KAPSARC
مركز الملك عبدالله للدراسات والبحوث البترولية
King Abdullah Petroleum Studies and Research Center



Discussion Paper

Technoeconomic Assessment and Carbon Dioxide Removal Potential for the Global Pulp and Paper Industry

Muhammad Adnan Hayat and Amro M. Elshurafa

January 2025 | Doi: 10.30573/KS--2024-DP78

About KAPSARC

KAPSARC is an advisory think tank within global energy economics and sustainability providing advisory services to entities and authorities in the Saudi energy sector to advance Saudi Arabia's energy sector and inform global policies through evidence-based advice and applied research.

This publication is also available in Arabic.

Legal Notice

© Copyright 2025 King Abdullah Petroleum Studies and Research Center ("KAPSARC"). This Document (and any information, data or materials contained therein) (the "Document") shall not be used without the proper attribution to KAPSARC. The Document shall not be reproduced, in whole or in part, without the written permission of KAPSARC. KAPSARC makes no warranty, representation or undertaking whether expressed or implied, nor does it assume any legal liability, whether direct or indirect, or responsibility for the accuracy, completeness, or usefulness of any information that is contained in the Document. Nothing in the Document constitutes or shall be implied to constitute advice, recommendation or option. The views and opinions expressed in this publication are those of the authors and do not necessarily reflect the official views or position of KAPSARC.

Abstract

The pulp and paper industry is the fourth largest industrial energy user globally and has significant CO_2 removal potential, as a large portion of emissions from this industry are biogenic. The decarbonization potential of this industry has been discussed in the literature at the national level, with a primary focus on regions that are rich in biomass. However, regional variability and the standalone paper mill sector are underexplored in the literature. Our analysis reveals that the carbon capture option is viable for pulp and integrated pulp and paper mills, with the cost of carbon avoidance in the range of 50 \$/t CO_2 to 66 \$/t CO_2. However, the decarbonization of standalone paper mills is challenging. In the case of paper mills, both electrification and carbon capture measures are expensive, with carbon avoidance costs of approximately 280 \$/t CO_2 and 210 \$/t CO_2, respectively. Nevertheless, countries rich in natural resources with low utility prices and high renewable potential are better able to deploy decarbonization measures in standalone paper mills than other countries. For such countries, fuel switching to natural gas can be an important transitional measure to reduce emissions without a considerable increase in price. Renewable electrification is likely to become a viable alternative in the future with a reduction in the price of firm renewable power generation. The results of this study can be helpful for policymakers in understanding the price incentives that may be required to reap the untapped carbon removal potential of this industry.

Keywords: Pulp and paper, Biomass, CCS, Decarbonization, Renewable Energy

Highlights

- The decarbonization potential of pulp and integrated pulp mills is significant.
- The cost of carbon avoidance is in the range of 53 \$/t CO_2 to 66 \$/t CO_2 for pulp mills.
- Decarbonizing the paper industry is challenging.
- The cost of carbon avoidance is in the range of 95 \$/t CO_2 to 281 \$/t CO_2 for paper mills.

1. Introduction

Paper is one of the most widely used products in everyday life and constitutes 15% of global wood consumption (IPCC 2022). The pulp and paper industry (PPI) is among the most energy-intensive industries worldwide, along with steel, chemical, and cement (IPCC 2022). The PPI provides enormous untapped decarbonization[1] potential (Saeed 2023), which can be leveraged by many countries to allow the PPI to contribute positively to the environment.

Pulp and paper are derived mainly from plant cellulose fibers, raw pulp, or recycled paper. The raw material from plants can be virgin wood, wood chips, or wood pellets derived from trees. This material can also be sourced from more sustainable supplies, such as forest waste, agricultural residue, or wood processing residue. Additionally, high-quality paper, newspaper, and corrugated boxes can be recycled to produce high-grade pulp. Owing to a range of factors, such as water availability, land suitability, and weather conditions, feedstock can be either sourced domestically or imported.

The following three major types of mills in the PPI exist: pulp mills, paper mills, and integrated pulp and paper mills. Pulp mills produce mainly market pulp that can be used in paper mills, whereas integrated pulp and paper mills perform both pulp and paper production in the same facility to increase efficiency. Notably, standalone paper mills are more energy intensive than pulp and integrated pulp and paper mills, and the produce paperboard products from market pulp.

In the pulping process, cellulose fibers from wood or recycled paper are separated via chemical or mechanical processes. The chemical pulping process uses harsh chemicals to separate cellulose fibers from lignin at approximately 170°C (Rutz et al. 2020). The remaining solid lignin residue is called pulp, which is processed into a paper cardboard. Conversely, mechanical pulping uses mechanical shear force by grinding to soften the lignin-binding fibers. Mechanical pulping is used for weaker papers with short life spans, such as newsprints (Ericsson 2018). Chemical mechanical pulping is a combination of chemical pretreatment and mechanical griding (Han et al. 2024). In terms of energy consumption, mechanical and chemical pulping processes differ greatly. Mechanical processes require external energy, whereas modern state-of-the-art chemical processes can be supplied using energy from the process residue. Mechanical pulping consumes mainly electrical energy, which can be recovered as steam and usable low-grade heat (IEA Bioenergy 2007). However, mechanical pulping is powered mainly by electricity; hence, decarbonization is dependent on grid emissions.

The papermaking process can be divided into the following three basic stages: stock preparation, wet end processing, and dry end processing. During stock preparation, pulp is mixed with water and additives and transformed via cleaning and refining into a slurry with properties suitable for entering the paper machine. The paper machine contains different sections in which water is removed by vacuuming, pressing, and drying. The drying section presents the greatest use of energy in the papermaking stage. The sheet pressing and vacuumizing step increases the solid content of the paper by removing some of the water contained in the sheet. Electricity is used mainly in sheet pressing and vacuuming. The drying section consists of steam-heated drying cylinders (Deng et al. 2023). One of the challenges of the paperboard industry is the significant amounts of process steam and hot water required for production, drying, and conversion (Cochran 2024).

Integrated mills can be more energy efficient than standalone mills, as no drying energy is needed for the intermediate drying of the pulp, which results in energy savings at the pulp mill. Furthermore, the integration of the different processes may result in the further optimization of steam use on site. Conversely, standalone pulp mills have excess steam that cannot be used.

The main utilities of pulp mills are electricity, steam, and cooling water. Electrical energy is used to drive pumps and fans. Chemical pulp mills have access to large volumes of residue, such as black liquor,[2] which can be used for energy purposes. A pulp mill that produces kraft pulp generates 1.8 tons of black liquor per ton of pulp, which can make modern kraft pulp mills important sources of renewable energy. Steam is produced mainly from the recovery boiler, which is free of black liquor, and the multifuel boiler. In modern kraft pulp mills, the lime kiln is the only equipment that typically consumes fossil fuels – mainly natural gas and fuel oil. The processes in the lime kiln require high temperatures that are reached by combusting fossil fuels. The conventional fuels for PPI are coal, natural gas, and fuel oil. Coal is increasingly being replaced with other alternatives, such as natural gas, in countries such as the UK and China.

Decarbonization essentially involves a reduction in emissions from the current levels; therefore, switching from coal or liquid fuel to a low-emitting fuel such as natural gas can also be considered decarbonization. The role of natural gas in industrial decarbonization and the transition to net-zero energy has also been acknowledged and considered in various studies (Mathur et al. 2022; AMEO 2024). Various studies on the decarbonization potential of the PPI exist. However, these studies are dominated by regions with well-established biomass and pulp industries or countries that are transitioning away from coal usage in the paper industry. Regions where standalone paper mills are common are underexplored. There are also no comprehensive studies exploring the cost of carbon avoidance (CCA) and the levelized cost of pulp and paperboard (LCOX) and its sensitivity to the regional context. In light of the above factors, this paper fills the gap in the literature by (1) quantifying the costs associated with the production of pulp and paper products from pulp mills, integrated pulp mills, and standalone paper mills while considering regional heterogeneities, (2) estimating the degree of CCA for the PPI, including standalone paper mills, and (3) performing a case study on the paper industry and its decarbonization potential in Gulf Cooperation Council (GCC) countries.

The remainder of this paper is organized as follows. In Section 2.1, we present a review of the decarbonization options for the PPI. Section 2.2 provides a comprehensive review of the literature on the decarbonization potential of the PPI. In Section 3, detailed inputs and assumptions are discussed, along with the methodology of assessment. Section 4 presents the results of the analysis in the form of the calculated levelized cost of pulp (LCOP), the levelized cost of paperboard (LCOB), the levelized cost of pulp and paperboard (LCOX), and CCA. Finally, Section 5 concludes the paper.

2. Decarbonization Potential and Review

2.1 Overview of the Global PPI

Globally, the PPI contributes to biogenic3 carbon emissions of approximately 800 Mt and approximately 400 Mt of CO2 emissions per annum (Ericsson 2018), which is approximately 1% of global CO2 emissions. The PPI presents a range of decarbonization and carbon removal4 options along the value chain, which includes raw material switching, improvements in energy efficiency, fuel switching, electrification, and carbon capture and storage (CCS) (GlobalCCS 2023). Decarbonization and energy efficiency measures such as lime kiln modification can reduce the water content of kilns and the energy required for evaporation, which improves efficiency. Additionally, heat can be captured from lime kiln exhaust to preheat incoming lime and combustion air (LBNL 2009). These energy efficiency measures are well adopted in the PPI and have resulted in a significant reduction in the energy intensity of the PPI over the years. Nevertheless, there are a wide range of potential CO2 emission removal opportunities that the PPI offers, which need to be further explored and investigated.

CO_2 emissions from the PPI vary from 2 tons to 6 tons of CO_2 per ton of pulp and paper, depending on the process and the type of product (Han et al. 2024). Boilers, recovery furnaces, and lime kilns are the dominant sources of emissions. CO_2 emissions from recovery boilers from the combustion of organic matter in black liquor are biogenic. Similarly, emissions from multifuel boilers originating from the combustion of bark and biosludge are biogenic. Lime kilns are generally the major source of CO_2 emissions in the PPI. Additionally, the emissions from calcination reaction in the limekiln are biogenic since they originate from the recovery process of black liquor.

Globally, the pulp industry processes approximately 170 million tons (Mt) of black liquor per year, with a total energy generation potential of approximately 556 TWh, making black liquor a significant source of biomass. This process residue also has the potential to generate 48 Mt of methanol (IEA Bioenergy 2007). The top wood pulp producers are the U.S., Canada, Brazil, Norway, Sweden, and Finland, whereas some European countries, such as France and Germany, produce more paper than they do pulp (U.S. DOE 2015). The major biofuel-producing countries are China, Malysia, Brazil, Sweden, the Netherlands, and the U.S.

In Nordic countries,[5] virgin wood is the main raw material for the pulping process, with a high share of biomass, and the use of fossil fuels is close to zero. Sweden and Finland have the most large mills, with a production capacity of approximately 0.5 Mt per year.

Overall, in Europe, there are approximately 900 pulp and paper mills with a production capacity of 40 Mt of pulp and 90 Mt of paper. These mills produce approximately 11 Mt of sludge per annum, which can be further used as fuel (Man et al. 2023). The European PPI directly emits 31.9 Mt of CO_2 emissions and 68 Mt of biogenic emissions, presenting opportunities to achieve biogenic carbon removal. European pulp companies are developing more businesses related to biobased products, with approximately 140 biorefineries currently in Europe (CEPI 2024).

The PPI is the sixth largest consumer of energy in the UK (Ouadi et al. 2019). The paper industry in the UK has been traditionally dominated by coal. Nevertheless, the use of coal has significantly decreased to well below 1%, with coal combined heat and power (CHP) being replaced by biomass CHP (WSP 2015). Wood pulp for the UK industry is typically produced from resources obtained via timber industries in Canada and Nordic countries. In the UK, there are just two mills that have fully integrated pulp and paper operations (Griffin et al. 2018). In the case of the UK, the majority of pulp comes from paper recycling.

The PPI in the UK is dominated by the usage of natural gas (at around 80%).

China is the world's largest producer of paper products, accounting for 30% of global production. China typically obtains energy for the PPI by combusting coal and black liquor in a boiler (Han et al. 2024). This process results in high emission intensity from such plants. The U.S. is the second leading producer of paper products after China. In the U.S., natural gas accounts for more than 50% of the fuel purchased by the PPI, with coal and fuel oil comprising the remaining fuel (LBNL 2009). The vast majority of U.S. wood pulp is produced via a chemical pulping process (LBNL 2009). U.S. fossil fuel in the PPI, such as coal, natural gas, and fuel oil, is displaced by black liquor and wood bark, which currently account for more than 55% of the total energy consumed in the country (U.S. DOE 2015). In addition to other decarbonization measures, countries such as Japan are pursuing the deployment of CCS in pulp and paper mills (GlobalCCS 2023).

Canada, which is rich in biomass, is also one of the countries where the PPI is well established. Canadian wood product companies have announced the need to integrate hydrothermal liquefaction (HTL)[6] technology with pulp mills to convert woody biomass into biofuels. In British Colombia, pulp and paper mills have the capacity to generate 726 MW of biofuels from pulp and paper mills (Nie and Bi 2018). The transatlantic shipment of biomass for the PPI is also common, and Canada exports wood pellets to Europe.

Saudi Arabia is home to some of the largest paper production companies in the GCC region, with a production capacity of more than one Mt per annum (MEPCO 2024). The most common paper and cardboard products are facial tissue paper, wrapping paper and bags, toilet paper, and paper towels (Saudi Paper Group 2024). Saudi Arabia's paper companies export their products to GCC countries, the Middle East and Africa, and South Asia. The paper industry in Saudi Arabia also presents significant decarbonization opportunities through various measures, which are explored in Section 4.3.

Pulp and paper products are widely traded globally, but importantly, each country has its own unique context, primarily with the availability of biomass as feedstock and the availability of low-emission fuel at a low cost, which can enable fuel switching. This situation impacts the decarbonization potential and associated costs. A study that performs technoeconomic assessment at the global level while incorporating regional heterogeneities is thus needed.

2.2 Literature Review

In general, the decarbonization of the PPI has received considerable research attention. Most of these studies cover broad policy, supply chain, decarbonization, and technoeconomic viability aspects for various countries. We provide a review of these studies below.

Some studies have explored the policy and standardization aspects of the PPI, noting its importance for the widespread adoption of decarbonization measures in the industry. Liang et al. (2023) identified the challenges associated with the standardization of greenhouse gas (GHG) emissions and proposed an emission accounting framework that can improve the credibility and comparability of carbon footprints in the PPI. Sonsale et al. (2021) suggested that policymakers should consider incentivizing negative emissions[7] to realize the carbon removal potential of the PPI. Similarly, Ouadi et al. (2019) noted that the energy input for paper mills accounts for a significant percentage (30%) of the total cost of paper production and proposed that decarbonization strategies need to consider the economic viability of the proposed measure.

Value chain management is another important dimension of the challenges faced by the PPI and has thus also been explored in the literature. Dai et al. (2023) focused on the feedstock stream of the PPI value chain and performed a comprehensive material flow analysis for the PPI in China. The above analysis highlighted the sustainability challenges faced in terms of fiber supply and proposed the need to increase the level of recycling of domestic wastepaper. Similarly, Furszyfer et al. (2022) suggested the need for increased collaboration between industries such as the chemical, forestry, and oil refining industries to adopt a holistic perspective in the complete value chain of the PPI. Moreover, Vazifeh et al. (2023) proposed that biofuel production in the PPI can benefit from optimization within the upstream supply chain and downstream biorefinery. Owing to the complexity associated with the PPI value chain, the prices of commodities traded in the international market, such as chemical pulp, can be volatile. The impact of the price of chemical pulp on the LCOB is explored in Section 5.

Some studies have focused on other aspects of the decarbonization of the PPI. Man et al. (2023) estimated the GHG emissions of more than 800 paper mills in China and concluded that GHG emissions have been overestimated by up to 56% by international organizations such as the International Energy Agency (IEA). Moreover, Andersson et al. (2021) evaluated the design and optimal utilization aspects of the PPI and showed that energy performance indicators, including electricity and heat utilization rates, can help identify design issues, such as the insufficient utilization of cooking chemicals in the digester of the pulp mill. Leeson et al. (2017) conducted a review of four major carbon-emitting industries and reported that the lowest carbon capture cost is that in the PPI, ranging from $16 to $35 per ton, whereas the cost of carbon capture in the cement, steel, and refinery sectors is considerably higher, with up to $140 per ton of CO_2.

Biofuel and biorefinery constitute another important decarbonization aspect that has been covered in the literature. Nie and Bi (2018) explored the feasibility of repurposing kraft pulp mills to produce biofuels and evaluated the viability of the HTL technique in a Scandinavian kraft pulp mill. The results showed that the biofuel price from HTL is estimated to be 0.97 $/L, which is more than double the standard fuel price (Nie and Bi 2018). In addition to liquid biofuel studies, Ahmadvand and Sowlati (2023) analyzed gaseous biofuels and assessed the potential of producing syngas from biomass at a kraft pulp mill to displace natural gas in the lime kiln. The projected cost of syngas produced in the pulp mill was $30 per GJ, and upgraded renewable natural gas was projected to cost approximately $60 per GJ. Similarly, Jafri et al. (2020) reported that black liquor and renewable methanol from kraft pulp mills are estimated to cost approximately 80 €/MWh to 100 €/MWh, respectively, and the syngas price is approximately 32.7 €/MWh. Moreover, Mäki et al. (2021) discussed different bioenergy retrofit technologies for the production of liquid, solid, and gaseous bioenergy products in the existing PPI, proposing that the wider uptake of bioenergy retrofitting technologies in the PPI would require overcoming the barriers related to uncertainty in terms of economic feasibility. Furthermore, Fornell et al. (2013) conducted an analysis of kraft pulp mills repurposed into biorefineries and reported that those repurposed via ethanol fermentation can achieve CO_2 avoidance of one ton of CO_2 per ton of product at a cost of approximately 20 €/ton of CO_2. However, as proposed by Kumar et al. (2024), the major obstacle to the integration of biorefineries in the PPI is their low yield and lack of market value for end products.

Several other studies have focused on the technoeconomic aspects of the decarbonization of the PPI. Roussanaly et al. (2021) evaluated the implementation of CCS in the PPI and concluded that the cost of CO_2 avoided for pulp mills ranges from 52 €/t CO_2 to 81 €/t CO_2 avoided for pulp mills and 72 €/t CO_2 to 82 €/t CO_2 avoided for pulp and board mills. Roussanaly et al. (2021) further reported that the production cost of pulp is approximately 523 €/t. Moreover, Onarheim et al. (2017) reported a CO_2 avoidance cost of approximately 50 €/t CO_2 to 60 €/t CO_2 for the PPI by incorporating the cost of CO_2 capture retrofit required in steam turbines and auxiliary boilers. Parkhi (2022) performed a technoeconomic analysis of retrofitting postcombustion capture to a pulp mill and estimated the capture cost to be 90$/t CO_2. Decarbonization potential by fuel switching is another important aspect, which was explored by Li et al. (2023), who reported that using biofuel from eucalyptus instead of coal and using pulping wastewater can reduce fuel consumption by 46%. Additionally, such measures can reduce emissions by 14% compared with traditional pulp mills.

Table 1 summarizes recent studies on the decarbonization of the PPI and the production of biofuels from the PPI to decarbonize other sectors, and it shows the foci of these studies and the regional contexts that were considered. The literature review suggests that extensive work has been performed on policy and standardization aspects.

Some studies have also discussed conventional decarbonization measures such as fuel switching and energy efficiency options. With respect to biofuel production in the PPI, the literature review highlights some of the challenges that need to be addressed, such as the high cost of bioproducts, the low production volume, and the lack of market availability for emerging bioproducts in most countries. Thus, this sector needs to be further developed to make it commercially viable.

With respect to the decarbonization potential of the PPI and on the basis of the above literature review, we find two important aspects that have not received adequate research attention. The first relates to regional variability based on parameters such as fuel and feedstock type and its associated costs. Extensive research has been conducted at the national level, as shown in Table 1. However, regional variability, which greatly impacts the viable options from which a country may choose, is not covered. The second aspect is the decarbonization of standalone paper mills. Studies that have been conducted on this subject have focused only on the efficiency of fuel

Table 1. Literature review of recent studies on the decarbonization of the PPI.

Reference	Focus area	Country context
Vazifeh et al. (2023)	Biofuel production feedstock supply chain and biorefinery optimization	Canada
Nie and Bi (2018)	Technoeconomic viability of biofuel from Scandinavian pulp mills	Canada
Ahmadvand and Sowlati (2023)	Potential of bioenergy (syngas) from pulp mills	Canada
Liang et al. (2023)	Emission accounting framework in the PPI	China
Dai et al. (2023)	Material flow analysis feedstock stream in the PPI	China
Li et al. (2023)	Fuel switching from coal to eucalyptus in the PPI	China
Man et al. (2023)	Estimation of GHG emissions from paper mills	China
Sonsale et al. (2021)	Incentivizing negative emissions in the PPI	India
Kumar et al. (2024)	End product markets for biofuels in the PPI	India
Jafri et al. (2020)	Renewable methanol from pulp mills	Europe
Roussanaly et al. (2021)	CCS in pulp and paper mills	Europe
Onarheim et al. (2017)	Technoeconomic analysis of pulp mills with CCS	Europe
Mäki et al. (2021)	Economic feasibility of bioenergy retrofitting in the PPI	Finland
Andersson et al. (2021)	Design and optimal utilization rate in pulp mills	Sweden
Jafri et al. (2020)	Renewable methanol from pulp mills	Sweden
Fornell et al. (2013)	Technoeconomic analysis of pulp-mill-based biorefinery with CCS	Sweden
Ouadi et al. (2019)	Biofuels from paper mill waste	UK
Furszyfer et al. (2022)	Collaboration between chemicals and the forestry industry in the PPI	UK
Leeson et al. (2017)	Decarbonization of the PPI along with the cement, steel and refinery sectors	UK
Parkhi (2022)	CCS in pulp and paper mill lime kiln	U.S.
This study	Decarbonization of pulp, integrated pulp and paper, and paper mills	Global

switching options. There is a need for extensive research on the decarbonization potential of standalone paper mills along with other PPI pathways. Hence, this paper contributes to the literature by providing an analysis of the benefits and associated costs for the PPI considering regional variations. Here, we conduct technoeconomic and environmental benefit assessments for pulp mills, integrated pulp and paper mills, and standalone paper mills in various countries. Furthermore, we assess the decarbonization potential of the paper industry in Saudi Arabia.

3. Data, Assumptions, and Method

3.1 Data Inputs and Assumptions

Owing to the complex value chains of the PPI and its associated electricity and fuel requirements, this section aims to outline the detailed inputs, assumptions and methodology of the analysis. The PPI value chain includes feedstock to processing mills to produce pulp and paper for decarbonization and energy efficiency measures. The inputs and assumptions are carefully selected to represent a pathway, with due consideration of regional variations, which evaluate feedstock, electricity, fuel, and processed water costs.

Table 2 shows the nomenclature of the technoeconomic input and output parameters used in this study. Expenses are categorized into region-specific and generic types. Region-specific expenses are assumed to be variable based on the country. Φ_{uRen}, Φ_{uMWh}, Φ_{uGJ} and Φ_{upw} represent region-specific variables and can be vastly different on the basis of local weather conditions, the economy, and a range of other factors.

- The region-specific variable is the unit price of feedstock Φ_{uFS}. The electricity, fuel, and process water prices Φ_{uMWh}, Φ_{uGJ} and Φ_{upw}, respectively, are also region specific.
- Generic expenses *TCR* and *O&M* costs include any energy-efficient measures deployed and any additional costs of carbon capture, transport, and storage. *TCR* further includes interest during construction.
- In terms of revenue, *LCOP* and *LCOB* are the unit costs of producing pulp and paperboard, respectively, over the plant's economic lifetime. *LCOX* is used to denote the levelized cost of integrated pulp and paperboard.
- CCA is calculated on the basis of the following expression while considering the incurred cost of the product and associated emissions:

$$CCA = \frac{LCOX^{CCS} - LCOX^{base\ case}}{{CO_2}^{base\ case} - {CO_2}^{CCS}}$$

Table 2. Nomenclature of the parameters used in this study.

		Parameters	Symbol	Unit	Description
Expenses	Region specific	Wood, market pulp	Q_{FS}/Q_{MP}	ton	Quantity of feedstock or market pulp required for the process
			Φ_{uFS}/Φ_{uMP}	$/ton	Unit price of feedstock or market pulp in the region
			$\Phi_{uFS} \times \Phi_{FS}$	$/ton	Price of wood or other feedstock required for the process
			$\Phi_{uMP} \times Q_{MP}$	$/ton	Price of market pulp required for standalone paper mills
		Grid electricity, firm renewables	Φ_{uMWh}	$/MWh	Unit price of grid electricity in the region
			Φ_{uRen}	$/MWh	Unit price of firm renewables in the region
			E_{MWh}	MWh	Electricity required for the process
		C_elec	$\Phi_{uMWh} \times E_{MWh}$ or $\Phi_{uRen} \times E_{MWh}$	$	Cost of grid electricity or firm renewables required per ton of the process
		Fuel	Φ_{uGJ}	$/GJ	Unit price of fuel in the region
			Q_{Fuel}^{GJ}	GJ	Fuel required for the process
			$\Phi_{uGJ} \times Q_{Fuel}^{GJ}$	$	Price of fuel required per ton of the process
		Process water Water required	Φ_{upw}	$/ton	Unit price of process water in the region
			Q_{water}^{ton}	ton	Quantity of process water required
			$\Phi_{upw} \times Q_{water}^{ton}$	$	Price of water required per ton of the process
	Generic				
		Plant costs	*O&M*	$	Operation and maintenance costs (excluding utilities)
			CO_2 T&S cost	$/ton	Carbon transport and storage cost
			TCR	$	Total capital required including that for carbon capture (where applicable)
Revenue		R_elec		$	Revenue generated from electricity generation
		Crude tall oil		$	Revenue generated from selling crude tall oil[a]
Calculated values		LCOP		$/ton	Levelized cost of pulp
		LCOB		$/ton	Levelized cost of paperboard
		LCOX		$/ton	Levelized cost of pulp and paperboard
		CCA		$/ton	Cost of carbon avoidance

Notes: [a] Crude tall oil is a byproduct of the pulping process and can be used to produce renewable diesel.

Table 3 shows the technical and economic inputs and assumptions, which are sourced from the published literature and cover the complete value chain of the PPI. The energy consumption per ton of product varies widely on the basis of the type of paper produced, the process involved, and the associated heat (typically less than 170°C) and electricity requirements.

Table 3. Data input and assumptions based on the literature.

	Process	Softwood ($/ton)	Recycle paper ($/ton)		Reference
Q_{FS}	Pulp mill	4.1			Roussanaly et al. (2021)
	Paper mill	2.08			Roussanaly et al. (2021)
	Paper mill recycled paper	–	1.1		Roussanaly et al. (2021)
	Process	$\Phi_{capital}$ ($/ton)	$\Phi_{O\&M}$ ($/ton)	$\Phi_{T\&S}$ ($/ton)	
Φ_{plant}	Pulp mill	67	143		IEAGHG 2016; Rademaker and Marsidi (2019)
	Pulp mill with CCS	87.9	180		IEAGHG (2016); Rademaker and Marsidi (2019)
	Integrated pulp and paper mill	79.6	270		IEAGHG (2016)
	Integrated pulp and paper mill with CCS	114	315		IEAGHG (2016)
	Paper mill	120	76.80		Han et al. (2024)
	CO_2 transport and storage costs			10	IEAGHG (2016)
	Process	Q_{Fuel}^{GJ} (GJ/ton)	E_{MWh} (MWh/ton)	Q_{water}^{ton} (ton/ton)	Reference
$Q_{process}$	Pulp mill	1.47	1.12	146	IEAGHG (2016); Rademaker and Marsidi (2019)
	Pulp mill with CCS	5.47	0	146	IEAGHG (2016); Rademaker and Marsidi (2019)
	Integrated pulp and paper mill	1.47	0.666	115	IEAGHG (2016); Onarheim et al. (2017)
	Integrated pulp and paper mill with CCS	5.47	0	115	Pilorge et al. (2020)
	Paper mill	15.65	1.31	22.58	Rademaker and Marsidi (2019)
	Paper mill with recycled paper	3.31	0.312	9.63	Roussanaly et al. (2021)
	Paper mill with CCS	1.45			UNIDO (2010)

Notes: All the units are in per ton of product.

With respect to process emission intensities, various generalized carbon intensities are suggested in the literature; for example, UNIDO (2010) suggested a carbon intensity of 0.42 tons of CO_2 per ton of paper. In some Chinese paper mills, emissions are estimated to be approximately 1 ton of CO_2 per ton of paper (Kong et al. 2013). Importantly, these emissions are based on the amount of fuel utilized. For example, China has the highest emissions from papermaking, with coal being used primarily in paper mills, whereas the emissions are lowest for Scandinavian countries because a significant quantity of biomass is used as fuel. Therefore, to make an accurate assessment, emissions are based on the advised emission intensity of the fuel utilized from the Energy Efficiency Assessment and Greenhouse Gas Emission Reduction (EAGER) tools for pulp and paper (LBNL 2009). The electricity generated in pulp mills is exported to the grid to generate revenue in the standard case, whereas it is used to supply the energy required for the carbon capture process in the CCS case.

In the case of standalone paper mills, our analysis covers a wide range of emission reduction options, including fuel switching, energy efficiency measures, CCS, and electrification. Energy efficiency and fuel switching measures have the potential to reduce emissions. Moreover, deploying CCS can reduce the emissions caused by the combustion of fossil fuels. However, emissions from the grid electricity supply, which are required to operate machine-driven equipment such as compressors, fans, and pumps, may still exist (U.S. DOE 2015). Therefore, electrification is an important decarbonization option for the standalone paper mill industry. Various forms of renewable electrification options, such as solar with battery storage, geothermal, or biogas, can be deployed in the standalone paper industry (LAZARD 2024 #94).

3.2 Methodology

After the data input and assumption are outlined, the following text covers the methodology and scenarios explored in the analysis. To evaluate the impact of the regional context on the *LCOP*, the *LCOB*, and *CCA*, the following scenarios are considered, as shown in Table 4:

- Scenario 1 represents a regional context, where the price of feedstock and process water is low, and where utility and fuel prices are high; examples of such countries are Sweden and Finland.
- Scenario 2 represents a regional context, where both the utility costs and feedstock prices are in the medium range; examples of such countries are China and the U.S.
- Scenario 3 represents a regional context, where not only feedstock and water prices but also utilities and fuel prices are quite high. An example of such a case is the UK.
- Scenario 4 represents a regional context, where feedstock and water availability are scarce due to local weather conditions, whereas fuel and utility prices are very low, as, for example, in the case of Saudi Arabia.
- Scenario 5 represents a regional context, where market pulp and process water prices are low, utility prices are in the high range with high electricity prices, and firm renewable prices are low.
- Scenario 6 represents a regional context, where market pulp prices and process water prices are intermediate, and where utility prices, including electricity prices and firm renewable prices, are also in the intermediate range.
- Scenario 7 represents a regional context, where market pulp prices and process water prices are high, and where utility prices, including electricity prices and firm renewable prices, are in the low range.

Table 4. Scenarios and ranges of the input parameters used to analyze regional variability.

Type of mill	Countries	Φ_{uFS}	Φ_{uGJ}	Φ_{uMWh}		Φ_{upw}	Description
Pulp and integrated pulp and paper mills	Scenario 1	10	8	100		0.05	Low feedstock price and high utility cost (e.g., in Nordic countries)
	Scenario 2	30	6	80		0.15	Medium feedstock price and medium utility cost (e.g., in the U.S.)
	Scenario 3	40	10	120		0.20	High feedstock price and very high utility cost (e.g., in the UK)
	Scenario 4	50	2	40		0.25	Very high feedstock price and low utility cost (e.g., in the GCC region)
Type of mill and country	**Countries**	Φ_{uMP}	Φ_{uGJ}	Φ_{uMWh}	$\Phi_{uRen.}$	Φ_{upw}	**Description**
Standalone paper mills	Scenario 5	50	8	100	160	0.05	Low market pulp price and high utility cost (e.g., in Europe)
	Scenario 6	100	6	80	140	0.15	Medium market pulp price and medium utility cost (e.g., in the U.S.)
	Scenario 7	200	2	40	120	0.20	High market pulp price and low utility cost (e.g., in the GCC region)

Our analysis is performed on pulp mills and integrated pulp and paper mills with and without CCS. Moreover, our analysis is performed on selected pathways and is focused mainly on emerging options that consider global trends, market needs, and achieving carbon removal potential. The following is a list of selected PPI pathways used to analyze their impact on the LCOP and CCA:

- Kraft pulp mill producing market pulp.
- Kraft pulp mill producing market pulp with CCS.
- Integrated kraft pulp and paperboard mill.
- Integrated kraft pulp and paperboard mill with CCS.
- Paper from chemical pulping using wood chips.
- Paper from chemical pulping using recycled paper.

Furthermore, an analysis is performed to explore the decarbonization potential of standalone paper mills. Our analysis considers (i) coal-fired, diesel and natural-gas-fueled, (ii) electrification, (iii) CCS, (iv) and energy efficiency options for shoe-press[8] and waste heat recovery:

- Standalone paper using market pulp with fuel switching, electrification, energy efficiency, and CCS measures.
- Standalone paper mill decarbonization potential in the GCC region.

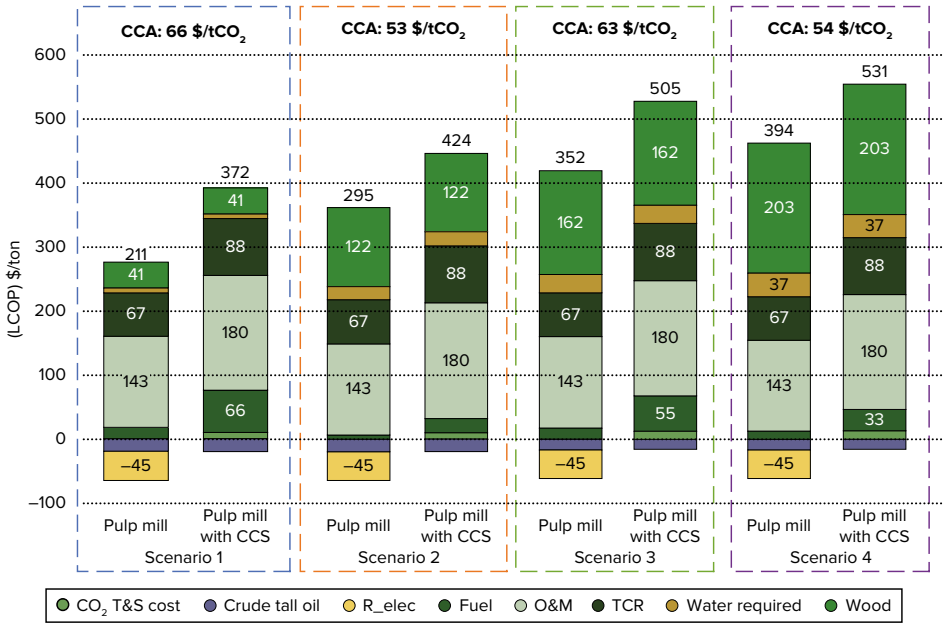
The next section presents and discusses the findings of the analysis on the basis of the data input and the assumptions described in this section.

4. Results and Discussion

4.1 Pulp

On the basis of the input assumption and methodology presented in the previous section, our analysis is performed on Scenarios 1-4 to calculate the LCOP and CCA. Figure 1 shows the impact of the regional variations considered in Scenarios 1 to 4 on the LCOP and CCA in the cases of pulp mills with and without CCS.9 While the LCOP ranges from 211 $/ton to 394 $/ton of pulp, the deployment of CCS in pulp mills increases the LCOP by 34%-76%, with the lowest increase observed in Scenario 4, i.e., low-fuel-price-regime countries. The CCA in pulp mills ranges from 53 $/tCO$_2$ to 66 $/tCO$_2$, with the lowest value occurring in low-fuel-price-regime countries, irrespective of feedstock cost.

Figure 1. LCOP and CCA for Scenarios 1 to 4 in the case of pulp mills with and without CCS.

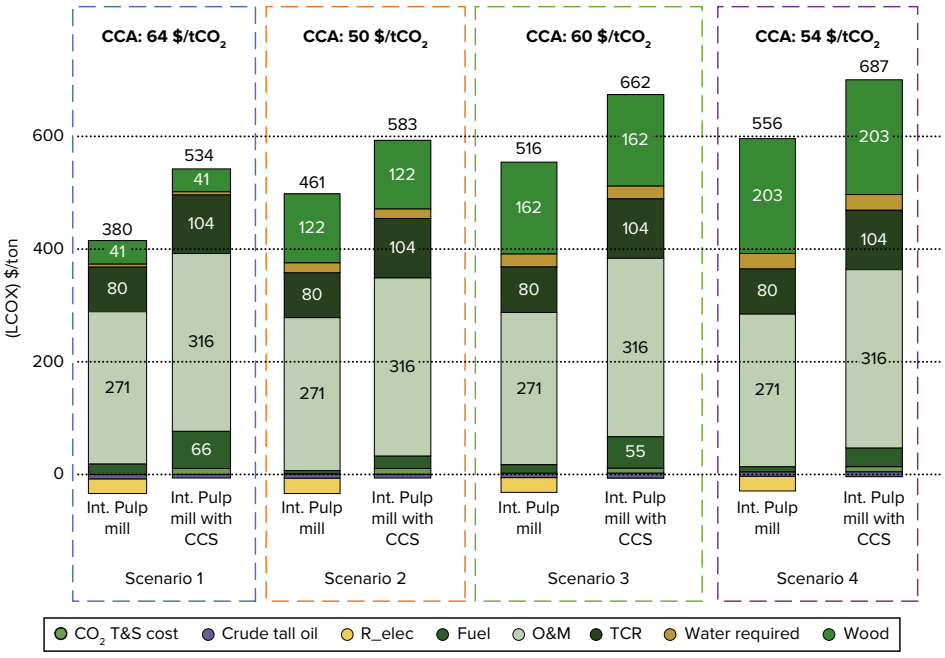


Source: Authors.

4.2 Integrated Pulp and Paper

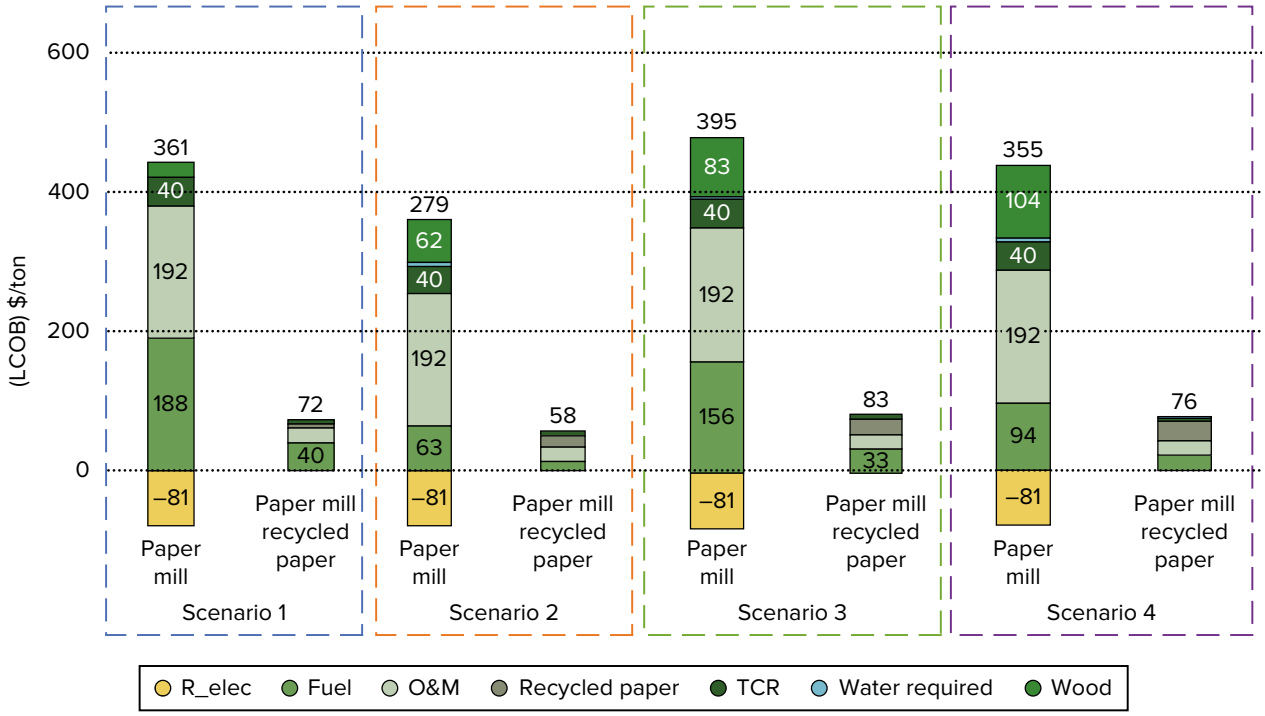
Figure 2 shows the case of the integrated pulp and paper board mill with and without CCS. The LCOX board ranges from 380 $/ton to 556 $/ton of product. The deployment of CCS increases the levelized cost of products from 24% to 41%. In this scenario, the lowest increase is again observed in Scenario 4, which represents low-price-regime countries. Interestingly, CCA is approximately 16% lower in Scenario 4 than in Scenario 1, which is driven mainly by low electricity and fuel prices. In a world where carbon emission mitigation options are now widely rewarded, countries with low fuel prices might look into exploring some of the decarbonization options in this industry. Another interesting observation is that the relative increase in the LCOP after the deployment of CCS is much lower in Scenario 4 than in Scenario 1. Although the amount of electricity generated that can be exported to the grid is reduced by more than 40% compared with that of a pulp mill in the case of an integrated pulp mill, it can still be better utilized for CCS.

Figure 2. LCOP and CCA for Scenarios 1 to 4 in the case of an integrated pulp mill with and without CCS.



Source: Authors.

Figure 3. LCOB for Scenarios 1 to 4 in the case of paper mills from biomass and recycled paper.



Source: Authors.

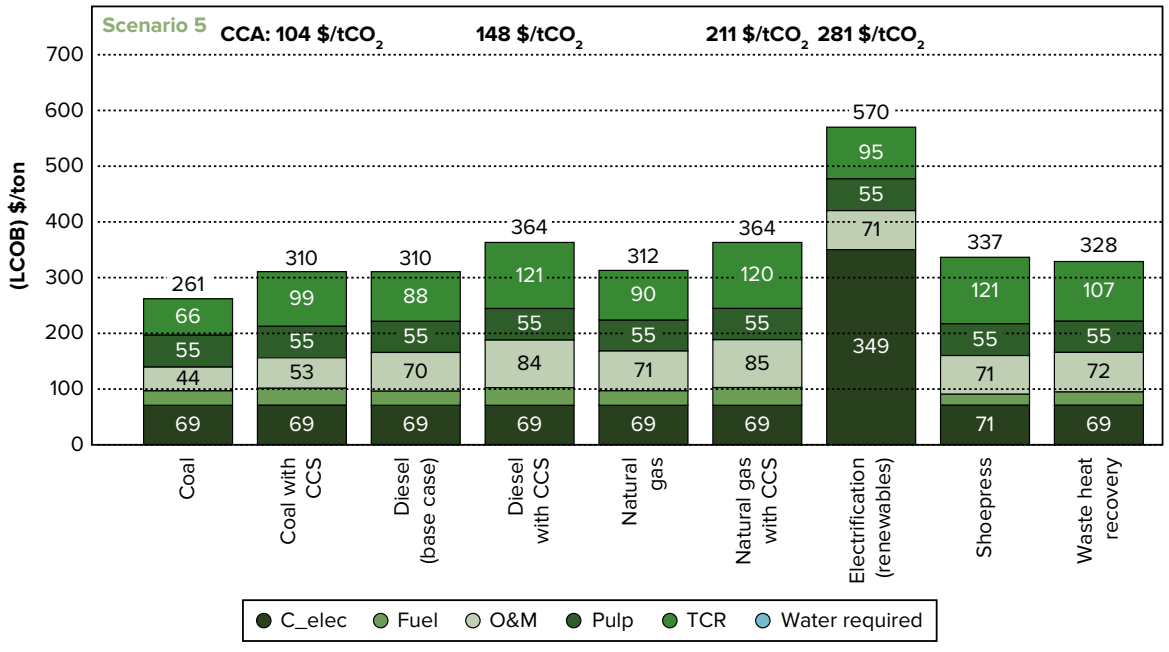
As shown in Figure 3, paper production directly from chemical pulping using biomass does not seem to be a preferable option due to factors such as process inefficiencies and excessive unused energy. Nevertheless, compared with the recycled wastepaper scenario, the LCOB scenario is an enormously effective alternative, where the LCOB is drastically reduced and is in the range of 76 $/ton to 121 $/ton of product with recycled paper. Additionally, paper from recycled paper pulping can reduce process emissions by approximately one-quarter in comparison with paper production from chemical pulping.

4.3 Standalone Paperboard Mills

This dedicated section analyzes the viability of decarbonization options in standalone paper mills. Scenario 5 presents a region where electricity and fuel prices are high and where pulp and process water prices are low, such as in the case of Europe, as shown in Figure 4.

Countries such as China and the UK are increasingly transitioning away from coal use in paper mills, and deploying CCS in such paper mills will increase the LCOB by 16%, with a CCA value of 104 $/t CO_2. Fuel switching to natural gas can be a viable option, as it decreases emission intensity by 33%, with only a small increase in cost (Geraghty 2013). However, considering the current high costs of firm renewables, decarbonization via electrification can incur a CCA value of 281 $/t CO_2.

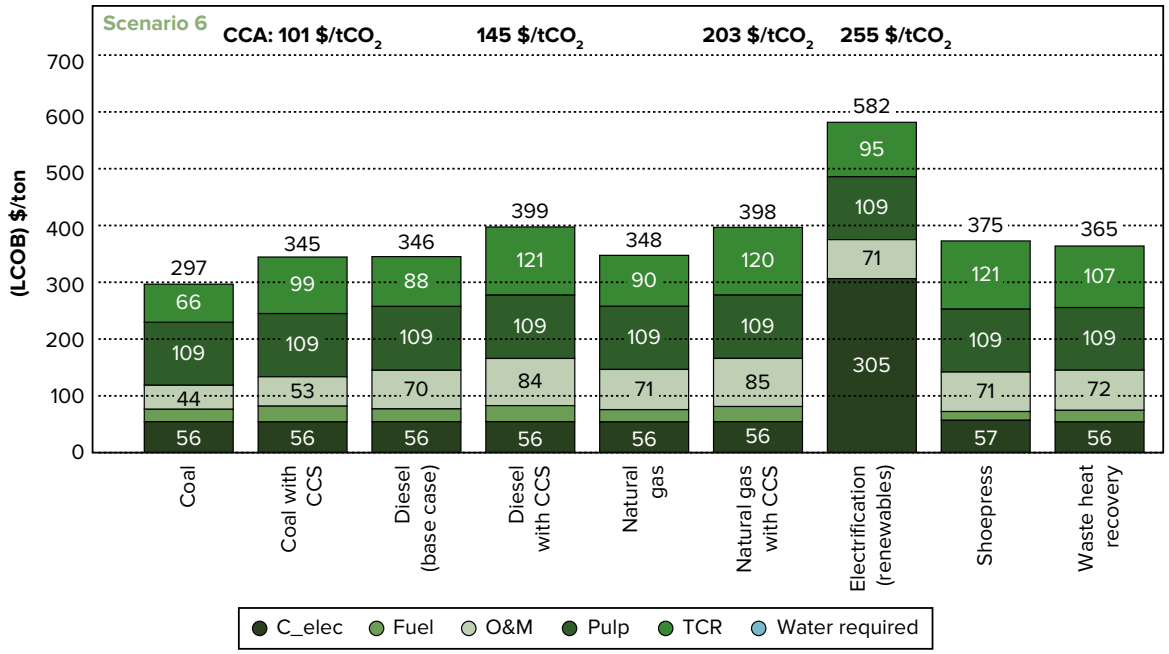
Figure 4. LCOB and CCA for Scenario 5 in the case of a paper mill incorporating decarbonization measures.



Source: Authors.

In the case of Scenario 6, as shown in Figure 5, countries that can readily import market pulp at reasonable prices and in which the utility prices are in the medium range include the U.S. and China. In such a context, where some paper mills that are currently using coal deploy CCS, the cost of the product is expected to increase by 16%. However, electrification by firm renewable energy can significantly increase the LCOB by approximately 68%. Additionally, the CCA value for this scenario is exorbitant, at 255 $/t CO_2 avoided.

Figure 5. LCOB and CCA for Scenario 6 in the case of a paper mill incorporating decarbonization measures.

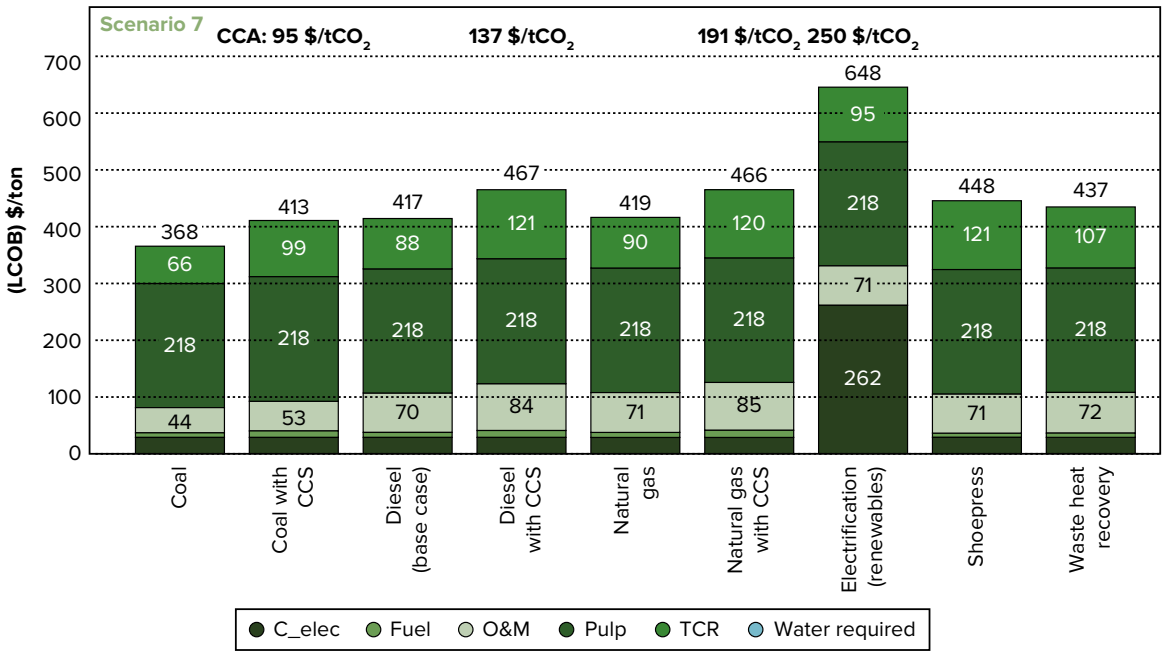


Source: Authors.

As seen in Section 3.2, Scenario 7 shows countries where market pulp and process water prices are higher and utility costs are lower; examples of such countries are GCC countries. Considering that firms renew at a price of 120 $/MWh and that the natural gas price is 2 $/GJ, switching to natural gas is economical for such countries, with only an 11% increase in the LCOB, as shown in Figure 6. However, owing to a small number of opportunities to capture emissions in standalone paper mills, the cost of avoidance is high, at 191 $/t CO_2. Although the electrification option is even higher, at 250 $/t CO_2, it enables us to avoid almost all of the carbon emissions when supplied by firm renewable energy.

In summary, the paper industry has an obvious converse impact compared with the pulp and integrated pulp and paper industries; in this case, the dominant factors are fuel and utility prices, along with market pulp prices. Thus, countries with lower fuel prices and greater availability of renewable energy resources are better able to deploy decarbonization measures such as fuel switching and electrification than other countries. Additionally, CCS is not well suited for paper mills because of the wide range of processes involved, some of which typically run on electricity. Hence, the CCA range for paper mills is more than double that of pulp and integrated pulp mills.

Figure 6. LCOB and CCA for Scenario 7 in the case of paper mill decarbonization measures.



Source: Authors.

4.4 Decarbonization Potential of Paper Mills in GCC Countries

The paper industry in GCC countries is a well-established and growing industry. Given the abundant availability of natural resources such as natural gas and renewable energy, the paper industry in this region possesses considerable decarbonization potential. Among GCC countries, the Kingdom of Saudi Arabia leads in terms of the number of factories operating in the paper and cardboard industries. The value of Saudi Arabia's investment in the paper industry represents more than 77% of the total investment of all GCC countries (Saudipedia 2024). In Saudi Arabia, more than 800 enterprises are registered under the category of manufacturers of paper and paper products (Monsha'at 2023). Additionally, the paper industry in Saudi Arabia is growing, with a 12% increase in production capacity in fiscal year 2023-2024 (GASTAT 2024). Considering a major portion of the market and with the expected range of input parameters for the LCOB and CCA being in the same range, Saudi Arabia can be considered a representative case for the GCC region.

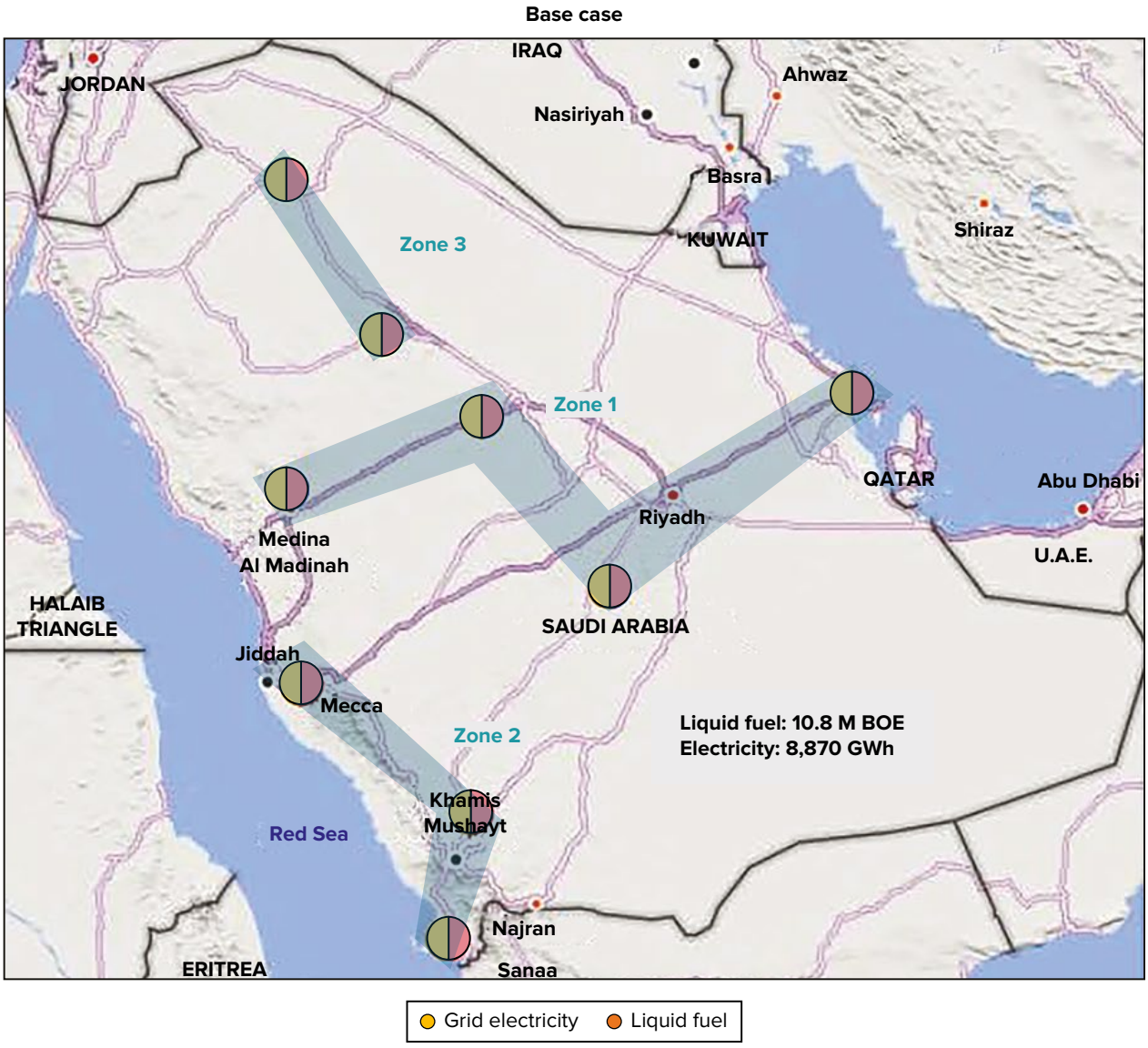
The paper mill database for Saudi Arabia is sourced from the National Industrial Information Center (NIIC 2024), which presents the name, the locality, and the production capacity of more than 500 paper mills in the country. The estimates from these data sources show that Saudi Arabia has a production capacity of approximately 12.8 Mt of paperboard per year. In Saudi Arabia, most paper mills are located close to major cities, as can be seen in Figure 7.

However, some paper mills are located in remote locations. While considering possible decarbonization options, Saudi Arabian announcements to achieve decarbonization targets are also considered, such as its goal of 1 million barrels of liquid fuel displacement by 2030 (MOEnergy 2024).

When liquid fuel is switched to natural gas, it can reduce emissions by 33% due to the typical low emissions observed with the combustion of natural gas (Geraghty 2013). However, once fuel is switched from liquid fuel to natural gas, it is more expensive to capture carbon from low-emission exhaust gases. Additionally, there are several processes in paper mills that are typically supplied by electricity, such as machine operations. Therefore, in a typical paper mill, natural gas with the CCS option can only partially decarbonize, whereas completely switching to natural gas would be inefficient. Furthermore, there is an option to deploy CCS in existing paper mills running on liquid fuels; however, owing to the energy penalty associated with carbon capture, this approach would further increase liquid fuel demand. Such an increase is not aligned with the Saudi Arabian policy of liquid fuel displacement. Therefore, options for both natural gas with CCS and liquid fuel with CCS are not further explored in this section.

To consider plausible options for the decarbonization of the paper industry in Saudi Arabia, the vicinity of paper mills from existing natural gas networks (also known as master gas systems (MGSs)) and planned extensions of the MGS are considered. In terms of locality, paper mills are categorized into three zones, as shown in Figure 7. Zone 1 is covered by the exiting MGS, Zone 2 is planned to be covered by the MGS in the near future (ARAMCO 2024), and Zone 3 is a remote locality that is not currently covered or planned to be covered by the MGS. In the base case, as shown in Figure 7, it is assumed that paper mills are supplied with liquid fuel and grid-connected electricity. The grid-connected electricity emission factor is assumed to be 0.568 t/MWh on the basis of the current energy mix of Saudi Arabia (Clean Development Mechasim 2021), which results in total emissions of 12.4 Mt of CO_2 per annum in the paper sector in Saudi Arabia.

Figure 7. Base case showing the fuel mix (liquid fuel and natural gas) and locality of paper mills in Saudi Arabia.



Source: Authors.

To explore the potential and associated cost of decarbonization options for paper mills in Saudi Arabia, four decarbonization cases are explored, as shown in Table 5. Figure 8(a) further shows the emissions from each zone on the basis of the production capacity of the paper mills. The greater production capacity of paper mills in zones 1 and 2 results in a greater portion of emissions attributed to them, with approximately 9.7 and 2.7 Mt of CO_2 per annum, respectively. However, with a production capacity of approximately 4,000 tons, zone 3 has negligible emissions compared with those of the other zones, but it is still important to explore the possible energy mix for such paper mills located in remote areas.

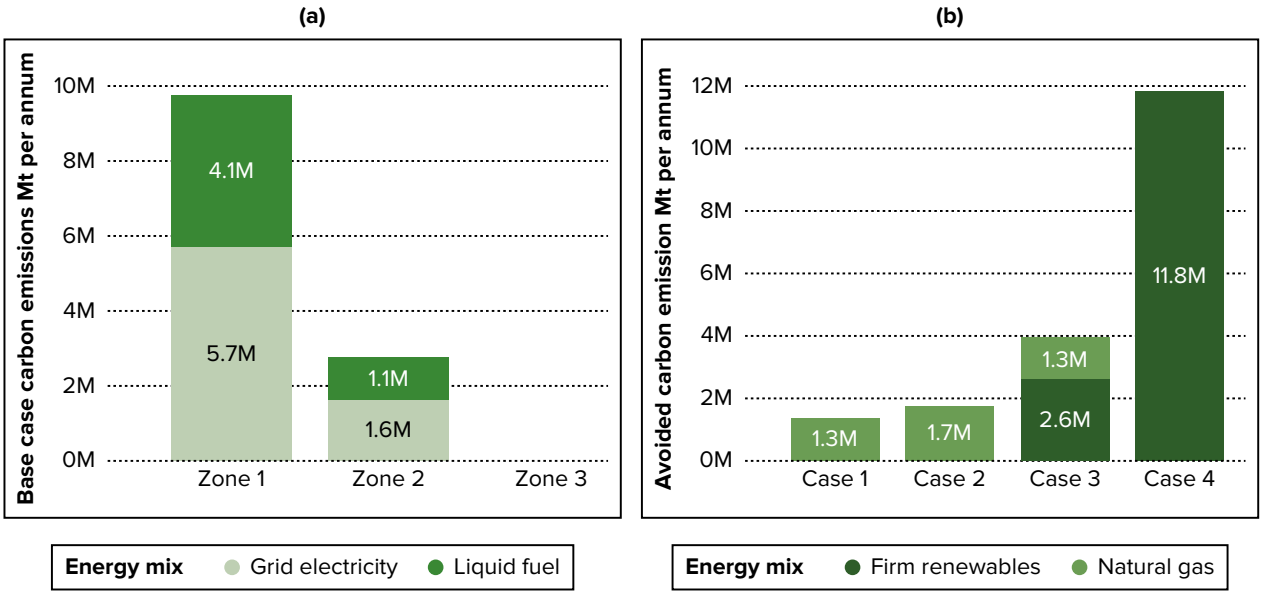
Table 5. Decarbonization measures analyzed for paper mills in Saudi Arabia.

Case	Zone	Network	Heat requirement provided by	Electricity requirement provided by
Base case	Zone 1	Existing MGS	Liquid fuel	Grid electricity
	Zone 2	Planned MGS	Liquid fuel	Grid electricity
	Zone 3	Noncovered	Liquid fuel	Grid electricity
Case 1	Zone 1	Existing MGS	Natural gas	Grid electricity
	Zone 2	Planned MGS	Liquid fuel	Grid electricity
	Zone 3	Noncovered	Electrification	Electrification
Case 2	Zone 1	Existing MGS	Natural gas	Grid electricity
	Zone 2	Planned MGS	Natural gas	Grid electricity
	Zone 3	Noncovered	Electrification	Electrification
Case 3	Zone 1	Existing MGS	Natural gas	Grid electricity
	Zone 2	Planned MGS	Electrification	Electrification
	Zone 3	Noncovered	Electrification	Electrification
Case 4	Zone 1	Existing MGS	Electrification	Electrification
	Zone 2	Planned MGS	Electrification	Electrification
	Zone 3	Noncovered	Electrification	Electrification

In Case 1, fuel is switched from liquid fuel to natural gas in zone 1, whereas zone 3 is electrified with firm renewables. This liquid fuel displacement can reduce the liquid fuel requirement from 10.8 M BOE[10] to only 2.36 M BOE. However, these measures, which involve fuel switching, can achieve emission avoidance of only 1.3 Mt CO_2 per annum, as shown in Figure 8(b).

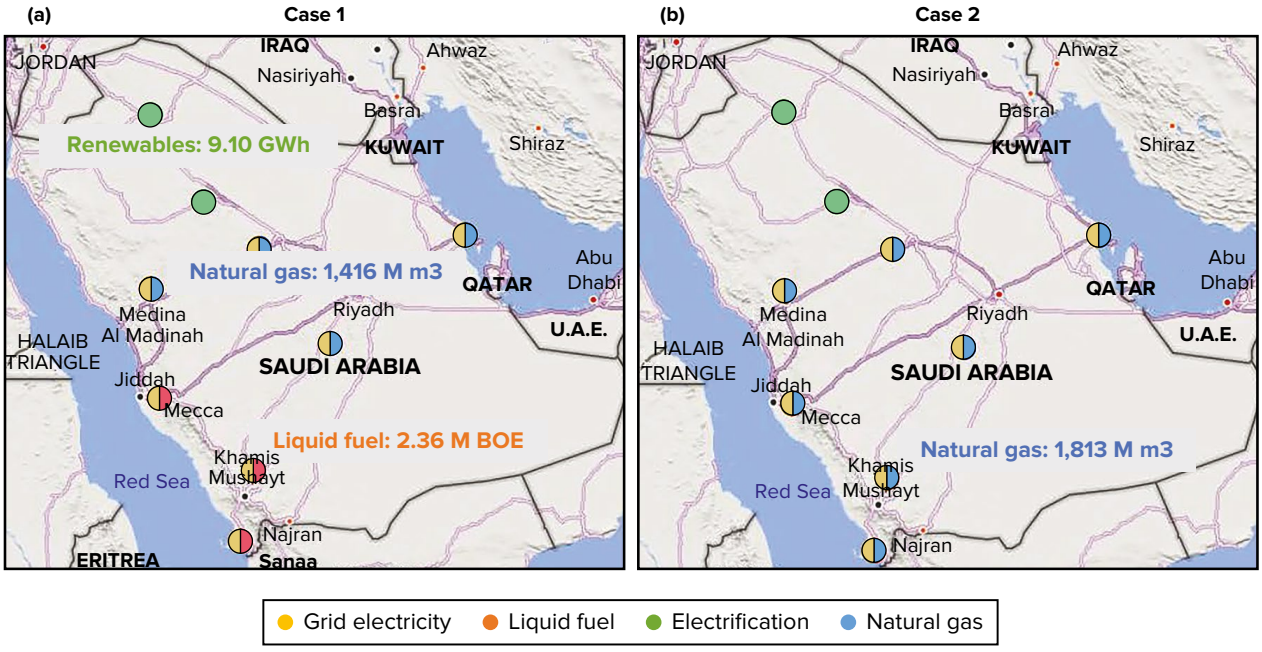
In Case 2, fuel switching in both Zones 1 and 2 from liquid fuel to natural gas and the electrification of Zone 3 can further increase emission avoidance to 1.7 Mt CO_2 per annum. Notably, the maximum emission reduction potential can be achieved from the fuel switching measure of the paper industry in Saudi Arabia. Moreover, this situation would require natural gas consumption of approximately 1,813 million m^3, as shown in Figure 9(b).

Figure 8. Emissions from (a) zones 1 to 3 in the base case and (b) avoided emissions from -cases 1 to 4.



Source: Authors.

Figure 9. Decarbonization measures in Cases and 2 showing the fuel mix and quantity of energy consumed.



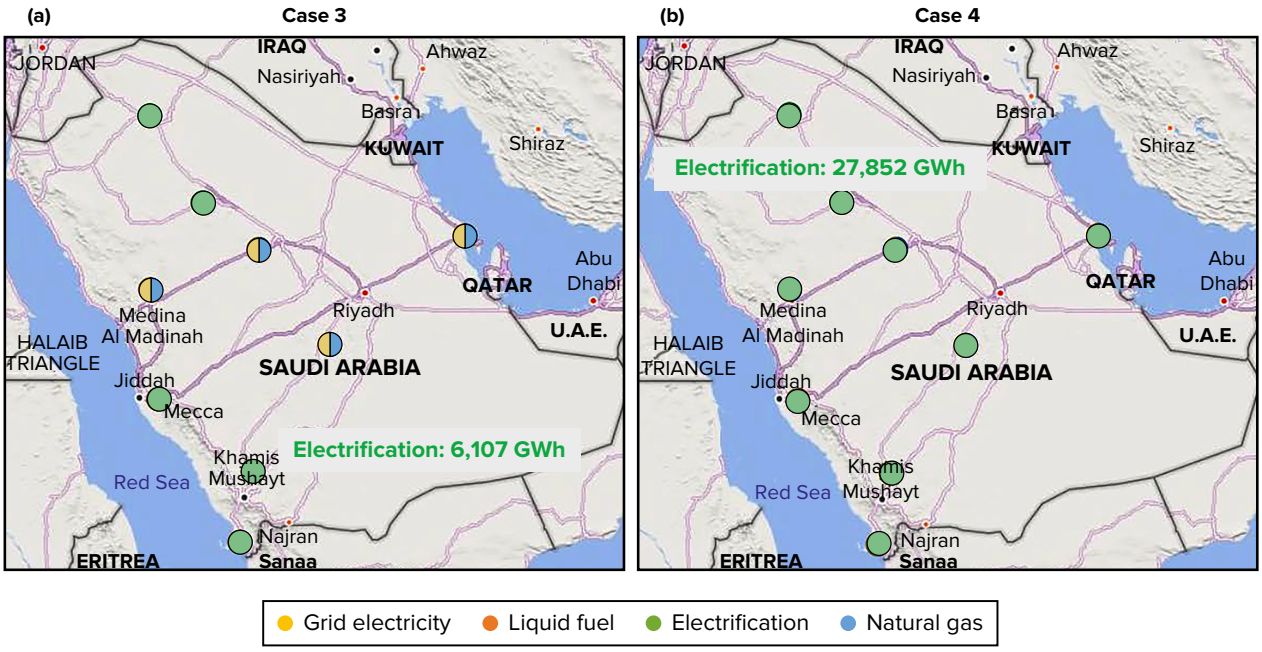
Source: Authors.

Case 3 can achieve an emission avoidance value of an additional 2.6 Mt of CO_2 per annum via the electrification of Zones 2 and 3, as shown in Figure 10, with a renewable generation of approximately 6 TWh. Furthermore, in Case 4, where all zones are switched to the electrification option, firm renewable power generation of approximately 28 TWh per annum, which is equivalent to more than 3,000 MW of firm renewable power, is required. This electrification measure can achieve an emission reduction value of approximately 11.8 MT CO_2 per annum. Considering the decarbonization potential in conjunction with the economic analysis performed in the previous section, the electrification measure would result in an LCOB increase of 55%, with a CCA value of 250 t CO_2 in the Saudi Arabian context.[11]

Another important aspect to consider is the capacity of the required energy generation mix, which is impacted primarily by the size of the paper mill. The data from paper mills in Saudi Arabia show that the production capacity of these paper mills ranges from 0.03 Mt to 1.2 Mt per annum (NIIC 2024). The higher production ranges of such mills typically require approximately 100 MW of firm capacity for partial electrification to supply electrical load, whereas fully electrified paper mills require approximately 300 MW of firm renewable capacity (U.S. DOE 2015).

In summary, while electrification options are viable for remote locations, fuel switching options can prove to be important transitional low-emission technologies for emission avoidance in the paper industry in Saudi Arabia. As a firm's renewable generation price is expected to decline significantly in future years, it can ultimately play a vital role in decarbonizing the entire paper industry.

Figure 10. Decarbonized measures in Cases 3 and 4 showing the fuel mix and quantity of energy consumed.



Source: Authors.

5. Conclusions

This study analyses the carbon removal potential of various PPI pathways and evaluates their impact on the levelized cost of products. The results from this study show that the LCOP increased from 34% to 76% with the deployment of CCS in pulp mills. Moreover, the CCA value is in the range of 50 \$/t CO_2 to 66 \$/t CO_2 for pulp mills and integrated pulp and paper mills. However, the paper decarbonization of standalone paper mills is challenging when the CCA value is in the range of 95 \$/t CO_2 to 281 \$/t CO_2. The deployment of CCS in paper mills also has limitations and can only partially reduce emissions since some of the associated processes are typically supplied by electricity. Nevertheless, fuel switching to natural gas in the paper industry has the potential to reduce emissions by more than 30% without a considerable increase in the LCOB.

Saudi Arabia has a potential of approximately 11.8 Mt CO_2 in emission avoidance per year through electrification. Additionally, in line with Saudi Arabia's decarbonization objectives, more than 10 million barrels of liquid fuel can be displaced from paper mills considering fuel switching and electrification options. The results also show that decarbonization measures increase the LCOB for Saudi Arabia by up to 55%, whereas the same decarbonization measures in high-price-regime countries increase the LCOB by approximately 83%.

In summary, the deployment of CCS in pulp mills and integrated pulp and paper mills can significantly reduce emissions in countries with high biomass potential. Decarbonization measures such as fuel switching and electrification are better suited for standalone paper mills in low-utility-price-regime countries. The analysis and results presented in this study provide important insights for policymakers to assess the carbon removal potential and associated costs of the PPI. A roadmap for developing strategies for the decarbonization of the PPI can be developed on the basis of the insights provided in this study.

In summary, countries with high biomass potential are suitable for the pulp industry and integrated PPIs for CO_2 removal via the deployment of CCS. Countries with high natural resource potential are well positioned to deploy decarbonization options in standalone paper industries.

Endnotes

[1] Decarbonization entails reducing those CO_2 emissions produced by the combustion of fossil fuels.

[2] The cooking phase of the pulping process leaves residual lignin, which can be removed in an aqueous solution to produce black liquor.

[3] Biogenic CO_2 emissions are those emissions related to the natural carbon cycle.

[4] Biogenic CO_2 emissions, which are captured and permanently stored, can be considered carbon dioxide removal.

[5] Nordic (northern Europe) countries include mainly Denmark, Finland, Sweden and Norway.

[6] The HTL process decomposes biomass into liquid fuels at approximately 300°C in pressurized water.

[7] Captured biogenic emissions from the natural carbon cycle can also be referred to as negative emissions.

[8] Shoe press technology is a papermaking technology that improves the dewatering of the board or paper sheet in the wet-pressing section and reduces the need for drying evaporation.

[9] CCS costs include carbon capture, transport, and storage costs.

[10] Here, BOE is a barrel of oil equivalent, and on the basis of the literature, one GJ of energy can be produced by 0.15829 BOE.

[11] In the context of the Kingdom of Saudi Arabia, we consider the price of natural gas to be 2 $/GJ and the price of firm renewables to be 120 $/MWh.

References

Ahmadvand, Sahar, and Taraneh Sowlati. 2023. "The Attractiveness of Syngas Production from Forest-Based Biomass for Pulp Mills Considering Carbon Pricing and Government Regulations." *Renewable Energy Focus* 45 (June): 287–306. https://doi.org/10.1016/j.ref.2023.04.007.

Australian Energy Market Operator (AEMO). 2024. *Integrated System Plan Fact Sheet*. https://aemo.com.au/energy-systems/major-publications/integrated-system-plan-isp/integrated-system-plan-fact-sheet.

Andersson, Elias, Henric Dernegård, Magnus Wallén, and Patrik Thollander. 2021. "Decarbonization of Industry: Implementation of Energy Performance Indicators for Successful Energy Management Practices in Kraft Pulp Mills." *Energy Reports* 7 (November): 1808–1817. https://doi.org/10.1016/j.egyr.2021.03.009.

ARAMCO. 2024. "Remarks by Amin H. Nasser at the Signing Ceremony for Jafurah Phase II and MGS Phase III." https://www.aramco.com/en/news-media/speeches/2024/remarks-by-amin-h-nasser-at-the-signing-ceremony-for-jafurah-phase-ii-and-mgs-phase-iii.

Confederation of European Paper Industries (CEPI). 2024. *Innovative Bio-Based Products for a Sustainable Future: A Cepi Study on Pulp and Paper Industry Biorefineries in Europe*. https://www.cepi.org/wp-content/uploads/2024/09/Cepi_BioRefineries_Executive-Summary_2024.pdf.

Clean Development Mechanism. 2021. *Development of the Kingdom's Updated Grid Emission Factor 2021*. https://cdmdna.gov.sa/content/files//aa4d63693729d06313ff24b1b9cb694d.pdf.

Cochran. 2024. *Cochran Ltd Energy for the Paperboard Industry*. https://cochran.co.uk/Downloads/Paper%20Profile%20Case%20Study.pdf.

Dai, Min, Mingxing Sun, Bin Chen, Hongyi Xie, Dingfan Zhang, Zhixiu Han, Lan Yang, and Yutao Wang. 2023. "Advancing Sustainability in China's Pulp and Paper Industry Requires Coordinated Raw Material Supply and Waste Paper Management." *Resources, Conservation and Recycling* 198 (November): 107612. https://doi.org/10.1016/j.resconrec.2023.107162.

Deng, Huijing, Dingfan Zhang, Huajun Yu, Yi Man, and Yutao Wang. 2023. "Assessing Life-Cycle GHG Emissions of Recycled Paper Products Under Imported Solid Waste Ban in China: A Case Study." *Science of The Total Environment* 891 (September): 164407. https://doi.org/10.1016/j.scitotenv.2023.164407.

Ericsson, Karin, and Lars J. Nilsson. 2018. "Climate Innovations in the Paper Industry: Prospects for Decarbonisation." *IMES/EESS Report Series*, Vol. 110. Lund University. https://lucris.lub.lu.se/ws/portalfiles/portal/53222132/Climate_innovations_in_the_paper_industry_IMES_report_110.pdf.

Fornell, Rickard, Thore Berntsson, and Anders Åsblad. 2013. "Techno-Economic Analysis of a Kraft Pulp-Mill-Based Biorefinery Producing Both Ethanol and Dimethyl Ether." *Energy* 50 (February): 83–92. https://doi.org/10.1016/j.energy.2012.11.041.

Furszyfer Del Rio, Dylan D., Benjamin K. Sovacool, Steve Griffiths, Morgan Bazilian, Jinsoo Kim, Aoife M. Foley, and David Rooney. 2022. "Decarbonizing the Pulp and Paper Industry: A Critical and Systematic Review of Sociotechnical Developments and Policy Options." *Renewable and Sustainable Energy Reviews* 167 (October): 112706. https://doi.org/10.1016/j.rser.2022.112706.

Geraghty, R. 2013. *Resource Efficiency Innovation Ireland*. Resource Efficiency Innovation Ireland. https://www.leanbusinessireland.ie/includes/documents/Resource%20Efficiency%20Dairy%20Processing%20Ireland%20TOTAL%20JUNE%202011.pdf.

GlobalCCS. 2023. "Seven CCS Projects to Receive Support from the Japanese Government." June 26. https://www.globalccsinstitute.com/news-media/latest-news/seven-ccs-projects-to-receive-support-from-the-japanese-government.

Griffin, Paul W., Geoffrey P. Hammond, and Jonathan B. Norman. 2018. "Industrial Decarbonisation of the Pulp and Paper Sector: A UK Perspective." *Applied Thermal Engineering* 134 (April): 152–162. https://doi.org/10.1016/j.applthermaleng.2018.01.126.

Han, Qian-long, Hai-long Zhao, Guo-xia Wei, Yu-wen Zhu, Tong Li, Mao Xu, Xin Guo, Hui-zhen Shi, Yi Lian, and Han-qiao Liu. 2024. "Sustainable Papermaking in China: Assessing Provincial Economic and Environmental Performance of Pulping Technologies." *ACS Sustainable Chemistry & Engineering* 12 (11): 4517–4529. https://doi.org/10.1021/acssuschemeng.3c07611.

IEA Bioenergy. 2007. "Black Liquor Gasification: Summary and Conclusions from the IEA Bioenergy ExCo54 Workshop." https://www.ieabioenergy.com/wp-content/uploads/2013/10/Black-Liquor-Gasification-summary-and-conclusions1.pdf.

IEAGHG. 2016. "Techno-Economic Evaluation of Retrofitting CCS in a Market Pulp Mill and an Integrated Pulp and Board Mill." https://ieaghg-publications.s3.eu-north-1.amazonaws.com/Technical+Reports/2016-10+Techno-Economic+Evaluation+of+Retrofitting+ccs+in+a+market+pulp+mill+and+an+integrated+pulp+and+board+mill.pdf.

Intergovernmental Panel on Climate Change (IPCC). 2022. "Industry." In *IPCC, 2022: Climate Change 2022: Mitigation of Climate Change*, 1161–1243. https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Chapter11.pdf.

Jafri, Yawer, Elisabeth Wetterlund, Sennai Mesfun, Henrik Rådberg, Johanna Mossberg, Christian Hulteberg, and Erik Furusjö. 2020. "Combining Expansion in Pulp Capacity with Production of Sustainable Biofuels – Techno-Economic and Greenhouse Gas Emissions Assessment of Drop-In Fuels from Black Liquor Part-Streams." *Applied Energy* 279 (December): 115879. https://doi.org/10.1016/j.apenergy.2020.115879.

Kong, Lingbo, Lynn Price, Ali Hasanbeigi, Huanbin Liu, and Jigeng Li. 2013. "Potential for Reducing Paper Mill Energy Use and Carbon Dioxide Emissions Through Plant-Wide Energy Audits: A Case Study in China." *Applied Energy* 102 (February): 1334–1342. https://doi.org/10.1016/j.apenergy.2012.07.013.

Kumar, Vineet, Sandeep Kumar Malyan, Wilgince Apollon, and Pradeep Verma. 2024. "Valorization of Pulp and Paper Industry Waste Streams into Bioenergy and Value-Added Products: An Integrated Biorefinery Approach." *Renewable Energy* 228 (July): 120566. https://doi.org/10.1016/j.renene.2024.120566.

Lawrence Berkeley National Laboratory (LBNL). 2009. *Energy Efficiency Improvement and Cost Saving Opportunities for the Pulp and Paper Industry.* Sponsored by the U.S. Environmental Protection Agency. https://international.lbl.gov/sites/default/files/2022-05/ee-guidebook-for-pulp-and-paper-industry.pdf.

Leeson, Duncan, Paul Fennell, Nilay Shah, Camille Petit, and Niall Mac Dowell. 2017. "A Techno-Economic Analysis and Systematic Review of Carbon Capture and Storage (CCS) Applied to the Iron and Steel, Cement, Oil Refining, and Pulp and Paper Industries." *Energy Procedia* 114 (July): 6297–6302. https://doi.org/10.1016/j.egypro.2017.03.1766.

Li, Yijing, Tian Zhu, Shijia Qin, Guangzai Nong, and Yongjun Yin. 2023. "Energy Conservation and Emission Reduction of a New Pulp Mill by Improving Production Processes." *Process Safety and Environmental Protection* 176 (August): 662–672. https://doi.org/10.1016/j.psep.2023.06.027.

Liang, Ziyang, Huijing Deng, Hongyi Xie, Bin Chen, Mingxing Sun, and Yutao Wang. 2023. "Rethinking the Paper Product Carbon Footprint Accounting Standard from a Life-Cycle Perspective." *Journal of Cleaner Production* 393 (March): 136352. https://doi.org/10.1016/j.jclepro.2023.136352.

Mäki, Elina, Heidi Saastamoinen, Kristian Melin, Doris Matschegg, and Hanna Pihkola. 2021. "Drivers and Barriers in Retrofitting Pulp and Paper Industry with Bioenergy for More Efficient Production of Liquid, Solid, and Gaseous Biofuels: A Review." *Biomass and Bioenergy* 148 (May): 106036. https://doi.org/10.1016/j.biombioe.2021.106036.

Man, Yi, Yukun Yan, Xu Wang, Jingzheng Ren, Qingang Xiong, and Zhenglei He. 2023. "Overestimated Carbon Emission of the Pulp and Paper Industry in China." *Energy* 273 (June): 127279. https://doi.org/10.1016/j.energy.2023.127279.

Mathur, Shivani, Greer Gosnell, Benjamin K. Sovacool, Dylan D. Furszyfer Del Rio, Steve Griffiths, Morgan Bazilian, and Jinsoo Kim. 2022. "Industrial Decarbonization via Natural Gas: A Critical and Systematic Review of Developments, Socio-Technical Systems and Policy Options." *Energy Research & Social Science* 90 (August): 102638. https://doi.org/10.1016/j.erss.2022.102638.

MEPCO. 2024. “Cardboard Paper Production Capacity.” https://www.mepco.biz/Website/En/investment-amounting-to1-78-billion-saudi-riyals-in-5th-production-line-to-boost-cardboard-paper-production-capacity-annually-by-450-thousand-ton/.

MOEnergy. 2024. “MOEnergy Energy Transition Challenges.” https://moenergy.gov.sa/en/DigitalDocuments/Documents/Energy_Transition_Challenges.pdf.

Monsha’at. 2023. “Manufacture of Paper and Paper Products.” https://atlas.monshaat.gov.sa/en/profile/sector/manufacture-of-paper-and-paper-products.

Nie, Yuhao, and Xiaotao T. Bi. 2018. “Techno-Economic Assessment of Transportation Biofuels from Hydrothermal Liquefaction of Forest Residues in British Columbia.” *Energy* 153 (June): 464–475. https://doi.org/10.1016/j.energy.2018.04.057.

National Industrial Information Center (NIIC). 2024. “Manufacture of Paper and Products.” https://fd.niic.gov.sa.

Onarheim, Kristin, Stanley Santos, Petteri Kangas, and Ville Hankalin. 2017. “Performance and Cost of CCS in the Pulp and Paper Industry Part 2: Economic Feasibility of Amine-Based Post-Combustion CO_2 Capture.” *International Journal of Greenhouse Gas Control* 66 (November): 60–75. https://doi.org/10.1016/j.ijggc.2017.09.010.

Ouadi, Miloud, Antzela Fivga, Hessam Jahangiri, Muhammad Saghir, and Andreas Hornung. 2019. “A Review of the Valorization of Paper Industry Wastes by Thermochemical Conversion.” *Industrial & Engineering Chemistry Research* 58 (35): 15914–15929. https://doi.org/10.1021/acs.iecr.9b00635.

LAZARD. 2024. *LAZARD LCOE*. https://www.lazard.com/media/xemfey0k/lazards-lcoeplus-june-2024-_vf.pdf.

Parkhi, Amod, Selen Cremaschi, and Zhihua Jiang. 2022. “Techno-Economic Analysis of CO_2 Capture from Pulp and Paper Mill Limekiln.” *IFAC-PapersOnLine* 55 (7): 284–291. https://doi.org/10.1016/j.ifacol.2022.07.458.

Pilorge, Hélène, Noah McQueen, Daniel Maynard, Peter Psarras, Jiajun He, Tecle Rufael, and Jennifer Wilcox. 2020. “Cost Analysis of Carbon Capture and Sequestration of Process Emissions from the U.S. Industrial Sector.” *Environmental Science & Technology* 54 (12): 7524–7532. https://doi.org/10.1021/acs.est.9b07930.

Rademaker, K., and M. Marsidi. 2019. *Decarbonisation Options for the Dutch Paper and Board Industry*. PBL Netherlands Environmental Assessment Agency, August 20. https://www.pbl.nl/uploads/default/downloads/pbl-2019-decarbonisation-options-for-the-dutch-paper-and-board-industry_3480.pdf.

Roussanaly, Simon, Niels Berghout, Tim Fout, Monica Garcia, Stefania Gardarsdottir, Shareq Mohd Nazir, Andrea Ramirez, and Edward S. Rubin. 2021. “Towards Improved Cost Evaluation of Carbon Capture and Storage from Industry.” *International Journal of Greenhouse Gas Control* 106 (March): 103263. https://doi.org/10.1016/j.ijggc.2021.103263.

Rutz, Dominik, Rainer Janssen, Patrick Reumerman, Jurjen Spekreijse, Doris Matschegg, Dina Bacovsky, Arne Gröngröft, Stephanie Hauschild, Niels Dögnitz, Emmanouil Karampinis, Dimitrios-Sotirios Kourkoumpas, Panagiotis Grammelis, Kristian Melin, Heidi Saastamoinen, Ana Isabel Susmozas Torres, Raquel Iglesias, Mercedes Ballesteros, Göran Gustavsson, Daniella Johansson, Anes Kazagić, Ajla Merzić, Dino Trešnjo, Hans Dagevos, Siet J. Sijtsema, Machiel J. Reinders, and Marieke Meeusen. 2020. “Technical Options for Retrofitting Industries with Bioenergy BIOFIT.” *BioFit Handbook*. 2nd ed. Munich: WIP Renewable Energies. https://www.biofit-h2020.eu/files/pdfs/BioFitHandbook_EN_2ndEdition_2022-03-15.pdf.

Saeed, Rami M. W., Elizabeth Kirkpatrick Worsham, Byung-Hee Choi, and Frederick Carl Joseck. 2023. “Industrial Requirements Status Report and Down-Select of Candidate Technologies.” *S&T Accomplishment Report*, May 31, 2023. https://www.osti.gov/biblio/1988130.

Saudi Paper Group. 2024. https://saudipaper.com.

Saudipedia. 2024. “Paper Industry in the Kingdom.” https://saudipedia.com/en/article/593/economy-and-business/industry/paper-industry-in-the-kingdom.

Sonsale, Anand Narhari, Yashpal, J. K. Purohit, and S. D. Pohekar. 2021. “Renewable & Alternative Energy Sources for Strategic Energy Management in Recycled Paper & Pulp Industry.” Bioresource Technology Reports 16 (December): 100857. https://doi.org/10.1016/j.biteb.2021.100857.

General Authority for Statistics (GASTAT). 2024. “Industrial Production Index.” https://www.stats.gov.sa/sites/default/files/IPI%20JULY%202024%20En.pdf.

U.S. Department of Energy (DOE). 2015. "Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Pulp and Paper Manufacturing." https://www.energy.gov/sites/default/files/2015/08/f26/pulp_and_paper_bandwidth_report.pdf.

United Nations Industrial Development Organization (UNIDO). 2010. "Carbon Capture and Storage in Industrial Applications: Technology Synthesis Report Working Paper." https://www.unido.org/sites/default/files/2010-12/synthesis_final_0.pdf.

Vazifeh, Zahra, Farid Bensebaa, Jalil Shadbahr, Giovanna Gonzales-Calienes, Fereshteh Mafakheri, Marzouk Benali, Mahmood Ebadian, and Pierre Vézina. 2023. "Forestry Based Products as Climate Change Solution: Integrating Life Cycle Assessment with Techno-Economic Analysis." *Journal of Environmental Management* 330 (March): 117197. https://doi.org/10.1016/j.jenvman.2022.117197.

WSP. "Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050." https://assets.publishing.service.gov.uk/media/5a817f9640f0b62302697a1b/Cross_Sector_Summary_Report.pdf.

About the Authors



Muhammad Adnan Hayat

Muhammad Adnan Hayat joined KAPSARC in December 2022 as a Research Fellow in the Utilities and Renewables Program. Before joining KAPSARC, Adnan worked as a Policy Analyst with the Energy Policy Government of Western Australia in the planning and analytics area. He has also worked with the Economic Regulation Authority Western Australia as an analyst on the wholesale electricity market team. He has more than 15 years of research and professional experience. He holds a Ph.D. in Electrical Engineering from Murdoch University, Australia.



Amro M. Elshurafa

Dr. Elshurafa is the Executive Director of the Utilities and Renewables Department and possesses 20+ years of experience garnered on three continents. His research interests lie in renewable energy policy, electricity market design and regulation, and power systems modeling. He has led and executed several national modeling initiatives at distributed and utility scales. Some aspects of his research have been adopted by BP in their seminal annual *Statistical Review*. He is listed among the top 2% of scientists globally as per Stanford, and he is a board member of the Saudi Water and Electricity Regulatory Authority. Credited with 50+ papers and patents, he holds a Ph.D. in Engineering and an MBA in Finance.

About the Project

This study falls under the project “Biobased industry decarbonization potential in the Kingdom of Saudi Arabia” within KAPSARC’s Utilities and Renewables Program. This study performs a technoeconomic assessment of the pulp and paper industry with respect to carbon capture in selected countries. Moreover, the decarbonization potential of paper mills in Saudi Arabia is analyzed in detail to evaluate their potential to achieve net-zero emissions in the industrial sector.



www.kapsarc.org