



# Decarbonization pathways for the pulp and paper industry: A comprehensive review

Farhan Haider Joyo<sup>a,\*</sup>, Benedetto Nastasi<sup>b</sup>, Davide Astiaso Garcia<sup>a</sup>

<sup>a</sup> Department of Astronautical, Electrical and Energy Engineering, Sapienza University of Rome, Italy

<sup>b</sup> Department of Industrial Engineering, Tor Vergata University of Rome, Italy

## ARTICLE INFO

### Keywords:

Pulp and paper industry  
Industrial decarbonization  
Climate change  
Net-zero emission  
Analytical hierarchy process (AHP)  
Multi-criteria decision making (MCDM)

## ABSTRACT

The world is experiencing the effects of climate change at an increasing rate, including rising average global temperature, caused primarily by greenhouse gas (GHG) emissions. Energy-intensive industries (EIIs) are major contributors to greenhouse gas emissions. The pulp and paper industry (PPI) is among the top five most energy-intensive industries, and it accounts for approximately 6 % of global industrial energy use and 2 % of direct industrial CO<sub>2</sub> emissions. Therefore, it is important to decarbonize this industrial sector to achieve the climate policy goal of achieving net-zero emissions as per the Paris Agreement. This paper presents a comprehensive review of the decarbonization options, also known as decarbonization pathways, for the pulp and paper industrial sector. These pathways are selected from available literature, and they mainly include energy efficiency measures (EEMs), paper recycling, switching to carbon-neutral fuels such as biomass and hydrogen, electrification of heat supply, and carbon capture & storage (CCS), among other emerging technologies. After identifying, each decarbonization pathway is discussed in detail with its drivers and barriers to implementation. The Analytical Hierarchy Process AHP, a multi-criteria decision-making MCDM technique, is carried out to rank the decarbonization pathways on five distinct criteria: cost, emission reduction potential, technological readiness level (TRL), implementation time, and scalability. The ranking is carried out in four distinct criteria weight regimes to present clear choices on different criterion weights. This review paper aims to add to the existing literature to provide clear indications in choosing the pathways toward the decarbonization effort in the pulp & paper industry under various strategic priorities.

## 1. Introduction

There is growing attention towards decarbonizing the industrial sector to reduce dependence on fossil fuels, reduce negative environmental impacts, and find new energy sources to achieve climate neutrality by 2050, as per the Paris Agreement [1]. Energy-intensive industries (EIIs) such as iron & steel, cement, pulp & paper, and chemicals are a significant part of the economy and are responsible for a large amount of energy consumption, resource use, and emissions [2]. Globally, EIIs are responsible for approximately 30 % of the total greenhouse gas (GHG) emissions [3]. Studies have identified energy efficiency, the use of best available technologies (BATs), and fuel switching towards renewable energy sources as the best pathways in reducing energy demand and cutting emissions from the industrial sector [4,5].

Additionally, enhancing circularity through recycling is identified as a significant decarbonization option for the EIIs [6]. The paper-making industry accounts for 6 % of global industrial energy consumption and is responsible for 2 % of direct industrial CO<sub>2</sub> emissions (Fig. 1). The global demand and production of pulp and paper are expected to increase significantly by 2050 [7], which will drive up associated energy use and GHG emissions. Thus, to achieve the climate policy objective of achieving net-zero CO<sub>2</sub> emissions globally by 2050, decarbonizing the pulp and paper industry (PPI) is essential [8]. The PPI, due to its heterogeneity, manufactures a range of products including tissue papers, currency notes, printing paper, packaging paper, and paper used for banners, displays, and advertisements. The annual production of PPI stands at over 400 million tons of paper and is expected to nearly double by 2050, in response to rising demand [9]. The major energy-consuming

This article is part of a special issue entitled: SDEWES2024 published in Renewable and Sustainable Energy Reviews.

\* Corresponding author. Department of Astronautical Electrical & Energy Engineering (DIAEE), Sapienza University of Rome, Italy.

E-mail addresses: [farhanhaider.joyo@uniroma1.it](mailto:farhanhaider.joyo@uniroma1.it) (F.H. Joyo), [benedetto.nastasi@outlook.com](mailto:benedetto.nastasi@outlook.com) (B. Nastasi), [davide.astiasogarcia@uniroma1.it](mailto:davide.astiasogarcia@uniroma1.it) (D. Astiaso Garcia).

<https://doi.org/10.1016/j.rser.2025.116070>

Received 26 January 2025; Received in revised form 26 June 2025; Accepted 7 July 2025

Available online 10 July 2025

1364-0321/© 2025 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

processes in PPI include black liquor evaporation, chemical pulp making, and the drying of paper [10]. The environmental emissions of the PPI are also significant, and specific factors such as high-temperature heat demand, process emissions, and the long life of the industrial plants make it challenging to mitigate these emissions [3]. The PPI has the potential to significantly reduce its energy consumption (Fig. 1) by implementing efficient and sustainable technologies. The main roadmaps for decarbonizing the pulp and paper industry, as presented by the Confederation of European Paper Industry (CEPI) [11], include energy efficiency measures (EEMs), fuel switching, electrification of heat supply, and emerging technologies such as carbon capture and storage (CCS). This review aims to evaluate the potential of the pathways available in the literature to achieve the goal of decarbonization in the PPI.

### 1.1. Overview of pulp and paper production process

The primary source (raw material) for the PPI is wood and wood residues, which must contain high levels of cellulose to meet the lignocellulosic biomass standards [12]. Recovered paper is also utilized by the PPI, which is obtained from the activities of waste management. The two most crucial stages in the production of pulp and paper are pulping and papermaking. Pulping is the process of breaking down raw materials into cellulose fibers, and papermaking involves converting the pulp into thin sheets of paper through the pressing and drying processes. These processes demand significant amounts of resources and energy inputs to be carried out effectively [13]. Pulping can be carried out using two processes: mechanical pulping and chemical pulping. Through mechanical procedures in the mechanical pulping, cellulose fibers are primarily separated, resulting in the transformation of around 95 % of the wood into pulp [14]. The lignin tends to cause yellowing of mechanical pulp; therefore, mechanical pulping is primarily utilized for producing products with a shorter lifespan, such as newsprints and magazine paper [15]. The process of chemical pulping involves the separation of cellulose fibers from lignin and other wood components using chemicals, which typically include sodium hydroxide and sodium sulfide (kraft pulping). This results in paper with improved qualities such as increased strength and brightness, but with a lower yield of around 40–55 %, due to the dissolution of lignin [16]. A key feature of kraft pulping is the recovery of spent cooking liquor, known as black liquor, which is burned as biofuel to generate steam and electricity for the mill. Different varieties of boards, fine paper, and sack paper products commonly utilize chemical pulp. Chemical pulping processes are predominantly used for producing pulp in the EU [14]. According to the estimates, over 90 % of the global pulp production is accounted for by kraft pulping [17].

After pulping, the pulp may be bleached (for high-brightness paper

grades) and then goes to the paper machine. The process of papermaking involves five main steps. Initially, the pulp is mixed with water and additives in stock preparation and then refined, screened, and deinked to attain the desired properties. In the next stage, the wire section, the water is eliminated through the application of gravitational forces and vacuuming. Following the wire section, the damp paper is passed through the press section, where water is removed mechanically. At this juncture, depending on the design of the press section and the grade of paper, the dry solid content ranges from 33 % to 55 % [18]. In the fourth stage of paper production, the remaining water is removed through thermal means in the pre-drying section. Depending on the desired product specifications, the paper may undergo a sizing step involving substances such as starch, glue, or coating. In case a second drying stage is required, a small amount of moisture, typically between 5 % and 9 %, remains in the paper even after drying. Then the paper sheet goes for finishing, which involves calendering and reeling. Fig. 2 illustrates the processes of virgin pulp-based and recycled paper mills, highlighting the key stages from raw material input to paper drying, including pulping, refining, deinking, pressing, and drying.

Fig. 3 illustrates a simplified block layout of the papermaking processes along with the energy consumption share, and Table 1 shows specific electricity and heat consumption for each process.

The PPI is unique in a way that, unlike other heavy industries (such as steel or cement) that rely predominantly on fossil fuels, the PPI sector utilizes a significant share of biofuels and waste for its energy needs. These include biomass residues and process waste such as black liquor, barks, and wood scraps. Black Liquor is a carbon-rich by-product of chemical pulping, which is used as fuel on-site in the recovery boilers to generate steam and electricity, reducing reliance on fossil fuels [25]. This intrinsic use of biomass has allowed the sector to decouple energy use from production growth to some extent. For instance, in the EU, a 23 % increase in paper output over two decades saw only a 1 % increase in energy use, due to high utilization of bioenergy and by-product utilization [26]. In contrast, more fossil-fuel-dependent industries do not share this advantage, meaning that decarbonization of PPI involves distinct considerations. The PPI's challenge is not only to replace fossil fuel use, but also to improve the sustainability of biofuel use itself. This involves ensuring biomass is sourced with minimal land-use change and biodiversity impacts, and maximizing energy efficiency to optimally use these resources.

### 1.2. Pulp and paper industry production & CO<sub>2</sub> emission status

The global industry produced 43.5 billion tons of CO<sub>2</sub>e GHG emissions, around 4.2 % of global GHG emissions derived from human activities, between 1961 and 2019 [27]. The PPI is the fourth largest industrial energy user and generates 1.3 % of global GHG emissions

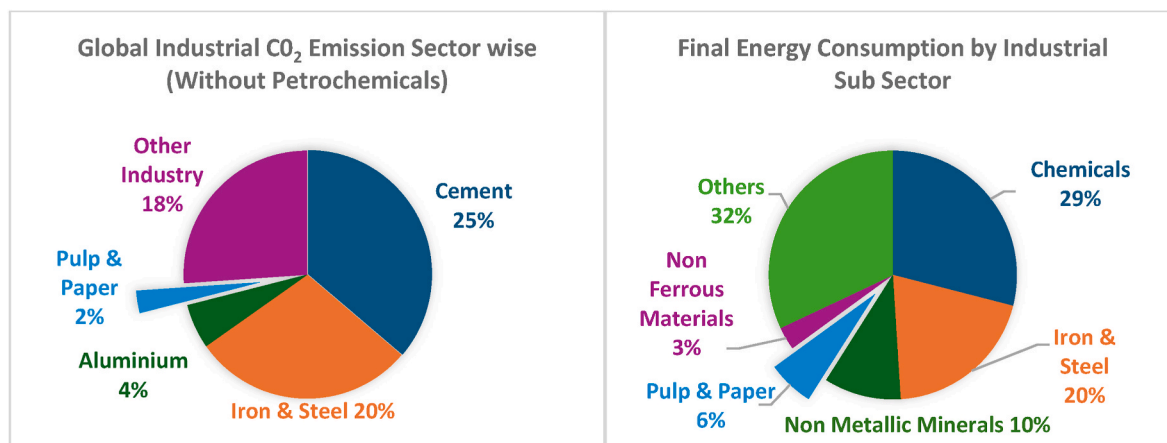


Fig. 1. Industrial CO<sub>2</sub> emissions and final energy consumption shares by sector.

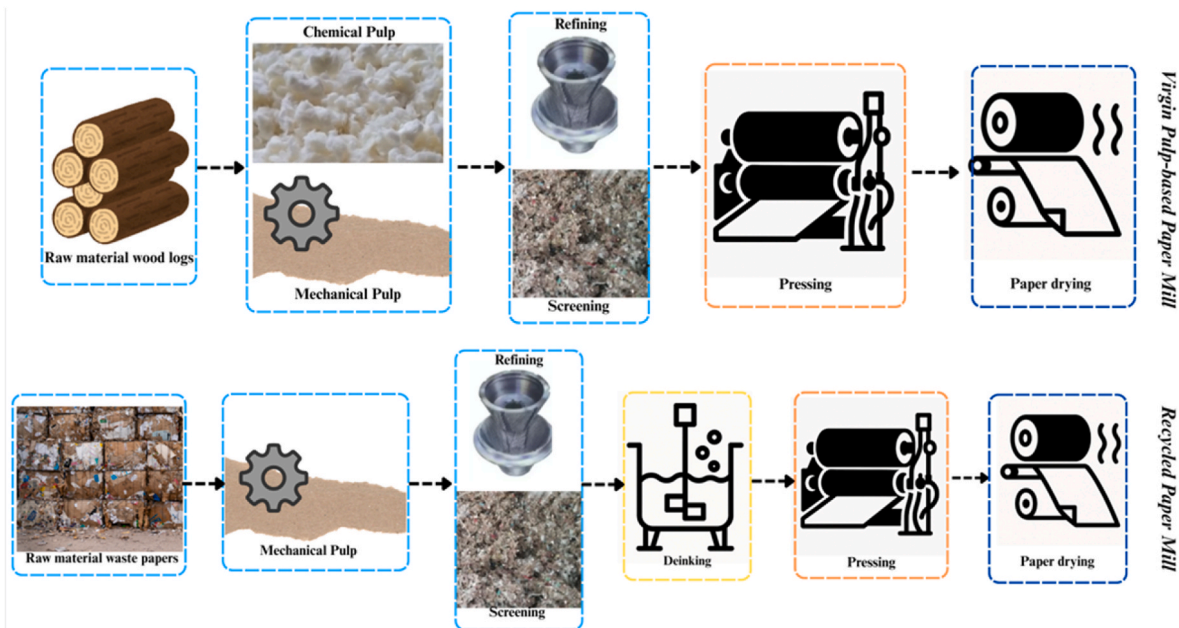


Fig. 2. Illustration of virgin and recycled paper mill processes: from raw materials to final drying.

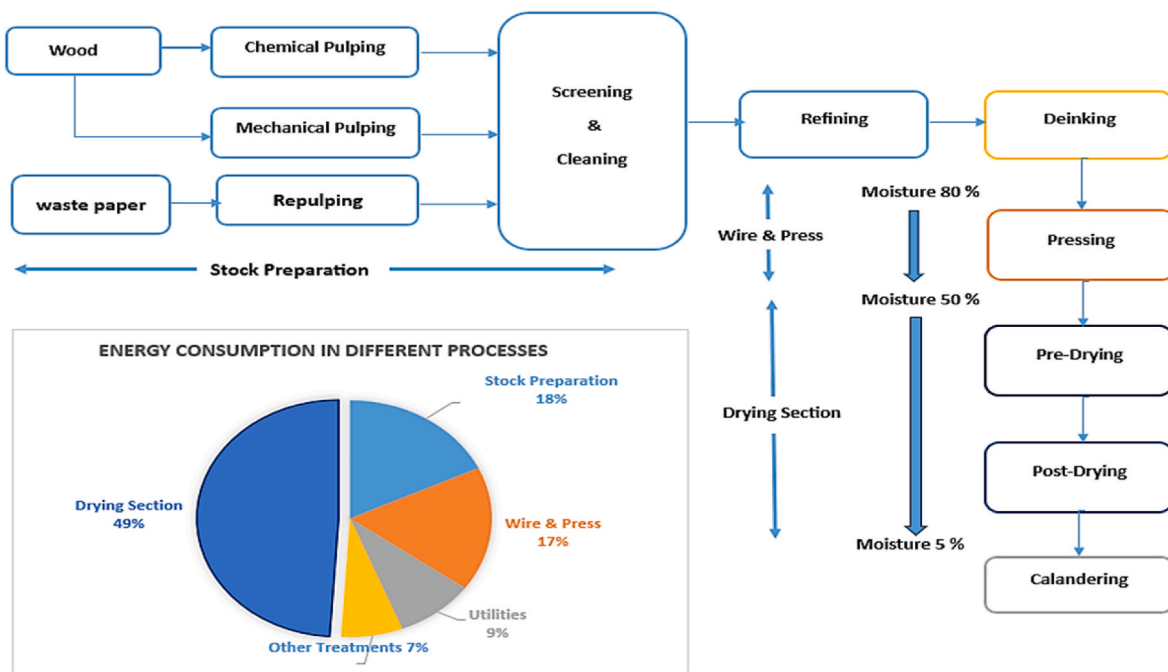


Fig. 3. Simplified paper industry process flow, illustrating major production stages and their relative energy consumption shares.

(nearly 2 % of industrial emissions across its lifecycle) [28]. The global consumption of paper products, including printing paper, writing paper, packaging, and tissue paper reached 417 million tons in 2021 [29]. The manufacturing processes are energy-intensive and require huge amounts of energy, including electricity, gas, and steam [29]. The global PPI consumed a total of around 1361 PJ of energy in 2021 [30]. Steam production in PPI is carried out by utilizing fossil fuels and biofuels, and the electricity requirement is met through purchase from the grid and on-site generation using biofuels (wood residues and black liquor). The study by Griffin et al. [31] identified that GHG emissions of PPI accounted for 6 % of UK industrial sector emissions. The PPI is globally distributed, but production is dominated by a few countries, as shown in

Fig. 4. Canada is one of the top global pulp and paper producer countries, and its PPI ranks 2nd in energy consumption and 7th in GHG emissions, excluding the oil and gas sectors [32]. The PPI of China ranks 1st in production in the world, representing around 25 % of worldwide output [33] and ranks among the top 10 for GHG emissions in its industrial sector [13].

Despite the impact of digitalization and the declining use of paper for communication and publishing, overall production has continued to rise, driven largely by growth in packaging and tissue products. Fig. 5 shows the global pulp production for the paper industry from 1961 to 2023.

Both direct and indirect emissions are generated by PPI. Direct

**Table 1**  
Specific electricity and heat consumption of papermaking processes, sources [19–24].

Process	Specific Electricity Consumption kWh/ton	Specific Heat Consumption GJ/ton
Chemical Pulping	600–800	4.4–7.0
Mechanical Pulping	1500–2000	0–1.0
Repulping	50–100	0.2–0.5
Screening & Cleaning	100–200	Negligible
Refining	150–300	Negligible
Deinking	100–200	0–0.2
Pressing	20–50	Negligible
Pre-Drying	50–100	6.0–8.0
Post-Drying	50–100	7.0–9.0
Calendering	10–30	Negligible

emissions primarily come from fuel and biomass combustion inside the PPI (in boilers, kilns). Indirect emissions are caused by purchased grid electricity generated through the combustion of fossil fuel resources, upstream production of raw materials (emissions from forest operations, chemicals manufacturing, etc.), and downstream disposal of paper

products. Studies have shown that off-site generation of steam and electricity for pulp/paper mills historically contributed heavily to the sector’s GHG profile [36]. A cradle-to-grave view reveals impacts at raw material and end-of-life stages: wood harvesting and pulpwood production entail fuel use and sometimes forest carbon stock changes, and paper disposal in landfills can produce methane [37]. According to Ref. [38], pulp and paper mills in the US emit 150 MtCO<sub>2</sub> each year, of which 77 % are biogenic (biomass-based). The PPI of India emitted around 30.5 MtCO<sub>2</sub> in 2019 with an average emission intensity of 1.58 tCO<sub>2</sub>e per ton of paper [39]. The CO<sub>2</sub> emissions of the Chinese paper-making industry in 2020 were 111.98 MtCO<sub>2</sub> [40], and Germany’s PPI stood at 13.2 MtCO<sub>2</sub> emissions in 2021, and contributes about 2.5 % of total energy-related GHG emissions [41]. Japan’s PPI was responsible for approximately 5.5 % of the nation’s industrial CO<sub>2</sub> emissions at approximately 21 MtCO<sub>2</sub> in 2019 [42]. For CEPI countries, the direct CO<sub>2</sub> emissions in 2022 were 27.03 MtCO<sub>2</sub> [43]. Sweden emits 21 MtCO<sub>2</sub> annually from its paper industry, with 97 % of biogenic origin. Finland’s paper sector accounts for 23–24 % of total energy demand and previously consumed over 25 % of total electricity. The UK emits 2.4 MtCO<sub>2</sub> yearly from fossil fuels and 0.9 MtCO<sub>2</sub> from electricity consumption in its paper industry. The Netherlands emits 1.054 MtCO<sub>2</sub> per year from

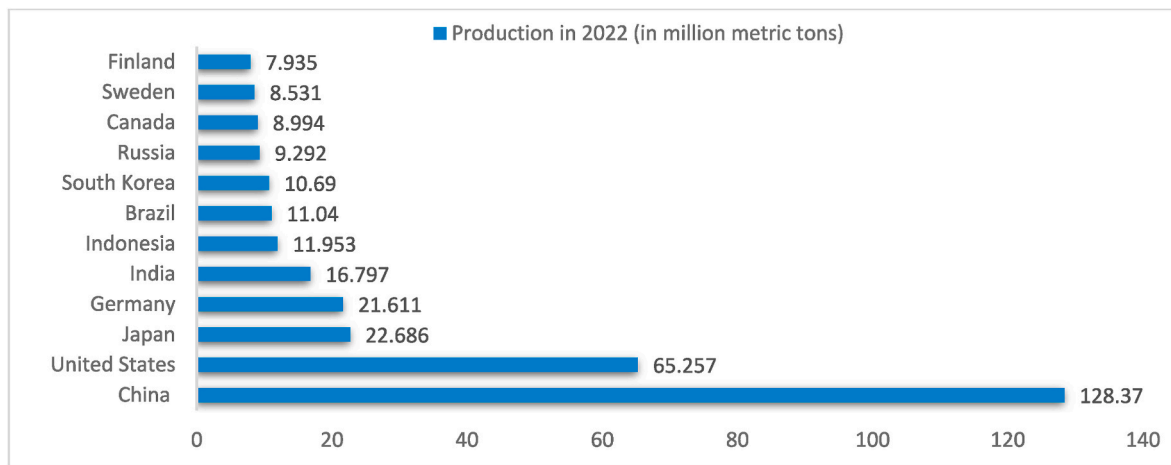


Fig. 4. Pulp and paper production per country. Source [34].

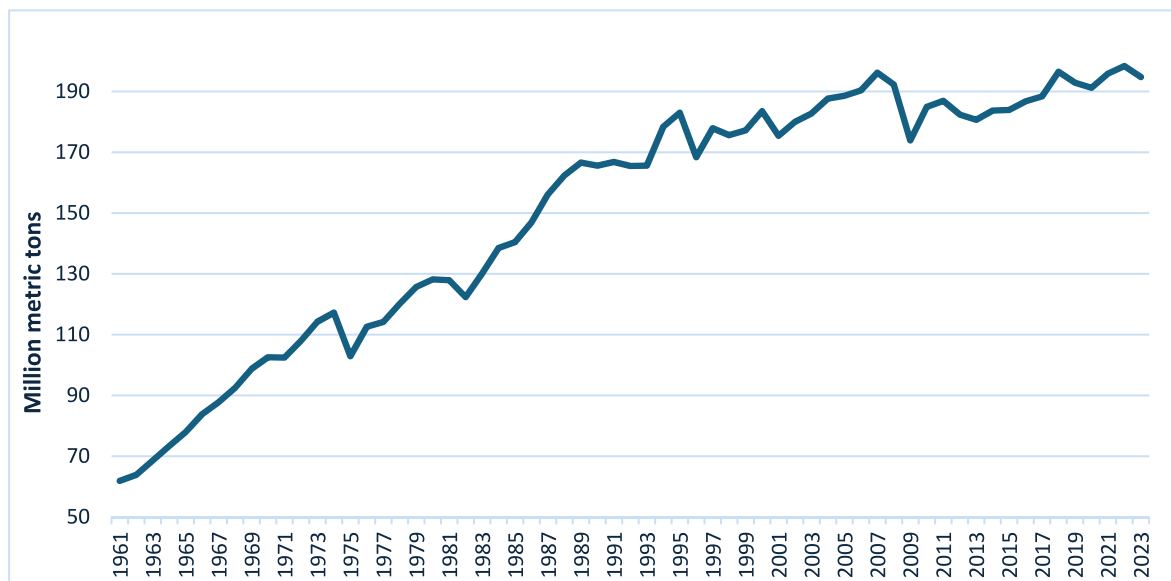


Fig. 5. Global pulp production from 1961 to 2023 (in million metric tons). Data source: Statista [35].

paper and board products, with additional emissions from specific mill operations. Austria's paper sector accounts for 7 % of industrial CO<sub>2</sub> emissions [26]. These figures highlight the CO<sub>2</sub> emissions of the paper industry across different countries, underscoring the need for continued efforts in sustainability and emission reduction.

The subsequent sections of this paper are organized as follows: Section 1.3 shows the methodology flowchart followed in this review. Section 2 provides a comprehensive review of the literature on energy consumption, high-emission processes such as black liquor evaporation, chemical pulping, and drying, and explores potential decarbonization pathways for the PPI. Section 3 discusses drivers and barriers to the identified decarbonization pathways, including energy efficiency measures, fuel switching, paper recycling, electrification, and carbon capture. Section 4 evaluates the pathways, their mapping with the PPI processes, and their economic feasibility. Section 5 outlines the methodology for ranking decarbonization pathways using the Analytical Hierarchy Process (AHP), evaluating them based on cost, emission reduction potential, technological readiness level, implementation time, and scalability. Section 6 prioritizes decarbonization technologies by ranking them based on AHP results. Section 7 concludes the work with recommendations.

### 1.3. Methodology flowchart

The methodology flowchart is shown in Fig. 6. Firstly, a comprehensive literature review is carried out to identify relevant decarbonization pathways for PPI. Next, the drivers and barriers for each pathway are analyzed to understand their feasibility and challenges. Thirdly, the Analytic Hierarchy Process (AHP) is used to rank these pathways based on five distinct criteria, including cost, emission reduction potential, technology readiness level (TRL), implementation time, and scalability. Finally, the pathways are ranked under four distinct criteria weight regimes to provide a nuanced understanding of their performance under varying priorities.

## 2. Literature review

Multiple studies have investigated strategies to reduce the PPI's energy use and carbon footprint, reflecting growing interest in sustainable industrial practices. A techno-economic analysis by Obrist et al. [44] for the Swiss PPI showed that by 2050, a 23 % reduction in energy consumption and a 71 % reduction in CO<sub>2</sub> emission will result through using

cost-effective technological options with no major policy change. The options include switching fuel to biomass, improvements in manufacturing processes, application of efficient technologies, and using high-temperature heat pumps. Energy efficiency and fuel saving translate into lower sector emissions since a major part of emissions is related to fossil fuel burning to cater to process heat and electricity requirements in the PPI. A study by Giuntini et al. [45] to assess the input of syngas derived from biomass, instead of fossil fuels, in the combustion chamber in a tissue paper mill drying section resulted in a reduction of CO<sub>2</sub> emission of around 8500 tons/yr compared to the use of fossil fuels. A study of the application of a set of EEMs to the PPI sector of Canada, carried out by Owtrim et al. [46], estimated that the adoption of energy efficiency measures by Canadian PPI would result in a 95 % reduction in natural gas (approximately 71 PJ) use and 41 % reduction in electricity (44 PJ) consumption annually. This translates into a cost reduction of \$81 per ton of product. The study of energy consumption through decomposition analysis of the PPI of Brazil for a period of 30 years, carried out by Fracaro et al. [47], demonstrated an annual reduction of 7.8 PJ in electricity consumption and 146.2 PJ of fuel savings compared to the PPI of other countries by the implementation of EEMs. Griffin et al. [48] evaluated energy saving potential and GHG emission reduction extent in the UK PPI through a set of low-carbon technological options. The study showed a possible reduction of emissions by 80 % in the period from 1990 to 2050. The reductions depend on technologies including heat recovery, energy efficiency improvement, use of bio-energy, electrification of heat supply, and use of carbon-neutral electricity supply.

The potential of energy efficiency to decarbonize the PPI sector was assessed by Owtrim et al. [49] which demonstrated that a 4.92 MtCO<sub>2</sub> e/yr reduction in emissions is possible through energy efficiency in the business-as-usual scenario (BAU) by 2050. The sector competitiveness can be improved by adopting full-scale EEMs with an approximate cost of \$162/tCO<sub>2</sub>e. Mobarakeh et al. [50] carried out a case study for PPI of Austria to analyze energy consumption and GHG emissions in the manufacturing processes of pulp and paper, and investigated options for energy saving and emission reductions. The study showed that the electrification of steam supply (electric boiler and heat pumps instead of fossil fuel combustion) can result in emissions reduction by 75 %, and carbon-neutral electricity is the key to the complete decarbonization of Austrian PPI. A report prepared by the Joint Research Center in 2018 [36] forecasted an increase of 1.1 % in energy usage in the PPI sector of the EU and a hike in emissions of up to 4.8 % in 2050 in comparison to 2015, in the case of no technological upgrade. The report analyzed that the utilization of the best available technologies (BATs) can result in energy savings of 14.4 % and CO<sub>2</sub> emission abatement of 62.2 % in the EU.

Recycling waste paper is considered one of the key options that significantly reduces the carbon footprint of the paper industry [13]. Manufacturing paper from recycled sources requires less energy compared to the virgin pulp production, leading to lower CO<sub>2</sub> emissions [51]. Studies show that improving recovered-fiber sorting and recycling can reduce paper sector emissions by up to 30 % [52]. Chang et al. [53] applied the LCA approach to evaluate the environmental impacts of replacing virgin pulp with recycled pulp in the U.S. PPI. The results revealed that using recycled pulp can lead to a significant GHG emissions reduction, with the magnitude of benefits depending on the grades and origin of recycled paper used. Project Drawdown [54] estimates that increasing recycled paper rates by 20 % compared to current rates of 55 % can avoid around 2.3–2.9 gigatons of CO<sub>2</sub> emissions over the next 30 years. Also, paper recycling is a commercially proven solution that can be scaled relatively easily.

The abatement in CO<sub>2</sub> emissions is also largely attributed to the use of biofuels and improving the efficiency of processes such as heat recovery. The CEPI, through the report named "Two Team Project" [55] aims at cutting CO<sub>2</sub> emissions by 80 % compared to 1990 through improving efficiency, switching fuel to low-carbon sources, and other

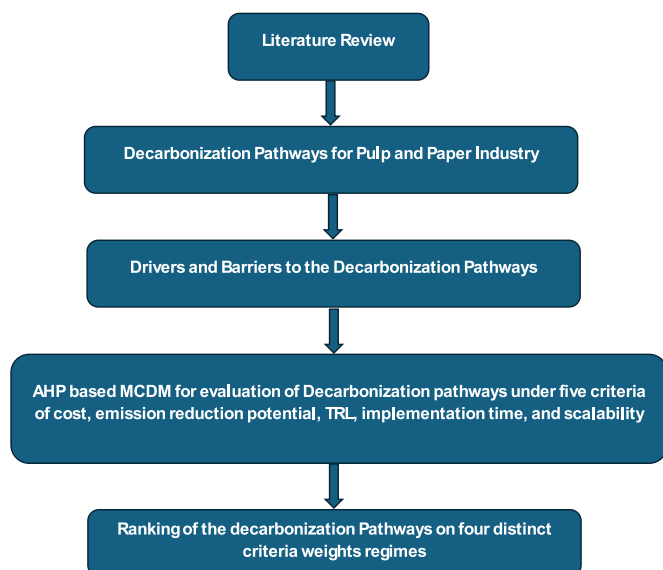


Fig. 6. Methodology flowchart.

innovative measures such as deep eutectic solvents technology, and electrification of heat supply. The study by Lipiäinen et al. [56] revealed that the PPI of Finland and Sweden has reduced its energy consumption per output through improved efficiency. The CO<sub>2</sub> emissions of PPI of both countries also decreased significantly, and green electricity production increased due to the shift towards low-carbon biofuels. By decreasing the use of oil, the CO<sub>2</sub> emissions of the PPI of Sweden were reduced by 80 % between 1973 and 1990, while the production surged by 18 % [57]. The examples of Finland and Sweden illustrate that decarbonization of the PPI is possible through an increased share of renewable energy sources in the fuel mix.

A techno-economic analysis by Mati et al. [58] explored using onsite hydrogen as fuel in a paper mill's cogeneration system. By modeling a multi-energy system with hydrogen produced via solar-powered PEM electrolyzers, the optimized solution reduced annual CO<sub>2</sub> emissions by 29,273 tons. A review of decarbonization pathways, along with their technological maturity, by Gailani et al. [59] identifies key pathways such as replacing fossil fuels with biomass and hydrogen, and CCS, having the potential to reduce emissions of industrial sectors by 85 %.

From the literature reviewed above, five primary pathways for decarbonizing the PPI are identified, which include: (1) energy efficiency measures (EEMs) and/or improved processes, (2) electrification of heat supply, (3) paper recycling, (4) switching to carbon-neutral fuels such as biomass and hydrogen to replace fossil fuels, and (5) CCS technologies, as summarized in Table 2.

Fig. 7 illustrates the potential of CO<sub>2</sub> abatement and TRL of the identified decarbonization pathways, which are thoroughly reviewed in section 3 to assess their potential drivers and barriers in implementation.

Table 2 highlights various decarbonization pathways that can help reduce GHG emissions in the PPI. EEMs such as waste heat recovery, energy management systems, equipment inefficiency checks, bioenergy retrofits, and cogeneration have the potential to save a lot of energy and reduce emissions significantly. However, the adoption of EEMs is often hindered by low returns, capital constraints, and policy uncertainties. Similarly, paper recycling can reduce energy consumption and cut emissions if the recycling processes use renewable energy sources. Decarbonization pathways such as steam supply electrification, switching to carbon-neutral fuels such as biomass, utilizing hydrogen in combined heat and power systems, and implementing CCS technologies can also help mitigate and even completely cut the CO<sub>2</sub> emissions. However, these pathways face barriers such as high capital costs for substantial equipment redesigns, lack of literature available regarding the overall effects of retrofits on the paper-making process, and a lack of incentives for negative emissions technologies. Hence, successful implementation with sustainable planning, investment, and collaboration among stakeholders is necessary to realize the full potential of these measures and pathways.

### 3. Drivers and barriers to the decarbonization pathways

After identifying the key decarbonization pathways, their specific drivers and barriers are discussed in the following sub-sections. Understanding these drivers and barriers is crucial for assessing real-world feasibility beyond just technical potential.

#### 3.1. Energy efficiency as a decarbonization measure for PPI

EEMs are universally regarded as the first step in industrial decarbonization. EEMs span a wide range of actions in PPI, which include equipment upgrades, heat integration, waste heat recovery, reducing steam leaks, insulating pipes, optimizing process controls, and implementing energy management systems. The availability and cost-effectiveness of energy-efficient technologies, along with their adoption, can address several issues such as reducing the costs of production, increasing a company's competitiveness, ensuring energy security, and decreasing pollution levels. Numerous case studies have shown that

**Table 2**  
Summary of decarbonization pathways in PPI along with their TRL and CO<sub>2</sub> abatement potential.

Decarbonization Pathway	Measure	Process	CO <sub>2</sub> abatement potential	TRL			
Energy Efficiency Measures (EEMs)	Recovery and reuse of waste heat	Pulp/paper drying	Up to 9 % [60]	9			
	Energy management systems	Mill-wide monitoring	Up to 15 % [61]	9			
	Equipment maintenance & optimization	Motors, pumps, heat exchangers	Up to 10 % [46]	9			
	Biological pre-treatment (enzymatic)	Mechanical pulping	Up to 15 % [60]	8–9			
	Membrane concentration of black liquor	Chemical recovery	Up to 36 % (evaporation) [44]	6–7			
	Closed-hood paper machine	Paper drying	13–45 % [62]	9			
	Forming-steam box	Sheet forming	Up to 5 % [26]	9			
	Hot pressing	Pressing section	Up to 8 % [63]	7–8			
	Condebelt drying	Paper drying	Up to 15 % [50]	7–8			
	Mechanical vapor recompression (MVR)	Paper drying	Up to 50 % (thermal) [64]	8–9			
Steam supply	Using electric boilers or heat pumps instead of fossil fuel boilers to generate heat and steam.	Paper making	Up to 8 % [56]	8–9			
					Paper making fillers	Up to 20 % [56]	5–6
Electrification.							
Paper Recycling	Reuse of post-consumer paper as pulp feedstock, thereby reducing the requirement for virgin pulp.	Pulp production	Up to 25 % [51]	9			
Switching to carbon-neutral fuels	Replacing fossil fuels in the boiler with on-site produced biomass (waste wood, sludge, and black liquor)	Steam boilers	Up to 40 % [64]	9			
	Replacing fossil fuels with Hydrogen	Boilers/CHP	Up to 100 % of combustion emissions (if green hydrogen is used) [58]	7–8			
Carbon Capture and Storage (CCS)	Biomass-fired CHP (onsite)	Power & steam generation	Up to 20 % [65]	9			
	BECCS (biomass energy + CCS)	Flue-gas capture (recovery boiler)	Up to 60 % [66]	7–8			
	Calcium Looping	Flue-gas capture	Up to 60 % [67]	7–8			
	Electric Plasma Calcination	Flue-gas capture	Up to 60 % [68]	7–8			

energy audits and efficiency measures can cost-effectively reduce energy use and emissions, for example, reducing thermal energy consumption by 20 % through heat recovery measures [69]. Stenqvist, C [70]. conducted a study on Swedish PPI energy use and performance between 1984 and 2011, revealing that energy efficiency improvements resulted

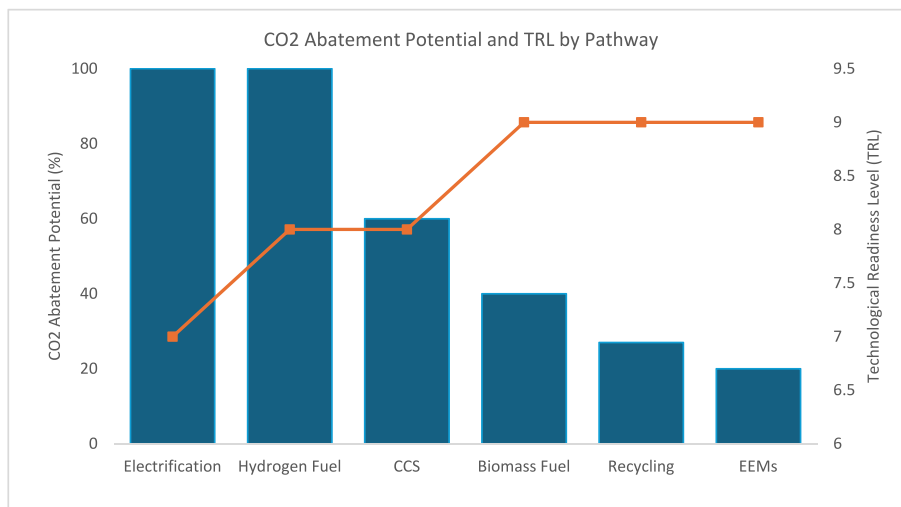


Fig. 7. CO<sub>2</sub> abatement potential of different decarbonization pathways for PPI and their TRL.

in a reduction of 50 PJ (40 %) of primary energy use. Another study, conducted by Kermeli et al. [71], revealed that energy efficiency improvements and increased recycling can decrease industrial energy demand by 23 % (11.3 EJ in 2050). Energy efficiency improvement potential was studied for PPI of Pakistan by Imran et al. [72], according to which, the implementation of various measures such as the use of heat recovery, boiler efficiency enhancements, steam traps, and economizers can result in a total energy saving of 854,000 MWh. This saving is equivalent to 43 % of the total energy consumption of the entire paper sector in Pakistan. Also, energy saving potential based on EEMs was assessed for PPI in Taiwan by Hsin-Chiu Lin et al. [10], estimating an overall saving of 762.1 TJ of energy use. From 1990 to 2010, a 30 % energy efficiency improvement was achieved by the PPI of China per ton of production, with a drop in the final energy use from 16.2 to 13.2 GJ/ton between 2005 and 2010 [73]. Also, PPI of India achieved a reduction of 42 % in energy intensity in the period 2003 to 2014 [74].

Efficiency improvements span all stages of pulp and paper production. In pulping, optimizing digesters and improving chip pre-treatment can lower energy and chemical use. In mechanical pulping, refining process upgrades such as minimizing friction losses can cut electricity consumption. In paper drying, enhancing wet pressing reduces moisture before drying, reducing thermal load. Ideally, EEMs should be a good investment and a useful tool, with the resulting energy savings making it an attractive option. However, in practice, the implementation of EEMs to their full potential is hindered by various barriers. This is shown by reports such as the "Best Available Techniques" reports from the European Commission [75], revealing that the energy usage and emissions of the average facility in a given sector are much higher than those of the top-performing facilities. This gap indicates that the adoption of energy efficiency technologies in industry is still limited by substantial barriers [76]. These barriers to energy efficiency include low returns, capital constraints, lack of awareness, technical risks, policy uncertainty, and low fuel prices [77], summarized in Table 3.

### 3.2. Fuel switching as a decarbonization measure for PPI

The industrial sector contributes almost one-fourth of global CO<sub>2</sub> emissions from fossil fuel combustion and industrial processes. In 2018, the CO<sub>2</sub> emissions released as a result of fuel combustion for industrial activities reached 14.4 Gt, with 54 % of it coming from direct fuel combustion and the remaining 46 % from indirect fuel combustion for electricity generation. Fuel switching refers to replacing high-carbon fossil fuels (coal, oil, natural gas) with low or zero-carbon alternatives. The PPI produces little process GHG emissions, and almost all PPI GHG

Table 3

Drivers and barriers to implement energy efficiency measures (EEMs) in PPI

Energy Efficiency Measure	Drivers	Barriers
Strategic Energy Management (ISO 50001, continuous audits, etc.)	Increasing and unstable energy/fuel prices. International competitiveness. Reduction in energy consumption by 10–15 % [78]	Requires strong management commitment [79]. Capital constraints for audits [80], metering, training, & time constraints.
Improving the equipment inefficiencies (motor-driven systems: pumps, fans, compressors)	Reduction by 2 %–20 % of total motor system electrical energy consumption [81].	Disruption in production and associated cost and risk [82] Time constraints and organizational priorities [83].
Steam and process heating (boilers, furnaces, dryers)	High-efficiency boilers can reduce process heat emissions by 10 %. Fuel and electricity savings [84].	High capital cost. Integration complexity (space, matching temperature). Requires skilled maintenance [84].
Bio energy retrofitting, such as Black liquor gasification, bark gasification, tall oil diesel, and bioethanol production	Added value for the mill transportation. Biofuels are considered carbon neutral. CO <sub>2</sub> emission reduction by 10 % [85].	Limited availability of feedstock, Sector dependency on pulp markets. Raw material for more valuable chemicals (limited supply) [86] Non-uniform composition of feedstock [87]
Cogeneration technology	Increasing cost of energy. Energy saving up to 15–30 % [88]	Initial investment. Complexity of operation and maintenance [60].

emissions are a direct consequence of energy use. For PPI, bioenergy (onsite biomass, black liquor, wood residues) has long been a primary alternative fuel used for heat and power generation. The remaining use of fossil fuels in boilers, lime kilns, and generators can be substituted with biomass fuels or emerging alternatives like hydrogen or biogas/syngas.

Biomass in particular is a significant fuel source due to the large amount of low-cost woody biomass (wood chips, pellets, agricultural residues) available at or near pulp & paper facilities. There is also an additional fuel source, known as black liquor, produced in the production of pulp, which is a biofuel and can be used in CHP to generate

electricity and heat with lesser CO<sub>2</sub> emissions, as described by Naqvi et al. [85]. Fuel-switching efforts in the sector to date have been highly successful at shifting from heavier fossil fuels to natural gas and biomass [89]. The use of biomass and hydrogen in CHP has been shown in some projects [90] and various working plants are set to work on a single fuel source of Hydrogen by 2030 [91]. Direct emissions can be eliminated from CHP using biomass compared to the use of fossil fuels in CHP. Satu Lipiäinen et al. [56] examined the energy transition in Sweden's and Finland's PPI sectors, noting CO<sub>2</sub> reductions of 70 % and 58 %, respectively, due to shifts from fossil fuels to biomass. Following the trend, the reduction in total emissions by PPI of the EU was around 43 % per ton of production in the period from 1990 to 2017 [92]. As discussed in Section 2, the Swedish PPI's transition from oil to biofuels resulted in an 80 % emission drop, illustrating the impact of fuel switching [93].

One of the emerging technologies in the production of hydrogen, known as green hydrogen, in which renewable electricity is used in its production, is being explored as a promising future fuel for high-temperature heat and CHP in industries, including PPI. Hydrogen could potentially replace natural gas in boilers and lime kilns or be used in fuel cells to generate electricity and heat. One attractive aspect for the pulp and paper sector is that hydrogen might be integrated with existing infrastructure. For instance, retrofitting natural gas boilers to be fully hydrogen-fueled or co-firing hydrogen blends. Various studies suggest the use of green hydrogen in massively reducing the GHG emissions from the PPI. One of the options to use green hydrogen in PPI is to use it in CHP, replacing fossil fuels, producing heat and electricity with no carbon footprint [92]. Moreover, green hydrogen also offers a sustainable energy storage option. Vialletto et al. [94] worked on improving the energy generation system of an Italian PPI by introducing hydrogen using reversible solid oxide cells (RSOCs). They conducted a primary energy analysis of the proposed system and evaluated the savings compared to the conventional configuration. The results indicated that there was a saving of 6 % in the primary energy use due to additional hydrogen production through SOFC operation of the RSOC system. Similarly, Alessandro Mati et al. [58] converted a cogeneration system in a paper mill to run on locally produced green hydrogen. The model used solar-powered PEM electrolyzers, storage in tanks, and a gas turbine for final use. By consuming 4209 tons of green hydrogen annually, the paper mill reduced 29,273 tons of direct CO<sub>2</sub> emissions. In summary, emerging hydrogen production pathways enable on-site hydrogen fuel usage, which can then be applied in boilers or turbines to decarbonize the mill energy supply. However, there are barriers to implementing these fuel switch measures, as discussed in Table 4.

It is worth noting that the carbon neutrality of biomass remains widely debated. When forest biomass is burned, there is a substantial upfront increase in atmospheric CO<sub>2</sub>, especially if harvesting exceeds regrowth or the regrowth takes a long time. The carbon emitted during biomass combustion is only removed from the atmosphere as the new biomass grows and absorbs it, which means there is a meaningful time lag before neutrality is achieved. For instance Ref. [99], demonstrated that substituting coal with wood pellets in power generation could

**Table 4**  
Drivers and barriers to implementing fuel switch measures

Fuel Switch Measure	Drivers	Barriers
Replacing fossil fuels in the boiler with onsite-generated biomass (wood waste, black liquor, and sludge)	Carbon-neutral fuel Availability of mill residues (black liquor, bark). Waste disposal cost saving. Up to 40 % emission reduction [95].	Feedstock variability & seasonal supply [96]. Competing demand for biomass (chemicals, materials) Additional handling & storage needed [97].
Replacing fossil fuels with hydrogen in CHP	Carbon-neutral target. Up to 100 % emission abatement if green hydrogen is used [94].	High production costs for green H <sub>2</sub> [64] lack of hydrogen infrastructure [98].

actually lead to increased CO<sub>2</sub> emissions for decades before any tangible climate benefit emerges. In the context of the PPI sector, using by-products like black liquor waste wood can help minimize this carbon debt, provided they are sustainably sourced. In short, achieving real climate benefits from biomass use in the PPI requires sustainable sourcing, ensuring regrowth (reforestation), and minimizing land-use emissions. Also, integrating carbon capture technologies such as BECCS to offset the remaining emissions. Without these measures, the climate benefits of large-scale biomass use are far from assured.

### 3.3. Electrification as a decarbonization measure for PPI

Electrification entails replacing combustion-based heat sources with electrical technologies to provide thermal energy. The IPCC lists electrification among the key strategies for the decarbonization of industry [100]. If electricity is sourced from renewable generation (directly or via the grid), it can essentially eliminate direct fossil fuel emissions at the mill. One of the most promising electrification options is the use of industrial heat pumps to recover and reuse waste heat from processes like paper drying. Modern high-temperature heat pumps can supply heat up to 160 °C, suitable for parts of the papermaking process, thereby significantly reducing steam demand from boilers [101].

The processes of chemical pulping and paper drying use around 67 % of the energy required for paper production [59]. These processes hold a high potential for energy savings that can directly or indirectly reduce CO<sub>2</sub> emissions. The chemical pulping and drying processes can be electrified by replacing fossil fuels with electric boilers, known as Direct Electric Heating (DEH), thereby reducing the dependence on fossil fuel sources [102]. The use of DEH holds the potential for achieving complete decarbonization within the industry, provided there is a reliable supply of carbon-free electricity to match the demand. The potential for decarbonization in Austrian PPI, as assessed by Mobarakeh et al. [50], revealed that a 75 % reduction in CO<sub>2</sub> emission is possible with steam supply electrification using an electric boiler instead of fossil fuel combustion to produce heat in a conventional boiler. One study suggests 70 % emission reduction through the electrification of the drying process of paper [103]. The study of energy flows in the PPI of the UK estimates a 29 % reduction in emissions by the electrification of heat [48]. Lipiäinen et al. [104] investigated the result of efficiency improvement measures implemented from 2002 to 2017 in the PPI and found significant emission reduction potential of heat electrification measures for global PPI. D. Obrist et al. [105] analyzed the pulp and paper sector on different scenarios and found that decarbonization can be achieved by 2045 using biomass as a fuel and heat supply electrification. However, it should be noted that electrification of the processes can only reduce overall CO<sub>2</sub> emissions if the electricity production has no carbon footprint. Various drivers and barriers to implementing electrification in PPI are summarized in Table 5.

### 3.4. Paper recycling as a decarbonization measure for PPI

Paper recycling is a crucial decarbonization pathway that reduces the need for energy-intensive virgin pulp production. The recycling processes involve collection, sorting, repulping, and de-inking of used paper, which generally consume less energy and result in lower CO<sub>2</sub> emissions than producing an equivalent amount of paper from the fresh wood pulp [36]. An overview of the recycled paper manufacturing processes is shown in Fig. 8. Replacing recycled fiber with virgin fiber can reduce lifecycle GHG emissions by roughly 25 % per ton of product [54]. This is because the energy-intensive processes in virgin pulp production (such as wood harvesting and chemical pulping) are avoided, reducing the overall energy requirement from 40 to 70 % [107]. Besides, recycling reduces demand for virgin wood, helping preserve forests and carbon sinks. Also, diverting paper waste from landfills avoids methane emissions, as around one-third of the PPI's carbon footprint in 2012 was linked to landfill emissions [28]. Consequently, increased paper

**Table 5**  
Drivers and barriers to implementing the electrification measures in PPI

Electrification Measure	Drivers	Barriers
Electric boilers & industrial heat pumps	Eliminate fossil fuels. 100 % emission abatement (if powered by RES [106].	The grid may need to be significantly decarbonized. High capex for substantial redesigns of industrial equipment [26].
Electric dryers (infrared, microwave)	Can replace steam drying, cutting 60 % of mill energy emissions.	Commercial readiness is still emerging. Potential impacts on paper quality must be examined.
Overall process electrification	Enables the use of renewable energy for heat. Future-proofs the mill against carbon pricing.	Very high power demand. Requires grid capacity and reliability. Operating costs can be higher unless electricity is cheap.

recycling directly decreases fossil fuel consumption and subsequently CO<sub>2</sub> emissions, particularly in facilities where virgin pulp production relies heavily on fossil energy sources. Despite its benefits, paper recycling faces several barriers (Table 6). One major limitation is the degradation of fiber quality with each reuse cycle, as paper fibers can be recycled typically 5 to 7 times before they become too weak for paper making [108]. This necessitates a continuous input of virgin pulp to maintain paper quality and shows that recycling alone cannot eliminate the need for fresh fiber. Also, collected paper can contain inks, adhesives, and other contaminants that require removal, leading to additional processing steps (de-inking, cleaning). Furthermore, if the energy used for recycling is derived from fossil fuels, the net emissions savings are reduced, in some cases even increased [28]. This underscores the importance of powering recycling processes with renewable energy sources.

3.5. Carbon capture & storage (CCS) as a decarbonization measure for PPI

CCS technologies offer a means to reduce emissions from processes

such as lime kilns and combustion of fuels, and hence can play a critical role in the decarbonization of industry [109]. CCS involves capturing CO<sub>2</sub> sources (boiler flue gases or lime kiln exhaust in a pulp mill) and then compressing, transporting, and storing or utilizing it in products. The PPI is a strong candidate for CCS deployment since a significant portion of PPI is biogenic (from biomass combustion), capturing it would result in negative emissions [110]. CCS offers a high potential for emission reduction, capture technologies can typically remove 50–90 % of CO<sub>2</sub> from flue gas, and could handle the emissions from processes that are otherwise hard to decarbonize (like recovery furnaces or lime kilns if they still use fossil fuels). CCS has three techniques, namely pre-combustion, post-combustion, and oxy-fuel combustion (Fig. 9), with the main objective of separating CO<sub>2</sub> from the effluent stream [111].

In pre-combustion, hydrocarbon fuel undergoes partial oxidation to form syngas (CO & H<sub>2</sub>O), which then undergoes a reaction producing CO<sub>2</sub> and H<sub>2</sub>, which are then separated, and H<sub>2</sub> is used as fuel. The oxy-fuel process involves the combustion of fuel in the presence of oxygen only (instead of air as in conventional combustion), which produces CO and H<sub>2</sub>O, from which CO<sub>2</sub> is separated later, Fig. 9. The post-combustion involves the separation of CO<sub>2</sub> from the effluent stream, which contains mainly N<sub>2</sub>, CO<sub>2</sub>, and H<sub>2</sub>O. From these three approaches, oxy-fuel and post-combustion are considered easier to integrate with PPI, used upstream or downstream, respectively. The CO<sub>2</sub> captured is utilized as input for different uses, including fuel production and fertilizers. It is

**Table 6**  
Drivers and barriers to paper recycling measures in PPI

Paper Recycling Measure	Drivers	Barriers
Use of post-consumer paper as pulp feedstock	Lower energy use compared to virgin pulp. Reduced GHG emissions (by 25 %) Protection of forests and carbon sinks [107].	Fiber quality degradation. Additional processing (de-inking, cleaning) Net emissions savings may be reduced, or even emissions increased, due to fossil fuel usage [108].



Fig. 8. Process flow of recycled paper manufacturing at an industrial facility.

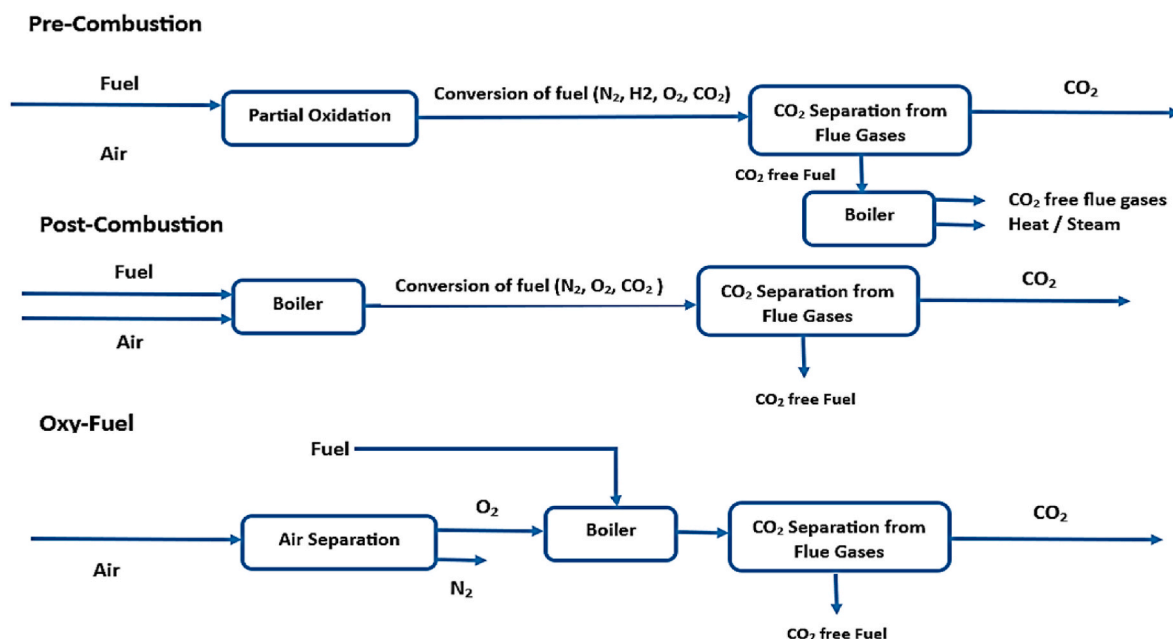


Fig. 9. Schematic block diagrams of CCS techniques, pre-combustion, post-combustion, and oxy-fuel combustion, illustrating how CO<sub>2</sub> is separated in each approach.

also used in the oil & gas industry and the food processing industry [112]. The highest emission reduction can be achieved using post-combustion carbon capture in the flue gases stream of the recovery boiler and bark boiler. A relative advantage of using Biomass Energy Carbon Capture and Storage (BECCS), a technology directed at the capture of emissions by combustion of biomass, in PPI is its relatively low investment compared to other industrial sectors [103]. The mitigation of emissions by BECCS technologies in PPI has been highlighted by several studies. The decarbonization potential of BECCS in PPI is around 3 % of global carbon capture [113]. The best approach to implementing BECCS in PPI is capturing CO<sub>2</sub> from the flue gases of the recovery boiler by stacks (fuel boiler, recovery boiler, and lime kiln).

The potential of the application of BECCS in PPI is high in Scandinavian countries, mainly due to high energy consumption and the availability of biomass. The potential is even greater in Finland and Sweden, which reported biogenic emissions of 64 % and 51 % respectively in 2017 [56]. The abundance of biomass in Sweden makes BECCS technology deployment an economical and efficient option to reduce PPI emissions, particularly biogenic emissions [114]. Implementation of CCS at four mills in Sweden showed a potential CO<sub>2</sub> capture of about 4.6 Mtons per year, Karlsson et al. [115]. On a global scale, the contribution of CCS in PPI decarbonization is often seen as limited but crucial for the last fraction. Studies suggest that CCS might need to handle 10–15 % of the sector’s emissions by 2050 in deep decarbonization scenarios, especially if other measures fall short [26]. The major barriers to the implementation of CCS are high costs associated with transporting captured gas to storage facilities and the remote location of plants [116], Table 7.

It can be assessed that each decarbonization measure presents a unique set of advantages and challenges in its implementation. The pathways vary in terms of CO<sub>2</sub> abatement potential, technological readiness, economic feasibility, and implementation complexity. While EEMs and bioenergy retrofits offer moderate abatement with high technological readiness, emerging technologies such as the electrification of steam supply and carbon capture promise significant reductions, but face barriers related to cost and scalability. To check the feasibility and effectiveness of the pathways, it is essential to systematically evaluate them across multiple dimensions, including their alignment with the PPI’s sub-processes, economic viability, technological feasibility and readiness, as well as relevant policy implications.

Table 7  
Drivers and barriers to CCS measures in PPI

CCS Measure	Drivers	Barriers
Capture of CO <sub>2</sub> from the recovery boiler flue gases by the deployment of CCS Technologies (BECCS, Calcium Looping, Electric Plasma Calcination)	Abatement of biogenic CO <sub>2</sub> [117] Negative emission credits. Captured CO <sub>2</sub> as raw material for another sector [118].	Transport & storage infrastructure. High capital Cost. Very high electricity demand [119].
Oxy-fuel combustion retrofit in lime kiln	Highly pure CO <sub>2</sub> stream. It can improve combustion efficiency.	Requires oxygen supply (energy-intensive to generate). Retrofits can be complex and costly.

#### 4. Evaluation of pathways: feasibility, readiness, and applicability

This section provides a multi-dimensional assessment of the identified decarbonization pathways, examining their alignment with PPI processes, technological maturity, feasibility of implementation, regional suitability, and environmental impacts.

##### 4.1. Decarbonization pathways mapped to PPI’s sub-processes

To better illustrate the impact of each decarbonization pathway upon the pulp, paper, and printing process, we summarize the interventions by major sub-processes and their indicative impacts. This addresses the need to aggregate and categorize pathways by the specific industrial operations they affect. The key sub-processes considered are wood & pulping, paper drying, energy/utilities (for steam and power generation), printing & finishing, and cross-cutting/end-of-life. The below sub-sections address each sub-process along with relevant decarbonization strategies.

##### 4.1.1. Wood preparation & pulping (fiber production)

For mechanical pulping, refining energy can be reduced by 10–20 % through optimizing refiner operations (EEMs), and using chemical treatments to soften chips [69], potentially saving 1–2 GJ/ton for

mechanical pulp. Switching refiners to run on renewable electricity (electrification) can cut emissions.

For chemical pulping, improving digester heat recovery, continuous cooking techniques, and higher efficiency black liquor evaporation (EEMs) can save energy. Further improvement like black liquor gasification (BLG) can increase energy efficiency of recovery from 65 % (boiler) to 75–80 % [85], while producing a combustible syngas that can drive gas turbines for power. BLG pilots show it can reduce overall mill CO<sub>2</sub> by 5–10 % through better energy conversion and enable new pathways like biofuel production from syngas.

Moreover, utilizing agricultural residues or recycled fibers in place of fresh wood can reduce the energy required for pulping. For instance, pulp from bagasse (sugarcane waste) or straw often has lower cooking energy needs and can be an effective GHG reduction if it displaces wood. Non-wood fibers also alleviate pressure on forests (supporting SDG 15).

#### 4.1.2. Papermaking & drying

Implementation of advanced pressing techniques, such as the shoe press, in the drying section can reduce moisture content, thereby reducing the evaporative load. For every 1 % increase in post-press dryness, around 4 % of dryer energy can be saved. Heat recovery from dryer hood exhaust via heat pumps or vapor recompression can cut steam demand by 10–50 % in the drying section. Besides, electrified drying (electrification), infrared dryers (for surface drying), or microwave drying for bulk water removal can cut emissions and enhance energy efficiency. If fully realized, electrified drying (with green power) could eliminate the majority of CO<sub>2</sub> emissions from the paper machine, which constitutes 60 % of mill energy. Furthermore, reducing steam leaks (blow-through), insulation of dryer hoods, and optimization of condensate removal increase thermal efficiency. These measures, as part of EEMs, can result in 5–15 % steam savings in drying. Technologies like condebelt drying (which uses pressurized steam and a conveyor belt press) can achieve even higher efficiency and potentially cut energy use by 20 % for certain grades.

#### 4.1.3. Energy and utilities (steam/power generation & CHP)

Fossil fuel boilers can be replaced with biomass boilers or biogas burners (fuel switching), reducing the unit's CO<sub>2</sub> emissions by 90 %. Bark boilers have already been in use by mills, maximizing their use and ensuring the supply of biomass is key. Also, natural gas in the gas turbine CHP or lime kiln can be blended with hydrogen (even a 20–30 % blend), which will further reduce CO<sub>2</sub> emissions. However, a complete conversion to hydrogen fuel will yield a 100 % reduction in direct CO<sub>2</sub> from those units. But this requires new hardware or retrofits (burner changes, materials) and is only expected beyond 2030 when hydrogen infrastructure may be more available.

The indirect emissions from grid electricity can be reduced by onsite renewable energy generation, which will also directly power electrified processes. Some mills have already started adding renewables to control energy costs and reduce indirect emissions. For instance, a paper mill in the US Midwest installed a 50 MW biomass cogeneration and solar array to offset grid use [120].

Also, the use of gas engines on renewable fuels in combined heat and power mode can achieve more than 80 % total efficiency. Even if fueled by natural gas, a very efficient CHP can lower emissions per energy output. But more suitably, a biomass-fueled CHP or a solid oxide fuel cell (SOFC) system (which could run on green hydrogen or biogas) can supply electricity and steam with minimal emissions. A study on modeling an SOFC in a mill's energy system showed substantial emission cuts [94]. Furthermore, the use of energy storage (thermal storage or batteries) can help optimize energy use and integrate variable renewables or variable electricity pricing.

#### 4.1.4. Printing and finishing

To minimize waste, it is important that printing facilities (whether part of an integrated mill or separate printing houses) use the most

efficient presses (modern presses with variable speed drives, efficient drying/curing of inks, etc.). Many commercial printers have moved to LED-UV curing, which uses LED lamps (electric) to cure inks instantly, reducing heat and energy compared to older heatset or UV systems [121]. Emissions from transporting paper to printers and printed products to consumers can be addressed by optimizing routes, using electric vehicles where possible, and reducing distances (printing closer to demand). Though outside the factory gate, these indirect emissions factor into the cradle-to-grave impact. Additionally, a broader societal shift, e.g. media moving from print to digital, has already slowed printing paper demand in many regions. While not exactly a “decarbonization technology” implemented by mills, it is an external factor that reduces the industry's emissions by reducing production volume. PPI can support this by diversifying into sustainable packaging or other products so that they can allow printing paper output to decline without business harm, thereby contributing to overall emission decline in the sector.

#### 4.1.5. Cross-cutting & end-of-life measures

Carbon Capture (BECCS) can be applicable across the board for emissions capture. As discussed, capturing CO<sub>2</sub> from the flue gases of the recovery boiler or multi-fuel boiler could significantly reduce the emissions [122]. Also, many pulp/paper mills have on-site wastewater treatment that can emit methane from anaerobic decomposition. Capturing this biogas can both reduce GHG emissions and provide fuel. Similarly, diverting paper waste from landfills to recycling or incineration with energy recovery avoids landfill methane. These are part of a circular economy approach and complement recycling efforts. Fig. 10 illustrates the measures discussed at the sub-process level, and Table 8 summarizes potential impacts of the pathways at the sub-process level.

In evaluating decarbonization pathways, it is also important to consider their technology readiness levels (TRLs) and real-world feasibility [123], as well as their economic and regional implications.

#### 4.2. Feasibility and technological readiness level

Established measures like EEMs and conventional biomass boilers are commercially mature (TRL 9) and already widely implemented. In contrast, emerging technologies like hydrogen combustion in high-temperature paper mill applications or large-scale CCS in a pulp mill are at earlier stages. According to the World Business Council for Sustainable Development (WBCSD), hydrogen combustion for boilers is currently in the “large prototype to first-of-a-kind” stage (TRL 7–8) [124]. Its economic feasibility in the near term is low due to the high fuel cost; indeed, as noted, the cost per ton CO<sub>2</sub> abated by hydrogen is estimated in the hundreds of euros. Therefore, while hydrogen offers 100 % emission abatement potential at the point of use, it scores low on short-term economic viability. By comparison, electrification via heat pumps is maybe TRL 7–8 (some pilot installations exist in Europe for paper drying), and though the upfront cost is significant, the abatement cost might be moderate and expected to fall as electricity grids decarbonize and carbon prices rise.

Biomass fuel switching is already happening, so its feasibility mostly hinges on feedstock supply and sustainability, rather than technical uncertainty. One can consider sustainability metrics (like lifecycle carbon intensity of biomass, land use impacts) as part of feasibility in the broad sense.

#### 4.3. Regional applicability

Regional differences significantly impact the feasibility of decarbonization pathways. For example, regions with high energy prices and strong policy incentives like carbon taxes, such as the Scandinavian countries, have widely adopted biomass combined heat and power (CHP) and energy efficiency measures. Whereas regions lacking similar policy incentives or with lower energy costs might find these technologies economically unfeasible. Similarly, in Europe, over 55 % of the PPI

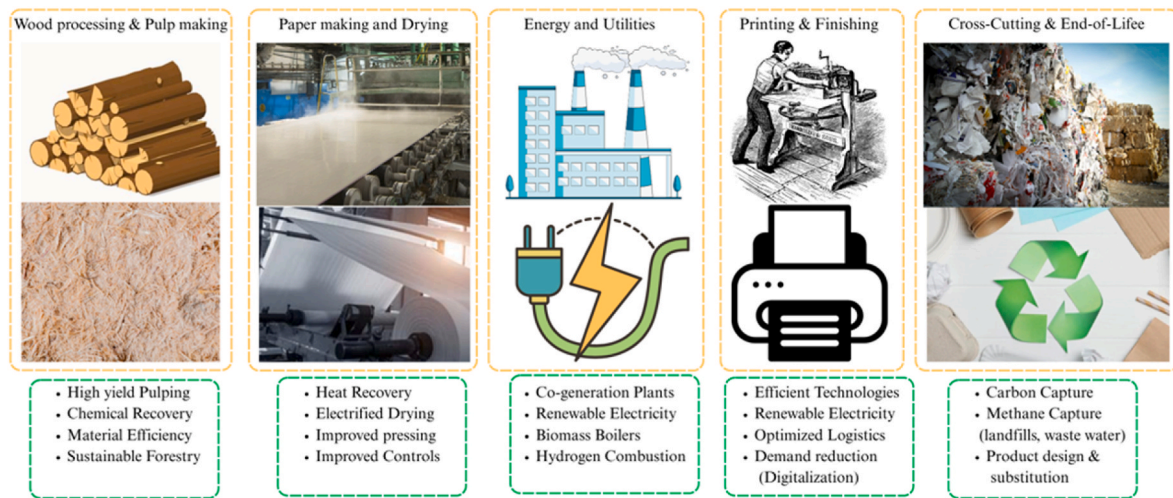


Fig. 10. Decarbonization measures at the sub-process level in PPI.

sector's primary energy currently comes from biomass, with the EU aiming to reach climate neutrality by 2050 through continued uptake of renewables and electrification. Reports from Material Economics [125] and the EU's Reference Scenarios [126] project that Europe's paper industry may exceed 80 % low-carbon energy penetration by 2030 and reach near-full low-carbon energy usage by 2050. In contrast, China's PPI sector remains heavily reliant on fossil fuels, with over 59 % of emissions from coal in the 2000s, but is expected to see this share decline below 50 % by 2030 due to expanded renewables in the power grid [125]. India may also see significant growth in low-carbon energy use; currently, coal accounts for around 75 % of its electricity generation (2023), with renewables making up just over 22 % [127]. These disparities underline how regional differences in resource availability, policy, and technology access create varied starting points and transition trajectories (Fig. 11).

It is noteworthy that the data such as emission factors, cost data, and energy consumption figures discussed in this review are primarily based on global averages, with a significant emphasis on data from Europe (particularly Italy, Finland, Sweden, and Germany), North America (notably the United States and Canada), and selected Asian countries such as China and India. It is important for readers to interpret the presented emission, cost, and energy consumption metrics within these particular geographical contexts, acknowledging that regional differences in technology, fuel sources, regulatory environments, and industrial practices can lead to notable variations in the data.

Life Cycle Assessment (LCA) serves as another critical tool for evaluating the environmental impacts tied to decarbonization pathways, spanning every phase from raw material extraction to final disposal. Within the PPI sector, where emissions and resource consumption occur at numerous stages, LCA is indispensable for revealing potential trade-offs, such as increased water consumption or land use, that might otherwise go unnoticed. By employing LCA metrics to systematically compare various options, stakeholders are equipped to make decisions that genuinely support long-term sustainability goals. Table 9 summarizes key LCA findings for each decarbonization pathway, highlighting their overall GHG impacts when upstream and downstream factors are considered.

While the above measures have technical merit, their viability will ultimately depend on economic feasibility and policy support.

#### 4.4. Economic feasibility and policy implications

Economic considerations are critical in assessing the real-world viability of decarbonization pathways, and current costs vary widely among the options. In particular, the cost of green hydrogen remains

very high today relative to conventional fuels. As of the mid-2020s, the levelized cost of green hydrogen production is roughly \$4–6 per kg (depending on region) [104], which is an order of magnitude higher than the equivalent energy cost of natural gas. Projections indicate that this could fall to about \$2–3 per kg by 2030 with continued investments and learning-curve improvements [130]. But even at \$2/kg, hydrogen would translate to a fuel cost of roughly \$15–\$20 per GJ, which is substantially above equivalent fossil fuel prices. Such costs imply CO<sub>2</sub> abatement costs for hydrogen well above \$200 per ton, given the current price gap between hydrogen and fossil fuels. Indeed, hydrogen's economic feasibility in PPI decarbonization will heavily depend on policy mechanisms. For example, government incentives like the United States' Inflation Reduction Act provide up to \$3 per kg for clean hydrogen production, which can effectively reduce the price of green hydrogen to below \$1/kg in favorable cases [131]. These subsidies, alongside carbon pricing or emissions trading systems, are expected to play a decisive role in closing the cost gap.

Other pathways show more favorable economics in the near term. EEMs often have negative or low marginal abatement costs, and many efficiency upgrades pay for themselves through energy savings, making them economically attractive even without climate policy drivers [132]. Paper recycling and utilization of waste biomass can also be cost-effective, especially in regions with high landfill tipping fees or where mills have access to inexpensive biomass residues (like black liquor, which is essentially a free by-product providing energy). For electrification, the economics hinge on electricity prices relative to fuel prices. In regions with low-cost renewable electricity (or where carbon taxes make fossil fuels expensive), electrified steam generation or drying can be competitive. Additionally, electrification is future-proofing against carbon regulations: as grids decarbonize, electric technologies will automatically yield lower emissions without further capital changes.

Carbon pricing mechanisms are increasingly influencing investment decisions. The EU Emissions Trading System (ETS), for instance, has seen permit prices rise to record highs (around €90–€100 per ton CO<sub>2</sub> in 2023) [133]. Such a carbon price makes previously cost-prohibitive options more economically viable by internalizing the climate cost of emissions. For example, at €100/tCO<sub>2</sub>, each ton of CO<sub>2</sub> avoided saves €100, which can tilt the balance in favor of adopting biomass fuel or electrification. Regions without carbon pricing or with minimal carbon costs may experience slower adoption of high-capex decarbonization technologies due to the absence of a strong economic incentive. Policy instruments like renewable energy subsidies, tax credits, and low-interest "green loans" further improve project economics. Some governments offer capital grants for industrial heat pumps or carbon

**Table 8**  
Mapping of decarbonization pathways with key sub-processes in PPI and their potential impacts.

Sub-process	Decarbonization measures	Potential Impact
Wood Preparation & Pulping	Mechanical pulping optimization	Reduce refining energy by 10–20 %, saving 1–2 GJ/ton
	Electrification of refiners	Significant emissions reduction if powered by renewable sources
	Chemical pulping improvements (BLG, efficiency)	Overall mill CO <sub>2</sub> reductions by 5–10 %
	Alternative fibers (bagasse, straw)	Reduced pulping energy and forest pressure
Papermaking & Drying	Sustainable forestry & electrified logistics	Reduced indirect transport emissions
	Advanced pressing (shoe press)	Each 1 % increase in dryness saves 4 % dryer energy
	Heat recovery via heat pumps or recompression	10–50 % reduction in drying steam demand
	Electrification (infrared/microwave dryers)	Potentially eliminate 60 % of mill energy CO <sub>2</sub> emissions
	Improved dryer controls and insulation	5–15 % steam savings
Energy & Utilities (CHP, Steam)	Dryer reconfiguration (Condebelt)	20 % energy reduction
	Biomass boiler replacement	90 % reduction in boiler emissions
	Hydrogen combustion	Up to 100 % direct emissions reduction
	On-site renewable electricity	Offset indirect grid emissions
Printing & Finishing	High-efficiency CHP (biomass, SOFC, renewable fuels)	>80 % total efficiency, significant emissions cuts
	Efficient printing technology	Energy reductions (e.g., LED-UV curing lowers energy use)
	Renewable electricity for printing plants	Reducing emissions from hundreds of kWh per ton processed
	Optimized logistics (electric vehicles/routes)	Indirect emissions reductions
Cross-Cutting & End-of-Life	Demand reduction (digitalization)	Reduced production and associated emissions
	Carbon Capture (BECCS)	Capture 50–90 % of total mill CO <sub>2</sub> , possibly net-negative emissions
	Methane capture (wastewater/landfills)	Reduced GHG emissions, renewable fuel source
	Product design and substitution	Reduced processing energy per product, indirect decarbonization through substitution effects

capture pilot installations, and green financing mechanisms are becoming available for mills committing to sustainability targets.

From a financial perspective, mills will consider not only the direct costs but also the reliability and future risk. Technologies with uncertain fuel supply or volatile prices (like hydrogen in today's market) carry economic risk, whereas securing a long-term biomass supply or investing in electrification (assuming grid reliability) might be seen as more stable strategies. In many cases, a step-by-step approach implementing energy efficiency first (since it often saves money), then moderate-cost fuel switching (natural gas to biomass where available), and finally considering hydrogen or CCS if/when they become cost-effective, is the most economically sound path.

On the policy side, different regions have varying levels of support and regulation, which affects the global applicability of pathways. For example, the EU not only prices carbon but also has renewable energy directives and is rolling out a Carbon Border Adjustment Mechanism to protect low-carbon producers, policies that collectively encourage PPI decarbonization. In contrast, a country without such policies might not see an immediate business case for expensive measures unless other

drivers (like corporate sustainability commitments or investor pressure) come into play. Government policies and international agreements through 2030 and 2050 will significantly shape decarbonization trajectories. If strong policies (like high carbon prices, green hydrogen incentives, or mandates on recycled content) are enacted, the industry could move rapidly along certain pathways; if policies are weak or inconsistent, progress may rely on voluntary action and could be uneven.

Moreover, the decarbonization pathways for the PPI align closely with multiple UN Sustainable Development Goals (SDGs), Fig. 12. Most directly, they contribute to SDG 13 (climate action) by reducing GHG emissions. Shifting the industry's energy supply to renewable energy and bioenergy supports SDG 7 (Affordable and clean energy), while adopting energy efficiency measures aligns with SDG 9 (Industry, Innovation, and Infrastructure). Also, Strategies like paper recycling promote SDG 12 (Responsible Consumption and Production). Besides, PPI has a significant interaction with SDG 15 (Life on Land), as it is one of the largest consumers of wood, impacting forests and biodiversity. This highlights that decarbonization of PPI should not be viewed in isolation, as a purely techno-economic case study, but in terms of broader sustainability outcomes.

In summary, the economics of decarbonization pathways in PPI are as crucial as their technical feasibility. Current cost data suggests a hierarchy. Energy efficiency and process optimization are often low-cost or cost-saving, fuel switching to biomass or increased recycling is moderate in cost (and already underway in many cases), electrification can be costly but feasible with cheap renewable power, hydrogen and CCS remain the most expensive and will likely require significant policy-driven cost mitigation to be viable. Long-term forecasts (to 2030 or 2050) are optimistic that costs for technologies like green hydrogen and CCS will decline (e.g., due to economies of scale and innovation), potentially bringing them within reach for widespread adoption [134]. Active policy support will be critical to bridge economic gaps, ensuring that by 2030, the industry has demonstrated and scaled up the key solutions needed for deep decarbonization.

In the following section, the Analytical Hierarchy Process (AHP) will be employed to rank these pathways based on five distinctive criteria which include cost, emission reduction potential, technical feasibility (Technology Readiness Level, TRL), implementation time, and scalability, ensuring a balanced and informed decision aligned with the industry's decarbonization goals.

## 5. Evaluating the decarbonization pathways of PPI through multi-criteria decision-making technique: AHP (Analytical Hierarchy Process)

Multi-Criteria Decision Making (MCDM) is a powerful approach utilized to assess and choose the most appropriate options from a range of alternatives based on multiple criteria. There are various MCDM methods that assist in identifying the best alternative from a list of options based on their performance against relevant criteria. This is particularly valuable in decision-making scenarios where multiple factors need to be considered to make an optimal choice. Several MCDM methods have been developed since the 1960s; however, there is no consensus on the best MCDM method [135]. Commonly used methods include: the Weighted Sum Method (WSM), the Analytical Hierarchy Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Elimination and Choice Expressing Reality (ELECTRE), and PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations) [136]. A review of MCDM methods in the field of sustainable energy identified the WSM as the most commonly used (of which the AHP, a type of hierarchical weighted sum, is a subset), with equal criteria weights being the most prevalent [137]. This work will assess the economic and environmental performance of the decarbonization pathways discussed above, and will apply the AHP method with four different criteria weight regimes to evaluate them on varying

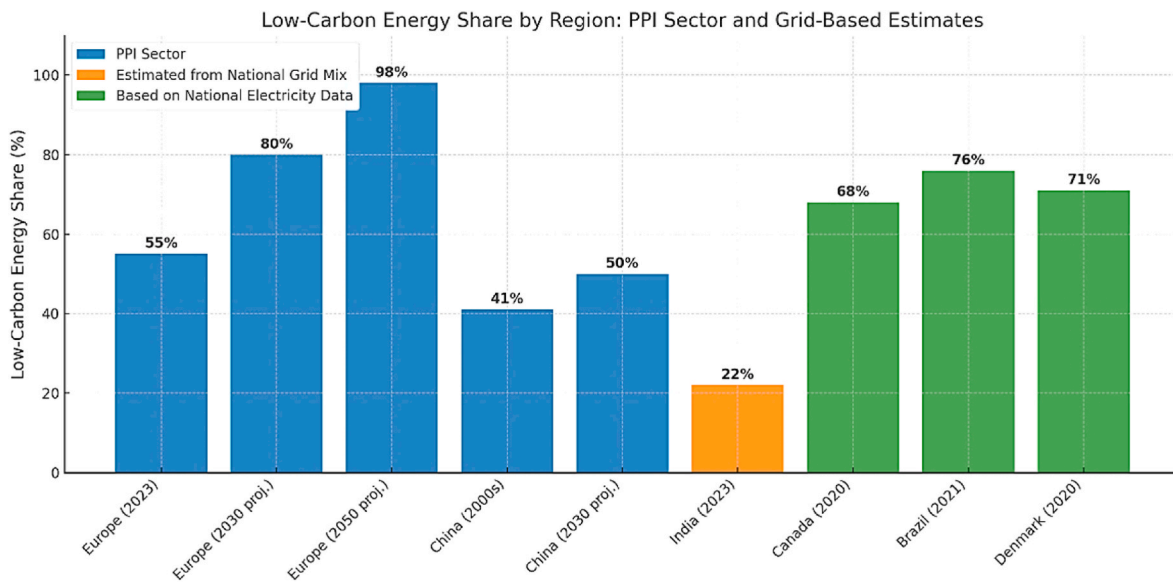


Fig. 11. Low-carbon energy share in the pulp and paper industry and the relevant electricity sector by region.

Table 9

Summary of LCA findings for decarbonization pathways in PPI (net greenhouse gas impacts, including upstream/downstream), synthesized from studies [25,50,52,53,85,94,128,129], & [67].

Decarbonization Pathway	LCA Highlights & Impacts (GHG, Water, Land, Toxics, & Waste)
Energy Efficiency Measures (EEMs)	LCA studies show EEM retrofits reduce cradle-to-gate impacts by up to 20 %. Energy and water use per ton of paper declines, with steam reduction by 10–30 %. Fewer chemical releases to air/water due to reduced bleaching needs.
Paper Recycling	LCA analyses indicate recycling can cut lifecycle (Cradle-to-grave) GHG emissions by 20–30 % per ton of paper compared to virgin production. Toxic contaminant risks from inks, bisphenol A, phthalates, and PCBs call for improved de-inking processes and regulatory controls. Waste slurry requires solidification or landfill treatment.
Fuel Switching (Biomass/ H <sub>2</sub> )	U.S. cradle-to-gate LCA (252 mills) attributes 942 kg CO <sub>2</sub> -eq/ton paper from fossil fuels, indicating major decarbonization potential from switching. Biomass production can increase water withdrawal and irrigation pressure; land use may affect biodiversity. H <sub>2</sub> production can have high embedded emissions unless renewable-powered.
Electrification	Nearly 100 % drop in on-site fossil CO <sub>2</sub> (Cradle-to-gate GHG) if grid electricity is renewable; otherwise, emissions are offloaded to the power sector. Electric boilers may lower mill-level water use, but shift intensity upstream. Potential for increased land footprint if dedicated renewables (solar PV, wind) are installed on-site. Reduced combustion emissions (SO <sub>2</sub> , NO <sub>x</sub> , PM), improving air quality; heavier electrical infrastructure may involve rare-earth metals and e-waste.
Carbon Capture & Storage (CCS)	LCAs of BECCS in kraft mills show potential for net-negative emissions, capturing over 90 % (Cradle-to-gate GHG) of process CO <sub>2</sub> when powered by renewables. CCS systems require additional cooling water and solvent circulation, raising the water footprint. Amine solvent leakage and degradation products require careful handling; the CO <sub>2</sub> leak risk is managed by site monitoring. Captured CO <sub>2</sub> must be safely stored or utilized; solvent waste streams require treatment.

criteria priorities.

The evaluation criteria considered are cost, emission reduction potential, technical feasibility (TRL), implementation time, and scalability. The cost criterion is a crucial factor in determining the feasibility and economic viability of any decarbonization technology [138]. The criteria of emission reduction evaluate the effectiveness of a technology in reducing carbon emissions, which is the primary goal of decarbonization [139]. Scalability evaluates whether a technology can be scaled up to meet the demands of large-scale industrial applications [137]. TRL measures the maturity of a technology, indicating how close it is to being commercially viable [136,140]. The Implementation time criterion is crucial for timely emissions reduction and meeting regulatory deadlines.

The MCDM method AHP chosen for this work is a structured technique for organizing and analyzing complex decisions. Developed by Thomas L. Saaty in the 1970s [138], AHP helps decision-makers model a complex problem in a hierarchical structure, breaking it down into a goal, criteria, and alternatives. The process involves several key steps, which involve defining the problem and structuring the hierarchy with the goal at the top, followed by criteria and alternatives at the bottom (Fig. 13). Next, pairwise comparisons are made between criteria using a scale of 1–5 to establish their relative importance, as explained in section 5.2 and Tables 10–14. The matrix is then normalized and averaged to calculate the weights of each criterion, section 5.3. Consistency of judgments is then checked using the consistency ratio (CR), which should be below 0.1, section 5.4. Finally, the weights are aggregated to evaluate the alternatives, with the highest-scoring option considered the best choice (section 6). Fig. 13 shows the hierarchical model of the problem.

The criteria weights were designed in four distinct sets of weight regimes. The first set of criteria weights (CW-1) assigns equal importance to all criteria (attempting to balance GHG reduction with economic performance and technical feasibility). The second set (CW-2) places all weight on the economic criterion, reflecting a strategy focused on financial viability. The third set (CW-3) places all weight on the emission reduction potential of a decarbonization pathway, aiming to maximize GHG mitigation regardless of the economic implications. The fourth set (CW-4) prioritizes total GHG emission saving potential (a high weight of 60 %), while still considering the other criteria (10 % each) to cost, TRL, scalability, and implementation time, representing a strategy prioritizing emissions but not exclusively. The rationale for these weightings is further explained in section 5.1.

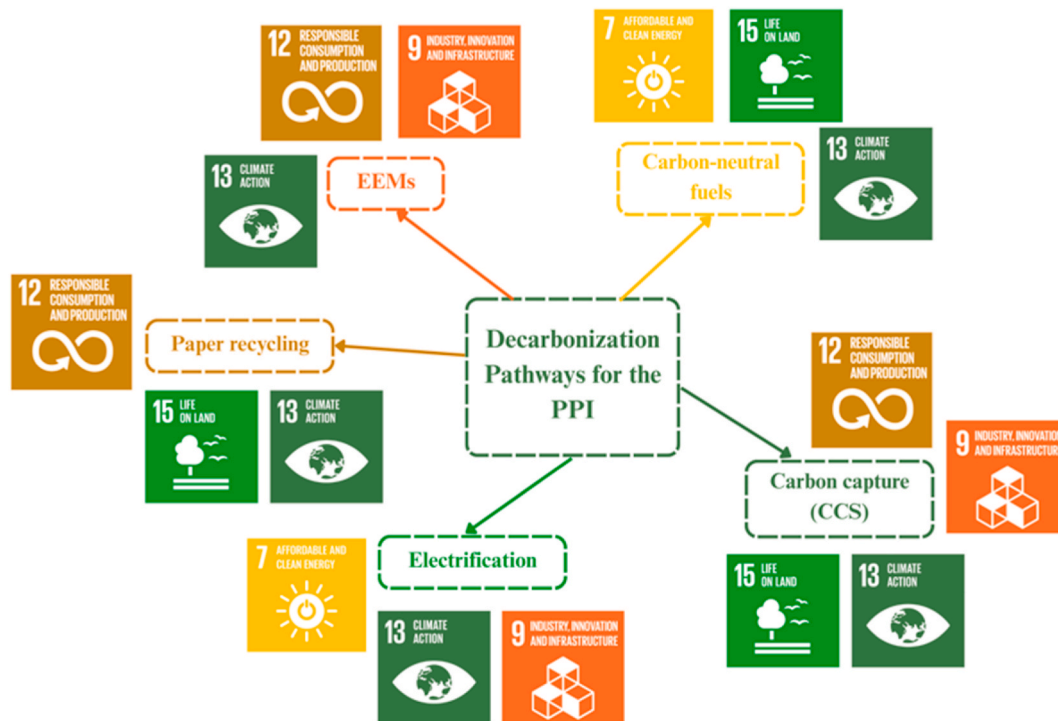


Fig. 12. Alignment of decarbonization pathways for the pulp and paper industry (PPI) with relevant UN Sustainable Development Goals (SDGs).

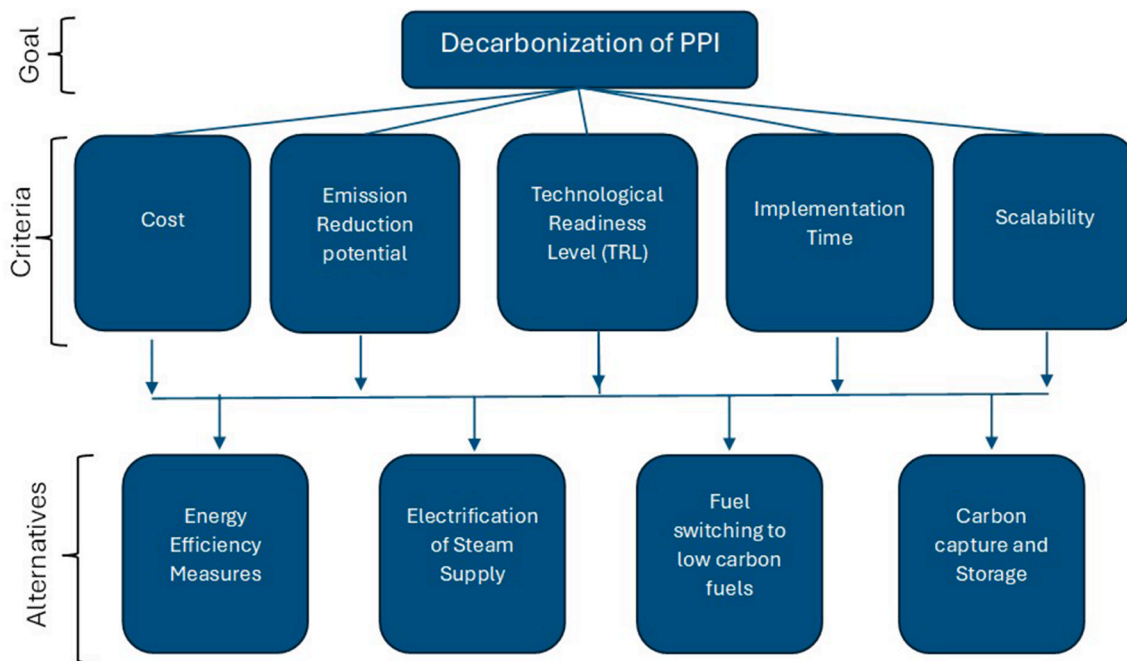


Fig. 13. Analytical hierarchy process AHP chart for the decarbonization of PPI.

5.1. Criteria weightings

The chosen criteria weightings are designed to reflect scenarios emphasized in the literature. Many studies note that cost is often the dominant criterion influencing industrial decarbonization decisions, given the high capital intensity of mitigation measures. Thus, CW-2 (cost-focused) captures a scenario where economic viability is paramount. On the other hand, aggressive climate policy approaches

prioritize maximizing emissions reductions regardless of cost, which is reflected in CW-3 (emissions-focused). CW-4 provides a balanced strategy where emission reduction is given the greatest importance, but some weight is still allocated to other factors, aligning with recommendations to balance environmental benefits with practical feasibility. Using multiple weighting regimes in this way follows MCDM best practices to test the robustness of the ranking outcomes under different priority assumptions.

**Table 10**  
Pairwise comparison matrix for Cost criterion (how alternatives compare on cost-effectiveness)

Alternatives	EEMs	Fuel Switching	Paper Recycling	CCS	Electrification
EEMs	1	3	2	5	4
Fuel Switching	1/3	1	1/2	3	3
Paper Recycling	1/2	2	1	5	2
CCS	1/5	1/3	1/5	1	1/4
Electrification	1/4	1/3	1/2	4	1

**Table 11**  
Pairwise comparison matrix for the Emission Reduction Potential criterion

Alternatives	EEMs	Fuel Switching	Paper Recycling	CCS	Electrification
EEMs	1	1/2	2	1/3	1/5
Fuel Switching	2	1	3	1/2	1/3
Paper Recycling	1/2	1/3	1	1/4	1/5
CCS	3	2	4	1	1/2
Electrification	5	3	5	2	1

**Table 12**  
Pairwise comparison matrix for Technological Readiness Level (TRL) criterion.

Alternatives	EEMs	Fuel Switching	Paper Recycling	CCS	Electrification
EEMs	1	2	1	3	4
Fuel Switching	1/2	1	1/2	2	3
Paper Recycling	1	2	1	4	3
CCS	1/3	1/2	1/4	1	2
Electrification	1/4	1/3	1/3	1/2	1

**Table 13**  
Pairwise comparison matrix for the Scalability criterion

Alternatives	EEMs	Fuel Switching	Paper Recycling	CCS	Electrification
EEMs	1	2	2	4	3
Fuel Switching	1/2	1	1/3	2	1/3
Paper Recycling	1/2	3	1	5	2
CCS	1/4	1/2	1/5	1	1/3
Electrification	1/3	3	1/2	3	1

**Table 14**  
Pairwise comparison matrix for the implementation time criterion

Alternatives	EEMs	Fuel Switching	Paper Recycling	CCS	Electrification
EEMs	1	3	3	4	4
Fuel Switching	1/3	1	2	4	3
Paper Recycling	1/3	1/2	1	3	2
CCS	1/4	1/4	1/3	1	1/2
Electrification	1/4	1/3	1/2	2	1

5.2. Alternatives pairwise comparison matrices

The pairwise comparison matrix A is constructed such that  $A_{ij}$  represents the relative importance of alternative i over alternative j. The matrix is reciprocal, meaning  $A_{ji} = 1/A_{ij}$ . Separate pairwise comparison matrices for cost, emission reduction potential, implementation time, scalability, and technology readiness level (TRL) are defined in tables (Tables 10–14). These matrices compare the alternatives, including

EEMs, electrification, paper recycling, fuel switching, and CCS, against each other for each criterion using a scale of 1–5. In this scale, a score of 1 indicates equal favorability, while scores of 2–5 represent increasing degrees of preference: 2 for slightly more favorable, 3 for moderately more favorable, 4 for strongly more favorable, and 5 for extremely favorable. The pair-wise comparison tables for different alternatives for each criterion are given in sections 5.2.1 to 5.2.5.

5.2.1. Cost

The pairwise comparison matrix for cost criteria highlights that EEMs are the most cost-effective option due to their low initial investment and operational costs [123,141]. Values in each cell indicate how much more favorable the row alternative is over the column alternative on cost (e.g., 3 = moderately more favorable, 1/3 = moderately less favorable).

EEMs are considered moderately more favorable than fuel switching (scored 3), extremely more favorable than CCS (scored 5), and strongly more favorable than Electrification (scored 4). Fuel switching is given a score of 1/3 against EEMs (EEMs being more cost-effective), and as fuel switching tends to be less costly than CCS (CCS being the most expensive [142]) due to lower capital requirements and somewhat manageable operational expenses, and rated moderately more favorable (scored 3). It is also slightly more cost-effective than electrification (scored 2), as electrification often entails higher infrastructure costs and electricity prices [142,143]. Paper recycling involves moderate capital and O&M expenses due to existing infrastructure and established processes [144]. Thus, it is rated slightly less cost-effective than EEMs, which have very low operational and capital costs. But recycling is more favorable compared to CCS [145] and Electrification [146], which typically involve higher infrastructure and operational costs. CCS can be the most expensive alternative due to high Capex and Opex; therefore, it is given low scores compared to other alternatives [142,147]. CCS is given a score of 1/4 against Electrification (showing electrification tends to be strongly more favorable than CCS based on cost). Electrification is less costly than CCS but more expensive than EEMs and Fuel Switching [142, 143]. A similar procedure is followed for pairwise comparisons of alternatives for the remaining criteria.

5.2.2. Emission reduction potential

EEMs have low emission reduction potential compared to other alternatives, as they primarily focus on improving efficiency rather than directly reducing emissions. Fuel switching offers moderate emission reductions by transitioning to lower-carbon fuels like biomass or hydrogen, but not as much as CCS or electrification [148–150]. Paper recycling reduces emissions by avoiding energy-intensive processes required in virgin pulp production. It is more effective than EEMs, which mainly optimize efficiency without substantial direct emission reductions [151], but less effective compared to CCS [119] and electrification, which can achieve deep decarbonization. CCS has a high potential for reducing emissions, especially in industries with high CO<sub>2</sub> output [150], and is ranked moderately favorable (scored 3) against EEMs, and slightly more favorable (scored 2) than fuel switching. Electrification has the highest potential for emission reduction by replacing fossil fuels entirely and switching to heat pumps, electric boilers, and electric furnaces, provided the electricity is green-sourced [152]. Therefore, Electrification is rated extremely favorable (scored 5) against EEMs, strongly favorable (scored 3) against fuel switching, and slightly more favorable (scored 2) than CCS in terms of emission reduction potential.

5.2.3. Technological readiness level (TRL)

EEMs have high TRL, are considered the most mature and widely implemented technologies, with high readiness for adoption, especially in industrial and commercial sectors [105]. Thus, EEMs are scored highest against all other alternatives. EEMs are ranked slightly more favorable (scored 2) against fuel switching, moderately more favorable

(scored 3), and strongly more favorable against electrification. Fuel switching has a medium TRL with ongoing developments in hydrogen use [152]. Paper recycling has high TRL, similar to EEMs due to proven technologies across global recycling facilities [153]. Thus, it is rated equally favorable compared to EEMs, and significantly more favorable than the CCS and Electrification. CCS has a lower TRL due to complexity and fewer large-scale implementations [150], but its TRL level is more than Electrification, Table 2. Thus, CCS is rated slightly more favorable (scored 2) against electrification. Electrification has the lowest TRL among other alternatives for industrial decarbonization due to its reliability and cost, inefficiencies, and inadequacies in transmission and distribution infrastructure [123], also due to its dependence on advancements in renewable electricity [152].

#### 5.2.4. Scalability

EEMs are easily scalable as they involve widespread techniques and practices with relatively low initial barriers [105]. Fuel switching can have less scalability in some cases, as it is dependent on the availability of alternative fuels [152]. Paper recycling has considerable scalability, given global infrastructure and widespread adoption [154]. It is highly favorable compared to CCS and moderately favorable to electrification, which requires substantial system transformations. However, it is slightly less favorable to EEMs, due to their easier and more universally applicable practices [36]. CCS is less scalable due to infrastructure costs and regulatory challenges [150]. Electrification is scalable but requires a complete overhaul of systems, heat pumps, electric boilers, and electric furnaces, making energy efficiency measures more easily scalable [152]. Therefore, EEMs are rated slightly more favorable than fuel switching (scored 2), strongly more favorable than CCS (scored 4), and moderately more favorable (scored 3) than electrification. Fuel switching is rated slightly more favorable (scored 2) than CCS based on scalability, and 1/3 against electrification (electrification being strongly favorable for scalability than Fuel switching).

#### 5.2.5. Implementation time

EEMs are generally faster to implement due to simpler modifications [155]. Fuel switching requires more time for infrastructure changes, as it involves infrastructure modifications and transitioning to new fuels like biomass or hydrogen, making it slower than EEMs and electrification but faster than CCS [155]. Paper recycling has short implementation times owing to pre-existing infrastructure and streamlined regulatory environments. It is rated less favorable than EEMs due to EEMs' simpler and quicker implementation, and slightly less favorable than fuel switching [156]. Paper recycling is rated more favorable compared to CCS and electrification, both of which require extensive infrastructure deployment. CCS has the longest implementation times due to complex infrastructure and permitting [150]. Electrification has an intermediate implementation time, depending on the availability of renewable electricity infrastructure [152]. EEMs are therefore moderately favored compared to fuel switching, extremely favored (scored 5) against CCS, and slightly more favored than electrification. Fuel switching is rated moderately favorable compared to CCS, and 1/2 against electrification (electrification being slightly faster than fuel switching). Electrification is rated strongly favorable against CCS (CCS being the slowest to implement).

It is noteworthy that the information for the values assigned in the pairwise comparison matrices for evaluating decarbonization technologies in the paper industry is derived from credible sources, including the Global CCS Institute report [150], IEA energy efficiency report [105], findings from the IPCC report [109], European Commission's Horizon 2020 program [157], European Commission's Net-Zero Industrial Act [158], Implementation time assessments from McKinsey & Company [155], Pathways Analysis Summary: Decarbonization Potential for Industrial Subsectors by US Department of Energy [123], scalability values from the International Renewable Energy Agency (IRENA) [152], and authors' interpretation of values adjusted to reflect the trends

available in the literature and to ensure consistency ratios within the context of AHP analysis. While the precise scoring values were not directly available in the literature, the authors have made a diligent effort to represent the relative importance of the criteria as indicated in the literature.

#### 5.3. Normalizing the pairwise comparison matrix

The next step is to normalize the values of each alternative with respect to each criterion. Normalizing the pairwise comparison matrix is done by dividing each element by the sum of its column, eq. (1):

$$\text{Normalized Matrix} = \frac{A_{ij}}{\sum_{i=1}^n A_{ij}} \quad (1)$$

Then the weights for each criterion and each alternative with respect to the criteria are calculated by eq. (2):

$$\text{Weights} = \frac{\text{Sum of Each Row of the Normalized Matrix}}{\text{Number of Criteria}} \quad (2)$$

Then weights of each alternative will be multiplied with the criteria weights to calculate the overall score for each alternative, eq. (3):

$$\text{Overall Score} = \text{Weights of Alternatives} \times \text{Criteria Weights} \quad (3)$$

#### 5.4. Consistency check

Consistency is checked for the pairwise comparisons using the consistency ratio (CR). If the CR is acceptable (typically less than 0.1), the comparisons are considered consistent. This is done by calculating the maximum eigenvalue ( $\lambda_{\max}$ ) of the pairwise comparison matrix and then calculating the Consistency Index (CI):

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (4)$$

where n is the number of criteria or the size of the matrix. Then calculate the Consistency Ratio (CR), eq. (5):

$$CR = \frac{CI}{RI} \quad (5)$$

where RI is the Random Index. The value RI is based on the average consistency index of randomly generated pairwise comparison matrices of the same size. Once the consistency ratio is checked (0.0583, 0.0152, 0.0190, 0.0558, 0.0378) for all the pair-wise comparison matrices, then the ranking is carried out based on the overall score of alternatives in a way that the alternative with the highest overall score is ranked 1st and is the most preferred option. The tables below summarize the overall Analytical Hierarchy Process (AHP) scores for each decarbonization pathway across different weighting regimes.

## 6. AHP results and ranking of alternatives

These AHP results are intended to provide clear insights into how the pathways perform under various strategic priorities such as cost-effectiveness, emission reduction potential, technological readiness, implementation timeline, and scalability. Each weighting scenario highlights distinct considerations, assisting stakeholders in making informed decisions aligned with specific goals or constraints. Tables 15–18 show the weights of alternatives and overall score in the criteria weight regimes CW-1, CW-2, CW-3, and CW-4. Table 19 shows the final AHP ranking of alternatives.

Based on the results from the Analytical Hierarchy Process (AHP) analysis, several key insights emerge (Table 19). When equal weights are assigned to all criteria (CW-1), EEMs rank first, highlighting their well-rounded performance across cost, emissions reduction, TRL, implementation time, and scalability. Paper recycling ranks 2nd, indicating

**Table 15**  
Overall AHP Score of alternatives for Criteria Weights (CW-1)

Criteria Weights (CW-1)	0.2	0.2	0.2	0.2	0.2	Overall Score
	Cost	Emission reduction	TRL	Implementation time	Scalability	
EEMs	0.0813	0.0186	0.0634	0.0863	0.0724	0.322
Fuel Switching	0.0349	0.0317	0.0367	0.0486	0.0226	0.174
Paper Recycling	0.0492	0.0124	0.0642	0.0321	0.0556	0.213
CCS	0.0106	0.0515	0.0209	0.0133	0.0126	0.109
Electrification	0.0239	0.0858	0.0148	0.0197	0.0367	0.181

**Table 16**  
Overall AHP Score of alternatives for Criteria Weights (CW-2)

Criteria Weights (CW-2)	1	0	0	0	0	Overall Score
	Cost	Emission reduction	TRL	Implementation time	Scalability	
EEMs	0.406	0	0	0	0	0.406
Fuel Switching	0.175	0	0	0	0	0.175
Paper Recycling	0.246	0	0	0	0	0.246
CCS	0.0530	0	0	0	0	0.0530
Electrification	0.119	0	0	0	0	0.119

**Table 17**  
Overall AHP Score of alternatives for Criteria Weights (CW-3)

Criteria Weights (CW-3)	0	1	0	0	0	Overall Score
	Cost	Emission reduction	TRL	Implementation time	Scalability	
EEMs	0	0.0929	0	0	0	0.0929
Fuel Switching	0	0.158	0	0	0	0.158
Paper Recycling	0	0.0619	0	0	0	0.0619
CCS	0	0.257	0	0	0	0.257
Electrification	0	0.429	0	0	0	0.429

**Table 18**  
Overall AHP Score of alternatives for Criteria Weights (CW-4)

Criteria Weights (CW-4)	0.1	0.6	0.1	0.1	0.1	Overall Score
	Cost	Emission reduction	TRL	Implementation time	Scalability	
EEMs	0.0406	0.0557	0.0317	0.0431	0.0362	0.207
Fuel Switching	0.0175	0.0950	0.0183	0.0242	0.0113	0.166
Paper Recycling	0.0246	0.0371	0.0320	0.0160	0.0278	0.137
CCS	0.0053	0.154	0.0105	0.0066	0.0063	0.183
Electrification	0.0119	0.257	0.0074	0.0098	0.0183	0.304

**Table 19**  
Final AHP ranking of Alternatives (decarbonization pathways) for Criteria weight regimes (CW-1 to CW-4)

Criteria Weight Regime	Decarbonization pathway	Rank
CW-1 (Equal weights)	EEMs	1st
	Paper Recycling	2nd
	Electrification	3rd
CW-2 (Max. weight on cost)	EEMs	1st
	Paper Recycling	2nd
	Fuel Switching	3rd
CW-3 (Max. weight on emission reduction)	Electrification	1st
	CCS	2nd
	Fuel Switching	3rd
CW-4 (high weight on emission reduction)	Electrification	1st
	EEMs	2nd
	CCS	3rd

strong overall benefits, followed by electrification in 3rd.

When cost is prioritized (CW-2), EEMs remain the top choice due to their economic viability and often negative or low net costs. However, it is noted that EEMs alone cannot fully decarbonize PPI (given remaining fossil fuel use for heat and fossil-based grid electricity), so they need to

be complemented by other solutions. Paper recycling emerges 2nd, followed by fuel switching 3rd. This outcome reflects the relatively lower cost impacts of recycling and certain fuel switches compared to high-capex or high-opex options like CCS and full electrification.

Prioritizing emission reduction (CW-3) drastically alters the ranking. Electrification takes the lead, owing to its ability to eliminate emissions by using carbon-neutral electricity to replace fossil fuels. CCS comes in 2nd, thanks to its high effectiveness in capturing and storing CO<sub>2</sub>, and fuel switching (to biomass/H<sub>2</sub>) is 3rd.

This order changes when emission reduction is given higher but not exclusive weight (CW-4). In a scenario giving emissions a strong but not exclusive weight, electrification still tops the ranking (leveraging zero-carbon power), followed by EEMs in 2nd (because they excel on other criteria as well), and CCS in 3rd, [Table 19](#). This reinforces that electrification is a very compelling option for deep decarbonization, especially as grids decarbonize.

In summary, the optimal decarbonization pathway for PPI depends on which criteria are prioritized. EEMs are the most balanced and cost-effective when all criteria are equally important. For emission reductions as the primary goal, electrification is the clear leader, making it the most compelling option for deep decarbonization efforts. Therefore, a combination of pathways such as energy efficiency improvements

along with energy supply solutions (fuel switching, and electrification), and enhancing material circularity through increased paper recycling will be required for the complete decarbonization of the PPI.

## 7. Conclusion

In this review, we investigated various decarbonization pathways for the pulp and paper industry, including energy efficiency measures (EEMs), switching fuels to low-carbon fuels such as biomass and hydrogen, paper recycling, electrification of heat supply, and carbon capture and storage (CCS). These options were evaluated using peer-reviewed literature, and their key drivers and barriers, including economic feasibility, technology maturity, feedstock availability, capital investment needs, and policy support, were systematically identified.

These decarbonization options were ranked using an AHP multi-criteria analysis across five distinct criteria and under four distinct criteria-weight regimes to examine how priorities influence the preferred option. The AHP results demonstrated that the optimal decarbonization pathway depends on various economic and environmental objectives. EEMs and paper recycling present immediate and economically attractive options, but are not sufficient for complete decarbonization. Whereas electrification and biomass fuel switching offer promising mid-term solutions contingent on renewable energy availability and supportive policy frameworks. Technologies such as hydrogen fuel integration and CCS hold high long-term complete decarbonization potential but require substantial investments and policy-driven incentives to become economically viable and widely adopted. Given these findings, successful decarbonization of the PPI will rely on an integrated approach that aligns technological innovation with robust policy support, industry collaboration, and targeted financial incentives.

Resource availability and broader sustainability impacts aligned with UN SDGs should also be considered for strategic decision-making. For instance, shifting to biomass supports climate goals (SDG 13) but can harm ecosystems (SDG 15) if not managed sustainably. Also, biomass combustion emits particulates and NO<sub>x</sub>, requiring pollution controls. On the other hand, electrification can reduce SO<sub>2</sub> and NO<sub>x</sub>, benefiting public health (SDG 3). Besides, decarbonization can further support innovation and green jobs (SDG 9), especially in technology, engineering, and sustainable forestry. In essence, a holistic approach is needed to ensure emissions cuts align with broader sustainability goals, leading to a more circular and resilient PPI.

### 7.1. Regional scope and data constraints

The authors acknowledge that much of the literature and data cited in this paper are Europe- or North America-centric, where PPI decarbonization has been more actively explored. Consequently, some assumptions, like ample biomass availability or strong policy support, may not apply globally. For example, China's pulp and paper sector is still coal-dependent, with more than double the carbon intensity of Europe. While our conclusions aim to be globally relevant, they should be viewed in light of regional differences. Region-specific strategies, such as focusing on agro-residues and solar in Asia or energy efficiency in resource-constrained areas, will be essential. Nonetheless, the core decarbonization options are broadly applicable, and global knowledge-sharing will be vital to support all regions in achieving climate goals.

### CRedit authorship contribution statement

**Farhan Haider Joyo:** Conceptualization, Data curation, Formal analysis, Writing – original draft. **Benedetto Nastasi:** Conceptualization, Methodology, Visualization, Writing – review & editing. **Davide Astiaso Garcia:** Supervision, Validation, Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The data used in this review, primarily the facts and figures for the pulp and paper industry, are sourced from publicly available literature including peer-reviewed articles, and technical reports. All data sources are cited appropriately within the manuscript.

## References

- [1] Bataille C, et al. Net-zero deep decarbonization pathways in Latin America: challenges and opportunities. *Energy Strategy Rev* 2020;30:100510. <https://doi.org/10.1016/j.esr.2020.100510>.
- [2] Wesseling J, Lechtenböhmer S, Åhman M, Nilsson LJ, Worrell E, Coenen L. The transition of energy intensive processing industries towards deep decarbonization: characteristics and implications for future research. *Renew Sustain Energy Rev* 2017;79:1303–13. <https://doi.org/10.1016/j.rser.2017.05.156>.
- [3] "Energy Technology Perspectives 2023 – analysis," IEA. <https://www.iea.org/reports/energy-technology-perspectives-2023>. [Accessed 5 August 2024].
- [4] IEA. Net Zero by 2050: A Roadmap for the Global Energy Sector. 2021. p. 121–31. Available: <https://www.energy.gov/sites/default/files/2021-12/IEA,%20Net%20Zero%20by%202050.pdf>.
- [5] World energy transitions outlook 1-5C pathway 2022 edition." Accessed: August 5, 2024. [Online]. Available: <https://www.irena.org/publications/2022/Mar/World-Energy-Transitions-Outlook-2022>.
- [6] C. Jaramillo, "Decarbonization, circular economy and sustainability in the European paper and packaging industry," *fastmarkets*. Accessed: May 23, 2025. [Online]. Available: <https://www.fastmarkets.com/insights/decarbonization-circular-economy-and-sustainability-in-european-paper-packaging/>.
- [7] Szabó L, Soria A, Forsström J, Keränen JT, Hytönen E. A world model of the pulp and paper industry: demand, energy consumption and emission scenarios to 2030. *Environ Sci Pol* 2009;12(3):257–69. <https://doi.org/10.1016/j.envsci.2009.01.011>.
- [8] Rissman J, et al. Technologies and policies to decarbonize global industry: review and assessment of mitigation drivers through 2070. *Appl Energy* 2020;266. <https://doi.org/10.1016/j.apenergy.2020.114848>.
- [9] "Energy Technology Transitions for Industry – Analysis," IEA. <https://www.iea.org/reports/energy-technology-transitions-for-industry>. [Accessed 5 August 2024].
- [10] Lin H-C, Chan DY-L, Lin W-C, Hsu C-H, Hong G-B. Status of energy conservation in Taiwan's pulp and paper industry. *Energy* 2014;73:680–5. <https://doi.org/10.1016/j.energy.2014.06.070>.
- [11] "The Forest Fibre Industry: 2050 Roadmap to a low-carbon bio-economy | www.cepi.org." Accessed: August 5, 2024. [Online]. Available: <https://www.cepi.org/the-forest-fibre-industry-2050-roadmap-to-a-low-carbon-bio-economy/>.
- [12] Amode NS, Jeetah P. Paper production from Mauritian hemp fibres. *Waste Biomass Valorization* 2021;12(4):1781–802. <https://doi.org/10.1007/s12649-020-01125-y>.
- [13] Sun M, Wang Y, Shi L, Klemeš JJ. Uncovering energy use, carbon emissions and environmental burdens of pulp and paper industry: a systematic review and meta-analysis. *Renew Sustain Energy Rev Sep*. 2018;92:823–33. <https://doi.org/10.1016/j.rser.2018.04.036>.
- [14] Joelsson JM, Gustavsson L. CO<sub>2</sub> emission and oil use reduction through black liquor gasification and energy efficiency in pulp and paper industry. *Resour Conserv Recycl Mar*. 2008;52(5):747–63. <https://doi.org/10.1016/j.resconrec.2007.11.002>.
- [15] Malachowska E, Dubowik M, Boruszewski P, Łojewska J, Przybysz P. Influence of lignin content in cellulose pulp on paper durability. *Sci Rep Nov*. 2020;10(1):19998. <https://doi.org/10.1038/s41598-020-77101-2>.
- [16] Novotny M, Laestadius S. Beyond papermaking: technology and market shifts for wood-based biomass industries – management implications for large-scale industries. *Technol Anal Strateg Manag* 2014;26(8):875–91. <https://doi.org/10.1080/09537325.2014.912789>.
- [17] "Key statistics report 2018 out now! | www.cepi.org." Accessed: August 5, 2024. [Online]. Available: <https://www.cepi.org/key-statistics-report-2018-out-now/>.
- [18] Laurijssen J, De Gram FJ, Worrell E, Faaij A. Optimizing the energy efficiency of conventional multi-cylinder dryers in the paper industry. *Energy Sep*. 2010;35(9):3738–50. <https://doi.org/10.1016/j.energy.2010.05.023>.
- [19] Smook GA. Handbook for pulp & paper technologists. Bing; 2003 [Online]. Available: [https://www.bing.com/search?pglt=297&q=Smook%2C+G.+A.+%20\(2003\).+Handbook+for+Pulp+%26+Paper+Technologists&cvid=8a344e1661b3425a9207cce292e65b1e&gs\\_lcrp=EgRIZGdlKgYIABFBGDKyBggAEEUYOdIBBzl2MmowajGoAgCwAgA&FORM=ANNTA1&PC=HCTS](https://www.bing.com/search?pglt=297&q=Smook%2C+G.+A.+%20(2003).+Handbook+for+Pulp+%26+Paper+Technologists&cvid=8a344e1661b3425a9207cce292e65b1e&gs_lcrp=EgRIZGdlKgYIABFBGDKyBggAEEUYOdIBBzl2MmowajGoAgCwAgA&FORM=ANNTA1&PC=HCTS). [Accessed 25 December 2024].
- [20] Bajpai P. Pulp and paper industry: energy conservation. Elsevier; 2016 [Online]. Available: <https://books.google.it/books?id=V5xZCgAAQBAJ>.

- [21] Fleiter T, Fehrenbach D, Worrell E, Eichhammer W. Energy efficiency in the German pulp and paper industry – a model-based assessment of saving potentials. *Energy Apr.* 2012;40(1):84–99. <https://doi.org/10.1016/j.energy.2012.02.025>.
- [22] Joint Research Centre: Institute for Prospective Technological Studies. Best available techniques (BAT) reference document for the production of pulp, *paper and board*. Publications Office; 2015. <https://doi.org/10.2791/370629>. et al.
- [23] Energetics Incorporated and Columbia, Maryland. Energy and environmental profile of the U.S. pulp and paper industry [Online]. Available: <https://www.energy.gov/eere/amo/articles/itp-forest-products-energy-and-environmental-profile-us-pulp-and-paper-industry>; Dec. 2005.
- [24] EU, “Integrated pollution prevention and control (IPPC) reference document on best available techniques in the pulp and paper industry.” [Online]. Available: [https://eippcb.jrc.ec.europa.eu/sites/default/files/2020-03/superseded\\_ppm\\_bref-1201.pdf](https://eippcb.jrc.ec.europa.eu/sites/default/files/2020-03/superseded_ppm_bref-1201.pdf).
- [25] Corcelli F, Fiorentino G, Vehmas J, Ulgiati S. Energy efficiency and environmental assessment of papermaking from chemical pulp - a Finland case study. *J Clean Prod Oct.* 2018;198:96–111. <https://doi.org/10.1016/j.jclepro.2018.07.018>.
- [26] Furszyfer Del Rio D, et al. Decarbonizing the pulp and paper industry: a critical and systematic review of sociotechnical developments and policy options. *Renew Sustain Energy Rev Oct.* 2022;167:112706. <https://doi.org/10.1016/j.rser.2022.112706>.
- [27] “World Bank Open Data,” world bank open data. <https://data.worldbank.org>. [Accessed 5 August 2024].
- [28] van Ewijk S, Stegemann JA, Ekens P. Limited climate benefits of global recycling of pulp and paper. *Nat Sustain Feb.* 2021;4(2):180–7. <https://doi.org/10.1038/s41893-020-00624-z>.
- [29] Hämäläinen E, Hilmola O-P. Energy efficiency at the paper mill—dilemma of improvement. *Energy Effic Aug.* 2017;10(4):809–21. <https://doi.org/10.1007/s12053-016-9490-3>.
- [30] Final energy consumption in industry - detailed statistics - statistics explained.” Accessed: December. 25, 2024. [Online]. Available: [https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Final\\_energy\\_consumption\\_in\\_industry\\_-\\_detailed\\_statistics#Paper\\_2C\\_pulp\\_and\\_printing\\_industry](https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Final_energy_consumption_in_industry_-_detailed_statistics#Paper_2C_pulp_and_printing_industry).
- [31] Griffin PW, Hammond GP, Norman JB. Industrial energy use and carbon emissions reduction in the chemicals sector: a UK perspective. *Trans Innov Sustain Futur Part III Oct.* 2018;227:587–602. <https://doi.org/10.1016/j.apenergy.2017.08.010>.
- [32] N. R. C. Government of Canada, “Comprehensive energy use database.” Accessed: August. 5, 2024. [Online]. Available: [https://oeenrncan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive\\_tables/list.cfm](https://oeenrncan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive_tables/list.cfm).
- [33] Man Y, Li J, Hong M, Han Y. Energy transition for the low-carbon pulp and paper industry in China. *Renew Sustain Energy Rev Oct.* 2020;131:109998. <https://doi.org/10.1016/j.rser.2020.109998>.
- [34] “Paper production by country 2022,” statista. Accessed: August. 5, 2024. [Online]. Available: <https://www.statista.com/statistics/240598/production-of-paper-and-cardboard-in-selected-countries/>.
- [35] “Global pulp for paper production 1961-2023,” statista. Accessed: June. 25, 2025. [Online]. Available: <https://www.statista.com/statistics/1333405/pulp-for-paper-production-worldwide/>.
- [36] Antonio MRJ, Claudiu P. Energy efficiency and GHG emissions: prospective scenarios for the pulp and paper industry [Online]. Available: <https://api.semanti scholar.org/CorpusID:133872025>; 2018.
- [37] Read “wood in our future: the role of life-cycle analysis: Proceedings of a symposium” at NAP.edu. doi: 10.17226/5734.
- [38] Sagues WJ, Jameel H, Sanchez DL, Park S. Prospects for bioenergy with carbon capture & storage (BECCS) in the United States pulp and paper industry. *Energy Environ Sci Aug.* 2020;13(8):2243–61. <https://doi.org/10.1039/D0EE01107J>.
- [39] P. V. K. Ananth, D. Ghai, and V. Girdhar, “Decarbonization in the INDIAN pulp & paper industry,” Pap. Ind.
- [40] Zhou Z, Wei F. Research on carbon peak and carbon neutrality technological pathways in the Chinese papermaking industry. *Pap Biomater* 2023;8(4):69–79. <https://doi.org/10.26599/PBM.2023.9260027>.
- [41] “CO2 emissions from paper and cardboard Germany,” statista. Accessed: December. 26, 2024. [Online]. Available: <https://www.statista.com/statistics/1385904/co2-emissions-paper-and-cardboard-manufacturing-germany/>.
- [42] Ministry of Economy, Trade and Industry. Technology Roadmap for “Transition Finance” in the Pulp and Paper Sector [Online]. Available: [https://www.meti.go.jp/policy/energy\\_environment/global\\_warming/transition/transition\\_finance\\_technology\\_roadmap\\_paper\\_eng.pdf](https://www.meti.go.jp/policy/energy_environment/global_warming/transition/transition_finance_technology_roadmap_paper_eng.pdf); March 2022.
- [43] KEY STATISTICS 2022 european pulp & paper industry. CEPI; 2022 [Online]. Available: <https://www.cepi.org/wp-content/uploads/2023/07/2022-Key-Statistics-FINAL.pdf>.
- [44] Obrist MD, Kannan R, Schmidt TJ, Kober T. Long-term energy efficiency and decarbonization trajectories for the Swiss pulp and paper industry. *Sustain Energy Technol Assessments Aug.* 2022;52:101937. <https://doi.org/10.1016/j.seta.2021.101937>.
- [45] Giuntini L, et al. Decarbonization of a tissue paper plant: advanced numerical simulations to assess the replacement of fossil fuels with a biomass-derived syngas. *Renew Energy Oct.* 2022;198:884–93. <https://doi.org/10.1016/j.renene.2022.08.076>.
- [46] Owttrim CG, Davis M, Kumar A. Development of technology-explicit energy saving bandwidths: a case study for the pulp and paper sector. *Energy Convers Manag Apr.* 2022;258:115535. <https://doi.org/10.1016/j.enconman.2022.115535>.
- [47] Fracaro G, Vakkilainen E, Hamaguchi M, Melegari de Souza SN. Energy efficiency in the Brazilian pulp and paper industry. *Energies* 2012;5(9):3550–72. <https://doi.org/10.3390/en5093550>.
- [48] Griffin PW, Hammond GP, Norman JB. Industrial decarbonisation of the pulp and paper sector: a UK perspective. *Appl Therm Eng Apr.* 2018;134:152–62. <https://doi.org/10.1016/j.applthermaleng.2018.01.126>.
- [49] Owttrim CG, Davis M, Shafique HU, Kumar A. Energy efficiency as a critical resource to achieve carbon neutrality in the pulp and paper sector. *J Clean Prod Aug.* 2022;360:132084. <https://doi.org/10.1016/j.jclepro.2022.132084>.
- [50] Mobarakeh MR, Silva MFS, Kienberger T. Pulp and paper industry: decarbonisation technology assessment to reach CO2 neutral emissions—an Austrian case study. *Energies* 2021;14(4):1161. <https://doi.org/10.3390/en14041161>.
- [51] Simão L, Hotza D, Raupp-Pereira F, Labrincha JA, Montedo ORK. Wastes from pulp and paper mills - a review of generation and recycling alternatives. *Cerâmica Sep.* 2018;64(371):443–53. <https://doi.org/10.1590/0366-69132018643712414>.
- [52] Optimize sorting & recycling for paper and textile - action library (EN).” Accessed: May 22, 2025. [Online]. Available: <https://www.theclimatedrive.org/action-library/sorting-and-recycling-technologies-for-paper-and-textile>.
- [53] Chang JC, Beach RH, Olivetti EA. Consequential effects of increased use of recycled fiber in the United States pulp and paper industry. *J Clean Prod Dec.* 2019;241:118133. <https://doi.org/10.1016/j.jclepro.2019.118133>.
- [54] Recycled paper | project drawdown.” Accessed: May 23, 2025. [Online]. Available: <https://drawdown.org/solutions/recycled-paper>.
- [55] Staff, “The Cepi two-team project,” paper industry world. Accessed: August. 5, 2024. [Online]. Available: <https://www.paperindustryworld.com/the-cepi-two-team-project/>.
- [56] Lipiäinen S, Kuparinen K, Sermayagina E, Vakkilainen E. Pulp and paper industry in energy transition: towards energy-efficient and low carbon operation in Finland and Sweden. *Sustain Prod Consum Jan.* 2022;29:421–31. <https://doi.org/10.1016/j.spc.2021.10.029>.
- [57] Lindmark M, Bergquist A-K, Andersson LF. Energy transition, carbon dioxide reduction and output growth in the Swedish pulp and paper industry: 1973–2006. *Energy Policy Sep.* 2011;39(9):5449–56. <https://doi.org/10.1016/j.enpol.2011.05.018>.
- [58] Mati A, Ademollo A, Carcasci C. Assessment of paper industry decarbonization potential via hydrogen in a multi-energy system scenario: a case study. *Smart Energy Aug.* 2023;11:100114. <https://doi.org/10.1016/j.segy.2023.100114>.
- [59] Gailani A, Cooper S, Allen S, Pimm A, Taylor P, Gross R. Assessing the potential of decarbonization options for industrial sectors. *Joule Mar.* 2024;8(3):576–603. <https://doi.org/10.1016/j.joule.2024.01.007>.
- [60] Kong L, Hasanbeigi A, Price L. “Assessment of emerging energy-efficiency technologies for the pulp and paper industry: a technical review.” *J Clean Prod May* 2016;122:5–28. <https://doi.org/10.1016/j.jclepro.2015.12.116>.
- [61] Abdelaziz EA, Saidur R, Mekhilef S. A review on energy saving strategies in industrial sector. *Renew Sustain Energy Rev Jan.* 2011;15(1):150–68. <https://doi.org/10.1016/j.rser.2010.09.003>.
- [62] Peng L, Zeng X, Wang Y, Hong G-B. Analysis of energy efficiency and carbon dioxide reduction in the Chinese pulp and paper industry. *Energy Policy May* 2015;80:65–75. <https://doi.org/10.1016/j.enpol.2015.01.028>.
- [63] Man Y, Hu S, Gao J, Li J, Hong M. Integrated chemical looping combustion in pulp mill for high energy efficiency and low carbon emission. *J Clean Prod Dec.* 2020;275:122979. <https://doi.org/10.1016/j.jclepro.2020.122979>.
- [64] Rademaker K, Marsidi M. Decarbonisation options for the Dutch paper and board industry. Delft, Netherlands: CE Delft; 2021 [Online]. Available: [https://www.pbl.nl/uploads/default/downloads/pbl-2019-decarbonisation-options-for-the-dutch-paper-and-board-industry\\_3480.pdf](https://www.pbl.nl/uploads/default/downloads/pbl-2019-decarbonisation-options-for-the-dutch-paper-and-board-industry_3480.pdf).
- [65] Yang F, Meerman JC, Faaij APC. Carbon capture and biomass in industry: a techno-economic analysis and comparison of negative emission options. *Renew Sustain Energy Rev Jul.* 2021;144:111028. <https://doi.org/10.1016/j.rser.2021.111028>.
- [66] Rootzén J, Kjärstad J, Johnsson F, Karlsson H. Deployment of BECCS in basic industry: A Swedish case study. *Mistra Carbon Exit.* 2018 [Online]. Available: [https://www.researchgate.net/publication/329143960\\_Deployment\\_of\\_BECCS\\_in\\_basic\\_industry-a\\_Swedish\\_case\\_study#fullTextFileContent](https://www.researchgate.net/publication/329143960_Deployment_of_BECCS_in_basic_industry-a_Swedish_case_study#fullTextFileContent).
- [67] Kuparinen K, Vakkilainen E, Tynjälä T. Biomass-based carbon capture and utilization in kraft pulp mills. *Mitig Adapt Strategies Glob Change Oct.* 2019;24(7):1213–30. <https://doi.org/10.1007/s11027-018-9833-9>.
- [68] Svensson E, Wiertzema H, Harvey S. Potential for negative emissions by carbon capture and storage from a novel electric plasma calcination process for pulp and paper mills. *Front Clim Oct.* 2021;3:705032. <https://doi.org/10.3389/fclim.2021.705032>.
- [69] Energy efficiency challenges in pulp and paper manufacturing: a tutorial review :: bioresources.” Accessed: May 26, 2025. [Online]. Available: <https://bioresources.cnr.ncsu.edu/>.
- [70] Stenqvist C. Trends in energy performance of the Swedish pulp and paper industry: 1984–2011. *Energy Effic Feb.* 2014;8:1–17. <https://doi.org/10.1007/s12053-014-9276-4>.
- [71] Kermeli K, Crijns-Graus W, Johannsen RM, Mathiesen BV. Energy efficiency potentials in the EU industry: impacts of deep decarbonization technologies. *Energy Effic Dec.* 2022;15(8):68. <https://doi.org/10.1007/s12053-022-10071-8>.
- [72] Shabbir I, Mirzaeian M, Sher F. Energy efficiency improvement potentials through energy benchmarking in pulp and paper industry. *Clean Chem Eng Sep.* 2022;3:100058. <https://doi.org/10.1016/j.clce.2022.100058>.

- [73] IEA CO2 emissions from fuel combustion statistics: greenhouse gas emissions from energy." Accessed: August 5, 2024. [Online]. Available: [https://www.iea.org/data/iea-co2-emissions-from-fuel-combustion-statistics\\_co2-data-en](https://www.iea.org/data/iea-co2-emissions-from-fuel-combustion-statistics_co2-data-en).
- [74] CII national conference on pulp and paper." Accessed: August 5, 2024. [Online]. Available: <https://www.cii-twi.in/National-Conference-on-Pulp-and-Paper.html>.
- [75] Energy efficiency | EU-BRITE." Accessed: August 5, 2024. [Online]. Available: <https://eippcb.jrc.ec.europa.eu/reference/energy-efficiency>.
- [76] Jaffe AB, Stavins RN. The energy-efficiency gap what does it mean? *Mark Energy Effic Oct*. 1994;22(10):804–10. [https://doi.org/10.1016/0301-4215\(94\)90138-4](https://doi.org/10.1016/0301-4215(94)90138-4).
- [77] U.S. Department of Energy. Barriers to Industrial Energy Efficiency (Report to Congress). Washington, DC: U.S. Department of Energy; 2015. Available: [http://www.energy.gov/sites/prod/files/2015/06/f23/EXEC-2014-005846\\_6%20Report\\_signed\\_0.pdf](http://www.energy.gov/sites/prod/files/2015/06/f23/EXEC-2014-005846_6%20Report_signed_0.pdf).
- [78] Lawrence A, Nehler T, Andersson E, Karlsson M, Thollander P. Drivers, barriers and success factors for energy management in the Swedish pulp and paper industry. *J Clean Prod Jun*. 2019;223:67–82. <https://doi.org/10.1016/j.jclepro.2019.03.143>.
- [79] Cagno E, Trianni A. Evaluating the barriers to specific industrial energy efficiency measures: an exploratory study in small and medium-sized enterprises. *J Clean Prod Nov*. 2014;82:70–83. <https://doi.org/10.1016/j.jclepro.2014.06.057>.
- [80] Bremer L, Den Nijs SJ, De Groot HLF. "The energy efficiency gap and barriers to investments,". 2023. <https://doi.org/10.2139/ssrn.4513887>.
- [81] Caffall C. Learning from experiences with energy management in industry [Online]. Available: <https://api.semanticscholar.org/CorpusID:166664094>; 1995.
- [82] Lawrence A, Thollander P, Karlsson M. Drivers, barriers, and success factors for improving energy management in the pulp and paper industry. *Sustainability* 2018;10(6). <https://doi.org/10.3390/su10061851>.
- [83] "Does ISO 50001 still live up to its promise?" ISO. Accessed: August 5, 2024. [Online]. Available: <https://www.iso.org/cms/render/live/en/sites/isoorg/contents/news/2016/11/Ref2135.html>.
- [84] Energy efficiency's role in industrial decarbonization | cutter consortium." Accessed: May 27, 2025. [Online]. Available: <https://www.cutter.com/article/energy-efficiency%E2%80%99s-role-industrial-decarbonization>.
- [85] Naqvi M, Yan J, Dahlquist E. Black liquor gasification integrated in pulp and paper mills: a critical review. *Bioresour Technol Nov*. 2010;101(21):8001–15. <https://doi.org/10.1016/j.biortech.2010.05.013>.
- [86] Carrasco JL, Gunukula S, Boateng AA, Mullen CA, DeSisto WJ, Wheeler MC. Pyrolysis of forest residues: an approach to techno-economics for bio-fuel production. *Fuel Apr*. 2017;193:477–84. <https://doi.org/10.1016/j.fuel.2016.12.063>.
- [87] Churchill JGB, Borugadda VB, Dalai AK. A review on the production and application of tall oil with a focus on sustainable fuels. *Renew Sustain Energy Rev Mar*. 2024;191:114098. <https://doi.org/10.1016/j.rser.2023.114098>.
- [88] Marshman DJ, Chmelyk T, Sidhu MS, Gopaluni RB, Dumont GA. Energy optimization in a pulp and paper mill cogeneration facility. *Appl Energy Nov*. 2010;87(11):3514–25. <https://doi.org/10.1016/j.apenergy.2010.04.023>.
- [89] Espinoza O, Laguarda-Mallo M, Weitzenkamp M. Overcoming barriers to biomass cogeneration in US wood products industry. *Wood Fiber Sci J Soc Wood Sci Technol Jul*. 2015;47:295–312.
- [90] Shang D, Lu H, Liu C, Wang D, Diao G. Evaluating the green development level of global paper industry from 2000-2030 based on a market-extended LCA model. *J Clean Prod Dec*. 2022;380:135108. <https://doi.org/10.1016/j.jclepro.2022.135108>.
- [91] O. US EPA, "Greenhouse gas reporting program (GHGRP)." Accessed: August 5, 2024. [Online]. Available: <https://www.epa.gov/ghgreporting>.
- [92] "Clean Hydrogen and Combined Heat and Power: a Roadmap for Industrial and Commercial Decarbonization | Combined Heat and Power Alliance." Accessed: August 5, 2024. [Online]. Available: <https://chpalliance.org/resources/publications/clean-hydrogen-and-combined-heat-and-power-a-roadmap-for-industrial-and-commercial-decarbonization/>.
- [93] "MIDDEN: manufacturing Industry Decarbonisation Data Exchange Network | PBL Netherlands Environmental Assessment Agency." Accessed: August 5, 2024. [Online]. Available: <https://www.pbl.nl/en/middenweb>.
- [94] Vialeto G, Noro M, Colbertaino P, Rokni M. Enhancement of energy generation efficiency in industrial facilities by SOFC – SOEC systems with additional hydrogen production. *Spec Issue Power Gas Hydrog Appl Energy Syst Differ Scales Build Dist Natl Level Apr*. 2019;44(19):9608–20. <https://doi.org/10.1016/j.j.ijhydene.2018.08.145>.
- [95] Global energy transformation: a roadmap to 2050 (2019 Edition)".
- [96] Pio DT, Tarelho LAC, Pinto PCR. Gasification-based biorefinery integration in the pulp and paper industry: a critical review. *Renew Sustain Energy Rev Nov*. 2020; 133:110210. <https://doi.org/10.1016/j.rser.2020.110210>.
- [97] Saidur R, Abdelaziz EA, Demirbas A, Hossain MS, Mekhilef S. A review on biomass as a fuel for boilers. *Renew Sustain Energy Rev Jun*. 2011;15(5): 2262–89. <https://doi.org/10.1016/j.rser.2011.02.015>.
- [98] Parra D, Valverde L, Pino FJ, Patel MK. A review on the role, cost and value of hydrogen energy systems for deep decarbonisation. *Renew Sustain Energy Rev Mar*. 2019;101:279–94. <https://doi.org/10.1016/j.rser.2018.11.010>.
- [99] Serman JD, Siegel L, Rooney-Varga JN. Does replacing coal with wood lower CO2 emissions? Dynamic lifecycle analysis of wood bioenergy. *Environ Res Lett Jan*. 2018;13(1):015007. <https://doi.org/10.1088/1748-9326/aaa512>.
- [100] "The evidence is clear: the time for action is now. We can halve emissions by 2030. — IPCC." Accessed: August 5, 2024.[Online]. Available:<https://www.ipcc.ch/2022/04/04/ipcc-ar6-wgiii-pressrelease/>.
- [101] "Pulp & paper," IEA. Accessed: August 5, 2024. [Online]. Available:<https://www.iea.org/energy-system/industry/paper>.
- [102] Cigolotti V, Genovese M, Fragiaco P. Comprehensive review on fuel cell technology for stationary applications as sustainable and efficient poly-generation energy systems. *Energies* 2021;14(16):4963. <https://doi.org/10.3390/en14164963>.
- [103] Gerres T, Chaves Ávila JP, Llamas PL, San Román TG. A review of cross-sector decarbonisation potentials in the European energy intensive industry. *J Clean Prod Feb*. 2019;210:585–601. <https://doi.org/10.1016/j.jclepro.2018.11.036>.
- [104] Hydrogen Council and McKinsey & Company. Hydrogen Insights December 2023. Dec. 2023 [Online]. Available: <https://hydrogencouncil.com/wp-content/uploads/2023/12/Hydrogen-Insights-Dec-2023-Update.pdf>.
- [105] Energy efficiency. IEA; 2022 [Online]. Available: <https://iea.blob.core.windows.net/assets/7741739e-8e7f-4afa-a77f-49dadd51cb52/EnergyEfficiency2022.pdf>.
- [106] Roelofs O, Somers K, Speelman E, Witteveen M. Plugging in: What Electrification Can do for Industry. McKinsey & Company; 2020 [Online]. Available: <https://www.mckinsey.com/business-functions/sustainability/our-insights/plugging-in-what-electrification-can-do-for-industry>.
- [107] Bajpai P, I - Introduction "Some excerpts taken from Bajpai Pratima. 'Advances in Recycling and Deinking', 2006 with kind permission from Pira International, UK.,". In: Bajpai P, editor. Recycling and deinking of recovered paper. Oxford: Elsevier; 2014. p. 1–19. <https://doi.org/10.1016/B978-0-12-416998-2.00001-5>.
- [108] "Virgin vs Recycled Paper," paper.net. Accessed: May 23, 2025. [Online]. Available:<https://www.paper.net/americas/en/virgin-vs-recycled-paper>.
- [109] Carbon dioxide capture and storage — IPCC." Accessed: August 5, 2024. [Online]. Available: <https://www.ipcc.ch/report/carbon-dioxide-capture-and-storage/>.
- [110] Charles M, Narayan KB, Edmonds J, Yu S. The role of the pulp and paper industry in achieving net zero U.S. CO2 emissions in 2050. *Energy Clim Change Dec*. 2024; 5:100160. <https://doi.org/10.1016/j.egycc.2024.100160>.
- [111] Figueroa JD, Fout T, Plasynski S, McIlvried H, Srivastava RD. Advances in CO2 capture technology—The U.S. department of energy's carbon sequestration program. *Int J Greenh Gas Control Jan*. 2008;2(1):9–20. [https://doi.org/10.1016/S1750-5836\(07\)00094-1](https://doi.org/10.1016/S1750-5836(07)00094-1).
- [112] "CCUS in Clean Energy Transitions – analysis," IEA. Accessed: August 5, 2024. [Online]. Available: <https://www.iea.org/reports/ccus-in-clean-energy-transition-s>.
- [113] Huang X, Chang S, Zheng D, Zhang X. The role of BECCS in deep decarbonization of China's economy: a computable general equilibrium analysis. *Energy Econ Oct*. 2020;92:104968. <https://doi.org/10.1016/j.eneco.2020.104968>.
- [114] Mac Dowell N, Fennell PS, Shah N, Maitland GC. The role of CO2 capture and utilization in mitigating climate change. *Nat Clim Change Apr*. 2017;7(4):243–9. <https://doi.org/10.1038/nclimate3231>.
- [115] Karlsson S, Normann F, Johnsson F. Cost-optimal CO2 capture and transport infrastructure—A case study of Sweden. *Int J Greenh Gas Control Feb*. 2024;132: 104055. <https://doi.org/10.1016/j.ijggc.2023.104055>.
- [116] Koytsouma EL, Bergins C, Kakaras E. The CO2 economy: review of CO2 capture and reuse technologies. *SI EMSF 2016 Feb*. 2018;132:3–16. <https://doi.org/10.1016/j.supflu.2017.07.029>.
- [117] Wall TF. Combustion processes for carbon capture. *Proc Combust Inst Jan*. 2007; 31(1):31–47. <https://doi.org/10.1016/j.proci.2006.08.123>.
- [118] Lockwood T. A comparative review of next-generation carbon capture technologies for coal-fired power plant. 13th Int Conf Greenh Gas Control Technol GHGT-13 14-18 Novemb 2016 Lausanne Switz Jul. 2017;114:2658–70. <https://doi.org/10.1016/j.egypro.2017.03.1850>.
- [119] Gaurina-Medimurec N, Novak Mavar K, Majič M. CCS technology: overview of projects, technology and monitoring. *Rud Geol Naft Zb Feb*. 2018;33:1–14. <https://doi.org/10.17794/rgn.2018.2.1>.
- [120] New wis. Power plant burns wood, sawdust." Accessed: May 26, 2025.[Online]. Available:<https://dailyreporter.com/2013/11/12/new-wis-power-plant-burns-wood-sawdust/>.
- [121] Reducing energy use and optimizing performance through UV LED printing - paper, film & foil converter." Accessed: May 28, 2025.[Online]. Available:<https://www.pffc-online.com/whitepaper/18255-reducing-energy-use-and-optimizin-g-performance-through-uv-led-printing>.
- [122] Skoglund H, Fu C, Harvey S, Svensson E. Integration of carbon capture in a pulp Mill—effect of strategic development towards better biomass resource utilization. *Front Therm Eng Nov*. 2023;3:1282028. <https://doi.org/10.3389/ftther.2023.1282028>.
- [123] U.S. Department of Energy. Pathways Analysis Summary: Decarbonization Potential for Industrial Subsectors – Preliminary Modeling Results. 2021 [Online]. Available: <https://www.energy.gov/sites/default/files/2024-05/pathway-analysis-summary-draft.pdf>.
- [124] World Business Council for Sustainable Development (WBCSD). Forest Sector Net-Zero Roadmap Phase II: Catalogue of Key Decarbonization Actions. Apr. 2024 [Online]. Available: [https://www.wbcd.org/wp-content/uploads/2024/04/WBCSD\\_Catalogue-of-key-decarbonization-actions.pdf](https://www.wbcd.org/wp-content/uploads/2024/04/WBCSD_Catalogue-of-key-decarbonization-actions.pdf).
- [125] Material Economics, A Net-Zero Transition for EU Industry – What Does It Mean for the Pulp & Paper Industry? pp. 3–4, Jun. 2024. [Online]. Available: <https://materialeconomics.com/sites/default/files/2024-06/200604%20Material%20Economics%20-%20Pulp%20and%20Paper%20in%20a%20net%20zero%20transition.pdf>.

- [126] European Commission. Directorate General for Energy. European commission. Directorate general for climate action., and european commission. Directorate general for mobility and transport., *EU reference scenario 2020: energy, transport and GHG emissions : trends to 2050*. LU: Publications Office; 2021 [Online]. Available: <https://data.europa.eu/doi/10.2833/35750>. [Accessed 24 June 2025].
- [127] "India - countries & Regions," IEA. Accessed: June. 24, 2025. [Online]. Available: <https://www.iea.org/countries/india>.
- [128] Deng H, Zhang D, Yu H, Man Y, Wang Y. Assessing life-cycle GHG emissions of recycled paper products under imported solid waste ban in China: a case study. *Sci Total Environ Sep. 2023*;891:164407. <https://doi.org/10.1016/j.scitotenv.2023.164407>.
- [129] Tomberlin KE, Venditti R, Yao Y. Life cycle carbon footprint analysis of pulp and paper grades in the United States using production-line-based data and integration. *Bioresources Apr. 2020*;15(2):3899–914. <https://doi.org/10.15376/biores.15.2.3899-3914>.
- [130] Scott D. The price of green hydrogen: How and why we estimate future production costs. International Council on Clean Transportation (ICCT). May 2024 [Online]. Available: <https://theicct.org/the-price-of-green-hydrogen-es-timate-future-production-costs-may24/>.
- [131] Clean Energy Hydrogen Production Consortium. Review of Projections Through 2040 of U.S. Clean Hydrogen Production, Infrastructure, and Costs. 2023 [Online]. Available: [https://www.sustainability.com/globalassets/caelp\\_revie-w-h2-projections-through-2040\\_08-08-23.pdf](https://www.sustainability.com/globalassets/caelp_revie-w-h2-projections-through-2040_08-08-23.pdf).
- [132] Author NG. "Energy efficiency as a low-cost resource for achieving carbon emissions reductions,". Sep. 2009, 1219670. <https://doi.org/10.2172/1219670>.
- [133] Igin M. EU carbon price tops symbolic €100/tonne for the first time. *Earth. Org. 2025* [Online]. Available: <https://earth.org/eu-carbon-price/>.
- [134] Frieden F, Leker J. Future costs of hydrogen: a quantitative review. *Sustain Energy Fuels 2024*;8(9):1806–22. <https://doi.org/10.1039/D4SE00137K>.
- [135] Kumar A, et al. A review of multi criteria decision making (MCDM) towards sustainable renewable energy development. *Renew Sustain Energy Rev Mar. 2017*;69:596–609. <https://doi.org/10.1016/j.rser.2016.11.191>.
- [136] Hwang Ching-Lai, Yoon Kwangsun. Multiple attribute decision making methods and applications A state-of-the-art survey [Online]. Available: <https://link.springer.com/book/10.1007/978-3-642-48318-9>; 1981.
- [137] Wang J-J, Jing Y-Y, Zhang C-F, Zhao J-H. Review on multi-criteria decision analysis aid in sustainable energy decision-making. *Renew Sustain Energy Rev Dec. 2009*;13(9):2263–78. <https://doi.org/10.1016/j.rser.2009.06.021>.
- [138] Saaty TL. How to make a decision: the analytic hierarchy process. *Decision Mak Anal Hier Proc Theory Appl Sep. 1990*;48(1):9–26. [https://doi.org/10.1016/0377-2217\(90\)90057-1](https://doi.org/10.1016/0377-2217(90)90057-1).
- [139] AR5 climate change 2014: mitigation of climate change — IPCC." Accessed: August. 4, 2024. [Online]. Available:<https://www.ipcc.ch/report/ar5/wg3/>.
- [140] Trl | EURAXESS." Accessed: August. 4, 2024. [Online]. Available:<https://euraxess.ec.europa.eu/career-development/researchers/manual-scientific-entrepreneurs-hip/major-steps/trl>.
- [141] "World Energy Outlook 2020 – analysis," IEA. Accessed: August. 5, 2024. [Online]. Available: <https://www.iea.org/reports/world-energy-outlook-2020>.
- [142] Carbon capture vs renewable energy." Accessed: January. 20, 2025. [Online]. Available: <https://energytracker.asia/carbon-capture-vs-renewable-energy/>.
- [143] Renewable power generation costs in 2021." Accessed: August. 7, 2024. [Online]. Available: <https://www.irena.org/publications/2022/Jul/Renewable-Power-Generation-Costs-in-2021>.
- [144] IMARC Group. Paper Recycling Processing Plant Project Report 2025: Industry Trends, Plant Setup, Machinery, Raw Materials, Investment Opportunities, Cost and Revenue. 2025 [Online]. Available: <https://www.imarcgroup.com/paper-recycling-processing-plant-project-report>.
- [145] Parkhi A, Cremaschi S, Jiang Z. Techno-economic analysis of CO2 capture from pulp and paper mill limekiln. *IFAC-PapersOnLine 2022*;55(7):284–91. <https://doi.org/10.1016/j.ifacol.2022.07.458>.
- [146] Buitrago-Tello R, Venditti RA, Jameel H, Hart PW, Ghosh A, Belalcázar-Cerón LC. Energy efficient alternatives to decarbonize the pulp and paper industry – the case of linerboard production. *Biofuel Bioprod Biorefining May 2025*;n/a(n/a). <https://doi.org/10.1002/bbb.2790>.
- [147] "Is carbon capture too expensive? – analysis," IEA. Accessed: January. 20, 2025. [Online]. Available: <https://www.iea.org/commentaries/is-carbon-capture-too-expensive>.
- [148] "Investing in Europe for Industry Transformation – 2050 Roadmap to a low-carbon bioeconomy | www.cepi.org." Accessed: August. 5, 2024. [Online]. Available: <https://www.cepi.org/investing-in-europe-for-industry-transformati-on-2050-roadmap-to-a-low-carbon-bioeconomy/>.
- [149] Bhandar G, Jozewicz W. Analysis of emission reduction strategies for power boilers in the US pulp and paper industry. *Energy Emiss Control Technol Aug. 2017*;5:27–37. <https://doi.org/10.2147/EECT.S139648>.
- [150] "Global Status of CCS," global CCS institute. [Online]. Available: <https://www.globalccsinstitute.com/wp-content/uploads/2023/01/Global-Status-of-CCS-2021-Global-CCS-Institute-1121-1-1.pdf>.
- [151] susan kinsella, "Paperwork: why recycled content is crucial for printing and writing paper," environmental paper network. [Online]. Available: <https://environmentalpaper.org/wp-content/uploads/2017/08/Paperwork.pdf>.
- [152] International Renewable Energy Agency (IRENA). World Energy Transitions Outlook 2024: Summary for Policy Makers. Nov. 2024 [Online]. Available: [https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Nov/IRENA\\_World\\_energy\\_transitions\\_outlook\\_2024\\_Summary.pdf](https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Nov/IRENA_World_energy_transitions_outlook_2024_Summary.pdf).
- [153] Çiçekler M, Tutuş A. Overcoming barriers to paper recycling: a review of challenges and solutions. *Int Conf Sci Innov Stud May 2023*;1(1):60–7. <https://doi.org/10.59287/icsis.575>.
- [154] Dataintel, "Paper recycling market report | global forecast from 2025 to 2033." Accessed: May 24, 2025. [Online]. Available: <https://dataintel.com/report/paper-recycling-market>.
- [155] "Decarbonization of industrial sectors: the next frontier | Oil & Gas | McKinsey." Accessed: August. 5, 2024. [Online]. Available: <https://www.mckinsey.com/industries/oil-and-gas/our-insights/decarbonization-of-industrial-sectors-the-next-frontier>.
- [156] Mäki E, Saastamoinen H, Melin K, Matschegg D, Pihkola H. Drivers and barriers in retrofitting pulp and paper industry with bioenergy for more efficient production of liquid, solid and gaseous biofuels: a review. *Biomass Bioenergy May 2021*;148:106036. <https://doi.org/10.1016/j.biombioe.2021.106036>.
- [157] Horizon 2020 - european commission." Accessed: August. 5, 2024. [Online]. Available: [https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-2020\\_en](https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-2020_en).
- [158] C. European, "EU Commission Net Zero Industry Act." March. 16, 2023. [Online]. Available: [https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/green-deal-industrial-plan/net-zero-industry-act\\_en](https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/green-deal-industrial-plan/net-zero-industry-act_en).