter can be expected to increase or remain constant into the future; decreasing population to reduce emissions is unlikely to be consistent with the principles of ethics or equity. Similarly, the *economic output/population* term, which can be roughly interpreted as a measure of prosperity, is one that should be increased over time. This leaves the two rightmost terms in the identity as the critical factors over which engineers, industry members, policy makers, and other stakeholders can exert control in order to reduce emissions. The *energy/economic output* parameter has the most similarity to a strict definition of efficiency as a ratio of outputs to inputs, although more precisely it measures energy intensity. The *emissions/energy* term directly measures the emissions intensity of energy use. Equation 1 highlights the interrelated role of energy efficiency and emissions intensity: they are linked by their shared relationship with energy and must therefore both be considered when evaluating the emissions abatement potential associated with changes in how energy is used. For the sake of simplicity and to account for this observation, I adopt a broad definition of *energy efficiency* as the management of energy use to reduce emissions, energy costs, or other undesirable impacts per unit of economic output or activity. This definition notably allows for consideration of impacts on both energy- and emissions-intensity. To further specify this definition, throughout this thesis I primarily use the term energy efficiency to reflect the act of *improving* energy- and/or emissions-intensity, unless otherwise stated.

Figure 1 compares the scope of energy efficiency used within this thesis to some commonly-considered classes of emissions abatement technologies.

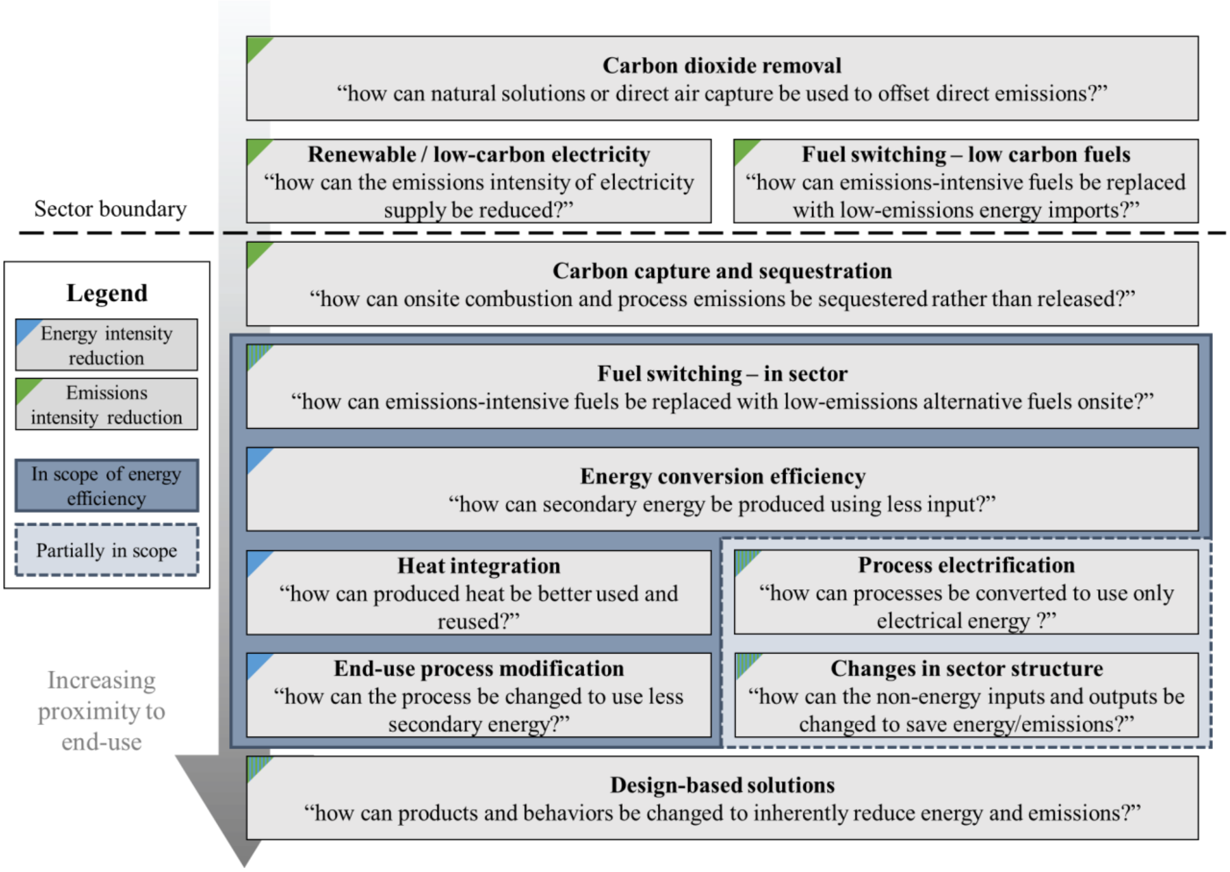

Figure 1: Emissions abatement options and scope of energy efficiency definition

A strict definition of energy efficiency would only include measures that directly impact energy intensity. However, as shown by Figure 1, the broader definition used in this thesis allows for a more complete understanding of how energy management can affect emissions via several different technology measures. The chosen definition also enables consideration of interactions between complementary measures; for example, the interplay between modifying a process to use less heat or changing the fuel used to provide heat to the process. The sector boundary provides a useful point of delineation and excludes measures that are better left as independent emissions abatement pathways such as procurement of renewable electricity. Within the sector boundary, carbon capture is likewise excluded because of its role as a distinct class of technology and its propensity to increase, rather than decrease, overall energy intensity. Structural changes and design-based solutions present a complicated area for analysis. Some changes may be relatively minor, wherein proportions of feedstock or product types are shifted towards those with lower-emissions without dramatically departing from historical or BAU sector structure. More significant structural changes could contemplate re-tooling or replacement of more emissions- and energy-intensive production capacity with new, lower-emissions alternatives. The definition of energy efficiency used in this thesis includes only the first style of structural change, because more significant changes are challenging to analyze in terms of data availability and impact and are more likely to be driven by socioeconomic factors rather than a desire to enhance energy efficiency. The same principle applies to electrification, which might involve only minor changes to processes or equipment (in-scope) or could require fundamental redesign of entire systems (out of scope.) For simplicity, I hereafter refer to all in-scope technologies as energy efficiency measures (EEMs).

Energy efficiency, as defined above, is recognized by governments, researchers, and industry as an essential emissions-abatement technique [6]. The potentially significant contribution of energy efficiency towards emissions reduction targets has been confirmed by numerous independent analyses, for example, two recent studies have found that efficiency could reduce economy-wide emissions by 10% for the case of the Unites States [7] and by over 32% for Canada [8]. Even greater potential may exist on a global scale; indeed, analysis from the International Energy Agency indicates that efficiency could contribute approximately 35% of the total emissions abatement required to achieve net-zero [9]. However, the emissions abatement potential associated with efficiency is not distributed evenly across economic sectors. Unlike more homogenous technology categories such as renewable energy or carbon capture, the intrinsic connection of energy efficiency to energy end-use creates significant variation in the technologies used to improve efficiency from sector to sector. For sectors with relatively simple energy-use profiles, efficiency can be a fairly straightforward concept; for example, the effects of changes in vehicle fuel mileage standards [10] or residential appliance efficiency [11] are well-understood and are driven by a comparatively small set of specific technology interventions. However, it can be significantly more challenging to define, characterize, and analyze energy efficiency for sectors with more complicated energy- and emissions-footprints where dozens of individual efficiency measures may be applicable. Some of the most important examples of this type of sector can be found among heavy manufacturing industries.

Industrial sectors contribute substantially to employment and economic activity in almost every jurisdiction [12, 13], but are also among the most significant producers of GHG emissions, contributing 24% of global emissions as of 2020 [14]. This considerable emissions footprint is driven in part by the large energy demand of such sectors; indeed, in 2020 37% of global energy demand was attributed to industry [14]. The scale of industrial energy use and emissions make industry an integral element of any credible decarbonization pathway [15]. However industrial sectors present unique challenges for energy use reduction and emissions abatement. Despite efforts to reduce costs and emissions, world industrial energy demand increased by an average of 0.9% annually from 2010-2020 and remains dominated by fossil fuels [14]. Industrial facilities may include hundreds of individual processes and pieces of equipment, which makes their energy- and emissions-footprints uncommonly complicated. Furthermore, heavy industrial sectors are characterized by large, capital-intensive facilities with long economic lifetimes and significant cost pressures. These factors place heavy industries among the most important yet challenging targets for analysis of efficiency-driven emissions abatement [13, 14].

This thesis focuses on analysis of energy efficiency as an emissions abatement tool for a key heavy industry in Canada: the pulp and paper (P&P) sector. Detailed sectoral background information, including the specific case study of the Canadian P&P sector, is provided in Chapter 2.

1.2. Policy context

Energy efficiency in industry has long been recognized by policymakers as an important tool to help achieve national energy and emissions targets while enhancing economic competitiveness [13, 15-18]. Efficiency improvements have direct benefits to industry in terms of fuel cost savings and productivity benefits and can also provide systems-level benefits such as reducing concurrent peak load on electricity grids. Theoretically, such cost savings should make energy efficiency attractive as both an investment and as a tool for policy compliance. However, in practice, the potential of energy efficiency has not been fully realized, as demonstrated by work such as the “Best Available

Technology" publications produced by the European Commission which indicate that the energy use and emissions for the average facility in any given sector significantly exceed those of top-performing facilities [19]. This so-called "efficiency gap" [20] suggests that there are substantial barriers that limit adoption of energy efficiency technologies in industry [21].

Numerous potential barriers to energy efficiency improvement have been contemplated in the literature, including low rates of return, capital constraints, lack of awareness, technical risk, policy uncertainty, and low fuel prices [13, 21, 22]. There are many policy levers that can help accelerate energy efficiency improvement, but the solutions vary depending on the type of barriers present. To deliver optimal outcomes, policymakers must develop a strong understanding of the barriers and drivers for efficiency in the jurisdiction and sector of interest. Here, robust analyses of industrial energy use and efficiency technologies can provide key insights for policymakers by determining the presence and scale of an efficiency gap and by characterizing the nature of potential barriers to efficiency improvement. For industry, efficiency modelling can overcome barriers such as technical risk, investment uncertainty, and lack of awareness of available solutions. Analysis of energy efficiency technology options can also identify technical gaps where further research and innovation may be required in addition to policy solutions.

Another important implication of energy efficiency policy is industry competitiveness. Many manufacturing industries are considered to be emissions-intensive and trade-exposed (EITE), meaning they are highly affected by changes in energy prices and emissions policy and must compete on worldwide markets. Policy decisions for an EITE sector should therefore be made with an extensive understanding of the sector's ability to respond, including its current efficiency level and the availability and costs of technology alternatives. If an EITE sector is already highly efficient or has limited access to new efficiency technologies, it has less capacity to respond to policy change because it may need to pursue other solutions that are more costly and disruptive. Conversely, an EITE sector identified to be less energy efficient than international competitors could derive significant competitiveness benefits from policies targeted at reducing its energy use. Understanding the current state of sector energy use and the scale of benefits achievable via efficiency can therefore help to inform the right level of aggressiveness of policies such as emissions targets or pricing regimens. At a fundamental level, this approach to policymaking requires the ability to model the energy demand and emissions profile of individual economic sectors as well as the potential impacts of efficiency technologies.

These issues of competitiveness, regulatory stringency, and policy choice have received considerable and growing attention in Canada in recent years. The volume and ambition of emissions and energy policy in Canada has increased dramatically since establishment of the Pan-Canadian Framework on Clean Growth and Climate Change (PCF) in 2016 [17]. The PCF represents the cornerstone of Canada's climate and energy policy [23] and has recently been augmented with more stringent targets and additional policies. Under the expanded plan, titled "A Healthy Environment and a Healthy Economy," Canada's emissions target will be increased from a 30% reduction from 2005 levels (as per the Paris Agreement) [24] to a 40-45% reduction target [25]. These emissions targets have significant implications for industrial policy. Canada's Fourth Biennial Report on Climate to the United Nations projects that, contrary to the emission decline predicted for most other economic sectors, absolute emissions from heavy industry will continue to rise through 2030 (15% in a current-policies scenario and 9.6% even with additional policy measures) because increases in activity will outweigh decreases in emissions intensity [24]. Given that non-oil and gas industry accounts for 10% of Canada's emissions as of 2017 and nearly 14% by 2030 [24], a 15% increase in industry emissions would require all other economic sectors to reduce their emissions by an additional 8% (53% total) relative to 2005 to achieve an economy-wide 45% reduction. Industry is therefore among the most critical sectors for additional action in support of Canada's emissions targets.

Arguably the most important yet most controversial element of Canada's climate policy landscape is an economy wide carbon price. Legislation establishing a carbon pricing backstop was passed in 2018 [24], and the program was recently found to be constitutional by the Supreme Court of Canada [26]. Under the latest version of the carbon pricing plan, the federal baseline carbon price will rise by \$10/tCO2e annually from \$30/tCO2e in 2020 to \$50/tCO2e in 2022, after which it will increase by \$15/tCO2e annually from until it reaches a maximum value of \$170/tCO2e in 2030 and remains constant thereafter [25]. Notably, in the PCF (and equivalent provincial policies) EITE industries and some other large emitters are not exposed to the full cost of carbon because they are subject to output-based allocations: credited emissions levels beyond which emissions are priced. The allocations are intended to maintain sector competitiveness on international markets and prevent carbon leakage while maintaining the per-tonne price signal for marginal emissions reductions [26]. Output-based allocations of emissions are most commonly established via comparison of facility emissions intensity to a benchmark average of comparable facilities; facilities are only exposed to the carbon price for emissions above the benchmark level [27]. Establishment of an appropriate emissions benchmark for each sector as well ratcheting-down of benchmarks to drive greater reductions over time both depend on accurate sector energy and emissions modelling.

In addition to carbon pricing, many policy levers relevant to industrial efficiency have been contemplated by both federal and provincial governments, including emissions limits, efficiency standards, rebate programs, research & development support, and energy management programs [17]. Most such programs are cross-cutting and are not targeted at specific industries such as pulp and paper; indeed, Canada's recent policy summary reporting under the Paris Agreement disaggregates policy only to the level of heavy industry and does not reference individual subsectors [24]. The PCF specifically identifies energy efficiency as a key tool for industrial emissions reduction and identifies a priority for "Federal, provincial, and territorial governments [to] work together to help industries save energy and money, including by supporting them in adopting energy management systems" [17]. In the absence of energy efficiency improvement, Natural Resources Canada estimates that manufacturing industry emissions in Canada would have been 46.3 Mt higher between 1990-2013 [28]. This underscores the important and ongoing role of effective energy efficiency policy in helping Canada meet its emissions targets. However, as compared to other policy mechanisms in the PCF, industrial efficiency policies tend to lack focus, specificity, and ambition. The most common approaches are financial in nature, such as programs that provide funding for emissions reduction technologies in industry; these include the Strategic

Innovation Fund, Clean Growth Program, and Low Carbon Leadership Fund [24, 29][2]. Policy mechanisms that do not involve direct government financing of industrial projects are significantly less common and typically receive lower funding allocations. This policy landscape, coupled with the previously-described importance of reducing industrial emissions, creates a renewed imperative to consider all policy alternatives for industrial emissions and energy efficiency moving forward.

Analyzing the overall policy landscape relevant to the Canadian P&P sector is a challenging topic whose complexity is beyond the scope of this thesis. The P&P sector is subject to significant regulations on air, water, and land impacts [30], but governments and industry have applied comparatively less focus to energy and GHG emissions. The most notable example of recent energy/emissions policy targeted specifically at the P&P sector is the Pulp and Paper Green Power Transformation Fund, which provided $1 billion CAD in funding for P&P energy efficiency projects from 2008-2012 [31]. This program demonstrated the existence of significant untapped investments in efficiency in the sector, but also highlighted the reluctance of industry to invest in efficiency in the absence of government intervention. Pulp and paper projects have also received support from multiple provincial programs, however, a major trend has been towards investment in new products such as lignin, materials, and biorefinery chemicals [23, 32] rather than towards improving the energy efficiency of existing P&P production lines [33]. Recent work suggests that a renewed focus on efficiency in P&P is merited: despite the aforementioned challenge of reducing heavy industry emissions, the International Energy Agency has published analysis showing that Canadian P&P energy consumption could be reduced by 28% by 2050 in a high energy efficiency scenario [16]. In the same report, P&P was found to have potential to make the greatest contribution to energy savings among all Canadian manufacturing industries [16].

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[2] In the interest of transparency, at the time of writing the author is employed by a provincial agency that provides funding for emissions reduction projects in industry.

As discussed previously, Canada's EITE industrial sectors must compete internationally, and many sectors such as P&P are significantly dependent on prices and demand for export of their products. Major trade partners such as the United States and European Union are considering border carbon tariffs that would penalize carbon-intensive imports as part of their climate policy approach [34]. It is therefore apparent that pressures on energy- and emissions-competitiveness will only increase over the coming decades. This elevates the need for effective industrial efficiency policy to ensure the competitiveness of Canadian industry is maintained.

Achieving Canada's ambitious 2030 and 2050 goals, including a push for net-zero emissions, will require ongoing policy support. Effective design of such policies will depend, in part, upon improved understanding and awareness of the potential of industrial energy efficiency by regulators and policymakers. To this end, analysis of energy efficiency as a key technology pathway for Canadian industries such as pulp and paper can play a valuable role in contributing to emissions abatement efforts.

1.3. Overview of relevant literature and modelling methods

Chapters 3, 4, and 5 contain focused literature reviews that provide in-depth consideration of work specifically relevant to their scope. To complement these specific reviews and to support the overall rationale for this thesis, this section provides a general overview of the literature and practices in the area of energy and emissions modelling. Where possible, references in this section use examples relevant to the pulp and paper sector.

In general, there are significant similarities in the tools used for energy/emissions forecasting and those used to assess energy efficiency potential. The core of any such analysis is a model-based representation of sector energy demand, which may then be affected by variables introduced to the model such as scenarios for energy prices, policies, or technology adoption. There exist dozens of private, academic, and commercial models for energy and emissions forecasting of individual countries or sectors [35, 36], including models specific to the pulp & paper sector e.g.: [37]. Two modelling tools relevant for this thesis are the Low Emissions Analysis Platform (LEAP) [38] and ENERGY 2020 [39]; these tools are discussed at length in Chapter 4 and Chapter 5, respectively.

The choice of modelling technique and model structure have significant implications for the analysis methods that can be applied and the results that can subsequently be produced. As such, the objectives of a given study typically dictate the modelling methods used. Some of the common types of studies in the literature include [35, 36, 40]:

- *Technology analysis and handbooks [32, 33, 41-46]:* these studies typically focus on the technical performance and impacts of specific technologies. As such, they may or may not include a sector/facility energy model but almost universally feature in-depth theoretical or empirical analysis of technology measures. A related class of study includes industry or government efficiency handbooks which may provide case studies and/or expert commentary on particular technologies without offering detailed modelling or scenario analysis.
- *Facility energy audits and studies [47-49]:* studies in this category feature analysis of a particular facility to assess its energy/emissions performance or assess the potential benefits of implementing a new technology at that site. These studies are seldom completed in the academic domain but rather are completed by the private sector or government agencies.
- *Benchmarking studies [19, 50-56]:* these studies attempt to provide a detailed characterization of sectoral energy- and/or emissions-footprints with a common objective of comparing their results to international benchmarks or performance targets. This style of study often, but not always, requires a detailed bottom-up sector process step model to be produced such that the physical causes of energy demand and emissions can be accurately reflected in the model [57-59]. The sector energy model developed in this thesis (see Chapter 3) follows a bottom-up approach in order to provide granular insights at the end-use level and to directly reflect the causal link between emissions and energy consumption.
- *Decomposition analysis [29, 55, 60-63]:* decomposition studies attempt to disaggregate the various drivers of energy use and emissions, such as activity level, structure, and efficiency, in order to determine which factors have more influence on sector performance. They share

characteristics with benchmarking studies but are often economic in nature rather than technical.

- *Energy/emissions potential studies [45, 64-69]:* this class of study combines technology analysis with benchmarking to assess the potential for energy/emissions savings associated with a particular set of technologies. Studies in this area can be top-down (focused on generic changes in sector energy profile) e.g.: [16] or bottom-up (based on technology measures), and often use tools such as cost of saved energy curves [70] or marginal GHG abatement cost curves [61, 71]. The analysis featured in this thesis falls within this classification but addresses common deficiencies with this type of study.
- *Energy/emissions forecasts and scenario analysis [8, 37, 72-75]:* forecasts typically seek to model the sector in its current state and predict future energy consumption and emissions levels based on realistic projections of future econometric factors such as sector production, energy prices, etc. Such studies are commonly used by governments to, for example, estimate how sector emissions will evolve over time [36]. They are also used by utilities and energy suppliers to predict demand growth. Scenario-based studies build upon forecasting methods by contemplating alternative scenarios for the factors that affect energy and emissions. This is a broad and complex category of study because scenarios can consider many different factors including new policies or price environments, and can be analyzed in several ways. The scenario analysis performed in this thesis (see Chapter 4) is focused on technology adoption scenarios.

Significant overlaps exist among the study classifications provided above, and a wide variety of methods have been developed and demonstrated for each type of study. Despite the considerable diversity of models in terms of structure, approach, and aims, most models can be categorized based on certain high-level traits. One common way of classifying models is according to their use of either a top-down or bottom-up hierarchy for representing and calculating energy demand and/or emissions [21, 35]. Top-down models avoid considering the specific technologies, facilities, or operations involved in a sector and instead use overall energy/emissions intensity parameters and macroeconomic factors to estimate energy use and emissions [21, 35]. Bottom-up models apply a technology-explicit approach to understand the drivers of energy demand within a sector beginning with individual production steps, processes, and technologies [21, 76]. While both approaches have valuable roles, top-down models tend to be most useful when considering macroeconomic effects and the interaction between different sectors while bottom-up models are better suited for characterizing the specific details of industrial energy/emissions footprints from a technological perspective [35, 76]. To fully understand and benefit from the promise of enhanced industrial energy efficiency, focused assessments that capture local characteristics and conditions for a given sector are essential. Bottom-up models are well suited for such purposes since they can account for the actual processes and technologies used in an industry [35, 60]. Developing such a granular model imposes significant data requirements and requires a highly technology-explicit approach but can provide more specific and actionable insights for the sector of interest [35]. In addition, bottom-up analyses provide insights that may be obscured by top-down models, such as identifying the most significant energy-consuming processes in a sector [76]. Outputs produced using bottom-up methods are therefore more transferrable between regions because they allow for results to be compared with due consideration for underlying region-specific factors. In keeping with the objectives of this thesis, my analyses exclusively employ a bottom-up approach.

Another key distinction between different energy/emissions analysis models is the nature of their mathematical derivation and calculation techniques. Here, the differences between economics- and engineering-based models are most apparent [35]. The simplest models, in terms of mathematical definition, are known as accounting models or “engineering economic” models [35]. Calculations in such models are primarily associated with solving energy balances, applying analytical engineering principles (such as mapping energy use to emissions), or analyzing basic economic relationships (such as calculating sector profit based on expenses and revenues). Accounting-based models employ little or no iteration since their calculations can typically be performed in a linear manner based on fundamental relationships between quantities. Engineering accounting models are very well-suited for benchmarking analysis and simple forecasts because they apply the greatest focus to the physical and technical causes of energy demand and emissions [21]. With appropriate inputs such as exogenously-defined technology adoption rates, they can also be used for scenario analysis [35]. Another type of model is a simulation model, which may be based on engineering accounting principles but features extended analysis of behaviors such as technology diffusion or stock turnover [35]. Technology diffusion approaches incorporate economic theories such as demand elasticity or marginal substitution rates to estimate how rapidly a new technology may be adopted based on costs and performance [35, 71]. Stock turnover models are a specific approach to diffusion modelling based on retirement of existing equipment and replacement with new technologies. Such simulation approaches impose significantly greater data inputs than a basic accounting model, including a stock-and-vintage database of existing equipment in the sector at the end use level, data on the costs of existing equipment, and parameters related to firms' procurement behavior [35]. Among the most complex of models are optimization-based methods, which require many of the techniques and inputs other modelling approaches in addition to iterative solution methods to parameterize and subsequently solve for the behaviors that will achieve a targeted outcome such as minimization of costs or emissions under certain constraints [35, 40]. These models are often used for so-called integrated assessments of the multimodal interactions between policies, econometric factors, and sector energy/emissions profiles [45, 71]. Because of the theoretical and practical complexity of optimization models, such analyses often depart from bottom-up techniques and instead rely on heavily-simplified top-down representations of technologies and systems to reduce their data requirements and computational intensity [35, 45].

Overall, the critical distinction between accounting models and optimization/simulation models is that the former can describe only what could happen based on technical parameters, while the latter attempt to predict what will or should happen, accounting for the complexities of human behavior. This thesis employs detailed engineering accounting-based modelling because of its focus on estimation of total efficiency potential rather than prediction of behavior. Unlike most accounting models, however, a moderate degree of iterative analysis is incorporated to estimate the effects of technology interactions as described in Chapter 3. Furthermore, exogenous technology adoption parameters are used to enable long-term scenario analysis without the use of detailed economic behavioral models.

There are numerous other ways to classify modelling techniques. In brief, some other relevant considerations include the approach to technology representation (technology-explicit or generic treatment), modelling duration (current, short-term, long-term), and model boundaries (general equilibrium, partial equilibrium, non-integrated). Technology treatment within models is a key distinguishing factor that is often but not always tied to the choice of bottom-up or top-down modelling techniques [21, 35, 71]. Technology-explicit models include specific consideration of technology options and their direct impacts on energy/emissions, thus, technology parameters such as costs and performance must be specified individually as exogenous inputs [35, 71]. Generic technology treatment, conversely, neglects consideration of individual technology parameters. In such approaches, impacts of technology change may be represented via "stylized" correlations, aggregated technology impacts, or single values for changes in top-down parameters such as sector-wide energy intensity [21, 35, 71]. Technology-explicit approaches have many advantages over generic approaches, with the chief disadvantage being their relatively greater data requirements [35]. Current or non-temporal models seek to represent the sector as-is without consideration for changes in the future; this approach is most commonly found in benchmarking studies. Short-term models account for changes over time but typically only to the extent that econometric factors such as marginal substitution rate may be modified in the near-term by policy changes. Long-term modelling is most commonly applied for scenario analysis and is particularly relevant for emissions abatement studies given the importance of cumulative emissions and the long-term nature of the emissions reduction challenge. Finally, model boundaries may consider the economic/energy balances and interactions within the entire energy system (general equilibrium) or a single sector (partial equilibrium), or may neglect interactions to focus just on sector performance (non-integrated.) Each of these approaches has different roles; equilibrium models are valuable for policymakers in understanding macroeconomic behavior and responses to policy, while sector-focused analysis is useful for technology developers and industry members to understand the concrete impacts of a technology.

As described in subsequent chapters, the overall methodology of this thesis incorporates several of the techniques and modelling approaches described above. The principles of bottom-up, technology-explicit modelling are at the core of the methods described herein, however the analyses performed span categories such as benchmarking, long-term scenario analysis, and system- and sector-level analysis.

Studies of resource potential are distinct from other energy/emissions modelling activities. Resource potential studies are commonly used to estimate the available quantities of fossil fuels [77], bioenergy resources [78], and renewable electricity sources including wind and solar [79-81]. Different classes of potential are defined based on the constraints imposed, starting from the broadest definition of total available resource and narrowing based on technical accessibility, economic viability, market acceptance, and other parameters. The United States National Renewable Energy Laboratory provides the following hierarchy of definitions for various potentials relating to renewable energy generation:

> *"The largest potential, resource potential, is the amount of energy physically available. Technical potential takes into account real-world geographic constraints and system performance, but not economics. Economic potential is the subset of the technical potential that is available where the cost required to generate the energy (which determines the minimum revenue requirements for development of the resource) is below the revenues available. Lastly, market potential is the amount of energy we expect to be generated through market deployment of renewable technologies after considering the impact of current or future market factors."* [79, p. 1]

Given that energy efficiency has often been considered to be an energy resource in its own right [13], it is curious that there are relatively few comparable studies that attempt to develop the above results for industrial energy efficiency. In my literature review, searches using various combinations of terms including "energy efficiency", "technical potential", "economic potential", and related terms identified the studies described above in the *energy/emissions potential* category. However, such studies are either top-down and generic in nature (contrary to the bottom-up, technology-explicit approaches at the core of most energy potential studies) or focus only on a limited number of measures. The lack of technical rigour and completeness in such studies sets them apart from other studies of resource potential. Here, I define completeness as the consideration of a sufficiently large set of energy efficiency technologies, spanning all relevant processes, end uses, measure types, and production types, such that full range of energy efficiency can reasonably be covered. One apparent reason for this gap in the literature is the considerable diversity of efficiency technologies as discussed previously, compared to the relatively smaller set of technologies needed to realize wind energy potential, for example. However, from the same comparison it follows that an efficiency potential study that considers a limited set of measures is no more valid than a wind potential study that considers only one wind regime or class of turbine.

The closest analogues to the study of energy efficiency potential completed in this thesis are the so-called bandwidth studies completed by the United States Department of Energy [66] or studies of best-available technologies [82], however those studies apply only a generic treatment of efficiency technologies and only consider a subset of sector end use processes in detail. Developing estimates of the potential of energy efficiency as a resource is therefore an under-served area that merits consideration by the research and policymaking community.

1.4. Knowledge gaps

The work completed within this thesis targets a number of knowledge gaps that were identified via literature review. Chapters 3, 4, and 4 provide focused discussions of the gaps that are most relevant to their scope; this section provides a general overview of the key gaps to inform the thesis objectives.

Gap 1: Limited focus on technoeconomic potential for efficiency as a resource.

Understanding the costs and energy/emissions impacts of energy efficiency as a holistic pathway or resource is highly valuable [21] but few studies endeavor to fully characterize this potential. There is a lack of studies that treat efficiency with the same rigorous approaches to technoeconomic assessments that are used for other resources.

Gap 2: Inconsistent model frameworks and lack of integrated analysis.

Worrell et Al. note a number of inconsistencies in model designs and suggest that standardization of common frameworks for modelling could enable greater transferability of techniques and results [35]. There is a notable lack of work that explicitly links bottom-up energy modelling with bottom-up modelling of specific efficiency technologies—most studies of efficiency potential focus on one or the other due in part to the significant data requirements described previously. The use of integrated modelling approaches to overcome these and other gaps has been proposed as an important frontier for studies of energy and emissions abatement potential by several review stuides [35, 40, 61]. Such methods would include detailed accounting of both the technological drivers of current energy/emissions profiles as well as the full suite of available mitigation technologies.

Despite this recognized potential, only a limited number of studies have attempted such a method (e.g.: [83]), particularly in the P&P sector (e.g.: [72]).

Gap 3: Dominance of top-down, technology-generic approaches to efficiency potentials.

Studies of overall efficiency potential in the literature are predominantly based on top-down methods and lack explicit treatment of specific efficiency technologies. This leads to less detailed reflections of technology change within the model and more generic results overall [21, 76]. The macroeconomic parameters and correlations used in top-down models must either be extrapolated from historical data or estimated by experts; in either case, there is a disconnect from the technical reality of current energy use and the potential range of changes in the future [71, 76].

Gap 4: Limited transferability of results

The results of energy benchmarking and efficiency potential studies are seldom able to be applied beyond the region/sector of interest because of the use of top-down modelling methods that obscure regional variations in technology characteristics, sector structure, and other factors [21, 35]. Inconsistencies in definitions and approaches also make it challenging to interpret or compare results between different models [35, 71, 84]. Moreover, the results of bottom-up studies of energy efficiency potential are difficult to compare to top-down benchmarks because of inconsistencies in technology treatment and incomplete technology coverage in the former and lack of detail in the latter (see Gaps 5 and 6).

Gap 5: Insufficient disaggregation of analysis and results.

Industrial sectors have extremely complicated energy/emissions footprints and often do not exhibit homogeneity of technologies and processes at the subsector level. For example, a chemical market pulp mill is significantly different from a recycled newsprint mill from a technological perspective. Energy efficiency technologies are also non-homogeneous and can affect energy and emissions via different mechanisms; these distinctions are not often considered in conventional models [35]. The ability of a model to provide results for suitable crosstabs (subsector, region, production type, measure type, etc.) has direct implications for the utility of its results. Top-down methods are inherently unable to offer disaggregation of analysis and results beyond a certain point, and bottom-up models may be prevented from doing so by data availability [35, 71]. In either case, this lack of granularity may obscure or distort important insights and reduces the relevancy and specificity of results, particularly for heterogeneous sectors such as P&P.

Gap 6: Treatment of efficiency technologies and technology interactions.

Energy efficiency fundamentally contemplates the physical adoption of new and improved technologies within a sector. Generic or stylized representations of technology, as are often used in top-down models, inherently introduce layers of abstraction from this reality [35]. This results in a loss of detail and the potential for additional sources of bias if expert-derived parameterizations are used in place of technical data [71]. However, bottom-up technology-explicit models also suffer from challenges in technology representation. Even a technology-explicit representation of technology options may be subjected to over-simplification in the absence of adequate data. One such gap is a lack of consideration of how different technology types affect energy use and costs differently [35]; a bottom-up model may miss this important detail if its energy savings estimates are simplified to the level of net final energy savings rather than examining energy use at the end-process level. Consideration and appropriate valuation of efficiency measure co-benefits is another important yet often-overlooked factor [35]. Lastly, it has been noted that many efficiency models, regardless of structure, lack of considerations of measure interactions and overlap. [21, 35, 71]. In practice, the energy and emissions savings associated with a bundle of technologies cannot be expected to be equal to the sum of the effects of the measures in isolation because technology interactions, interference, complementarity, cumulative impacts, and diminishing returns can all affect the overall energy/emissions impacts of the measures acting in concert [21, 35, 61].

Gap 7: Lack of consideration for a comprehensive suite of efficiency measures.

A key gap that has prevented bottom-up models from being used more frequently for energy efficiency potential assessments is their significant data requirements [35]. Multiple inputs must be compiled, standardized, and specified for each technology in a bottom-up model. This, combined with the reality that the scope of energy efficiency in industry may include hundreds of technology options, makes quantification of energy efficiency potential via bottom-up methods very data- and labour-intensive [35]. As a result, many bottom-up studies limit their analysis to a relatively small number of measures. Such studies implicitly or explicitly focus their efforts away from attempting to quantify overall energy/emissions savings potential and instead focus on the costs, benefits, and diffusion/adoption of their particular set of measures in isolation. Without consideration of an exhaustive set of efficiency measures comprising the full array of available efficiency technologies and spanning all major energy-consuming processes in the sector, bottom-up models cannot hope to quantify the total potential associated with efficiency. Methods to compile extensive technology databases have typically contemplated either quantitative technology modelling or expert input; these approaches have opposing advantages and disadvantages [21]. There is a lack of hybrid methods that take advantage of expert input within the context of model-based analysis [21].

Gap 8: Limitations of bottom-up methods.

Although they have some advantages over top-down models [76], bottom-up methods may underestimate the costs of energy savings/emissions abatement due to inability to accurately estimate non-energy parameters and under-reporting of transaction costs and other hidden costs [35, 71]. More broadly, the focus of bottom-up models on engineering principles and technology impacts limits their compatibility with more advanced economic/behavioral modeling techniques—often, such analysis would need to be performed outside the scope of the bottom-up model and then incorporated as an exogenous input [35, 76]. Another potential limitation of bottom-up approaches is that they may employ pseudo-top-down means to reduce their data requirements, for example, by using exogenous values for emissions reductions or primary energy savings rather than calculating such parameters endogenously based on end-use energy savings. Such shortcuts can inadvertently obscure complex impacts such as the effects of changing boiler efficiency on downstream processes.

Gap 9: Lack of long-term analysis.

Studies of efficiency potential are often snapshots of current sector potential and do not provide implications over a long-term planning horizon. While this is reasonable for energy savings analysis, it is often insufficient for the purposes of emissions abatement analysis given the importance of cumulative emissions abatement over time. Most modelling methods and their outputs such as cost of saved energy curves or marginal abatement cost curves are well-suited to represent the potential at the present moment [71]. Analysis and forecasting of future potential requires additional data such as projections of econometric parameters and may also require more significant reliance on assumptions, such as those regarding the future baseline scenario or technology learning rates [35, 71].

Gap 10: Inadequate consideration of multiple sector/system boundaries.

In practice, the energy and emissions impacts of energy efficiency technologies may have far-reaching implications and feedback loops that extend beyond model-imposed boundaries [21, 35]. For example, significant reductions in electricity demand within a sector might eliminate the need for generation capacity additions on the electricity grid, which in turn could affect the grid emissions intensity and change sector emissions. Consideration of such effects requires a highly integrated modeling approach, and is often neglected by bottom-up models given their specific focus on the technical parameters within sectoral/regional boundaries. The total costs and benefits of efficiency measures may also be different at the system level than the sectoral level; this may be of interest for policymakers who could benefit from assisting both the specific and system-wide effects of policy. Despite this apparent value, there are few examples of efficiency potential studies that directly compare their results across multiple system boundaries, as compared to the example of lifecycle assessment studies where this practice is commonplace.

Although it is beyond the scope of this thesis to propose complete solutions for all of these gaps, recognition of their existence is instructive regarding best practices in energy and emissions modelling. As described in the subsequent section, the objectives of this work are relevant to addressing key aspects of each gap within the context of the P&P sector.

1.5. Research rationale and objectives

This thesis explores the following central hypothesis:

> "Energy efficiency improvement has the potential to be the most significant pathway towards achieving minimal fossil fuel use and net-zero emissions in the Canadian pulp and paper sector."

In order to evaluate this hypothesis, my work focuses on the primary objective of characterizing the energy savings and emissions abatement potential related to energy efficiency as a technology pathway in the pulp and paper sector. This overarching objective is defined by the following sub-objectives to:

Objective 1:	Develop a novel method to assess the technoeconomic potential associated with energy efficiency, based on the principles of rigour, completeness, and technology-explicitness used in other studies of resource potential. (Chapters 3 and 4)
Objective 2:	Develop a bottom-up, technology explicit efficiency analysis framework that integrates disaggregated sector energy modelling with analysis of specific efficiency measures. (Chapter 3)
Objective 3:	Populate and validate the sector energy and emissions model for the case study of the Canadian P&P sector. (Chapters 3 and 4)
Objective 4:	Develop a detailed database characterizing key technoeconomic parameters for a comprehensive suite of energy efficiency measures available to the Canadian P&P sector by adapting modelled data, expert input, and empirical data from real-world projects to the local context via integration with the sector energy model. (Chapter 3)
Objective 5:	Develop and implement integrated analysis techniques that account for efficiency measure interactions, feedback effects, cumulative impacts, and diminishing returns. (Chapter 3)

Objective 6: Evaluate and characterize the technoeconomic potential for energy savings from efficiency technologies in the Canadian P&P sector with the use of tools including cost-of-saved-energy curves and energy savings bandwidths. (Chapter 3)

Objective 7: Develop technology-explicit scenarios to assess emissions reduction potential, considering the linkage of energy savings to emissions abatement. (Chapter 4)

Objective 8: Implement and evaluate scenarios within a long-range modelling framework to assess annual and cumulative emissions reductions (Chapter 4)

Objective 9: Compare the sectoral and systems-level impacts of energy efficiency modelling to identify additional policy implications. (Chapter 4)

Objective 10: Provide insights to policymakers and other stakeholders regarding the overall potential of energy efficiency as a resource or technology pathway. (Chapters 3 and 4)

Objective 11: Demonstrate extension of the method to other modelling approaches and policy queries by developing efficiency trade-off curves as inputs for an alternative modelling tool. (Chapter 5)

1.6. Organization of thesis

This thesis consists of six chapters.

Chapter 1 provides an introduction to the motivation and objectives for this thesis alongside an overview of the literature and policy landscape relevant to industrial GHG emissions reductions.

Chapter 2 contains background technical, economic, and statistical information on the Canadian pulp and paper sector to provide context for the subsequent analyses.

Chapter 3 focuses on the development of a sector energy model and energy efficiency measure database. The energy savings bandwidths and cost of saved energy curves developed from these inputs are presented.

Chapter 4 expands on the energy savings analysis to focus on long term emissions abatement potential by implementing the sector energy model and energy efficiency measures as scenarios within the LEAP-Canada model. Sector emissions abatement potentials and marginal abatement cost curves are used to characterize and interpret the results.

Chapter 5 presents further extension of the methods and data developed in this thesis for use in a second energy and emissions modelling tool, ENERGY 2020. Technology-explicit energy efficiency trade-off curves for ENERGY 2020 are presented.

Chapter 6 includes discussion of the overall findings and recommendations arising from the research presented in this thesis. The chapter concludes the thesis with a discussion of the potential avenues for future work.

There are 14 appendices containing detailed data for the key inputs and results associated with this thesis, including summaries of the energy efficiency measure survey, energy savings analysis outputs, and emissions abatement cost curve results.

2. Pulp and Paper Sector Background[3]

2.1. Sector overview and economic context

Canada's forest resources are among the largest in the world, with over 347 million hectares of forest land and an estimated 47 billion cubic meters of growing stock [85]. This abundant natural resource has driven development of a strong forest products sector over Canada's history. An important vertical within the overall forest products economy is the pulp and paper (P&P) sector which has clear ties to forestry and natural resource management but also shares many commonalities with value-added heavy manufacturing industries.

Pulp is a fibrous material produced by breaking down the physical structure of wood via chemical or mechanical processes, leaving only the cellulosic fibres [19, 86]. Its primary use is as a feedstock for paper production. Pulp may also be produced by recycling fibres from waste paper or other materials [86]. Market pulp is pulp intended for sale to other industrial users (as opposed to self-consumption) and must be partially dried for ease of transportation and/or export [41]. *Paper* is a material produced by aligning and drying the cellulose fibres in pulp to produce thin sheets [19, 86]. There are many subcategories and grades of paper, including typical printing and writing paper, bathroom tissue, and speciality papers. *Newsprint* is a subclass of paper that is typified by lower strength and brightness than writing paper, often used for disposable applications such as newspapers [19, 33]. *Paperboard* is a category encompassing many of the thicker, stiffer, and more durable forms of paper such as boxboard and cardboard [19, 33]. Unless noted otherwise, in this thesis I use paper as a broad term that also includes newsprint and board. Beyond direct pulp and paper production, there are also *converted paper products* that involve further processing of P&P products (not raw materials) into finished goods such as folded corrugated cardboard containers [33]. Although these activities are sometimes integrated with P&P production, they

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[3] Portions of this chapter were originally developed as part of an unpublished final report to Environment and Climate Change Canada, entitled "Efficiency Potential in the Canadian Pulp & Paper Sector" by Christophe Owttrim, Matthew Davis, and Amit Kumar. All writing and analysis is my original work.

constitute a significantly smaller energy/emissions footprint [87] and are often categorized as light industry [88]. Converted P&P products are outside the scope of this thesis.

The pulp & paper sector is a major constituent of Canada's overall forest product economy and a significant contributor to Canadian manufacturing as a whole. Pulp & paper contributed $7,225,000,000 (CAD 2007) to Canada's real gross domestic product (GDP) in 2017, with direct employment estimated at over 54,000 [85]. Statistics Canada reports 43 pulp mills and 59 paper mills across Canada for a total of 102 manufacturing facilities in the sector as of 2017 [89]. The facilities are dispersed geographically across the country and are closely correlated with local available forest resources. The heaviest concentration of P&P facilities is in Ontario (41 mills), followed by Quebec (20), British Columbia (20), and Alberta (7), with the remainder of mills located in central and Atlantic Canada [89]. This geographic diversity results in significant heterogeneity in terms of feedstock mix, product type, energy sources, cost structures (including energy prices), and operating conditions for the mills across the country.

In 2017, Canada's pulp & paper sector produced 10,067,000 air dry metric tonnes (ADMT) of paper, newsprint, and board and 16,302,000 ADMT of pulp [85, 90]. The majority of paper production and approximately half of all pulp production is exported, while the remaining pulp is used domestically as a feedstock for papermaking [85]. Kraft chemical pulp represents the largest single product category among all subsectors [85].

Over the past two decades, many factors have contributed to competitive pressures in the Canadian P&P sector and have led to declining production, export volumes, economic activity, and employment [86]. Pulp and paper is an EITE sector and as such is highly sensitive to market prices for energy, feedstocks, and products. Energy costs account for between 15%-25% of the sector's total production costs [51, 91]. Structural factors also impact the sector's competitiveness: Canada's mills have a relatively high technical age and are primarily configured to process virgin wood resources rather than recycled feedstock [66]. Canadian mills must also deal with harsh winter conditions and remote locations, both of which can contribute to higher energy costs. Canada's P&P production mix has historically been aligned with certain types of paper products such as newsprint which are now experiencing declining demand globally [86]. These factors have led to significant reductions in production volumes in the Canadian pulp & paper sector and the shuttering of many mills [86]. Despite these competitive pressures, there remains a positive outlook for the sector in the long-term because of Canada's abundant, well-managed natural resources and the potential for diversification into new products [86]. Energy efficiency could play a major role in enhancing the competitiveness of current P&P production capacity while also establishing the sector as a leader in the future low-carbon economy.

2.2. Pulp and paper production technologies and processes

The pulp & paper sector is large and highly diverse in terms of feedstocks, facility design, and outputs. Even within a product category such as pulp there are variations in production technologies and grades; for example, a single mill may produce multiple different specifications of pulp that each require various levels of processing and bleaching. A distinctive attribute of the P&P industry is that different production technologies can yield dramatically different properties and grades of final product [33]. For the purposes of energy modelling, it is therefore essential to effectively categorize and characterize different subsectors according to their specific production technology to the extent possible while maintaining alignment with statistical and literature definitions. The heterogeneity of facility types in the P&P sector has the potential to lead to inconsistencies and overlap in nomenclature and classifications at the mill level. Statistics Canada does not clearly identify how mills with multiple product lines should be classified [92], and paper/newsprint/board mills have significant overlap in products that could lead to mis-categorization if definitions are applied to facilities rather than units of production capacity [59]. For consistency with other work in the Canadian context, I adopted definitions aligned with those of the North American Industry Classification System (NAICS) [88] applied only to aggregate units of production capacity rather than discrete facilities. Thus, I hereafter use the terms production capacity, mill type, and subsector interchangeably.

P&P mills may be *standalone* or *integrated.* Integrated mills are defined by their production of both pulp and paper in a single facility [41]. Such mills therefore consume raw wood and/or recycled paper as feedstocks to produce pulp onsite for their own use in papermaking. They may also supplement their feedstock mix with purchased market pulp to achieve the desired paper properties [41]. Standalone paper mills do not have onsite pulp production equipment and rely on purchased market pulp, which must be repulped (mixed with water) for use in papermaking [33]. Integrated mills have all the unit processes of both pulp mills and paper mills (with the exception of pulp drying), however, they are expected to be inherently more efficient than standalone mills due to greater opportunities for process and utility integration [41]. Unfortunately, NAICS and most other sources do not differentiate between standalone and integrated paper mills [88]. The limited extent of disaggregation in the data therefore presents a challenge for accurate modelling of sector energy use. Standalone pulp mills produce only market pulp from raw wood/fibre inputs, and are treated separately from other P&P mills in the NAICS definitions [88].

P&P production technologies and processes have been described extensively in the literature [19, 33, 41, 66]. This work does not seek to duplicate such efforts but rather to adapt them to a standardized energy modeling framework. Chapter 3 provides additional discussion on the development of definitions of production capacity, end-use process flow models, and energy demand trees for the five major mill types. To establish consistent context for this thesis, the following sections provide brief summaries of the key processes and energy profiles of P&P operations in Canada.

2.2.1. Chemical market pulp mills

Chemical pulp (CP) mills, NAICS 322112, produce market pulp using chemical processes to dissolve the natural binders in the wood [33, 88]. A large proportion of chemical pulping in Canada uses the kraft (sulphate) chemical digestion process, while a smaller number of mills use a sulphite-based process instead [51, 86]. The overall process is similar in both cases; however, the equipment, process conditions, chemicals, recovery methods, and pulp properties are different, which leads to moderate differences in energy intensity and end uses of the pulp [51]. Figure 2 provides an overview of the key processes in CP mills:

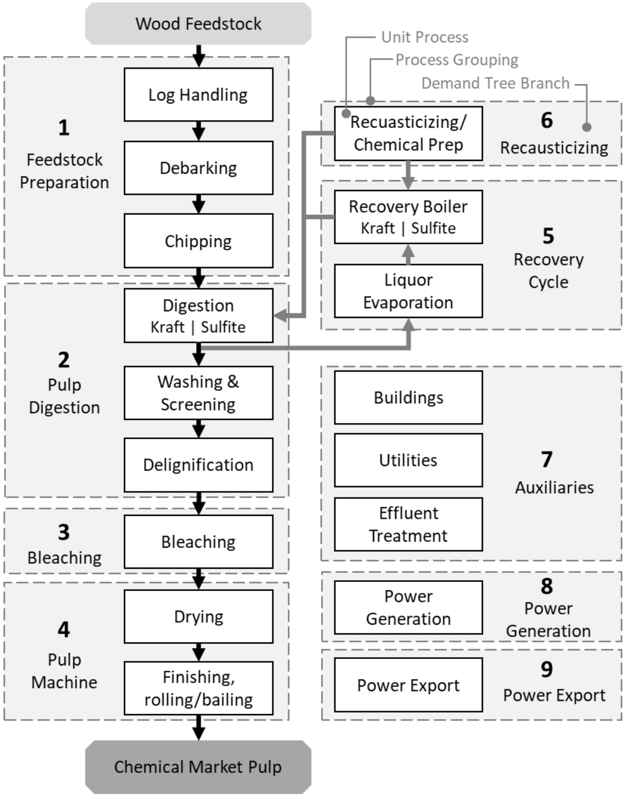


Figure 2: Chemical pulp mill process overview, developed from [33, 41, 51]

As a first step, wood feedstock in the form of logs or chips is processed. If the feedstock is raw logs, they must be debarked and chipped [51]. The core process in chemical pulping is digestion: treatment of wood with chemicals, pressure, and heat to partially dissolve undesired compounds such as hemicellulose and lignin. Following digestion, the desired pulp fibres are separated from other compounds via stages of washing and screening [33]. Many CP mills in Canada also use some degree of post-digestion delignification treatments to further break down remaining lignin in the pulp [33, 51]. The washing process separates the desired pulp fibre slurry (*brownstock*) from a mixture of undesired compounds, pulping chemicals, and chemical by-products known in kraft processes as *black liquor.* The chemicals and energy in the black liquor are then extracted in a chemical recovery cycle consisting of evaporation, combustion, and chemical regeneration [33]. A lime kiln/recausticization plant (kraft) or acid plant (sulphite) are also needed to support the recovery cycle [51]. The chemicals regenerated in the recovery cycle return to the digestion stage of the process, while the energy generated from liquor combustion is used by other processes in the mill. Meanwhile, the brownstock is subjected to a bleaching process to achieve the desired pulp qualities [33]. Finally, the bleached chemical pulp is prepared for transportation and sale via finishing activities including drying and bailing [33, 66].

The CP process removes almost all pulp contaminants and is more gentle on cellulose, producing stronger and longer fibres in the finished pulp [33, 41]. Depending on the extent of bleaching it can be used to produce many grades of paper including printing/writing, packaging, and tissue [41].

The most significant energy-consuming processes in chemical pulping are chip digestion and pulp drying [51]. Evaporation of liquor in the recovery cycle also requires significant thermal energy [51]. However, the recovery cycle itself is a net producer of energy via combustion of liquor in a recovery boiler, often enough to offset a major portion of the other process energy demands. CP mills (and integrated paper mills that use chemical pulping) are often equipped with onsite cogeneration equipment to convert excess steam from the recovery boiler to electricity, reducing their net grid demand [33, 51, 93]. Another distinctive characteristic of CP mills compared to other P&P operations is their requirement for high-grade direct process heat in their lime kilns as part of the recausticization process [41, 66]. Historically, this has been a significant source of demand for heavy fossil fuels in CP mills [94]. However, pollution restrictions and the low price of natural gas has led to a dramatic reduction in the use of fuels such as fuel oil in kilns in favour of natural gas or biofuels [29, 94].

2.2.2. Mechanical Pulping

Mechanical pulp (MP) mills, NAICS 322111, produce market pulp via physical processing of feedstock to separate and process fibres [33, 88]. There are several classes of mechanical pulping technology, typically delineated by their use of hybrid thermal and/or chemical approaches to supplement mechanical processing. Purely-mechanical pulping may involve the stone groundwood process, wood refining process, or high-pressure variants thereof [41]. Hybrid mechanical approaches augment refiner-based pulping with high temperatures and pressures, known as thermomechanical pulping (TMP) [33, 41]. TMP can be further augmented with the addition of chemicals to improve the effectiveness of the process and to achieve desired pulp properties, in which case the process is known as chemi-thermomechanical pulping (CTMP) or bleached chemi-thermomechanical pulping (BCTMP) [33, 86]. Because of the feedstocks and products common to the local market, almost all MP mills in Canada use either TMP, CTMP, or BCTMP [51, 86]. Within these three categories the process flow within a MP mill is relatively similar, as presented in Figure 3:

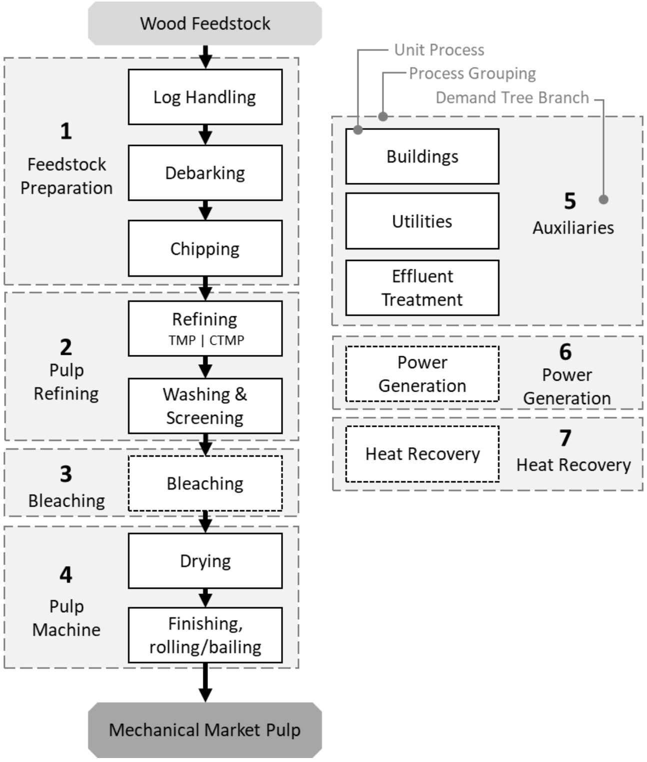


Figure 3: Mechanical pulp mill process overview, developed from [32, 40, 50]

Like CP mills, mechanical pulping begins with feedstock processing to produce uniform chips [41]. The chips are then subjected to refining: mechanical grinding to separate fibres [33]. This stage may also incorporate heat and/or chemical treatments depending on the process [33, 51]. Multiple stages of refining using different speeds and refiner designs may be used to achieve the desired pulp qualities. Refining makes up the vast majority of electricity and total energy demand in the MP process [51]. However, the waste heat from the refining system can be recovered via so-called reboilers and used elsewhere in the process in lieu of imported fuel [51]. Following refining, the pulp must be screened and washed to remove impurities. The BCTMP process is identical to TMP except that chemicals are used prior to refining to make the wood easier to process, and the final pulp product is bleached for use in different applications [33, 41]. Downstream of refining and bleaching, the pulp is finished in a pulp machine that incorporates drying and bailing.

The chief advantage of mechanical pulping is that it delivers significantly higher yield (pulp produced per unit of wood feedstock) than chemical pulping [33, 41]. However, mechanical pulping is less effective at removing contaminants such as lignin and produces shorter, weaker, and darker fibres [41]. MP has excellent printability and is commonly used for newsprint, publication paper, and paperboard [41].

Because of the reliance on motor-driven refiners as the primary unit process, mechanical pulping tends to be highly electricity-intensive but has lower thermal energy demands than CP [33, 50]. Almost all thermal energy demand in an MP mill is attributable to the pulp bleaching and drying steps [51]. However, by recovering heat from the refining system, the TMP process has the potential be a net producer of thermal energy for use elsewhere in both MP mills and integrated paper mills [33, 51].

2.2.3. Paper mills, newsprint mills, and paperboard mills

Print paper (PP), newsprint (NP), and paperboard (PB) mills are categorized independently based on their products, but generally share significant similarities in their technical processes. They are therefore discussed collectively in this section. PP mills, NAICS 322121, produce a wide range of papers including printing and writing paper and tissue [33, 88]. NP mills, NAICS 322122, primarily produce newsprint and publication papers [33, 88]. PB mills, NAICS 322130, produce a range of board products including containerboard and linerboard [33, 88]. In this section, paper is used to collectively refer to print paper, newsprint, and board for simplicity.

As discussed previously, paper mills may be integrated or standalone and may use mixes of various feedstocks such as virgin wood, market pulp, and recovered fibre. To achieve the desired properties, integrated paper mills may combine chemical and mechanical pulping processes (such as refining pulp after it has been chemically digested) and/or may incorporate various additives to the paper stock before forming [33]. This results in significantly greater process heterogeneity than pulp mills. In development of the sector energy model used in this thesis, I account for this heterogeneity by reflecting different pulp supply options as weighted alternatives within the *pulp supply* process branch. In effect, this means that the full process flows (except for pulp finishing) from CP and MP are built into the process flows and energy models for paper mills in my analysis framework. Observations and measures that apply to MP or CP mills also typically apply to integrated PP, NP, and PB mills as a result. A generic process flow for PP, NP, and PB production is provided in Figure 4:

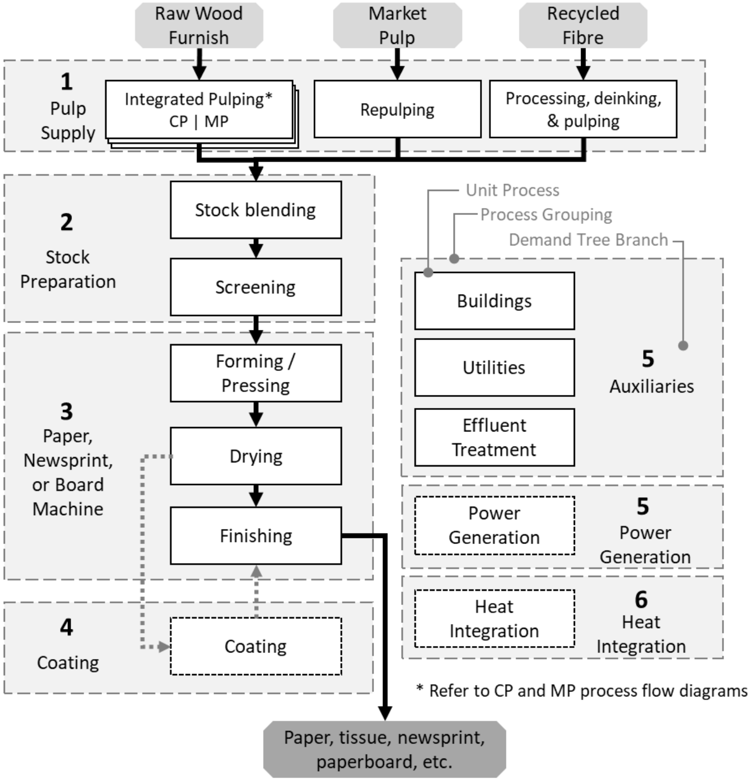


Figure 4: Paper, newsprint, and paperboard mill process overview, developed from [32, 40, 50]

The feedstocks for paper mills can include raw wood, recovered fibre, and market pulp. The processes for production of CP and MP from raw wood have been described in previous sections. Recovered fibre pulping has attributes of both CP and MP processes, and consists of waste paper feedstock preparation, addition of water, chemi-thermal separation of inks and other contaminants, repulping via mechanical means, and optional bleaching before the recovered pulp is in a ready state for papermaking [33, 50]. Market pulp feedstock preparation consists simply of repulping:

returning the dried/bailed pulp to a production-ready state via addition of warm water followed by mechanical mixing [33]. The next step downstream of pulp supply is stock preparation, in which different types of pulp and other additives are blended, remaining impurities are reduced via dispersion, white-water from the paper machine is reintroduced, and the mixture is screened to achieve the ideal properties for papermaking [33, 41, 50, 66]. The heart of any PP, NP, or PB mill is the paper, print, or board machine, where the stock mixture is converted to the end product and prepared for sale. This includes several steps. The pulp stock is passed through a series of forming, pressing, and rolling processes intended to reduce the moisture content of the pulp while aligning the fibres to achieve the desired paper properties [33, 50]. Rolling dryers are then used to achieve the final moisture content while maintaining the product in a continuous sheet [33, 50]. Depending on the type of product, coatings and other finishing steps may be applied to enhance the printability of the product or other desired properties [33, 50, 56]. The end product is then cut into rolls or sheets that are an appropriate size for shipping to customers or to converted paper operations.

Paper, newsprint, and board are broad product categories, each with a myriad of subtypes and grades for customers. The properties of such products including thickness, strength, stiffness, brightness, printability, and resistance to fading/discolouration are highly customizable to meet market demand [33, 41]. Although the process flow models for PP, NP, and PB mills are largely similar, each mill type is implemented independently in the sector energy model as described in Chapter 3. This allows the model to account for differences in energy intensities for the same process in each mill type, which may be driven my many factors including mill vintage, the specific technologies used, and the inherent energy requirements of a particular grade of product.

The energy consumption of paper, newsprint, and board production is highly variable between different mills [50, 51]. Generally, large amounts of electricity are required to run the roller systems and to power vacuum water extraction processes in the paper/board machine [50, 51, 56]. Thermal energy demand for paper is primarily from drying activities in the paper machine. Finishing steps, such as adding coatings to the paper, are often highly energy intensive [50, 51, 56]. However, this is highly dependent on the grade and type of paper produced and is often inconsistent from plant to plant, making analysis of this aspect complex.

2.2.4. Production trends

Capacity utilization, mill expansions, and mill closures have all contributed to significant changes in production rates for each P&P subsector in Canada, as shown in Figure 5. An important note is that pulp produced at integrated PP, NP, and PB mills is not included in these production statistics.

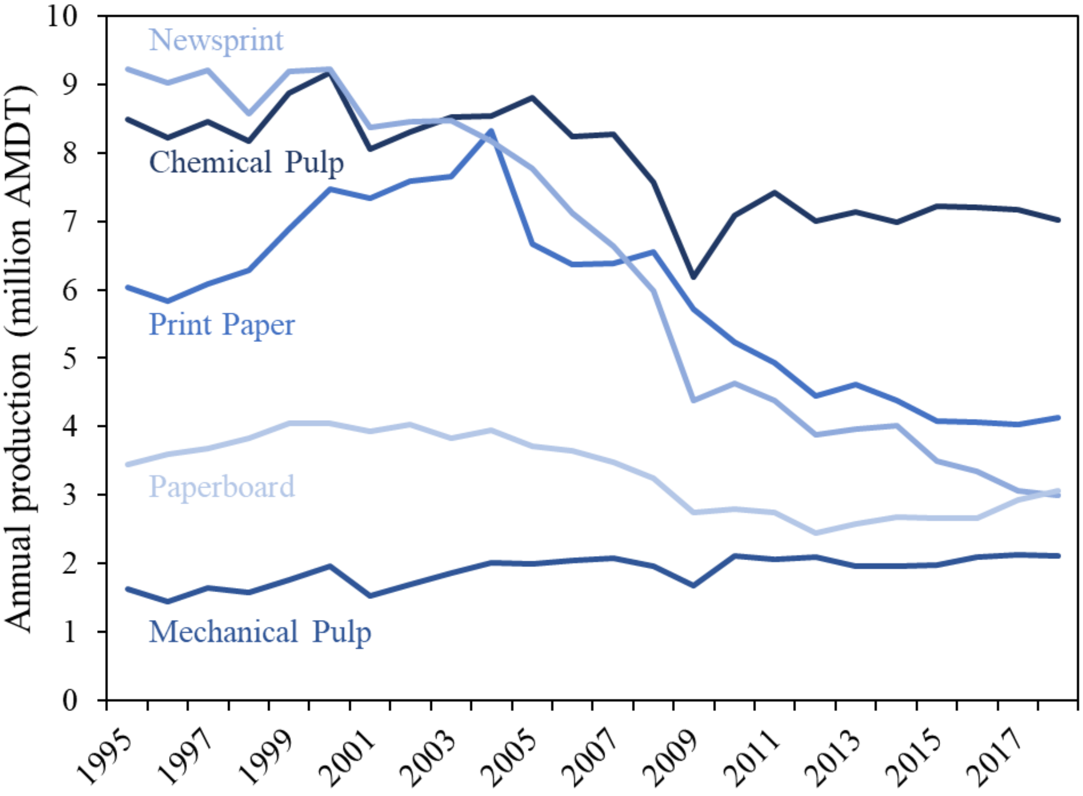


Figure 5: Canadian P&P subsector production trends (data from [90])

Figure 5 demonstrates that the overall structure of the P&P sector has shifted significantly over the past two decades. All mill types except MP and PB have experienced reductions in output, with the most dramatic decrease observed for NP mills. Production of CP and MP has been relatively constant since 2010. PB is the only capacity type that has experienced significant increases in output since 2015. CP accounts for more than one third of all sector production as of 2018. The ratio of pulp to paper production has also shifted from about 1:2 in 1995 to about 1:1 in 2018. Because of the relative energy- and emissions- footprint of each production type, these intra-sectoral shifts and the overall decrease in P&P sector output have major implications for the energy and emissions levels for the sector.

2.3. Pulp and paper energy and emissions profile

2.3.1. Energy and emissions overview

Pulp & paper production is an energy-intensive process requiring extensive raw material preparation, processing, conversion, and product finishing. Moderate changes in feedstock, process conditions, technologies, and practices throughout the production chain can significantly change the quality and utility of the end products. This section explores the main drivers of P&P energy demand and emissions in comparison to other industries in Canada.

P&P energy demand is distributed among many individual processes and end uses of which the two most significant categories are steam process heating and machine drive [41]. Drying of products comprises up to two thirds of thermal energy demand for all mill types [41, 51]. Drying and most other process heat end-uses in P&P require moderate-temperature heat sources and are primarily met by low- and medium-enthalpy steam [33, 41, 66]. Unlike many heavy industrial sectors, P&P has a relatively small number of processes that require high-grade direct process heat. Chemical conversion in a recovery boiler occurs at high temperatures but such temperatures are produced by the recovery boiler itself [41, 51, 56]. Lime recausticization in kilns also requires high temperature direct heat, mainly supplied by natural gas and fuel oil [41, 51]. Motor-driven equipment is the main electricity consumer in P&P mills; the processes involved in P&P production require significant amounts of energy for mass transport via pumps, fans, and solid material conveyance [33]. Liquid/slurry mixing operations, such as those in bleach plants, repulpers, stock preparation, and effluent treatment also require large electric motors [33, 41, 56]. The two machine-drive processes that are unique to the P&P sector are refining of wood chips in mechanical pulping processes and the vacuum/press/roller arrays in paper, print, and board machines; these two processes are the major sources of electricity demand in their respective mill types [33, 41, 51, 56].

Another attribute that distinguishes P&P from many other heavy industries is its near-total lack of process GHG emissions: almost all P&P GHG emissions are a direct consequence of energy use [46, 87]. The largest driver of emissions in the P&P sector is stationary combustion of fossil fuels including natural gas, fuel oil, and other liquid fuels in boilers to produce steam [41, 51, 87]. The other major processes involving combustion of fossil fuels are lime kilns and woodyard feedstock preparation activities including vehicles and stationary diesel-powered equipment [41, 51, 56]. Indirect emissions associated with grid electricity consumption are also a significant source of emissions attributable to the P&P sector, although in some cases mills can be net-exporters of cogenerated electricity [41, 51, 56]. The small level of process emissions from the pulp and paper sector arise mainly from chemical reactions in the lime kilns of chemical mills and from releases of methane at various points in the process, most notably from effluent treatment [41, 56]. Process emissions, as well as emissions impacts from upstream activities such as forest management, are excluded from the scope of this thesis because their magnitude is typically small in comparison to energy-related emissions [46, 87] and they lack a direct connection to energy efficiency.

The emissions footprint of the P&P industry is affected by several distinctive attributes of energy use in the sector. Most notable among these is the significant use of and access to bioenergy in the sector, driven by the energy production associated with pulping liquor combustion inherent to chemical pulping processes and the widespread availability of waste wood and hog fuel available at almost every P&P mill [51, 66]. The P&P sector is a leader among industries in fuel switching to bioenergy [46, 91], and current sources over 57% of its energy from biomass and other biofuels [51]. Another important attribute is the suitability of the sector for heat recovery and integration. This is driven by the moderate temperature requirements (by industrial standards) of most P&P processes and the exothermic nature of processes such as mechanical pulp refining [33, 41, 51]. For this reason, most integrated mechanical mills in Canada already meet a significant portion of their heat load from heat recovered from their refining stages, offsetting their demand for fossil fuels [33, 51]. A final important characteristic that affects the energy-emissions profile of the Canadian P&P sector is the use of low-emitting electricity. Most CP mills and many paper/board mills have some level of cogeneration capacity whereby they generate electricity onsite using condensing turbines and backpressure turbines [51, 93]. In addition, many provinces in Canada have significant quantities of hydroelectric and/or nuclear electricity generation, which results in substantially lower grid electricity emissions for mills in such provinces [87, 91].

The heterogeneity of the different production technologies in the P&P sector leads to significant disparity in the specific energy- and emissions-per tonne production. Figure 6 summarizes the annual energy consumption and emissions of the five major mill types in Canada's pulp & paper sector.

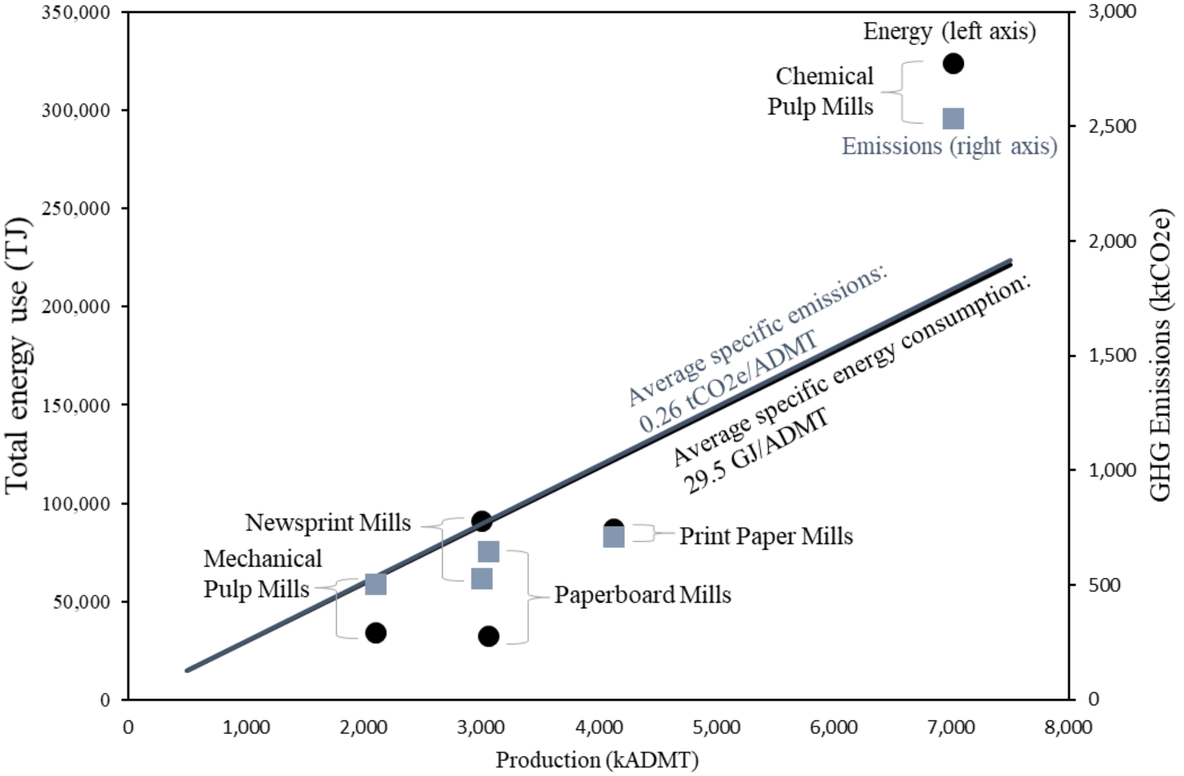


Figure 6: Energy and emissions intensity comparison for major Canadian P&P subsectors, 2018 (data from [87, 90])

As shown in Figure 6, CP mills dominate the sector in terms of production, energy use, and emissions. PB mills have the lowest energy intensity relative to the sector average, while PP mills have the lowest emissions intensity. The figure also demonstrates the close linkage between energy use and emissions in the sector, and reinforces the need for individual modelling of each class of production capacity.

2.3.2. Energy and emissions trends

Figure 7 compares the energy consumption and GHG emissions in the P&P sector to other Canadian industrial sectors as of 2018:

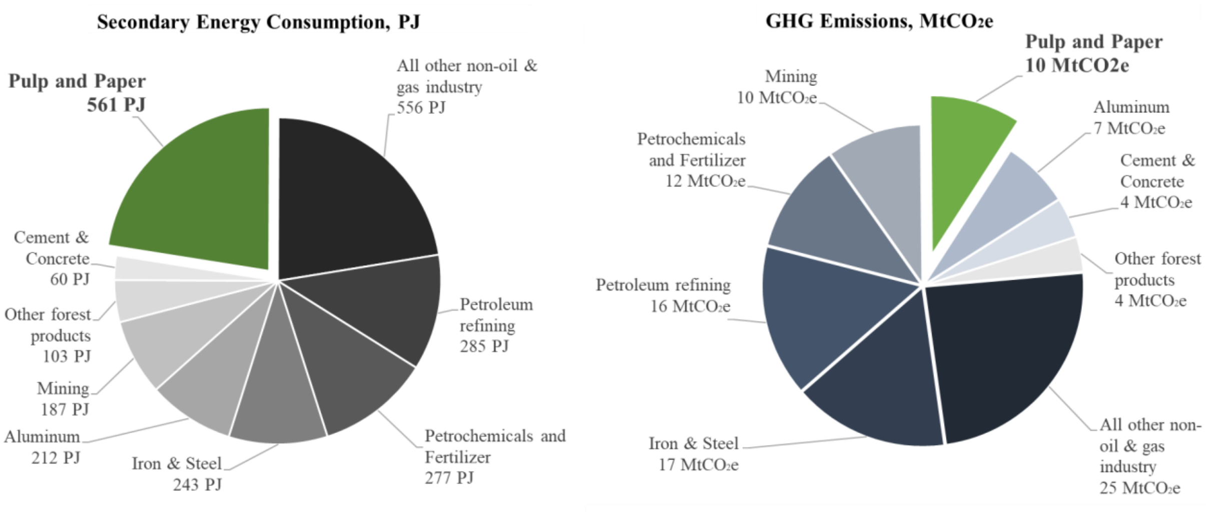


Figure 7: Energy consumption (left) and GHG emissions (right) of Canadian industrial sectors excluding oil & gas in 2016 [95]

In 2018, the pulp & paper sector was the single largest energy consumer among non-oil & gas industries, accounting for 23% of industrial manufacturing energy use in Canada. Despite this large share of energy consumption, pulp & paper was only the 5th largest GHG emitter in the manufacturing sector with total emissions of 10 $MtCO_2e$ in 2018, reflecting the relatively low-carbon nature of the fuels used in the sector discussed above [95].

Figure 8 compares the trends in energy- and emissions-intensity of the P&P sector to other Canadian industries since 1995.

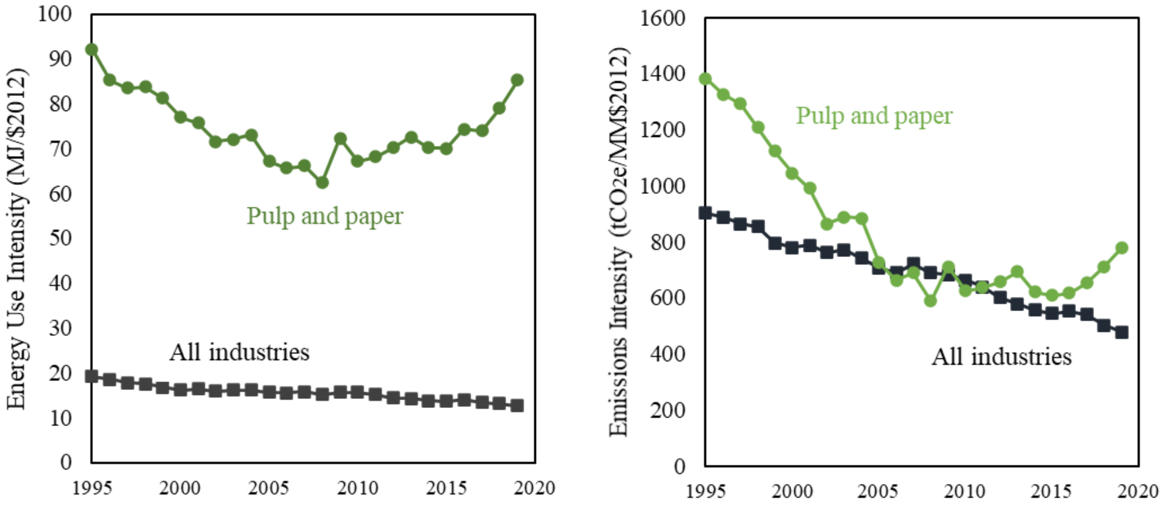


Figure 8: Trends in energy intensity (left) and emissions intensity (right) among Canadian industrial sectors (data from [90])

Figure 8 has several interesting implications. The first is that the energy intensity of the P&P sector is more than five times that of the average industrial sector per unit of GDP. This observation notwithstanding, the emissions intensity of the sector is only moderately above the average. Although Canada's industries in aggregate demonstrate steady reductions in energy- and emissions- intensity since 1995, these trends only apply to P&P prior to 2010. In the past decade, the intensity trends for P&P have reverted to growth in intensity, particularly for energy. One potential cause of this is trend is a simultaneous decline in the value of P&P export products [86]. Nonetheless, the trends indicate that more progress is needed in the P&P sector to decouple economic performance from energy- and emissions- impacts.

Figure 9 shows the absolute final energy consumption in the sector between 1999 and 2016.

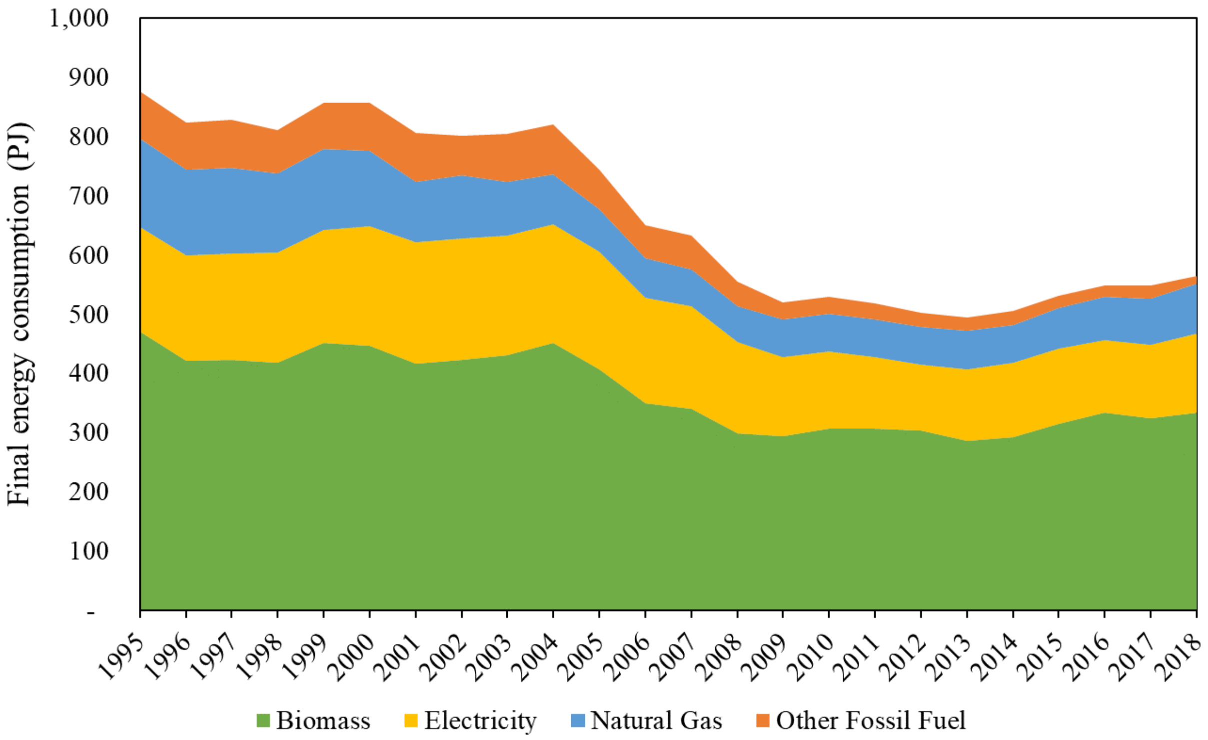


Figure 9: Energy consumption trends in the Canadian P&P sector (data from [87])

Energy supply in the sector has historically been dominated by electricity and biomass, with less than 25% of energy sourced from fossil fuels. Biomass in particular is a significant fuel source due to the large amount of low-cost woody biomass available at or near pulp & paper facilities. As previously discussed, mills with chemical pulping also produce large quantities of pulping liquor as a by-product that is burned to produce energy [33]. Some data sources and studies disaggregate the different forms of bioenergy while others combine all bioenergy types into a single category. The latter approach was used in this study to align with available data; throughout this thesis, I use *biomass* as a generic term covering all bioenergy. The consumption of fossil fuels other than natural gas in the sector has declined significantly and is essentially negligible in the current fuel mix; remaining other fossil fuel use is dominated by diesel and heavy fuel oil [87]. Notably, zero coal consumption has been reported in the sector since 2010 [87]. Overall final energy consumption in the sector has fallen from a recent high of about 820 PJ in 2004 to a minimum of less than 500 PJ in 2016, commensurate with declining sector production [85]. However, from

2013 to 2018 total energy use increased by 14%, driven mostly by natural gas and biomass, and is now 565 PJ annually [87].

To analyze the trends in energy use independent from sector activity level (production rate), Figure 10 presents the specific energy consumption per tonne of product for each of the four main energy types since 1995.

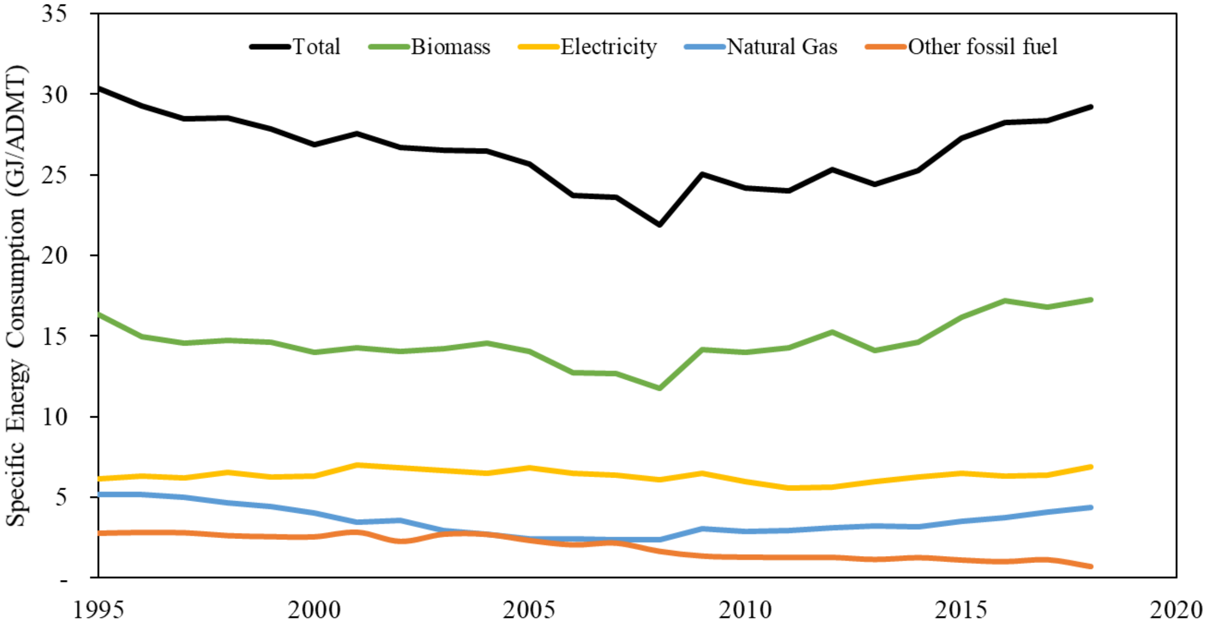


Figure 10: Specific energy consumption trends for the Canadian P&P sector (data from [90])

Overall specific energy consumption has increased by roughly 25% over the past decade. This increase, closely correlated with reductions in output, has been almost entirely driven by increases in biomass consumption intensity. Natural gas and electricity intensity have increased moderately since 2010 while the consumption of other fuels has declined to near zero. These trends reflect a number of important factors influencing pulp & paper energy demand and emissions. Biomass consumption is the main driver of trends in overall sector specific energy use. Fuel switching efforts in the sector to date have been highly successful at shifting from heavier fossil fuels to natural gas as well as biomass [28, 29, 46]. This leaves natural gas as the key fuel to address to achieve further emissions reductions. Despite rising electricity prices [96] and energy efficiency efforts, electricity use in the sector has been essentially stagnant over time. This suggests that here may be untapped efficiency potential for electricity end uses, or that efficiency efforts to date have been countered by the rebound effect and changes in sector structure [28, 29, 40].

Figure 11 summarizes trends in GHG emissions for the sector over time.

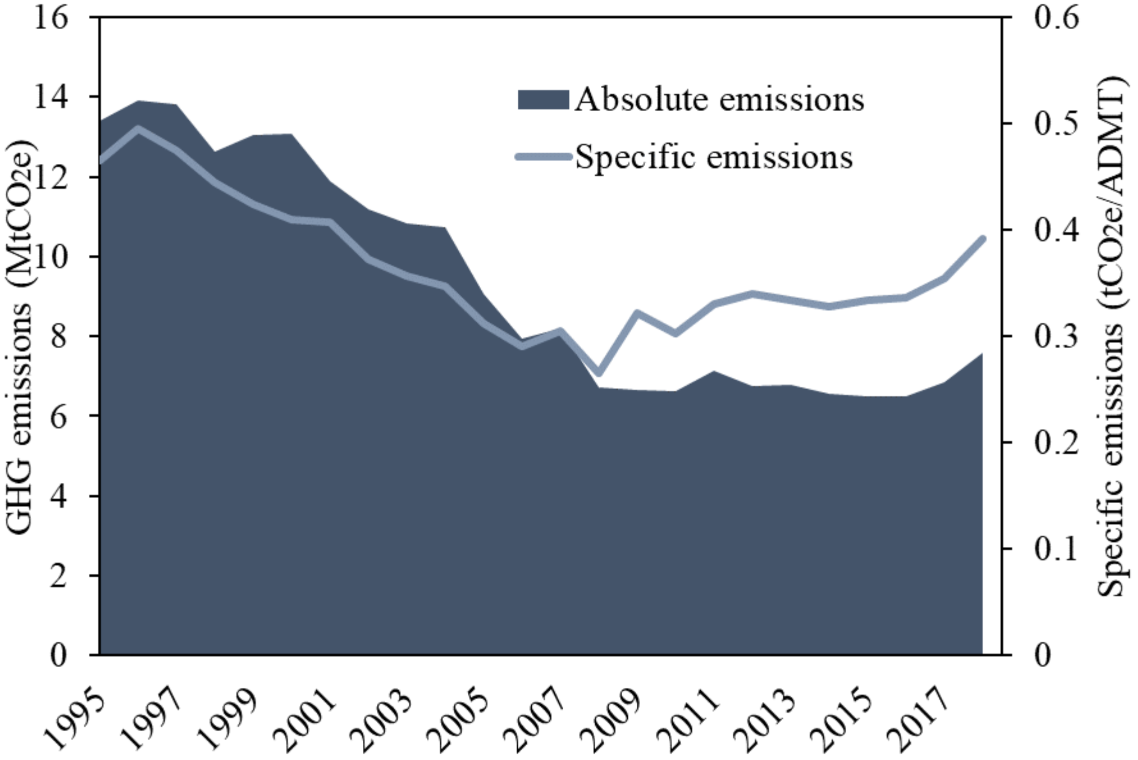


Figure 11: GHG emissions trends in the Canadian P&P sector

Similar to energy consumption, absolute emissions have fallen by roughly 50% since 2000 but a moderate rebound can be observed in recent years. Notably, the trends in absolute and specific emissions align well prior to 2008 and diverge thereafter, which indicates that changes in emissions after 2008 are likely driven by sector activity rather than reductions in efficiency or increases in fuel emissions intensity.

Decomposition analysis of the Canadian P&P sector is not within the scope of this thesis and has been recently completed by Talaei et al. [29]. However, it is instructive to observe the trends in key econometric parameters for the sector in the context of the energy use trends discussed above. Figure 12 indexes key parameters for the sector over time.

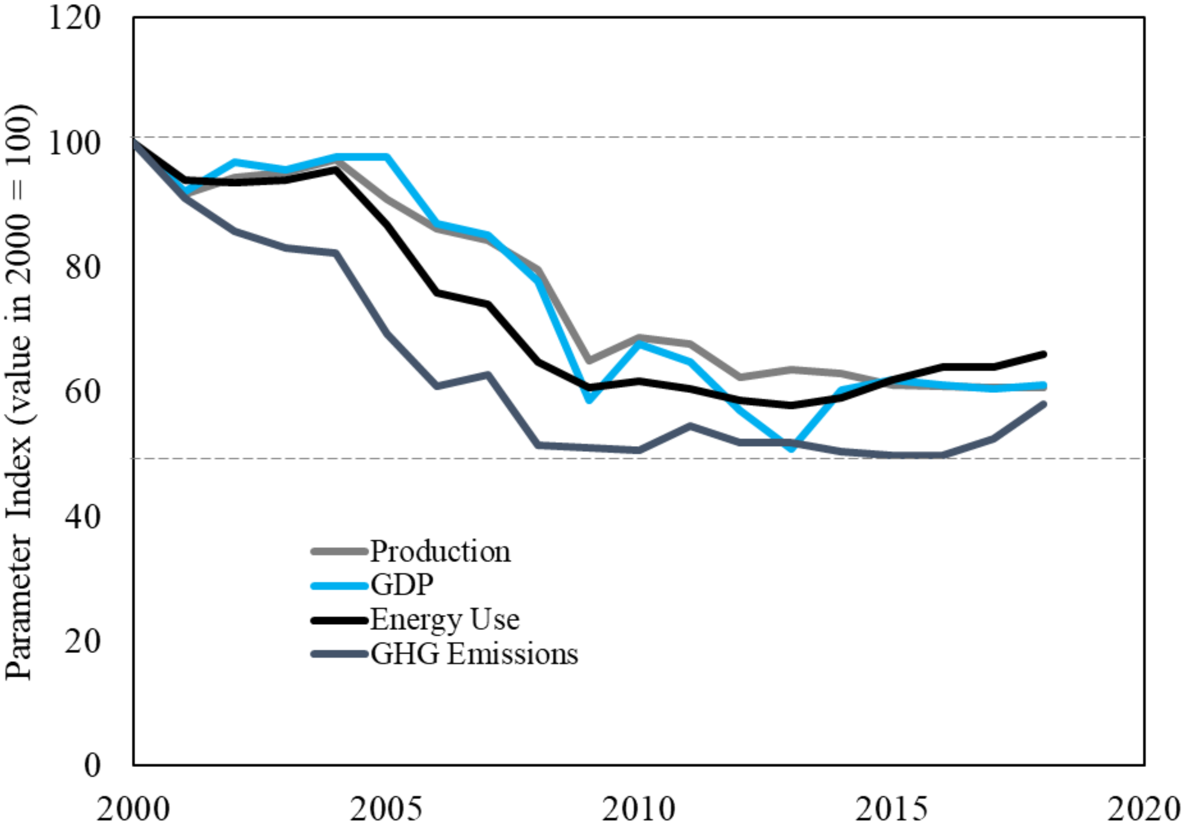


Figure 12: Comparison of indexed P&P sector parameters

As shown in Figure 12, the energy and emissions footprints of the Canadian P&P sector are closely tied to sector production, which is in turn closely tied to the sector's GDP contribution. Emissions have fallen faster than the other indicators, indicating that factors such as fuel mix may have played an outsized role. However, both emissions and energy intensity in the sector have increased since 2015 while sector output has remained constant. This suggests that other factors such as sector structure or efficiency level may have worsened during that time.

Figures 9-12 provide a consistent indication that P&P sector energy and emissions footprints have been dominated by factors other than energy efficiency and fuel type, particularly in recent years. As a result, while significant absolute reductions in energy use and emissions have been achieved by the P&P sector there remains work to be done to re-establish downward trends in energy and emissions intensity. Given the lesser roles of energy efficiency and fuel choices in the past five years, it is possible that those two levels may have additional untapped potential to support such efforts.

2.3.3. International context

Canada is a significant P&P producer in a global context, and ranked among the top five nations for P&P production and exports as of 2018 [97]. Historically, kraft chemical pulp has been Canada's largest single P&P export product, followed by newsprint [86, 98]. By total capacity, Canada has also been the largest exporter of mechanical pulp worldwide [66]. Figure 13 compares production data for the top 20 nations in 2020.

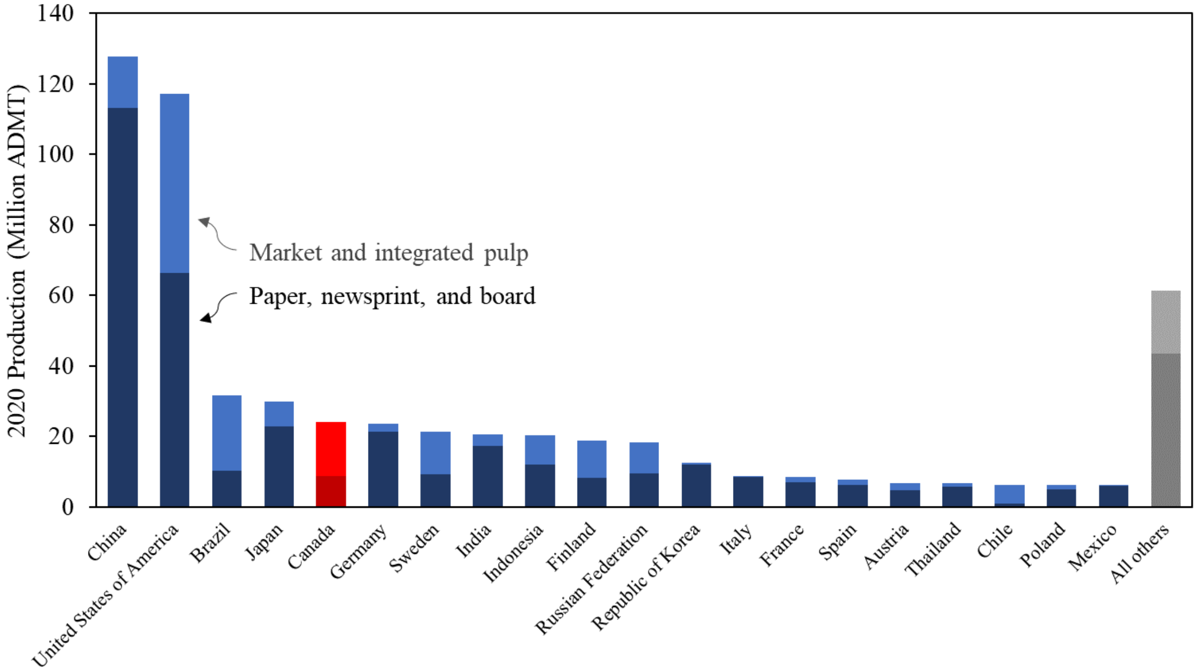


Figure 13: Pulp and paper production for top 20 nations, 2020 (data from [97])

Figure 13 demonstrates that Canada's P&P production is commensurate in scale with Brazil, Japan, Germany, and Sweden. Canada is one of the only nations with a pulp/paper ratio greater than 1.0 and is therefore one of the largest net-exporters of market pulp.

Several studies have compared specific energy consumption across the P&P sectors of several countries [56, 63, 66]. Figure 14 compares the energy intensity of pulp & paper production in various countries, based on work from the United States Department of Energy [66]:

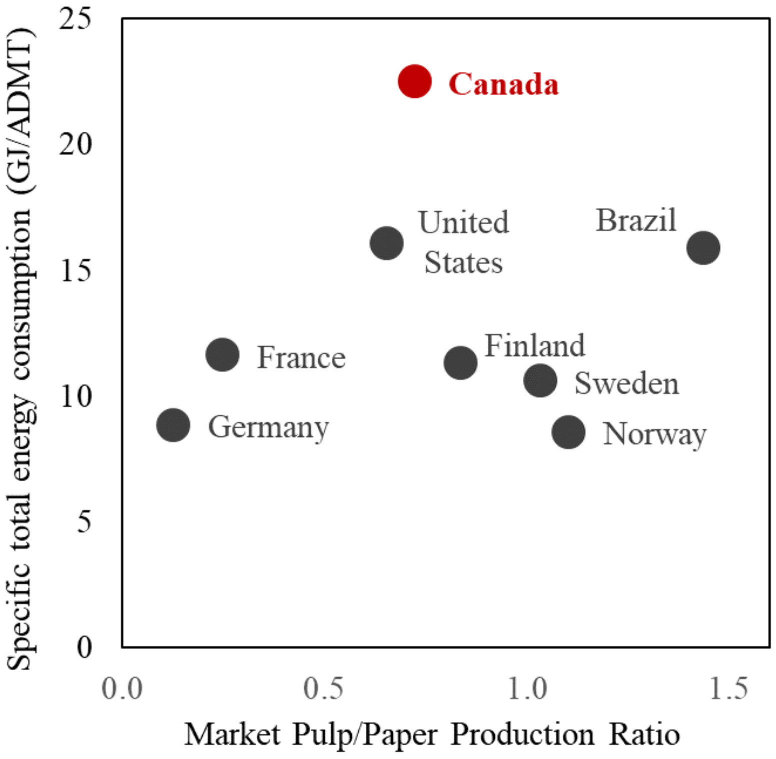
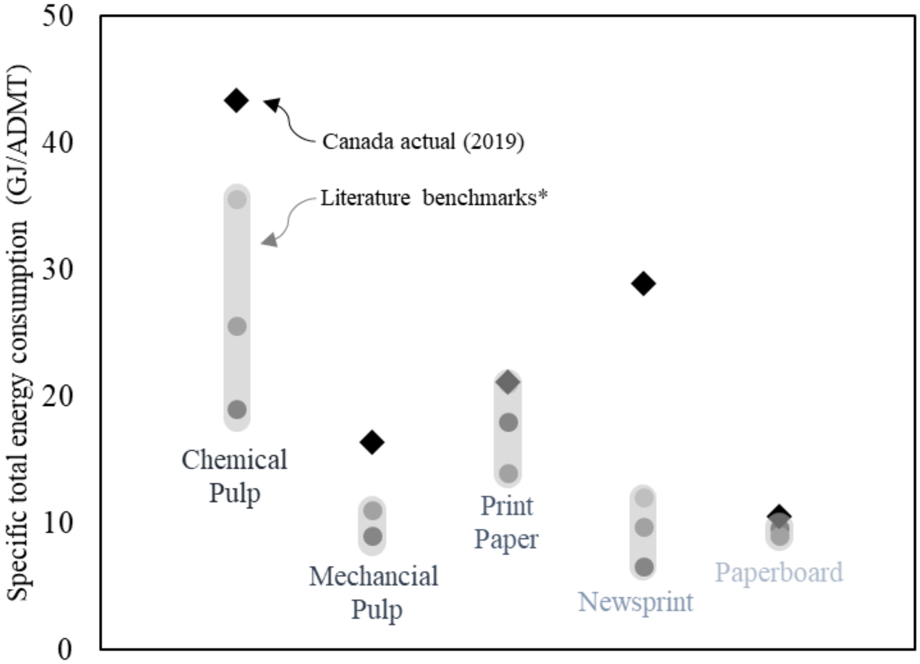


Figure 14: Pulp & paper specific energy consumption by country, total production basis, 2012, reproduced from [66]

Even when accounting for Canada's pulp/paper production ratio, the specific energy consumption of the sector in Canada is significantly higher than elsewhere. The relative gap between Canada and other countries is instructive in terms of assessing overall potential and the effect of recent increases in intensity.

Figure 15 compares total specific energy consumption in Canadian P&P subsectors to international benchmarks [19, 53, 99].



*benchmarks for comparison (adjusted for energy conversion efficiency):

- Worrell et Al. best-available technologies (2008) [53]
- European Commission best-available technologies (2013) [19]
- Sweden "model mill" benchmarks (2011) [99]

Figure 15: Canadian P&P sector energy use [90] compared to international benchmarks

Figure 15 demonstrates that the energy performance of the Canadian P&P sector lags international benchmarks across all subsectors. The most dramatic efficiency gap is observed for CP and NP mills, while PP and PB mills have an average SEC comparable to the upper end of the range of literature benchmarks. The poor performance of NP in particular may be attributable to the heavy use of virgin wood as NP feedstock in Canada compared to the predominant use of recycled fibre elsewhere [19, 86].

A 2012 study applied decomposition analysis to isolate the effects of structure, activity level, energy efficiency performance, and other factors and used the results to compare selected P&P producing countries [63]. That study ranked Canada behind Finland, Sweden, Brazil, and the United States for energy efficiency performance in 2009 [63]. Moreover, while all other countries increased their energy efficiency performance over the study period, Canadian P&P sector efficiency worsened at an average annual rate of 0.19% from 1985-2009 [63].

Overall, comparison to actual and benchmark data for competition P&P producers internationally suggests that the Canadian P&P sector suffers from relatively poor energy performance and could significantly improve its energy use and emissions simply by meeting the specific energy consumption levels achieved by other similar countries.

3. Pulp and Paper Sector Energy Modelling and Energy Savings Potential[4]

3.1. Introduction

Improved industrial energy efficiency – the concept of reducing the ratio of energy inputs to industrial output – is widely regarded as a critical opportunity to reduce global greenhouse gas (GHG) emissions and enhance the competitiveness of local industries [6, 100]. As policymakers and industry members look ahead towards the growing urgency to reduce fossil fuel use and achieve net zero emissions, there is a need to develop a more comprehensive understanding of industrial energy use and of the opportunities to improve industrial efficiency, particularly for sectors that are emissions intensive and trade-exposed [12, 15]. Despite the apparent advantages of energy efficiency initiatives, the realization of their full potential is limited by several barriers [101] including low awareness of available technologies and high uncertainty regarding their potential benefits [20]. Such barriers can be overcome, in part, by developing advanced and up-to-date analyses of industrial energy use and efficiency opportunities to enable informed decisions regarding energy efficiency policies, investment strategies, and technology development [102]. To this end, industrial energy demand, emissions, and energy efficiency opportunities have been the subject of numerous analyses in all major industrial sectors including petroleum extraction [103], refining [104], iron and steel [105], cement [106] , mineral mining [107], and pulp and paper (P&P) [50, 72].

Analyses of energy efficiency potential in the P&P sector can be broadly classified into two categories. The first consists of studies that focus on sector-wide energy efficiency potential by assessing best available technologies and/or developing benchmarks for energy consumption. In contrast, the objective of studies in the second category is to analyze the

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[4] The content in this chapter will be submitted for publication in a peer-reviewed journal as "Development of technology-explicit energy saving bandwidths: a case study for the pulp and paper sector" by Christophe Owttrim, Matthew Davis, and Amit Kumar. All analysis, results, and writing are my original work.

costs and energy savings associated with the adoption of specific energy efficiency measures (EEMs) in the sector.

Studies of the first type have been completed using various methods for most major P&P-producing regions. A common approach is to compare sector-average energy consumption values to benchmark values; this has been completed for Canada by Francis et al. [52] and for the Netherlands by Laurijssen et al. [50], among others. Top-down energy benchmarking has also been combined with methods such as energy demand decomposition analysis as demonstrated by Kähkönen et al. for the Finnish P&P sector [62] and by Fracaro et al. [63] for Brazil. Other studies in this category have expanded the analysis to also account for emissions levels, such as those completed for China and the United Kingdom by Peng et al. [64] and Griffin et al. [58, 73], respectively. Outside of the academic literature, similar work has been completed by government researchers to support policymaking. Notable examples include the characterization of best-available technology energy demands by the European Commission [19] and Worrell et al. [53]. In an extension of this approach, Miller et al. [66] used surveys of subject matter experts to develop top-down energy-saving bandwidths for the United States (U.S.) P&P sector. These studies are useful for characterizing the theoretical boundaries of efficiency potential but in general do not consider the specific technology changes required to achieve a given benchmark while accounting for the current technology mix. Even in cases where a bottom-up sector energy model is used, such studies tend to employ generic estimates of the sector-wide potential for measures such as heat recovery rather than developing specific estimates based on individual technologies. In addition, most studies of this type do not provide results disaggregated by the type of product or production process; this lack of granularity may obscure or distort important insights. These limitations fundamentally restrict the transferability of results between different regions whose P&P sectors may have different technological characteristics.

Studies in the second category are also highly diverse in terms of analysis technique and region of interest. The most basic studies of this type simply describe the energy savings and costs of implementing measures at individual mills; for example, Kong et al. published results based on the completion of an energy audit and EEM analysis at a mill in China [48].

Similarly, data for a more comprehensive set of EEMs was presented by Kramer et al. by compiling case studies of real-world efficiency projects in the U.S. [108]. Other studies have built upon simple EEM analyses by applying tools such as cost of saved energy (CSE) curves to compare measures and assess their sector-wide potential. Examples of such studies have been completed for the U.S. and China by Xu et al. [69] and Kong et al. [65], respectively. These studies can provide valuable insights into pathways to reducing sector-wide energy consumption and emissions but are also subject to several limitations. Although they incorporate technical detail in their assessment of EEMs, studies of this type tend to lack explicit integration with a detailed sector energy model. The combination of bottom-up technology assessment with bottom-up energy modelling is expected to yield significant insights [61], so the relative lack of such work in this area is a notable gap that also restricts the transferability of study results between regions. We identified only one study, by Fleiter et al. [72], in which a disaggregated bottom-up P&P sector energy model was coupled with analysis of specific EEMs. A more significant limitation of studies in this category is their strong tendency to focus on a relatively small set of measures, which means they cannot be used to estimate the total possible sectoral energy savings. Rather, they are limited to providing insight on the potential associated with their particular set of technologies and/or the diffusion and adoption of certain measures by industry.

Our review of the relevant literature, as summarized above, identified several key gaps that define a significant and underserved opportunity for study. First, studies of overall savings potential and best available technologies do not typically consider the specific EEMs required to achieve a given benchmark, and thus are of limited utility for research and investment decision making. A second major gap is the poor transferability of results between different P&P producing regions because of the lack of methods that incorporate technology-explicit bottom-up sector energy models. Critically, the integration of EEM analysis with both a robust sector energy model and consideration of interactions between measures has been attempted in only a small subset of studies that we reviewed. The third gap is that, to the best of our knowledge, no study of sector-wide potential has been completed with a set of measures that can be considered to be exhaustive, i.e., comprising the full array of available efficiency technologies and spanning all major energy-consuming processes in the sector. Thus, studies of individual EEM impacts cannot be directly compared with top-down energy-use benchmarks.

To resolve these gaps and provide greater insights, we developed a novel method that uses individual analyses of a comprehensive set of discrete measures to estimate the overall sector bandwidth for energy savings. Notably, this hybrid approach overcomes the limitations of previous works by integrating a technology-explicit sector energy model with analyses of individual EEMs, enabling data from other regions to be adapted and applied more realistically in the local context. The disaggregated results produced via our method are of greater value for policymaking and technology investment decisions because they show how each EEM in each type of P&P mill contributes to the overall sectoral energy savings potential. To the best of our knowledge, this study is the first to provide a technology-explicit, bottom-up estimate of the energy savings bandwidth for the P&P sector.

In this paper, our novel approach is demonstrated via its application to the case study of the Canadian P&P sector. Canada is a significant global pulp and paper producer, ranking in the top five countries for P&P production as of 2018 [97]. However, the sector faces considerable competitive pressures including a significant disadvantage in energy-related production costs. Compared with other regions, the P&P sector in Canada is less energy efficient, using significantly more energy per tonne of product based on cross-national analyses [56, 66]. Pulp and paper ranked 2nd and 7th in energy demand and GHG emissions, respectively, among non-oil & gas industrial sectors in Canada in 2017 [87]. The closely related challenges of reducing energy costs while maintaining compliance with environmental and emissions regulations such as Canada’s growing set of climate policies and targets [17, 25] make the sector a timely and relevant focus area for energy system modelling and energy efficiency analysis [47, 109].

The overall objective of this study is to characterize the energy savings bandwidths in the Canadian pulp and paper sector through an integrated assessment of the costs and benefits associated with a comprehensive set of energy efficiency technologies. This overarching objective is defined by the following five sub-objectives:

1. To develop a standardized framework to facilitate integrated energy demand and energy saving analysis for any sector and region;
2. To populate a disaggregated bottom-up sector energy model by characterizing the processes and technologies used in the P&P sector;
3. To survey energy efficiency measures that are applicable to the sector and to determine their benefits and costs in the Canadian context using the sector energy model;
4. To analyze the cumulative energy savings potential and cost impacts of implementing energy efficiency measures to produce cost of saved energy curves and energy saving bandwidths; and
5. To provide insights to policymakers and industry regarding energy savings potential and pathways.

3.2. Method

3.2.1. Study framework

We used a systematic approach to assess the energy efficiency opportunities in the sector, as shown in Figure 16:

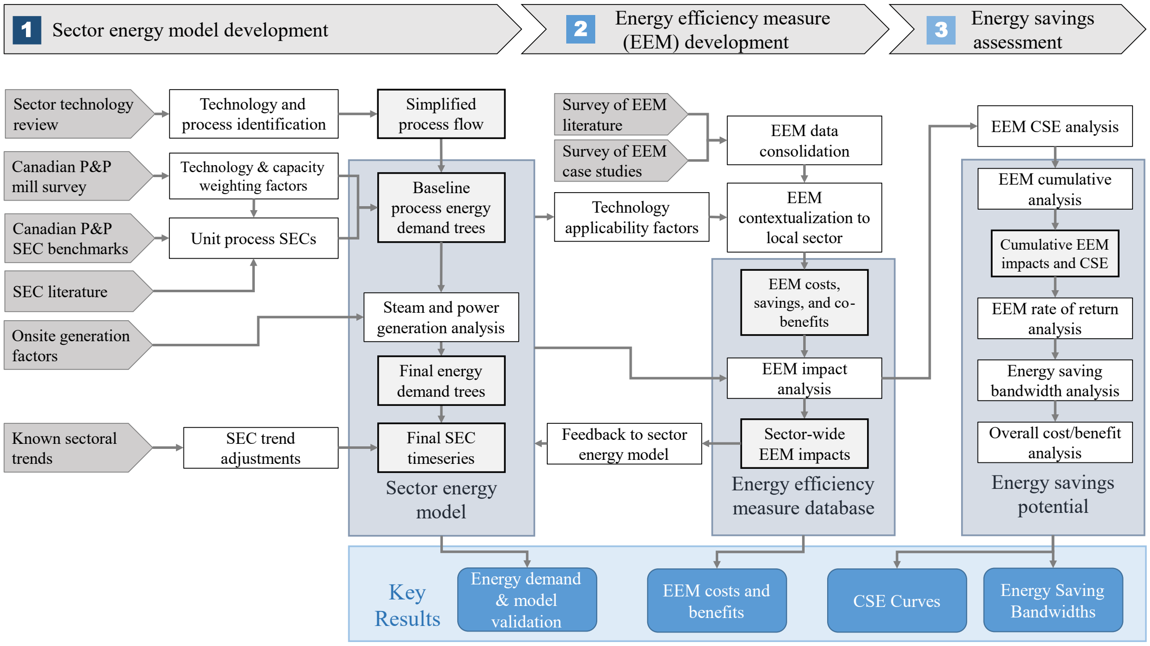

Figure 16: Study phases and modelling framework

In the first phase of the study, we developed a disaggregated sector energy model (SEM) that incorporates details of the typical technologies, processes, and operating conditions of the P&P sector. Section 3.2.2 describes the methods used to develop the SEM including characterization of the unit process steps and specific energy consumption (SEC) associated with each mill type and subsequent analysis of how energy demand is served by energy imports and onsite generation. In the second stage of the study, summarized in Section 3.2.3, we conducted a comprehensive survey of EEMs available to the sector. The EEM data was then compiled and adapted to the local context with the use of technology-explicit applicability factors developed using the SEM. The sector-wide impacts and costs of implementing each EEM were then estimated. In the third phase of the study, the outputs of the EEM analysis were used to produce the targeted results for the study, including CSE curves and energy saving bandwidths.

Our analysis framework successfully links technology-explicit energy demand modeling with consideration of discrete energy efficiency measures and can be applied to any similar industrial sector in any jurisdiction.

3.2.2. Sector energy model development

3.2.2.1. Sector energy model structure

To accomplish the objectives of this study we developed a disaggregated, technology-explicit, bottom-up, accounting-based sector energy model. The sector energy model is the foundation of the analyses performed in this study and supports several key functions including:

- Providing insight into the energy-consuming processes in the sector and the drivers of energy demand;
- Enabling a forecast of the base case for business-as-usual energy demand in the sector in future years;
- Enabling disparate data for possible EEMs to be standardized and contextualized for application specifically in jurisdiction of interest; and

- Providing a framework for consistent analysis and comparison of efficiency measures and policies.

The SEM uses an energy demand tree (EDT) structure to disaggregate the components of sectoral energy demand.

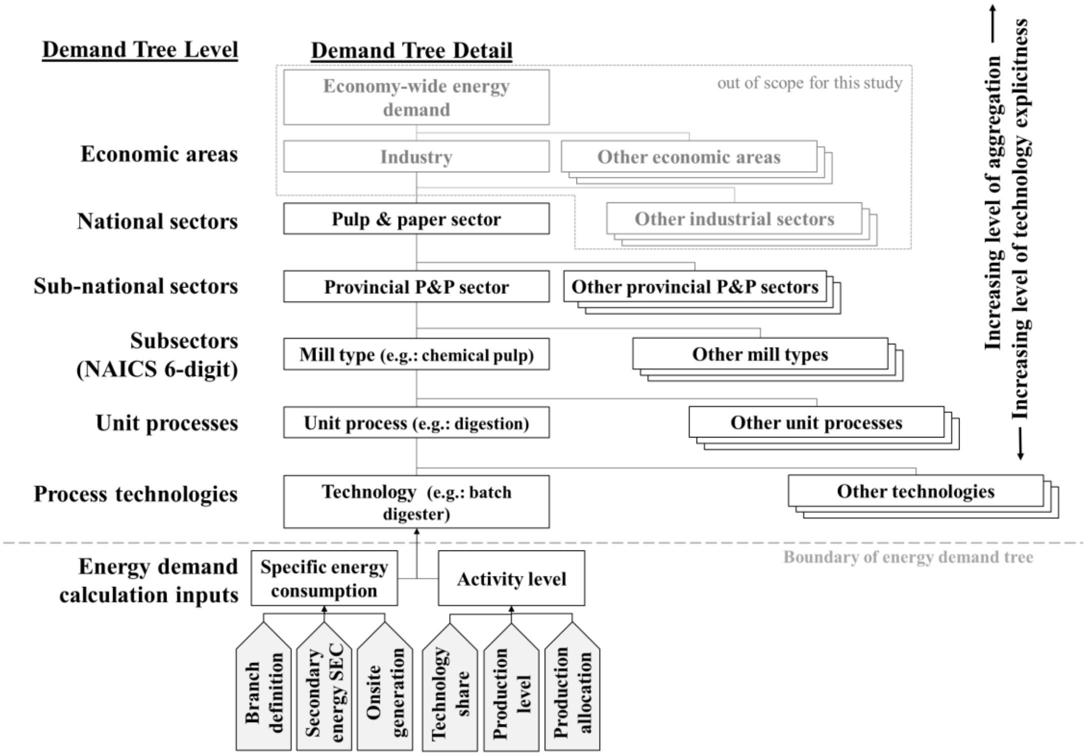

Figure 17: Sector energy model demand tree structure

As shown in Figure 17, the EDT structure disaggregates energy demand into multiple branches at increasing levels of specificity. The branches at the bottom layer of the model represent individual technologies such as refiners, digesters, dryers, etc. that are used in pulp and paper production. The energy use in the sector can be fully defined by populating the sector-average SEC values for each base-level branch and propagating their sums up to higher levels of the EDT. This approach is well suited for characterizing the drivers of energy demand while avoiding the complexity of attempting to simulate the behavior of individual firms or other stakeholders in response to changing conditions. Thus, a distinct advantage of the developed model is that it can be used to analyze the technical potential for efficiency gains in isolation from other factors.

3.2.2.2. Sector process flow and specific energy consumption

As an initial step in SEM development, we conducted a review of P&P production technologies and practices to establish definitions for the EDT branches. In keeping with the high level of disaggregation that we targeted, we classified P&P production into five distinct subsector definitions according to mill type. This demarcation of production capacity allows key technological, operational, and structural differences between different mill types to be captured in the model and our results. Our definitions are functionally aligned with those of the North American Industry Classification System (NAICS) 6-digit level. In most cases this level is the highest degree of disaggregation available for the data sources we used in this study; this system is also used by Statistics Canada for their disaggregated sector data [88]. Unlike NAICS and Statistics Canada, however, our model considers only aggregate production capacity rather than the number of facilities in a category. Thus, our model avoids the potential issues created by attempting to classify mills that contain multiple production lines using different technologies. We therefore use the term “mill type” interchangeably with “production category” rather than to describe classifications of individual facilities.

The five types of production capacity that we consider are as follows:

1. Chemical pulp (CP) mills – NAICS 322112: produce market pulp using kraft or sulphite chemical digestion processes.
2. Mechanical pulp (MP) mills – NAICS 322111: produce market pulp using mechanical, thermomechanical, or chemi-thermomechanical processes.
3. Print paper (PP) mills – NAICS 322121: produce printing and writing paper and tissue from various feedstocks such as virgin wood, market pulp, and recovered fibre.
4. Newsprint (NP) mills – NAICS 322122: produce newsprint and publication paper from various feedstocks such as virgin wood, market pulp, and recovered fibre.
5. Paperboard (PB) mills – NAICS 322130: produce linerboard, containerboard, and other paperboard products from various feedstocks such as virgin wood, market pulp, and recovered fibre.

By developing individual EDT branches for each NAICS 6-digit class of production capacity, our model achieves higher fidelity with the energy demand profile of the local sector than top-down approaches and avoids issues with double counting of sector by-products such as pulp produced in integrated paper mills [59].

We developed process flow sheets for each mill type by consulting the available literature on pulp and paper production methods and technologies. Details are provided in Section 2.2. We then reviewed the available literature on the consumption of secondary energy within each defined branch of the EDT. Secondary energy is energy that is ready for end use within the mill and includes electricity, steam, and direct heat. We developed estimates of the secondary SEC for all branches, relying primarily upon a recent benchmark study of typical mills in the Canadian P&P sector completed by Natural Resources Canada (NRCan) [51]. For this step, it was essential to use local estimates where possible because production SEC values can vary significantly by country because of differences in sector structure, feedstock, climate, regulatory or product standards, and other factors [59]. In the limited number of cases where local data was lacking, we supplemented our primary source with additional inputs [33, 50, 56, 57, 66]. Where applicable, several technologies were considered for each unit process branch by using a weighted average of the SEC for each process technology option. For example, both batch digestion and continuous digestion technologies were considered in the development of the SEC for the pulp digestion branch of the CP EDT. To develop the technology weighting factors for our Canada case study, we conducted a systematic survey of publicly available data on 93 pulp and paper mills in Canada to classify them by production capacity, mill type, and their use of specific technologies. This exercise provided us with a highly granular and current technology profile of pulp and paper operations in Canada. A benefit of the disaggregated bottom-up EDT approach is that our SEM can be adapted to the P&P sector of other jurisdictions of interest simply by altering the EDT branch SEC and technology weighting factors to reflect the desired context. The SEM framework can also be adapted to other sectors by modifying the branch definitions for the EDT and populating them with the appropriate data.

At this point, we validated the completeness and accuracy of the secondary energy values for each branch by comparing the sum of SEC values estimated by our model for each mill type to those presented in top-down analyses. We found that our model results were well aligned with the top-down estimates, indicating that no significant energy-consuming processes had been neglected in the analysis. The validation results are presented in the appendices.

3.2.2.3. Onsite generation analysis and final energy demand tree development

After the validation of the foundational layer, the next step in SEM development was to analyse how secondary energy demands for electricity and heat are served by final energy inputs to the sector, such as grid electricity, natural gas, and wood. Unlike models that begin with direct estimates of final energy SEC, this intermediate step in our analysis provides for additional customizability and insights. We refer to this step as the onsite generation analysis as it pertains primarily to behind-the-fence generation of steam and power with the use of boilers and turbines within the mill. The onsite generation analysis was conducted for each mill type with the use of spreadsheet-based calculations. First, the quantity of cogenerated electricity from backpressure turbines, condensing turbines, and other means was estimated based on mill type. Consultation with experts indicated that 94%, 23%, and 42% of CP, PP, and NP mills, respectively, are outfitted with cogeneration systems, while MP and PB mills lack cogeneration [93]. We assumed a steam-to-electricity heat rate of 1.88 $\mathrm{GJ_{thermal}/GJ_{electric}}$ (53% conversion efficiency) for all mills [51]. We then accounted for the impacts of power generation demand, heat integration, and steam system losses on the total steam demand in each mill. The required steam production was then translated to input fuel demand by considering the efficiency of steam generation equipment such as boilers as well as the ratio of natural gas, biomass, and other fossil fuel inputs to the mill, as per Equation 2:

$$E_{f,b} = SEC_b \times \frac{1}{\eta_m} \times FR_{f,m} \tag{2}$$

where $E_{f,b}$ is the final specific energy demand for fuel f in branch b in GJ/t, SEC_i is the specific steam energy consumption of branch b (GJ/t), η_m is the average thermal efficiency of steam production in mill type *m* (%), and $FR_{f,m}$ is the share of steam demand met by fuel *f* in mill type *m* (%).

By applying the onsite generation analysis to each process-level branch of the EDT, the final energy demands for each branch were estimated. This result fully characterizes the intensity of final energy consumption of the Canadian P&P sector per unit of output from the national level down to the individual unit process level. The subsector EDT branches and values are shown in Figure 18:

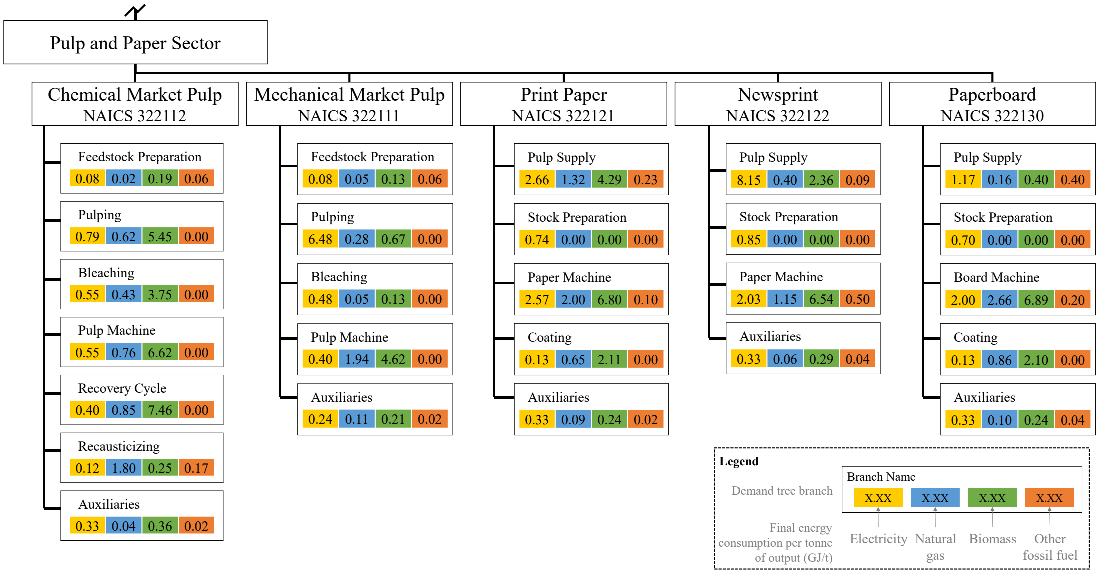

Figure 18: Comprehensive energy demand tree for Canada's pulp & paper sector (2020)

The energy demand tree can be expected to change over time due to implementation of new technologies, the retirement of inefficient equipment, and structural changes in the types of feedstocks and/or products. These changes would be reflected in the SEM via changes to unit process SECs, technology weighting factors, cogeneration parameters, and other values over time. However, economics-based efficiency decomposition studies for the sector suggest that energy use changes are dominated by activity level (production rate) rather than the product mix, sector structure, or efficiency changes [29, 55, 63]. To reduce the data requirements for the model, we therefore assume that most of the EDT parameters remain constant over the study period. The only exceptions to this assumption occurred in a limited number of cases where a significant technological trend was identified in the literature or via expert consultation and was incorporated in the model by adjusting the SEC values over time. Notable examples include adjusting the ratio of fossil fuels to biomass to reflect fuel switching efforts [28, 93] and accounting for sector-wide initiatives to increase power exports [31]. The final output of this exercise was a set of time series values for each EDT branch reflecting the SEC for each energy type in each year from 1995 to 2050.

With the energy consumption per unit of output fully defined, the SEM was then used to calculate annual energy demand in absolute units (GJ) as per Equation 3:

$$E_{f,m,n} = \sum_{b} AL_{m,n,b} \times SEC_{f,m,n,b} \tag{3}$$

where $E_{f,m,n}$ is the demand for fuel f in year n for mill type m in GJ, $AL_{m,n,b}$ is the annual production level for mill type m in year n in t, and $SEC_{f,m,n,b}$ is the specific energy consumption of fuel f for process branch b of mill type m in year n (GJ/t).

An advantage of the bottom-up EDT approach is that Equation 2 can be generalized to any level of the EDT, enabling granular energy demand estimates at various levels of aggregation. Annual production values in air dry metric tonnes of pulp or paper were obtained from the Pulp and Paper Products Council of Canada for each mill type via the Canadian Energy and Emissions Data Centre [90].

A sample of key parameters for the SEM for the year 2018 is provided in the appendices.

As a validation exercise, we compared the annual energy demand estimated using our SEM with the historical values reported by Statistics Canada through NRCan [87]. We found that our model produces highly accurate estimates of sectoral energy use compared to historical values when we use consistent system boundaries and consistent treatment of electricity self-generation and exports. The mean annual error in the total energy use estimate for the Canadian P&P sector was less than 3% over the validation period (1995-2018.) Additional validation results are presented in the appendices. The results of the validation exercise confirm that our SEM accurately characterizes energy use in the P&P sector and can therefore be confidently used to support our energy savings analyses.

3.2.3. Energy efficiency measure development

We employed a systematic approach to review existing academic, government, and industry literature to compile a near-exhaustive list of commercial and near-commercial technology options to improve energy efficiency in the sector. In general, the literature considered in the survey fits into three broad categories:

1. Peer-reviewed studies similar to this study, typically focusing on analysis of the sector-wide potential of one or more efficiency measures [64, 69, 72, 108];
2. Non-peer-reviewed government and/or analyst reports and industry handbooks, typically assessing total energy savings opportunities and/or long-term projections for several measures [33, 41-45, 67, 68]; or
3. Case studies, white papers, and news reports providing detail on real-world implementation of individual efficiency projects (summarized in the appendices).

We focused our survey on efficiency measures that save electricity, natural gas, or biomass because these three energy types account for more than 97% of total P&P energy consumption in Canada as of 2018 [87]. In total, approximately 500 individual datapoints and case studies were surveyed. Because of the data-intensive nature of the bottom-up approach – in particular, the need for marginal cost data – early-stage technologies are not suitable for analysis in the chosen framework and so were excluded. We observed significant variety in the focus (sector-wide, single mill, individual unit process), analysis method (direct results, investment metrics, single measure, sector-wide), and types of data (% savings, absolute savings, energy intensity, energy cost, payback period, etc.) reported in the literature. A key benefit of the technology-explicit sector energy model developed in this study is that it enables disparate datasets for efficiency measures to be standardized, contextualized for the jurisdiction of interest, and subsequently analyzed.

For each datapoint identified in the survey, we extracted key parameters related to the energy savings, capital cost, operation and maintenance (O&M) impacts, lifetime, current level of adoption, and other impacts such as process yield improvements. The types of EEMs considered in this study may impact sector energy demand in four ways: 1) by reducing the process secondary energy requirements; 2) by improving heat integration and reducing steam system losses; 3) by improving the efficiency of steam or power generation; or 4) through fuel switching from one type of energy input to another. Our detailed SEM enabled us to assess the impact of each measure at the appropriate area of the model and to then develop standardized estimates of the ultimate impact on sector energy demand. We converted all datapoints to standard units of gigajoules (GJ), metric tonnes (t), and 2020 Canadian dollars (2020CAD) based on an assumed annual inflation rate of 2% and publicly available currency conversion factors. For ease of analysis, we expressed all values in physical units per air-dry metric tonne (ADMT) of product (e.g., GJ/ADMT, 2020CAD/ADMT).

After analyzing the dataset of 500+ efficiency opportunities, we developed aggregated definitions for similar or overlapping EEMs. As an example, several heat recovery options were combined into a single representative EEM definition. Parameters for the aggregated EEMs were developed by averaging the values from individual datapoints. This approach condenses the ranges of costs and benefits expected for multiple implementations of the same EEM at different mills into a single midpoint estimate of the values expected on average for adoption across the sector, helping to further reflect the variability and variety of real-world efficiency opportunities.

For each EEM we estimated an applicability factor (AF), a parameter that reflects the percentage of total production capacity for which the measure can be adopted. The AF therefore functions as a discount on the single-implementation costs and benefits of an EEM to reflect the average sector-wide impacts expected from implementing that EEM to its maximum technical potential. For each EEM, the AF was estimated based on three factors: the production fraction of mills to which the EEM applies, the share of capacity with the right characteristics for the EEM to be applied, and the current level of adoption of the EEM. The parameters used to develop the AF estimate for each EEM were derived from our mill survey and from applicable EEM literature or were estimated using professional judgment. In cases where EEMs could not be implemented simultaneously, their associated AFs were reduced to prevent over-estimation of potential impacts. The AF approach is advantageous as it avoids the need for complex simulations of individual mill behavior while still producing a more credible and conservative estimate of the technical potential associated with a given EEM compared with studies that assume uniform adoption rates (e.g., Ahmadi et al. [67]). The use of the technology-driven AF technique supports the study objectives of using EEM data from several jurisdictions to generate a reasonable estimate of the sector-wide potential in Canada and also supports differentiation of EEM impacts based on mill type and process technology. To the best of our knowledge, this study is the first example of using technology-driven applicability factors to translate results from other jurisdictions to the region of interest in the context of pulp and paper.

Following data compilation and cleanup, EEM categorization and grouping, and the combination of individual datapoints, a final database containing 115 distinct EEMs was produced. Eighteen of the EEMs can be considered emerging technologies with minimal commercial deployments to date, while the remainder are commercially available technologies with varying levels of adoption in industry. The aggregated EEMs considered in this study are summarized in Table 1.

Table 1: Energy efficiency measure definitions and parameters*

EEM	Name	Process Branch	Capital Cost (2020CAD/t)	Change in O&M Cost (2020CAD/t)	Energy Savings (GJ/t)		
					Elec.	Steam	Direct Fuel
ALL-AHO	Air heating optimization	Auxiliaries	$2.10			0.24	
ALL-APC	Process control / energy management systems	General	$9.95	$0.04	0.46	0.98	
ALL-APH	Combustion air preheating	Cogeneration	$1.78				0.25
ALL-ASD	Adjustable speed drives	General	$3.38		0.14		
ALL-AWT	Anaerobic water treatment	Auxiliaries	$0.93			0.16	
ALL-BBP	Boiler best practices & maintenance	Cogeneration	$0.84	$0.02			0.23
ALL-BBU	Boiler burner upgrade	Cogeneration	$0.52				0.15
ALL-BDP	Blowdown best practices	Cogeneration	$0.11				0.05
ALL-BGE	Biogas production from effluent	Cogeneration	$41.45	$0.24	-0.01		2.60
ALL-BHR	Blowdown heat recovery	Cogeneration	$0.52				0.11
ALL-BMG	Biomass gasification to offset natural gas	Cogeneration	$113.95				5.75
ALL-BRE	Replace inefficient boilers before end of life	Cogeneration	$119.17				1.40
ALL-BSB	Biomass supplementary boiler	Cogeneration	$128.01				4.89
ALL-CAO	Compressed air system optimization	General	$0.23		0.01		
ALL-CAU	Compressed air equipment upgrades	General	$0.09		0.01		
ALL-CDR	Improved condensate return and use	Cogeneration	$1.58	$0.00		0.26	
ALL-DVC	Deaerator vent rate control	Cogeneration	$0.43				0.13
ALL-EAC	Boiler combustion air practices	Cogeneration	$1.15				0.42
ALL-EFA	Effluent aerator upgrade.	Auxiliaries	$1.58		0.06		
ALL-EFL	Efficient facility lighting	Auxiliaries	$1.12		0.03		
ALL-FSU	Fan system and equipment upgrades	General	$0.19		0.07		
ALL-FWE	Feedwater economizers	Cogeneration	$3.54				0.42
ALL-HAI	Hog boiler ash injection	Cogeneration	$3.20				0.21
ALL-HRI	General heat recovery and integration	General	$10.66	$0.11		1.08	
ALL-HWS	Hot water system upgrades	General	$6.77			0.55	
ALL-IER	Idle equipment reduction	General	$0.07	-$0.10	0.10		
ALL-INS	Add and repair insulation	General	$0.21			0.09	
ALL-MDS	Motor downsizing	General	$1.91		0.`05		
ALL-MMR	Improved motor maintenance and rewinding	General	$0.00	$0.25	0.05		
ALL-MST	Microturbine to replace pressure letdown valves	Cogeneration	$3.66	$0.14	0.03		

EEM	Name	Process Branch	Capital Cost (2020CAD/t)	Change in O&M Cost (2020CAD/t)	Energy Savings (GJ/t)		
					Elec.	Steam	Direct Fuel
ALL-MSU	Motor-driven system upgrades	General	$0.46		0.05		
ALL-MVC	Motor voltage controllers	General	$1.21		0.08		
ALL-PEM	Upgrade to premium efficiency motors	General	$2.46		0.19		
ALL-PFH	Power boiler flue gas heat recovery	Cogeneration	$46.15	$0.05			0.55
ALL-PRM	General preventative maintenance	General	$3.20		0.04	0.16	
ALL-PSU	Pump system upgrades	General	$0.94	-$0.01	0.13		
ALL-SRC	Sludge recovery and combustion	Cogeneration	$1.46				0.22
ALL-SSO	Steam system optimization	Cogeneration	$2.47			0.23	
ALL-STS	Solar thermal supplemental steam	Cogeneration	$13.12				0.58
ALL-STU	Steam trap maintenance and upgrades	Cogeneration	$1.07	$0.06		1.34	
BLE-BFR	Bleach filtrate recycling	Bleaching	$5.14	-$0.11		0.32	
BLE-CPH	Bleach CLO_2 preheating	Bleaching	$1.57	-$0.05		0.30	
BLE-OBC	Oxygen/ozone based bleaching & delignification	Bleaching	$88.52	-$3.55	0.16	-0.58	
BLE-PHR	Bleach plant heat recovery	Bleaching	$6.00	-$0.23		1.62	
CPP-ADA	Advanced digestion additives	Digestion	$0.41			0.10	
CPP-AEE	Additional evaporation effect	Recovery cycle	$78.69	-$0.47	-0.02	1.05	
CPP-BDM	Batch digester modifications	Digestion	$143.68	$0.02		1.81	
CPP-BGK	Biomass gasification to kiln	Recausticization	$61.04				1.79
CPP-BLB	Boilout with black liquor	Recovery cycle	$1.72	-$0.07		0.13	
CPP-BLC	Black liquor concentration / high solids firing	Recovery cycle	$29.07	-$0.13			0.67
CPP-BLG	Black liquor gasification (full scale)	Recovery cycle	$836.70	-$18.56	1.89		1.18
CPP-BWP	Bleach washing presses	Bleaching	$19.68	-$0.01		0.39	
CPP-BWU	Brownstock washer upgrades.	Digestion	$68.16	-$0.04	0.05	0.01	
CPP-CDM	Continuous digester modifications	Digestion	$1.48	$0.16			
CPP-CDR	Batch to continuous digester retrofit	Digestion	$177.59		-0.16	3.73	
CPP-CSC	Chip screening and conditioning for CP	Feedstock prep.	$1.30	-$0.35		0.30	
CPP-CSI	Condensate stripping integration	Recovery cycle	$5.60	-$0.13		0.61	
CPP-DFC	Brownstock washing dilution factor control	Digestion	$1.72	-$0.05		0.13	
CPP-DHR	Digester heat recovery	Digestion	$12.45	-$0.19		1.15	
CPP-DSH	Decker shower water from condensate stream	Pulp Machine	$2.47	-$0.07		0.10	
CPP-FFE	Falling film evaporation	Recovery cycle	$109.58			0.80	
CPP-HTM	Recovery boiler temperature monitoring	Recovery cycle	$0.14	-$0.02			0.15

EEM	Name	Process Branch	Capital Cost (2020CAD/t)	Change in O&M Cost (2020CAD/t)	Energy Savings (GJ/t)		
					Elec.	Steam	Direct Fuel
CPP-KEP	Kiln electrostatic precipitator	Recausticization	$1.32	-$0.05			0.01
CPP-LKG	Lime kiln modifications	Recausticization	$8.16	-$0.06			0.29
CPP-MLR	Stripper methanol rectification & liquification	Recovery cycle	$6.41			0.06	
CPP-RBH	Recovery boiler upgrade to high pressure	Recovery cycle	$824.50	-$46.67			3.31
CPP-RBS	Recovery boiler tertiary/quaternary stage	Recovery cycle	$1.05	-$0.17			0.13
CPP-RFH	Recovery boiler flue gas heat recovery	Cogeneration	$58.45				6.25
CPP-SCW	Steam cycle washing	Digestion	$45.52	-$27.86	0.24	0.44	
MPP-APT	Advanced TMP pretreatment methods	Refining	$25.88	-$5.49	0.67	-0.10	
MPP-AQC	TMP quality control improvements	Refining	$0.12		0.26		
MPP-ARS	Additional (and/or low consistency) refining stage	Refining	$0.36		0.59		
MPP-BTM	TMP line blowthrough reduction	Refining	$0.53	-$0.01		0.52	
MPP-CSC	Chip screening and conditioning for MP	Feedstock prep.	$0.37	-$0.35	0.61		
MPP-CTI	CTMP Improvements	Refining	$30.00		1.20		
MPP-HER	High efficiency refiners	Refining	$8.99	$1.91	0.76		
MPP-RTS	RTS mechanical pulping techniques	Refining	$64.35		0.83		
MPP-THR	Add/improve TMP heat recovery	Refining	$17.46		-0.54	1.63	
MPP-TPP	Thermopulp (interheating) process	Refining	$0.00		0.72		
PNB-AFF	Advanced fibrous fillers	Pulp supply	$0.00	$0.54	0.64	1.01	
PNB-ASO	Paper machine air system optimization	Paper machine	$6.48	-$0.03	0.01	0.36	
PNB-BSO	Batch stock optimization	Stock prep.	$0.55			0.22	
PNB-CNU	Coating nozzle upgrades	Coating	$1.00			0.25	
PNB-DMS	Dryer management system	Paper machine	$1.21	-$0.08		0.29	
PNB-DSF	Dry sheet forming	Paper machine	$578.14		-0.79	5.26	
PNB-FWP	Felt water preheating	Paper machine	$0.77	-$0.31		0.17	
PNB-GPF	Gap forming	Paper machine	$104.82	$0.51	0.16		
PNB-HCF	High consistency forming	Paper machine	$156.33	$0.54	0.15		
PNB-IMD	Improved drying technologies	Paper machine	$72.70	$0.23	0.05	1.57	
PNB-IRD	Infrared drying	Paper machine	$188.96	$1.01	-4.50	9.00	
PNB-IRP	Advanced web profiling	Paper machine	$1.61		-0.08	0.74	
PNB-MHR	Paper machine heat recovery	Paper machine	$11.10	$0.67		0.79	
PNB-MWD	Microwave drying	Paper machine	$7.71		-0.56	0.72	
PNB-PRU	Press section upgrades	Paper machine	$40.49	$1.06	-0.03	0.74	

EEM	Name	Process Branch	Capital Cost (2020CAD/t)	Change in O&M Cost (2020CAD/t)	Energy Savings (GJ/t)		
					Elec.	Steam	Direct Fuel
PNB-RFS	Increase use of recycled pulp	Pulp supply	$129.90	-$19.78	0.49	3.16	
PNB-SHP	Superhot pressing	Paper machine	$37.57			0.64	
PNB-SSI	Stationary siphon use/optimization	Paper machine	$3.27	-$0.04		0.58	
PNB-TRB	Turbulent bars	Paper machine	$0.59			0.59	
PNB-VSO	Paper machine vacuum system optimization	Paper machine	$0.00		0.02		
PNB-WBS	White water/broke system optimization	Paper machine	$6.03	-$0.19		0.17	
PUL-MHR	Pulp machine heat recovery	Pulp machine	$1.96			0.18	
PUL-PMR	Efficient pulp machine rebuild	Pulp machine	$128.87	-$25.47		0.13	
RPB-CLR	Closed loop recovered pulping	Pulp supply	$7.69			1.29	
RPB-DFO	Deinking flotation optimization	Pulp supply	$1.75		0.05		
RPB-DHR	Heat recovery on deinking system	Pulp supply	$1.16	-$0.01		0.14	
RPB-FRR	Fibre recovery from rejects	Stock prep.	$1.21			0.71	
RPB-HCR	High consistency recovered fibre pulping	Pulp supply	$4.35		0.02		
RPB-RPO	Recovered fibre processing upgrades	Pulp supply	$5.98		0.04		
SPB-CRR	Continuous repulping	Pulp supply	$0.52		0.23	0.24	
SPB-DRP	Drum repulping	Pulp supply	$11.02		0.10		
SPB-RRU	Repulping rotor upgrades	Pulp supply	$9.31		0.15		
VFP-BFD	Biomass fuel moisture reduction	Cogeneration	$44.87				0.88
VFP-EAD	Enzyme assisted debarking	Feedstock prep	$1.68		0.01		
VFP-UDB	Debarking upgrade	Feedstock prep	$18.69	-$0.01	0.02		
VFP-WHD	Debarking using waste heat	Feedstock prep	$1.23	-$0.05		0.27	

*Note: Some values are too small to display in the table. True zero values are indicated by blank cells.

We consider this group of EEMs to represent a near-exhaustive set of the available options, based on the following criteria:

1. The population of EEMs considered in this study spans all mill types and all process branches used in the Canadian P&P sector;
2. The EEMs were developed from a comprehensive survey of available current literature on energy efficiency technologies for the sector; and
3. Applicability to the jurisdiction of interest was validated through the use of technical applicability factors and, where available, case studies of real-world implementation.

3.2.4. Energy savings assessment

3.2.4.1. Cumulative energy savings and cost of saved energy analysis

Building on the completed EEM database, we developed a spreadsheet-based tool linked to the sector energy model to systematically analyze the individual and cumulative impacts of each EEM. The EEM analysis was conducted individually for each mill type.

As a first step in the analysis, EEM parameters such as cost and energy savings were adjusted to reflect the effect of sector-wide implementation. Any given EEM is not expected to be implemented across 100% of production capacity in the sector, and therefore the values expected for a single implementation must be discounted to produce an estimate of its sector-wide impact. We accomplished this with the use of the AF developed for each EEM, as represented formulaically in Equation 4:

$$P_{adjusted,k} = P_{reference,k} \times AF_k \tag{4}$$

where $P_{adjusted,k}$ is the sector-average value for parameter P for EEM k, $P_{reference,k}$ is the single-implementation value for parameter P for EEM k, and AF_k is the applicability factor for EEM k. In this calculation, parameter P may represent any parameter of interest for the EEM such as capital cost, O&M cost, or energy savings. This calculation effectively provides a first-order estimate of the sector-wide potential for each EEM by discounting the values expected for a single installation.

For each EEM, we used the SEM to determine the impacts on final energy demand, using the same procedure as for the onsite generation analysis described in Section 3.2.2.3. Fuel switching EEMs and EEMs that reduce electricity demand directly impact final energy consumption. Heat integration and steam-saving EEMs affect final energy demand indirectly and thus require a more involved approach. The final energy demand impacts associated with such EEMs are determined by the steam generation efficiency and ratio of input fuels. Additionally, mills with cogeneration capacity may route saved steam to power generation rather than reducing boiler fuel inputs. These factors were used to calculate the final energy savings as per Equation 5:

$$ES_{f,k} = SS_k \times (1 - SP_m) \times \frac{1}{\eta_m} \times SR_f \tag{5}$$

where $ES_{f,k}$ is the final energy savings for fuel *f* for measure *k* in GJ/t, SS_k is the steam savings for measure *k* in GJ/ADMT, SP_m is the portion of steam savings used for power generation for mill type *m* (%), η_m is the overall fuel-to-steam efficiency for mill type *m* (%), and SR_f is the final energy savings ratio for fuel *f (%)*. The value of *SP* was assumed to be 31%, 8%, and 14% for CP, PP, and NP mills, respectively, and 0% for other mill types, based on expert consultation [93]. We set the value of *SR* based on the assumption that the ratio of natural gas savings to biomass savings would be 2:1 for all mill types because mills can be expected to prioritize reductions in natural gas consumption over reductions in biomass consumption. For options that improve cogeneration efficiency, an updated value for the overall steam generation efficiency was calculated in lieu of a direct energy savings using Equation 6 as follows:

$$\eta_k = \frac{\eta_0}{1 - PS_k} \tag{6}$$

where η_k is the updated cogeneration efficiency after implementing measure *k* in %, η_0 is the cogeneration efficiency before implementing the measure (%), and PS_k is the percent energy savings associated with measure *k* (%).

We also estimated the associated energy cost impacts of EEMs that indirectly increase or decrease demand for more than one type of energy. For example, a process efficiency improvement may reduce steam demand in tandem with electricity demand, while a heat recovery EEM may require an increase in power consumption because of added pumping requirements. In all cases, the net result of indirect energy demand impacts were calculated using the SEM and subsequently converted to costs per tonne using energy prices. Hereafter, we refer to such impacts as co-benefits.

Next, we calculated the cost of saved energy (CSE) for each measure using the previously derived costs, O&M impacts, co-benefits, and energy savings. CSE is a commonly used metric for comparing energy efficiency measures on a consistent basis by taking the ratio of the change in total annual costs to the magnitude of energy savings for each measure [76]. The difference between the CSE and the true energy price reflects the value of the saved energy and can be used to assess the economic favourability of an EEM [70, 84]. If the cost of the energy saved by an EEM is less than the energy price, it is economically favorable to implement the EEM rather than to consume the energy. For all measures, the CSE was calculated using Equations 7 and 8, as follows:

$$CSE_k = \frac{CRF_k \times CC_k + OM_k - CB_k}{ES_k} \tag{7}$$

$$CRF_k = \frac{d}{1-(1+d)^{-n_k}} \tag{8}$$

where CSE_k is the cost of saved energy for measure *k* in CAD/GJ, CC_k is the capital cost of measure *k* (CAD/ADMT), OM_k is the increase in operations & maintenance costs for measure *k* (CAD/ADMT), CB_k is the credit for co-benefits of measure *k* (CAD/ADMT), ES_k is the final energy savings for the measure (GJ/t), *d* is the discount rate used for the analysis (%), and n_k is the life of measure *k* in years.

The discount rate, *d,* accounts for the time value of money in investment decisions. In this instance, *d* is equivalent to the internal rate of return targeted by a company implementing an EEM. At higher values of *d*, the capital investment in a project must be repaid more quickly, resulting in a higher cost of saved energy, as shown by Equations 7 and 8. The discount rate chosen has a significant impact on the CSE of a measure. Similar studies have used a range of 5% [11] to 30%

[69]; 5% reflects lower required rates of return, close to the cost of capital for firms, while a discount rate of 30% or higher is suggestive of the internal risk-adjusted hurdle rates used by many capital-constrained industries. For the purposes of this study, we used an assumed discount rate of 20% for the central CSE estimate; this reflects a compromise between the two extremes.

In keeping with the definition of CSE, we did not consider the effect of carbon pricing or energy prices directly in the CSE calculation. As shown in Equation 7, the CSE reflects only the true cost to implement an EEM; thus, the CSE can be directly compared with the energy and carbon costs that would be incurred if the EEM were not implemented. For simplicity, we accounted for carbon pricing as a surcharge on the price of natural gas. Carbon prices were not applied to electricity or biomass energy prices. The energy and carbon prices used in the analysis were obtained from Canada Energy Regulator forecasts [96] and are summarized in the appendices.

To improve the accuracy of the CSE analysis and to support overall energy savings bandwidth development, we next considered the cumulative impacts of implementing EEMs simultaneously in the sector. EEMs are expected to interact and potentially interfere with one another when implemented in tandem. To produce a conservative estimate of savings potential, we assumed that all interactions would result in diminishing returns, i.e., that the savings associated with a group of EEMs would be less than the sum of the individual measure savings. In accordance with this principle, we implemented a recursive algorithm to re-estimate the CSE and energy savings of each EEM if implemented in parallel. The procedure is as follows:

1. Calculate energy savings and costs for all measures;
2. Use the baseline SEC and energy savings to calculate percentage savings for each measure;
3. Calculate the CSE of each measure;
4. Select the measure with the lowest CSE, implement that measure, and remove it from the list of potential measures to implement;
5. Update baseline cogeneration efficiency and branch SEC, final energy demand, and other parameters as applicable based on the impacts of the selected measure;
6. Recalculate energy savings and CSE for all measures using the new baseline values;
7. Iterate steps 4-6 until all measures have been implemented.

The final output of the cumulative impact analysis is a ranked list of EEMs and their cumulative energy savings and costs in order from lowest CSE to highest.

Importantly, our analysis methods can be applied irrespective of the number and types of EEMs considered, provided only that each measure has sufficient data for inclusion in the analysis. Our method therefore allows for the results to be quickly updated to include additional emerging technologies in future work once appropriate data is available.

3.2.4.2. CSE curves and bandwidth development

CSE curves are a common tool for the analysis of energy efficiency technologies and are produced via stepwise plotting of marginal CSE values against cumulative energy savings for a set of EEMs [70]. By applying this technique to the results of our cumulative EEM analysis, we produced CSE curves for each mill type individually and for the sector as a whole. We selected electricity and natural gas as the energy types of focus for the CSE curve development because according to our analysis they are the energy types most commonly targeted by energy reduction initiatives and constitute the majority of mill energy costs. Separate curves were produced for each energy type given their differences in terms of price and applicable EEMs, resulting in twelve curves overall.

We next grouped the EEMs by economic favourability in order to calculate energy savings bandwidths. For this analysis, we compared the CSE of each EEM to the true energy price under different discount rate scenarios. The economic viability test was based on the previously discussed equivalence between discount rate and internal rate of return (IRR). By recalculating the CSE of each EEM for different values of d and comparing it to the reference energy price, we estimated the IRR of each EEM. EEMs were then sorted into five categories based on IRR, ranging from EEMs with very strong economics (an IRR of at least 35%) to those that are uneconomic at the reference energy price (an IRR of less than the assumed cost of capital, 5%). The aggregate energy savings of the EEMs in each group define the energy saving bandwidth for that category. We defined the sum of the energy savings in the first four categories (IRR ≥ 5%) as the *economic energy savings bandwidth* (EESB). The total possible energy savings from all EEMs in all five categories was similarly defined as the *technical energy savings bandwidth* (TESB). The minimum energy consumption levels can then be derived by subtracting the energy savings bandwidths from the sector baseline energy demand, as shown in Equation 9.

$$economic\ minimum\ energy\ demand = baseline\ energy\ demand - EESB \qquad (9a)$$

$$technical\ minimum\ energy\ demand = baseline\ energy\ demand - TESB \qquad (9b)$$

Lastly, we used the energy savings bandwidths for each mill type to estimate the absolute energy and cost savings for the sector using Equations 10 and 11, respectively:

$$\Delta E_{f,m} = EESB_{f,m} \times AL_m \qquad (10)$$

$$\Delta EPC_{f,m} = EESB_{f,m} \times EP_f \qquad (11a)$$

$$\Delta EC_{f,m} = EESB_{f,m} \times EP_f \times AL_m \qquad (11b)$$

where $\Delta E_{f,m}$ is the absolute energy savings for fuel type f and mill type m in GJ, $EESB_{f,m}$ is the economic energy savings bandwidth (GJ/ADMT), AL_m is the activity level for the mill type (t), $\Delta EPC_{f,m}$ is the change in energy production costs for fuel type f and mill type m (CAD/ADMT), EP_f is the price of energy source type f, and $\Delta EC_{f,m}$ is the change in absolute energy costs (CAD). This set of results allows for direct comparison between the savings estimated by this study and the absolute energy demand and costs experienced in the P&P sector.

3.3. Results and discussion

3.3.1. Cost of saved energy curves

Twelve CSE curves were produced to characterize the natural gas and electricity savings potential for each of the five mill types and sector as a whole. Some EEMs directly save both steam and electricity demands and are thus plotted on both types of curve. Each step in a CSE curve represents an individual EEM; the width of the step corresponds to the incremental energy savings of that EEM and the height of the step represents the marginal CSE. Steps are plotted end-to-end such that the x-coordinate of the curve represents the additive energy savings for all EEMs below that point. The y-coordinate along the CSE curve represents the marginal cost to achieve a given level of energy savings and can be directly compared to the true price of energy. Thus, the curves can be used both to identify the cost to achieve a given savings level as well as the energy price at which a given EEM becomes economical. Higher values of the discount rate, *d*, increase the marginal CSE and thus stretch the curve vertically. This reflects the causal relationship between higher energy prices and higher rates of return for energy efficiency investments. CSE curves were plotted using an assumed discount rate of 20% consistent with the assumptions described in Section 3.2.4.1. Complete CSE results for each mill type are provided in the appendices.

The sector-wide CSE curve for natural gas is shown in Figure 19.

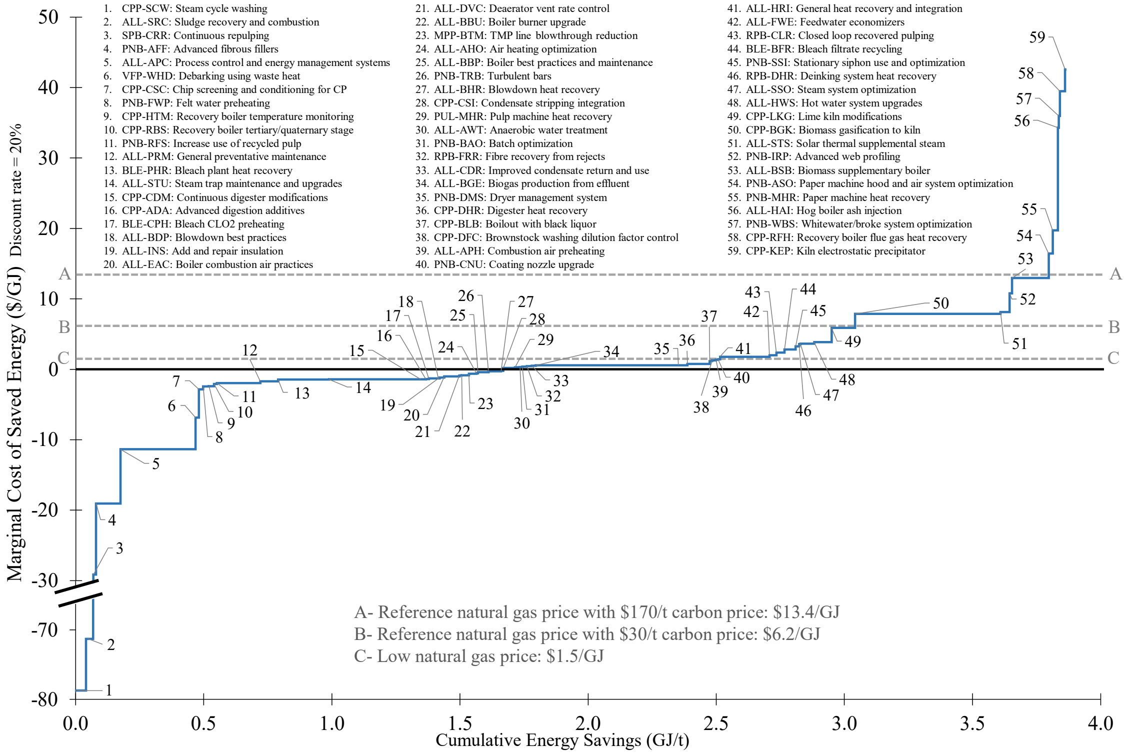

Figure 19: Sector-wide cost of saved energy curve for natural gas

EEMs are labelled according to their 6-letter designations as defined in Table 1. Figure 19 shows that the technically achievable savings of 3.85 GJ/ADMT are possible sector-wide for natural gas; this corresponds to a reduction of more than 98% from the current baseline. Importantly, most of these savings, totalling 2.51 GJ/ADMT (64%) of natural gas demand, are achievable at a cost less than $1.7/GJ. This result suggests that significant savings are achievable at high rates of return on investment under almost any future natural gas price scenario. In fact, 27 measures with a combined savings of 1.66 GJ/ADMT (42%) can be implemented at a negative CSE because their capital cost is exceeded by co-benefits such as reduced O&M costs, improved product yield, and/or increased revenue from electricity exports. This is consistent with the results of a previous study for the U.S. P&P sector that includes similar accounting of co-benefits [69], but our study is the first that we know of to confirm the applicability of this phenomenon to the Canadian context. This finding is instructive for future analyses in other sectors and/or regions where co-benefits may not have been explicitly accounted for previously.

Another key result illustrated by Figure 4 is that the maximum technical savings potential can be reached using the 60 lowest-cost measures, meaning that the full set of 80 measures available to the sector are not required to minimize natural gas consumption. In reality, a mix of all measures is expected to be considered by industry to reduce natural gas consumption, but our results suggest that industry has significant flexibility and capacity to achieve ambitious reductions targets for this fuel using commercially available technologies.

The top three EEMs by magnitude of natural gas savings are biogas use in CP mill kilns, increased production and use of biogas from effluent, and steam trap improvements. Notably, two of the top three measures involve fuel switching and as such will not reduce net fuel use because they require a commensurate increase in biomass consumption to offset natural gas.

Figure 20 plots the disaggregated natural gas CSE curves for each of the five mill types.

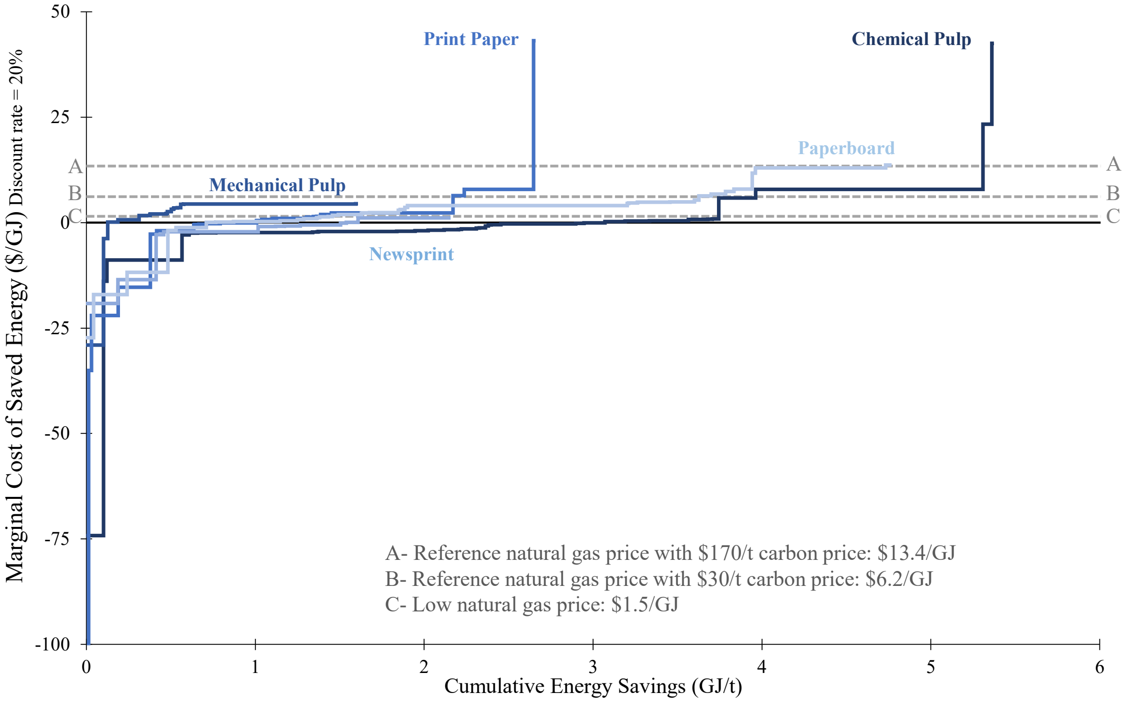

Figure 20: Cost of saved energy curves for natural gas by mill type

Each curve terminates at the point where the maximum technical potential for natural gas savings is achieved. A comparison of these points shows that NP mills can achieve their technical natural gas abatement potential at the lowest marginal cost. CP mills have the greatest energy saving potential but require high-cost options to minimize natural gas use due in part to the high energy intensity and cost of their chemical recovery processes [33]. CP mills also have the highest number of EEMs with negative CSEs, a phenomenon that can be partially attributed to their near-ubiquitous use of cogeneration which drives greater co-benefits from natural gas EEMs. Unexpectedly, we found that MP and NP mills can achieve 100% of their technical potential at a marginal cost below the reference natural gas price at a 20% discount rate. CP, PP, and PB mills can achieve 74%, 82%, and 76% respectively, of their technical savings potential under the same economic constraints. These results suggest that the industry has the ability to substantially reduce natural gas consumption using commercially available technologies at high rates of return.

The sector-wide cost of saved energy curve for electricity-saving EEMs is plotted in Figure 21.

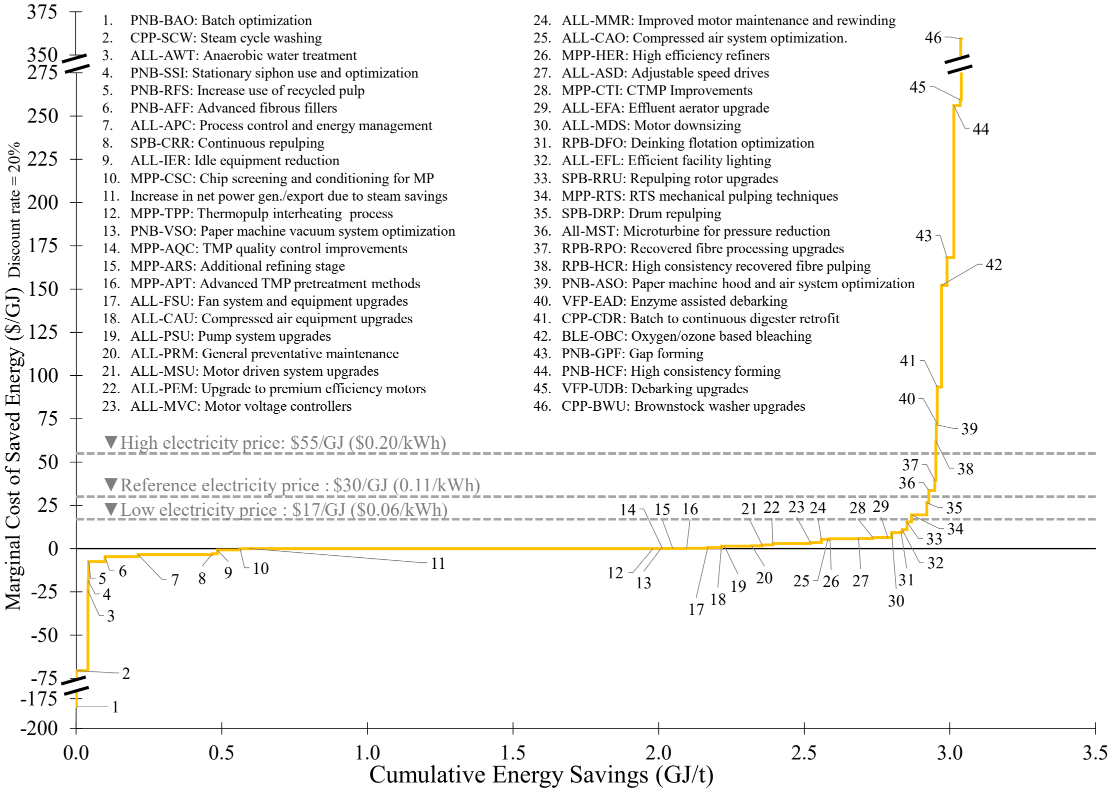

Figure 21: Sector-wide cost of saved energy curve for electricity

The electricity CSE curve includes all measures that directly reduce electricity consumption as well as a single entry that captures the net increase in electricity exports associated with all steam-saving measures. For the purposes of this study, increases in net electricity export are treated as equivalent to reductions in electricity consumption but are attributed a CSE of $0/GJ for electricity because their costs are already accounted for in the natural gas CSE results. Similar to the results for natural gas, the electricity CSE curve demonstrates that significant electricity savings of 2.93 GJ/ADMT (52%) are possible at a marginal cost less than the reference electricity price at a discount rate of 20%. Only ten of the electricity EEMs were found to have a negative CSE, which may be because electricity EEMs typically have fewer associated co-benefits such as steam savings or productivity enhancements. The top three electricity EEMs (not including net generation increase from steam EEMs) by magnitude of sector-wide energy savings are advanced process controls, upgrades to high-efficiency motors, and the use of advanced fibrous fillers to offset the need for virgin pulp.

Figure 22 shows the disaggregated electricity CSE curves for each mill type.

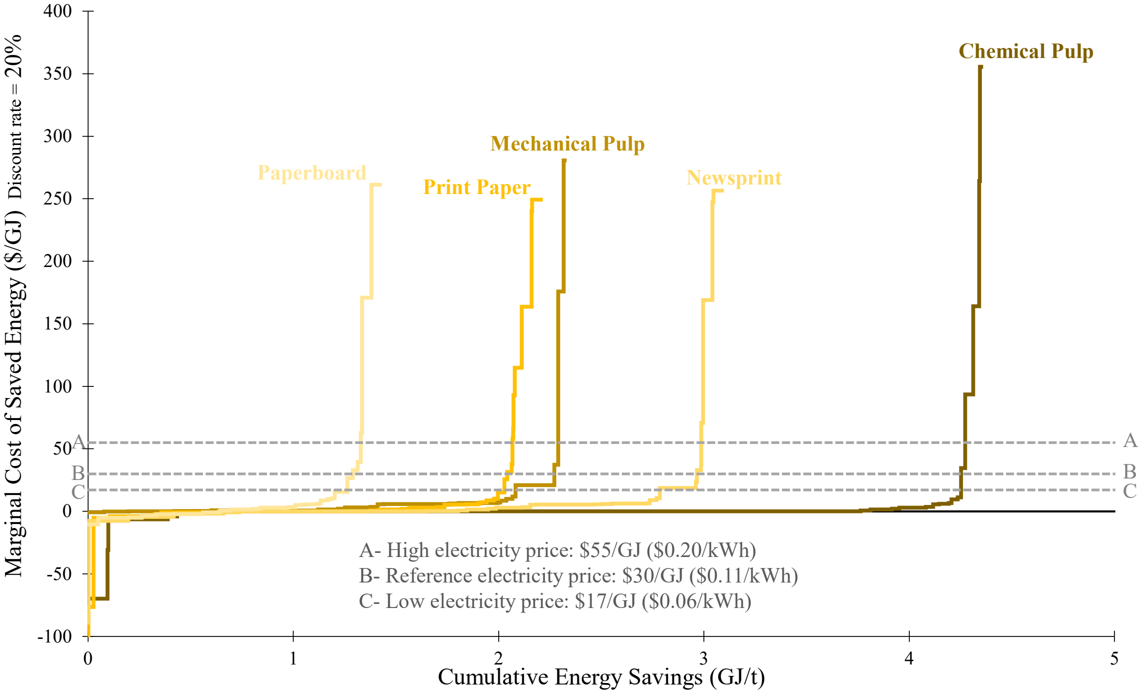

Figure 22: Cost of saved energy curves for electricity by mill type

Unlike the disaggregated CSE curves for natural gas, the curves for electricity are more similar in shape and average cost. However, the potential savings vary significantly depending on mill type. CP mills have the greatest potential to increase their net electricity exports, mainly due to their large cogeneration capacity. NP and MP mills have the most significant potential for direct electricity savings, commensurate with their higher baseline electricity use.

Overall, the results of the CSE analysis confirm that a large number of off-the-shelf and economically viable EEMs are available to the P&P sector to substantially reduce demand for electricity and natural gas. However, the cumulative analysis confirms that the net costs and benefits of any individual measure depend significantly on the order in which measures are adopted. This suggests that firms should prioritize energy efficiency investments based on holistic, mill-wide analyses rather than analysis of individual measures. While no one measure is a silver bullet for reducing sectoral energy demand, the large number of measures that were found to have strong economics suggests that the sector has considerable potential to reduce its overall costs and energy demand via energy efficiency.

3.3.2. Energy savings bandwidths

Figure 23 shows the disaggregated economic and technical energy savings bandwidths for biomass, natural gas, and electricity for each mill type.

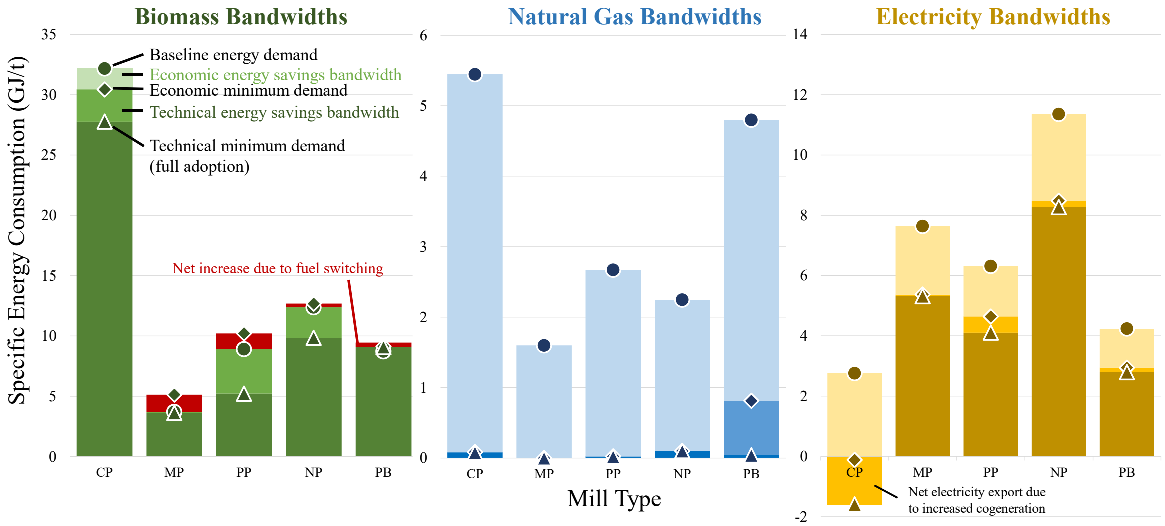

Figure 23: Energy savings bandwidths by mill type

The top of each column represents the current baseline SEC for a particular energy source and mill type. Below this, the EESB is plotted showing the level to which the SEC can be reduced by implementing measures with an IRR >5%. The additional technical savings potential is then plotted to show further reductions potential from currently uneconomic measures. The remaining dark coloured sections, therefore, represent our estimate of the technical minimum SECs. The reported bandwidths are net of any increases due to fuel switching from natural gas to biomass or from thermal fuels to electricity, although this phenomenon only has a material impact on the biomass results. Detailed bandwidth results are provided in the appendices.

Figure 23 indicates that the most significant fuel savings are achievable for natural gas, where the TESB is at least 96% less than the initial value across all mill types. Large savings potentials were also calculated for biomass energy across all mill types. CP mills have the largest absolute bandwidths for both natural gas and biomass, likely because this mill type has the highest baseline SEC for those energy sources. CP mills can also achieve net-negative electricity due to their significant cogeneration capacity. The electricity TESBs for the other mill types range from 27%-35%.

Figure 24 summarizes the sector-wide energy saving bandwidths for natural gas.

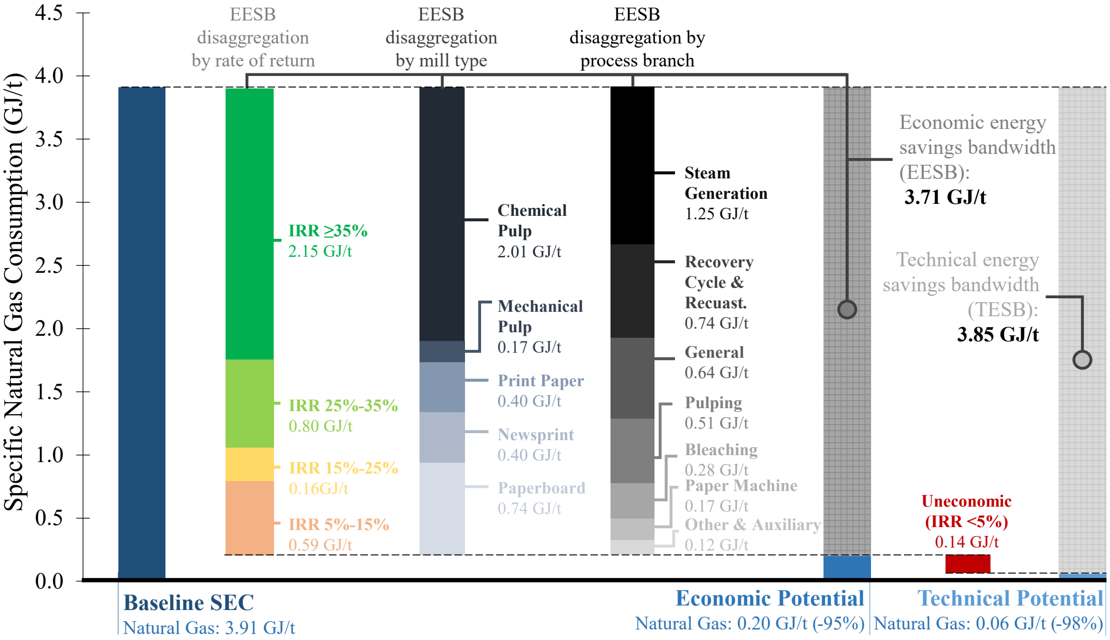

Figure 24: Overall sector bandwidths for natural gas

The leftmost column shows current consumption of natural gas. The EESB and TESB reflect the gaps between current energy consumption and the consumption levels that are economically and technically possible, respectively. Our granular analysis allows for disaggregation of the EESB in three different ways: by EEM rate of return, by mill type, and by process branch, all of which are presented in Figures 24 and 25.

Our analysis indicates that the overall EESB for natural gas is 3.71 GJ/ADMT (95%), and additional savings of 0.14 GJ/ADMT could be economical at higher energy prices for a total TESB of 3.85 GJ/ADMT (98%). The largest driver of the overall energy savings bandwidth is adoption of EEMs in CP mills, which is consistent with the fact that CP mills consume the most thermal energy and have the largest production capacity. Measures that improve steam generation efficiency, reduce losses in cogeneration systems, and reduce energy demand for chemical recovery processes account for more than 50% of the EESB.

Figure 25 summarizes the sector-wide energy saving bandwidths for electricity.

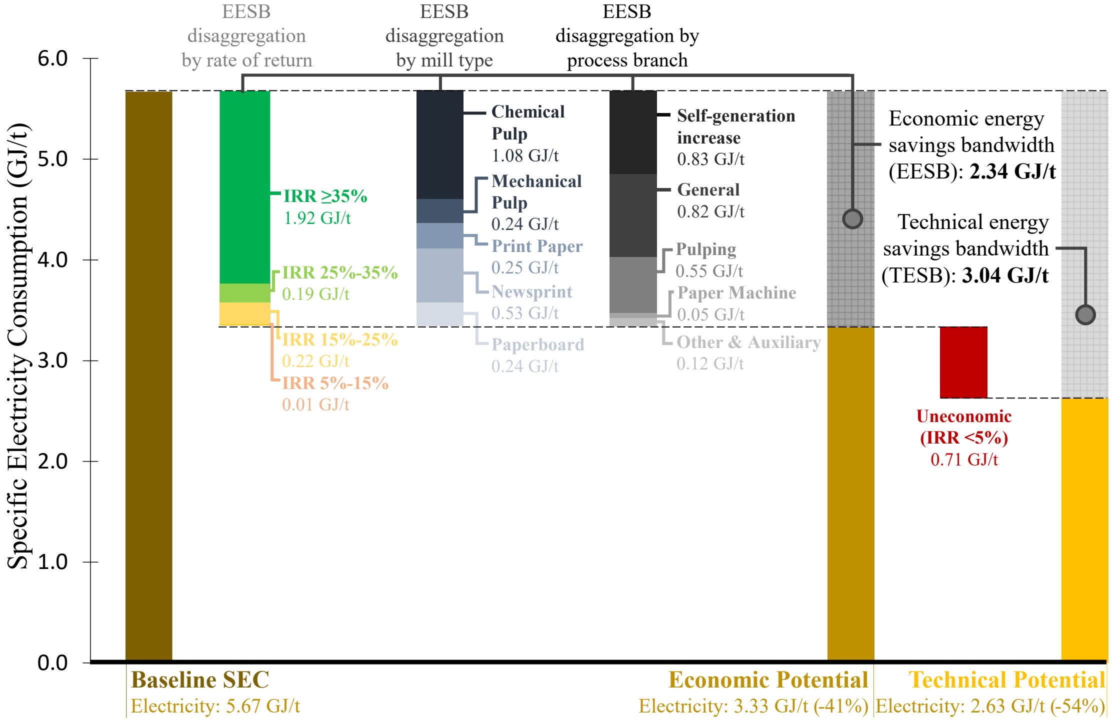

Figure 25: Overall sector bandwidths for electricity

The overall EESB for electricity is 2.34 GJ/ADMT (41%). An additional 0.71 GJ/ADMT (13%) in savings are technically possible; the TESB is therefore 3.04 GJ/ADMT (54%). CP mills have the largest contribution to the sector EESB, driven by their ability to increase cogeneration of electricity to offset demand. Cogeneration increases account for 35% of the EESB. A similar portion of the EESB is driven by general electricity efficiency measures such as motor upgrades, and refining improvements in pulping processes also have a significant role.

Unexpectedly, Figures 24 and 25 also reveal that the largest energy savings potentials are derived from measures with an IRR >35%. The use of an IRR hurdle rate of 35% is consistent with significant capital constraints and low internal risk tolerance. Nonetheless, we found that significant energy savings are possible at this hurdle rate across all energy sources and mill types.

This finding confirms that significant portion of possible energy savings are low-hanging fruit that can be achieved at high rates of return.

Table 2 summarizes the absolute annual energy savings and cost savings possible for the Canadian P&P sector using representative production and energy price values from 2018.

Table 2: Absolute energy savings potential associated with economic savings bandwidth

		Mill Type					
Parameter	**Units**	**CP**	**MP**	**PP**	**NP**	**PB**	**Entire Sector**
Annual production (2018)	kt	7,020	2,106	4,131	3,001	3,065	19,323
Annual biomass savings	PJ	12	-3	-5	-1	-1	1
Annual natural gas savings	PJ	38	3	11	6	12	71
Annual natural gas cost savings (at $4.6/GJ)	Million $	173	15	50	30	56	325
Annual electricity savings	PJ	20	5	7	9	4	44
Annual electricity cost savings (at $0.10/kWh)	Million $	560	133	191	240	110	1,234
Overall energy cost savings	$/tonne	104	70	59	90	54	81

Our evaluation of the overall energy savings potential indicated that adopting measures with an IRR >5% has the potential to save 71 PJ of natural gas and 44 PJ of electricity annually at a production level similar to that of 2018. At 2018 prices of $4.6/GJ for natural gas and $0.10/kWh for electricity [96], these savings would reduce sector energy costs by $81/ADMT, substantially improving the competitiveness of the Canadian P&P sector. To achieve natural gas savings, biomass consumption increases across all mill types except CP. The cost changes associated with biomass are not quantifiable at this time because of the broad range of costs and fuel types associated with the biomass category. However, for most EEMs the incremental biomass energy is expected to be derived from onsite waste streams (such as wood waste or effluent) and would therefore incur minimal additional costs.

3.3.3. Limitations

The data and approach used in this study were subject to several limitations that, if addressed, could further improve the results.

The data-intensive nature of our analysis means that we were unable to consider efficiency measures for which there is no commercial-scale cost or energy saving data. Consequently, we excluded many novel emerging technologies at the research or pilot stage but whose potential for energy savings may be significant, such as membrane-based black liquor concentration [33]. The design of our model permits additional measures to be incorporated in the analysis once sufficient data is available; this is a key avenue for future work that may be of interest to technology developers, industry, researchers, and other stakeholders.

The energy use and EEM analysis performed in this study were focused on assessing the potential for energy savings, not on the optimal or realistic behavior of companies. However, analysis of stakeholder behavior and realistic EEM adoption rates are possible avenues for future work.

Lastly, this study did not assess EEM adoption potential, costs, or benefits for individual mills. Rather, our results represent the effect of EEMs across the entire sector on average. Our survey of real-world case studies suggest that even mills of the same type and vintage may incur different costs and benefits for a given EEM due to their unique situation, and therefore may prioritize different measures. Capturing such nuance would require mill-level energy audits but is not necessary to achieve the aims of this study given our current focus on average sector-wide potential across a large sample size of mills.

3.3.4. Policy implications

The results of this study have significant implications for policy choices in the areas of industrial energy efficiency, GHG emissions reductions, and industry competitiveness. A key finding is that the quantity of low-cost energy savings available to the Canadian P&P sector indicates that the sector has significant capacity to respond to government-mandated policy such as maximum SEC standards. Our results strongly suggest that net industry compliance costs for well-designed policies of this type would be minimal if not negative.

Our analysis also indicates that some energy efficiency policy choices are likely more effective than others. The high rates of return for a large portion of the EEMs analyzed indicates that economic performance is not a major limiting factor for energy efficiency investments in the Canadian P&P sector. Indeed, our analysis shows that many of the EEMs would represent extremely attractive investments. We therefore expect that policies focused on further improving the return on investment (ROI) of EEMs such as subsidies, rebate programs, or tax allowances would have limited effectiveness in stimulating EEM adoption.

The lack of adoption of energy efficiency measures despite their high rates of return suggests that other barriers to adoption are more impactful than economic concerns. Insofar as these barriers cannot be addressed via direct economic incentives, they should instead be targeted by other policy approaches. For example, awareness and appropriate valuation of EEMs are major barriers to adoption that can be addressed by practice-based, systematic energy efficiency policies such as incentives for hiring energy managers and supports for establishment of energy efficiency programs within firms. Such policies would foster EEM adoption while requiring less government spending than direct subsidization of individual projects. Compilation and publication of energy audits and the results of efficiency projects by governments could also help reduce the perceived risk of efficiency investments by providing contextualized real-world case studies for other companies to emulate.

Given the large number of low- and negative-cost measures identified, programs or policies that incentivize reinvestment of energy cost savings into additional EEMs can also be highly effective. Examples of such policies include government loan guarantees or repayable grants for efficiency projects. The strong economic performance of the EEMs considered in this study means that such policies could be implemented at low net cost and low risk to the government.

Improved awareness, monetization, and capture of co-benefits can significantly improve the attractiveness of EEM investments and can be supported via policies such as those that enable greater electricity export from mills. Similarly, predictable increases in carbon pricing can provide greater certainty on the ROI of energy efficiency investments compared with investment decisions based only on volatile energy prices.

Lastly, the results of this study indicate that the minimization of natural gas and other fossil fuel consumption is feasible for the sector at forecasted energy and carbon prices. Therefore, policy supports and mandated targets for fuel switching measures could drive major reductions in the consumption of natural gas and other fossil fuels. This also implies that the P&P sector has a clear pathway to net zero emissions via energy efficiency, fuel switching, and electricity grid emissions reductions. Our results suggest that with appropriate policy design the Canadian P&P sector could feasibly be the first major industrial sector in Canada to approach near-zero onsite fossil fuel consumption.

3.4. Conclusions

The objective of this study was to characterize the energy savings potential in the pulp and paper sector by developing disaggregated cost of saved energy curves and energy saving bandwidths. We targeted key gaps in the current literature by developing a granular, technology-explicit approach to estimating overall energy savings potential. Our novel method integrates bottom-up energy demand modelling with analysis of a comprehensive set of energy efficiency technologies to provide greater insights into the pathways to reducing sector energy consumption via energy efficiency and fuel switching. The innovative framework and techniques developed in this study can be easily adapted to other regions or sectors of interest.

The results of our energy efficiency measure analysis suggest there is significant potential to improve the energy efficiency and energy cost-competitiveness of Canada's pulp and paper sector by implementing commercially available technologies. We estimate that the technical energy saving bandwidths in the Canadian P&P sector are 3.85 GJ/ADMT (98%) for natural gas and 3.04 GJ/ADMT (54%) for electricity. Furthermore, we found that significant sector-wide reductions in natural gas (95%) and electricity (41%) are economically viable at current energy prices. In particular, we found that it is both technically and economically feasible to almost entirely eliminate natural gas consumption for all mill types in the sector through a combination of efficiency improvements and fuel switching. Implementation of efficiency technologies that are economic at current energy prices could result in annual energy savings of 71 PJ and 44 PJ of natural gas and electricity, respectively, and would reduce average sector energy costs by $81/ADMT.

Along with ongoing reductions in use of other fossil fuels and decreases in grid emissions intensity, the results suggest that there is a clear path to near-zero fossil fuel consumption and elimination of onsite GHG emissions for the Canada pulp and paper sector using low-cost commercially available technologies. With deliberate policy design, energy efficiency and fuel switching could play a key role in establishing the pulp and paper sector as a leader in the transition to a low carbon economy.

4. Pulp and Paper Sector Emissions Abatement Potential[5]

4.1. Introduction

Industrial greenhouse gas (GHG) emissions account for over 24% of the global total [14] and must therefore be a key consideration in the effort to achieve humanity's urgent emissions reduction goals [15]. Given the high energy consumption of industrial sectors, improvements to energy efficiency have been deemed a "necessary but not sufficient" [6] strategy for industrial emissions abatement. This implies that although efficiency alone cannot fully eliminate industrial emissions, it must be one of several essential tools contemplated by policymakers and industry participants. However, it is also recognized that emissions abatement efforts face significant practical constraints including time and availability of capital. To this end, modelling and characterization of the magnitude of the opportunity associated with efficiency-driven abatement and the associated costs and trade-offs compared with other abatement options are vital to understanding and following the optimal pathways to a lower-emissions future.

In this context, it is particularly important to analyze emissions-intensive trade-exposed sectors given the complexity of their emissions footprints and their heightened sensitivity to policy changes and energy/emissions costs [18, 29]. One such sector is the pulp and paper (P&P) industry. P&P accounts for about 2% of worldwide industrial GHG emissions [14] and has several distinctive characteristics including high bioenergy consumption, large process-integrated cogeneration capacity, and significant heterogeneity of products and end-use technologies [56]. The sector also faces severe constraints on capital spending combined with pressure to reduce energy costs [12, 67]. These factors create barriers for investments into emissions abatement and reinforce the need to identify and prioritize only the best opportunities for energy, emissions, and cost savings [110].

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[5] The content in this chapter will submitted for publication in *Journal of Cleaner Production* as "Energy efficiency as a critical resource to achieve carbon neutrality in the pulp and paper sector" by Christophe Owttrim, Matthew Davis, Hafiz Umar Shafique, and Amit Kumar. All analysis, results, and writing are my original work.

Like other major energy-consuming industries, the P&P sector has been the focus of numerous government and academic studies of sectoral energy efficiency potential. We conducted a detailed review of the available literature with a focus on studies that consider the links between energy savings and emissions abatement in the P&P sector. A common approach we identified is the use of top-down modelling methods to assess the changes in sector emissions and energy demand under various scenarios for overall sector emissions intensity or specific energy consumption (SEC), e.g.: the study of China's P&P industry presented by Peng et al. [64]. This approach does not rigorously account for the impacts of specific energy efficiency technologies and therefore can only provide a theoretical, as opposed to technical, estimate of the associated emissions abatement potential. Xu et al. demonstrated a more sophisticated approach by considering specific efficiency technologies alongside a sector-wide model of the P&P industry in the United States [69]. However, their method relies on simple estimates of top-down SEC changes for each technology, lacks consideration of technology interactions, and does not contemplate a long-term planning horizon. Griffin et al. developed a hybrid top-down/bottom-up method to provide a more robust efficiency analysis for the P&P industry in the United Kingdom [73]; this approach improves the transferability of results between regions but is similarly limited by its generic and isolated treatment of efficiency technologies. In the most advanced technique we identified, Fleiter et al. demonstrated a fully bottom-up analysis of efficiency technologies over multi-year scenarios in the German P&P industry [72]. However, that study focused on the diffusion of a small set of technologies rather than assessing the overall potential associated with a complete array of efficiency opportunities.

Our review of the literature highlights several key gaps that reduce the relevance and value of existing studies for policymaking and industry decision-making. Many studies use top-down methods which do not account for regional differences in sector structure and technologies; thus, their results are not directly transferable to other regions. Furthermore, top-down analyses cannot provide granular insights into the emissions abatement opportunities associated with specific mill types or end-use processes, rendering their policy insights blunt and imprecise. Even those analyses that consider the impacts of specific efficiency technologies at an end-use level often neglect important considerations such as interactions between technologies and the combined impacts of the full suite of available efficiency measures. Lastly, most of the studies we reviewed do not consider long-term planning horizons and/or the system-level impacts of energy efficiency and are thus constrained in their ability to provide insights into the broader impacts of policy choices or technology pathways. To address these gaps, we have developed a modelling approach to assess the impacts of efficiency technologies from the bottom end-use process level up to the overall system level. By considering an exhaustive set of measures, we aim to fully characterize the overall emissions abatement potential associated with improved energy efficiency. Our method allows for a full disaggregation of results by subnational jurisdiction, subsector, end-use process, and type of energy input. This level of detail is further enhanced by the upstream and cross-sectoral analysis capabilities of our modelling framework. In another advancement, our analysis incorporates estimates of technology interactions and secondary effects within both the sector and the broader energy system to more accurately capture the costs and benefits of energy efficiency as a holistic tool rather than as a bundle of discrete technology options. In this study, we expand the application of our previously developed energy-focused analysis framework [111] to an analysis of emissions abatement potential over a long-term planning horizon.

In keeping with the identified literature gaps and policy context, our overall objective for this study was to determine the GHG abatement potential associated with the implementation of energy efficiency technologies in the Canadian P&P sector. To accomplish this objective, we established the following sub-objectives:

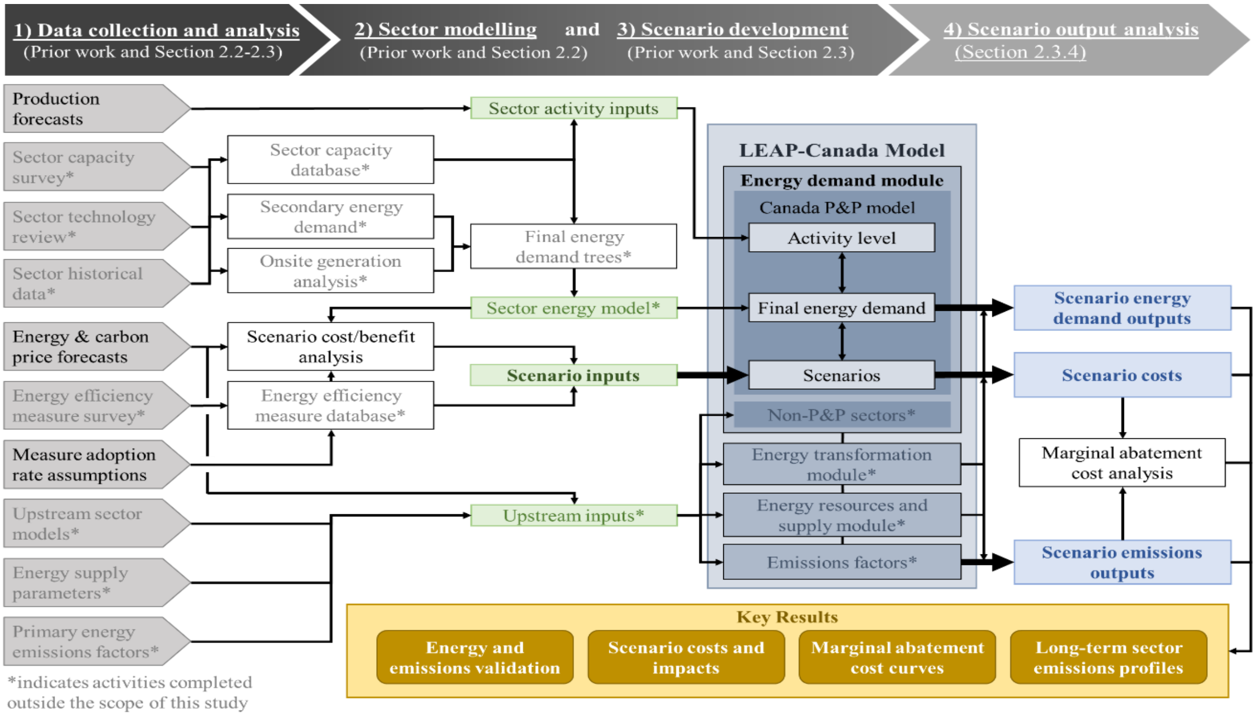
1. To develop a bottom-up long-range energy and emissions modelling framework for the pulp and paper sector,
2. To model a comprehensive set of technology-explicit energy efficiency scenarios,
3. To analyze the costs and benefits of all scenarios to provide insights to policymakers and industry regarding the overall opportunity associated with energy efficiency, and
4. To compare the emissions abatement potential and marginal abatement costs across multiple system boundaries to provide additional insights.

This study demonstrates the application of our novel method for the case study of the Canadian P&P sector. Canada is among the top five global P&P producers as of 2018 [97] and is a significant net exporter of P&P products, particularly market pulp [98]. This global scale translates to a large contribution to domestic energy demand and emissions footprint; among non-oil & gas sectors in Canada, P&P ranked 2nd in energy demand and 7th in GHG emissions in 2017 [95]. Canada has committed to an ambitious target of achieving 30% lower GHG emissions in 2030 compared to a business-as-usual (BAU) scenario and has established the Pan-Canadian Framework on Climate Change to provide policies that will support this target [112]. This framework has recently been augmented with more stringent targets and more aggressive interventions that will see previously implemented carbon prices increase to \$170/tCO_2e by 2030 and will include additional targeted industrial measures to help "develop and implement plans to transition [large industrial emitter] facilities to net-zero emissions by 2050" [25, p.36]. This economic and policy landscape creates a significant need for updated studies of the costs, benefits, and trade-offs of the emissions abatement measures available to Canadian industries such as pulp and paper.

4.2. Method

4.2.1. Study framework

The study was conducted using a framework consisting of four phases, as shown in **Figure 26**:



*indicates activities completed outside the scope of this study

Figure 26: Modelling and analysis framework

In the first phase, raw data was collected for all critical areas for analysis (sector information, model inputs, and scenario development). Data sources included available academic, government, and industry literature and datasets as well as manual surveys of publicly available information. In the second stage, a technology-explicit, bottom-up sector energy and emissions model was developed and validated. The model accounts for the end-use energy demand of each major production process in the sector and, when combined with future production forecasts, reflects the BAU case for comparison with the scenarios of interest. The sector energy model was implemented in the Low Emissions Analysis Platform (LEAP) modelling tool for the purpose of long-term analysis incorporating system interactions. In the third stage, energy efficiency-driven emissions abatement scenarios were developed. These scenarios reduce energy consumption in one or more process areas relative to the BAU case and therefore reduce sectoral emissions based on the emissions intensity of the affected energy type(s). In the fourth and final step, the scenarios were run in the model over a long-term planning horizon to assess their cumulative impacts and costs. The model outputs for each scenario were then analyzed using tools such as marginal abatement cost curves.

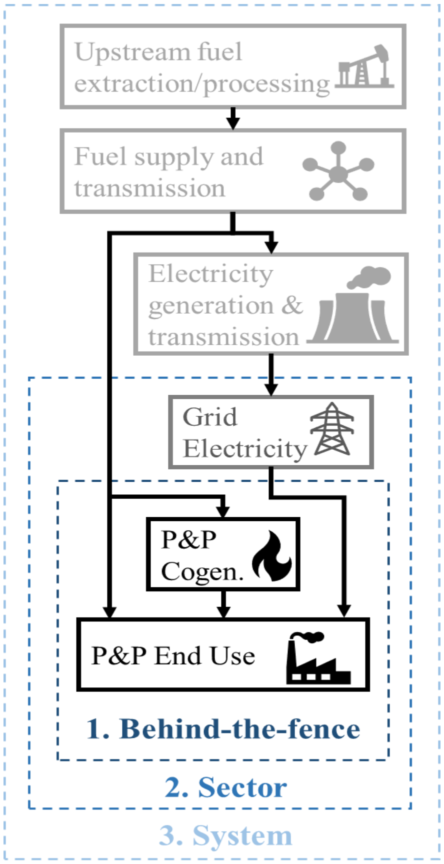


Figure 27: Study boundaries

The capabilities of the LEAP modelling tool allow for analysis at various levels of aggregation. In this study we consider three separate domains defined by proximity to the P&P sector, as shown in Figure 27. The behind-the-fence boundary is the most restrictive domain and includes only energy use and emissions within sector facilities. The sector boundary expands this definition to include imports of grid electricity and the associated emissions via grid emissions factors. The broadest boundary is the system boundary, which accounts for the totality of upstream primary energy and emissions required to supply the end-use energy demand for the sector as well as energy balances with other economic sectors. In this study, we primarily present results from the sector boundary, i.e., capturing energy and emissions associated with onsite energy use and supply of grid electricity but excluding upstream factors. This boundary is the most consistent with national energy/emissions statistics and policies and is therefore the most relevant. A novel aspect of our approach is that we also develop results using the system-wide boundary in order to provide additional insight into the overall impacts of each scenario and to compare the implications of using each boundary

In previous work (see Chapter 3), we presented standardized classifications for production capacity in the Canadian P&P sector, roughly aligned with those used by the North American Industry Classification System (NAICS). For consistency, we adopted the same categories in this study. These and other key parameters used to define the study scope are summarized in Table 3:

Table 3 : Key definitions

Parameter	**Study definition**	
Geography	National (Canada-wide)	
Study period	Validation:	1995-2018
	Future projections:	2019-2050
Sector/Industry Subsectors (Mill types)	Pulp and paper	NAICS 322
	Chemical market pulp	NAICS 322112
	Mechanical market pulp	NAICS 322111
	Print paper (incl. tissue)	NAICS 322121
	Newsprint	NAICS 322122
	Paperboard	NAICS 322130
Exclusions from scope	Off-site sector energy demands (harvesting, transportation, chemical supply, etc.) Converted pulp and paper operations	
Key indicators	Annual energy demand	
	Electricity total/net demand from grid	
	Natural gas	
	Biomass including wood, biogenic waste, biofuels, and pulping liquor	
	Other fossil fuels, e.g., fuel oil, transportation fuels, propane, etc.	
	Annual and cumulative GHG emissions	
	Net scenario costs	
Units (unless otherwise stated)	Energy:	Gigajoules (GJ)
	GHG Emissions:	100 year global warming potential metric tonnes CO_2 equivalent (tCO_2e)
	Sector production:	Air dry metric tonnes (ADMT or t)
	Monetary values:	2020 Canadian dollars (2020CAD or $)

4.2.2. Energy and emissions modelling

4.2.2.1. Model structure

In this study, we present a novel modelling framework that leverages the LEAP modelling tool to comprehensively analyze the costs and benefits of energy efficiency and emissions reduction technologies. LEAP is an energy and GHG emission modelling system developed by the Stockholm Environment Institute [113] featuring a framework that integrates energy demand with energy supply, energy transformation, and emissions factors to provide detailed energy and emissions analysis capabilities over long time horizons.

The LEAP framework, as shown in the centre of Figure 26, is comprised of three integrated modules. The consumption of final energy to provide end-use services is modeled in the energy demand module. The energy transformation module analyzes the conversion of units of primary energy to final energy for consumption (modeled in the demand module). In turn, the energy supply module models how primary energy demand is met via extraction and trade. In each module, process and energy emissions factors are used to estimate the direct and indirect environmental impacts of economic activity.

The present work is integrated with an existing implementation of this framework, the LEAP-Canada model. The LEAP-Canada model has been continuously developed since 2008 with a goal of providing bottom-up, systems-based analysis capabilities across the Canadian economy. The associated energy supply, transformation, and demand modules and emissions factors have been developed and validated in previous work and are summarized in Section 4.2.2.2.

4.2.2.2. LEAP-Canada transformation, supply, and emissions modules

The energy transformation module calculates energy use and emissions associated with activities conducted upstream of the P&P sector including the generation of grid electricity and transmission of electricity and natural gas. The electricity generation and dispatch component of the module, developed by Gupta et al. [114] and Davis et al. [115], features a robust model of the Canadian electricity system at the sub-national level. The main outputs of this portion of the model are estimates of the evolution of the emissions intensity factors for grid-supplied electricity in each province through to 2050. Emission factors associated with the supply of natural gas were derived from data from Canada's National Inventory Report [116] and Statistics Canada [117] and include fugitive, vented, and flared emissions during production, processing, transmission, and delivery. Emissions factors for fuel combustion were sourced from the Intergovernmental Panel on Climate Change Fifth Assessment and are contained in LEAP's emissions database [38].

Further relevant parameters for the transformation, supply/resource, and emissions modules are summarized in the appendices and referenced works [114, 115, 118].

4.2.2.3. Energy and carbon prices

Historical and forecasted industrial delivered energy prices for electricity and natural gas through 2050 were obtained from the Canada Energy Regulator [96]. We used the price and emissions factor for fuel oil as a representative for the *other fossil fuels* energy type based on data availability and the fact that fuel oil accounts for >75% of non-natural gas fossil fuel use in the P&P sector [87]. We did not assign a cost to changes in biomass use; such costs are difficult to estimate because of the lack of data and the variety of bioenergy types considered. However, the scenarios of interest primarily contemplate the use of already available waste or coproduced biomass sources that we expect would have minimal incremental cost for mills. Energy prices are summarized in the SI.

In our analysis, the main impact of carbon prices is their effect on upstream modules, e.g., electricity generation dispatch [114]. Carbon prices do not directly impact the P&P energy efficiency scenarios but instead are used for comparison with the model's scenario outputs, as discussed in Section 4.2.3.4.

4.2.2.4. P&P sector energy demand module

The LEAP-Canada energy demand module accounts for energy demand from all major economic sectors in Canada as part of the overall energy balance. Non-P&P sector energy demands were developed in previous work [114, 118] and are represented as combined inputs in the energy module. The P&P sector is set apart as its own branch, which is the focus of the remainder of this section.

We have previously developed a detailed technology-explicit bottom-up sector energy model for the Canadian P&P sector (see Chapter 3). The model accounts for energy consumption in each major end-use process in each of the five major mill types in the P&P sector. We functionally aligned our energy model definitions (e.g., treatment of net vs. total electricity demand) with Natural Resources Canada [93] to enable comparison with official statistics [87]. When developing the model, we accounted for how secondary energy demands (steam, direct heat, and electricity) are met by four types of final energy inputs: natural gas, biomass (including pulping liquor), grid electricity, and other fossil fuels. Through this exercise, we developed estimates for the specific final energy demand of each P&P EDT branch in each year; these estimates are the key inputs to complete the LEAP energy demand module. Sample SEC values per tonne of pulp or paper production for each branch in the P&P EDT for the reference year (2018) are summarized in Table 4.

Table 4: P&P Energy demand tree parameters (2018)

Energy Type	**Mill Type**	**Specific energy consumption by process per tonne of output (GJ/t)**										
		Feedstock preparation	*Pulping (digestion/refi*	*Bleaching*	*Recovery Cycle*	*Lime recausticizing*	*Pulp machine (drying)*	*Pulp supply*	*Stock preparation*	*Paper machine*	*Coating*	*Auxiliaries*
Electricity	**CP**	0.08	0.79	0.55	0.40	0.12	0.40	← Not applicable →				0.33
	MP	0.08	6.48	0.48	NA	NA	0.49	← Not applicable →				0.24
	PP	←Included in pulp supply branch→					NA	3.28	0.74	2.51	0.13	0.33
	NP	←Included in pulp supply branch→					NA	8.15	0.85	2.03	NA	0.33
	PB	←Included in pulp supply branch→					NA	1.68	0.70	2.39	0.13	0.33
Natural Gas	**CP**	0.02	0.62	0.43	0.40	1.31	0.02	← Not applicable →				0.03
	MP	0.05	0.28	0.05	NA	NA	1.51	← Not applicable →				0.10
	PP	←Included in pulp supply branch→					NA	2.56	-	3.31	1.21	0.14
	NP	←Included in pulp supply branch→					NA	0.56	-	0.65	NA	0.06
	PB	←Included in pulp supply branch→					NA	0.17	-	2.89	0.86	0.10
Biomass	**CP**	0.23	7.47	5.01	7.28	0.23	3.62	← Not applicable →				0.41
	MP	0.05	0.61	0.13	NA	NA	3.59	← Not applicable →				0.23
	PP	←Included in pulp supply branch→					NA	5.37	-	6.67	2.03	0.23
	NP	←Included in pulp supply branch→					NA	2.05	-	6.04	NA	0.29
	PB	←Included in pulp supply branch→					NA	0.38	-	7.03	2.10	0.24
Other fossil fuel	**CP**	0.06	-	-	-	0.87	-	← Not applicable →				0.04
	MP	0.06	-	-	NA	NA	-	← Not applicable →				0.04
	PP	←Included in pulp supply branch→					NA	0.38	-	0.25	-	0.04
	NP	←Included in pulp supply branch→					NA	0.13	-	1.50	NA	0.04
	PB	←Included in pulp supply branch→					NA	-	-	0.49	-	0.04

Each energy efficiency scenario modifies SEC value(s) relative to the BAU scenario in various branches of the P&P energy demand module over time based on the scenario adoption level.

The model was validated by analyzing three key parameters against historic/literature values: specific secondary energy demand, absolute final energy demand, and absolute emissions level. Energy validation results are presented in the appendices and the emissions validation results are summarized in Section 4.3.1.

4.2.2.5. Sector activity level

We defined the activity level for the P&P sector as the metric tonnes of pulp or paper produced. Assumed future activity levels were defined individually for each mill type based on recent historical values [90], our previously-completed sector production capacity survey (see Chapter 3), and discussions with sector experts [93]. The activity level assumptions used in the analysis are summarized in Table 5.

Table 5: Sector production level assumptions

		Annual production (million ADMT)					
		Actual [90]		Forecast			
Mill type	Key assumption	2013-2018 avg.	2018	2020	2030	2040	2050
CP	Moderate growth; 15% increase by 2040	7.12	7.02	7.13	7.66	8.19	8.19
MP	Slow growth; 10% increase by 2040	2.06	2.11	2.12	2.19	2.26	2.26
PP	Slow growth; 10% increase by 2040	4.14	4.13	4.17	4.36	4.55	4.55
NP	Managed decline; 20% decrease by 2040	3.38	3.00	2.97	2.84	2.71	2.71
PB	High growth; 20% increase by 2040	2.80	3.07	3.09	3.23	3.36	3.36

4.2.3. Scenario modelling and analysis

In previous work (see Chapter 3), we developed a database of 115 energy efficiency measures (EEMs) available to the Canadian P&P sector. Each scenario considers the incremental adoption of a single EEM in the sector over time, as defined by combining cost and performance parameters with assumptions regarding the EEM adoption rate (AR). It is critical to note that our integrated, cumulative analysis of EEM energy savings means that the scenarios presented in this study are not constructed as independent alternatives but instead are integrated parts of an overall whole. The key elements pertaining to scenario development are summarized in the following sections.

4.2.3.1. Scenario cost and energy savings development

To facilitate scenario cost input to the model, we developed estimates for the total implementation cost (TIC) of each EEM. This parameter annualizes the non-energy cost impacts of a measure over its life, as defined by Equation 12:

$$TIC_s = \frac{CC_s \times \left(\frac{d}{1-(1+d)^{-l_s}}\right) + OM_s - CB_s}{AL_s} \tag{12}$$

where TIC_s is the total implementation cost for the scenario EEM in 2020CAD/t of product, CC_s is the incremental capital cost of the scenario EEM in 2020CAD, d is the discount rate representing the sector's required return on investment in %, l_s is the installed lifetime of the EEM in years, OM_s is the increase in operations & maintenance costs for the EEM in 2020CAD, CB_s is the net savings from non-energy co-benefits (e.g. improvements in productivity or yield) in 2020CAD, and AL_s is the production activity level to which the EEM applies in ADMT.

We assumed that any measures whose lifetime expires before the end of the study period would be replaced in kind. This assumption is inherently accounted for in the model because the TIC values are held constant and are applied to monotonically increasing levels of production. All measures in the database were assumed to be implemented as retrofit initiatives rather than the replacement of old equipment at end of life; hence, the TIC is equivalent to the marginal scenario cost. This assumption results in a conservative estimate of scenario costs since the true marginal costs are likely to be lower, such as in cases where existing equipment would need to be replaced in the BAU scenario. However, this phenomenon cannot be analyzed without mill-level data on equipment type and vintage and is beyond the scope of this study. A discount rate of d=20% was used in all TIC calculations, reflecting the assumption that the P&P industry has a strong preference for high rates of return and short payback periods.

As part of the EEM analysis performed previously (see Chapter 3), we characterized the energy savings potential for each scenario EEM with the use of our detailed sector energy model.

Integration with the energy model enabled the adaptation of results from other jurisdictions to the Canadian context as well as a more accurate representation of EEM effects on secondary and final energy demands. This analysis included adjusting the individual EEM energy savings to account for the diminishing marginal returns expected from the implementation of many energy efficiency technologies in concert [21]. Estimating each individual interaction between measures would require a mill-specific energy model and is not feasible for a sub-national or national level model; however, our approach provides a first-order approximation of this effect. We next assessed the energy savings of each measure iteratively by implementing measures in order of increasing cost of saved energy (CSE), recalculating the CSE and energy savings for the remaining measures at each iteration [111]. This assumption approximates the higher priority placed on investments with more rapid payback periods and produces a more conservative estimate of energy savings. This additional analysis step means that the order of implementation affects the energy and emissions savings of subsequent measures; thus, our results reflect the overall sector potential for lowest-cost emissions abatement at a sector-wide level rather than attempting to quantify the specific abatement potential for a given technology in isolation in a single mill.

When developing scenarios, we focused on measures that reduce natural gas consumption and/or net electricity grid imports, because these two fuels are the largest sources of emissions for the sector [87]. Scenarios were also included that change biomass demand and/or directly impact consumption of fossil fuels. A key characteristic of the energy model-driven analysis conducted with LEAP is that scenario emissions reductions are not defined inputs but rather are calculated endogenously based on the scenario energy savings and energy emissions factors.

4.2.3.2. Scenario adoption rate and technical potential analysis

We have previously developed technology-driven estimates of the technical maximum share of P&P production to which a measure could be applied, which we define as the EEM applicability factor (AF) as discussed in Chapter 3. AF estimates were based on technical requirements/limitations, the prevalence of compatible production capacity in the sector, and the current level of adoption of the EEM. In situations where two or more EEMs may overlap or be mutually exclusive, we reduced the respective AFs to prevent over-estimation of benefits.

For this study, we considered both the technical and economic potential associated with each efficiency scenario. We defined the technical potential as the energy savings and emissions reductions associated with the adoption of an EEM to its maximum AF; thus, the technical potential is constant throughout the study period. The economic potential changes over time and accounts for the reality that no EEM can be adopted to its full AF instantaneously but instead will be gradually implemented across the sector based on its economic performance and other factors. In a given year, each scenario will have been adopted by some portion of production capacity between 0% and 100%. We define this proportion as the scenario penetration level (PL). We assumed that all EEMs would have a PL of 0% for the first two study years, 2019 and 2020, since all scenarios were defined as incremental to the current state of the sector and are expected to require lead time for design and implementation. The PL was calculated for each scenario in each year from 2021-2050 as per Equation 13:

$$PL_{n,s} = \text{mininum}(PL_{n-1,s} + (AR_{n,s} \times AF_s), AF_s) \tag{13}$$

where $PL_{n,s}$ is the penetration level of scenario s in the year of interest n in %; $PL_{n-1,s}$ is the penetration level for the scenario in the previous year; $AR_{n,s}$ is the adoption rate for the scenario in the year of interest in %; and AF_s is the applicability factor for the scenario in %.

Equation 2 reflects our core assumption that the penetration of each scenario would monotonically increase by a given proportion of its technical maximum penetration level until that level was reached. We assumed linear adoption because most of the measures are off-the-shelf options that can be reasonably expected to not experience rapid shifts in cost, performance, or industry awareness. As presented in Chapter 3, we estimated the internal rate of return (IRR) for each EEM by comparing its CSE to the relevant energy price(s). In this study, we used the IRR results for each measure to assign an annual AR for the associated scenario based on a set of standardized assumptions, as summarized in Table 6.

Table 6: Scenario adoption rates

Economic Performance (IRR Range)	Adoption Rate (%) 2020-2035	2036-2050	Adoption rate assumption
High (H) IRR ≥35%	11.1%	Max PL reached	Rapid adoption; full technical potential achieved by 2030.
Moderate (M) IRR 15% - 35%	2.6%	4.2%	Slow adoption; full technical potential achieved by 2050.
Weak (L) IRR <15%	0%	2.6%	Minimal adoption before 2035; 40% of technical potential achieved by 2050.

We assumed ARs will increase in the latter half of the study period as demand for GHG-abatement options grows; notably, this drives our results to include a portion of the potential associated with marginally economic measures in later years. Overall, our approach to scenario adoption rates represents a compromise between arbitrary penetration level estimates and infeasible behavioral simulation of industry decision making at the mill level.

4.2.3.3. Scenario descriptions and parameters

Each GHG mitigation scenario is centred around a single energy efficiency technology in our database. We consider five categories of technology in this study:

- *Process efficiency measures:* improvements to end-use devices and processes to directly reduce their energy consumption;
- *Cogeneration efficiency measures:* improvements to equipment and processes used to generate and distribute steam and electricity onsite;
- *Heat integration:* improvements to heat exchange, recovery, and reuse to reduce losses and to offset fresh steam demand with waste or secondary heat streams.
- *In-sector fuel switching:* increased use of available onsite fuels such as wood, black liquor, and biogas from waste streams in place of fossil fuels; and
- *Structural changes:* minor modifications to feedstock supply to reduce energy demands.

Several categories of GHG mitigation technologies were excluded from this study but present avenues for future work. These include precommercial technologies, activities beyond the sector boundary such as renewable energy and low-carbon fuels, and technologies whose primary mechanism is not related to efficiency, such as carbon capture. The appendices provide a summary of out-of-scope technologies.

In LEAP, each GHG abatement scenario is fully defined by the TIC and energy savings associated with a particular EEM in addition to the level of adoption of that EEM in each year in the study period. We assumed no changes to scenario energy savings or costs over the study period because most of the scenarios consider fully commercial technologies. Scenario parameters were assumed to be uniform across all provinces due to the lack of sub-national data. Table 7 provides a brief description of each scenario; detailed scenario inputs are provided in the appendices.

Table 7: Energy efficiency scenario definitions and parameters

Scenario	EEM name	Description
	Process efficiency measures (72)	
ALL-AHO	Air heating optimization	Improve equipment, system design, and practices for hot air production and end uses.
ALL-APC	Advanced process control / energy management systems	Implement advanced process controls and/or real-time energy management systems for individual systems or entire mill.
ALL-ASD	Adjustable speed drives	Add adjustable speed drives (or variable frequency drives) to motors to reduce losses from letdown/throttling and enable motors to run closer to their peak efficiency point.
ALL-AWT	Anaerobic water treatment	Implement or optimize anaerobic water treatment to reduce energy demand.
ALL-CAO	Compressed air system optimization	Implement measures to improve the performance of compressed air systems, such as eliminating leaks, eliminating unused lines, and reducing oversized/redundant equipment.
ALL-CAU	Compressed air equipment upgrades	Upgrade equipment that produces and consumes compressed air (such as compressors or actuators) with more efficient models.
ALL-EFA	Effluent aerator upgrade	Upgrade the effluent lagoon aeration system, reducing energy demand for water treatment.
ALL-EFL	Efficient facility lighting	Replace facility lighting with more efficient fixtures.
ALL-FSU	Fan system and equipment upgrades	Upgrade fan/blower systems and equipment, e.g., by optimizing ducting, eliminating losses, upgrading equipment internals, etc.
ALL-HWS	Hot water system upgrades	Improve hot water system design and equipment to improve efficiency and reduce losses.
ALL-IER	Idle equipment reduction	Eliminate idling and redundant equipment.
ALL-MDS	Motor downsizing	Replace oversized motors with smaller motors to enable operation closer to optimal efficiency point.
ALL-MMR	Improved motor maintenance and rewinding	Improve motor maintenance and rewinding practices.
ALL-MSU	Motor driven system upgrades	Upgrade motor-driven systems (other than those in other EEMs) to use more efficient equipment.
ALL-MVC	Motor voltage controllers	Implement voltage controllers on motors to improve efficiency.
ALL-PEM	Upgrade to premium efficiency motors	Upgrade or replace motors with premium efficiency models.
ALL-PRM	General preventative maintenance	Improve maintenance practices to prevent equipment breakdowns and correct inefficient operation.

Scenario	EEM name	Description
ALL-PSU	Pump system upgrades	Upgrade pump equipment and systems to improve efficiency and reduce losses, such as eliminating throttle valves, implementing improved controls, or upgrading pump internals.
BLE-BFR	Bleach filtrate recycling	Implement counterflow mixing of bleach wash filtrates in post-bleach washing stage, reducing water use and chemical losses.
BLE-OBC	Oxygen/ozone-based bleaching & delignification	Implement or optimize oxygen delignification / ozone bleaching and similar methods to reduce the need for bleaching chemicals.
CPP-ADA	Advanced digestion additives	Use emerging chemical or biological additives for treatment of chips before and during digestion, reducing digestion energy requirements.
CPP-AEE	Additional evaporation effect	Add an additional evaporation effect (typically up to 7 effect evaporation), improving efficiency, chemical recovery, and yield.
CPP-BDM	Batch digestor modifications	Implement improvements to batch digesters, such as indirect heating, improved controls, and/or cold blow optimization.
CPP-BLB	Boilout with black liquor	Use black liquor instead of fresh water to clean evaporators during boilout. Eliminates heat loss to water and allows washings to be returned to the recovery boiler, increasing output.
CPP-BWP	Bleach washing presses	Implement press-based washing after the bleach plant, reducing steam use compared to filter-based pressing.
CPP-BWU	Brownstock washer upgrades	Upgrade brownstock washing equipment to reduce vacuum requirements and improve thermal performance.
CPP-CDM	Continuous digester modifications	Implement improvements to existing continuous digesters, such as improved controls, optimized operating parameters, or improved insulation.
CPP-CDR	Batch to continuous digester retrofit	Replace batch digesters with continuous digesters.
CPP-CSC	Chip screening and conditioning (CP)	Improve chip screening and conditioning practices. Can include improved screening practices (low cost), bar-type screens (medium cost), or chip conditioners (higher cost). For CP mills this option saves steam energy and improves yield.
CPP-CSI	Condensate stripping integration	Integrate condensate stripping with evaporation and chemical recovery to improve heat recovery and reduce losses.
CPP-DFC	Brownstock washing dilution factor control	Implement controls to optimize the dilution of black liquor during the brownstock washing step.
CPP-DSH	Decker shower water from condensate stream	Replace fresh hot water used for decker showers with an alternative secondary source such as evaporator condensate.
CPP-FFE	Falling film evaporation	Replace rising film or direct contact evaporators with falling film models to improve efficiency.
CPP-KEP	Kiln electrostatic precipitator	Implement an electrostatic precipitator on the lime kiln to capture particulates and return them to the lime cycle, reducing chemical losses, air pollutants, and energy use.
CPP-LKG	Lime kiln modifications	Implement improvements to lime kiln such as upgraded equipment, refractory, insulation, oxygen enrichment, etc.
CPP-MLR	Stripper methanol rectification & liquification	Implement rectification and liquification for the stripper system to enable methanol recovery and storage, reducing system upsets and improving recovery.
CPP-SCW	Steam cycle washing	Implement or optimize improved washing techniques including counterflow washing and steam washing.
MPP-APT	Advanced TMP pre-treatment methods	Implement existing and emerging pre-treatment options to reduce TMP specific energy use. Possible options include enzymatic, fungal, chemical, or microwave treatment (average values used).

Scenario	EEM name	Description
MPP-AQC	TMP quality control improvements	Implement sensors and automated control for refiners to optimize refining energy use.
MPP-ARS	Additional refining stage	Modify refining line to incorporate a third stage—typically a low consistency refining stage— to reduce total refining energy.
MPP-BTM	TMP line blowthrough reduction.	Implement controls and practices to reduce steam blowthrough on the TMP line, reducing steam use by maintaining steady state operation
MPP-CSC	Chip screening and conditioning (MP)	Improve chip screening and conditioning practices and/or equipment, e.g., by implementing fine wire baskets. For MP mills this option saves electrical energy and improves yield.
MPP-CTI	CTMP improvements	Optimize CTMP chemical mix, PH, and temperatures to reduce energy demand.
MPP-HER	High efficiency refiners	Upgrade refiner equipment (rotors, motors, controls, etc.) to reduce refiner energy. Options include conic refiners, double-disc, etc.
MPP-RTS	RTS mechanical pulping techniques	Implement and/or optimize RTS (retention time, temperature, speed) mechanical pulping techniques.
MPP-TPP	Thermopulp (interheating) process	Implement thermopulp process (additional heating of chips between stages) to reduce refining energy in later stages.
PNB-ASO	Paper machine air system optimization	Add or improve paper machine hoods, ventilation, and air-air heat transfer equipment, controls, and setpoints to reduce losses and improve performance.
PNB-BSO	Batch stock optimization	Monitor and control mixing of pulp batches in paper mill stock prep to optimize proportions of different feeds, reducing process variability.
PNB-CNU	Coating nozzle upgrade	Upgrade coating nozzles and equipment to reduce coating energy consumption.
PNB-DMS	Dryer management system	Implement advanced dryer controls and setpoint optimization.
PNB-DSF	Dry sheet forming	Implement advanced dry sheet forming techniques.
PNB-GPF	Gap forming	Modify paper/board machine to use gap forming.
PNB-HCF	High consistency forming	Implement modifications to paper machine to allow higher consistency furnish, reducing losses and drying energy needs
PNB-IMD	Improved drying technologies	Implement available advanced drying technologies such as Condebelt drying, impingement drying, direct fired drying, or impulse drying.
PNB-IRP	Advanced web profiling	Implement advanced monitoring and profiling techniques to improve paper/board machine performance and avoid breaks. May use infrared, ultrasonic, and/or laser-based techniques.
PNB-PRU	Press section upgrades	Improve paper/newsprint/board machine press section equipment, techniques, and practices. Examples include implementing shoe presses, extended nip, and controls.
PNB-SHP	Superhot pressing	Implement superhot pressing for applicable grades.
PNB-SSI	Stationary siphon use/optimization	Implement and/or optimize use of stationary siphons to improve paper/newsprint/board machine efficiency.
PNB-TRB	Turbulent bars	Add turbulent bars to dryer cylinders to improve heat transfer.
PNB-VSO	Paper machine vacuum system optimization	Optimize practices and control setpoints to improve paper machine vacuum system operation.
PNB-WBS	Whitewater/broke system optimization	Improve whitewater/broke system to better handle upsets and increase water recycling.
PUL-PMR	Efficient pulp machine rebuild	Rebuild and upgrade pulp machine to improve efficiency and improve capacity.

Scenario	EEM name	Description
RPB-CLR	Closed loop recovered pulping	Implement closed loop recovered pulping to conserve heat and chemicals.
RPB-DFO	Deinking flotation optimization	Improve control of deinking system pumps and mixers to optimize deinking efficacy and energy use.
RPB-FRR	Fibre recovery from rejects	Recover usable fibre from screens and centrifuges, reducing waste and improving recovered pulping yield.
RPB-HCR	High consistency recovered fibre pulping	Improve recovered pulp refining practices by moving to high consistency recovered pulping.
RPB-RPO	Recovered fibre processing upgrades	Upgrade recovered pulping dispersion and screening equipment to improve process efficiency.
SPB-CRR	Continuous repulping	Implement continuous repulping of market pulp.
SPB-DRP	Drum repulping upgrades	Implement/improve drum repulping of market/recovered pulp.
SPB-RRU	Repulping rotor upgrades	Upgrade repulping rotors to reduce electricity consumption in recovered pulp operations.
VFP-EAD	Enzyme-assisted debarking	Apply enzymes to feedstock to break down bark and reduce energy needed for debarking.
VFP-UDB	Upgraded debarking	Implement improved debarking equipment such as advanced ring or cradle debarkers.
	Cogeneration efficiency measures (18)	
ALL-APH	Combustion air preheating	Implement heat exchangers to preheat boiler combustion air.
ALL-BBP	Boiler best practices & maintenance	Improve boiler operational and maintenance practices and controls to improve combustion and steam generation efficiencies.
ALL-BBU	Boiler burner upgrade	Upgrade boiler burners to improve efficiency.
ALL-BDP	Blowdown best practices	Improve blowdown controls and practices to improve boiler efficiency and reduce blowdown heat loss.
ALL-BHR	Blowdown heat recovery	Apply heat recovery to boiler blowdown system.
ALL-BRE	Replace inefficient boilers before end of life	Replace inefficient boilers with upgraded new models before end of life.
ALL-CDR	Improved condensate return and use	Collect and return condensate to produce low pressure steam and reduce steam system losses.
ALL-DVC	Deaerator vent rate control	Improve controls and setpoint optimization for deaerator.
ALL-EAC	Boiler combustion air practices	Improve practices and controls for boiler air, including reducing air leaks, improving excess air and oxygen trim controls, and monitoring air balance.
ALL-FWE	Feedwater economizers	Implement feedwater economizers on power boilers.
ALL-INS	Add and repair insulation	Improve insulation of steam lines and equipment to reduce heat losses.
ALL-PFH	Power boiler flue gas heat recovery	Implement flue gas heat recovery on power boilers to improve thermal efficiency.
ALL-SSO	Steam system optimization	Implement various steam system improvements including advanced controls, equipment and line layout improvements, and use of steam accumulators. Does not include steam traps or insulation.
ALL-STU	Steam trap maintenance and upgrades	Improve steam trap maintenance practices and hardware.
CPP-HTM	Recovery boiler temperature monitoring	Monitoring of boiler temperatures and soot deposition to reduce sootblower use and boiler shutdowns.
CPP-RBH	Recovery boiler upgrade to high pressure and cogen.	Replace old recovery boilers with high efficiency high pressure models with integrated cogeneration to increase electricity export.
CPP-RBS	Recovery boiler tertiary/quaternary stage	Adopt or expand use of third and fourth recovery boiler stages to reduce the need for sootblowing and improve overall boiler efficiency.

Scenario	EEM name	Description
CPP-RFH	Recovery boiler flue gas heat recovery	Implement flue gas heat recovery on recovery boilers to improve thermal efficiency.
Heat integration measures (10)		
ALL-HRI	General heat recovery and integration	Apply techniques such as pinch analysis to identify and implement general heat integration improvements including preheating, counterflow mixing, and heat recovery. Excludes other specific heat recovery measures.
BLE-CPH	Bleach CLO_2 preheating	Preheat chlorine dioxide using counterflow heat exchange to improve heat integration, reduce losses, and improve the performance of the bleach plant.
BLE-PHR	Bleach plant heat recovery	Apply heat recovery to bleach plant and/or bleach plant effluent. Improves recovery of bleach plant chemicals.
CPP-DHR	Digester heat recovery	Apply heat recovery to digesters (blow/flash, vapour take-off, etc.) Applicability discounted to account for overlap with digester modification EEMs.
MPP-THR	Add/improve TMP heat recovery	Modify mechanical mill refining lines to add or increase heat recovery from refiners.
PNB-FWP	Felt water preheating	Preheat felt water to improve heat integration in the paper machine.
PNB-MHR	Paper machine heat recovery	Implement/improve heat recovery in the paper machine.
PUL-MHR	Pulp machine heat recovery	Implement/improve heat recovery in the pulp machine.
RPB-DHR	Heat recovery on deinking system	Recover heat from de-inking effluent.
VFP-WHD	Debarking using waste heat	Retrofit debarking hot water supply to use waste heat and/or warm effluent rather than fresh hot water.
Fuel switching measures (13)		
ALL-BGE	Biogas production from effluent	Implement/improve digestion of effluent to produce biogas to offset natural gas consumption.
ALL-BMG	Biomass gasification to offset natural gas	Add full-scale biomass gasification to offset natural gas consumption in boilers and, where possible, direct use.
ALL-BSB	Biomass supplementary boiler	For mills with no biomass boilers or constrained boiler capacity, add a supplementary biomass boiler to offset natural gas steam production.
ALL-HAI	Hog boiler ash injection	Reinject ash into hog boilers to improve combustion efficiency and reduce the need for supplemental firing.
ALL-MST	Microturbine to replace pressure reducing valves	Replace steam pressure letdown valves with microturbines to generate power, offsetting grid import.
ALL-SRC	Sludge recovery and combustion	Recover and combust sludge from effluent system, offsetting fossil fuels.
ALL-STS	Solar thermal supplemental steam	Implement solar steam generation to offset a portion of fossil fuel use.
CPP-BGK	Biomass gasification for kiln	Implement small-scale biomass gasification to fuel the lime kiln with biogas.
CPP-BLC	Black liquor concentration / high solids firing	Increase concentration of black liquor to improve recovery boiler efficiency, reducing the need for supplemental fuel.
CPP-BLG	Black liquor gasification (full scale)	Implement gasification of black liquor to improve overall combustion efficiency, reducing supplemental fuel demand and improving recovery cycle yield.
PNB-IRD	Infrared drying	Rebuild dryer section to use infrared drying.
PNB-MWD	Microwave drying	Implement supplemental microwave drying to reduce overall drying energy requirement and debottleneck paper machine.

Scenario	EEM name	Description
VFP-BFD	Biomass moisture reduction (press/dryer)	Implement pressing and drying techniques to reduce the moisture content of biomass fuels prior to firing.
	Structural change measures (2)	
PNB-AFF	Advanced fibrous fillers	Use advanced fillers to offset the need for virgin pulp. Reduces energy demand for pulp production in integrated mills.
PNB-RFS	Increase use of recycled pulp	Increase use of recovered fibre in paper, newsprint, and board, displacing virgin pulp.

4.2.3.4. Marginal abatement cost analysis

Using LEAP, we calculated the impacts of each scenario on energy demand and emissions in each study year at various levels of disaggregation, as discussed in Section 4.2.2. We then used these parameters to assess the performance of each scenario based on its net present value (NPV), GHG emissions abatement, and marginal GHG abatement cost (MAC).

We calculated NPV based on changes in capital, O&M, and energy costs, as per Equation 14:

$$NPV_s = \sum_{n=2020}^{2050} \frac{\left((TIC_s - TIC_{BAU}) \times PL_{s,n} \times AL_n\right) + \sum_f \left(EC_{s,n,f} - EC_{BAU,n,f}\right)}{(1+d)^{n-2020}} \tag{14}$$

where NPV_s is the net present value of scenario s in 2020CAD, TIC_s is the total implementation cost of scenario s in 2020CAD/ADMT, $PL_{s,n}$ is the penetration level of the scenario in year n, AL_n is the sector activity level in ADMT, $EC_{s,n,f}$ is the system energy cost for fuel f in year n under scenario s in 2020CAD, and d is the discount rate in % which reflects the time value of money for the NPV calculation. Note that TIC_{BAU} has a value of \$0/ADMT due to the construction of our scenarios as purely incremental to the current sector state. For the purposes of NPV calculation, a value of d=5% was used, reflecting the assumed long-term cost of capital for the P&P sector.

We next calculated the MAC of each scenario using its standard definition per Equation 15:

$$MAC_s = \frac{change\ in\ total\ costs}{change\ in\ GHG\ emissions} = \frac{NPV_s}{\sum_{n=2020}^{2050}\left(GHG_{BAU,n} - GHG_{s,n}\right)} \tag{15}$$

where MAC_s is the marginal abatement cost of scenario s in 2020CAD/tCO$_2$e, NPV_s is the net present value of costs associated with scenario s in 2020CAD, and $GHG_{s,n}$ is the emissions produced in year n under scenario s in tCO$_2$e.

Because carbon costs are not included in the NPV, the MAC can be directly compared with carbon pricing levels. A MAC less than or equal to the carbon price implies that it is economically preferrable to implement the EEM to avoid emissions rather than to pay the associated carbon costs. The carbon price used for comparison was $170/t (nominal Canadian dollars) as per the long-term value prescribed by Canada's federal climate policy [25] for 2030 and onwards.

4.3. Results and discussion

4.3.1. Model validation

Chapter 3 presents work that validates the ability of the model to accurately characterize sector energy demand. In this chapter, the validation is expanded to focus on sector emissions. Figure 28 compares the LEAP-Canada modelled sector emissions to estimates developed from Statistics Canada/Natural Resources Canada data [87, 90] and Environment Canada's National Inventory Report [116] over the validation period.

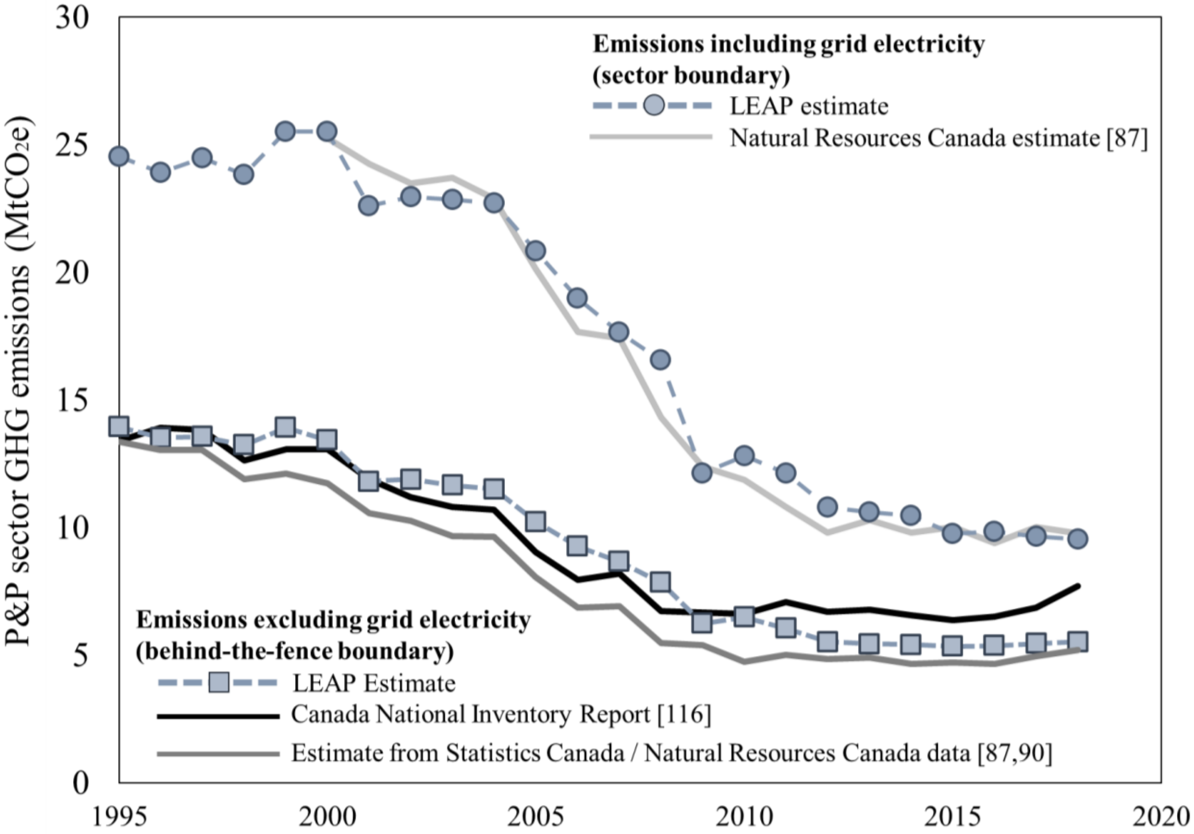


Figure 28: Model emissions validation

Figure 28 demonstrates that our model accurately characterizes the emissions in the sector when compared with official estimates across various boundaries. For behind-the-fence emissions, the LEAP-Canada model achieves an average annual error of -4% and a cumulative error of -2% over the validation period compared to Canada's National Inventory Report. Errors in recent years are larger; however, the LEAP model estimate falls between the two official estimates, which differ by as much as 48%. When expanding the scope of the validation to the sector boundary, the LEAP-Canada model estimate demonstrates very high conformity with Natural Resources Canada estimates, with an average annual error of < 3% and a cumulative error of < 2%.

Taken together, the results of the validation exercises demonstrate that our model can accurately characterize the energy demand and GHG emissions of the P&P sector and is therefore suitable for subsequent scenario analyses.

4.3.2. Overall abatement potential

Figure 29 illustrates the combined emissions reduction potential for all scenarios compared with Canada's emissions targets [25].

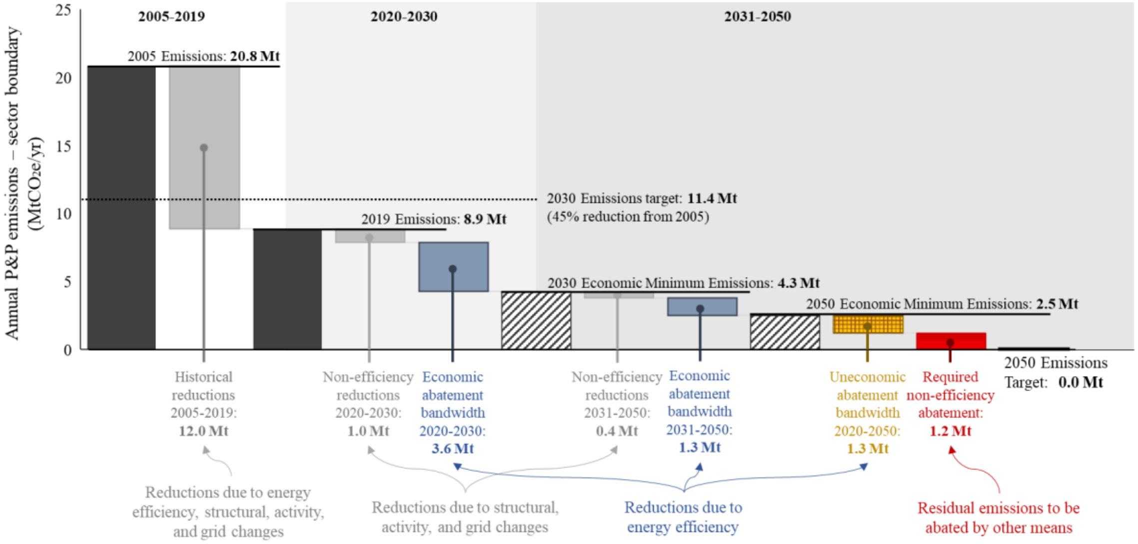


Figure 29: Overall sector emissions abatement potential (sector boundary)

Figure 29 plots historical P&P sector emissions levels for 2005 (the reference year for emission targets) and 2019 (the most recent historical year) alongside forecasted emissions levels for 2030 and 2050 based on changes over time. Absolute emissions reductions are caused by BAU changes in production and upstream energy emissions factors, or else are the result of the energy efficiency scenarios considered in this study. Figure 29 plots these effects separately, demonstrating that the emissions reductions associated with the energy efficiency scenarios are much larger than the BAU changes to sector emissions. The figure shows that by 2019, P&P sector emissions were already below the 2030 target on an absolute basis. The decrease from 2005 to 2019 is mainly the result of reduced sector production and lower electricity grid emissions intensity. Our results show that the adoption of economically viable energy efficiency technologies can further reduce annual P&P sector emissions relative to the BAU case by 3.6 $MtCO_2e/yr$ (46%) in 2030 and by 4.9 $MtCO_2e/yr$ (66%) in 2050. If all scenarios are adopted to their technical maximum level, an additional 1.3 $MtCO_2e/yr$ of reductions could be realized by 2050. This leaves at least 1.2 $MtCO_2e/yr$ that must be mitigated by other means to achieve a net-zero 2050 target.

Figure 30 compares the overall abatement potential estimate for the sector- and system-boundaries in 2030 and 2050.

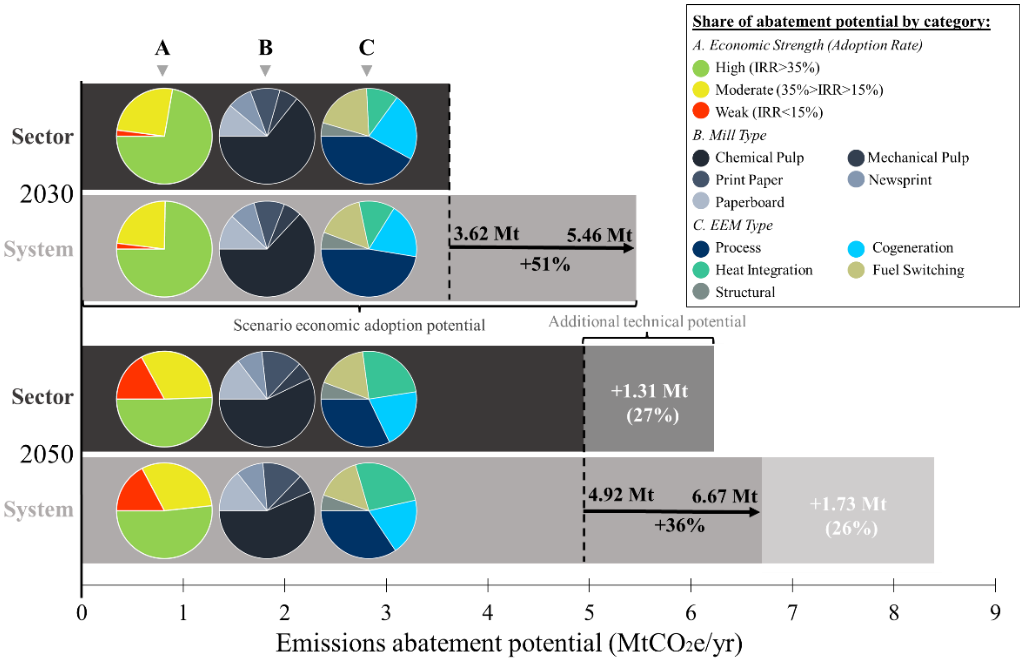


Figure 30: Overall abatement potential by category

Figure 30 demonstrates the capability of our analysis framework to provide disaggregated results across different system boundaries. The three pie charts in each bar demonstrate how the associated emissions abatement potential is distributed by A) economic category (EEM adoption rate), B) mill type, and C) EEM type. The figure demonstrates that overall abatement estimates are 36%-51% higher when using the system boundary over the sector boundary. When accounting for the expanded system boundary, the economic abatement potential is 5.46 $MtCO_{2e}$/yr in 2030 and 6.67 $MtCO_{2e}$/yr in 2050. There are only minor observable differences in the scenario category shares between system boundaries, indicating that the system-level analysis does not significantly distort the results but rather increases the abatement for all scenarios in an approximately uniform manner.

Beyond the economic abatement potential, Figure 5 also shows the estimated additional abatement potential associated with implementing all scenarios to their full AF in 2050. When considering this technical maximum, the annual abatement potential in 2050 increases to 6.23 $MtCO_{2e}$/yr and 8.40 $MtCO_{2e}$/yr for the sector and system cases, respectively.

4.3.3. Sector emissions profile and wedge diagrams

Figure 31 visualizes the emissions abatement potential for the P&P sector associated with various EEM categories over time.

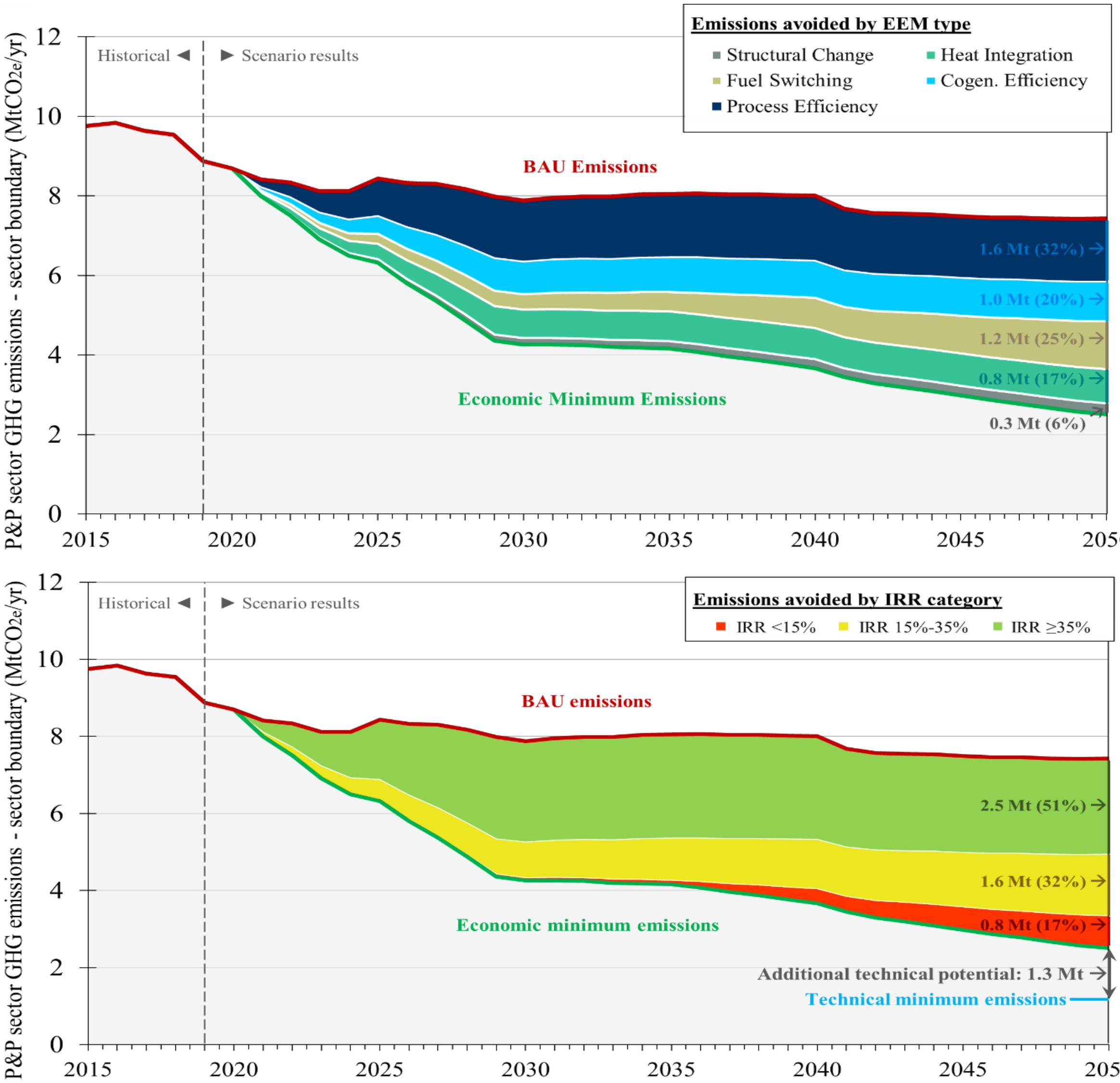


Figure 31: P&P Sector emissions abatement wedges (sector boundary) by EEM category (top) and EEM adoption rate (bottom)

In Figure 31, emissions in the BAU scenario are denoted by the red line. Below this, wedges are plotted for each EEM category, showing the reductions associated with scenarios in that category compared to the baseline over time. The remaining sector emissions, denoted by the green line below the wedges, are the economic minimum emissions for the sector after the adoption of all the

EEMs to their economic level in a given year. In 2050, the annual reductions associated with the process, cogeneration, heat integration, fuel switching, and structural categories are 1.6 $MtCO_2e/yr$ (32% of total reductions), 1.0 $MtCO_2e/yr$ (20%), 0.85 $MtCO_2e/yr$ (17%), 1.2 $MtCO_2e/yr$ (25%), and 0.28 MtCO2e/yr (6%), respectively. This confirms that although conventional energy efficiency options can achieve significant emissions reductions on their own, a combination of all technology types considered in this study are needed to achieve the full potential of energy efficiency in the P&P sector.

The lower portion of Figure 6 demonstrates the impact of the AR assumptions discussed in Section 2.4.2. EEMs with high rates of return were assumed to be adopted rapidly, and emissions abatement in this category grows swiftly and plateaus after 2030. In comparison, EEMs with low rates of return were assumed to have no adoption prior to 2030 and thus only make a small contribution to the overall abatement potential by 2050. Because our AR assumptions do not allow all scenarios to reach 100% of their technical potential, the economic minimum emissions in a given year are larger than the technical minimum. This effect is shown in the figure for the year 2050, where the annual emissions would be 1.3 $MtCO_2e/yr$ lower if ARs were set for all measures to achieve their full technical potential by that year. By 2050, high IRR EEMs account for 2.5 $MtCO_2e/yr$ (51%) of the economic emissions abatement potential, while moderate and weak IRR EEMs contribute 1.6 $MtCO_2e/yr$ (32%) and 0.84 $MtCO_2e/yr$ (17%), respectively. This demonstrates that substantial emissions abatement potential is accessible to industry at very high rates of return.

Figure 32 summarizes the sector emissions profile over the study period, with emissions categorized by the associated type of final energy demand.

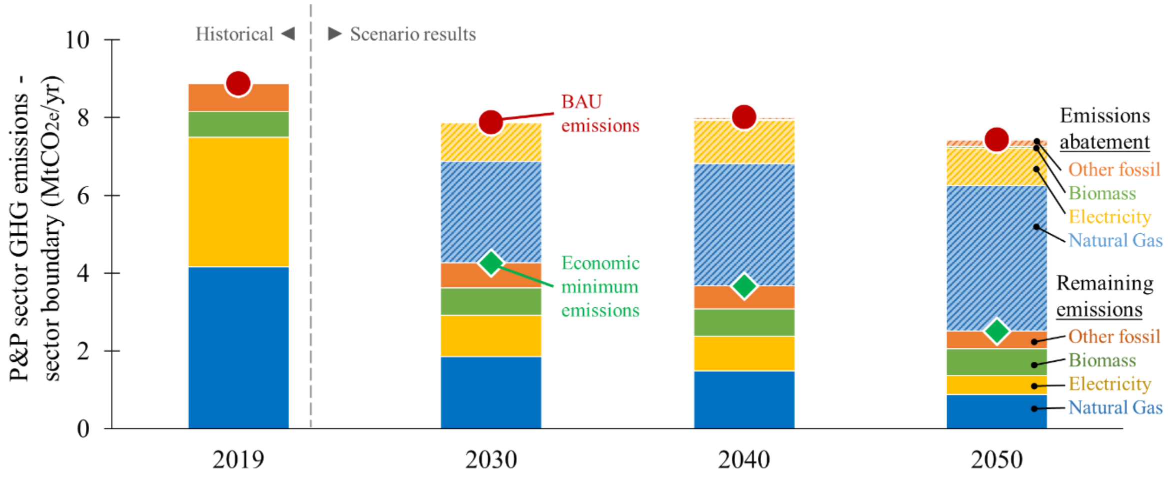


Figure 32: Sector emissions profile by energy type (sector boundary)

Figure 32 shows that almost all of the economic abatement potential is attributable to reductions in consumption of natural gas and electricity, whose associated emissions fall by 79% and 85%, respectively, by 2050. Critically, of the 2.5 $MtCO_2e/yr$ of remaining sector emissions in 2050, 0.5 $MtCO_2e/yr$ (19%) is associated with grid electricity and thus could be externally abated by further reductions in grid emissions intensity. Biomass emissions (which include methane, nitrogen oxides, and other biomass combustion products but not biogenic CO_2) remain roughly constant on an absolute basis and account for 0.7 $MtCO_2e/yr$ (27%) in 2050. Elimination of such emissions would likely require dramatic changes in sector structure such as a redesign of the chemical recovery cycle and other emerging options [33].

Emissions from fossil fuels (natural gas and other) constitute 1.35 $MtCO_2e/yr$ (54%) of sector emissions by 2050; this segment of emissions is difficult to fully abate with current energy efficiency technologies and would therefore require improvements to the EEMs considered in this study and/or more invasive actions including carbon capture or import of low-carbon fuels. Nonetheless, the substantial reductions potential observed in this study indicates that energy efficiency could have a significantly larger role to play in overall abatement compared with alternative interventions.

Figure 33 summarizes the sector emissions profile over the study period, disaggregated by mill type:

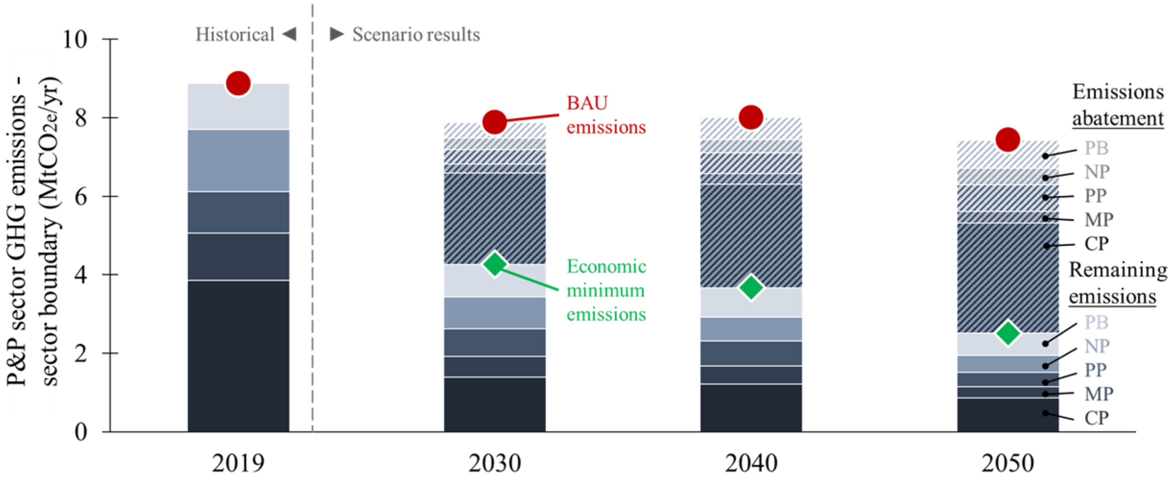


Figure 33: Sector emissions profile by mill type (sector boundary)

Figure 33 demonstrates how each mill type contributes to sector-wide emissions and emissions abatement over the study period. CP mills account for the largest share of sector emissions in all years but are also the largest driver of sector-wide reductions with the potential to reduce their emissions by 2.81 $MtCO_{2e}$/yr (76%) compared to BAU in 2050. This accounts for 57% of total sector abatement potential and reduces the CP share of sector emissions from 43% in 2019 to 34% in 2050. This finding is consistent with the large BAU emissions associated with CP mills and their considerable share of sector production capacity. In 2050, MP, PP, NP, and PB mills contribute 6%, 14%, 9%, and 15% of the abatement potential, respectively. PB mills rise from the second lowest contributor to sector emissions in 2019 to the second highest contributor in 2050, a phenomenon driven in part by the assumed higher-than-average production growth in that subsector.

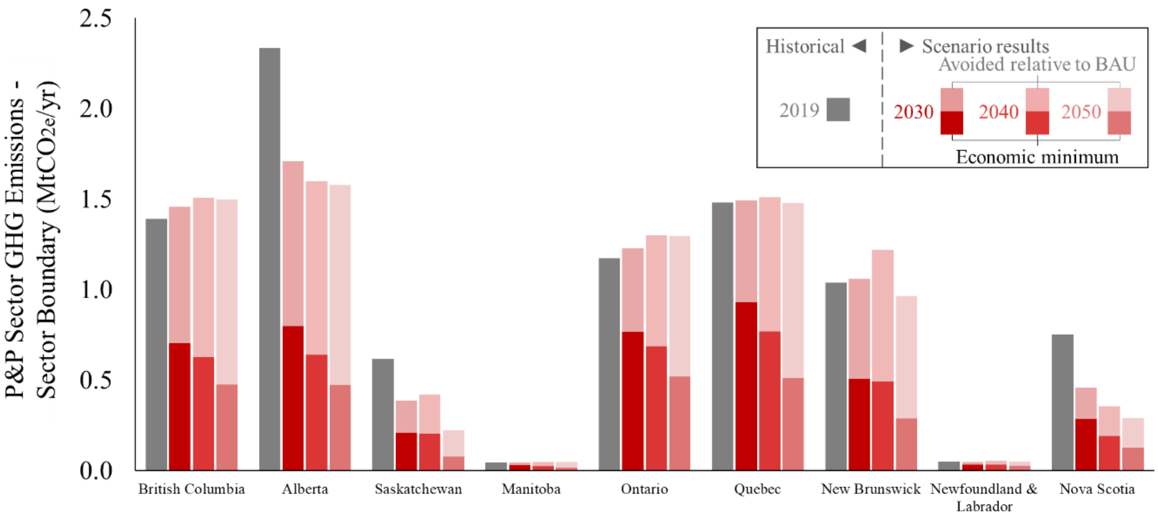


Figure 34: Sector emissions profile by province (sector boundary)

In Figure 34, annual emissions from the P&P sector in every Canadian province with P&P production are plotted for the most recent historical year and for 2030, 2040, and 2050. A key finding demonstrated by Figure 9 is that the overall emissions abatement potential is distributed roughly evenly across the country rather than being dominated by a small number of regions. Comparing the BAU case to the scenario case shows that in most provinces the abatement relative to 2019 is almost entirely driven by the EEMs considered in this study. The exceptions to this observation are provinces with high grid emissions intensities such as Alberta and Saskatchewan, where BAU emissions decrease significantly over the study period because of improvements to the local electricity grid. This finding reinforces the consensus that electricity grid improvements are a critical tool for emissions reductions in end-use industries. All provinces have the potential to achieve at least 50% abatement relative to BAU in 2050; British Columbia has the largest percentage abatement (74%) while Newfoundland & Labrador has the smallest (50%). This range can be attributed in part to the different mix of production and product types in each province.

4.3.4. Marginal abatement cost curves

Marginal abatement cost curves are a commonly used tool to visualize and compare the impacts and costs of emissions abatement opportunities. In a MAC curve, each opportunity is represented by a rectangle wherein the width and height represent the abatement potential (compared to the

BAU scenario) and the marginal abatement cost, respectively. By plotting opportunities in order of ascending MAC, the curve can be used to analyze the cost to achieve a certain level of cumulative abatement or (equivalently) the cumulative abatement that can be achieved at or below a given cost. Figure 35 shows the MAC curve for the sector and system boundaries.

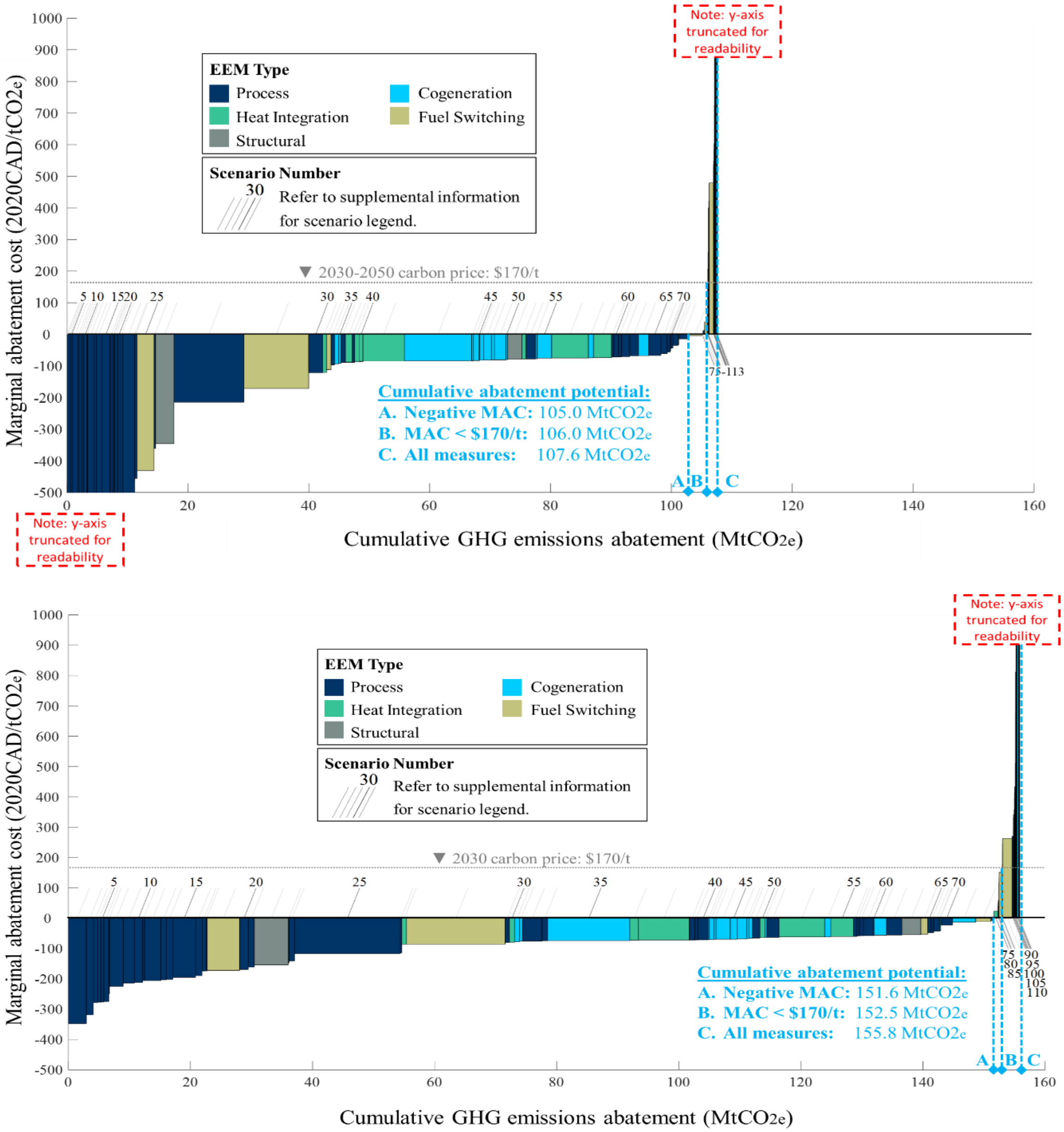


Figure 35: Marginal abatement cost curve for the Canadian P&P industry for the sector boundary (top) and system boundary (bottom)

The figure demonstrates that significant abatement potential (105 $MtCO_2e$ cumulative to 2050) is accessible to the sector at zero or negative marginal cost when accounting for avoided energy costs. This accounts for 98% of the total economic abatement potential. The large number of measures with negative abatement cost is driven by two key factors. First, all measures in this study were constructed such that their emissions reductions are directly driven by energy savings. We have previously shown that most such measures have energy cost savings that equal or exceed their annualized capital cost (see Chapter 3), and thus the associated GHG emissions reductions have low or negative net cost when accounting for energy costs. The second contributing factor is that many options have associated productivity or quality benefits that are included in our NPV calculation. This phenomenon is particularly apparent for process efficiency options and can be observed for the large cluster of process efficiency scenarios with negative costs on the left side of Figure 35. The figure highlights the key finding that energy efficiency can be an extremely cost-effective means of GHG emissions abatement for the sector because the emissions reductions are directly coupled to valuable energy savings.

Measures with MAC values greater than \$0/t but less than the carbon price (\$170/t) are important to note on the MAC curve because it is these measures whose adoption would likely not occur in the absence of carbon pricing. Figure 35 shows that there are eight such EEMs, with a combined cumulative abatement of 1.04 $MtCO_2e$.

Notably, thirty-three measures have MACs larger than the long-term carbon price of \$170/t, but such measures account for only 1.6 $MtCO_2e$ (1.5%) of the cumulative abatement potential. The low abatement and extreme MAC values for these measures are partially the result of the cumulative analysis method discussed in Section 4.2.3.1, whereby the most expensive measures are also those most affected by diminishing marginal returns.

Critically, the 50 most profitable measures alone would deliver 2.6 $MtCO_2e$/yr in emissions reductions (72% of total abatement) compared to BAU in 2030 at an average abatement cost of -\$355/tCO_2e prior to applying carbon pricing. When including all measures, the average abatement cost cumulative to 2030 is -\$289/t CO_2e.

By 2050, the assumed adoption of more costly measures dramatically increases the annual costs to industry. This cost increase is accompanied by a 37% increase in emissions abatement, and thus the weighted average MAC rises to -\$162/tCO_2e in 2050. These changes in response to the adoption of less cost-effective measures inform two critical conclusions. Firstly, while low-hanging-fruit energy efficiency measures can reduce emissions at excellent rates of return, attempting to drive very high shares of reductions via efficiency alone can lead to rapidly escalating costs. Secondly, the first point notwithstanding, the high returns associated with the most profitable energy efficiency measures could be used to finance subsequent lower-return measures, yielding an overall abatement cost that is still less than zero.

The top five measures by cumulative abatement through 2050 are ALL-APC (11.6 MtCO_2e), ALL-STU (11.1 MtCO_2e), ALL-BGE (10.7 MtCO_2e), BLE-PHR (6.9 MtCO_2e), and ALL-HRI (6.1 MtCO_2e).

Two scenarios (ALL-BMG and BLE-OBC) were found to increase emissions within the sector boundary and were therefore excluded from the top portion of Figure 35. When analyzed in the context of the expanded system boundary, the BLE-OBC scenario resulted in emissions reductions and it is therefore included in the system-level MAC curve.

The lower portion of Figure 35 demonstrates that the performance of each measure significantly changes depending on which boundary is considered. When analyzed in the context of the system boundary, the abatement potential increased for 95% of the measures compared to the sector boundary. Similarly, the system-level MAC decreased for 39% of the measures. Both these effects are primarily driven by the wider scope of upstream and indirect emissions in the system boundary. The cumulative average abatement cost in 2050 rises to -\$97/t at the system level, while total cumulative abatement increases by 44% to 155.8 MtCO_2e – well beyond the abatement within the P&P sector only. This finding indicates that considering effects at both the sector and system level is critical to guide effective policy design.

Detailed MAC results are provided in the appendices.

4.3.5. Sensitivity of results

We performed a sensitivity analysis to identify the impacts of key assumptions and data inputs on the results. The sensitivity analysis confirmed that discount rate and energy price have the most impact on the average marginal abatement cost, while EEM performance (energy savings) has the greatest impact on cumulative GHG abatement. In all sensitivity scenarios, the average MAC remained less than \$0/tCO_2e in 2050 and the cumulative GHG abatement remained greater than 50 MtCO_2e. EEM implementation costs have a limited impact on the results: increasing TIC by 100% for all scenarios resulted in the average abatement cost rising by about 33% to -\$109/tCO_2e. This result demonstrates the dominant effect of energy cost savings relative to capital costs. Two sensitivity variables were also examined at the system boundary: the emissions factors for upstream natural gas and for grid electricity. In a scenario in which upstream natural gas emissions are 5 times as high as the base case, the cumulative emissions abatement increases by roughly 10%. In a scenario in which the electricity grid rapidly decarbonizes by 2035, the emissions abatement associated with electricity savings is significantly diminished; this sensitivity scenario reduces cumulative GHG abatement in 2050 by roughly 15% at a system level.

Additional details and results from the sensitivity analysis are provided in the appendices.

4.3.6. Limitations

We note the following limitations of the current study that may provide opportunities for future work.

We assumed that scenario performance and costs remain static over the study period. This assumption is consistent with our focus on the current potential available to the P&P sector and the fact that most scenarios featured fully commercial technologies that can be reasonably expected to have minimal changes in costs and performance over time. The implementation of learning rates in the scenario analysis is therefore expected to have minimal impact on the results except for the case of emerging/non-commercial technologies. Incorporating cost and performance improvements over time in future work would further improve the relevance of the results for long-term pathway and policy analysis but would also substantially increase the data requirements for the analysis.

We used simple adoption rate assumptions as exogenous inputs to the model to forecast scenario penetration over time. This approach is in contrast to simulation, stock turnover, or optimization models in which ARs are dynamically and endogenously calculated. Our approach is therefore best interpreted as an investigation of what could happen in the sector rather than an attempt to suggest what is likely to occur. The use of IRR-driven adoption rates is among the most basic methods for scenario adoption modelling and has known limitations including oversimplification of industry decision-making behavior. Such limitations can be overcome with more advanced behavioral simulation techniques [35]; however, this would divert the focus of the study from assessing the overall potential which, like the technical potential associated with energy reserves, is theoretically unaffected by behavior or the policy landscape.

4.3.7. Policy Implications

Our efforts to characterize the overall emissions abatement potential of energy efficiency technologies in the P&P sector, as presented in this study, have highlighted several key implications for policymakers and industry decision makers.

Crucially, we find that energy efficiency has the potential to be the single most impactful driver of emissions reductions in the Canadian P&P sector in the coming decades. Adopting commercially proven technologies whose capital and operating costs are more than offset by their energy cost savings can deliver substantial emissions abatement for the sector – up to 66% of the required reductions to achieve zero emissions compared to BAU in 2050. This level of emissions abatement would help the P&P sector avoid $837 million CAD (nominal) in carbon costs in 2050 (assuming full exposure to the carbon price) in addition to a net profit of $162/tCO$_2$e due to associated energy cost savings and productivity improvements. These results suggest the Canadian P&P sector is very well positioned to respond to tightening carbon emissions standards or similar policies through the adoption of energy efficiency technologies while enhancing (rather than reducing) its cost competitiveness.

Given the significant abatement potential associated with energy efficiency, it follows that the level of adoption of efficiency technologies will dictate the scale of additional reductions required to achieve a net-zero target. Lower investment in energy efficiency will require greater investment in measures with positive abatement costs such as carbon capture or import of low-carbon fuels. As a result, a strategy that focuses on such technologies is likely to be costlier than one with efficiency as its main thrust. The appropriate balance of various abatement options to achieve net zero should therefore be a key avenue for future investigation.

Prioritization of EEM investments will require ongoing study, particularly at the level of individual mills where facility energy audits can help to narrow the uncertainty for the costs and benefits of implementing specific efficiency technologies. Nonetheless, our results provide several implications for best practices when conducting such work. A portfolio approach is key; our results show that technologies from all five categories we considered play important roles in the overall emissions abatement pathway. Although dedicated studies for individual efficiency projects are valuable, our cumulative analysis shows that technology interactions and implementation order can significantly change their costs and benefits. Therefore, industry should embrace a holistic approach to emissions reduction by considering as many efficiency options as possible in integrated initial analyses before narrowing their focus to the most promising opportunities.

Our consideration of multiple boundaries demonstrates that policymakers and researchers must take care to define and consider sectoral and regional bounds for policymaking and analysis. Deploying technologies within a sector can have impacts on upstream emissions at a scale relevant for sub-national and national policymaking. Therefore, we recommend that analysts adopt frameworks that can provide insights at multiple levels of disaggregation and demarcation to ensure that both the sectoral- and system-level implications of policies and investments are understood.

The results presented in this study also have implications for the use of carbon price and other policies that affect technology rates of return. Carbon pricing plays a critical role; indeed, the avoided carbon price alone exceeds the measure implementation costs for well over 50% of the scenarios considered. However, the extreme abatement costs for measures at the upper end of the MAC curve indicate that further increases to the carbon price beyond \$170/t are unlikely to materially change the economic viability of currently uneconomic measures. Similarly, given the already excellent rates of return observed for most of the measures considered in the study, it is unlikely that additional government subsidies or similar incentives would motivate increased uptake of efficiency technologies. Policy instruments that focus on removing non-financial barriers to the adoption of energy efficiency may therefore be more effective than those that only address economic returns. With this in mind, policymakers should consider alternatives such as loan guarantees, support for energy efficiency programs, education, and audits, or sector-specific energy and emissions targets.

4.4. Conclusions

Our objective in this study was to explore the overall GHG emissions abatement potential associated with the adoption of commercially available energy efficiency technologies for the case study of the Canadian pulp and paper sector. In pursuit of this objective, we developed a modeling and analysis framework that leverages the long-term system-integrated scenario analysis capabilities of the LEAP modelling tool combined with a detailed sector energy model to assess a comprehensive suite of energy efficiency opportunities.

Our results indicate that energy efficiency could be an essential tool to decarbonize the P&P sector. Compared to business-as-usual, the adoption of cost-effective energy efficiency technologies could reduce P&P sector emissions by 46% in 2030 and by 66% in 2050, two-thirds of the way to net-zero emissions. At forecasted energy prices, 74 measures were found to have negative abatement costs over the study period prior to any carbon price, and the weighted average abatement cost for all measures was -\$162/tCO_2e through 2050. This makes energy efficiency an extremely financially attractive option to reduce emissions compared with other technologies that may increase overall costs.

Taken together, our results indicate that Canada's P&P sector has significant untapped potential to improve its energy efficiency and that such improvements would constitute very attractive investments. Indeed, the magnitude and cost of emissions abatement accessible via energy efficiency suggest that the P&P sector has a clear pathway to meeting emissions reduction and energy transition goals. As governments and industry participants look ahead to 2050 and beyond, effective policy design and investment strategies will be critical to ensuring that the pulp and paper sector delivers on its potential to be one of the first sectors to achieve net-zero emissions.

5. Efficiency Trade-off Curves as Inputs to *ENERGY 2020:* Alternative Application of the Modelling and Analysis Framework[6]

5.1. Executive summary

Many Canadian industrial sectors are emissions-intensive and trade-exposed, meaning they are characterized by high energy use, emissions intensity, and exposure to worldwide commodity markets. In Canada, these sectors include cement, iron & steel, pulp & paper, chemicals, and petroleum refining. Such industries can be disproportionately impacted by energy and emissions policies given their need to compete internationally. It is therefore key to understand the efficiency potential available to energy-intensive sectors to ensure that policies will deliver the intended outcomes.

Accurate modelling and forecasting of industrial energy demand is a key element in the toolset used by policymakers and government agencies to assess the potential impacts of various policies. Such forecasts are commonly produced via bottom-up modelling, which requires highly detailed data inputs specific to the jurisdiction, industry, and time period(s) of interest. Environment and Climate Change Canada uses the ENERGY 2020 model to project the long-term energy demands of the Canadian residential, commercial, and industrial sectors. It is expected that existing and emerging energy efficiency measures will be adopted by Canada's industries, altering the long-term profile of industry energy demand. However, it is not known what specific energy efficiency measures will be pursued or to what extent these measures will impact industry.

In this study, a novel method was developed and used to generate Canada-specific inputs to the ENERGY 2020 model that represent the energy price-driven trade-off between capital costs and energy efficiency for incremental industrial production capacity. Supported by a detailed database compiled for sectoral statistics and efficiency measure data, the spreadsheet-based model

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[6] The content of this chapter was originally prepared as part of an unpublished final report to Environment and Climate Change Canada, entitled "Efficiency Potential in the Canadian Pulp & Paper Sector" by Christophe Owttrim, Matthew Davis, and Amit Kumar. Acknowledgement is given to Saiedreza Radpour for insight on the technology adoption component of the work, and to Robin White for consultation on Environment Canada's modelling methods and assumptions. A version of this chapter is anticipated to be submitted for publication following acceptance of this thesis. All analysis, results, and writing are my original work.

developed for this study generates estimates of parameters specific to ENERGY 2020 that are not available elsewhere in the literature. The model uses a simple payback period criterion to evaluate which energy efficiency measures are viable at various energy prices and subsequently estimates the optimal cumulative efficiency potential and capital spending for all viable measures. The end result is a set of correlations that can be used by ENERGY 2020 to endogenously select the efficiency level and associated capital spend profile that industry can be expected to adopt for a given energy price scenario.

In this study, marginal efficiency selection and cost curves were generated for the Canadian pulp & paper sector. These curves represent efficiency selection behavior driven solely by changes in energy prices. At higher energy prices, more efficient technologies become increasingly viable and will be selected more often by firms when upgrading or adding to production capacity. The marginal efficiency correlations developed in this study reflect this behavior for the sector at the margin and are used in conjunction with a number of other inputs to ENERGY 2020 to determine the overall efficiency (and hence energy demand) for the sector.

In 2010, the base year for the study, the Canadian pulp & paper consumed 554 PJ of energy with 25% and 59% derived from electricity and wood/spent pulping liquor, respectively. The sector produced 18.5 million air dry tonnes of market pulp & paper for an overall energy intensity of 30 GJ/t. In the sector, energy is consumed through a number of pathways from fuel input to final product. The electric machine drive, natural gas process steam, and biomass process steam energy pathways, as defined in ENERGY 2020, make up an estimated 76% of final energy demand in the sector. These three pathways are the focus of this study. 46 energy efficiency measures were considered in the analysis; these include the use of more efficient versions of existing technologies, such as motors, and the implementation of emerging technology options, such as advanced chip pretreatment and novel paper drying systems.

ENERGY 2020 defines four families of curves for each energy pathway; these curves represent efficiency selection and capital cost trade-offs for devices and processes. Correlations for each curve in each study year were generated in this study to be used as inputs to ENERGY 2020 by Environment and Climate Change Canada. The developed correlations indicate that there is significant potential for producers to adopt equipment and systems that are more efficient than the sector average at relatively low cost for all energy pathways. The greatest difference between the marginal potential and the current average was observed for electric machine drive processes. The results for each pathway also suggest that efficiency gains beyond the available "low hanging fruit" options will be subject to moderately diminishing returns for energy prices at the upper end of the study range.

5.2. Introduction and scope

5.2.1. Scope and objectives

Industrial sectors such as pulp and paper are significant producers of greenhouse gas emissions due to their large energy consumption. As such, improving industrial energy efficiency merits in-depth consideration as a pathway for emissions mitigation. At the same time, understanding the drivers and potential benefits of enhanced efficiency presents a challenge for policymakers and modellers due to the complexity of industrial energy use and the large number of available energy efficiency measures. Environment and Climate Change Canada (ECCC) is one of several bodies that contributes to industrial energy and emissions policymaking in Canada under the Pan-Canadian Framework (PCF) on Climate Change [17]. ECCC also conducts internal modelling and analysis for a number of purposes relating to climate and energy policy. To support these efforts, ECCC uses the Energy, Emissions, and Economy Model for Canada (E3MC) to estimate the effects of various policies on energy demand and emissions. A key component of E3MC is ENERGY 2020, a self-contained model of economy-wide energy consumption [119]. As a data-intensive, bottom-up model, ENERGY 2020 requires extensive inputs customized for a given jurisdiction and sector. Therefore, ECCC is currently developing and improving the Canada-specific inputs to ENERGY 2020 in several areas.

In support of these ECCC efforts, the Sustainable Energy Research Laboratory at the University of Alberta was engaged to generate technoeconomic input correlations to further improve the E3MC model. The specific purpose of this study is to generate an input dataset for ENERGY 2020: efficiency capital cost trade-off curves for devices and processes in the Canadian pulp & paper sector. The relevant sub-objectives are to:

1. Establish a complete set of formalized definitions for ENERGY 2020's energy pathways, variables, and desired inputs;
2. Develop a customized, flexible method for generating these inputs that will enable users to obtain similar results for other Canadian industrial sectors in future work;
3. Conduct a literature review to establish a complete understanding of the sector of interest;
4. Develop a comprehensive database of available efficiency measures;
5. Implement the chosen curve generation method;
6. Produce the desired families of input curves for each energy pathway of interest in the Canadian pulp & paper sector.

5.2.2. Literature review

At the outset of the study, a comprehensive literature review was conducted to inform the work to be undertaken. The objectives of the literature review were to:

1. Develop a detailed understanding of the Canadian pulp & paper sector and establish data sources for sector statistics and indicators;
2. Review the available literature on energy efficiency potential and energy efficiency measures in the worldwide pulp & paper sector;
3. Analyse the documentation for the ENERGY 2020 model to establish definitions for the desired results;
4. Review the literature on efficiency trade-offs and energy demand elasticity modelling to perform a gap analysis and develop a method for use in this study.

The results of the literature review are summarized in the following sections.

5.2.3. Sectoral data

Natural Resources Canada (NRCan) and Statistics Canada (StatsCan) publish extensive datasets of sector production and econometric indicators [85, 89, 92, 98, 120], as well as energy use and emissions [95, 121, 122]. At the time of this study, the most recent data available was for 2017 for most datasets. Data quality and availability in general was quite high; however, some years were subject to redactions for confidentiality reasons. Minor discrepancies were found in the energy use statistics provided by NRCan and StatsCan; however, the difference was not statistically significant. Production data from StatsCan was obtained in the form of trade balances for pulp& paper products. This top-level data was augmented by production numbers for specific pulp &

paper varieties reported by FP Innovations Canada [123]. The data was particularly valuable because it provided estimates of market pulp vs. total pulp production. Knowing the market pulp ratio ensures that self-consumed pulp is not double counted, resulting in a better quality energy intensity analysis. Unfortunately, this data is only available up to 2010.

In conjunction with the Pulp and Paper Research Institute of Canada, Paprican, NRCan has published reports with energy benchmark data obtained from surveys of actual mills in Canada [52]. This dataset, although somewhat outdated and limited to only two mill types, was highly valuable in that it allowed us to adjust worldwide energy intensities to the Canadian sector.

One gap in the data is the extent of disaggregation of energy and production data by mill type. StatsCan data is available at the six-digit NAICS level, which for pulp & paper allows us to analyze data at the level of the individual mill types discussed in Section 2.2. However, the data does not differentiate between standalone and integrated paper mills. This is an important gap given the higher efficiency expected for integrated mills. Unfortunately, the available production data is not disaggregated by pulp type or paper grade and thus does not align with the level of disaggregation of the energy data. A second difficulty in managing the sectoral data is in the system boundaries for energy reporting. Where NAICS codes are not explicitly used, it is possible that some datasets include other paper-related products such as wood products, paperboard, and cardboard. Some datasets do not make it clear whether the reported electricity use is net of grid imports/exports or if it is simply total consumption. For a sector such as pulp & paper with very high levels of cogeneration, this distinction can have a significant impact on the results. With guidance from NRCan, we assumed that all reported electricity values include self-produced electricity [124].

Important sources of data on the highly specific energy flows considered in this study were a series of reports commissioned by the U.S. Department of Energy [54, 125]. That work, based on comprehensive surveys of actual manufacturing facilities in the United States, provides an understanding of the sub-plant-level energy flows and fuel allocation to end uses in the sector. This level of detail is of key importance to the analysis done in this study. Data from these sources was mapped to the Canadian sector using several techniques including comparison of energy consumption data, analysis of equipment types, and consideration of industry structure. The result is an approximation of the desired energy flows and balances for the Canadian sector. A key conclusion from this portion of the literature review is that a similarly detailed survey and analysis completed for Canadian industrial facilities would be extremely valuable in future modelling and efficiency efforts.

5.2.4. Efficiency potential and efficiency measures

The potential for energy efficiency in various sectors and jurisdictions has been well studied in academia and by government and non-governmental organizations. Many sources were consulted to develop an understanding of the general potential for efficiency improvements as well as the most significant technology opportunities available [16, 19, 33, 41, 53, 66, 68, 72, 110, 126]. Wherever possible, studies with a specific focus on Canada were considered; however, we found that the bulk of government literature in this area was produced in the United States and Europe. Given the high level consistencies in the equipment and processes used across the sector, these reports were of considerable value, especially those that provide insight into the best-available technologies to assess the outer bounds of efficiency potential for the sector [19, 66].

A second important outcome of the efficiency literature review is the compilation of a database of available energy efficiency measures (EEMs). Many studies have attempted to compile semi-exhaustive lists of available EEMs for the sector [33, 41, 44, 68, 127]. The objective of this study is not to replicate such works but rather to adapt their data, where possible, to the specific needs of this analysis. Data from large-scale reports on efficiency potentials was combined with literature specific to single measures, especially for emerging options, to develop a full understanding of the array of EEMs available. A key source of data for this step was the various publications and releases from Canadian pulp & paper manufacturers with data for actual efficiency measures implemented in the sector [128-136]. In addition to Canada-specific details, these sources provide inherent validation for the applicability of the technologies to the Canadian sector.

5.2.5. ENERGY2020

Given the primary objective of developing specific inputs to the ENERGY 2020 model for Canada, establishing a comprehensive understanding of ENERGY 2020 was an essential component of the literature review. ENERGY 2020 was developed by Systematic Solutions, Inc. and has a robust documentation package available online. Our initial efforts were focused on understanding the basic functionality and requirements of ENERGY 2020 based on a review of the top level documentation provided [39, 137]. However, given the need to develop inputs that were closely aligned with ENERGY 2020's definitions and code implementation, it became necessary to undertake a more detailed review of the model's theoretical derivation, code outline, and assumptions [138-140]. Following the review, we established accurate and detailed definitions for key parameters and desired outputs. Given the importance of these definitions to the method used in this study and the interpretation of the results, further details on ENEGRY 2020 are provided in Section 5.3.2.

5.2.6. Energy and efficiency modelling

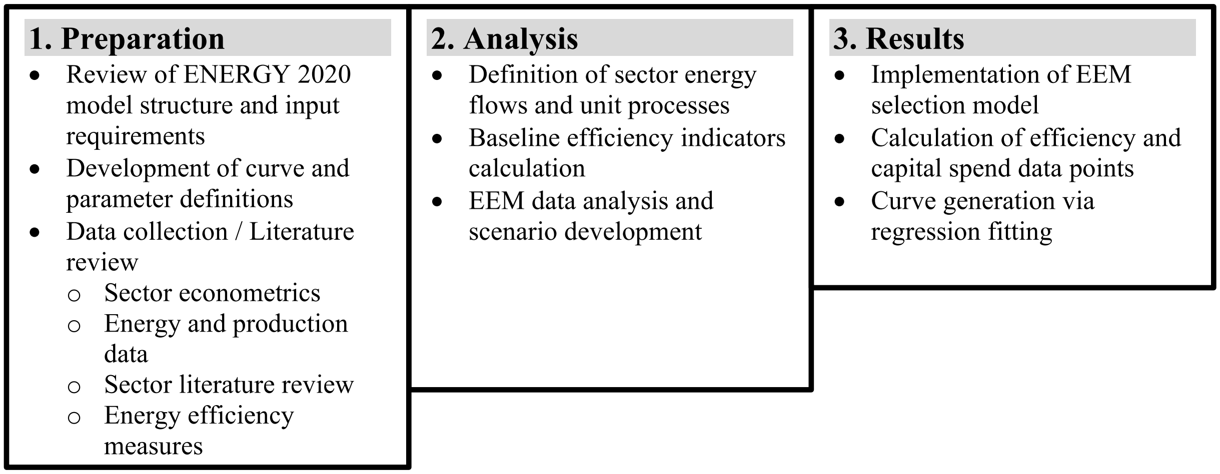
A wide variety of models for performing such analysis have been described in the literature [36], many of which are open source or publicly available. Three such models analyzed as part of the literature review are LEAP [113], ISTUM [141], and ENERGY 2020 [142]. These models also focus on delivering absolute energy values as their primary outputs; however, they are flexible and can be used in conjunction with other data to provide averaged efficiency indicators such as specific energy consumption (SEC, GJ/$) and energy intensity (EI, GJ/t), which measure energy consumption intensity per unit of economic output in dollars and natural units, respectively.

We identified many strong examples of studies that focus on market penetration analysis for efficiency technologies [69, 70, 126, 141, 143-145]. These studies generally rely less on engineering analysis and more on consideration of economic factors. A key focus of such work is on developing estimates for costs of saved energy and/or analysing the rate of technology adoption under various scenarios. In effect, the results of such studies mirror the outputs of ENERGY 2020 and as such are a level removed from the desired inputs. No studies were found to analyse marginal efficiency changes; instead, market adoption studies typically hold marginal efficiency constant and assume all average efficiency changes are driven by adoption rates. Similarly, no industrial studies were found that divide energy intensity into device and process efficiencies, although standalone device efficiencies have been included in residential sector studies such as Talaei et al.'s [144]. While the latter type of study is similar to the design of ENERGY 2020 in the treatment of specific energy pathways, none of the studies aligned with the particular structure and definitions of ENERGY 2020 and none of them provided results that were directly compatible with the ENERGY 2020 input requirements. Critically, many of these studies lack reliable cost data because they state efficiency potentials in isolation without reference to capital or operating costs. While this approach is acceptable for assessing overall theoretical potential, the lack of connection to direct costs limits the value of such studies as inputs to the cost data-intensive ENERGY 2020 model. Despite these gaps between the needs of ENERGY 2020 and the available literature, the methods used in such studies were instrumental in developing the method used in this analysis.

5.3. Methods

5.3.1. Overview

This study was conducted in alignment with the needs of ECCC and with the structure, features, and intent of the ENERGY 2020 model. The key phases of the study are shown in Figure 36.



1. Preparation

- Review of ENERGY 2020 model structure and input requirements
- Development of curve and parameter definitions
- Data collection / Literature review
  - Sector econometrics
  - Energy and production data
  - Sector literature review
  - Energy efficiency measures

2. Analysis

- Definition of sector energy flows and unit processes
- Baseline efficiency indicators calculation
- EEM data analysis and scenario development

3. Results

- Implementation of EEM selection model
- Calculation of efficiency and capital spend data points
- Curve generation via regression fitting

Figure 36: Study phases

In the initial stage, we reviewed ENERGY 2020 and its associated documentation to understand the model’s function and input requirements. Working with ECCC, we established definitions and requirements for the variables of interest. We also gathered data and conducted a detailed literature review that included studies on efficiency potential, energy saving measures, energy use elasticity, market adoption modelling, and sector-specific data. In the second stage, we analyzed the sector’s energy use profile and developed a comprehensive model of the sector's energy flows and end uses. With this model, we determined baseline estimates for sector energy efficiency metrics. In parallel with this effort, EEM data was used to develop consistent scenarios for energy savings potential and associated costs. In the final phase, we implemented a spreadsheet-based EEM selection and efficiency forecast model consistent with the constraints and assumptions of ENERGY 2020. The baseline efficiency measures and EEM scenarios were then input to this model, yielding sets of data points representing economically viable energy efficiency levels and associated capital spending levels. Finally, we applied curve fitting techniques to the output dataset to develop the desired correlation results.

The study structure and curve generation method developed in this study were made into a template and can be applied to any industrial sector. Future work for other sectors will therefore require only the data collection, EEM analysis, and curve generation steps in the framework.

2010 was selected as the base year for this study. Using that year keeps the analysis consistent with the broader historical trends in energy use and avoids the effects of structural changes to the sector, which are outside the scope of this study.

5.3.2. ENERGY 2020 overview

ENERGY 2020 is a comprehensive energy demand modelling tool developed by Systematic Solutions, Inc. It uses a data-intensive, bottom-up approach to model energy demand across residential, commercial, transportation, and industrial sectors. The overall approach to energy demand modelling is relatively similar across the sectors. In the industrial sector, demand is further divided into specific industries that are themselves subdivided into energy pathways consisting of end uses (e.g., process heat, machine drive, direct heating) paired with specific fuels (e.g., natural gas, electricity) [142]. Each end-use pathway has associated device and process efficiency values. The sections below summarize the approach used in ENERGY 2020, based on the publicly available documentation for the model [137-139].

ENERGY 2020 Demand Calculation Procedure

Energy prices and econometric factors (such as sector activity level) are the primary drivers of energy demand in ENERGY 2020 [39]. In the demand module for each sector, energy demand for each fuel type is determined by a stack of various factors, as shown in Figure 37 [138].

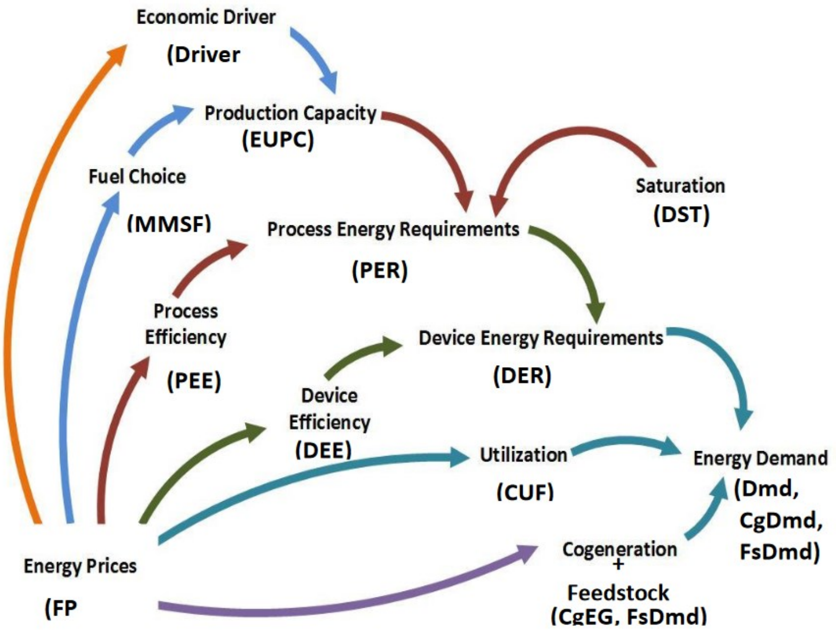


Figure 37: ENERGY 2020 energy demand calculation tree
(Figure produced by Systematic Solutions, Inc.) [138]

The energy demand calculation starts with an estimate of the economic driver for the calculation, which for industrial sectors is defined as the sector production. The economic driver corresponds to a certain amount of production capacity required to produce that output. It is at this stage that ENERGY 2020 considers fuel switching, since each unit of production capacity is associated with a particular fuel mix. The required production capacity determines how much energy input is needed. Unlike typical engineering energy models, ENERGY 2020 does not use a simple energy intensity of production (EI) metric at this step. Rather, EI is divided into two complementary factors: process efficiency (PE) and device efficiency (DE). In ENERGY 2020, each unit of production capacity requires a certain amount of process energy, determined by the PE. This process energy is provided by energy-converting devices (such as motors and boilers) that consume units of fuel energy per unit of process energy at a ratio defined by the DE. The last step in the calculation stack is to modify the device fuel consumption value by considering device utilization rates and any onsite cogeneration of energy.

Energy price influences each of the factors in the calculation stack, leading to a cumulative effect on overall energy demand. A key aspect of ENERGY 2020 is the use of exogenous input functions that define the relationship between energy price and each of the factors. It is important to note that each factor represents the average value for the sector in the time period of interest. ENERGY 2020 employs a stock turnover model that retires old capacity and brings on line new production capacity in each time step. Therefore, the inputs of interest are a) the stock values at the beginning of the analysis period and b) the values expected for incremental new capacity at a given energy price. For PE and DE, these incremental values are defined as marginal process efficiency (MPE) and marginal device efficiency (MDE), respectively. ENERGY 2020 accepts these inputs in the form of correlation curves that express the desired factor as a function of energy price. The focus of this study is on developing the input curves for MPE and MDE for the pulp & paper sector.

MDE and MPE Curve Theoretical Derivation

In ENERGY 2020, the definitions for MDE and MPE energy price response curves are driven by the concept of energy demand elasticity as a function of energy prices. Industrial facilities will, in the long run, seek to minimize their overall costs of production in order to maximize profits. When installing new equipment or retrofitting existing equipment, facility owners have various options. A core premise of ENERGY 2020, and this study, is that in general a device or process with higher efficiency will incur a higher capital cost than an option with lower efficiency. Therefore, industrial facility owners must trade off higher initial capital expenditure for lower expenditure on energy over time. In the long run, and on an aggregate basis, this behavior will lead to downward sloping energy demand curves (upward sloping efficiency curves) in response to higher fuel prices. It is expected that this relationship will demonstrate diminishing marginal returns, i.e., the rate of efficiency improvement is less than the rate of increase for capital costs for efficiency measures.

In ENERGY 2020, the long-term change in the average energy efficiency of all production capacity is driven by stock turnover; less efficient devices and processes are retired and new, more efficient devices and processes are added to meet the desired production capacity. This structure necessitates mapping the overall efficiency changes to the efficiency level of only new capacity at the margin. In other words, the impact of energy prices on the efficiency level selected for new equipment is the foundational driver of efficiency improvement. It is this relationship that is captured in the MDE and MPE curves. However, this presents a challenge in that most available data and previous studies have focused on the aggregate, average effects on energy efficiency rather than the effects at the margin. The correlations that map energy price to MDE and MPE are the first class of inputs required in this section of ENERGY 2020.

A second required input is the capital spending on efficiency at each energy price. Again, two separate inputs are required due to the division between devices and processes. These curves reflect the capital cost side of the efficiency trade-off problem. For a chosen efficiency level, a certain level of capital spending above the baseline is required. As efficiency levels increase, more marginal capital spending is required, resulting in curves that increase asymptotically towards some theoretical maximum efficiency. These capital cost trade-off correlations, mapping MDE/MPE to capital costs, are the second class of inputs developed in this study. Definitions for both types of curve are provided in Section 5.3.3.

With a known energy price and efficiency/capital curve inputs, ENERGY 2020 can calculate the optimal marginal efficiency level and the corresponding level of capital spending required. First, the energy price is input to the efficiency selection curves, yielding values for MDE and MPE. Then, the calculated efficiencies are input to the capital trade-off curves, yielding capital spending levels per unit of energy. Using these four values and other inputs outside the scope of this study, ENERGY 2020 calculates an estimate of the capacity retirement, retrofit, and new build rates for each fuel type and end use. These values are then used to calculate average device and process efficiencies, which in turn feed into the overall energy demand estimate for the sector.

For more detail on ENERGY 2020, including a detailed overview of the theoretical basis and model implementation, it is recommended that the reader review the ENERGY 2020 documentation, accessible at https://www.energy2020.com/publications at the time of writing.

5.3.3. Curve definitions and application

Following a thorough review of the ENERGY 2020 documentation, we developed compact definitions for each parameter of interest. The critical parameter definitions are summarized in Table 8. In most cases, parameter symbols were chosen to match those used in ENERGY 2020.

Table 8: ENERGY 2020 Parameter Definitions

Parameter ***Symbol***	**Description**	**Units**
Process Energy E_p	Energy that has been converted from a primary fuel or secondary source to a form of useful energy input to a specific end use (e.g., rotational energy, steam energy).	GJ
Device Energy *E*	Energy input to an energy conversion device. Typically in the form of a primary fuel (e.g., natural gas) or a secondary source (e.g., electricity). Equivalent to the standard definition for final energy.	GJ
Process Efficiency *PE*	Parameter describing how effectively the sector's process energy is converted to units of output in \$. Efficiency measure for end-use processes.	\$ gross output / GJ process energy
Device Efficiency *DE*	Parameter describing how effectively fuel input energy is converted to process energy. Efficiency measure for energy conversion devices.	GJ fuel energy/ GJ process energy (%)
Marginal Process Efficiency *MPE*	Average efficiency of end-use processes in incremental (retrofit/new build) production capacity.	\$ gross output / GJ process energy
Marginal Device Efficiency *MDE*	Average efficiency of incremental (retrofit/new build) energy conversion devices.	GJ fuel energy/ GJ process energy (%)
Fuel Price *ECFP*	Price of fuel input. The cost per unit of primary or secondary energy supplied to the plant.	\$ / GJ
Process Energy Price *MCFU*	Marginal cost of fuel use. Parameter capturing fuel energy costs plus the cost to convert fuel to process energy via energy conversion devices.	\$ / GJ
Process Capital Cost *PCC*	Parameter describing the capital cost of incremental process capacity per unit of output generated by the process.	\$ capital cost / \$ gross output
Device Capital Cost *DCC*	Parameter describing the capital cost of incremental device capacity per unit of process energy supplied by the device.	\$ capital cost / GJ process energy

Maintaining consistency with the ENERGY 2020 documentation, we defined the four curve types to be generated for each fuel-end use pair. Precise definitions for each curve were essential both to ensure the results were compatible with ENERGY 2020's and to maintain alignment with engineering best practices. The curve definitions used throughout the study are presented in Table 9.

Table 9: Efficiency curve descriptions

Curve	Name & Description	X Axis	Y Axis
DEE-1	**Device Efficiency Price Response Curve** The economic marginal device efficiency level of new production capacity at a given fuel price.	**Fuel Price (ECFP)** ($ / J fuel)	**Marginal Device Efficiency (MDE)** (J process/J fuel)
DEE-2	**Device Capital Cost Trade-Off Curve** The capital spending intensity needed to achieve a given MDE level.	**Device Capital Cost (DCC)** ($ capital spend / J process energy)	**Marginal Device Efficiency (MDE)** (J process/J fuel)
PEE-1	**Process Efficiency Price Response Curve** The economic marginal process efficiency level of new production capacity at a given energy price.	**Process Energy Price (MCFU)** ($ / J process energy)	**Marginal Process Efficiency (MPE)** ($ gross output / J process energy)
PEE-2	**Process Capital Cost Trade-Off Curve** The capital spending intensity needed to achieve a given MPE level.	**Process Capital Cost (PCC)** ($ capital spend / $ gross output)	**Marginal Process Efficiency (MPE)** ($ gross output / J process energy)

To summarize, the DEE-1 and PEE-1 curves map marginal device and process efficiency levels, respectively, to energy price. These two curves represent the economically optimal efficiency choice at a given energy price. The DEE-2 and PEE-2 curves represent the trade-off between efficiency level and capital investment. Together, the curves approximate the economically optimal trade-off decision between capital costs and energy costs as driven by energy prices.

5.3.4. Curve calculation method

Using on the curve definitions, ENERGY 2020 requirements, and the results of the literature review, we developed a method for generating the desired curves. The specialized nature of the curves and the unique definitions for variables defined in ENERGY 2020 required us to develop a new approach specifically tailored to this application.

As described in Section 5.3.2, the MDE and MPE curves represent the efficiency level and capital cost of incremental devices and processes, respectively. There were three major challenges in deriving these curves using typical engineering methods. First, most of the available data is for energy demand and productive output. This data can be used to estimate production energy intensity but cannot be directly used to estimate DE and PE since they both influence overall EI. Effectively, there is one equation with two unknowns. The second challenge is that the desired curves represent not the overall (average) efficiency for the sector but rather the efficiency of marginal capacity alone. This means that traditional market adoption, scenario analysis, and similar methods cannot be directly used since they only estimate average efficiency for the sector. The third challenge is the limited availability of data required to assess potentials for changes in efficiency levels. The data-intensive nature of the curves means that energy, cost, and applicability data is needed for each unit of incremental production capacity. This type of information (at the quality required) is typically only directly available to industry members in the process of procuring new facilities. Moreover, even where data is available it is often not disaggregated in the manner required by ENERGY 2020; for example, the overall energy use, production, and capital cost for a new mill may be published in an investor report, but this gives little to no insight on the individual performance and costs for a particular process in the mill.

The method developed here overcomes these challenges by attempting to directly quantify the efficiency potential for the sector and then mapping this to the corresponding marginal efficiency levels. A key assumption is that efficiency selection decisions at the margin will, on average, reflect the overall sector optimal behavior if all production capacity were affected. This approach is possible because the desired efficiencies and spending intensities are on a per unit of production (or energy) basis, rather than absolute metrics. In this way, the use of sector-wide values and bandwidths can simply be thought of as a scaling factor to capture the relative potential of various measures. The assumed correlation between industry-average optimal behavior and marginal decision making is supported by the large number of firms, facilities, and pieces of equipment in the sector, meaning that variances between individual decisions will be supressed in the overall average result. The data availability challenge is addressed by applying the concept of energy savings bandwidths. Many studies have attempted to quantify the overall potential of various energy efficiency measures at a sector-wide level. The data in this case is often associated with modifications to existing production capacity rather than entirely new capacity. However, the sector-optimal assumption above is independent of the vintage of capacity (retrofit or new build), and this type of data input is therefore acceptable for an on-the-margin analysis. This approach provides the added benefit that all efficiency potentials are derived from actual projects and technologies implemented within industry, providing an inherent validation mechanism.

The curve generation method is primarily based on the concept of economically optimal trade-offs between spending on capital costs and spending on energy costs. At low fuel prices, there is little incentive for facility owners to upgrade their equipment or seek out more efficient equipment when expanding capacity, so they tend to install equipment similar to their current stock. As fuel prices increase, more expensive but more efficient options (for both devices and processes) become economically viable. In this study, the trade-off between capital cost and energy costs is directly modelled using the simple payback period of each EEM as the viability metric. This approach is consistent with other studies of industrial efficiency potential and proves to be an effective measure given that it is frequently the first metric applied by facility owners when assessing an investment and does not require any assumptions about interest rates, internal hurdle rates, or imperfect behavior. As energy prices increase, more EEMs meet the target payback period and are therefore considered viable. By calculating the cumulative energy savings and capital spending on viable EEMs at or below each energy price and comparing these to the baseline values, we can establish the desired relationships between energy price, efficiency level, and capital cost.

Figure 38 illustrates the structure of the spreadsheet-based curve generation method developed in this study.

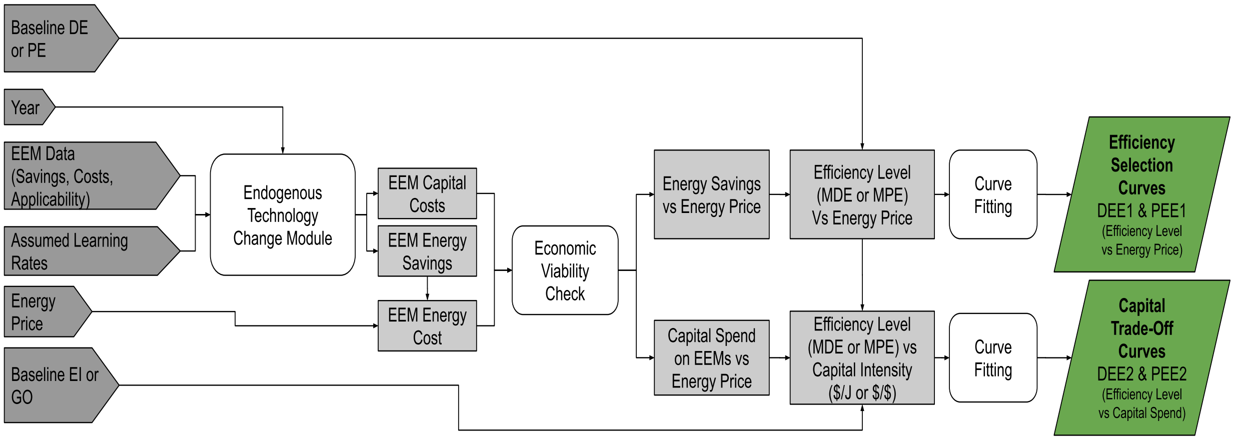


Figure 38: Efficiency curve generation method

As shown in the figure, the curve generation procedure for a given fuel type, end use, energy category, and year is essentially the same, and can be divided into six distinct steps:

1. EEM data for the energy pathway of interest was populated (costs, energy savings, applicable fraction of base energy);
2. Base EEM costs and savings were modified to reflect improvements over time (referred to as endogenous technology change in ENERGY 2020). The chosen approach uses assumed exponential learning rates that drive improvements for performance and costs with a base year of 2010.
    - The baseline learning rates used in ENERGY 2020 are values from the U.S. Energy Information Administration Annual Energy Outlook [146]. These values provide the initial estimate for learning rates in this study.
        - Baseline learning rates for the pulp & paper sector are 0.026% for steam systems and 0.013% for all other technologies [146].
    - Where possible, the base learning rate was adjusted based on assumptions derived from the literature, technology trends, and engineering practices.

3. Costs and savings for each EEM in the year of interest were used to determine the viable energy savings level and capital spend over the energy price domain.

    - As discussed previously, the trade-off between capital costs and energy costs was modelled with the single measure simple payback period as the chosen indicator for viability.

    - A target of three years for the simple payback period was used across the analysis. While the curves are sensitive to the duration of payback used as the criterion, the choice of three years is a reasonable approximation of the upper limit on what might be considered a viable energy efficiency investment and strikes a balance between risk-averse operators who may have aggressive targets (<1 year payback) and those that are willing to pursue longer-term strategic opportunities (with payback >5 years.) As such, it is intended to represent a first "rule of thumb" for plant owners or operators in deciding whether it will be economically reasonable to pursue an efficiency opportunity. The three year duration is also reflective of the upper range of payback periods reported for efficiency projects that have actually been implemented in the real world [5,21,23,28], suggesting this payback period threshold emulates a key go/no go criterion for real efficiency investment decisions.

    - The energy savings and capital costs for all measures that were viable at or below a given energy price were summed to determine the cumulative energy savings potential and corresponding capital spend on viable EEMs at that price. Here, the energy price was set equal to the value of saved energy necessary to make the capital investment viable.

4. The energy savings and capital spend potentials were combined with baseline energy and gross output data to calculate the desired efficiency levels and capital cost intensities

    - For device efficiency curves, MDE and capital cost intensity can be directly calculated.

    - For process efficiency curves, fuel price and fuel energy savings were calculated in final energy units and then converted to the desired ENERGY 2020 variables (MCFU and process energy savings, respectively) using fixed factors. This is based on the assumption that firms make efficiency decisions based on bottom line fuel cost savings, which are more directly visible to firm decision makers.

5. The outputs of step 4 are sets of discrete points representing cumulative marginal efficiency levels and cumulative capital cost intensities. To produce a continuous, smooth output, curve fitting techniques were used. The curve generation method is described in more detail below.
    - This method relies on ENERGY 2020's assumption that all efficiency potentials will fall along the same curve. With this assumption, efficiencies and costs across the entire energy price range of interest can be estimated from discrete measures within that range.
    - The final outputs are the curve correlation coefficients that can be used to estimate the desired parameters at any point in the domain.
6. The method was then repeated for each year of interest and fuel & end use combination.

The process shown in Figure 38 was applied separately to each energy category (device or process) associated with each energy flow (fuel and end use) and was applied iteratively for each year in the study period to generate full families of curves. For the Canadian pulp & paper sector, where three energy flows are of interest, the process was applied six times for each year.

5.3.5. Curve generation and correlation fitting

Twelve distinct families of curves were developed, corresponding to four curve sets (DEE-1, DEE-2, PEE-1, and PEE-2) for each of the three energy pathways of interest. The desired smooth curve correlations were extracted from the discretized data points generated in step 4 above with the use of regression fitting. This was done using Microsoft Excel's LINEST function, which provides a streamlined tool for generating least square error correlations for discrete datasets. By default, LINEST provides purely linear correlations but users can derive a number of other fit types by varying the input parameters. For example, when LINEST is applied to an input dataset of {ln(x),y}, a correlation of the form $y = b + a \times \ln{(x)}$ can be produced. Best practices for curve fitting, in conjunction with engineering judgment, were applied in selecting the correlation type to be used for each curve. Based on the qualitative trends observed, logarithmic fits with the form $y = b + a \times \ln{(x)}$ were used for the majority of the curves. Inverse square root fits with the form $y = b + ax^{-1/2}$ were used in situations where logarithmic curves did not provide adequate fits or produced nonphysical results (such as a device efficiency exceeding 100%). The validity of the assumed correlation type and the quality of the derived fit were assessed by analyzing the coefficient of determination (r^2) value for each curve. This parameter defines the deviation between a particular dataset and a curve passing through it. In general, an r^2 value of 1 corresponds to zero deviation from the underlying data, whereas a value closer to 0 indicates that the correlation does not fit the data well. The r^2 values for each curve (in the representative midpoint year of 2025) are reported in the results section and in general indicate that the correlations closely match the underlying results.

Correlation coefficients were generated for individual years on five-year intervals from 2000-2045, with each set assumed to be valid for the following five years. Years prior to the current year were included to allow for ENERGY 2020 to calibrate against historical data. The domains for curve plotting were based on energy price ranges supplied by ECCC from 2000 to 2050 (roughly -50% and +75% of the minimum and maximum values, respectively). A recommended domain is provided for each curve because correlations are not expected to hold for extreme fuel price scenarios.

5.3.6. Model inputs and base case development

The method developed for this study relies on a robust understanding of the energy flows, unit processes, and end uses in the sector. A key exercise that we completed at the outset was the development of an energy flow model for the sector that aligns with ENERGY 2020's inherent linearized energy flow assumption; that is, the assumption that fuel energy enters the plant, is converted by devices, and is then applied to production in processes in a unidirectional manner.

This assumption requires a modified energy flow model, derived from the broader sector energy model used elsewhere in this thesis.

The energy flow model, including the energy pathways and end uses considered in this study, are shown in Figure 39.

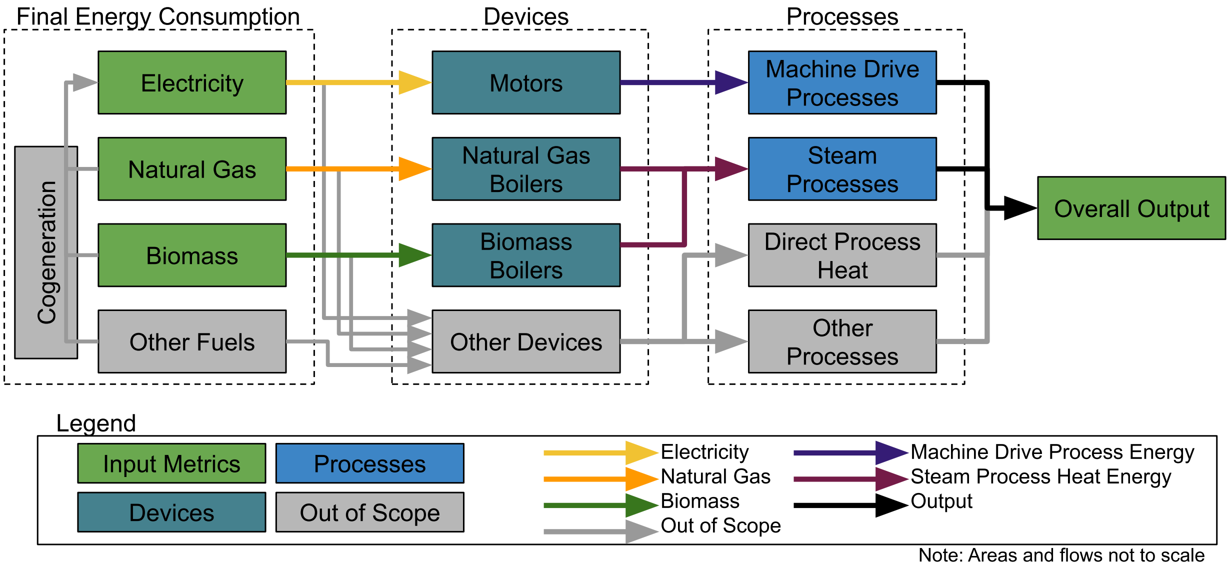


Figure 39: Simplified sector energy pathways

Of particular note are the three energy pathways (consisting of three fuel types, three device types, and two end-use processes) that were selected as the focus of the analysis:

Pathway 1:
- ○ **Fuel:** Electricity
- ○ **End use:** Machine drive
- ○ Device examples: Electric motors
- ○ Process examples: Motor-driven pumps, fans, and other rotating equipment

Pathway 2:
- ○ **Fuel:** Natural gas
- ○ **End use:** Steam process heat
- ○ Device examples: Natural gas boiler
- ○ Process examples: Steam systems including dryers and chip cookers

Pathway 3:
- ○ **Fuel:** Biomass (wood + pulping liquor)
- ○ **End use:** Steam process heat
- ○ Device examples: Biomass boilers and black liquor recovery boilers

- Process examples: Steam systems including dryers and chip cookers

To develop the energy flow model, econometric, energy, and process data for the sector was compiled from various sources. This data is readily available at the sectoral level (and in some cases, further levels of disaggregation.) 2010 was selected as the base year for this study. The model inputs for sectoral baselines are summarized in Table 10.

Table 10: Model Inputs: Sectoral Baseline Values (Base Year: 2010)

Input Name	Value	Units	Source(s) and Notes
Production (Market Pulp+Paper)	18,532,824	ADMT	[85]
Gross Output	$21,156,759,215	CAD 1997	[120]
Total Final Energy Consumption	552.7	PJ	[121]
Electricity Consumption	144.1	PJ	[121]
Natural Gas Consumption	72.5	PJ	[121]
Biomass Consumption	322.2	PJ	[121]
Other Fuel Consumption	13.9	PJ	[121] – Includes liquid fuels
Energy Intensity	29.8	GJ/ADMT	Calculated from above
Electricity Intensity	7.8	GJ/ADMT	Calculated from above
Natural Gas Intensity	3.9	GJ/ADMT	Calculated from above
Biomass Intensity	17.4	GJ/ADMT	Calculated from above

With the sectoral baselines established, we then completed the more nuanced work of developing process and device efficiency baselines for each energy pathway of interest. Analysis at this level of disaggregation required further insight into the energy flows in the sector. To the best of the authors' knowledge, no analysis of this kind had been previously completed for the Canadian pulp & paper sector. While the most accurate and detailed approach would be to conduct surveys and analyze a representative sample of actual facilities in the sector, the time, personnel, and data access required for such an undertaking are beyond the resources available for this study. Fortunately, a comprehensive study of this nature had been completed for several industrial sectors in the United States by the U.S. DOE Office of Advanced Manufacturing [125]. While these results were not expected to perfectly map those in the Canadian sector, it was anticipated that they would provide a reasonable first order approximation suitable for use in this study. Due to the similarities between the sectors in the two countries, including mill technologies and vintages, it is reasonable to expect that this approximation would not introduce an unacceptable level of error into the analysis. The specific data used in the analysis was extracted from an updated excerpt of an earlier study [54]. Energy flows aligning with the definitions above were estimated and mapped to the Canadian sectoral baseline energy use and production. This, coupled with the baseline econometric data for the sector, enabled us to calculate baseline PE and DE values for the sector in the base year, as summarized in Table 11.

Table 11: Model inputs: calculated device and process efficiency baselines for energy pathways of interest

Fuel Type	End Use	Device Energy (PJ)	Share of Final Energy (%)	Process Energy (PJ)	Share of Process Energy Subclass (%)	Baseline DE (%)	Baseline PE ($/GJ)
Electricity	Machine Drive	118.0	21	103.3	100*	87.6	204.7
Natural Gas	Steam Process Heat	57.6	10	47.2	22+	82.0	96.4
Biomass	Steam Process Heat	246.9	45	159.3	73+	64.5	96.4

*Excludes rotating equipment not driven by electricity

+Other fuels and imported steam contribute ~5% of steam process heat

It should be noted that two fuels – natural gas and biomass – jointly provide process energy to a single end-use category, steam process heat. This illustrates the complexity of energy flows in the sector. Some mills burn only natural gas, while others burn a combination of fuels. Moreover, steam systems in a multi-fuel mill are often not divided by fuel; all produced steam is routed to end uses, and the end-use equipment does not differentiate by the type of fuel used to generate the steam. However, as will be discussed in subsequent sections, different process EEMs apply to different types of plants with different biomass firing ratios. The net result of these considerations is that the natural gas steam and biomass steam pathways begin with a common PE baseline but do not have identical PE curves or potential.

As shown in the table, the three energy pathways selected for curve development in this study account for roughly 76% of final energy consumption in the Canadian pulp & paper sector. The balance of final energy consumption is associated with energy pathways that are out of scope for this study, shown in Figure 39. This consumption includes the use of electricity for non-machine-drive end uses, the use of biomass, natural gas, and other liquid fuels for direct process heat end uses, and liquid fuel consumption by motorized equipment (such as material handling equipment and backup generators).

5.3.7. Energy efficiency measures

A comprehensive literature review was completed to establish a database of available energy efficiency measures for the pulp & paper sector. A variety of sources were considered, including peer-reviewed publications, government reports, and industry white papers. In general, EEMs fall into one of two categories: 1) the best available efficiency for existing technologies, or 2) emerging technologies that may provide enhanced efficiency potential in the near term. Many EEMs were identified; however, we could only include a subset in the analysis because of the data-intensive nature of the curve parameters. The opportunity to add additional EEMs to the analysis could prove valuable but would require significant engineering and manufacturer input to derive the required data.

EEMs were selected according to the following criteria:

- Availability and quality of data for energy savings, capital cost, and applicability;
- Applicability to the technologies, plant vintage, and regulations specific to Canada;
- Potential for material efficiency improvements across the sector (thereby excluding niche opportunities); and
- Minimization of additionality or EEM overlap. For example, a single motor cannot simultaneously be upgraded to both NEMA “Efficient” and NEMA “Premium” efficiency levels.

Wherever possible, single-measure EEM scenarios were used. However, in certain cases the highest quality data was in the form of a package of EEMs. Engineering judgment was applied in the selection of EEM scenarios to avoid mutually exclusive EEMs. However, it should be noted that some overlapping of EEMs is permissible given that results are only at the margin and do not indicate how many producers would adopt a particular EEM or how rapidly they would do so. As discussed previously, the majority of steam process heat EEMs are mutual to both biomass and natural gas fuel types. Costs and performance values for EEMs implemented outside Canada were adjusted to reflect their potential for the local sector. This was done using the sectoral data compiled earlier along with Canada-specific manufacturer data for EEMs where possible [126, 147]. For example, data from a comprehensive study on motor efficiency improvements in the U.S. [127] was adjusted to reflect the actual motors available in Canada with data extracted from the Canadian Motor Selection Tool (CANMOST) [147].

In total, a set of 46 EEMs specifically pertaining to process- and device-efficiency were used. These measures are defined and parameterized moderately differently than those used in Chapters 3 and 4, although there is significant overlap between the two sets. The measures used for this portion of the study are summarized in Appendix M.

The method developed in this study is highly flexible and allows the user to incorporate new EEMs easily as data becomes available. The cumulative nature of the curve generation process and the reliance upon regression fitting both drive higher quality, more consistent results as the number of EEMs considered increases.

5.3.8. Use of results: limitations and constraints

This study was explicitly targeted at generating specific results to be used as inputs to ENERGY 2020. The nature of these results, in addition to the method used to generate them, is closely tied to the structure and design of ENERGY 2020. As such, it is important to note a number of limitations and constraints associated with the curves provided in this study.

- Due to their specialized nature, the curves are not intended for use in isolation but instead must be considered alongside other inputs and factors in the overall ENERGY 2020 energy derivation calculation.
- The curves do not explicitly reflect second-order effects or risk-adjusted responses to future energy prices.

- The curves do not account for non-energy drivers for selecting more efficient equipment.
- The curves are based on a non-exhaustive list of EEMs; the potential of emerging technologies may not be fully captured due to lack of available data.
- The curves do not capture cross-fuel effects because they are driven by single fuel prices. Fuel switching is explicitly considered elsewhere in the calculation stack; however, the DE and PE values can influence the model's choice of fuel.
- These curves represent individual decisions in the selection of each incremental unit of capacity in isolation and do not reflect other behavior such as how much new capacity will be added or how much old capacity will be retired. Similarly, the MDE and MPE curves alone do not provide an indication of the average efficiency level that the sector will achieve.
- The curves do not account for structural changes in the sector (e.g., a mill choosing to produce a different quality of paper). Similarly, measures that are driven by factors such as product quality, additional revenue streams, or environmental regulations were explicitly excluded from the analysis given that the MDE and MPE curves seek to only capture energy price-driven behavior.
- Given the above constraints, the method used in this study assumes that the overall product and feedstock compositions remain unchanged throughout the study period.
- The study assumes that EEMs are compared to a fixed baseline efficiency value for all study years. This assumption is highly conservative at the beginning of the study period and becomes less conservative in future years.

These and other limitations mean that the efficiencies calculated in this study are conservative and do not necessarily represent the upper limits of efficiency potential. Furthermore, it is critical to note that the primary value of the curves is as inputs to ENERGY 2020 and they are therefore best interpreted through the lens of that model.

5.4. Results and discussion

The key results of the study are the correlation formulas and coefficients that enable a desired curve to be generated for a particular year. In general, correlations with high alignment for each input curve were found, with regression coefficient of determination (r^2) values very close to 1. The correlation with the poorest fit for the data was natural gas DEE-1 with an r^2 value of 0.821 in the midpoint year (2025); all other correlations have r^2 values exceeding 0.91 and in several cases greater than 0.99.

All curves were found to exhibit diminishing marginal returns as anticipated by economic theory. Technology change was found to increase the viable efficiency levels for each pathway, with the most significant effects of technology change evident at high energy prices. Due to the relatively low learning rates assumed for most technologies, in all cases the total efficiency gain from technological change was less than the efficiency gain driven by energy prices. It is important to note that the rate of technology change is subject to calibration in ENERGY 2020 and can be exogenously increased or decreased to represent alternative scenarios independent of the efficiency curve inputs.

Several of the capital cost (DEE-/PEE-2) curves are plotted with visibly jagged ends at which each subsequent year extends significantly beyond the endpoint of the previous year. This is simply an artifact of the plotting strategy where the range of values from the DEE-/PEE-1 curve is translated to the domain of the DEE-/PEE-2 curve. We implemented this deliberately so that any point on the DEE-/PEE-1 curves can be found on the corresponding DEE-/PEE-2 curve. When the DEE-/PEE-2 curve is significantly less elastic than DEE-/PEE-1, its plotted domain must increase significantly in each year to keep pace with technological improvements. This demonstrates how higher efficiency values are possible in future years but at substantially higher costs. In reality, no such overhang exists between different years because the correlations can be plotted over any arbitrary domain.

The following sections provide the details, correlation constants, and plots for each curve set produced in this study.

5.4.1. Electric machine drive pathway curves

5.4.1.1. Electric machine drive device curves

The following two tables and associated figures present the results for the electric machine drive device efficiency and capital cost curves.

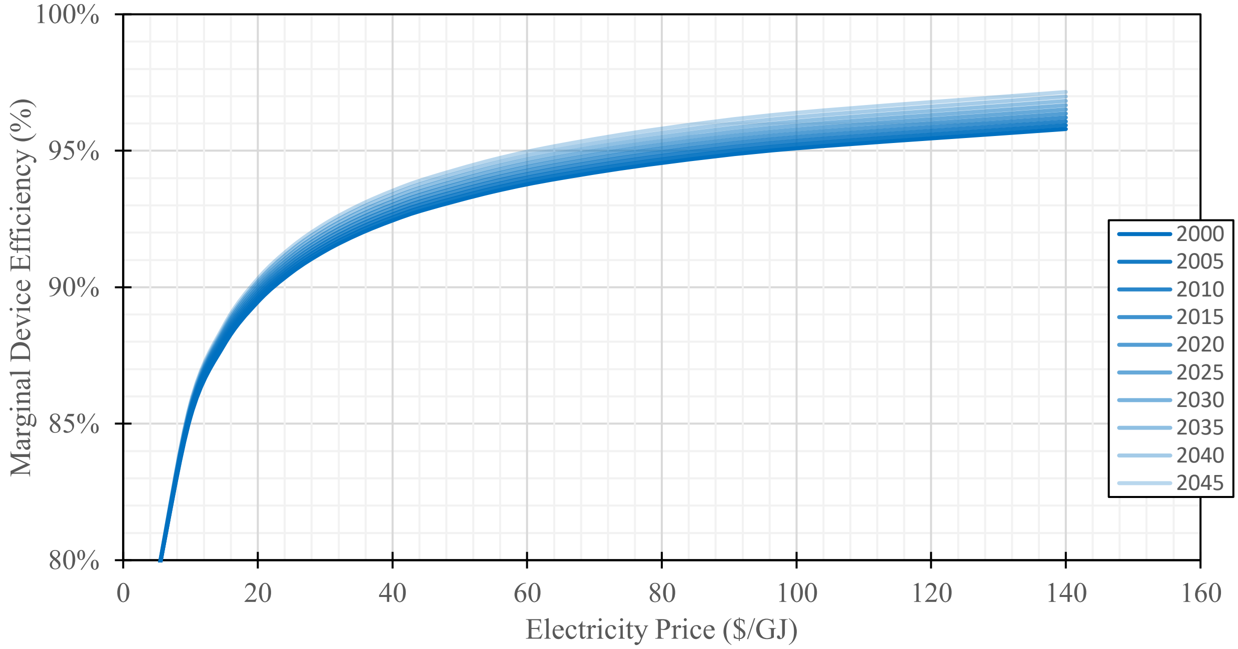


Figure 40: Electricity DEE-1 curves

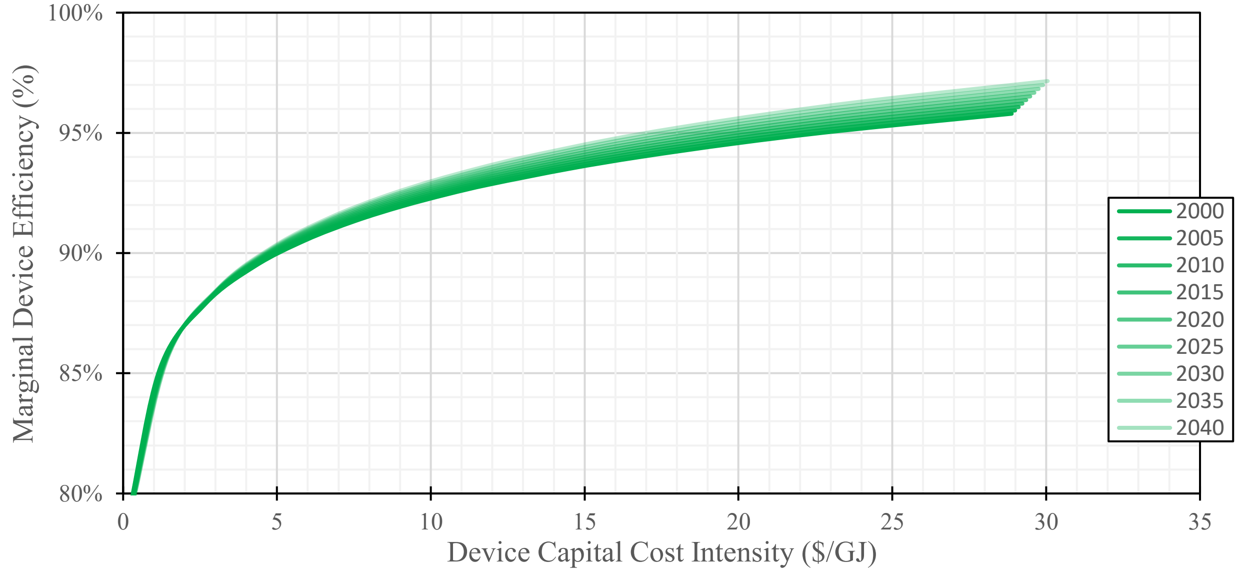


Figure 41: Electricity DEE-2 curves

The analysis suggests that individual machine drive device (motor) efficiencies greater than 97% are economically viable in very high electricity price scenarios. This represents a roughly 17 percentage point improvement over current average efficiency levels. However, such efficiency levels are only possible at device capital cost intensities several times higher than current values. The curves also demonstrate high elasticity in motor efficiency at the lower range of electricity prices, as represented by the steepness of the curves in that region. This suggests that policies that impose moderate increases on current electricity prices can drive substantially higher adoption rates for premium efficiency motors. Lastly, the differences between the curves for early years and those later in the study period indicate that technological change has minimal impact on efficiency for lower energy prices. This is likely due to the significant proportion of motor stock in the sector that is larger than 200HP. In the analysis, these motors were found to already be highly efficient and therefore have less potential improvement in the future. At higher energy prices, it becomes more economical to upgrade smaller motors that are expected to benefit more from technology change due to their lower average efficiency at present.

Unlike for the majority of other curves that use logarithmic correlations, we chose a reciprocal square root correlation for the DEE-1 curve. While the coefficients of determination for both regression fits were similar, the reciprocal curve exhibits behavior that is more consistent with the reality of motor efficiencies; namely, asymptotic improvement towards a fixed maximum, rather than diminishing but unbounded growth. A similar rationale was applied in selecting a reciprocal correlation for the machine drive PEE-1 curve.

5.4.1.2. Electric machine drive process curves

The following two tables and associated figures present the results for the electric machine drive process efficiency and capital cost curves.

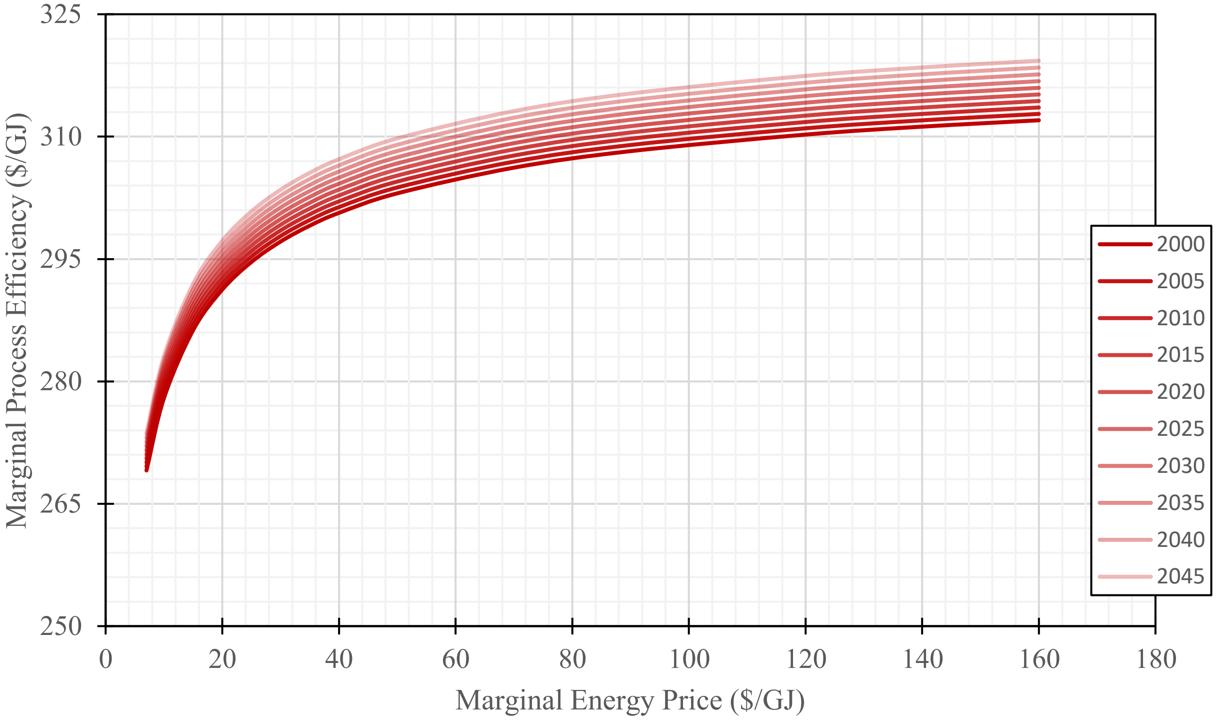


Figure 42: Electricity PEE-1 curves

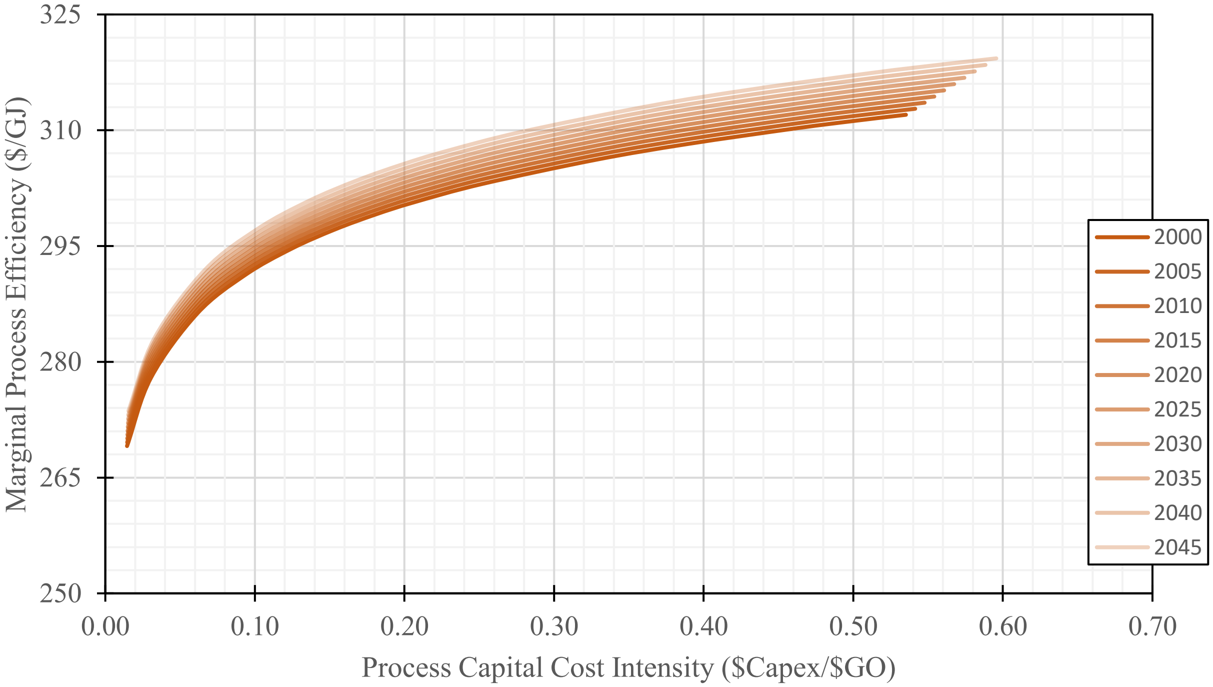


Figure 43: Electricity PEE-2 curves

The analysis shows that the electric machine drive pathway already enjoys high process efficiency in terms of units of output per unit of machine drive energy consumed. However, high energy prices could motivate producers to select technologies with even higher process efficiency – up to 55% higher than the current average of 205 $/GJ. The costs of implementing such improvements are fairly low, with less than $0.60 in capital investment required per unit of gross output. This suggests that the machine drive process area has the potential to be a significant driver of relatively inexpensive efficiency gains. Improvements to pump systems and the use of chip pretreatment in TMP mills were the two measures with the most significant potential, commensurate with the large role of pump systems and TMP refining in driving overall electricity demand. In particular, chip pretreatment is an emerging option that has significant potential to reduce the energy intensity of mechanical pulping. At the same time, qualitative comparison of the curve shapes to the electricity device curves indicates that the overall efficiency substitution elasticity is lower than for electric devices, indicating that more significant energy price changes are necessary to motivate efficiency gains. The large marginal efficiency potential and relatively low costs for this area are likely attributable in part to the very significant role of machine-driven processes such as pumps, rollers, and refiners in the pulp & paper sector.

5.4.2. Natural gas process heat pathway curves

5.4.2.1. Natural gas process heat device curves

The following two tables and associated figures present the results for the natural gas process heat device efficiency and capital cost curves.

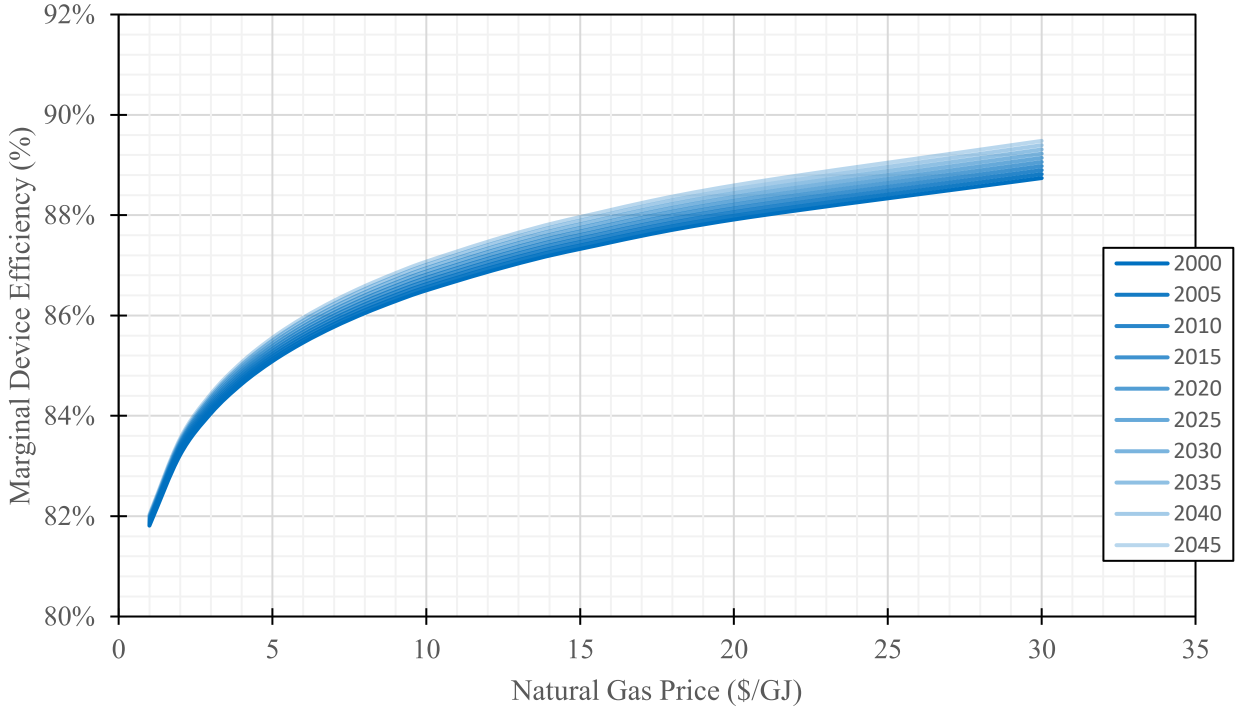


Figure 44: Natural Gas DEE-1 curves

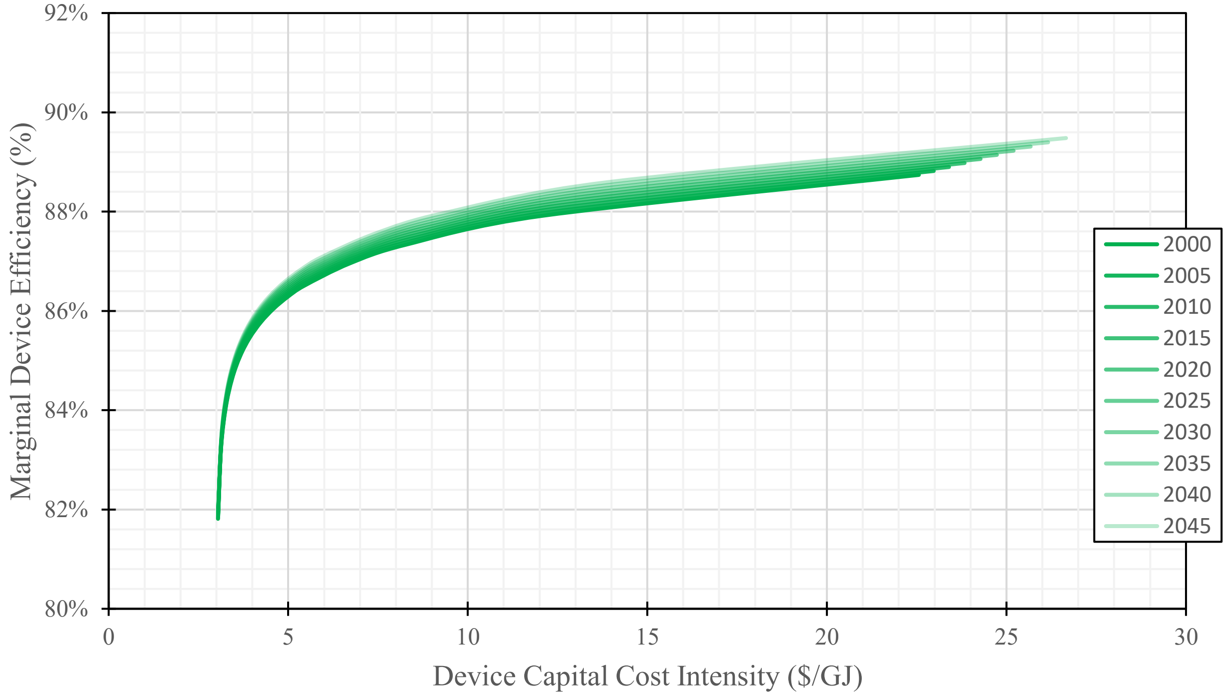


Figure 45: Natural Gas DEE-2 curves

The natural gas device curves suggest that under high energy prices, marginal natural gas devices could have efficiencies as high as 89%; the current average is 82%. This is a notably smaller improvement potential compared with motors and may be attributed to several factors including the relative age of the two technologies as well as the higher unavoidable thermodynamic losses associated with combustion and heat transfer processes. Interestingly, the natural gas energy price response curve exhibits much less elasticity than does the corresponding capital cost trade-off curve. This suggests that relative changes in capital spending for this pathway will be larger than the relative change in energy price.

5.4.2.2. Natural gas process heat process curves

The following two tables and associated figures present the results for the natural gas process heat process efficiency and capital cost curves.

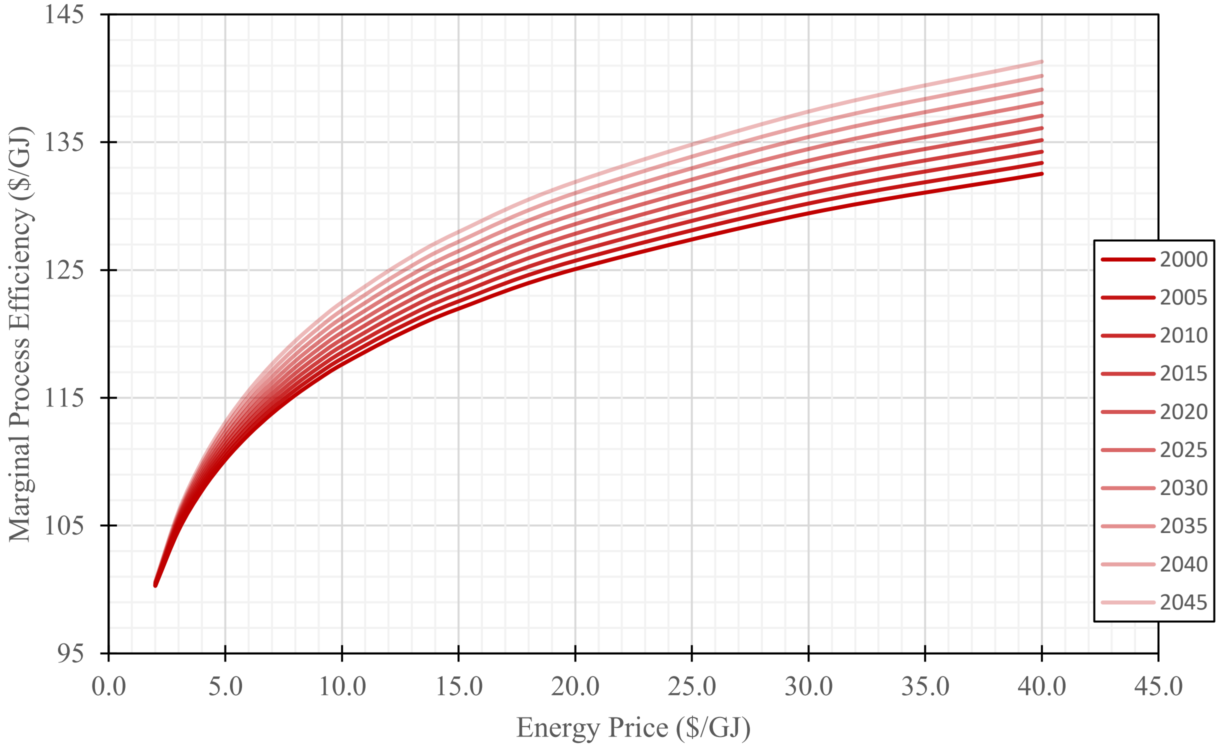


Figure 46: Natural Gas PEE-1 curves

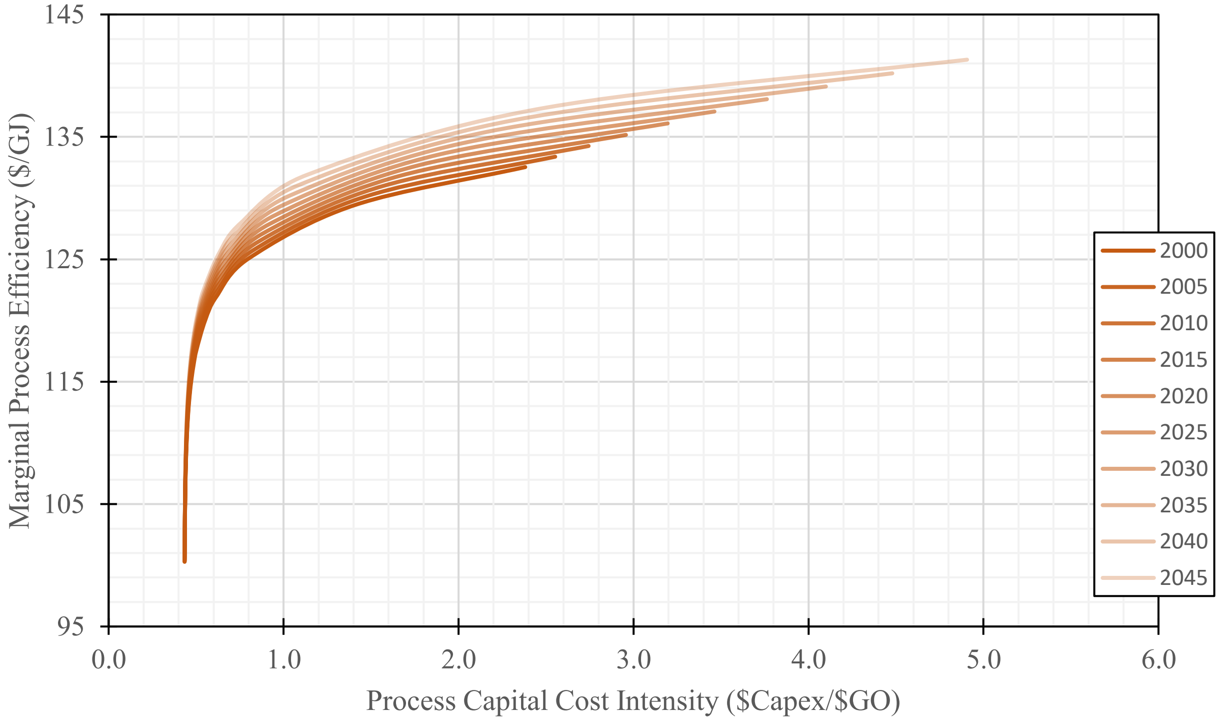


Figure 47: Natural Gas PEE-2 curves

This set of results demonstrates that incremental new steam process capacity could achieve an efficiency level of 141 $/GJ, representing the potential for marginal production capacity to achieve a process efficiency roughly 1.5 times as high as the current average. Three of the most significant EEMs contributing to this potential are the use of pinch analysis to design (or redesign) plants for optimal use of heat, use of continuous pulp digestion in chemical mills, and use of emerging advanced drying technologies with reduced heat requirements. The relative potential improvement is comparable to that of electric machine drive processes except that the natural gas pathway has a systemically lower process efficiency. This is likely due to the significant heat losses and waste of low grade heat inherent to thermally driven processes. Nonetheless, the potential for natural gas processes is still significant as a potential driver of sector-wide efficiency improvement. Similar to natural gas devices, the process capital cost trade-off curve exhibits high elasticity, with over half of the improvement potential achieved within the first 20% of the capital cost range. This suggests that moderate increases in capital costs can deliver substantial benefits in terms of energy performance but that such improvements would require larger changes in energy price to be economically attractive.

5.4.3. Biomass process heat pathway curves

5.4.3.1. Biomass process heat device curves

The following two tables and associated figures present the results for the biomass process heat device efficiency and capital cost curves.

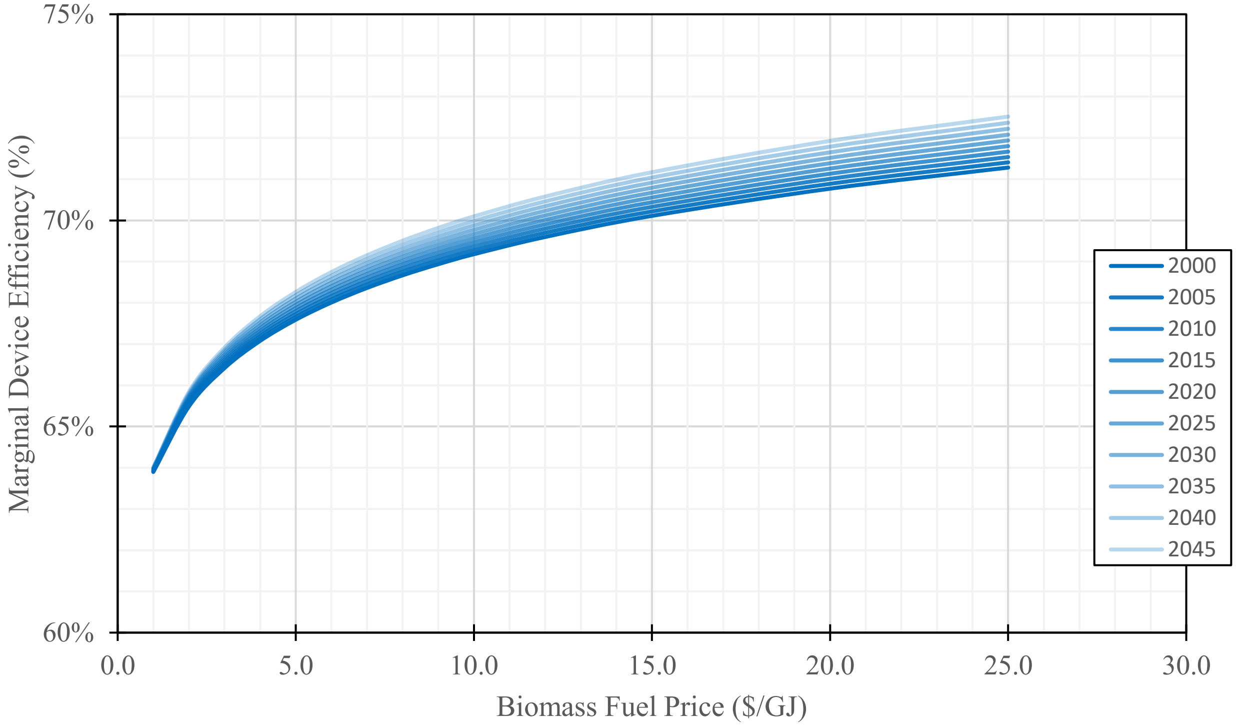


Figure 48: Biomass DEE-1 curves

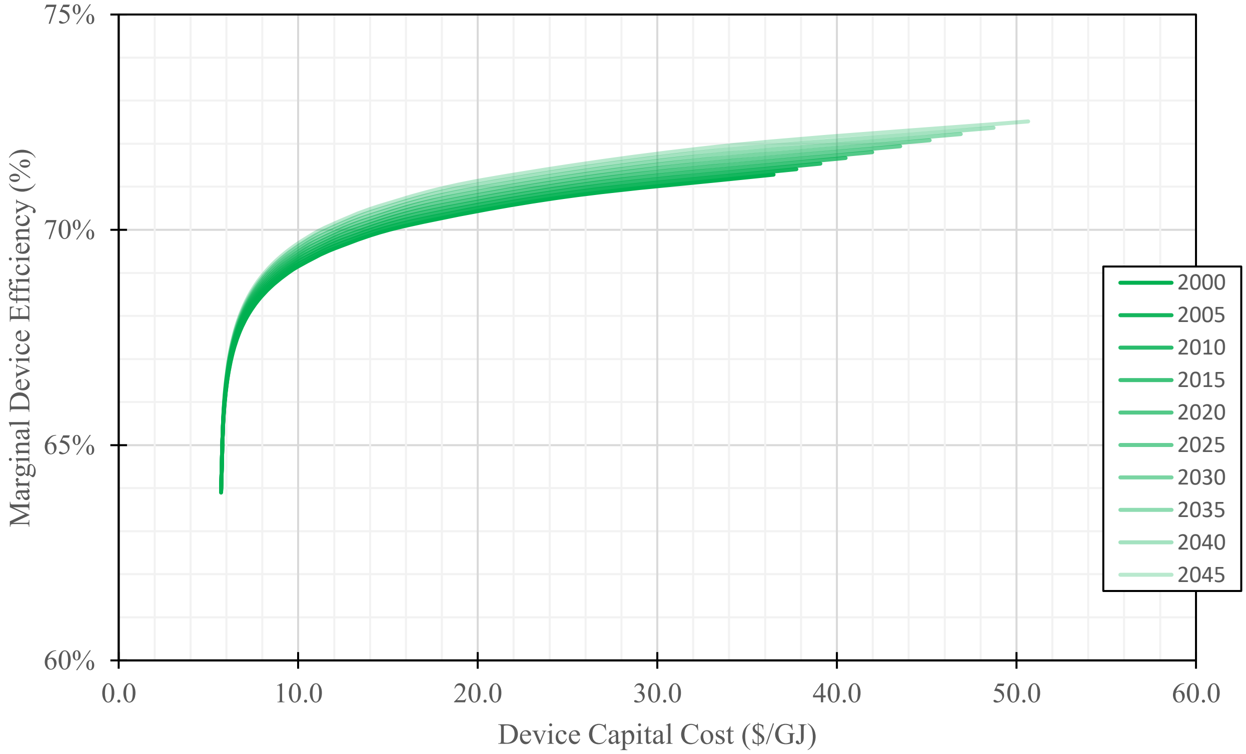


Figure 49: Biomass DEE-2 curves

The lowest improvement potential for devices is in the biomass pathway, where results show an improvement to 72.5% from 64% over the range of studied fuel prices. This reflects the relatively poor quality of biomass fuels consumed in the sector and the inherent difficulties in maintaining efficient combustion of solid and/or liquid biomass fuels compared to natural gas. A second cause is the narrower fuel price range for this fuel, which limits the maximum MDE value. It is also important to note that the capital costs for such improvements were found to be much higher than for natural gas; as an example, an improvement of 10 percentage points for biomass (64% to 69%) could be realized at a capital cost intensity of $10/GJ, whereas the same absolute improvement for natural gas (82% to 87%) is aligned with a capital cost intensity of just $4/GJ. The higher costs, coupled with the fact that biomass prices are typically low (or even free of direct costs), suggests that biomass energy prices alone are unlikely to be a strong motivator for improvements to biomass boiler efficiencies. However, the low average efficiency and significant fuel share of biomass means that this is still a critical area for policy makers to consider, particularly if other drivers such as emissions standards or fuel switching prove to be more effective. It is likely that, due to the fixed consumption of spent liquor inherent to chemical pulping, improvements in efficiency will not result in less biomass consumption but rather more steam production. This in turn can have other benefits such as offsetting natural gas use or enabling increased steam or electricity export. These secondary drivers are beyond the scope of this study but we expect they will be captured in the full ENERGY 2020 analysis.

5.4.3.2. Biomass Process Heat Process Curves

The following two tables and associated figures present the results for the biomass process heat process efficiency and capital cost curves.

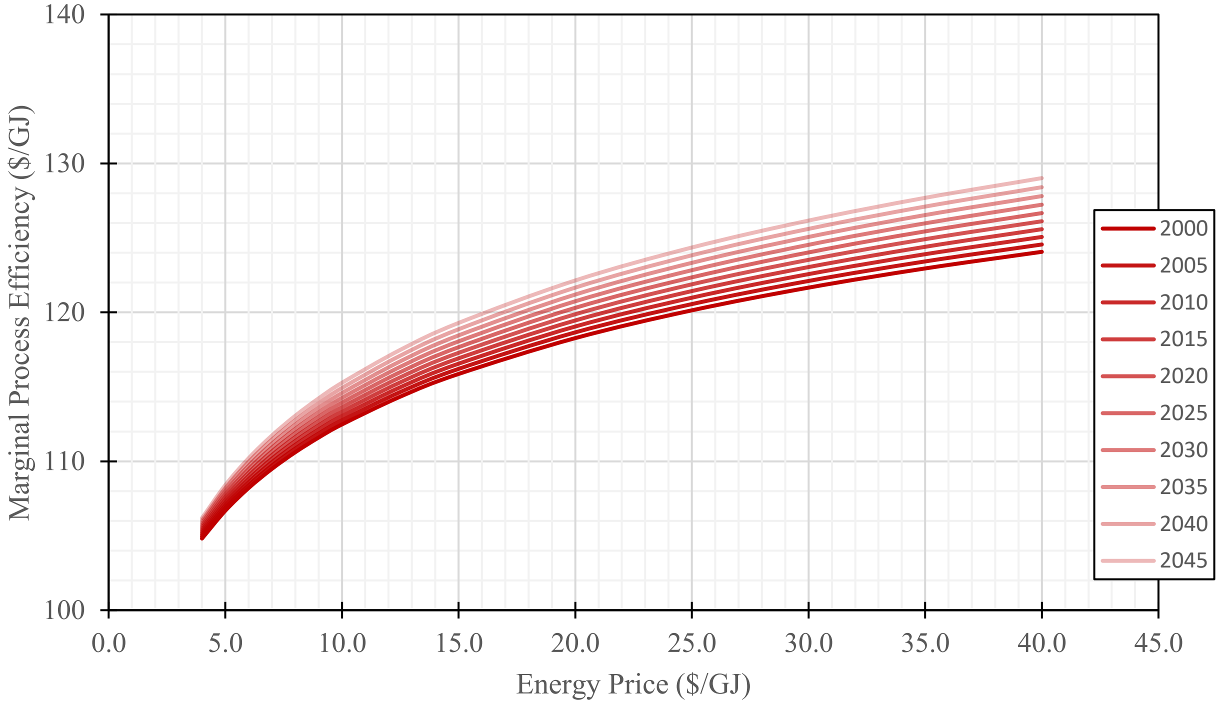


Figure 50: Biomass PEE-1 curves

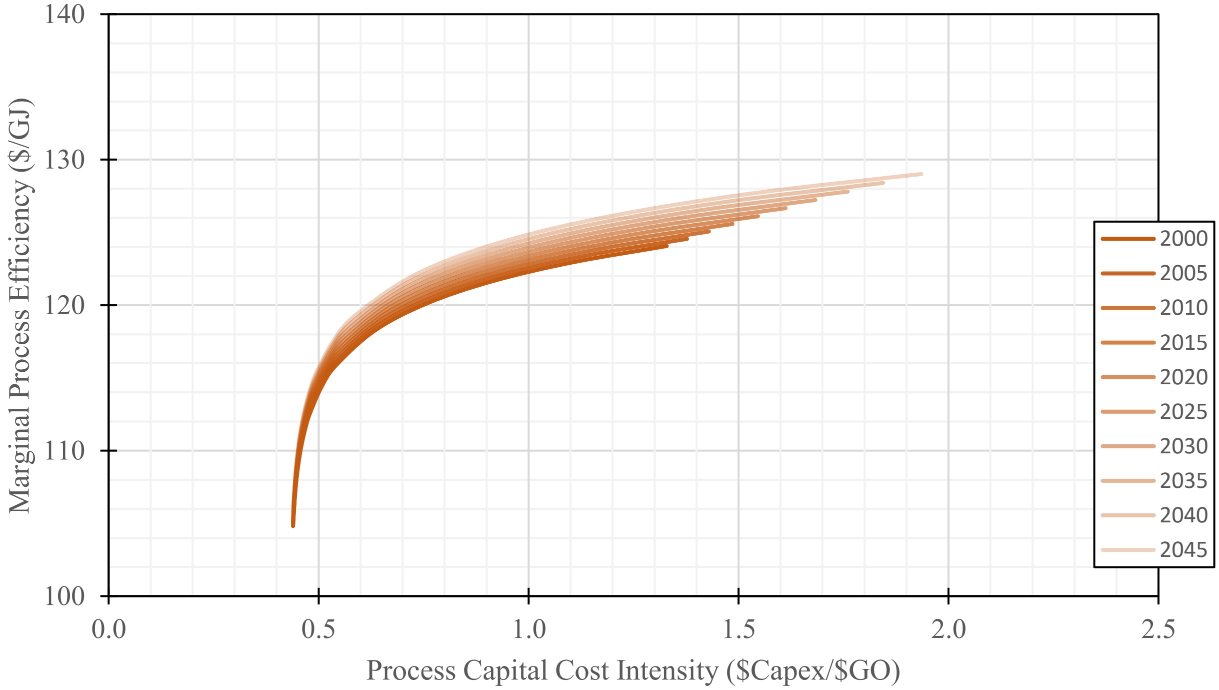


Figure 51: Biomass PEE-2 curves

A notable implication of the biomass process curves is the MPE potential of 129 $/GJ at the upper range of fuel prices studied. This is lower than the maximum MPE of 141 $/GJ found for natural gas steam processes, primarily because of the narrower fuel price range considered. Over the same range of MPE values the process capital cost intensity is almost identical to that for natural gas process heat, an expected result given that many of the measures and systems for these pathways overlap in whole or in part. Similar to the natural gas curves, the PEE-1 curves for biomass are moderately elastic while the PEE-2 curves are more elastic.

5.5. Conclusions

This study was conducted as part of a broader effort to support the energy and emissions modelling work of Environment and Climate Change Canada by developing data-intensive, Canada-specific inputs for the ENERGY 2020 model for the pulp & paper sector. This was accomplished through the development of a novel method for estimating sectoral marginal efficiency potentials and costs in alignment with the requirements of ENERGY 2020.

A comprehensive literature review was completed to establish a robust set of sector econometric and energy statistics as well as a database of 46 energy efficiency measures for the sector. Next, a spreadsheet-based model was developed to analyze the efficiency measure data alongside sectoral baselines and efficiency potentials to develop correlations that map the economically viable marginal efficiency levels to energy prices and capital costs. Three energy pathways – electric machine drive, natural gas process steam, and biomass process steam – were selected for analysis, representing 76% of final energy consumption in the sector. Efficiency selection and capital cost trade-off curves were developed for devices and processes in each pathway, resulting in six distinct sets of curves. These correlations can be directly used as inputs to the ENERGY 2020 model to more accurately estimate energy demand trends in the sector.

The developed curves all demonstrate diminishing marginal return behavior as predicted by economic theory. It was found that the majority of measures with adequate data quality and applicability lie in the lower half of the energy price ranges under consideration in this study. This large local efficiency elasticity suggests that relatively minor changes in energy prices driven by policy shifts can incent firms to select significantly more efficient equipment. However, it also indicates that policies that solely influence energy price will also be subject to diminishing marginal benefits. It is important to note that the developed curves are highly specific to the ENEGY 2020 model and are thus fairly limited in terms of the conclusions that they can support independent deeper analysis of the various factors contributing to energy efficiency decision making. While the developed method is useful in providing initial estimates of where emerging technologies might fall on the efficiency-capital cost trade-off curve, there may be future price or performance improvements for technologies outside the present dataset that would shift the curves. Because cumulative potentials were used in the developed method, adding more efficiency measures to the dataset in future work will further increase the accuracy and applicable range of the results.

Overall, the curves indicate that there is significant low-cost efficiency improvement potential in the Canadian pulp & paper sector. For the energy price ranges considered, improvement potential of at least 8% above the baseline was found to be viable for all pathways considered, with the largest possible improvement, 55%, observed for electric machine drive processes such as pumps and compressed air systems. The pathway-specific results suggest there is significant potential for efficiency improvement in almost every major end-use category in the sector.

The method developed for this study is highly flexible and can be used for any other industrial sector. Future work in this area will involve:

- Developing similar results for other Canadian emission intensive industrial sectors to improve the accuracy of Environment Canada’s energy, emissions, and policy analysis.
- Future work could also include more detailed modelling of energy flows in Canada’s industrial sectors as well as the incorporation of more efficiency measures via cost estimation and overall sectoral potential methods.

6. Conclusion and Recommendations

6.1. Key contributions and major findings

This thesis focused on the development of improved techniques for characterizing the energy savings and emissions abatement potential associated with energy efficiency technologies for the case study of the Canadian pulp and paper sector. The key objective of the research presented herein was to address a series of knowledge gaps in both academic and grey literature that have prevented the true potential of energy efficiency as a critical decarbonization pathway from being recognized and achieved. This need for renewed consideration of energy efficiency at the sectoral level is merited as part of an "all of the above" approach to addressing the urgent challenge of reducing emissions in service of Canada's 2030 and 2050 targets to avoid the worst impacts of climate change. The results presented in this thesis confirm that energy efficiency has the potential to be the most important technological wedge to drive down energy use and emissions in the Canadian P&P sector by 2050. This thesis also identifies where further work is needed in the areas of modelling, policymaking, and industry decision making in order for that potential to be realized.

In pursuit of the objectives of this thesis, several key research activities were undertaken within a novel analysis framework that was developed to link sector energy modelling with integrated, cumulative energy savings analysis. Design of the framework was driven by adoption of leading techniques for energy and emissions modelling, incorporating best practices from other analyses of resource potential. Because its level of disaggregation and granularity exceeds other modelling approaches, the sector energy model developed as part of the framework will be an effective starting point for future analyses by helping to identify which processes and practices are the key drivers of energy use in the sector. The analysis framework is also highly adaptable to other sectors and/or jurisdictions, meaning that the analyses conducted in this thesis could easily be replicated for other sectors of interest.

At the core of the framework, a disaggregated, bottom-up, technology-explicit model was developed and validated to characterize the energy demand in the chosen case study of the Canadian pulp and paper sector. This work extends and improves upon previous approaches by incorporating a detailed cogeneration and steam saving analysis and by using technology-explicit weightings to refine how end-use process energy demands are represented. Development of the sector energy model was supported by an exhaustive survey of publicly-available information on nearly all P&P mills in Canada to classify production technologies and capacities. Data from the survey was augmented with information from local and international benchmarking reports as well as consultation with local sector experts to verify key technological parameters that were not available elsewhere in the literature. In total, hundreds of datapoints corresponding to 93 individual mills were collected and processed to develop highly granular estimates of the technologies used within each class of production capacity. The sector energy model fully characterizes the energy demands of the P&P sector from the level of individual end-uses processes in each single mill type up to the sector-wide perspective. A second detailed survey was then carried out to gather data on available energy efficiency measures. Over 500 datapoints and case studies relating to energy efficiency technologies of relevance to the P&P sector were considered. In a novel approach, the sector energy model was used to adapt various classes of data from several jurisdictions to the Canadian context by mapping their impacts to individual mill types and production processes within the sector. A further innovation was the development and implementation of technology-explicit measure applicability factors to account for current measure adoption levels and potential future interference between measures to reduce overestimation of benefits. Literature values were supplemented and validated by incorporating results from real-world efficiency projects to provide more accurate cost-benefit data. Following completion of the database, the cumulative sector wide costs and benefits of all available energy efficiency measures acting together were estimated. Several best practices for energy savings analysis were used including modelling of different energy-savings effects and approximation of the diminishing returns expected for concurrent adoption of multiple efficiency measures. The results of this analysis included sector energy savings bandwidths and cost of saved energy curves; these outputs provide unparalleled insights into the pathways to reducing P&P sector energy consumption via energy efficiency.

Next, the sector energy model and energy savings analysis were implemented within the long-range, system-integrated LEAP-Canada model. LEAP was used to develop and analyze energy-savings-driven emissions reductions scenarios over a long-term planning horizon at both the sectoral and system-wide level. From this work, overall emissions reduction estimates and marginal abatement cost curves for the Canadian P&P sector were developed to provide detailed insights into the emissions abatement potential associated with energy efficiency. In parallel to the above efforts, the transferability of the analysis framework was demonstrated via application to the challenge of developing technology-explicit inputs for the ENERGY 2020 model for use in Environment & Climate Change Canada modelling and policymaking efforts.

The modelling approach used in this work was found to be highly accurate: over the validation period, total error between the model estimates and historical statistics was less than 3% for total energy use and less than 2% for GHG emissions. In the business-as-usual forecast produced by the model, energy use and emissions in the Canadian P&P sector cumulatively increase by 10% and decrease by 16%, respectively, through 2050. These changes are due to shifts in sector composition and external factors such as changes in electricity grid emissions intensity. Analysis of the energy savings potential found that significant bandwidths for savings in natural gas and electricity exist across all mill types. Most notably, there exists the technical potential for natural gas use across all mill types to be reduced to near-zero. Fuel-switching from natural gas to biomass was found to be largely offset by reductions in steam demand, thus, biomass use can be moderately reduced even while natural gas consumption is minimized. The energy-savings bandwidths developed in this thesis are summarized in Figure 52:

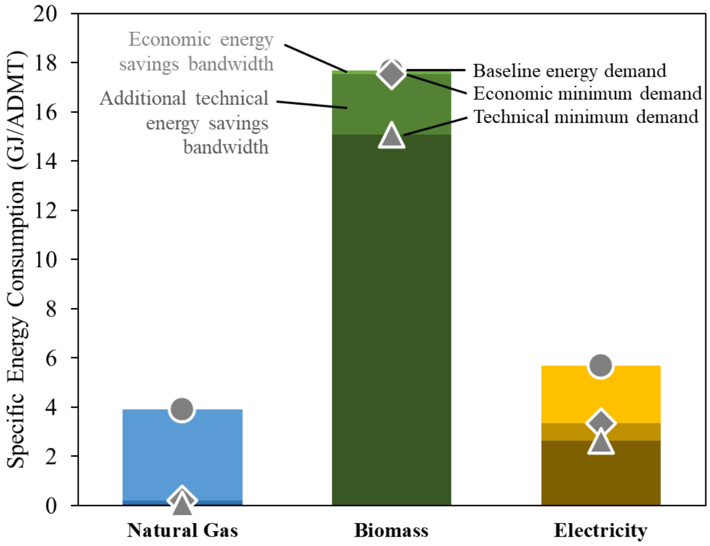
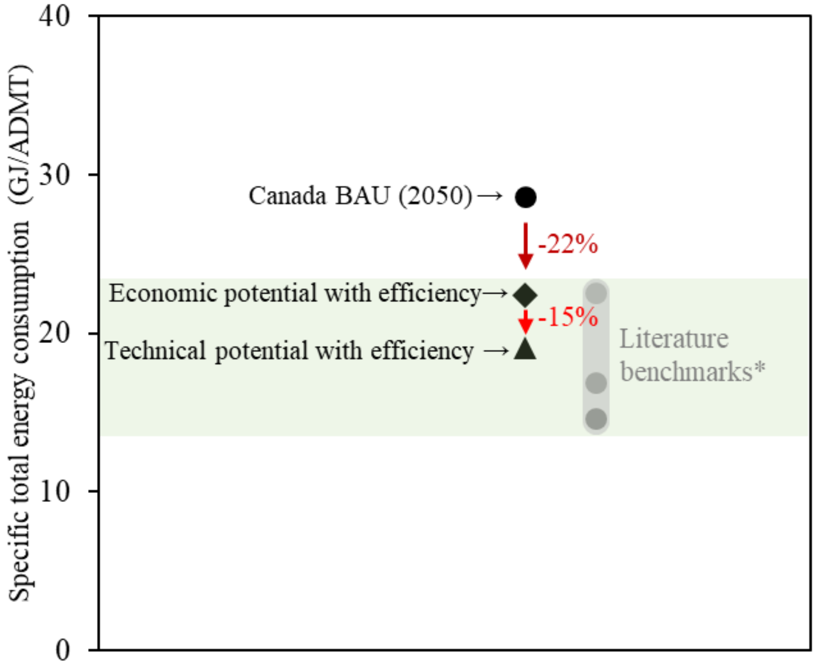


Figure 52: Summary of sector energy saving bandwidth results

As shown in Figure 52, it was determined that reductions of 95%, 1%, and 41% in consumption of natural gas, biomass, and electricity, respectively are economically viable for the sector at current energy prices. These savings potentials rise to 98%, 15%, and 54%, respectively, when considering the technical potential of all efficiency measures considered. Realization of this energy-saving potential would bring total specific energy consumption in Canada's P&P sector into alignment with international benchmarks, significantly enhancing the sector's competitiveness. This finding is visualized in Figure 53:



*benchmarks for comparison (adjusted for energy conversion efficiency and Canadian P&P sector structure):

- Worrell et Al. best-available technologies (2008) [53]
- European Commission best-available technologies (2013) [19]
- Sweden "model mill" benchmarks (2011) [99]

Figure 53: Total energy savings bandwidths compared to literature benchmarks

Reducing energy use to align Canada's P&P sector with international competitors, as shown in Figure 53, is both technically and economically feasible. At current energy prices, achieving the economic savings potential would reduce sector energy-related production costs by $81/ADMT on average—equivalent to increasing sector profit by $1.56 billion (2020CAD) at 2019 production levels. Because of measure co-benefits such as productivity gains, yield improvements, and increases in electricity exports, the net annual cost of achieving the economic savings potential is -$10/ADMT at a 20% discount rate – in other words, the most profitable energy efficiency measures more than pay for those that are marginally economic. Overall, the results presented in this thesis strongly suggest that deliberate action to reduce the P&P sector's energy footprint could significantly improve its global competitiveness.

The annual economic emissions abatement potential was found to be 3.62 MtCO2e by 2030 and 4.92 MtCO2e by 2050, as shown in Figure 54.

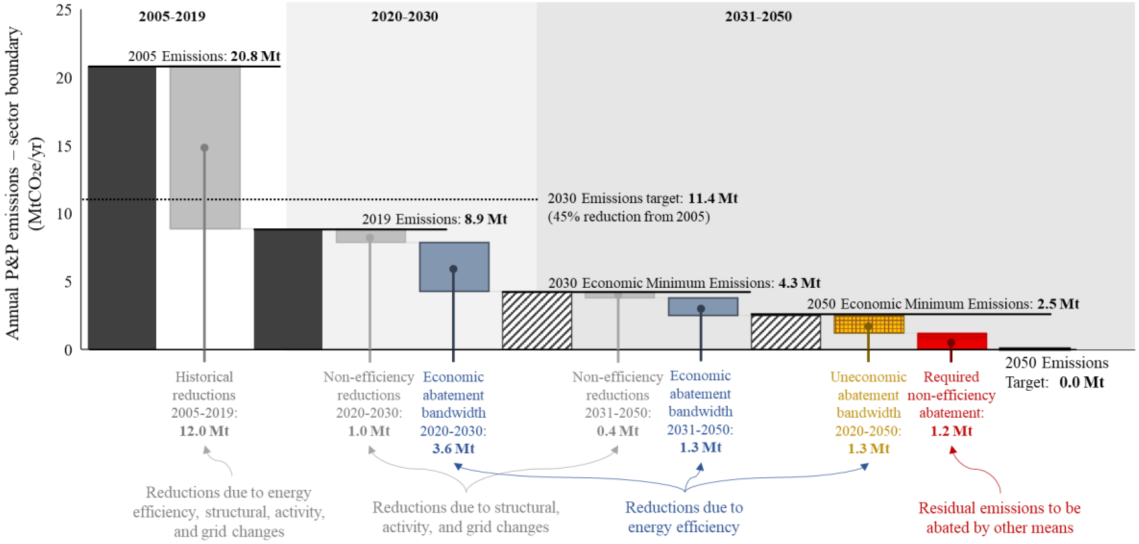


Figure 54: Overview of emissions abatement potential compared to Canadian emissions reduction targets

Although the sector has already exceeded the required absolute reductions for a -45%-by-2030 target, further reductions are needed to meet a 2050 net-zero target. The results indicate that economic energy efficiency measures can account for over 55% of the abatement required, with an additional 15% achievable if the economic performance and/or adoption rate of efficiency technologies can be improved. The total technical potential for emissions abatement from efficiency in 2050 was found to be 6.2 $MtCO_2e$. Thus, just 1.2 $MtCO_2e$ (13%) of abatement for net-zero must come from non-efficiency technologies in a maximum efficiency adoption scenario once structural changes are accounted for. This suggests that even partial realization of the potential associated with energy efficiency will significantly reduce the cost- and technical-burden of meeting a net-zero target in the P&P sector by reducing the need for low carbon fuels, carbon capture, or other more costly alternatives. The MAC curves presented in Chapter 4 demonstrate that cumulative abatement of 107.6 $MtCO_2e$ is technical feasible though 2050 at a weighted average abatement cost of -\$162/tCO_2e. The negative abatement cost is driven primarily by avoided energy costs, indicating the inherent advantage of energy-savings-driven emissions abatement compared to other technology options. When considering system-level effects, the cumulative abatement rises to 155.6 $MtCO_2e$ while the average cost increases to -\$97/tCO_2e.

Energy efficiency in the P&P sector has considerable value as an energy resource. In absolute terms, energy efficiency has the economic potential to reduce natural gas consumption by 71 PJ/year and increase net electricity exports by 44 PJ/year. For the sake of comparison, if P&P sector efficiency were to be treated as a new source of production of these energy types it would be equivalent to 1% of Canada's annual natural gas production[7] and 2% of its annual electricity generation[8] as of 2019. Similarly, energy efficiency has significant potential as a resource for emissions mitigation. According to Canada's fourth biennial report to the IPCC, heavy industry must reduce its total emissions by 27 $MtCO_2e$ by 2030 to meet Canada's more stringent targets, while a total of 92 $MtCO_2e$ of reductions are needed economy-wide [24]. With the economic potential to supply 3.62 $MtCO_2e$ of annual reductions in 2030, energy efficiency in the P&P sector alone could deliver 13% of the required heavy industry abatement and 4% of the needed economy-wide abatement. When considering the need to achieve roughly 600 $MtCO_2e$ in absolute annual abatement to achieve a 2050 net-zero goal [24], the 6.67 $MtCO_2e$ in system-level reductions from efficiency in the P&P sector could contribute more than 1% of the required abatement for the entire Canadian economy. Accessing this energy efficiency resource will require up to \$318 million per year (CAD 2020) in capital and net operations spending by the sector by 2050. However, this

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[7] Annual Canadian natural gas production is 7184 PJ as of 2019, per https://www.nrcan.gc.ca/science-and-data/data-and-analysis/energy-data-and-analysis/energy-facts/energy-and-economy/20062#L2 [Accessed September 19 2021]

[8] Annual Canadian electricity generation is 2308 PJ as of 2019, per https://www.nrcan.gc.ca/science-and-data/data-and-analysis/energy-data-and-analysis/energy-facts/electricity-facts/20068 [Accessed September 19 2021]

additional spending will be more than countered by more than $815 million (CAD 2020) in annual avoided energy and carbon costs, meaning that the resource potential of energy efficiency can be achieved at excellent rates of return.

6.2. Recommendations for researchers, governments, and industry

Chapters 3, 4, and 5 provide detailed discussion and recommendations based on their specific results. This section supplements these discussions and provides a general summary of the key findings.

The efforts documented in this thesis to more rigorously characterize the costs and benefits of energy efficiency based on comprehensive technical data and results of real-world projects may help to overcome the known barriers of poor awareness of efficiency opportunities and perceived risk of efficiency investments. However, the compelling economic performance found for many of the efficiency technologies considered herein suggests that additional non-economic barriers to efficiency adoption exist in the Canadian P&P sector. For the potential of energy efficiency to be realized, it is therefore possible that the gap between EEM rates of return and industry hurdle rates for investment will need to be further reduced. This could be accomplished by many mechanisms, including reducing the costs of capital for efficiency investments with government loans, increasing awareness and reducing perceived uncertainty around efficiency by publishing results of efficiency projects, or by providing direct government support for efficiency analysis and technology piloting. The need for investment certainty is also important, and can be addressed via clear, long-term policy design from government such as the robust carbon price schedule imposed by the PCF [17]. Appropriate decision-making can also be informed by accurate recognition and valuation of the co-benefits of efficiency such as potential yield improvements that can materially improve the economic performance of many measures. In particular, policies that allow, encourage, and valorize increased power exports from mills can significantly enhance the economic performance of many measures, a finding that should also apply to other sectors with large onsite cogeneration capabilities where steam savings can translate into new revenue streams from power sales.

The methods developed in this thesis include efforts to overcome the limitations of previous efficiency analyses that may not accurately capture the full potential of energy efficiency. Indeed, comparison of the results developed herein to those produced by other approaches demonstrates a consistent underestimation of efficiency potential in existing literature. The results presented in previous chapters suggest potential sector-wide energy savings of 22% are economically feasible and savings of up to 33% are technically feasible. In comparison, a study considering 22 measures for the Canadian P&P sector found 11% economic potential savings and 16% technical potential for savings when adjusting for mill shares [67]. Notably, that study found no measures with negative cost of saved energy prior to carbon pricing, compared to the significant number of low- or negative- cost measures identified in Chapter 3. In contrast, a broader top-down study performed by the International Energy Agency found that the total potential for energy intensity reduction in the Canadian P&P sector by 2050 is 32% [16]. Although this is almost identical to the results discussed in Chapter 3, that study accounted for more options beyond energy efficiency including electrification of all low-temperature heat and significant sectoral structural changes towards lower-intensity products in general [16]. This suggests that the potential for ‘pure’ energy efficiency, as defined in this thesis, is similarly understated in that study.

There is a need for improved industry education to see efficiency as a key opportunity for competitiveness, supported by robust analysis by government, academia, and industry associations. Mill-level studies are a critical tool to help direct industry towards investing in identified efficiency opportunities. However, effective design of such studies is essential. The results presented in this thesis show how holistic, comprehensive analyses of many efficiency measures can yield dramatically different results than studies that consider only a handful of technologies. Misguided prioritization of certain options based on cost/benefit analyses done in isolation could significantly increase the overall abatement costs required to meet tightening emissions targets in the future. Governments should work with industry to carry out periodic facility- and sector- level benchmarking activities to identify leaders and laggards and to promote best practices. This also highlights the importance of accurate, accessible statistics and frequently-updated technology-explicit government benchmarks for sector performance in the local context. In the course of the work presented in this thesis, multiple deficiencies in Canada’s current energy, emissions, and economic statistics were observed. These include a lack of basic data such as disaggregated historical energy use statistics, especially at the provincial level, and an over-reliance on modelling rather than surveying in government data methodologies. Canada lacks comparable institutions (in mandate and breadth of work) to the Energy Information Administration, Department of Energy Office of Advanced Manufacturing and National Renewable Energy Laboratory in the United States, although the recently-announced creation of the Canadian Centre for Energy Information is a welcome step in the right direction.

Overall, energy efficiency can be very low cost, presents low-risk area for government intervention. Government policies that incentivize uptake of efficiency technologies can deliver strong results per dollar invested if designed appropriately; three key examples include a) programs that recycle the profits of efficiency projects into new investments such an energy efficiency bank loan program; b) "first X unit" subsidies that encourage early adopters but phase out rapidly once a technology is proven; or c) guaranteed return policies that partially shift the financial risk of future policy change from industry to government. In designing such policies, it is critical for policymakers to incorporate systems-level analysis where possible such that the broader cost and emissions impacts can be accounted for. More specific analysis of the impacts of specific policies, accounting for the potential role for efficiency suggested by this work, is an important area for future work by both government and academia.

6.3. Recognizing efficiency as an essential tool for energy savings and emissions abatement

The results presented in this thesis identify energy efficiency as having the potential to be the single most important tool for minimizing emissions in the Canadian P&P sector. Indeed, significant progress can be made towards emissions-reduction targets for the sector with strategic implementation of commercially available efficiency technologies. This "off-the-shelf efficiency first" approach could be augmented by increasing the applicability or benefits of the EEMs considered in this study to boost adoption rates or alternatively via non-efficiency measures such as grid emissions reductions, carbon capture, or low-carbon fuel switching. Given that it is reasonable for the remaining abatement to be achieved by some combination of these options, transformative new technology solutions are not needed to achieve net-zero emissions in the P&P

industry but could further improve ability of the sector to decarbonize in the most cost-effective manner.

The results are also highly instructive regarding specific pathways to maximizing energy savings and emissions reductions in the sector. The overall strategy suggested by the results is one where the P&P sector would implement efficiency opportunities to reduce process steam demands while simultaneously increasing the energy supplied via biomass. The results suggest that it is possible to reach a point where the combination of steam demand reduction and bioenergy increase means that all process steam demands could be met with bioenergy, enabling natural gas use for steam generation to be nearly eliminated sector-wide. Under such a pathway, achievable with a subset of the measures considered, almost all remaining fossil fuel use in the sector would be associated with lime kilns and woodyard operations. The granularity of the results allows for additional synergies between measures to be investigated at the process level; this presents an avenue for expanding the utility of the current body of results.

Energy efficiency has the potential to be much more cost effective than some other mitigation strategies that are being actively considered. For example, a 2018 NRCan study found that abating 9.5% of forest product sector emissions via switching to external low carbon fuels would cost the sector \$102 million per year and would reduce emissions at a net cost of \$162/tCO$_2$e [46] – this abatement cost is two times higher (in absolute terms) than the -\$162/tCO$_2$e cost to reduce P&P emissions by >50% estimated in this work. Similarly, a 2020 study found that implementation of the bioenergy plus carbon capture concept at pulp and paper facilities in the United States would incur abatement costs of at least \$55 CAD/tCO$_2$e prior to tax credits, not including the cost of permanent sequestration [148]. Again, this cost vastly exceeds the abatement cost of the energy efficiency pathway. Because the costs of abatement achieved via energy efficiency are so low (or even negative), a failure by industry and government to achieve greater uptake of efficiency technologies means that more expensive methods must be used; ultimately, this will increase the overall costs of target compliance.

Taken together, the results indicate that substantial energy savings are possible across all mill types in the Canadian pulp and paper sector, and that deliberate policy design could achieve a target of near-zero fossil fuel consumption in the sector via adoption of low cost off-the-shelf technologies. With adequate policy support, the P&P industry can be among the first sectors in Canada to minimize fossil fuel use on the way to meeting 2030 and 2050 emissions targets, and can do so at low or even negative net costs.

6.4. Research limitations and recommendations for future work

Specific limitations pertaining to the methods used in Chapters 3, 4, and 5 are discussed in detail in each relevant chapter. However, it is valuable to consider the broad limitations associated with the methods and results presented in this thesis to inform future work.

There remain challenges relating to accurately predicting behavior associated with technology adoption rates based on costs and performance [35]. The simple approach taken to adoption rates in this thesis has known limitations that will likely require solutions from the domain of economics rather than engineering [35]. Additional work is needed to identify and integrate predictive economic theories with engineering modelling such that technology adoption models can better account for decision-making behavior, non-economic factors, and irrationality [35].

Because of data limitations and the computational constraints of the modeling tools used, the energy saving scenarios in Chapters 3 and 4 use fixed parameters over the study period. A more detailed analysis could recalculate the effects of EEMs at the process level in an integrated and iterative fashion, but at the cost of significantly increased computational requirements. Similarly, Chapter 5 demonstrates that the modification of EEM parameters over time with the use of learning rates produces small but non-negligible changes in the results over time. This approach may oversimply technology change over time, but is aligned with the assumptions of the ENERGY 2020 model considered in Chapter 5. A similar simple learning-rate based approach is not suitable for the analyses presented in Chapters 3 and 4 because they are focused mainly on the potential associated with the current set of off-the-shelf efficiency options available to industry. Furthermore, the impacts of the learning rates would need to be calculated outside of LEAP as exogenous inputs and would significantly increase the data and computation requirements for the EEM analysis.

The results presented in this thesis should not be interpreted as applying to any single mill in Canada. Individual mills will be faced with unique situations based on their access to biomass, electricity export contracts, current equipment stock, and site constraints, among other limitations. In combination, these factors may lead individual mills to prioritize different EEMs and may result in different costs and benefits than those estimated for the sector as a whole in this work. An interesting avenue for future investigation could be to perform comprehensive analyses at the mill level, accounting for facility-specific factors. By aggregating such studies, the accuracy of the modelling framework presented in this thesis could be tested. However, performing such studies at the mill level over a meaningful sample size of mills would be very labour-intensive and would require unprecedented collaboration between industry and researchers/government to provide sufficient data and access.

The technology framework developed in this thesis is capable of supporting expanded analysis based on the results developed to date. This could include re-running the analysis for alternative cases such as various electricity grid emissions intensity levels over the study period. One such case was considered in the sensitivity analysis presented in Chapter 4, but this could be expanded to reflect different degrees of renewables penetration in different provinces. Such analysis would provide insights regarding the declining value of electricity-saving measures in a future where the grid is dominated by zero-emissions electricity generation.

The results of this thesis could also be leveraged to perform a more comprehensive analysis of the overall pathway to decarbonizing the P&P sector. By comparing the optimal efficiency scenario(s) alongside scenarios for renewables, electrification, low-carbon fuels, carbon capture, sector restructuring, and other major technology options, the optimal pathway for emissions abatement could be assessed. This analysis could be expanded by considering the cumulative emissions and cost implications of different starting years and different adoption rates for efficiency technologies. Understanding the opportunity cost of failing to invest in efficiency at present and therefore needing to invest more in alternative abatement technologies in the future holds significant potential as an avenue for future investigation.

One of the most immediate avenues for future work could be to add additional efficiency technologies to the database. At present, only 18 technologies in the database can be classified as emerging options at are not fully commercialized. This limitation is driven by the chosen focus of this work on commercially-available technologies as well as the relative lack of accurate cost and performance data for nascent technologies. However, the analysis framework can be applied to any number of measures so it could be easily leveraged to provide valuable insights regarding the potential associated with emerging technologies once sufficient data on them is available. The most immediate candidates for additions to the technology database are electrification measures. Electrification of heat was only partially considered in this work due to lack of data on heat pump and electric boiler costs and performance in the P&P context. Process electrification such as microwave drying was similarly considered by only a small number of scenarios. Electrification of woodyard equipment and other mobile equipment is also likely to become a viable option in the future given transportation electrification trends, but again data is lacking. Periodic updates to the technology database over time will help ensure new technology trends and opportunities are accounted for such that the overall potential estimate remains as accurate and comprehensive as possible.

The other near-term possibility for future work is to apply the framework and methodology developed here to other industrial sectors in Canada or beyond. This work is focused only on the P&P sector, but the fundamental principles and practices involved are entirely transferable to other industrial sectors. The framework could therefore support a systematic approach to characterizing the technoeconomic potential for efficiency across the economy. In this way, the work presented here could be leveraged and expanded upon to support the ongoing efforts to characterize and optimize Canada’s pathways towards achieving a low-carbon future.

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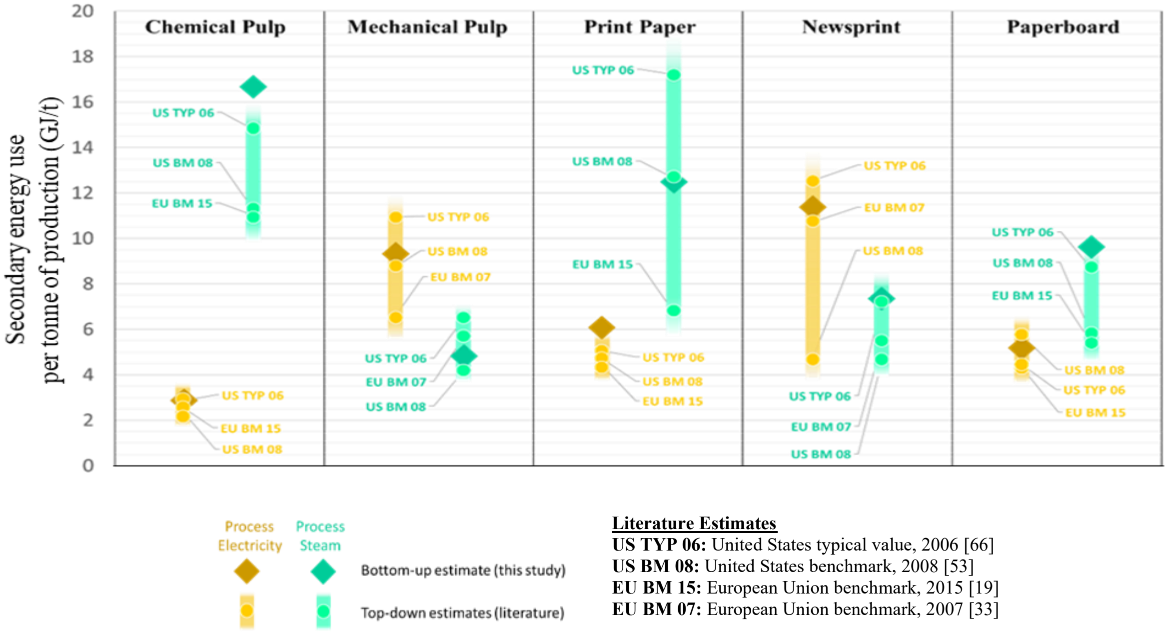
Appendices

Appendix A: Sector energy model validation



Literature Estimates

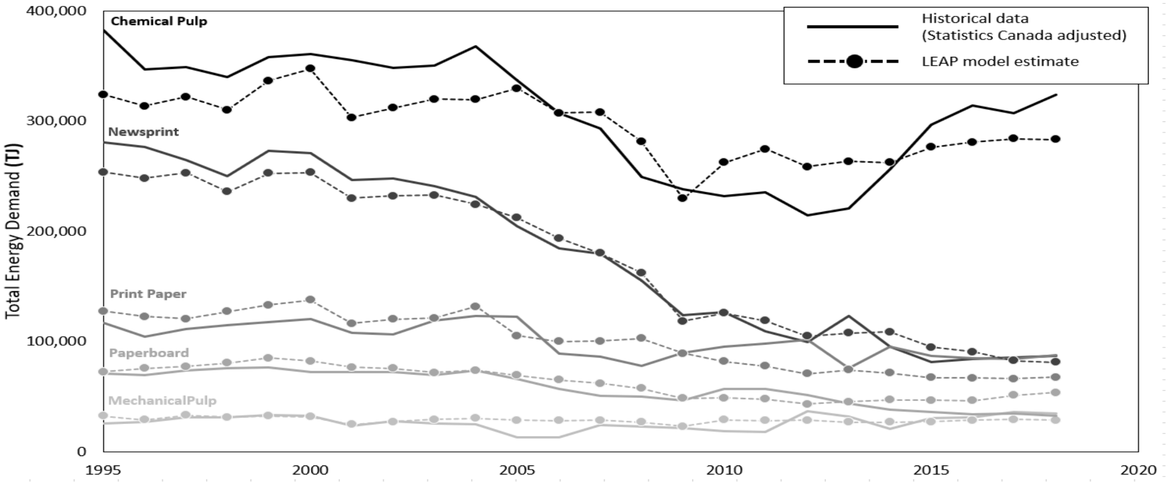
US TYP 06: United States typical value, 2006 [66]

US BM 08: United States benchmark, 2008 [53]

EU BM 15: European Union benchmark, 2015 [19]

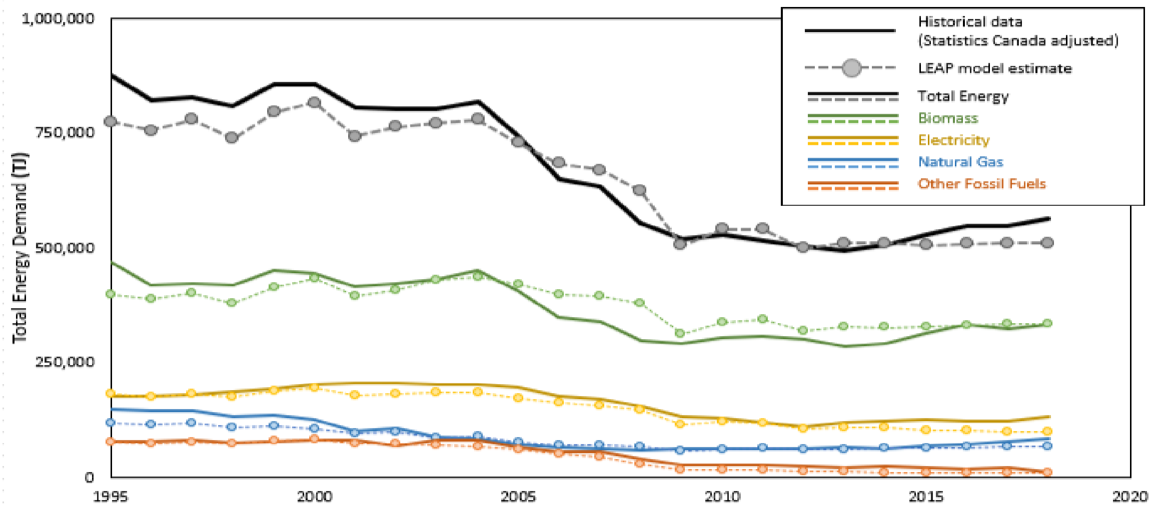
EU BM 07: European Union benchmark, 2007 [33]

Figure 55: Comparison of model estimated secondary energy demand with literature values



Mill type	**CP**	**MP**	**PP**	**NP**	**PB**
Mean annual error $= \frac{\sum_{\substack{validation \\ period}} \frac{estimated - actual}{actual}}{2018 - 1995}$	3.0%	4.2%	0.1%	-0.8%	7.5%

Figure 56: Model estimated vs. historical reported [87] total final energy consumption by mill type



Energy type	**Electricity**	**Natural Gas**	**Biomass**	**Other Fossil**	**Total**
Mean annual error $= \frac{\sum_{\substack{validation\\ period}} \frac{estimated - actual}{actual}}{2018 - 1995}$	-8.9%	-5.9%	2.9%	-23%	-2.7%

Figure 57: Model estimated vs. historical reported [87] final energy consumption by energy type

Appendix B: Selected sector energy model parameters

Table 12: Key sector energy model parameters for reference year (2018)

Parameter	Units	CP	MP	PP	NP	PB	Sector Overall
Activity level, AL [90]	kt/y of production	7,020	2,106	4,131	3,001	3,065	19,323
Share of mills with cogeneration [93]	%	94%	0%	23%	42%	0%	44%
Baseline steam generation efficiency, η_m [51, 93]	%	62%	69%	66%	66%	66%	N/A
Baseline specific electricity consumption	GJ/t	2.76	7.64	6.31	11.36	4.23	5.67
Baseline specific natural gas consumption	GJ/t	5.45	1.60	2.67	2.25	4.80	3.92
Baseline specific biomass consumption	GJ/t	32.17	3.73	8.90	12.38	8.72	17.69
Baseline specific other fuel consumption	GJ/t	0.30	0.08	0.40	1.14	0.97	0.57

Appendix C: Energy efficiency measure database

Table 13: Selected data from energy efficiency measure database

Measure	Name	Type	Process Branch	Capital Cost (2020CAD/t)	Change in O&M Cost (2020CAD/t)	Final Energy Savings (GJ/t) Elec.	Nat. Gas	Bio.	Other Fossil	Applic. Factor (%)	References and Case Studies
ALL-AHO	Air heating optimization	Process	Auxiliaries			0.01	0.19	0.10		8%	[44]
ALL-APC	Process control / energy management systems	Process	General	$2.10		0.51	0.58	0.29		50%	[42, 45, 67]
ALL-APH	Combustion air preheating	Cogen	Cogeneration	$9.95	$0.04	0.01	0.08	0.10		10%	[42, 44]
ALL-ASD	Adjustable speed drives	Process	General	$1.78		0.12				40%	[65, 67, 149]
ALL-AWT	Anaerobic water treatment	Process	Auxiliaries	$3.38		0.01	0.06	0.07		15%	[65]
ALL-BBP	Boiler best practices & maintenance	Cogen	Cogeneration	$0.93		0.01	0.08	0.08		50%	[44]
ALL-BBU	Boiler burner upgrade	Cogen	Cogeneration	$0.84	$0.02	0.01	0.06	0.06		50%	[41, 44]
ALL-BDP	Blowdown best practices	Cogen	Cogeneration	$0.52		0.00	0.02	0.02		20%	[41, 42, 44]
ALL-BGE	Biogas production from effluent	Fuel Switch	Cogeneration	$0.11		0.57	1.11	-3.12		50%	[65, 67, 150]
ALL-BHR	Blowdown heat recovery	Cogen	Cogeneration	$41.45	$0.24	0.01	0.04	0.04		20%	[41, 43-45]
ALL-BMG	Biomass gasification to offset natural gas	Fuel Switch	Cogeneration	$0.52						50%	[151, 152]
ALL-BRE	Replace inefficient boilers before end of life	Cogen	Cogeneration	$113.95		0.09		0.95		15%	[43, 153]
ALL-BSB	Biomass supplementary boiler	Fuel Switch	Cogeneration	$119.17		0.22	0.43	-1.76	0.56	33%	[154-156]
ALL-CAO	Compressed air system optimization	Process	General	$128.01		0.01				75%	[42, 153, 157]
ALL-CAU	Compressed air equipment upgrades	Process	General	$0.23		0.01				75%	[41, 127]
ALL-CDR	Improved condensate return and use	Cogen	Cogeneration	$0.09		0.01	0.09	0.11		18%	[41, 44]
ALL-DVC	Deaerator vent rate control	Cogen	Cogeneration	$1.58	$0.00	0.01	0.05	0.05		19%	[44]
ALL-EAC	Boiler combustion air practices	Cogen	Cogeneration	$0.43		0.02	0.18	0.13		33%	[41, 44, 153]
ALL-EFA	Effluent aerator upgrade.	Process	Auxiliaries	$1.15		0.05				25%	[158]
ALL-EFL	Efficient facility lighting	Process	Auxiliaries	$1.58		0.02				66%	[43, 45, 65, 67]
ALL-FSU	Fan system and equipment upgrades	Process	General	$1.12		0.06				75%	[127]
ALL-FWE	Feedwater economizers	Cogen	Cogeneration	$0.19		0.02	0.14	0.20		19%	[44]
ALL-HAI	Hog boiler ash injection	Fuel Switch	Cogeneration	$3.54		0.00	0.01	0.06		33%	[43]
ALL-HRI	General heat recovery and integration	Integration	General	$3.20		0.06	0.41	0.50		50%	[41-43, 45]
ALL-HWS	Hot water system upgrades	Process	General	$10.66	$0.11	0.03	0.20	0.24		33%	[43, 44, 159]
ALL-IER	Idle equipment reduction	Process	General	$6.77		0.10				75%	[42, 45]
ALL-INS	Add and repair insulation	Cogen	General	$0.07	-$0.10	0.00	0.04	0.03		50%	[41, 65, 153]
ALL-MDS	Motor downsizing	Process	General	$0.21		0.04				75%	[43, 127, 160]
ALL-MMR	Improved motor maintenance and rewinding	Process	General	$1.91		0.05				50%	[127]
ALL-MST	Microturbine for pressure letdown	Fuel Switch	Cogeneration	$0.00	$0.25	0.03				75%	[41]
ALL-MSU	Motor-driven system upgrades	Process	General	$3.66	$0.14	0.05				75%	[127]
ALL-MVC	Motor voltage controllers	Process	General	$0.46		0.07				50%	[42, 43, 127]
ALL-PEM	Upgrade to premium efficiency motors	Process	General	$1.21		0.17				75%	[42, 45, 127, 153]

Measure	Name	Type	Process Branch	Capital Cost (2020CAD/t)	Change in O&M Cost (2020CAD/t)	Final Energy Savings (GJ/t)				Applic. Factor (%)	References and Case Studies
						Elec.	Nat. Gas	Bio.	Other Fossil		
ALL-PFH	Power boiler flue gas heat recovery	Cogen	Cogeneration	$2.46		0.00		0.18		50%	[43, 45, 161]
ALL-PRM	General preventative maintenance	Process	General	$46.15	$0.05	0.05	0.09	0.05		75%	[43]
ALL-PSU	Pump system upgrades	Process	General	$3.20		0.12				75%	[45, 127, 160]
ALL-SRC	Sludge recovery and combustion	Fuel Switch	Cogeneration	$0.94	-$0.01	0.48	0.10	-1.24		28%	[65, 67]
ALL-SSO	Steam system optimization	Cogen	Cogeneration	$1.46		0.01	0.07	0.11		75%	[41, 43-45]
ALL-STS	Solar thermal supplemental steam	Fuel Switch	Cogeneration	$2.47		0.10	0.11	0.40		33%	[162]
ALL-STU	Steam trap maintenance and upgrades	Cogen	Cogeneration	$13.12		0.07	0.71	0.36		50%	[41, 45, 65, 67]
BLE-BFR	Bleach filtrate recycling	Process	Bleaching	$1.07	$0.06	0.02	0.10	0.09		50%	[43, 45]
BLE-CPH	Bleach CLO_2 preheating	Integration	Bleaching	$5.14	-$0.11	0.02	0.10	0.08		40%	[43, 45, 65, 163]
BLE-OBC	Oxygen/ozone bleaching & delignification	Process	Bleaching	$1.57	-$0.05	0.08		-1.31		25%	[43, 45]
BLE-PHR	Bleach plant heat recovery	Integration	Bleaching	$88.52	-$3.55	0.08	0.66	0.33		33%	[33, 41, 45, 163]
CPP-ADA	Advanced digestion additives	Process	Digestion	$6.00	-$0.23	0.00	0.02	0.02		50%	[33, 41, 42]
CPP-AEE	Additional evaporation effect	Process	Recovery cycle	$0.41		0.05		0.43		33%	[33, 43, 45, 164]
CPP-BDM	Batch digester modifications	Process	Digestion	$78.69	-$0.47	0.10		0.61		15%	[43, 45, 65, 67]
CPP-BGK	Biomass gasification to kiln	Fuel Switch	Recaust.	$143.68	$0.02		0.94	-1.13		75%	[42, 43]
CPP-BLB	Boilout with black liquor	Process	Recovery cycle	$61.04		0.01	0.03	0.02		33%	[33, 43, 45]
CPP-BLC	Black liquor concentration / high solids firing	Fuel Switch	Recovery cycle	$1.72	-$0.07	0.04		0.28		24%	[43, 45, 67]
CPP-BLG	Black liquor gasification (full scale)	Fuel Switch	Recovery cycle	$29.07	-$0.13	1.05		0.35		50%	[33, 41, 72]
CPP-BWP	Bleach washing presses	Process	Bleaching	$836.70	-$18.56	0.02		0.16		15%	[45]
CPP-BWU	Brownstock washer upgrades.	Process	Digestion	$19.68	-$0.01	0.01		0.02		15%	[43, 45]
CPP-CDM	Continuous digester modifications	Process	Digestion	$68.16	-$0.04	0.02	0.13	0.10		17%	[45, 65]
CPP-CDR	Batch to continuous digester retrofit	Process	Digestion	$1.48	$0.16	0.15		1.28		10%	[33, 45, 165]
CPP-CSC	Chip screening and conditioning for CP	Process	Feedstock prep.	$177.59		0.01	0.09	0.05		20%	[33, 42, 45]
CPP-CSI	Condensate stripping integration	Process	Recovery cycle	$1.30	-$0.35	0.02	0.14	0.12		33%	[43, 45]
CPP-DFC	Brownstock washing dilution factor control	Process	Digestion	$5.60	-$0.13	0.01	0.03	0.02		50%	[43, 45]
CPP-DHR	Digester heat recovery	Integration	Digestion	$1.72	-$0.05	0.04	0.26	0.21		33%	[33, 41-43, 45, 163]
CPP-DSH	Decker shower water from condensate stream	Process	Pulp Machine	$12.45	-$0.19	0.00		0.04		33%	[33, 43, 45]
CPP-FFE	Falling film evaporation	Process	Recovery cycle	$2.47	-$0.07	0.04		0.31		30%	[45, 65, 67]
CPP-HTM	Recovery boiler temperature monitoring	Cogen	Recovery cycle	$109.58		0.01	0.04	0.02		50%	[42, 45]
CPP-KEP	Kiln electrostatic precipitator	Process	Recaust.	$0.14	-$0.02		0.00	0.00		33%	[45]
CPP-LKG	Lime kiln modifications	Process	Recaust.	$1.32	-$0.05		0.21	-0.05		75%	[33, 42, 43, 45, 65, 67]
CPP-MLR	Stripper methanol rectification & liquification	Process	Recovery cycle	$8.16	-$0.06	0.00		0.02		50%	[41, 43]
CPP-RBH	Recovery boiler upgrade to high pressure	Cogen	Recovery cycle	$6.41		0.15		1.04		33%	[166]
CPP-RBS	Recovery boiler tertiary/quaternary stage	Cogen	Recovery cycle	$824.50	-$46.67	0.00	0.04	0.02		33%	[33, 42, 45]
CPP-RFH	Recovery boiler flue gas heat recovery	Cogen	Cogeneration	$1.05	-$0.17	0.20	0.03	2.28		75%	[167, 168]
CPP-SCW	Steam cycle washing	Process	Digestion	$58.45		0.15	0.14	0.07		33%	[33, 41]

Measure	Name	Type	Process Branch	Capital Cost (2020CAD/t)	Change in O&M Cost (2020CAD/t)	Final Energy Savings (GJ/t)				Applic. Factor (%)	References and Case Studies
						Elec.	Nat. Gas	Bio.	Other Fossil		
MPP-APT	Advanced TMP pretreatment methods	Process	Refining	$45.52	-$27.86	0.33	-0.02	-0.05		33%	[33, 41, 45, 68, 169]
MPP-AQC	TMP quality control improvements	Process	Refining	$25.88	-$5.49	0.11				50%	[45, 170]
MPP-ARS	Additional (or low consistency) refining stage	Process	Refining	$0.12		0.24				33%	[43, 45, 134]
MPP-BTM	TMP line blowthrough reduction	Process	Refining	$0.36		0.01	0.14	0.07		33%	[42, 45]
MPP-CSC	Chip screening and conditioning for MP	Process	Feedstock prep.	$0.53	-$0.01	0.18				20%	[33]
MPP-CTI	CTMP Improvements	Process	Refining	$0.37	-$0.35	0.29				20%	[33, 68]
MPP-HER	High efficiency refiners	Process	Refining	$30.00		0.30				50%	[33, 41, 45, 65, 67]
MPP-RTS	RTS mechanical pulping techniques	Process	Refining	$8.99	$1.91	0.29				30%	[33, 45, 68]
MPP-THR	Add/improve TMP heat recovery	Integration	Refining	$64.35		-0.20		0.20	0.82	25%	[33, 42, 43, 45, 67, 72]
MPP-TPP	Thermopulp (interheating) process	Process	Refining	$17.46		0.20				15%	[33, 68]
PNB-AFF	Advanced fibrous fillers	Structural	Pulp supply	$0.00		0.34	0.29	0.14		33%	[33, 41]
PNB-ASO	Paper machine air system optimization	Process	Paper machine	$0.00	$0.54	0.01	0.03	0.10		30%	[42, 43, 45, 65, 67]
PNB-BSO	Batch stock optimization	Process	Stock prep.	$6.48	-$0.03	0.00	0.05	0.03		33%	[153]
PNB-CNU	Coating nozzle upgrades	Process	Coating	$0.55		0.00	0.04	0.02		50%	[42]
PNB-DMS	Dryer management system	Process	Paper machine	$1.00		0.00	0.07	0.04		50%	[33, 42, 45, 171]
PNB-DSF	Dry sheet forming	Process	Paper machine	$1.21	-$0.08	-0.36		1.87	0.19	15%	[33, 45]
PNB-FWP	Felt water preheating	Integration	Paper machine	$578.14		0.00	0.05	0.02		50%	[42, 45]
PNB-GPF	Gap forming	Process	Paper machine	$0.77	-$0.31	0.07				35%	[33, 43]
PNB-HCF	High consistency forming	Process	Paper machine	$104.82	$0.51	0.07				33%	[33, 45]
PNB-IMD	Improved drying technologies	Process	Paper machine	$156.33	$0.54	0.04		0.57		33%	[33, 41, 45]
PNB-IRD	Infrared drying	Fuel Switch	Paper machine	$72.70	$0.23	-0.01			0.02	15%	[33]
PNB-IRP	Advanced web profiling	Process	Paper machine	$188.96	$1.01	-0.04	0.07	0.20		15%	[33, 45]
PNB-MHR	Paper machine heat recovery	Integration	Paper machine	$1.61		0.01	0.07	0.22		30%	[33, 41, 45, 65, 67]
PNB-MWD	Microwave drying	Fuel Switch	Paper machine	$11.10	$0.67	-0.07			0.09	33%	[33]
PNB-PRU	Press section upgrades	Process	Paper machine	$7.71		-0.01		0.24	0.07	42%	[33, 41, 43, 65, 67]
PNB-RFS	Increase use of recycled pulp	Structural	Pulp supply	$40.49	$1.06	0.28	0.86	0.43		33%	[41, 45]
PNB-SHP	Superhot pressing	Process	Paper machine	$129.90	-$19.78	0.00		0.06		10%	[33, 45]
PNB-SSI	Stationary siphon use/optimization	Process	Paper machine	$37.57		0.00	0.05	0.16		25%	[33, 45, 65, 67]
PNB-TRB	Turbulent bars	Process	Paper machine	$3.27	-$0.04	0.00	0.15	0.08		32%	[65, 67]
PNB-VSO	Paper machine vacuum system optimization	Process	Paper machine	$0.59		0.01				48%	[65]
PNB-WBS	White water/broke system optimization	Process	Paper machine	$0.00		0.00	0.01	0.05		33%	[43, 45]
PUL-MHR	Pulp machine heat recovery	Integration	Pulp machine	$6.03	-$0.19	0.01	0.06	0.04		33%	[172, 173]
PUL-PMR	Efficient pulp machine rebuild	Process	Pulp machine	$1.96		0.01		0.07		50%	[174]
RPB-CLR	Closed loop recovered pulping	Process	Pulp supply	$128.87	-$25.47		0.12	0.10		33%	[43]
RPB-DFO	Deinking flotation optimization	Process	Pulp supply	$7.69		0.01				50%	[72]
RPB-DHR	Heat recovery on deinking system	Integration	Pulp supply	$1.75		0.00	0.01	0.02		50%	[33, 45, 153]

Measure	Name	Type	Process Branch	Capital Cost (2020CAD/t)	Change in O&M Cost (2020CAD/t)	Final Energy Savings (GJ/t) Elec.	Nat. Gas	Bio.	Other Fossil	Applic. Factor (%)	References and Case Studies
RPB-FRR	Fibre recovery from rejects	Process	Stock prep.	$1.16	-$0.01		0.07	0.06		33%	[153]
RPB-HCR	High consistency recovered fibre pulping	Process	Pulp supply	$1.21		0.01				50%	[72]
RPB-RPO	Recovered fibre processing upgrades	Process	Pulp supply	$4.35		0.01				50%	[72]
SPB-CRR	Continuous repulping	Process	Pulp supply	$5.98		0.08	0.04	0.02		33%	[33, 41, 42]
SPB-DRP	Drum repulping	Process	Pulp supply	$0.52		0.03				33%	[33, 42, 43, 45]
SPB-RRU	Repulping rotor upgrades	Process	Pulp supply	$11.02		0.04				50%	[33, 41, 42]
VFP-BFD	Biomass fuel moisture reduction	Fuel Switch	Cogeneration	$9.31		0.06		0.55		33%	[43]
VFP-EAD	Enzyme assisted debarking	Process	Feedstock prep	$44.87		0.00				15%	[43]
VFP-UDB	Debarking upgrade	Process	Feedstock prep	$1.68		0.01				33%	[33, 45]
VFP-WHD	Debarking using waste heat	Integration	Feedstock prep	$18.69	-$0.01	0.02	0.03	0.16		50%	[33, 41, 43, 45]

Appendix D: Energy and carbon price assumptions for Chapter 3

Table 14: Energy and carbon prices*

Parameter		Energy Type	
		Electricity	**Natural Gas**
Energy price 2020CAD/GJ ($/kWh)	Low	$17 ($0.06)	$1.50
	Reference [96]	$27 ($0.10)	$4.60
	High	$55 ($0.20)	$4.60
Carbon surcharge 2020CAD/tCO2e (2020CAD/GJ)	Low	$0	$0
	Reference [25]	$0	$30 ($1.56)
	High [25]	$0	$170 ($8.84)
Overall price 2020CAD/GJ	Low	$17	$1.50
	Reference	**$27**	**$6.16**
	High	$55	$13.44

*Note: Reference prices are used for cost of saved energy (CSE) and internal rate of return (IRR) analysis. Low and high prices are used for illustration on CSE plots.

Appendix E: Cumulative energy saving analysis results

Table 15: Energy efficiency measure analysis results for chemical pulp mills

Measure	Energy Savings (GJ/t) Natural Gas	Energy Savings (GJ/t) Biomass	Energy Savings (GJ/t) Electricity	Cost of Saved Energy, d=20% (2020CAD/GJ) Natural Gas	Cost of Saved Energy, d=20% (2020CAD/GJ) Biomass	Cost of Saved Energy, d=20% (2020CAD/GJ) Electricity	IRR Category
ALL-AHO	0.02	0.01	0.00	-0.56	-13.03	-25.96	>35
ALL-APC	0.44	0.22	0.29	-8.87	-29.64	-6.31	>35
ALL-APH	0.02	0.01	0.00	-0.81	-13.51	-27.60	>35
ALL-ASD			0.05			6.07	>35
ALL-AWT	0.02	0.01	0.00	-1.32	-14.54	-31.04	>35
ALL-BBP	0.09	0.04	0.01	-1.69	-15.29	-33.97	>35
ALL-BBU	0.06	0.03	0.01	-1.89	-15.68	-35.63	>35
ALL-BDP	0.01	0.00	0.00	-2.19	-16.28	-38.75	>35
ALL-BGE		-1.56	0.55			9.43	>35
ALL-BHR	0.02	0.01	0.00	-1.61	-15.11	-32.87	>35
ALL-BRE		0.20	0.03		16.11	114.08	<5
ALL-CAO			0.01			5.68	>35
ALL-CAU			0.01			1.43	>35
ALL-CDR	0.03	0.02	0.01	-1.21	-14.32	-30.37	>35
ALL-DVC	0.02	0.01	0.00	-1.91	-15.72	-35.87	>35
ALL-EAC	0.11	0.05	0.02	-2.05	-15.99	-37.49	>35
ALL-EFA			0.01			6.65	>35
ALL-EFL			0.02			11.22	25-35
ALL-FSU			0.05			0.63	>35
ALL-FWE	0.06	0.03	0.01	-0.47	-12.84	-25.37	>35
ALL-HRI	0.44	0.22	0.07	-0.32	-12.53	-24.08	>35
ALL-HWS	0.14	0.07	0.02	0.36	-11.18	-19.26	>35
ALL-IER			0.08			-0.79	>35
ALL-INS	0.04	0.02	0.01	-2.13	-16.15	-38.27	>35
ALL-MDS			0.03			9.46	>35
ALL-MMR			0.02			5.53	>35
All-MST			0.02			34.51	<5
ALL-MSU			0.04			2.02	>35
ALL-MVC			0.04			3.60	>35
ALL-PEM			0.13			2.97	>35
ALL-PRM	0.11	0.05	0.04	-2.44	-16.78	-4.07	>35
ALL-PSU			0.09			1.45	>35
ALL-SRC		-0.84	0.36			1.43	>35
ALL-SSO	0.12	0.06	0.02	0.28	-11.34	-20.36	>35
ALL-STS		0.13	0.08		-3.27	10.60	25-35
ALL-STU	0.57	0.29	0.08	-2.34	-16.59	-44.05	>35

	Energy Savings (GJ/t)			Cost of Saved Energy, d=20% (2020CAD/GJ)			
Measure	Natural Gas	Biomass	Electricity	Natural Gas	Biomass	Electricity	IRR Category
BLE-BFR	0.12	0.06	0.02	0.74	-10.41	-16.91	>35
BLE-CPH	0.09	0.05	0.01	-1.81	-15.52	-34.74	>35
BLE-OBC	-0.19	-0.38	0.03			164.03	<5
BLE-PHR	0.43	0.21	0.06	-2.09	-16.08	-37.80	>35
CPP-ADA	0.03	0.02	0.00	-1.50	-14.89	-32.17	>35
CPP-AEE		0.32	0.04		13.90	112.68	<5
CPP-BDM		0.24	0.04		15.60	110.90	<5
CPP-BGK	1.35	-1.62		7.87			5-15
CPP-BLB	0.03	0.01	0.00	0.81	-10.28	-16.50	>35
CPP-BLC		0.13	0.02		8.14	64.92	<5
CPP-BLG		0.41	1.02		147.03	75.19	<5
CPP-BWP		0.05	0.01		8.61	67.29	<5
CPP-BWU	0.00	0.01	0.01	546.98	270.89	355.48	<5
CPP-CDM	0.06	0.03	0.01	-1.51	-14.92	-32.25	>35
CPP-CDR		0.34	0.04		9.23	93.41	<5
CPP-CSC	0.04	0.02	0.01	-2.91	-17.72	-48.47	>35
CPP-CSI	0.12	0.06	0.02	-0.07	-12.03	-22.51	>35
CPP-DFC	0.04	0.02	0.01	0.88	-10.14	-16.06	>35
CPP-DHR	0.23	0.12	0.04	0.43	-11.04	-18.85	>35
CPP-DSH		0.03	0.00		2.78	31.48	5-15
CPP-FFE		0.21	0.03		28.73	189.45	<5
CPP-HTM	0.05	0.03	0.01	-2.48	-16.87	-45.41	>35
CPP-KEP	0.00			42.51			<5
CPP-LKG	0.22			5.81			15-25
CPP-MLR		0.03	0.00		23.99	160.49	<5
CPP-RBH		0.79	0.13		47.20	302.52	<5
CPP-RBS	0.03	0.01	0.00	-2.21	-16.32	-39.07	>35
CPP-RFH	0.05	3.49	0.38	23.32	0.76	19.07	15-25
CPP-SCW	0.10	0.05	0.09	-74.18	-160.25	-69.95	>35
PUL-MHR	0.05	0.03	0.01	-0.19	-12.28	-23.31	>35
PUL-PMR		0.08	0.01		9.76	74.47	15-25
VFP-BFD		0.33	0.05		7.15	59.85	<5
VFP-EAD			0.00			73.21	<5
VFP-UDB			0.00			264.04	<5
VFP-WHD	0.02	0.16	0.02	-13.89	-2.05	-5.32	>35

Table 16: Energy efficiency measure analysis results for mechanical pulp mills

Measure	Energy Savings (GJ/t) Natural Gas	Energy Savings (GJ/t) Biomass	Energy Savings (GJ/t) Electricity	Cost of Saved Energy, d=20% (2020CAD/GJ) Natural Gas	Cost of Saved Energy, d=20% (2020CAD/GJ) Biomass	Cost of Saved Energy, d=20% (2020CAD/GJ) Electricity	IRR Category
ALL-APC	0.10	0.05	0.23	-29.03	-69.96	0.93	>35
ALL-APH		0.02			1.30		<5
ALL-ASD			0.05			6.33	>35
ALL-AWT		0.01			2.00		<5
ALL-BBP	0.02	0.01		4.37	-3.16		15-25
ALL-BBU	0.01	0.01		3.15	-5.59		25-35
ALL-BDP	0.00	0.00		1.79	-8.32		>35
ALL-BGE	1.02	-1.56		4.44			15-25
ALL-BHR	0.00	0.00		4.45	-2.99		15-25
ALL-BRE		0.12			26.17		<5
ALL-CAO			0.01			5.63	>35
ALL-CAU			0.01			1.55	>35
ALL-CDR		0.04			1.09		<5
ALL-DVC	0.00	0.00		3.30	-5.30		25-35
ALL-EAC	0.02	0.01		2.60	-6.70		>35
ALL-EFA			0.01			7.07	>35
ALL-EFL			0.02			11.77	25-35
ALL-FSU			0.04			0.69	>35
ALL-FWE		0.07			1.67		<5
ALL-HAI		0.06			3.06		<5
ALL-HRI		0.27			3.57		<5
ALL-HWS		0.09			4.45		<5
ALL-IER			0.08			-0.79	>35
ALL-INS	0.01	0.00		2.18	-7.53		>35
ALL-MDS			0.03			10.01	25-35
ALL-MMR			0.02			5.52	>35
All-MST			0.02			37.24	<5
ALL-MSU			0.03			2.12	>35
ALL-MVC			0.04			3.63	>35
ALL-PEM			0.12			3.10	>35
ALL-PFH		0.16			24.98		<5
ALL-PRM	0.02	0.01	0.03	-3.79	-19.48	8.55	25-35
ALL-PSU			0.09			1.57	>35
ALL-SRC	0.06	-0.08		1.71			>35

Measure	Energy Savings (GJ/t) Natural Gas	Biomass	Electricity	Cost of Saved Energy, d=20% (2020CAD/GJ) Natural Gas	Biomass	Electricity	IRR Category
ALL-SSO		0.14			2.20		<5
ALL-STS		0.19			3.87		<5
ALL-STU	0.13	0.06		0.70	-10.49		>35
BLE-BFR		0.07			5.01		<5
BLE-CPH	0.02	0.01		3.57	-4.75		25-35
BLE-OBC	-0.19	-0.38	0.03			175.92	<5
BLE-PHR	0.09	0.05		2.04	-7.81		>35
MPP-APT	-0.03	-0.10	0.25			0.70	>35
MPP-AQC			0.12			0.11	>35
MPP-ARS			0.18			0.14	>35
MPP-BTM	0.06	0.03		0.14	-11.61		>35
MPP-CSC			0.12			-0.11	>35
MPP-CTI			0.19			6.73	>35
MPP-HER			0.32			5.81	>35
MPP-RTS			0.19			20.83	15-25
MPP-THR		0.44	-0.13		6.72	-3.55	<5
MPP-TPP			0.10			0.00	>35
PUL-MHR		0.03			3.36		<5
PUL-PMR		0.03			-58.25		15-25
VFP-BFD		0.19			12.21		<5
VFP-EAD			0.00			78.53	<5
VFP-UDB			0.00			280.78	<5
VFP-WHD	0.02	0.02		3.49	-2.38		15-25

Table 17: Energy efficiency measure analysis results for print paper mills

Measure	Energy Savings (GJ/t) Natural Gas	Biomass	Electricity	Cost of Saved Energy, d=20% (2020CAD/GJ) Natural Gas	Biomass	Electricity	IRR Category
ALL-APC	0.19	0.10	0.23	-15.34	-42.57	-0.87	>35
ALL-APH		0.01	0.00		3.07	133.69	<5
ALL-ASD			0.05			5.64	>35
ALL-AWT		0.01	0.00		2.10	89.95	<5
ALL-BBP		0.05	0.00		1.54	64.96	<5
ALL-BBU		0.04	0.00		1.15	47.01	5-15
ALL-BDP	0.00	0.00	0.00	0.85	-10.21	-153.35	>35

	Energy Savings (GJ/t)			**Cost of Saved Energy, d=20% (2020CAD/GJ)**			
Measure	**Natural Gas**	**Biomass**	**Electricity**	**Natural Gas**	**Biomass**	**Electricity**	**IRR Category**
ALL-BGE	0.72	-1.56	0.21	2.32		3.33	25-35
ALL-BHR		0.01	0.00		1.65	69.25	<5
ALL-BRE		0.08			47.82		<5
ALL-CAO			0.01			5.21	>35
ALL-CAU			0.01			1.41	>35
ALL-CDR		0.02	0.00		2.38	102.69	<5
ALL-DVC		0.01	0.00		1.11	45.32	5-15
ALL-EAC	0.04	0.02	0.00	1.34	-9.23	-137.03	>35
ALL-EFA			0.01			6.11	>35
ALL-EFL			0.02			10.19	>35
ALL-FSU			0.05			0.63	>35
ALL-FWE		0.06	0.00		1.86	78.74	<5
ALL-HAI		0.04	0.00		5.52	208.11	<5
ALL-HRI		0.24	0.01		2.73	114.93	<5
ALL-HWS		0.11	0.00		3.75	140.78	<5
ALL-IER			0.08			-0.79	>35
ALL-INS	0.01	0.01	0.00	1.14	-9.62	-143.83	>35
ALL-MDS			0.03			8.65	>35
ALL-MMR			0.02			5.10	>35
All-MST			0.02			31.47	<5
ALL-MSU			0.04			1.95	>35
ALL-MVC			0.04			3.35	>35
ALL-PEM			0.13			2.85	>35
ALL-PFH		0.11			46.55		<5
ALL-PRM	0.04	0.02	0.03	-0.36	-12.62	7.30	25-35
ALL-PSU			0.10			1.44	>35
ALL-SRC	0.06	-0.08		1.94			>35
ALL-SSO		0.14	0.00		2.42	103.19	<5
ALL-STS		0.19			4.84		<5
ALL-STU	0.22	0.11	0.01	-0.06	-12.03	-196.61	>35
BLE-BFR		0.10	0.00		4.27	160.59	<5
BLE-CPH		0.07	0.00		1.26	51.91	5-15
BLE-OBC	-0.05	-0.10	0.03			114.80	<5
BLE-PHR	0.19	0.09	0.01	0.98	-9.95	-149.07	>35
CPP-ADA		0.01	0.00		1.82	77.16	<5
CPP-AEE		0.04			37.75		<5
CPP-BGK	0.41	-0.49		7.87			5-15
CPP-BLB		0.01	0.00		4.37	164.41	<5

	Energy Savings (GJ/t)			Cost of Saved Energy, d=20% (2020CAD/GJ)			
Measure	**Natural Gas**	**Biomass**	**Electricity**	**Natural Gas**	**Biomass**	**Electricity**	**IRR Category**
CPP-BLG		0.05	0.29		371.69	80.61	<5
CPP-BWP		0.02			26.78		<5
CPP-CDM		0.01	0.00		1.80	76.35	<5
CPP-CSC	0.01	0.00	0.00	-1.53	-14.97	-247.11	>35
CPP-CSI		0.03	0.00		3.02	127.58	<5
CPP-DFC		0.01	0.00		4.46	167.74	<5
CPP-DHR		0.06	0.00		3.85	144.44	<5
CPP-DSH		0.00			9.02		<5
CPP-FFE		0.03			75.70		<5
CPP-HTM	0.01	0.00	0.00	-0.48	-12.86	-211.18	>35
CPP-KEP	0.00	0.00		43.11			<5
CPP-LKG	0.07	-0.08		6.41			15-25
CPP-MLR		0.00			64.74		<5
CPP-RBH		0.09			127.26		<5
CPP-RBS	0.00	0.00	0.00	0.77	-10.36	-155.87	>35
CPP-RFH		0.82	0.02		3.09	130.82	<5
CPP-SCW	0.01	0.01	0.03	-163.57	-339.03	-76.53	>35
MPP-APT	0.00	0.00	0.06	402.52		0.01	>35
MPP-AQC			0.03			0.10	>35
MPP-BTM	0.02	0.01	0.00	-0.44	-12.77	-209.28	>35
MPP-HER			0.08			5.37	>35
MPP-THR		0.12	-0.03		5.21		<5
PNB-AFF	0.16	0.08	0.22	-22.01	-55.93	-3.88	>35
PNB-ASO		0.13	0.01		4.05	92.98	<5
PNB-BAO	0.03	0.02	0.00	0.50	-10.90	-164.45	>35
PNB-CNU	0.02	0.01	0.00	1.41	-9.08	-132.77	>35
PNB-DMS	0.06	0.03	0.00	0.72	-10.46	-157.44	>35
PNB-DSF		0.47	-0.11		41.20		<5
PNB-FWP	0.04	0.02	0.00	-2.73	-17.37	-288.06	>35
PNB-GPF			0.05			163.60	<5
PNB-HCF			0.04			249.19	<5
PNB-IMD		0.36	0.03		13.31	188.78	<5
PNB-IRD		0.90	-0.65		18.99		<5
PNB-IRP		0.07	-0.01		3.43		<5
PNB-MHR		0.17	0.00		4.73	177.80	<5
PNB-MWD		0.14	-0.18		25.22		<5
PNB-PRU		0.19	-0.01		21.07		<5
PNB-RFS	0.21	0.11	0.08	-1.94	-15.78	-5.11	25-35

	Energy Savings (GJ/t)			Cost of Saved Energy, d=20% (2020CAD/GJ)			
Measure	Natural Gas	Biomass	Electricity	Natural Gas	Biomass	Electricity	IRR Category
PNB-SHP		0.04			17.53		<5
PNB-SSI		0.09	0.00		1.38	57.46	5-15
PNB-TRB	0.08	0.04	0.00	-0.27	-12.43	-203.49	>35
PNB-VSO			0.01			0.00	>35
PNB-WBS		0.04			8.51		<5
RPB-DFO			0.00			9.45	>35
RPB-DHR		0.01	0.00		2.26	97.41	<5
RPB-HCR			0.00			59.76	<5
RPB-RPO			0.00			37.75	<5
SPB-CRR	0.02	0.01	0.04	-35.03	-81.95	-2.52	>35
SPB-DRP			0.01			25.77	5-15
SPB-RRU			0.03			15.03	15-25
VFP-BFD		0.07			24.01		<5
VFP-EAD			0.00			66.49	<5
VFP-UDB			0.00			240.17	<5
VFP-WHD	0.02	0.01	0.00	1.49	-8.91	-130.10	>35

Table 18: Energy efficiency measure analysis results for newsprint mills

	Energy Savings (GJ/t)			Cost of Saved Energy, d=20% (2020CAD/GJ)			
Measure	Natural Gas	Biomass	Electricity	Natural Gas	Biomass	Electricity	IRR Category
ALL-APC	0.23	0.11	0.24	-13.49	-38.89	-1.80	>35
ALL-APH		0.01	0.00		2.16	56.47	<5
ALL-ASD			0.05			5.77	>35
ALL-AWT		0.01	0.00		1.38	37.80	5-15
ALL-BBP		0.06	0.00		0.91	26.63	5-15
ALL-BBU		0.04	0.00		0.60	19.17	15-25
ALL-BDP		0.01	0.00		0.16	8.06	25-35
ALL-BGE	0.54	-1.56	0.27	1.12		6.70	25-35
ALL-BHR		0.01	0.00		1.00	28.74	5-15
ALL-BRE		0.07			53.95		<5
ALL-CAO			0.01			5.26	>35
ALL-CAU			0.01			1.47	>35
ALL-CDR		0.03	0.00		1.59	42.92	5-15
ALL-DVC		0.01	0.00		0.57	18.42	15-25
ALL-EAC		0.08	0.00		0.34	12.73	15-25

	Energy Savings (GJ/t)			Cost of Saved Energy, d=20% (2020CAD/GJ)			
Measure	**Natural Gas**	**Biomass**	**Electricity**	**Natural Gas**	**Biomass**	**Electricity**	**IRR Category**
ALL-EFA			0.01			6.34	>35
ALL-EFL			0.02			10.53	>35
ALL-FSU			0.05			0.66	>35
ALL-FWE		0.04	0.00		2.67	68.50	<5
ALL-HAI		0.03	0.00		6.88	165.19	<5
ALL-HRI		0.22	0.01		2.77	70.54	<5
ALL-HWS		0.11	0.00		3.69	90.92	<5
ALL-IER			0.08			-0.79	>35
ALL-INS		0.03	0.00		0.25	10.43	25-35
ALL-MDS			0.03			8.97	>35
ALL-MMR			0.02			5.17	>35
All-MST			0.02			32.81	<5
ALL-MSU			0.04			2.01	>35
ALL-MVC			0.04			3.40	>35
ALL-PEM			0.13			2.92	>35
ALL-PFH		0.09			52.76		<5
ALL-PRM	0.05	0.03	0.03	-0.85	-13.60	5.70	>35
ALL-PSU			0.09			1.49	>35
ALL-SRC		-0.01	0.00			137.47	<5
ALL-SSO		0.09	0.00		3.65	91.29	<5
ALL-STS		0.19	0.01		3.60	58.70	<5
ALL-STU	0.24	0.12	0.01	-0.58	-13.05	-104.19	>35
MPP-APT	-0.01	-0.02	0.21			0.01	>35
MPP-AQC			0.10			0.10	>35
MPP-ARS			0.15			0.13	>35
MPP-BTM	0.10	0.05	0.01	-0.92	-13.74	-110.35	>35
MPP-CSC			0.10			-0.11	>35
MPP-CTI			0.17			6.12	>35
MPP-HER			0.28			5.43	>35
MPP-RTS			0.17			18.62	15-25
MPP-THR		0.22	-0.05		5.11		<5
MPP-TPP			0.09			0.00	>35
PNB-AFF	0.19	0.09	0.22	-19.15	-50.19	-4.62	>35
PNB-ASO		0.13	0.01		3.97	70.81	<5
PNB-BAO	0.03	0.02	0.00	-0.14	-12.18	-89.07	>35
PNB-DMS	0.07	0.03	0.00	0.05	-11.79	-85.87	>35
PNB-DSF		0.48	-0.10		40.31		<5
PNB-FWP	0.04	0.02	0.00	-2.86	-17.63	-144.99	>35

		Energy Savings (GJ/t)			Cost of Saved Energy, d=20% (2020CAD/GJ)		
Measure	**Natural Gas**	**Biomass**	**Electricity**	**Natural Gas**	**Biomass**	**Electricity**	**IRR Category**
PNB-GPF			0.05			168.99	<5
PNB-HCF			0.04			256.40	<5
PNB-IMD		0.34	0.03		13.67	157.64	<5
PNB-IRP		0.08	-0.01		2.49		<5
PNB-MHR		0.17	0.01		4.62	112.68	<5
PNB-MWD		0.24	-0.18		15.28		<5
PNB-PRU		0.20			20.23		<5
PNB-RFS	0.56	0.28	0.19	-2.19	-16.29	-7.61	25-35
PNB-SSI		0.11	0.00		0.78	23.54	15-25
PNB-TRB	0.09	0.05	0.01	-0.77	-13.44	-107.66	>35
PNB-VSO			0.01			0.00	>35
PNB-WBS		0.04			8.66		<5
VFP-BFD		0.10			26.60		<5
VFP-EAD			0.00			69.12	<5
VFP-UDB			0.00			247.13	<5
VFP-WHD		0.08	0.00		0.50	16.73	15-25

Table 19: Energy efficiency measure analysis results for paperboard mills

		Energy Savings (GJ/t)			Cost of Saved Energy, d=20% (2020CAD/GJ)		
Measure	**Natural Gas**	**Biomass**	**Electricity**	**Natural Gas**	**Biomass**	**Electricity**	**IRR Category**
ALL-APC	0.24	0.12	0.23	-11.81	-35.52	-2.31	>35
ALL-APH	0.01	0.00		4.55	-2.81		25-35
ALL-ASD			0.05			5.71	>35
ALL-AWT	0.01	0.00		2.91	-6.08		>35
ALL-BBP	0.04	0.02		2.28	-7.33		>35
ALL-BBU	0.03	0.01		1.78	-8.35		>35
ALL-BDP	0.00	0.00		1.06	-9.79		>35
ALL-BGE	1.30	-1.56		4.02			25-35
ALL-BHR	0.01	0.00		2.26	-7.38		>35
ALL-BMG				0.00		0.00	<5
ALL-BRE		0.16			24.23		<5
ALL-BSB	0.77	-1.94		12.96			<5
ALL-CAO			0.01			5.34	>35
ALL-CAU			0.01			1.41	>35

	Energy Savings (GJ/t)			Cost of Saved Energy, d=20% (2020CAD/GJ)			
Measure	Natural Gas	Biomass	Electricity	Natural Gas	Biomass	Electricity	IRR Category
ALL-CDR	0.02	0.01		3.58	-4.74		25-35
ALL-DVC	0.01	0.00		1.73	-8.44		>35
ALL-EAC	0.05	0.03		1.36	-9.19		>35
ALL-EFA			0.01			6.21	>35
ALL-EFL			0.02			10.45	>35
ALL-FSU			0.05			0.63	>35
ALL-FWE	0.03	0.01		5.37	-1.16		15-25
ALL-HAI	0.02	0.01		11.74	11.58		5-15
ALL-HRI	0.15	0.07		4.94	-2.02		25-35
ALL-HWS	0.07	0.04		6.31	0.72		15-25
ALL-IER			0.08			-0.79	>35
ALL-INS	0.02	0.01		1.21	-9.49		>35
ALL-MDS			0.03			8.81	>35
ALL-MMR			0.02			5.22	>35
All-MST			0.02			32.86	<5
ALL-MSU			0.04			1.96	>35
ALL-MVC			0.04			3.42	>35
ALL-PEM			0.13			2.88	>35
ALL-PFH		0.21			23.39		<5
ALL-PRM	0.06	0.03	0.03	0.05	-11.80	4.95	>35
ALL-PSU			0.10			1.43	>35
ALL-SRC	0.06	-0.08		1.94			>35
ALL-SSO	0.05	0.03		7.37	2.83		15-25
ALL-STS	0.19			4.84			25-35
ALL-STU	0.28	0.14		0.28	-11.35		>35
PNB-AFF	0.20	0.10	0.21	-17.06	-46.03	-5.24	>35
PNB-ASO	0.09	0.04	0.00	6.74	1.59	33.91	15-25
PNB-BAO	0.04	0.02		0.77	-10.36		>35
PNB-CNU	0.03	0.01		1.45	-9.00		>35
PNB-DMS	0.08	0.04		0.94	-10.01		>35
PNB-DSF		0.70	-0.12		28.21		<5
PNB-FWP	0.05	0.02		-1.83	-15.56		>35
PNB-GPF			0.05			170.92	<5
PNB-HCF			0.04			261.33	<5
PNB-IMD		0.39	0.02		12.77	291.85	<5
PNB-IRP	0.05	0.03	-0.01	4.64	-2.62		>35
PNB-MHR	0.11	0.05		7.94	3.98		5-15
PNB-MWD		0.24	-0.18		15.28		<5

	Energy Savings (GJ/t)			Cost of Saved Energy, d=20% (2020CAD/GJ)			
Measure	**Natural Gas**	**Biomass**	**Electricity**	**Natural Gas**	**Biomass**	**Electricity**	**IRR Category**
PNB-PRU		0.30	-0.01		13.84		<5
PNB-RFS	0.18	0.09	0.05	-1.20	-14.30	-10.41	25-35
PNB-SSI	0.07	0.04		1.93	-8.03		>35
PNB-TRB	0.10	0.05		0.12	-11.66		>35
PNB-VSO			0.01			0.00	>35
PNB-WBS	0.02	0.01		13.68	15.47		5-15
RPB-CLR	0.17	0.09		2.39	-7.12		>35
RPB-DFO			0.02			9.65	>35
RPB-DHR	0.03	0.01		3.12	-5.66		>35
RPB-FRR	0.10	0.05		0.45	-11.00		>35
RPB-HCR			0.01			62.74	<5
RPB-RPO			0.02			39.49	<5
SPB-CRR	0.04	0.02	0.07	-27.28	-66.46	-3.37	>35
SPB-DRP			0.03			26.77	5-15
SPB-RRU			0.06			15.43	15-25

Appendix F: Detailed energy saving bandwidth results

Table 20: Summary of energy saving bandwidths by energy source and mill type

Fuel type		Biomass					Natural Gas					Electricity				
Mill type		**CP**	**MP**	**PP**	**NP**	**PB**	**CP**	**MP**	**PP**	**NP**	**PB**	**CP**	**MP**	**PP**	**NP**	**PB**
Baseline SEC (GJ/t)		32.17	3.70	8.90	12.38	8.72	5.45	1.60	2.67	2.25	4.80	2.76	7.64	6.31	11.36	4.23
Economic Savings Bandwidth (GJ/t)	IRR >35%	-0.38	0.04	0.48	0.51	0.77	3.74	0.48	1.19	1.05	1.76	2.37	2.01	1.30	2.22	1.15
	IRR 25-35%	0.13	0.03	-1.43	-1.25	-1.39	0.00	0.06	0.98	1.10	1.84	0.10	0.07	0.32	0.47	0.05
	IRR 15-25%	3.57	-1.50	-0.08	0.33	0.12	0.27	1.06	0.07	0.00	0.23	0.40	0.19	0.03	0.19	0.06
	IRR 5-15%	-1.59	0.00	-0.29	0.12	0.08	1.35	0.00	0.41	0.00	0.15	0.00	0.00	0.02	0.00	0.03
Economic min. (GJ/t)		30.44	5.14	10.22	12.68	9.14	0.08	0.00	0.02	0.10	0.81	-0.11	5.37	4.64	8.48	2.94
Savings vs. Baseline		5%	-39%	-15%	-2%	-5%	98%	100%	99%	96%	83%	104%	30%	26%	25%	31%
Technical Savings Bandwidth (GJ/t)	IRR <5%	2.67	1.51	4.99	2.83	0.05	0.01	0.00	0.00	0.00	0.77	1.48	0.05	0.54	0.21	0.15
Technical min. (GJ/t)		27.77	3.63	5.22	9.85	9.08	0.08	0.00	0.02	0.10	0.04	-1.59	5.32	4.11	8.27	2.80
Savings vs. Baseline		14%	2%	41%	20%	-4%	99%	100%	99%	96%	99%	158%	30%	35%	27%	34%

Appendix G: Selected inputs for LEAP upstream modules

Table 21: Selected electricity grid emissions factors for LEAP scenario analysis [114, 115]

	Grid emissions factor ($g_{CO2e/kWh}$)			
	2020	**2030**	**2040**	**2050**
British Columbia	3	1	1	1
Alberta	500	307	263	264
Saskatchewan	495	255	274	74
Manitoba	1	0	2	6
Ontario	12	14	17	17
Quebec	6	4	3	1
Newfoundland and Labrador	16	14	28	31
New Brunswick	264	246	304	175
Nova Scotia	459	281	187	134

Table 22: Selected LEAP upstream natural gas emissions factors [38, 116, 118]

Parameter Description	Region	Units	2020	2025	2030	2035	2040	2045	2050
Natural gas transmission and distribution fugitives	All	tCO2e per TJ	2.11E-07	2.11E-07	2.11E-07	2.11E-07	2.11E-07	2.11E-07	2.11E-07
Natural gas transmission and distribution venting	All	tCO2e per TJ	2.11E-08	2.11E-08	2.11E-08	2.11E-08	2.11E-08	2.11E-08	2.11E-08
Natural gas transmission and distribution other emissions	All	tCO2e per TJ	4.84E-07	4.84E-07	4.84E-07	4.84E-07	4.84E-07	4.84E-07	4.84E-07
Natural gas production venting	All	tCO2e per TJ	1.50E+00	1.50E+00	1.50E+00	1.50E+00	1.50E+00	1.50E+00	1.50E+00
Natural gas production flaring	All	tCO2e per TJ	1.91E-01	1.91E-01	1.91E-01	1.91E-01	1.91E-01	1.91E-01	1.91E-01
Natural gas production fugitives	All	tCO2e per TJ	1.41E+00	1.41E+00	1.41E+00	1.41E+00	1.41E+00	1.41E+00	1.41E+00
Natural gas upstream processing energy use	British Columbia	GJ per GJ	5.81E-02	5.81E-02	5.81E-02	5.81E-02	5.81E-02	5.81E-02	5.81E-02
Natural gas upstream processing energy use	Alberta	GJ per GJ	9.15E-02	9.15E-02	9.15E-02	9.15E-02	9.15E-02	9.15E-02	9.15E-02
Natural gas upstream processing energy use	Saskatchewan	GJ per GJ	4.91E-01	4.91E-01	4.91E-01	4.91E-01	4.91E-01	4.91E-01	4.91E-01
Natural gas upstream processing energy use	New Brunswick	GJ per GJ	4.83E-01	4.83E-01	4.83E-01	4.83E-01	4.83E-01	4.83E-01	4.83E-01
Natural gas upstream processing energy use	Nova Scotia	GJ per GJ	1.03E-01	1.03E-01	1.03E-01	1.03E-01	1.03E-01	1.03E-01	1.03E-01
Natural gas upstream processing energy use	Newfoundland	GJ per GJ	9.47E-01	9.47E-01	9.47E-01	9.47E-01	9.47E-01	9.47E-01	9.47E-01

Appendix H: Sample energy prices

Table 23: Sample industrial delivered energy prices for LEAP scenario analysis [96]

Province	Electricity price (2020CAD/GJ)		Natural gas price (2020CAD/GJ)		Fuel oil price (2020CAD/GJ)	
	2020	**2050**	**2020**	**2050**	**2020**	**2050**
Alberta	15.46	21.61	2.23	4.31	27.60	31.44
British Columbia	24.54	31.35	10.41	12.84	28.50	30.51
Manitoba	15.58	20.66	7.08	8.40	34.83	38.82
New Brunswick	24.2	34.04	6.75	8.06	23.58	27.28
Newfoundland and Labrador	26.15	37.89	6.29	8.19	16.58	22.69
Nova Scotia	31.49	37.31	7.05	10.80	24.24	29.40
Ontario	41.03	40.98	7.94	9.25	21.09	26.13
Quebec	16.17	21.33	9.14	11.40	21.90	26.66
Saskatchewan	27.65	31.26	5.91	7.21	29.70	33.32

Appendix I: Out of scope technologies

Table 24: Out of scope technology summary

Technology category	Reasons for exclusion
Precommercial technologies	• Lack of reliable cost and performance data at commercial scale.
Carbon capture and sequestration	• Complimentary abatement option (distinct parallel pathway to energy efficiency). • Increases energy use and therefore does not align with the EEM categories adopted in the study. • Insufficient data on P&P-specific implementation. • Costs depend in part on proximity and means of sequestration which are highly variable.
Fuel switching from electricity to steam and/or fuels	• Tendency to increase emissions given electricity emissions intensity relative to fuels. • Runs contrary to general trends towards electrification and away from fossil fuel use.
Low-carbon fuel imports (renewable natural gas, hydrogen, biofuels, etc.)	• Focus of this study is on fuels that are readily-available to the sector rather than imports of new fuel types. • Does not inherently reduce energy consumption (complimentary pathway to energy efficiency). • Lack of data on costs required to adapt processes to new fuel types.
Major sector structure changes	• Focus of this study is on potential to improve efficiency for the sector in its current state. • Major changes in production mix or balance of mill types are driven by market forces; energy and emissions impacts are a secondary consideration. • Lack of data on costs/benefits of total mill conversions (or retire-and-replace pathway). • Lack of data on costs/benefits/energy impacts of new product lines such as biorefinery concepts.

Appendix J: Marginal abatement cost results

Table 25: Marginal abatement cost curve scenario legend

MAC Curve Label	Scenario Designation
1	PNB VSO
2	RPB DFO
3	MPP APT
4	SPB RRU
5	MPP AQC
6	ALL IER
7	MPP TPP
8	MPP ARS
9	MPP CSC
10	ALL FSU
11	ALL CAU
12	ALL PSU
13	ALL MSU
14	MPP HER
15	ALL PEM
16	ALL MVC
17	ALL MMR
18	ALL CAO
19	ALL ASD
20	MPP CTI
21	ALL MDS
22	CPP SCW
23	SPB DRP
24	SPB CRR
25	ALL SRC
26	MPP RTS
27	PNB AFF
28	ALL APC
29	ALL BGE
30	ALL PRM
31	VFP WHD
32	ALL STS
33	CPP CSC
34	CPP HTM
35	CPP RBS
36	CPP CDM
37	BLE CPH
38	CPP ADA
39	MPP THR

MAC Curve Label	Scenario Designation
40	PNB FWP
41	BLE PHR
42	ALL STU
43	ALL DVC
44	ALL BBU
45	ALL BDP
46	ALL INS
47	ALL BBP
48	ALL CDR
49	ALL EAC
50	ALL BHR
51	PNB RFS
52	PUL MHR
53	CPP CSI
54	ALL APH
55	CPP RFH
56	ALL HRI
57	ALL FWE
58	CPP DHR
59	CPP BLB
60	MPP BTM
61	CPP DFC
62	BLE BFR
63	PNB TRB
64	ALL SSO
65	ALL HWS
66	PNB DMS
67	RPB FRR
68	PNB CNU
69	All MST
70	PNB SSI
71	RPB CLR
72	RPB DHR
73	CPP LKG
74	CPP BGK
75	PNB ASO
76	PNB IRP
77	CPP DSH
78	ALL BSB
79	PNB MHR
80	RPB RPO
81	PNB WBS

MAC Curve Label	**Scenario Designation**
82	ALL HAI
83	CPP KEP
84	PNB MWD
85	PNB BAO
86	CPP BLC
87	PUL PMR
88	CPP CDR
89	CPP BLG
90	VFP EAD
91	CPP BWP
92	VFP BFD
93	ALL AHO
94	ALL AWT
95	CPP BDM
96	CPP AEE
97	ALL EFA
98	RPB HCR
99	CPP MLR
100	PNB IRD
101	PNB DSF
102	PNB IMD
103	CPP FFE
104	ALL BRE
105	PNB SHP
106	CPP RBH
107	ALL EFL
108	PNB PRU
109	VFP UDB
110	CPP BWU
111	PNB GPF
112	ALL PFH
113	PNB HCF
114	ALL BMG
115	BLE OBC

Table 26: Scenario marginal abatement cost results

	Penetration Level (%)		Annual Abatement – Sector Boundary (ktCO$_2$e/yr)		Cumulative Abatement through 2050 (MtCO$_2$e)		Marginal Abatement Cost, cumulative to 2050 ($/tCO$_2$e)	
Scenario	**2030**	**2050**	**2030**	**2050**	**Sector**	**System**	**Sector**	**System**
ALL-AHO	8%	8%	0.49	0.48	0.01	0.02	584.0	430.8
ALL-APC	50%	50%	445.14	423.15	11.57	17.32	-214.5	-117.0
ALL-APH	4%	7%	9.23	10.56	0.26	0.31	-77.0	-63.7
ALL-ASD	40%	40%	21.46	15.73	0.53	1.41	-656.4	-169.4
ALL-AWT	8%	11%	0.20	0.18	0.01	0.01	601.6	394.8
ALL-BBP	28%	39%	48.66	51.85	1.31	1.60	-81.0	-68.2
ALL-BBU	30%	43%	33.63	35.91	0.91	1.11	-82.8	-69.5
ALL-BDP	18%	20%	5.32	5.49	0.14	0.17	-82.4	-71.1
ALL-BGE	27%	50%	264.10	640.14	10.73	16.16	-170.9	-85.8
ALL-BHR	11%	16%	10.20	10.89	0.27	0.34	-79.9	-67.4
ALL-BMG	0%	19%	0.00	0.00	0.00	0.00	N/A	0.0
ALL-BRE	0%	6%	0.00	4.78	0.04	0.06	1662.7	996.8
ALL-BSB	0%	8%	0.00	55.01	0.45	0.51	39.3	151.0
ALL-CAO	75%	75%	2.92	2.14	0.07	0.19	-667.0	-173.4
ALL-CAU	75%	75%	4.65	3.41	0.11	0.30	-750.2	-205.8
ALL-CDR	8%	13%	17.64	20.17	0.49	0.60	-80.5	-66.6
ALL-DVC	11%	16%	10.76	11.49	0.29	0.35	-83.0	-69.7
ALL-EAC	30%	33%	72.25	74.57	1.92	2.33	-80.4	-69.5
ALL-EFA	25%	25%	0.52	0.39	0.01	0.03	961.6	414.8
ALL-EFL	42%	66%	0.24	0.49	0.01	0.03	2721.1	901.4
ALL-FSU	75%	75%	20.94	15.38	0.52	1.36	-767.2	-212.3
ALL-FWE	8%	14%	30.03	34.40	0.83	1.02	-74.0	-61.4
ALL-HAI	0%	8%	0.00	1.54	0.01	0.01	162.8	131.9
ALL-HRI	20%	31%	222.18	247.51	6.09	7.48	-74.6	-61.6
ALL-HWS	14%	24%	73.45	85.16	2.04	2.51	-66.7	-55.6
ALL-IER	75%	75%	34.66	25.39	0.86	2.24	-797.9	-224.8
ALL-INS	45%	50%	23.11	23.85	0.61	0.75	-81.6	-70.4
ALL-MDS	69%	75%	12.51	10.28	0.32	0.89	-597.2	-141.2
ALL-MMR	50%	50%	10.09	7.39	0.25	0.66	-669.1	-174.3
All-MST	0%	29%	0.00	2.54	0.02	0.05	-50.4	40.6
ALL-MSU	75%	75%	16.31	11.96	0.40	1.06	-740.5	-201.5
ALL-MVC	50%	50%	16.24	11.90	0.40	1.06	-711.2	-189.7
ALL-PEM	75%	75%	56.99	41.79	1.41	3.69	-720.0	-195.4
ALL-PFH	0%	12%	0.00	1.29	0.01	0.01	5631.7	4823.0
ALL-PRM	57%	75%	83.76	93.20	2.30	3.20	-121.3	-75.6
ALL-PSU	75%	75%	41.54	30.49	1.03	2.70	-750.0	-205.8
ALL-SRC	24%	26%	112.02	89.46	2.81	5.32	-430.4	-172.2

	Penetration Level (%)		Annual Abatement – Sector Boundary (ktCO$_2$e/yr)		Cumulative Abatement through 2050 (MtCO$_2$e)		Marginal Abatement Cost, cumulative to 2050 ($/tCO$_2$e)	
Scenario	**2030**	**2050**	**2030**	**2050**	**Sector**	**System**	**Sector**	**System**
ALL-SSO	31%	54%	60.37	69.00	1.67	2.05	-67.5	-56.2
ALL-STS	5%	24%	14.07	52.60	0.75	1.12	-111.4	-53.1
ALL-STU	50%	50%	421.75	428.85	11.14	13.45	-83.6	-74.2
BLE-BFR	17%	24%	51.29	52.82	1.36	1.68	-70.3	-57.5
BLE-CPH	15%	21%	42.14	45.03	1.14	1.40	-88.6	-72.3
BLE-OBC	0%	6%	0.00	0.00	0.00	0.02	N/A	1688.7
BLE-PHR	22%	22%	258.33	264.82	6.85	8.35	-84.4	-72.1
CPP-ADA	19%	21%	15.54	15.88	0.41	0.51	-88.5	-71.9
CPP-AEE	0%	6%	0.00	5.68	0.05	0.08	724.7	434.4
CPP-BDM	0%	2%	0.00	4.62	0.04	0.07	602.9	358.1
CPP-BGK	0%	13%	0.00	263.25	2.11	2.48	-3.8	-11.2
CPP-BLB	12%	14%	12.91	13.19	0.34	0.42	-71.5	-58.4
CPP-BLC	0%	4%	0.00	2.65	0.02	0.04	260.0	179.1
CPP-BLG	0%	9%	0.00	88.20	0.74	1.57	478.9	262.8
CPP-BWP	0%	3%	0.00	1.00	0.01	0.01	537.6	331.2
CPP-BWU	0%	2%	0.00	0.51	0.00	0.01	3378.4	1622.2
CPP-CDM	6%	7%	27.64	28.26	0.73	0.90	-88.6	-72.0
CPP-CDR	0%	1%	0.00	5.23	0.04	0.07	421.6	270.3
CPP-CSC	9%	9%	21.65	22.18	0.57	0.70	-96.7	-80.4
CPP-CSI	12%	14%	60.84	62.20	1.61	1.99	-77.9	-63.5
CPP-DFC	19%	21%	19.36	19.79	0.51	0.63	-70.9	-58.0
CPP-DHR	12%	14%	112.94	115.42	2.99	3.69	-73.8	-60.3
CPP-DSH	0%	6%	0.00	0.50	0.00	0.01	28.2	49.2
CPP-FFE	0%	5%	0.00	4.18	0.03	0.06	1439.3	811.7
CPP-HTM	22%	23%	26.12	26.75	0.69	0.85	-93.2	-77.7
CPP-KEP	0%	6%	0.00	0.35	0.00	0.00	187.1	144.7
CPP-LKG	9%	35%	29.55	120.10	1.65	1.93	-14.5	-22.9
CPP-MLR	0%	9%	0.00	0.51	0.00	0.01	1186.2	675.5
CPP-RBH	0%	6%	0.00	15.67	0.13	0.23	2456.4	1360.7
CPP-RBS	15%	15%	14.33	14.66	0.38	0.47	-91.7	-75.7
CPP-RFH	7%	31%	46.13	161.06	2.39	3.79	-75.2	-13.0
CPP-SCW	15%	15%	76.74	72.38	2.00	2.93	-569.0	-347.7
MPP-APT	9%	9%	21.72	11.59	0.51	1.16	-1126.4	-318.9
MPP-AQC	14%	13%	14.01	8.97	0.34	0.68	-856.0	-278.2
MPP-ARS	9%	9%	18.48	11.62	0.44	0.83	-778.9	-275.1
MPP-BTM	9%	9%	30.82	29.53	0.79	0.93	-71.5	-74.3
MPP-CSC	4%	4%	12.32	7.75	0.29	0.55	-778.7	-277.3
MPP-CTI	4%	4%	20.10	12.62	0.48	0.90	-643.7	-203.2
MPP-HER	14%	13%	37.35	23.91	0.89	1.82	-725.1	-214.4

	Penetration Level (%)		Annual Abatement – Sector Boundary (ktCO_2e/yr)		Cumulative Abatement through 2050 (MtCO_2e)		Marginal Abatement Cost, cumulative to 2050 (\$/tCO_2e)	
Scenario	**2030**	**2050**	**2030**	**2050**	**Sector**	**System**	**Sector**	**System**
MPP-RTS	2%	8%	5.70	14.19	0.25	0.55	-360.9	-48.0
MPP-THR	0%	2%	0.00	87.53	0.70	0.67	-86.5	23.2
MPP-TPP	3%	3%	10.51	6.61	0.25	0.47	-779.9	-276.4
PNB-AFF	17%	17%	118.42	111.92	3.05	5.58	-345.4	-154.1
PNB-ASO	2%	15%	4.05	17.47	0.23	0.28	1.1	-7.9
PNB-BAO	17%	17%	0.13	0.08	0.00	0.01	259.1	220.2
PNB-CNU	7%	8%	1.89	1.98	0.05	0.06	-50.9	-56.7
PNB-DMS	26%	25%	40.09	40.25	1.05	1.23	-60.6	-65.5
PNB-DSF	0%	3%	0.00	17.56	0.14	0.07	1407.6	2992.0
PNB-FWP	26%	25%	25.43	25.51	0.67	0.78	-85.6	-86.0
PNB-GPF	0%	7%	0.00	1.40	0.01	0.04	5026.1	1359.7
PNB-HCF	0%	6%	0.00	1.29	0.01	0.04	8398.3	2219.4
PNB-IMD	0%	6%	0.00	3.66	0.03	0.05	1420.1	918.8
PNB-IRD	0%	1%	0.00	2.34	0.02	0.02	1404.7	1703.2
PNB-IRP	2%	4%	9.58	10.09	0.26	0.22	12.4	-6.1
PNB-MHR	0%	6%	0.00	8.11	0.06	0.08	75.7	59.5
PNB-MWD	0%	6%	0.00	7.33	0.06	0.03	206.9	511.7
PNB-PRU	0%	8%	0.00	1.56	0.01	0.01	3312.8	6439.5
PNB-RFS	2%	9%	45.07	165.96	2.37	3.11	-78.3	-54.6
PNB-SHP	0%	1%	0.00	0.16	0.00	0.00	2351.9	1920.1
PNB-SSI	5%	9%	13.67	15.14	0.37	0.44	-43.2	-47.4
PNB-TRB	16%	16%	54.98	55.22	1.44	1.69	-67.6	-71.3
PNB-VSO	25%	24%	1.02	0.74	0.02	0.12	-1674.9	-248.9
PNB-WBS	0%	6%	0.00	2.09	0.02	0.02	147.3	117.1
PUL-MHR	12%	14%	24.79	25.36	0.66	0.81	-78.0	-63.8
PUL-PMR	6%	25%	1.76	6.09	0.09	0.14	400.2	270.1
RPB-CLR	6%	6%	31.93	33.57	0.85	0.99	-34.7	-42.8
RPB-DFO	9%	9%	0.58	0.51	0.02	0.14	-1587.2	-147.2
RPB-DHR	7%	7%	4.66	4.92	0.12	0.15	-32.0	-40.5
RPB-FRR	6%	6%	18.80	19.76	0.50	0.58	-55.7	-59.9
RPB-HCR	0%	3%	0.00	0.08	0.00	0.00	1177.5	245.7
RPB-RPO	0%	3%	0.00	0.16	0.00	0.01	100.8	53.6
SPB-CRR	8%	8%	15.13	15.19	0.40	0.99	-455.7	-161.3
SPB-DRP	0%	3%	0.00	0.38	0.00	0.02	-464.3	-42.4
SPB-RRU	3%	13%	0.71	2.31	0.04	0.23	-1037.1	-114.5
VFP-BFD	0%	9%	0.00	6.73	0.06	0.09	548.6	342.0
VFP-EAD	0%	4%	0.00	0.08	0.00	0.00	528.7	289.2
VFP-UDB	0%	9%	0.00	0.53	0.00	0.01	3342.9	1499.5
VFP-WHD	28%	36%	23.26	25.11	0.63	0.83	-120.6	-79.3

Appendix K: Annual cost impacts

Table 27: Annual cost impacts

	Scenario IRR before carbon price	A **Annualized capital, and O&M costs** Million 2020CAD	B **Annual avoided energy costs** Million 2020CAD	C **Annual avoided carbon costs*** Million 2020CAD	D = A-B-C **Net annual cost** Million 2020CAD	E **Annual emissions abatement** $MtCO_2e/yr$	F = (A-B)/E **Average abatement cost (annual)** $\$/tCO_2e$
2030	> 35% (55 measures)	57	1,362	445	-1,750	2.42	-539
	15% - 35% (19 measures)	91	333	158	-400	0.93	-260
	<15% (44 measures)	22	34	13	-24	0.06	-182
	Total	**171**	**1,730**	**615**	**-2,174**	**3.41**	**-457**
2050	> 35% (55 measures)	63	1,583	423	-1,943	2.32	-656
	15% - 35% (19 measures)	197	614	271	-688	1.60	-261
	<15% (44 measures)	1,118	489	142	487	0.72	868
	Total	**1,378**	**2,686**	**837**	**-2,145**	**4.64**	**-282**

Appendix L: Sensitivity analysis results

Table 28: Sensitivity analysis parameters

Sensitivity Variable	Low Case	High Case	Notes
Sector Boundary			
Discount rate for NPV calculation	2%	30%	Rate used for discounting costs/benefits
Energy prices	-50%	+50%	Change relative to base case
EEM adoption rates	Slow	Fast	Slow: H 5%, M 2%, L 0% Fast: H 20%, M 11%, L 3%
EEM energy savings	-50%	+25%	Change relative to base case
EEM implementation costs	-25%	+100%	Change relative to base case
System Boundary			
Upstream natural gas emissions factor	-80%	+400%	Change relative to base case
Electricity grid emissions intensity	Net-zero by 2035	N/A	Rapid grid decarbonization case

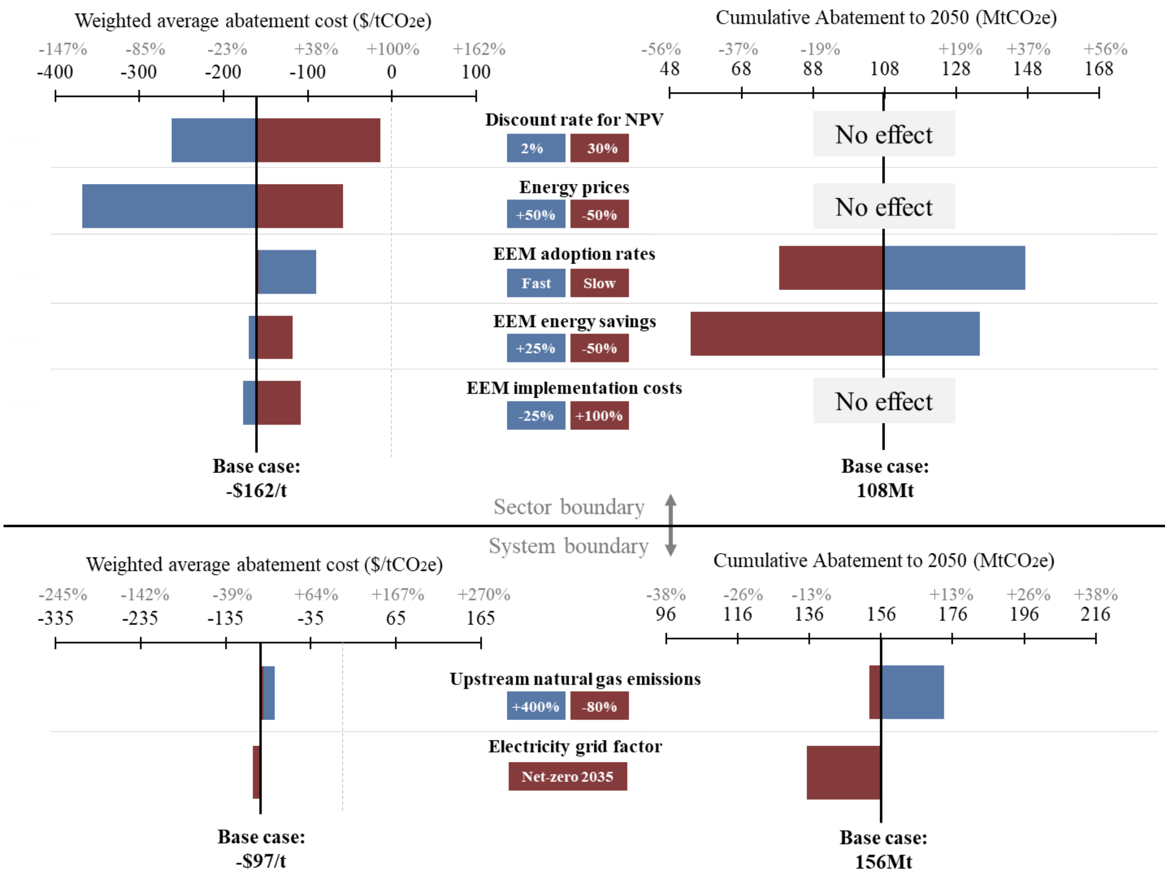
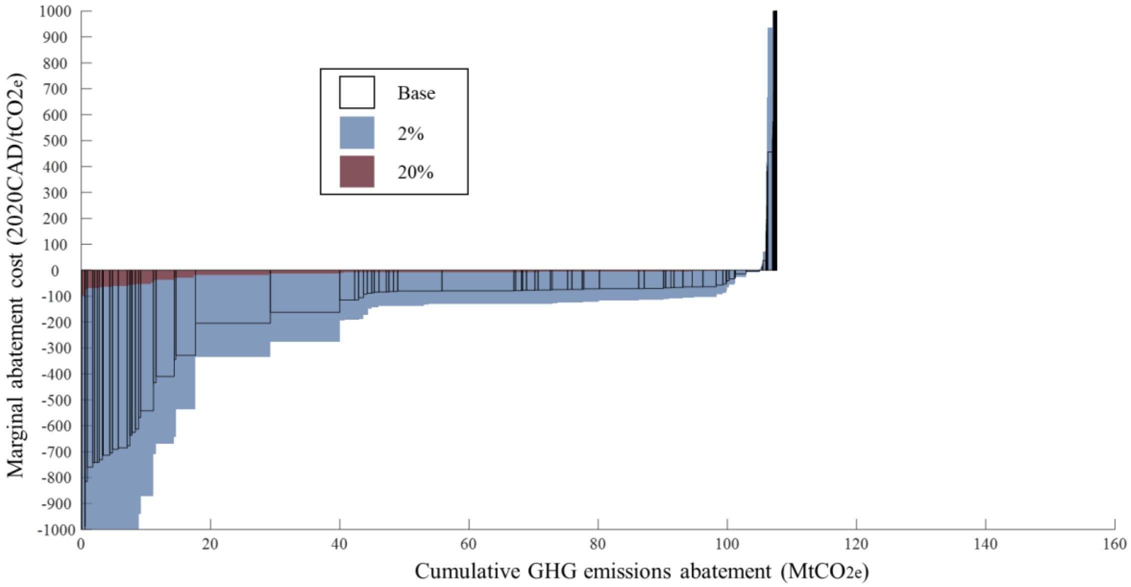


Figure 58: Sensitivity analysis results summary

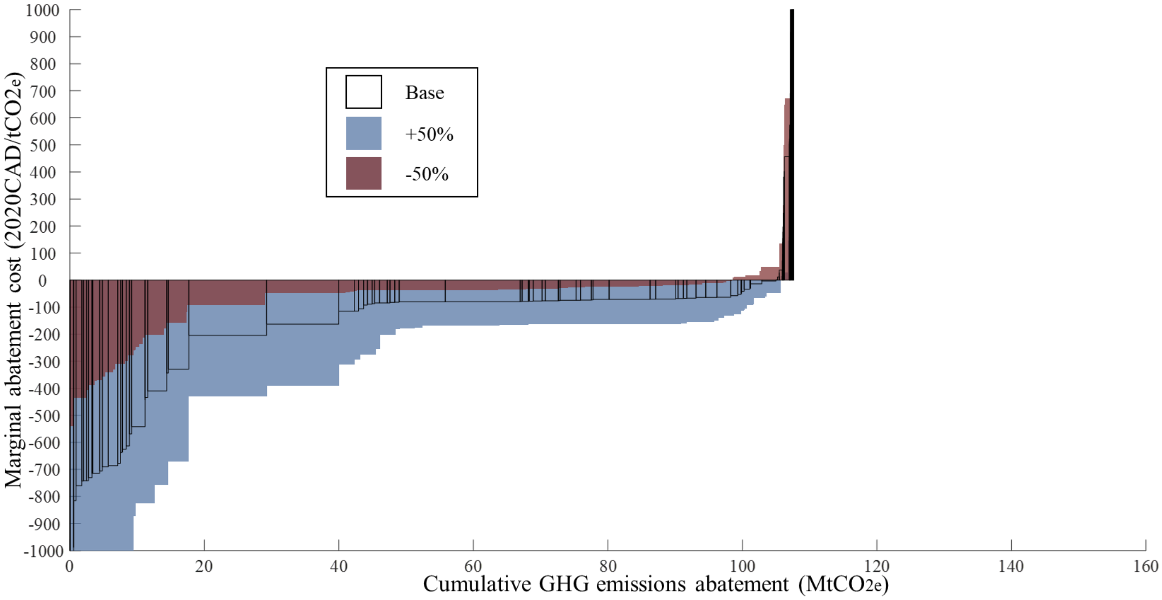
Table 29: Sensitivity analysis results

Sensitivity Variable	Cumulative Abatement to 2050 (MtCO2e)		Average abatement cost 2050 ($/tCO2e)	
	Low	High	Low	High
Sector boundary				
Discount rate for NPV calculation	Unchanged		-261	-15
Energy prices	Unchanged		-368	-59
EEM adoption rates	79	147	-159	-94
EEM energy savings	54	135	-171	-119
EEM implementation costs	Unchanged		-177	-109
System boundary				
Upstream natural gas emissions factor	153	173	-94	-83
Electricity grid emissions intensity	135	N/A	-106	N/A

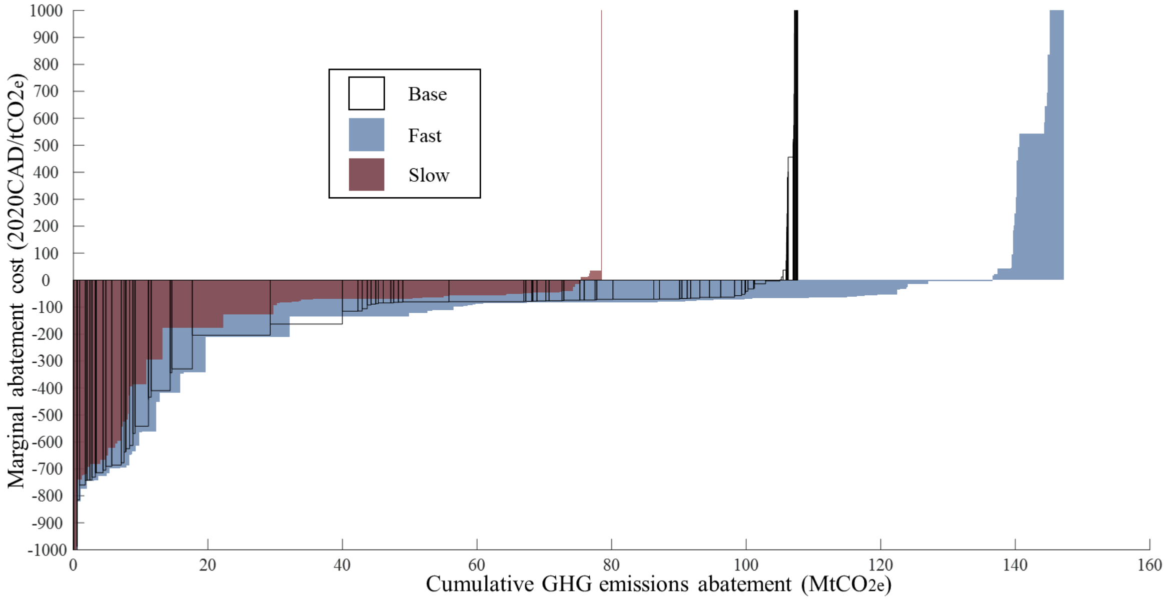
a) Discount rate (sector boundary)



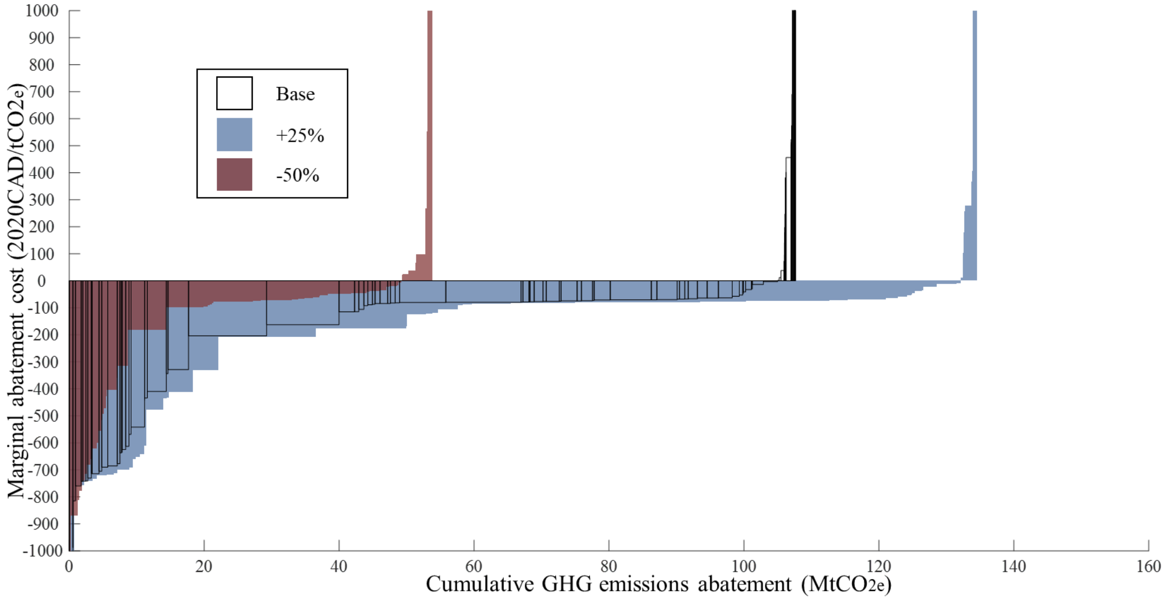
b) Energy prices (sector boundary)



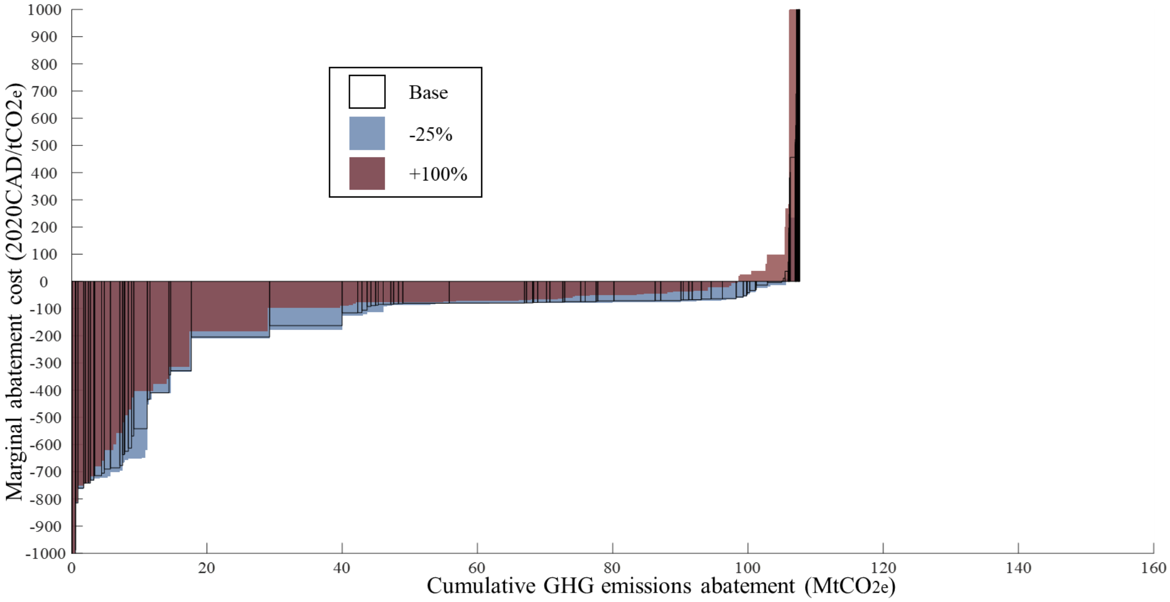
c) Adoption rates (sector boundary)



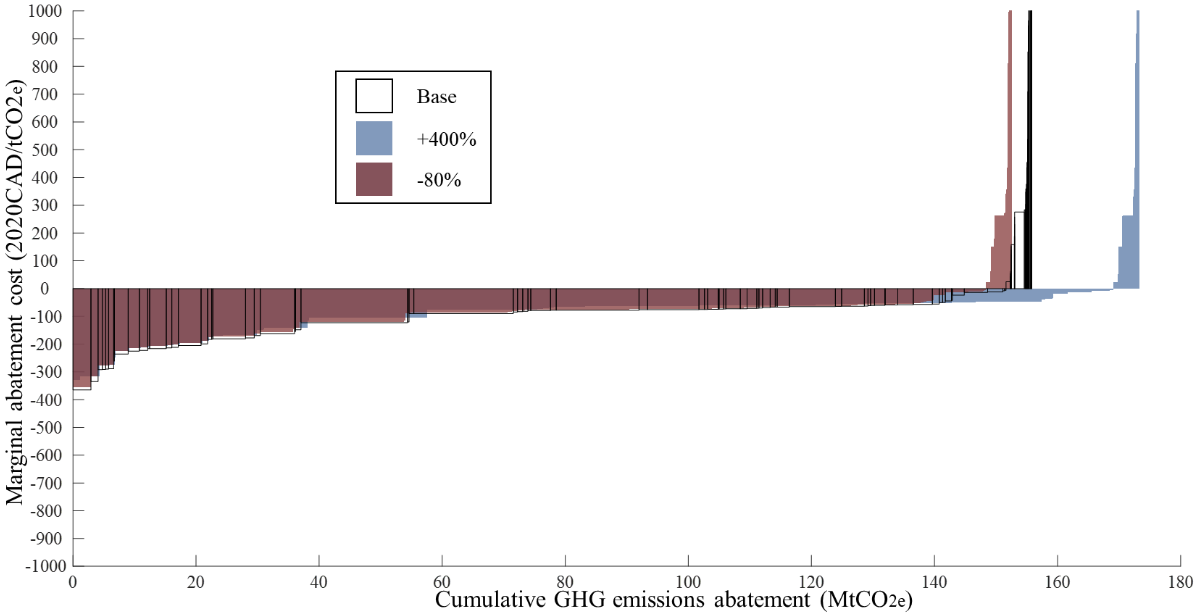
d) Energy savings (sector boundary)

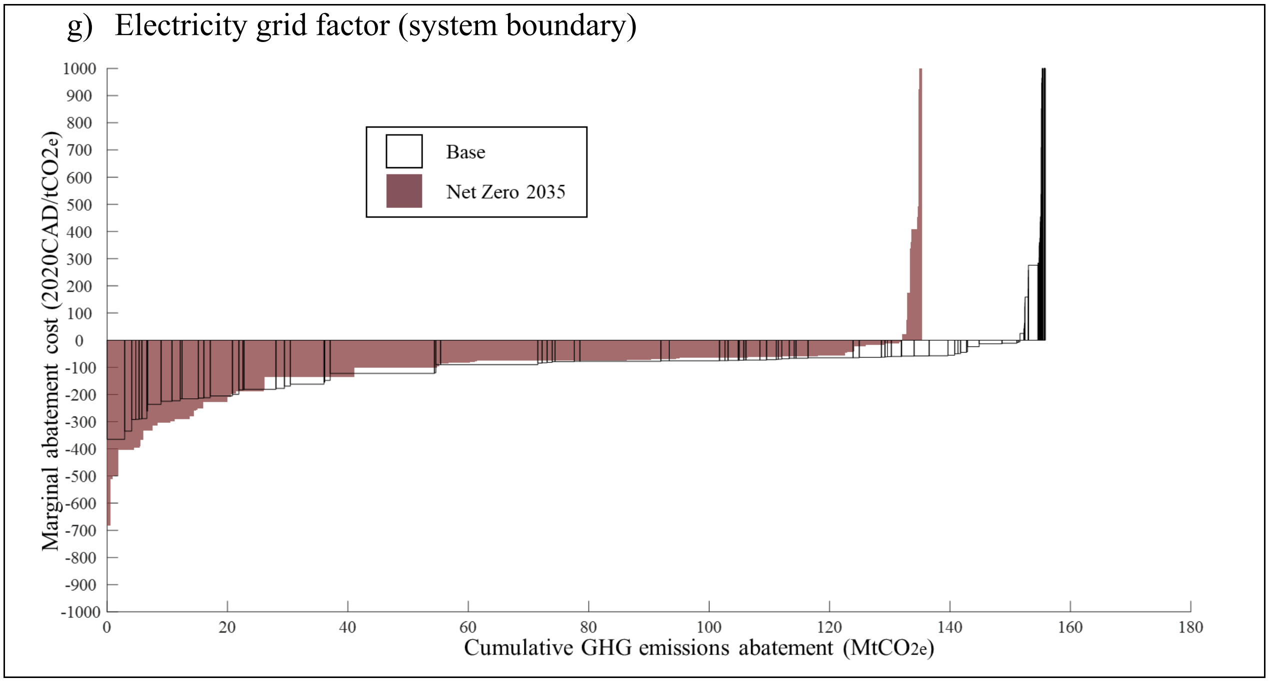


e) Total implementation cost (sector boundary)



f) Natural gas upstream emissions (system boundary)





g) Electricity grid factor (system boundary)

Figure 59a-g: Marginal abatement curve sensitivity results

Appendix M: Modified efficiency measures for trade-off curve analysis

Table 30: Process and device efficiency measures

Name and Description	Adjusted Applicability Factor*	Base Adjusted Energy Savings $^+$	Base Capital Cost ($/GJ)	Source
Electric Machine Drive Device EEMs				
Upgrade Motors 1-5 HP Implementation of premium efficiency motors (NEMA Premium where applicable) for small motors.	2.0%	9.0%	58.3	[127, 147]
Upgrade Motors 6-20 HP Implementation of premium efficiency motors (NEMA Premium where applicable) for small/medium motors.	5.0%	6.7%	22.5	[127, 147]
Upgrade Motors 21-50 HP Implementation of premium efficiency motors (NEMA Premium where applicable) for medium motors	9.0%	6.3%	13.5	[127, 147]
Upgrade Motors 51-100 HP Implementation of premium efficiency motors (NEMA Premium where applicable) for medium/large motors.	13.0%	5.5%	8.9	[127, 147]
Upgrade Motors 101-200 HP Implementation of premium efficiency motors (NEMA Premium where applicable) for large motors.	13.0%	4.3%	7.7	[127, 147]
Upgrade Motors 200+ HP Implementation of premium efficiency motors (NEMA Premium where applicable) for extra large motors.	59.0%	3.0%	6.1	[127, 147]
Motor Downsizing Replacement of oversized motors with smaller motors to reduce partial loading.	10.0%	8.5%	4.5	[127]
Voltage Controllers Implementation of voltage controllers on motor systems to reduce voltage imbalance.	75.0%	1.6%	1.0	[41]
Improved Rewinding Implementation of best practices for motor repairs to avoid de-rating the motor efficiency.	10.0%	8.8%	4.7	[127]
Electric Machine Drive Process EEMs				
Pump System Upgrades Package of measures including pump system optimization, elimination of throttle-based control, implementation of VFDs, and installation of more efficient pump internals and controls.	31.4%	20%	10.76	[127]
Fan System Upgrades Package of measures including improving blower system design, eliminating damper-based control, implementation of VFDs, and upgrades to fan blades, belts, controls, and other components.	19.8%	6.0%	2.93	[127]
Air System Upgrades	4.6%	17%	9.02	[127]

Name and Description	Adjusted Applicability Factor*	Base Adjusted Energy Savings $^{+}$	Base Capital Cost ($/GJ)	Source
Package of measures including eliminating air leaks, optimization of compressed air systems, implementation of VFDs, and implementing more efficient compressor designs and controls.				
Other Motor System Upgrades Package of measures applicable to other motor-driven systems (e.g.,: conveyors) including system optimization, improved equipment design, improved controls, and implementation of VFDs.	44.3%	2.0%	9.46	[127]
TMP Chemical Pretreatment Pretreatment of wood chips with chemicals, enzymes, fungi, or other inoculants to reduce the energy needed for TMP refining.	23.2%	37.3%	0.77	[126]
High Consistency Papermaking Improved paper machine system and equipment design to improve the consistency of the pulp slurry mixture, reducing the vacuum and roller energy demand in the paper machine.	49.5%	4.5%	36.89	[19, 126]
Refiner & Screening Upgrades Implementation of best practices for refiner and screening systems and equipment design to improve performance and reduce the need for secondary refining / re-refining.	17.4%	17.2%	0.14	[19, 41]
RTS TMP Pulping Implementation of equipment and controls to optimize residence time (R), temperature (T), and speed (S) in TMP pulping systems.	11.6%	20.0%	7.39	[41, 68]
Refiner Idle Time Optimization Improved refiner rotor design and utilization to reduce no-load energy consumption and improve the utilization ratio.	26.1%	14.7%	0.28	[126]
Natural Gas Process Heat Device EEMs				
Feedwater Economizers Use of economizers to preheat feedwater entering the boiler.	19.0%	3.6%	0.91	[41, 44]
Optimize Excess Air Use of advanced controls and monitoring to optimize air supply and management within the boiler.	32.8%	3.0%	0.16	[41, 44]
Combustion Air Preheaters Use of heat exchanger(s) to preheat combustion air.	9.7%	2.4%	1.52	[41, 44]
Operation Best Practices General measure consisting of several control and operational measures to improve combustion efficiency and boiler operations.	18.6%	2.8%	0.19	[41, 44]
Upgrade Burners	13.9%	2.4%	0.69	[41, 44]

Name and Description	Adjusted Applicability Factor*	Base Adjusted Energy Savings $^{+}$	Base Capital Cost ($/GJ)	Source
Improvement of natural gas burner system in the boiler to improve combustion efficiency and heat delivery characteristics.				
Boiler Surface Cleaning Improved practices and materials to reduce buildup of soot and other contaminants on heat transfer surfaces to improve steam generation efficiency.	11.2%	1.9%	0.37	[41, 44]
Blowdown Heat Recovery Use of heat exchangers to limit thermal losses due to blowdown.	20%	1.2%	0.26	[41, 44]
Blowdown Best Practices Improved blowdown practices (including continuous blowdown in some cases) to reduce thermal losses and limit boiler upsets.	20%	1.1%	0.07	[41, 44]
Deaerator Vent Rate Optimization Improved deaerator controls and management to reduce thermal losses in steam generation.	14.8%	1.3%	0.16	[41, 44]
Improve Boiler Refractory Improved boiler materials to reduce heat losses and improve heat delivery.	4.6%	1.1%	0.87	[41, 44]
Steam System Pressure Optimization Improved controls and monitoring of boiler inlet and outlet pressures to optimize steam generation efficiency.	17.8%	3.0%	0.17	[41, 44]
Natural Gas Process Heat Process EEMs				
Distribution System Improvement Improved steam system design to reduce system inefficiencies, reduce total piping length, and reduce pressure drop.	20.0%	2.0%	0.29	[44]
Minimize Steam Venting Best practices for steam system operation and design to reduce vented steam.	16.6%	4.0%	0.38	[33, 44]
Repair Steam Leaks Maintenance of steam lines and equipment to reduce leaks.	25.6%	2.0%	0.15	[44]
Isolate Unused Lines System analysis and active control to eliminate losses in unused lines/equipment.	12.5%	2.0%	0.11	[44]
Optimize System Balance Controls to manage steam flows and balance the steam distribution system.	12.3%	2.0%	0.51	[33, 44]
Optimize Drying Process Package of measures including improved controls, equipment, and operational practices to reduce steam use for pulp & paper drying.	18.0%	8.0%	2.41	[33, 44]
Optimize Air Heating	15.0%	2.0%	0.67	[44]

Name and Description	Adjusted Applicability Factor*	Base Adjusted Energy Savings $^+$	Base Capital Cost ($/GJ)	Source
Package of measures including improved controls, equipment, and operational practices to reduce steam use for air heating.				
Optimize Water Heating Package of measures including improved controls, equipment, and operational practices to reduce steam use for hot water supply.	15.0%	3.0%	0.85	[44]
Condensate Recovery Upgraded steam traps to improve condensate recovery and reduce energy losses.	31.2%	4.0%	0.48	[44]
Nip/Shoe Press Implement advanced press technology to reduce steam demand in pressing operations.	25.0%	3.0%	4.3	[33, 41]
Condebelt Drying Implement advanced drying technology to improve drying efficiency. Adjusted for overlap with drying measure above.	25.0%	12%	3.5	[33, 41]
Wood Chip Screening Improved automation, equipment, and system design to deliver more consistent wood chips to the pulping process.	25.0%	12%	0.2	[41]
Recovered Heat for Debarking Heat recovery system to eliminate incremental low-temperature steam demand used for log thawing and debarking.	2.0%	2.0%	1.8	[41]
High Pressure Condensate Utilization System redesign to allocate high pressure condensate to plant uses to offset incremental steam / hot water demand.	15.1%	3.0%	1.0	[44]
Pinch Analysis for Process Heat Optimization Conduct pinch analysis on steam systems to enable installation of heat exchangers to optimize heat allocation and reduce energy losses.	30.0%	15%	0.9	[41]
Conversion to Continuous Digesters Replace batch kraft digesters with continuous digesters.	15.0%	36%	20.2	[33]
Biomass Process Heat Device EEMs				
Feedwater Economizers Use of economizers to preheat feedwater entering the boiler.	19.0%	3.6%	0.91	[41, 44]
Optimize Excess Air Use of advanced controls and monitoring to optimize air supply and management within the boiler.	32.8%	3.0%	0.16	[41, 44]
Combustion Air Preheaters Use of heat exchanger(s) to preheat combustion air.	9.7%	2.4%	1.52	[41, 44]
Operation Best Practices	18.6%	2.8%	0.19	[41, 44]

Name and Description	Adjusted Applicability Factor*	Base Adjusted Energy Savings $^+$	Base Capital Cost ($/GJ)	Source
General measure consisting of several control and operational measures to improve combustion efficiency and boiler operations.				
Boiler Surface Cleaning Improved practices and materials to reduce buildup of soot and other contaminants on heat transfer surfaces to improve steam generation efficiency.	11.2%	1.9%	0.37	[41, 44]
Blowdown Heat Recovery Use of heat exchangers to limit thermal losses due to blowdown.	20.0%	1.2%	0.26	[41, 44]
Blowdown Best Practices Improved blowdown practices (including continuous blowdown in some cases) to reduce thermal losses and limit boiler upsets.	20.0%	1.1%	0.07	[41, 44]
Deaerator Vent Rate Optimization Improved deaerator controls and management to reduce thermal losses in steam generation.	14.8%	1.3%	0.16	[41, 44]
Improve Boiler Refractory Improved boiler materials to reduce heat losses and improve heat delivery.	4.6%	1.1%	0.87	[41, 44]
Steam System Pressure Optimization Improved controls and monitoring of boiler inlet and outlet pressures to optimize steam generation efficiency.	17.8%	3.0%	0.17	[41, 44]
Black Liquor Concentration Implementation of equipment to concentrate black liquor, improving the combustion efficiency of the recovery boiler.	33.0%	2.0%	0.83	[33]

Biomass Process Heat Process EEMs				
Distribution System Improvement Improved steam system design to reduce system inefficiencies, reduce total piping length, and reduce pressure drop.	20.0%	2.0%	0.29	[44]
Minimize Steam Venting Best practices for steam system operation and design to reduce vented steam.	16.6%	4.0%	0.38	[33, 44]
Repair Steam Leaks Maintenance of steam lines and equipment to reduce leaks.	25.6%	2.0%	0.15	[44]
Isolate Unused Lines System analysis and active control to eliminate losses in unused lines/equipment.	12.5%	2.0%	0.11	[44]
Optimize System Balance	12.3%	2.0%	0.51	[33, 44]

Name and Description	Adjusted Applicability Factor*	Base Adjusted Energy Savings +	Base Capital Cost ($/GJ)	Source
Controls to manage steam flows and balance the steam distribution system.				
Optimize Drying Process Package of measures including improved controls, equipment, and operational practices to reduce steam use for pulp & paper drying.	18.0%	8.0%	2.41	[33, 44]
Optimize Air Heating Package of measures including improved controls, equipment, and operational practices to reduce steam use for air heating.	15.0%	2.0%	0.67	[44]
Optimize Water Heating Package of measures including improved controls, equipment, and operational practices to reduce steam use for hot water supply.	15.0%	3.0%	0.85	[44]
Condensate Recovery Upgraded steam traps to improve condensate recovery and reduce energy losses.	31.2%	4.0%	0.48	[44]
Nip/Shoe Press Implement advanced press technology to reduce steam demand in pressing operations.	25.0%	3.0%	4.3	[33, 41]
Condebelt Drying Implement advanced drying technology to improve drying efficiency. Adjusted for overlap with drying measure above.	25.0%	12%	3.5	[33, 41]
Wood Chip Screening Improved automation, equipment, and system design to deliver more consistent wood chips to the pulping process.	25.0%	12%	0.2	[41]
Recovered Heat for Debarking Heat recovery system to eliminate incremental low-temperature steam demand used for log thawing and debarking.	2.0%	20.%	1.8	[41]
High Pressure Condensate Utilization System redesign to allocate high pressure condensate to plant uses to offset incremental steam / hot water demand.	15.1%	3.0%	1.0	[44]
Pinch Analysis for Process Heat Optimization Conduct pinch analysis on steam systems to enable installation of heat exchangers to optimize heat allocation and reduce energy losses.	30.0%	15%	0.9	[41]
Conversion to Continuous Digesters Replace batch kraft digesters with continuous digesters.	15.0%	36%	20.2	[33]

*Adjusted applicability factors are provided as % of production capacity associated with a given end use, defined by the share of final energy consumption.

+ Energy savings reported as % of final energy consumption for the applicable production capacity.

Appendix N: Trade-off curve correlations and parameters

Table 31: Electricity DEE-1 Curve Results

Curve Information		Correlation Coefficients		
Sector	Canada Pulp & Paper (NAICS 322)	**Years**	**a**	**b**
Fuel Type	Electricity	2000-2005	-0.455323	0.996440
End Use	Machine Drive	2005-2010	-0.459008	0.998122
Curve Type	DEE-1: Device Efficiency Selection Curve	2010-2015	-0.462782	0.999843
x-axis	Electricity Price ($/GJ)	2015-2020	-0.466646	1.001605
y-axis	Marginal Device Efficiency (%)	2020-2025	-0.470604	1.003408
Correlation Details		2025-2030	-0.474658	1.005255
Correlation Type	Inverse Square Root	2030-2035	-0.478810	1.007145
Equation	$MDE = b + a \times ECFP^{-1/2}$	2035-2040	-0.483065	1.009082
Input Range	$5 \le ECFP \le 140$	2040-2045	-0.487424	1.011066
2025 r^2 Value	96.8%	2045-2050	-0.491890	1.013099

Table 32: Electricity DEE-2 Curve Results

Curve Information		Correlation Coefficients		
Sector	Canada Pulp & Paper (NAICS 322)	**Years**	**a**	**b**
Fuel Type	Electricity	2000-2005	0.033241	0.846166
End Use	Machine Drive	2005-2010	0.033717	0.845804
Curve Type	DEE-2: Device Capital Cost Trade-Off Curve	2010-2015	0.034203	0.845433
x-axis	Device Capital Cost Intensity ($/GJ)	2015-2020	0.034699	0.845054
y-axis	Marginal Device Efficiency (%)	2020-2025	0.035204	0.844666
Correlation Details		2025-2030	0.035720	0.844270
Correlation Type	Logarithmic	2030-2035	0.036247	0.843863
Equation	$MDE = b + a \times \ln(DCC)$	2035-2040	0.036784	0.843448
Input Range	$0.5 \le DCC \le 30$	2040-2045	0.037332	0.843023
2025 r^2 Value	99.6%	2045-2050	0.037891	0.842588

Table 33: Electricity PEE-1 Curve Results

Curve Information		Correlation Coefficients		
Sector	Canada Pulp & Paper (NAICS 322)	**Years**	**a**	**b**
Fuel Type	Electricity	2000-2005	-143.6014	323.3588
End Use	Machine Drive	2005-2010	-144.5811	324.2146
Curve Type	PEE-1: Process Efficiency Selection Curve	2010-2015	-145.5707	325.0791
x-axis	Energy Price ($/GJ)	2015-2020	-146.5704	325.9526
y-axis	Marginal Process Efficiency (%)	2020-2025	-147.5803	326.8352
Correlation Details		2025-2030	-148.6006	327.7269
Correlation Type	Inverse Square Root	2030-2035	-149.6314	328.6278
Equation	$MPE = b + a \times MCFU^{-1/2}$	2035-2040	-150.6728	329.5382
Input Range	$7 \leq MCFU \leq 160$	2040-2045	-151.7249	330.4581
2025 r^2 Value	97.5%	2045-2050	-152.7878	331.3876

Table 34: Electricity PEE-2 Curve Results

Curve Information		Correlation Coefficients		
Sector	Canada Pulp & Paper (NAICS 322)	**Years**	**a**	**b**
Fuel Type	Electricity	2000-2005	11.89720	319.4440
End Use	Machine Drive	2005-2010	11.96283	320.1255
Curve Type	PEE-2: Process Capital Cost Trade-Off Curve	2010-2015	12.02899	320.8127
x-axis	Process Capital Cost Intensity ($/GJ)	2015-2020	12.09568	321.5058
y-axis	Marginal Process Efficiency (%)	2020-2025	12.16291	322.2047
Correlation Details		2025-2030	12.23069	322.9096
Correlation Type	Logarithmic	2030-2035	12.29901	323.6205
Equation	$MPE = b + a \times \ln(PCC)$	2035-2040	12.36789	324.3375
Input Range	$0.02 \leq PCC \leq 0.6$	2040-2045	12.43733	325.0606
2025 r^2 Value	97.7%	2045-2050	12.50734	325.7899

Table 35: Natural Gas DEE-1 Curve Results

Curve Information		Correlation Coefficients		
Sector	Canada Pulp & Paper (NAICS 322)	**Years**	**a**	**b**
Fuel Type	Natural Gas	2000-2005	0.020369	0.818119
End Use	Steam Process Heat	2005-2010	0.020535	0.818346
Curve Type	DEE-1: Device Efficiency Selection Curve	2010-2015	0.020701	0.818577
x-axis	Natural Gas Price ($/GJ)	2015-2020	0.020869	0.818812
y-axis	Marginal Device Efficiency (%)	2020-2025	0.021039	0.819051
Correlation Details		2025-2030	0.021210	0.819293
Correlation Type	Logarithmic	2030-2035	0.021382	0.819540
Equation	$MPE = b + a \times \ln{(ECFP)}$	2035-2040	0.021556	0.819791
Input Range	$1 \leq ECFP \leq 30$	2040-2045	0.021731	0.820045
2025 r^2 Value	92.1%	2045-2050	0.021908	0.820304

Table 36: Natural Gas DEE-2 Curve Results

Curve Information		Correlation Coefficients		
Sector	Canada Pulp & Paper (NAICS 322)	**Years**	**a**	**b**
Fuel Type	Natural Gas	2000-2005	0.010706	0.855571
End Use	Steam Process Heat	2005-2010	0.010787	0.855895
Curve Type	DEE-2: Device Capital Cost Trade-Off Curve	2010-2015	0.010868	0.856221
x-axis	Device Capital Cost Intensity ($/GJ)	2015-2020	0.010949	0.856551
y-axis	Marginal Device Efficiency (%)	2020-2025	0.011032	0.856883
Correlation Details		2025-2030	0.011115	0.857219
Correlation Type	Logarithmic (Offset)	2030-2035	0.011198	0.857557
Equation	$MDE = b + a \times \ln{(DCC - 3.01406)}$	2035-2040	0.011282	0.857899
Input Range	$3.02 \leq DCC \leq 27$	2040-2045	0.011367	0.858243
2025 r^2 Value	99.7%	2045-2050	0.011453	0.858591

Table 37: Natural Gas PEE-1 Curve Results

Curve Information		Correlation Coefficients		
Sector	Canada Pulp & Paper (NAICS 322)	**Years**	**a**	**b**
Fuel Type	Natural Gas	2000-2005	10.76453	92.82350
End Use	Steam Process Heat	2005-2010	11.03917	92.65731
Curve Type	PEE-1: Process Efficiency Selection Curve	2010-2015	11.32282	92.48737
x-axis	Energy Price ($/GJ)	2015-2020	11.61575	92.31369
y-axis	Marginal Process Efficiency (%)	2020-2025	11.91826	92.13626
Correlation Details		2025-2030	12.23062	91.95514
Correlation Type	Logarithmic	2030-2035	12.55311	91.77036
Equation	$MPE = b + a \times \ln(MCFU)$	2035-2040	12.88601	91.58199
Input Range	$2 \leq MCFU \leq 40$	2040-2045	13.22959	91.39013
2025 r^2 Value	82.1%	2045-2050	13.58411	91.19489

Table 38: Natural Gas PEE-2 Curve Results

Curve Information		Correlation Coefficients		
Sector	Canada Pulp & Paper (NAICS 322)	**Years**	**a**	**b**
Fuel Type	Natural Gas	2000-2005	4.475210	129.5481
End Use	Steam Process Heat	2005-2010	4.536551	129.9720
Curve Type	PEE-2: Process Capital Cost Trade-Off Curve	2010-2015	4.599136	130.4047
x-axis	Process Capital Cost Intensity ($/GJ)	2015-2020	4.663000	130.8465
y-axis	Marginal Process Efficiency (%)	2020-2025	4.728176	131.2976
Correlation Details		2025-2030	4.794701	131.7583
Correlation Type	Logarithmic (Offset)	2030-2035	4.862610	132.2288
Equation	$MPE = b + a \times \ln(PCC - 0.4328)$	2035-2040	4.931943	132.7094
Input Range	$0.44 \leq PCC \leq 4.8$	2040-2045	5.002738	133.2005
2025 r^2 Value	91.1%	2045-2050	5.075037	133.7022

Table 39: Biomass DEE-1 Curve Results

Curve Information		**Correlation Coefficients**		
Sector	Canada Pulp & Paper (NAICS 322)	**Years**	**a**	**b**
Fuel Type	Biomass	2000-2005	0.022939	0.638977
End Use	Steam Process Heat	2005-2010	0.023299	0.639080
Curve Type	DEE-1: Device Efficiency Selection Curve	2010-2015	0.023666	0.639187
x-axis	Biomass Price ($/GJ)	2015-2020	0.024040	0.639300
y-axis	Marginal Device Efficiency (%)	2020-2025	0.024420	0.639419
Correlation Details		2025-2030	0.024808	0.639543
Correlation Type	Logarithmic	2030-2035	0.025203	0.639673
Equation	$MDE = b + a \times \ln(ECFP)$	2035-2040	0.025605	0.639809
Input Range	$1 \leq ECFP \leq 25$	2040-2045	0.026014	0.639951
2025 r^2 Value	92.0%	2045-2050	0.026431	0.640099

Table 40: Biomass DEE-2 Curve Results

Curve Information		**Correlation Coefficients**		
Sector	Canada Pulp & Paper (NAICS 322)	**Years**	**a**	**b**
Fuel Type	Biomass	2000-2005	0.010870	0.675555
End Use	Steam Process Heat	2005-2010	0.010999	0.675930
Curve Type	DEE-2: Device Capital Cost Trade-Off Curve	2010-2015	0.011130	0.676310
x-axis	Device Capital Cost Intensity ($/GJ)	2015-2020	0.011263	0.676695
y-axis	Marginal Device Efficiency (%)	2020-2025	0.011398	0.677086
Correlation Details		2025-2030	0.011535	0.677482
Correlation Type	Logarithmic (Offset)	2030-2035	0.011673	0.677884
Equation	$MDE = b + a \times \ln(DCC - 5.6679)$	2035-2040	0.011813	0.678291
Input Range	$5.7 \leq DCC \leq 50$	2040-2045	0.011955	0.678704
2025 r^2 Value	99.6%	2045-2050	0.012099	0.679124

Table 41: Biomass PEE-1 Curve Results

Curve Information		Correlation Coefficients		
Sector	Canada Pulp & Paper (NAICS 322)	**Years**	**a**	**b**
Fuel Type	Biomass	2000-2005	8.361001	93.22109
End Use	Steam Process Heat	2005-2010	8.516138	93.14095
Curve Type	PEE-1: Process Efficiency Selection Curve	2010-2015	8.675352	93.05913
x-axis	Energy Price ($/GJ)	2015-2020	8.838772	92.97560
y-axis	Marginal Process Efficiency (%)	2020-2025	9.006532	92.89030
Correlation Details		2025-2030	9.178772	92.80320
Correlation Type	Logarithmic	2030-2035	9.355635	92.71424
Equation	$MPE = b + a \times \ln(MCFU)$	2035-2040	9.537270	92.62338
Input Range	$2 \leq MCFU \leq 40$	2040-2045	9.723831	92.53058
2025 r^2 Value	99.5%	2045-2050	9.915480	92.43579

Table 42: Biomass PEE-2 Curve Results

Curve Information		Correlation Coefficients		
Sector	Canada Pulp & Paper (NAICS 322)	**Years**	**a**	**b**
Fuel Type	Biomass	2000-2005	3.886231	124.4896
End Use	Steam Process Heat	2005-2010	3.926548	124.7801
Curve Type	PEE-2: Process Capital Cost Trade-Off Curve	2010-2015	3.967454	125.0751
x-axis	Process Capital Cost Intensity ($/GJ)	2015-2020	4.008958	125.3747
y-axis	Marginal Process Efficiency (%)	2020-2025	4.051072	125.6791
Correlation Details		2025-2030	4.093804	125.9882
Correlation Type	Logarithmic (Offset)	2030-2035	4.137166	126.3021
Equation	$MPE = b + a \times \ln(PCC - 0.4328)$	2035-2040	4.181168	126.6210
Input Range	$0.435 \leq PCC \leq 1.9$	2040-2045	4.225821	126.9449
2025 r^2 Value	98.9%	2045-2050	4.271136	127.2740