NEW HORIZONS FOR PRODUCTIVE TRANSFORMATION IN THE ANDEAN REGION

NET-ZERO INDUSTRY:
options for Plastics, Textiles, Automobiles, and Fisheries in Colombia, Ecuador, and Peru

Francis Li
Chris Bataille
Adrien Vogt-Schilb

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EXECUTIVE SUMMARY

CHALLENGES AND OPPORTUNITIES FOR THE ANDEAN REGION

As the world begins to move toward creating a low-carbon economy, the Andean region is poised on the cusp of changes that are likely to transform economic, social, and ecological development trajectories over the coming decades. The region faces many challenges as it confronts these profound shifts. In the near term, the Andean region faces inflation, supply-chain disruption, economic fallout from the COVID-19 pandemic, and energy- and food-security complications arising from the Russian invasion of Ukraine. In the medium term, the region also faces the risks from potentially destabilizing climate impacts. Forecasts show that water supplies are likely to fall and to become more variable, and that heat waves and flooding are likely to become more commonplace. Such changes threaten agricultural production, hydropower reliability, and disrupt society and the economy. Thus, Andean countries will need to act in the short term to reorient industrial policies and create pathways that foster sustainable economic development; improve the quality of life; and address deep, structural, and prevailing inequalities (Stern & Valero, 2021).

This period of profound change offers Andean countries opportunities to improve their economies and societies. Indeed, Andean countries are well positioned for a potential economic resurgence. The region benefits from favorable demographics, abundant renewable energy and material resources, and geographic proximity to powerful economies in North America. Andean countries have well-established trade routes to North America, Europe and East Asia.

Government, industry, and civil society must work together as never before to make the transformative economic and societal changes needed to achieve the Paris Agreement's aims and to limit global warming 1.5—2°C above pre-industrial levels. This report examines these intertwined issues by focusing on three countries in the Andean region – Colombia, Ecuador, and Peru – and on four industrial sectors within them – plastics, textiles, automotive manufacturing, and fisheries. The three countries were selected based on the availability of key data – assembled from the Andean country department of the Inter-American Development Bank – needed to underpin the analysis; the four sectors were selected based on the Bank's diagnostic assessment of industry sectors that are likely to be important to the region in the near future.

The report explores pathways that can achieve carbon-neutral industrial production in the region. It examines the technical and operational challenges and opportunities for each sector, the energy and environmental policy landscape for each country, and the ways in which these issues interact with one another, against a wider backdrop of global, technological innovation and the context of international governance and finance.

This report deliberately focuses on one goal: achieving carbon neutrality. It does not delve into any intermediate emission-reduction pathways (e.g., proposals to reduce emissions by 50% or 80%) that may be ambitious but ultimately fall short of the overarching goal of net-zero emissions. In this respect the report takes at face value the aspirations of the Paris Agreement – to which all three countries in this report are signatories – and its goal to contain global temperature rise to 1.5—2°C above pre-industrial levels.

To achieve this goal and to avoid potentially altering the global climate system in irreversible ways, greenhouse gas emissions must plummet, reaching net zero by mid-century. The term *net zero* means that all sources of emissions are drastically reduced, and that any remaining emissions must be balanced, with the equivalent amount absorbed from the atmosphere. To reach the net-zero goal will require a transformation of how the world produces and consumes goods, and of how people and goods travel.

The Case for Net-zero Manufacturing

Achieving the aspirations of the Paris Agreement (UNFCCC, 2015) to limit global temperature rise between 1.5°C and 2°C above pre-industrial levels has far-reaching implications for global manufacturing, commerce, and economic development. To achieve net-zero goals – by 2050 for carbon dioxide (CO2) and by 2070 for all types of greenhouse gases (GHGs) – requires significantly altering the picture for global trade and the production and transportation of goods.

All potential pathways to achieve the Paris Agreement require industrial emissions to fall precipitously to a level that is very close to zero, or they require adding verifiable offsets that are permanent and will almost certainly continue to be more expensive than most mitigation measures (Bataille et al., 2018; Rissman et al., 2020).

A strategy to decide how to pivot toward net-zero manufacturing – and how quickly to do so – is urgent for the following reasons:

I. **The time lag for manufacturing investments required means that changes must begin this decade.** The long economic lifetimes of most equipment in manufacturing plants mean that to achieve 2050 and 2070 goals requires all new facilities have very low emissions starting this decade (from 2023 to 2033). Manufacturers in a wide range of sectors – particularly those dependent on energy-intensive inputs such as steel, aluminum, chemicals, and concrete – may need to invest in low-carbon manufacturing equipment and processes at the first available opportunity, when replacing or upgrading existing capacity (Bataille, Nilsson, et al., 2021). Otherwise countries risk missing the window for achieving climate targets on time simply from inertia (Vogt-Schilb & Hallegatte, 2014). This is a critical factor for national industrial strategies of countries that seek to further their own economic development through value-added manufacturing.

II. **An emphasis on low-carbon, international trade is accelerating.** In major economies such as the United States (US), the European Union (EU), and China, decarbonization of economic activity has momentum that is likely to lead to new, more stringent emissions requirements for certification and product standards for international trade. The EU has clear aspirations to use its global position and market power to make trade in low-carbon goods the "new normal" rather than the exception. Indeed, the EU has imposed new trade tariffs on carbon-intensive goods that will come into full force in 2026 (European Commission, 2021b). Such "climate diplomacy" through trade also appears to have momentum. The US and the EU have already formed a partnership to cooperate on creating a market for green steel and green aluminum (European Commission, 2021a; Executive Office of the President of the United States, 2021). The US is initiating other forms of green-procurement policies. India, the UK, Canada, the United Arab Emirates, and Germany have agreed to work together on common green-procurement standards (Clean Energy Ministerial, 2021). China has also committed to green transformations of major industries and the creation of aligned product standards, certification and labeling systems (National People's Congress, 2021). There is a real prospect of other major players in the G7 and G20 economies joining together to lay the foundations for a new low-carbon trade zone or for multiple, overlapping markets for low-carbon goods before 2030. Being excluded from a "climate club" (Nordhaus, 2015) of low-carbon economies may put industrial players in a difficult position, leaving them to make large, unplanned and time-consuming capital investments to pivot to low-carbon manufacturing late in the game (Ivleva et al., 2022).

III. **Net-zero shifts will likely create winners and losers.** The changing nature of production inputs in a net-zero future has the potential to create new winners and losers (Drake, 2018). Countries with abundant renewable-energy resources may find themselves in advantageous positions relative to states in which manufacturing or fiscal revenues depend on fossil fuels. This creates the potential for relocation and reconfiguration of established industries (Gielen et al., 2020; Samadi et al., 2021), and the prospect for countries with renewable-energy resources to capture much more of the global value chain than is now the case.

IV. **Early movers are likely to benefit; latecomers risk being left behind.** Proactive assessments of strengths, weaknesses, opportunities and challenges vis-à-vis the shift to carbon-neutral economic activity in critical economic sectors offer the best chance of securing favorable outcomes. Early engagement gives industrial players and policymakers the best chance to successfully anticipate and respond to changing pressures in the wider economic landscape, avoid stranding assets, and maneuver to capture value across supply chains (Hallegatte et al., 2013).

The Essentials for Industry Decarbonization

Decarbonization pathways for the plastics, textiles, automotive-manufacturing and fisheries sectors share many cross-cutting strategic elements. These are important not only for achieving net-zero aims in these specific industries but for the wide range of other industries that are linked to them (Bataille et al., 2018; Bataille, Nilsson, et al., 2021; Lechtenböhmer et al., 2016; Rissman et al., 2020). A straightforward industrial decarbonization roadmap includes the following elements:

I. Making industrial processes and the use of materials as energy efficient as possible.

II. Switching processes to use electricity instead of coal, oil, natural gas, or other fossil sources of energy wherever possible.

III. Shifting to use low-carbon fuels (e.g., green hydrogen, green ammonia, green methanol) for combustion when using electricity is not possible.

IV. Adopting processes that capture emissions during manufacturing for use as production inputs or for permanent geological disposal.

V. Achieving zero waste through reuse, recycling, and structural changes to eliminate materials or products that cannot be recycled (Costello, (2019).

VI. Removing carbon dioxide from the air for permanent and verifiable storage where emissions cannot otherwise be eliminated using the above options; this must be a last resort.

Government leadership and coordination, and private-sector partnerships are essential to transform industry. Any plant or industry operating in isolation and under market pressures cannot undertake the changes needed to make net-zero manufacturing a reality. This is in part because the control of critical infrastructure such as electricity and fuel grids encompasses more than any individual business or economic sector. Only governments can set the right direction, mobilize capital and financing at sufficient scales and speed, and leverage breakthrough technologies to achieve the large-scale changes required. With massive, transformative changes needed within the next few decades, coordinated action between industry and government and within government departments and levels is essential (Fazekas et al., 2022). Only such partnerships are likely to have the capacity to create conditions that enable full decarbonization of the electricity grid, and to make low-carbon, synthetic fuels viable and available at scale.

The following analysis of four industries – plastics, textiles, auto manufacturing, and fisheries – provides insight into both the particular issues for these sectors and the enormity of the coordination and scale required to bring about change.

Plastics

Plastics production is an important source of GHG emissions. It is a particularly difficult industry to address because changes must take place across the sector's entire value chain and life cycle – beginning with the fossil fuel-based inputs, continuing with the energy used to refine the chemicals and produce plastic products, and culminating with end-of-life disposal of products.

More than 99% of global plastics are made from fossil fuels. Only 8% to 15% are recycled (Geyer et al., 2017; Mulvaney et al., 2021). Globally, most plastic waste that is collected is either burned (producing more CO2) or ends up in landfills, where it can contaminate water and food ecosystems (Ahamed et al., 2021; Lau et al., 2020). Therefore, switching the entire manufacturing part of the plastics supply chain to use clean energy – in itself an enormous undertaking – is simply not enough on its own to achieve net-zero goals for the plastics sector.

Technologies for fully recycling plastics without emissions are only at a nascent development stage; an easy, cheap way to manufacture plastics at scale without using fossil fuels as the raw material inputs has not yet been devised. Achieving carbon neutrality for plastics thus will be a long-haul endeavor. Coordinated action among governments, producers, and consumers is required to:

I. eliminate the use of cheap, disposable plastic products.

II. explore the substitution of plastics with alternative materials

III. rationalize plastics production to use only recyclable polymers

IV. enhance efforts to recycle the plastics that are still maintained in circulation.

Such measures are likely to disrupt the established business models of existing producers; thus, a combination of regulatory pressures, economic incentives, and technological advances will be needed to bring about transformational changes to their operations.

Textiles

The production of textiles is also an important source of emissions. Because roughly two-thirds of all textiles are created from plastics (Palacios-Mateo et al., 2021), the issues that affect the plastics sector also concern the textiles sector.

Cotton, the second most commonly used textile fiber after synthetics (Juanga-Labayen et al., 2022; Tobler-Rohr, 2011), presents its own net-zero challenge. Agricultural production of cotton at scale requires using nitrogen fertilizer to some extent (Ouikhalfan et al., 2022; Walling & Vaneeckhaute, 2020). Because crops do not absorb all the fertilizer applied, such fertilizer use leads to emissions of nitrous oxide, a powerful greenhouse gas (Gregorich et al., 2015). To address this, the residual emissions must be balanced with carbon sinks, either through nature-based solutions such as planting trees or expanding wetlands (Harwatt et al., 2020; Reay, 2020), or by using techniques to directly remove emissions from the atmosphere (Hanna et al., 2021).

Structural changes to enable a more circular economy will be required for net-zero textiles manufacturing. The manufacturing of products that for whatever reason cannot be recycled will need to be phased out over time. Coordinated action between retailers, manufacturers, and regulators is needed, and consumer behaviors will have to change. Such changes will be needed to eliminate the proliferation of "disposable" clothing, and to instead focus on higher-quality garments with longer lifetimes and greater durability.

Automotive Manufacturing

The technologies to decarbonize most of the automotive-manufacturing value chain already exist, but the market and regulatory incentives do not. To achieve carbon neutrality, the industry must both conduct net-zero manufacturing operations and produce net-zero vehicles. At the time of writing (early 2023), all major auto manufacturers either have brought or are about to bring electric drivetrain vehicles to market, but most are also still making and selling fossil fuel-powered vehicles.

A rapid transition to exclusively focus on the production of electric vehicles only in a few decades will almost certainly require regulatory interventions (IEA, 2021d; Rietmann & Lieven, 2019). Moreover, decarbonizing the assembly of vehicles will not be enough. Significant emissions occur throughout the value chain and life cycle of the industry – from the upstream supply chains for materials and manufacturing of component parts to the end-of-life disposal of vehicles and their various components. Decarbonizing must thus take place on both ends – in the upstream supply chain that mines materials and produces component steel, aluminum, plastics, glass and battery packs; and in the end-of-life disposal of vehicle materials and parts. The outlook for achieving net-zero, end-of-life disposal of vehicles and material circularity is favorable. It is already technically possible to recycle nearly 90% of most vehicles by weight (D'Adamo et al., 2020). To create the market conditions for full recycling, however, will require both regulatory measures and changes to vehicle designs to enable near total recycling (K. E. Daehn et al., 2017; Khodier et al., 2018; Vermeulen et al., 2011; Weidenkaff et al., 2021).

Fisheries

Marine vessels and port infrastructure have long asset lifetimes (Bullock et al., 2022). As a result, price competition and technological innovation alone are unlikely to achieve the large-scale decarbonization of the fisheries industry on timelines that can help achieve the Paris Agreement goals. Regulatory and market interventions will almost certainly be needed to require and incentivize critical technological shifts (Cullinane & Yang, 2022; Psaraftis & Kontovas, 2020). Such interventions will be essential at both national levels (e.g., for fisheries, fish farms, feed production, fish processing, energy supply, and cold chain/refrigeration) and international levels (e.g., for fishing activities in international waters and long-distance transport).

To decarbonize the seafood value chain will require large-scale provision of net-zero electricity and low-carbon, synthetic fuels, such as green hydrogen (Atilhan et al., 2021; Bicer & Dincer, 2018), green ammonia (Al-Aboosi et al., 2021; Zincir, 2022), or synthetic hydrocarbons and alcohols (Helgason et al., 2020; Korberg et al., 2021).

Measures must be taken to address emissions throughout the value chain and life cycle of vessels used in fishing operations and fish farming. Measures will need to address:

I. the building of ships (Vakili, Ölçer, et al., 2022; Vakili, Schönborn, et al., 2022)

II. the operation of fishing vessels (Balcombe et al., 2019) and their fueling with low-carbon, synthetic fuels (see above)

III. the production of feed pellets for fish farms (Hedayati et al., 2019; M. MacLeod et al., 2015)

IV. the operation of fish farms (Bujas et al., 2022; Scroggins et al., 2022; Vo et al., 2021)

V. the operation of fish-processing plants (Alzahrani et al., 2019, 2020, 2022)

VI. the building and operation of long-distance cargo vessels that transport products to market (Bouman et al., 2017; Mallouppas & Yfantis, 2021);

VII. the recycling of ships at the end of their life cycles (Milios et al., 2019).

An important first step would be to begin national road-mapping exercises to understand the baseline condition of the fishing fleet and seafood-farming sectors in each country and to chart a course toward zero emissions in line with national decarbonization plans (Fazekas et al., 2022). Implementation will require coordination among parties responsible for governing agricultural, food, and industrial policy; shipping and maritime activities; and the energy-supply sector, with dedicated support for business. Downstream disposal of fishing vessels requires a move toward a more circular economy. The international nature of the shipbreaking and recycling business requires strong coordination at the global level between governments and multilateral organizations.

Regional Opportunities and Pain Points

A number of common themes emerge in this report. There are opportunities and pain points for all three economies. (See chapters 5, 6 and 7 for detailed analysis of the policy landscape in each country).

Establishing policy ambition and articulating a strategic vison. An overarching political and legislative framework across the whole economy is needed to create the strategic vision and establish the underpinning legal authority for a net-zero transition. This is foundational. Such a vision must be clearly articulated before specific, strategic roadmaps for individual sectors can be created. Colombia, Ecuador, and Peru are at varying stages of development in terms of articulating their climate strategies and putting into place policies needed to achieve the climate targets they have pledged to meet. Colombia has already submitted a net-zero strategy to the United Nations (Gobierno de Colombia, 2021) and is in the process of revising its latest national energy plan (*Plan Energético Nacional (PEN) 2020 – 2050*) (UPME, 2019a) with this vision; Ecuador and Peru have submitted documents that outline steps they intend to take to decarbonize, but these do not yet (at the time of writing, early 2023) set net-zero targets. It is worth underscoring that creating net-zero outcomes requires long-term thinking and actions that extend beyond the short-term election cycles of politicians worldwide (Fay et al., 2015). Energy and environment policies in all countries suffer from both short-term thinking in general and changes in government that lead to inconsistent prioritization of climate strategy. Colombia, Ecuador, and Peru are no exception. Political instability continues to be a challenge for putting in place an ambitious, long-term, transformative policy architecture for industry that can outlast any single administration.

Fostering coordination among institutions and avoiding fragmentation. The experiences of other regions that have developed industrial decarbonization strategies, like the UK and the EU (BEIS, 2021; Merten et al., 2020), show that a first iteration of such strategies can be generated in three to five years. This rapid pace is possible provided that a country has key ingredients: a national climate strategy, coordination between government departments, and a base of required institutional knowledge and capabilities. For Colombia, Ecuador, and Peru, major challenges lie in developing mechanisms to coordinate the many players involved in devising and implementing a net-zero strategy. Many players must work together – including diverse energy, environment, commerce, and transportation departments; government actors at all levels; regulatory authorities for multiple sectors; and industry organizations and leaders. Fragmentation of net-zero industrial strategies and initiatives between government branches and levels – or, worse, policies that are at cross-purposes – will only slow down or halt progress. In addition, many industries involve actors and operations that span multiple countries. Thus, countries in the region that seek to realize their potential as net-zero industrial hubs may also wish to explore and pursue additional coordination at the regional level through forums such as the *Comunidad Andina*[1] or the *Alianza del Pacífico*.[2]

Embracing low-carbon energy. Achieving a shift to net-zero industrial production in time to achieve the aims of the Paris Agreement requires large-scale policy leadership and investment decisions in energy supply to serve the entire country. Such a requirement is beyond the remit or capability of any individual

1 All countries covered in this report are members and parties to the Cartagena Agreement of 1969.

2 Both Colombia and Peru are members, with Ecuador maintaining, at the time of writing (early 2023), observer status.

business, facility, or industry. National-level, strategic infrastructure that is directly or indirectly under the remit of national governments is an essential component. To embrace clean energy, governments must accomplish two missions: 1) finance and build a zero-emission power grid, and 2) provide access to either imported or domestically produced low-carbon, synthetic fuels (such as green hydrogen or green ammonia). Unless the required supporting infrastructure is in place, businesses may be unwilling or unable to change long-established fossil fuel-based production methods or techniques and to adopt clean alternatives (electrifying more processes, switching to zero-emission fuels). A pain point for all three countries is the rapid timetable required for transformations in energy- supply infrastructure, and the complexities of shifting from a fiscal and export strategy focused on fossil-fuel extraction to one that embraces clean energy as the fuel of the 21st century (Solano-Rodríguez et al., 2021; Welsby et al., 2021). Substantial progress must be made in just the next 10 years.

Capitalizing on abundant resources for renewable energy and attracting foreign direct investment. Colombia, Ecuador, and Peru have vast renewable-energy resources that provide enormous potential for powering clean industrial sectors. All three countries face challenges to grid development, however. For example, all three countries must strengthen power-grid connections between the areas of highest demand (where most existing industrial activity takes place) and the areas of highest renewable-energy potential (where hydro, wind and solar power can be best deployed). Ecuador is ahead in this regard; over the past decade, it has built both large-scale hydropower stations and the associated grid to carry the load (Ponce-Jara et al., 2018). In Colombia and Peru, however, the largest resources are largely untapped. All three countries have found it challenging to attract foreign direct investment into the energy-supply sector. This may be the result of uncertainties about the future direction of energy policy, which may itself have created the perception of a weak business environment for investment in renewables. To counteract this, measures to boost confidence in the durability of national industrial and climate policy are required to demonstrate commitment (e.g., through legislation) and capability (e.g., through inter-departmental coordination) from government. The latest national development plan for Colombia (DNP, 2023), which emphasizes knowledge intensive reindustrialization of the economy, is one example of this.

Adopting clean fuels and pivoting away from fossil fuels. Oil-and-gas industry players represent powerful economic actors within the region. There is great opportunity for this sector to provide much-needed solutions to the challenge of decarbonizing industry. Existing knowledge and skills associated with the production and handling of petrochemical products translate very well to the manufacturing of synthetic, low-emission fuels (such as either green ammonia or green hydrogen) and to providing infrastructure for carbon capture and storage. The prospect of domestic production of fuels from renewable energy is attractive one in all three countries; such an approach has the potential to enhance both domestic energy security and create an export market opportunity to supply energy to regions where low-emission fuels cannot be produced cheaply. Both Colombia and Peru have begun to develop roadmaps for domestic, green-hydrogen production. All three countries may want to explore the potential to establish greenhouse gas-neutral industrial clusters so that businesses can share access to critical transport and storage infrastructure for high-voltage clean electricity, carbon capture, green hydrogen, and green ammonia. This is an inherently political decision, as it requires spatial planning of industrial production. At the same time, such an approach could be used in a strategic manner, by deliberately seeking to improve livelihoods in various ways. For example, this approach could be used to improve supporting infrastructure (roads, water, power) and to create opportunities in economically depressed regions.

Fostering material circularity and improving waste management. Like most other countries in the world, Colombia, Ecuador, and Peru are a long way from achieving material circularity. Regulations and policies are required to create market incentives for ecological design of products to better enable recycling, improve infrastructure for waste collection and recycling, and phase out the production of goods that cannot be recycled. Though the situation is improving, problems remain across the region, as evidenced by uncontrolled waste disposal in open dumps, wastes leaking into natural environments, and gases that contribute to climate change emerging from waste. Colombia is a regional leader in thinking about the circular economy and has already produced its first national strategy document outlining how to move waste management in this direction (Ministerio de Ambiente y Desarrollo Sostenible & Ministerio de Comercio, 2019). The Peruvian government has also signaled its intention to move industrial policy in this direction by approving principles for a circular-economy roadmap (Gobierno del Perú, 2020b).

Next Steps

This report provides a framework for thinking about ways to achieve clean industrial production in the Andean region. It provides a starting point for more detailed road mapping, industrial strategy planning, and exploratory scenario analysis of the economic, political, and environmental impacts. More work is urgently required in to support effective policy development to address emerging issues. For example, policies would benefit from:

- Examining successful decarbonization projects through case studies in the Andean region.
- Conducting quantitative analysis to explore and understand emissions reduction potential by sector and by country.
- Studying synergies and trade-offs between different strategic options in industrial sectors with significant overlaps (e.g., plastics and textiles).
- Using policy scenarios (e.g., fossil fuel subsidy reform, technology subsidies, different regulatory mechanisms) to explore the feasibility and impacts on industrial decarbonization pathways.
- Analyzing the ways that different levels of governance (e.g., local, national, regional, and international) can support effort to decarbonize industries in the Andean region.
- Studying the potential environmental co-benefits (e.g., air, soil, and water quality) of decarbonization strategies for industry.
- Conducting spatial analysis of energy resources and industrial demand centers as a means of understanding future priorities for infrastructure planning.
- Analyzing industrial decarbonization transition costs over time and the financing mechanisms for achieving targets.

- Conducting detailed analysis of capital and labor markets for each industrial sector.

As this report underscores, efforts to achieve a transformation of this enormity require measures that can transcend short-term visions and address key issues in the wider political economy. That is, an industrial transition of such magnitude must consider the ramifications over time on key actors and interest groups in each country – in government departments, business and industry lobbies, NGOs, civil society groups, political parties, social and labor movements, and among interests operating at international, national, state, and local levels. Direct engagement with key groups at all levels is a prerequisite to designing and executing durable and effective net-zero strategies that can work for individuals, industries, countries, and the planet. Many of the technical barriers have been surmounted, or are on the horizon. Indeed, the technological barriers to achieving net-zero goals are lower than those that must be surmounted to coordinate action among key players, mediate conflicts between different and competing interests, and thus ensure a just transition (Saget et al., 2020). Widespread social and political buy-in that a coming transition will be fair and just in efforts to make industries green and clean is essential to create enduring structural changes that can overcome the systemic inertia associated with two centuries of high-emissions industrial production.

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1

TECHNICAL ANALYSIS

CHAPTER 1
PLASTICS MANUFACTURING

1.1 Key Conclusions

Plastics production is a major source of GHG emissions and a particularly difficult sector for transitioning to net zero.

Key strategies for achieving net zero in the manufacturing part of the product life cycle are energy-efficient processes, electrification with decarbonized grid electricity, and switching to net-zero synthetic fuels like green hydrogen for high-temperature-process heat

Major challenges for net-zero plastics come not from the refining and finished product parts of the life cycle, but from the upstream resource extraction and end-of-life disposal segments.

Pain point: Upstream substitution of fossil fuels for alternative feedstocks does not present relatively cheap or easy solutions that are commercially available at scale. It is not clear whether future research and development innovations will bring these to market on a timeline to meet net-zero targets.

Pain point: Recycling is unlikely to be a panacea for emissions and waste from plastics production. Moving to a more circular flow of materials does offer a pathway to mitigate some of the environmental damage associated with the existing value chain, but technologies for fully recycling plastics without emissions are only at a nascent stage of technological development. Consequently, coordinated action among government, producers and consumers is required to eliminate the use of cheap disposable plastic products, explore the material substitution of plastics with alternative materials, promote eco-design principles, rationalize plastics production to only polymers that are amenable to recycling, and supercharge efforts to recycle the plastics that are still maintained in circulation.

Pain point: All of the above may disrupt the established business models of existing producers. A combination of regulatory pressures and incentives may be needed to bring about transformational changes to their operations. Coordinated action between industry and government will be required to create the conditions that enable full decarbonization of the electricity grid and create the availability of low-carbon, synthetic fuels such as hydrogen at scale.

1.2 Overview of Emissions from Plastics

Plastic materials are in high demand and are mostly made from fossil fuels. The plastics industry creates synthetic polymer materials used in the manufacturing of products for other sub-sectors such as packaging, construction, consumer electronics, and components for vehicles (e.g., automotive, aerospace, marine). Because synthetic rubbers are also polymer materials made using the same general principles (techniques, equipment, feedstocks) as plastics, we include them in this discussion. Most common plastics in widespread use today are made from fossil fuels; as such, the plastics industry can be considered part of the broader chemical and petrochemical industries. Global demand for plastics has grown at around 4% per annum since 2000 (Geyer et al., 2017), representing the fastest growing category of any bulk material (IEA, 2018).

Plastics represent a major source of GHG emissions. Much of the environmental literature on plastics focuses on plastic waste and the implications for ecosystem and human health via, for example, microplastics in the oceans (Jambeck et al., 2015) and plastic rain (Brahney et al., 2020). But plastic production from fossil fuels also contributes significantly to atmospheric GHG emissions. The plastics industry is estimated to represent around 4% of total global emissions, with the production of most common plastics in use today resulting in just over 4 kg CO_2e (kilograms of CO_2 equivalent) per kg of plastic produced (Zheng & Suh, 2019). The United Nations and representatives from 175 countries recently committed to create a legally binding international agreement for ending plastic pollution that would come into force in 2024 (*United Nations Draft Resolution UNEP/EA.5/L.23/Rev.1: End Plastic Pollution: Towards an International Legally Binding Instrument*, 2022). The manufacturing of plastics produces planet warming GHG emissions at several key stages **(i-v)** in the product life cycle.

I. Upstream resource extraction

The industry association European Bioplastics estimates that only around 1% of total global plastic production in 2021 was for bio-based plastics (European Bioplastics, 2021). The main feedstocks for plastics production are fossil fuels, typically crude oil or natural gas. Therefore, by definition, the production of the remaining 99% of global plastics involves emissions associated with the extraction, refining and transportation of fossil fuel-based feedstocks to the production site. Emissions include direct emissions from extraction, such as methane leakage and flaring (Scarpelli et al., 2020), emissions released by fuel combustion from drilling and refining equipment (Jing et al., 2020), work site and bulk fuel transport vehicles (tanker trailers, ships, etc.). Emissions are also associated with any grid electricity used in these processes (unless the grid itself is decarbonized).

II. Resin production

The resin production stage (also called plastic refining) involves the chemical synthesis of bulk polymers. This essentially involves using high temperatures and pressures to create intermediate chemistries (monomers) from fossil fuels before mixing these with, dyes, stabilizers and other additives (with the precise process varying by plastic type) to create various types of end-use plastic (polymers) such as polyethylene, polypropylene, and polyvinyl chloride. Depending on the target application these could take the form of flat sheets, tubes, rods, pellets or powders (American Chemistry Council (ACC) & Franklin Associates, 2010). These processes all involve the provision of power for running pumps, compressors, motors, lighting and other specialized equipment required to move solid and liquid products around the refinery or factory as well as heat energy required for various chemical reactions and for enabling material phase changes (e.g., from solids to liquid). GHGs will be released both directly from fossil fuel combustion on site for high-temperature heat production but also from indirect emissions associated with providing electricity from the power grid (unless this is already a zero-emission grid).

III. Conversion of polymers into products

Converting bulk polymers into final products relies on various industrial processes such as injection molding, blow molding, thermoforming, and extrusion (Franklin Associates, 2011). Though the processes vary from one another in terms of their specific details, all require energy inputs to power mechanical forces, provide lighting (including lasers), and to heat and cool equipment and products.

IV. Transport of products to market

Unless directly used at the manufacturing site most value chains will involve the transport of plastic products to other manufacturing businesses or to retailers for final sales to end users. Most transport mechanisms for freight rely on fossil fuels (IEA, 2021g).

V. End-of-life disposal

End-of-life disposal options for plastics include sending waste to landfill, incinerating items, or recycling them (CEIL, 2019). Sending waste to landfill produces the lowest GHG profile of all three options but introduces other significant risks, primarily plastic particle contamination of water and food ecosystems with knock-on impacts for human health (Ahamed et al., 2021; Lau et al., 2020). The profile of GHGs released from plastics decomposing in the natural environment depends on the precise plastic in question. As one example, polyethylene will degrade and produce methane and ethylene (both are GHGs) when exposed to water and/or sunlight. Incineration is the most emission-intensive disposal option; moreover, releasing GHGs to atmosphere creates a range of additional environmental and human health risks from airborne plastic particulates and toxins. Recycling plastics offers the lowest GHG path but is constrained by challenges such as high labor and capital costs for effectively separating and processing plastics, and a limited range of applications for recycled plastics compared to freshly produced plastics from virgin material. Recycling approaches fall into two main categories, mechanical and chemical (Meys et al., 2020) (which by extension, includes biological enzymes (Singh et al., 2021)). Mechanical recycling is the most common and involves cleaning and sorting plastic before cutting it into fragments and melting it to produce a stream of reusable material that is (mostly) free of impurities. Chemical recycling involves transforming plastic waste back into monomers. It is worth noting that chemical recycling is a technology still in its infancy (Ragaert et al., 2017) and the overall sustainability of chemical recycling remains contested (Mah, 2021).

1.3 Decarbonization Options for Plastics

Technological interventions can be made to eliminate emissions throughout the plastics life cycle. Carbon is the main element in plastic materials, so "decarbonization" in the context of plastics is an oxymoron. However, the term is in widespread use to describe the concept of decoupling of plastics production from fossil fuels and/or creating plastics without releasing GHGs to atmosphere. Early corporate initiatives such as IKEA's goal to use only bioplastics in products or Coca-Cola corporation producing a bottle with bioplastic content (Coca-Cola Company, 2015) do represent incremental steps in the right direction but ultimately fall short of the ambition required for continued use of plastics to be aligned with Paris Agreement targets. We discuss here specific options for reducing the emission footprint from plastics production at each stage **(i-v)** in the product life cycle.

I. Upstream resource extraction

Decoupling plastics manufacturing from unabated fossil fuel feedstocks would eliminate emissions associated with oil or natural gas extraction from the product life cycle. A number of options exist for replacing the carbon atoms required for plastics with non-fossil fuel sources. These include (a) creating bioplastics from biomass, (b) recycling carbon from the air to create carbon dioxide-based plastics, or (c) recycling carbon from waste to create carbon dioxide-based plastics.

a) Creating bioplastics from biomass

Replacing fossil feedstocks with biomass is a frequent recommendation from studies exploring emissions reductions from plastic production (Rosenboom et al., 2022; Saygin & Gielen, 2021; Scott et al., 2020; Zheng & Suh, 2019). Biomass cultivation can be used to supply feedstock for so-called drop-in replacements for common plastics (e.g., polyethylene made from sugarcane ethanol) (Negri & Ligthart, 2021), or for entirely new plastic types (e.g., polylactide, also called polylactic acid (PLA) (Griffin et al., 2018). The main challenge for bioplastics is that their development is likely to be constrained by concerns about their overall sustainability when taking into account land-use change and competition for crops grown for food (Brodin et al., 2017; European Commission, 2018; Nanda et al., 2015).

b) Recycling carbon from the air to create carbon dioxide-based plastics

In principle the carbon from carbon dioxide can be combined with hydrogen from water to create hydrocarbons needed to make any kind of plastic (Lange, 2021; Palm et al., 2016; Palm & Svensson Myrin, 2018). Capturing carbon dioxide, a major greenhouse gas, from the air is a feature of many climate-mitigation scenarios (Realmonte et al., 2019), even though key dimensions such as the economic and technological feasibility of such a strategy remain contested (Chatterjee & Huang, 2020). Creating useful products from this waste stream has the benefit of preventing its atmospheric circulation; nevertheless, disposal (see stage (v)) represents a potential source of emissions if when these products reach their end-of-life. A disadvantage of carbon dioxide-based plastics from air-captured CO_2 is the energy intensity of the process, which may increase their cost to between two to three times more than fossil-fuel based plastics (Palm et al., 2016).

c) Recycling carbon from waste to create carbon dioxide-based plastics

A third potential source of carbon for use as plastic feedstock is actually recycling of waste plastics (Carus et al., 2020) or waste feedstocks (Moretti et al., 2020). The technological and commercial viability of various approaches are not well understood and may require significant investment in research and development. Documented past efforts have been abandoned before reaching commercial scale (Ren & Patel, 2009).

II. Resin production

Producing the intermediate chemicals that go into making polymer resins involves chemical reactions under heat and pressure. Typical heating requirements in plastics refining vary but reaction temperatures range from 700-950°C (Le Van Mao et al., 2013). For example, polyethylene, the most common plastic by volume, is commonly made by converting natural gas liquids into ethylene in a plant called an ethane cracker, which requires heat at around 850°C (Posch, 2011). Supplying this heat from non-fossil resources is a requirement for net-zero plastics production. For high-temperature steam cracking the main net-zero option is to use renewable hydrogen as the fuel instead of natural gas or other fossil fuels. This is already technologically viable today but does require the supporting infrastructure for hydrogen in industry to be put in place (e.g., as proposed by the federal government in Germany (BMWI, 2020)). An alternative that is under development but not yet technologically mature at scale is electrochemical cracking of ethylene at much lower temperatures (less than 400°C), which could in principle use energy from a net-zero electricity grid (Tullo, 2021).

III. Conversion of polymers into products

The main strategies for eliminating emissions from the conversion of bulk polymers into plastic products are energy-efficiency improvements, electrification of process energy wherever possible (Negri & Ligthart, 2021; Van Geem et al., 2019), fuel switching to zero-carbon fuels where electrification is not feasible (Rissman et al., 2020), and capturing emissions (Lange, 2021). Heating requirements in plastics production range from 50°C (for preheating) to as high as 300°C (for high-temperature injection molding). Over the last 10 years there has been a significant improvement in delivered temperatures available from heat pumps, and commercial solutions from multiple manufacturers are now able to supply heat in the 90-150°C range; in the near future, the capacity to go above 150°C is also likely to be possible, with many demonstration and commercialization projects either recently completed or close to completion. (Arpagaus et al., 2018). Electrification with decarbonized grid electricity and provision of green-hydrogen infrastructure requires large-scale policy and investment decisions beyond the level of individual manufacturing plants (Lechtenböhmer et al., 2016).

IV. Transport of products to market

For net-zero targets to be achieved nearly all forms of freight transport (i.e., road (Meyer, 2020), rail (IEA, 2019; Rungskunroch et al., 2021), aviation (Bauen et al., 2020; IEA, 2021c; Schäfer et al., 2019), shipping (Bouman et al., 2017; IEA, 2021e; Mallouppas & Yfantis, 2021)) will need to be decarbonized using electricity or synthetic zero-GHG fuels like hydrogen.

V. End-of-life disposal

Claims by many manufacturers that bioplastics are inherently environmentally benign are not backed by evidence (Walker & Rothman, 2020). The biological origin of the molecules has no bearing on the challenges posed by their disposal. So-called biodegradable plastics are problematic, as the enzymes and environmental conditions needed for them to fully break down often do not occur commonly in nature (Ajayi & Reiner, 2020; Narayan, 2012; Palm & Svensson Myrin, 2018), and GHGs are still released in the process of decomposition. Bioplastics proponents argue that emissions are sequestered during the process of growing the plant feedstocks, rendering the overall decomposition process somewhat neutral; nevertheless, for this to be true, many other aspects of production would also have to adjust to reduce emissions from the use of fossil fuel-intensive fertilizers and from agricultural harvesting, and transportation; additives to the plastic would also need to achieve net-zero emissions (Bishop et al., 2021). Recycling is the only real option for keeping plastics out of the emissions loop, but current approaches are beset with problems. It is estimated that only 8%-15% of plastics are recycled (Geyer et al., 2017; Mulvaney et al., 2021), and of these, only around 2% are recycled into products with largely the same function as the original because recycling produces lower-grade polymers (Ellen MacArthur Foundation, 2017b). Recycled plastics are also often contaminated with chemicals that are toxic to human health (Caballero et al., 2016; Pivnenko et al., 2016). Making current plastics more recyclable or enabling them to biodegrade into harmless material through their physical or chemical design may require entirely new polymer chemistries (Gandini, 2008; Hatti-Kaul et al., 2020) and require industry to completely rethink the product-design process for the end-of-life phase (K. Daehn et al., 2022). Even some of the most ambitious recycling action plans for plastics in the EU, a circular-economy thought leader, currently acknowledge that this may still only reduce emissions by half (EIT Climate-KIC, 2021).

1.4 Implementation Strategy

Creating a net-zero plastics industry is much more challenging than just moving to green energy and materials. Merely using renewable energy does not align plastic manufacturing and use with net-zero ambitions because end-of-life disposal accounts for significant part of the emissions (CEIL, 2019). Achieving net-zero emissions from the plastics life cycle demands a total departure from the established production, consumption and disposal chain, and requires action at the level of national governments and international collaboration between countries (Barrowclough & Birkbeck, 2022). Transformative concepts that go well beyond plastics manufacturing itself include eliminating disposable plastics; reimagining packaging, packaging standards, and packaging design for reuse; creating and strengthening markets for reuse of plastic products; and adopting circular economics through new global frameworks on trade and regulation (K. Daehn et al., 2022; Ellen MacArthur Foundation, 2017b; Mulvaney et al., 2021; World Economic Forum et al., 2016). As a result of the challenges discussed and the extremely short time frame for aligning industry with the Paris Agreement-based targets (i.e., this decade), reducing total plastics demand is also an important dimension to address. Examples include designing products so that parts can be reused and replaced, reducing the quantity of plastics in products, extending the lifetime and durability of plastic parts that remain in use, encouraging less wasteful behaviors involving plastic products, and substituting plastics with other materials (UNCTAD, 2023) (e.g., wood and metal in construction, natural fibers in packaging (Scott et al., 2020)).

Serious moves toward net-zero plastics represents a significant threat to the way established players have done business in the past, and represent a potential pain point for the transition. Bringing about these transformative changes represents a huge challenge to established industries, threatening their established practices, business models, and resource use. In a world that has declared its ambition to reduce emissions to a net-zero level, the petrochemical industry sees great opportunity to pivot from producing fuels to producing feedstocks – that is from producing chemicals to burn for energy to producing chemicals to manufacture products (Cui, 2020; Tullo, 2019). But as we have discussed above, cutting out fossil fuel extraction from the supply chain is a major pillar of moving toward net-zero plastics production. The fossil fuels, petrochemical, and plastics industries are tightly interlinked by organizational and material structures. They share a common disciplinary knowledge foundation (chemical engineering), corporate links (e.g., petrochemical companies and plastics companies are frequently key shareholders in each other's companies), and may share executive personnel (F. Bauer et al., 2018). Existing players are reluctant to see their key profit centers eliminated by government or consumer action to align with Paris Agreement-based net-zero targets. Researchers have documented ongoing efforts by firms to maximize the future market for disposable high-GHG plastics by ensuring that legislation to encourage more circular resource flows and efforts to shift to bioplastics do not happen, mostly by trying to shift the emphasis of these discussions toward hypothetical recycling potential using unproven technologies (F. Bauer & Fontenit, 2021; Mah, 2021). These kinds of reactive strategies are typical for industries that have underestimated the pace of changes in regulation (Hurmelinna-Laukkanen et al., 2021). The regional and national power dynamics between governments and industrial players are complex and varied. Tackling this challenge may require policymakers to use regulatory requirements and offer incentives for industries to consider shifting course at scale and on appropriate timescales.

CHAPTER 2
TEXTILES MANUFACTURING

2.1 Key Conclusions

Textiles production is a major source of emissions. The sector is closely tied to plastics production because roughly two-thirds of all textiles produced today are created from plastics. Thus, all conclusions from chapter 1 apply equally to textiles made wholly or partially from plastics..

Cotton is the second most used textile fiber after synthetics. Net-zero cotton cultivation requires not only fossil fuel-free energy in agricultural operations and fertilizer production, but also some balancing of residual emissions with carbon sinks. This is because some level of GHG emissions from nitrogen fertilizer use seems inevitable as not all fertilizer applied can be 100% absorbed by crops.

Opportunity: Advances in heat-pump design and performance mean that textile manufacturing processes (including process heating requirements) can in principle now be supplied entirely from decarbonized grid electricity, which will be a key strategy for achieving net zero in the sector.

Pain point: Coordinated action is required between retailers, manufacturers and regulators to eliminate disposable clothing, and to focus instead on higher-quality garments with longer lifetimes and durability. This is a challenge because it requires policy action across multiple scales and jurisdictions, and disrupts the “fast fashion” business model of many producers.

Pain point: Creating the necessary infrastructure to support a net-zero textiles industry is likely to require coordinated action between industry and government because large-scale decarbonization of the power grid is required. In turn, promoting investment in clean technologies is likely to require regulatory interventions and strengthening of institutions and governance structures (Mielke & Steudle, 2018).

2.2 Overview of Emissions from Textiles

The textiles industry is a complex value chain with a diverse raw materials base. The textile industry encompasses a broad range of activities aimed at producing products made of interlacing fibers for end uses such as clothing, packaging, home furnishings, and construction materials. The raw inputs for textiles production are diverse and are mainly sourced from plants (e.g., cotton), and synthetic chemicals (e.g., polymer fibers like nylon), although other notable sources include animals (e.g., wool from sheep) and minerals (e.g., glass fiber). The largest single application for textiles is clothing (~73%), followed by various technical applications in the construction, transport and medical industries (~15%), and household furnishings (~9%) (Uddin, 2019). Over the last decade, polyester and cotton have been the two most in-demand textiles by mass (Juanga-Labayen et al., 2022; Tobler-Rohr, 2011) with the share of polyester growing over time. This follows a general trend that began in the 1970s, with synthetic fibers progressively displacing natural fibers (Shishoo, 2012), and Asia replacing Europe as the dominant production hub (Nayak & Padhye, 2015; Scheffer, 2012). Around two-thirds of all fibers produced today are synthetic (Palacios-Mateo et al., 2021), tightly linking textiles production and the petrochemical industry. Global demand for textiles is growing continuously over time and was estimated at 110 million tonnes in 2018 (Juanga-Labayen et al., 2022).

Textiles are a major source of GHG emissions. Emissions from the textiles industry are estimated to be 1.2bn tCO_2e (tonnes of CO_2 equivalent), which is more than the entire aviation industry and maritime shipping combined (Ellen MacArthur Foundation, 2017a). Though the sheer variety of textile types and their end-use applications makes generalizations difficult, the manufacture of such goods is an energy- and water-intensive process (Muthu, 2014). The production of the most common forms uses an estimated 15 – 36 kg CO_2e per kg of fiber (Beton et al., 2014). Focusing on the most common fiber types, we find that the full life cycle of 1kg of polyester is estimated to be responsible for around 30 $kgCO_2e$; for cotton the equivalent value is 20 $kgCO_2e$ (Beton et al., 2014). Below we outline several key stages **(i-iv)** in the product life cycle that result in GHG emissions.

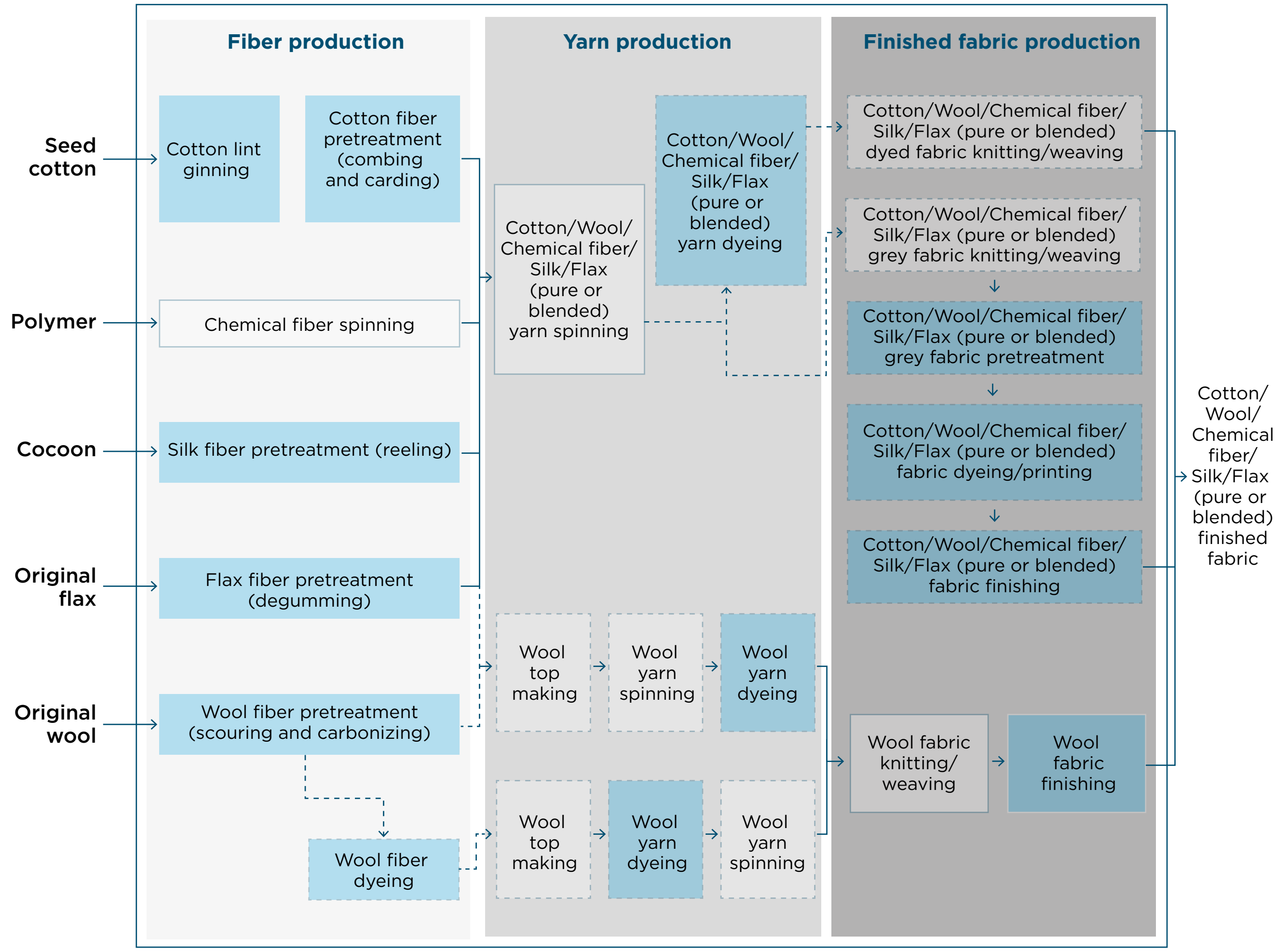
i. Upstream resource extraction

Textiles made from synthetic fibers or fiber blends with synthetic polymer content are generally manufactured with fossil fuel-derived plastics, and thus involve the same emissions issues outlined in chapter 1 on plastics. The sourcing of natural fibers from plants or animals also involves emissions released to atmosphere during various agricultural processes. Energy is needed to produce fertilizers, run cultivation machinery, pump water to irrigate crops, provide heating and lighting for farm and warehouse buildings, and transport key inputs to the production site and for collection and harvesting of the final products. A detailed overview of environmental impacts for cotton can be found in Chen et al. (F. Chen et al., 2021). Upstream production of fertilizer for agriculture (e.g., growing cotton) is also a source of emissions. The main fertilizer groups are nitrogen, phosphorous, and potassium (Ouikhalfan et al., 2022; Walling & Vaneeckhaute, 2020). The latter two are mined minerals while nitrogen-based fertilizers are overwhelmingly made today from natural gas. Nitrogen fertilizer production is an energy-intensive process that uses some of the gas for energy to power the chemical reactions and some of the gas as a feedstock as a source of molecules to make the fertilizer product itself. Nitrous oxide is a major greenhouse gas has a global warming potential of approximately 300 times greater than that of carbon dioxide.

ii. Conversion of raw materials to fibers and finished products

An overview of this stage can be found in a concise diagram by Chen et al. (L. Chen et al., 2019), replicated here in Figure 2.1. The figure omits upstream and downstream processes, but it provides good detail on fiber production, yarn production, and finished fabric production. Emissions result from various energy-consuming processes that use fossil fuels as inputs. A typical composite textile plant may use around 50% of its final energy as electricity (for processes such as spinning and weaving humidification) and 50% as heat (for processes such as bleaching, finishing, dyeing, and printing) (Hasanbeigi & Price, 2015).

Figure 2.1: Conversion of Raw Materials to Finished Products (L. Chen et al., 2019)



iii. Transport of products to market

Both business-to-business and business-to-consumer products require freight transport from the manufacturing site, which in most regions is provided using energy from fossil fuels (IEA, 2021g).

iv. End-of-life disposal

Textiles are disposed of when they are damaged or have no further value to consumers (Domina & Koch, 1997). Disposal options include sending textiles to landfills, incinerating them, or recycling them. At a global scale, around 75% of all textiles are sent to landfills, where they release GHGs to atmosphere as they degrade; only 1% are recycled into clothing (Juanga-Labayen et al., 2022). Because the world's most common fabric – polyester – is effectively plastic, the entire discussion on end-of-life-disposal for plastics covered in chapter 1 also applies to textiles.

2.3 Decarbonization Options for Textiles

Options for reducing the emissions footprint from textiles production at each stage (i-iv) in the product life cycle are discussed here:

i. Upstream resource extraction

For synthetic fibers (e.g., polyester), all of the discussion on decarbonizing plastics under chapter 1 is relevant. For natural fibers, a full adoption of net-zero agricultural practices is required. Direct energy use in agricultural vehicles, irrigation pumps, or other harvesting and processing equipment should be electrified with net-zero electricity and/or replaced with zero-carbon fuels to the fullest extent possible (Hedayati et al., 2019). Indirect energy use for agriculture arises largely from fertilizer production and use. High-yield cotton cultivation, for example, is reliant on fertilizers, particularly nitrogen (Khan et al., 2017). Decarbonizing potassium and phosphorous fertilizers would require a transition to net-zero mining operations for the needed ores (Ouikhalfan et al., 2022); net-zero production of nitrogen-based fertilizers requires green ammonia (Chehade & Dincer, 2021; IEA, 2021b), which shares many process components with net-zero hydrogen (C. Bauer, Treyer, et al., 2022). Even if all upstream inputs to agriculture are net-zero, not all fertilizer applied is completely absorbed by plants and nitrogen leakage from the soil (as nitrous oxide) remains a powerful greenhouse gas (Gregorich et al., 2015). Organic cultivation of fibers like cotton depends on fertilizers, typically animal manures, which often emit more nitrous oxide per unit of production than synthetic fertilizers (Walling & Vaneeckhaute, 2020). Net-zero agriculture therefore requires moving the conversation away from an organic/synthetic dichotomy and focusing instead on balancing of emission sources and sinks. Planned land-use interventions – for example repurposing agricultural land for forest cover to provide carbon sinks (Harwatt et al., 2020; Reay, 2020) – are important non-technological measures for achieving net zero in the agricultural sector, with various technological options for direct removal from the atmosphere also on the table (Hanna et al., 2021).

ii. Conversion of raw materials to fibers and finished products

The main strategies for achieving net-zero emissions from the conversion stage are energy efficiency and electrification/fuel switching. Improving the efficiency of textile production may require novel processes and methods of production (Hasanbeigi & Price, 2015), as well as optimizing the layout and control of plant facilities (Moon et al., 2013). Electricity provides much of the energy required for lighting and running equipment in textile plants; thus, decarbonization of the grid is required. Heating requirements in textiles production range from 40°C-160°C, with the higher end of the range used for dyeing. Electric heat pumps can already supply heat in the 90°C-150°C range, with solutions for going above 150°C already successfully completing demonstration projects (Arpagaus et al., 2018). Full electrification of textile production with decarbonized grid electricity is therefore already technical possibility.

iii. Transport of products to market

Transport of finished products will need to achieve net-zero emissions. Depending on the destination market and final retail location for the products this may mean decarbonizing road freight, aircraft, railways, and shipping using electricity or synthetic zero-emission liquid fuels; and shifting freight to the lowest-emission modes available (Kaack et al., 2018).

iv. End-of-life disposal

Two-thirds of textiles are plastics. The discussion in chapter 1 covering end-of-life disposal of plastics is also relevant for textiles. The end-of-life phase of the sector must be modified so that textile waste does not wind up in landfills outgassing GHG emissions as it degrades, or being incinerated, releasing GHGs to atmosphere as it burns. The main avenue for achieving net-zero, end-of-life disposal is material circularity, which requires improved recycling and the adoption of circular-economy principles (Ellen MacArthur Foundation, 2017a; McKinsey & Company, 2022; Shirvanimoghaddam et al., 2020; Wojciechowska, 2021). While the methods and techniques may slightly differ, the challenges for recycling textiles mirror those for plastics. For example, such processes are time and labor intensive; it can be difficult to separate materials that are blended together, and contamination in recovered materials can be an issue (Juanga-Labayen et al., 2022; Sadeghi et al., 2021).

2.4 Implementation Strategy

Net-zero textile manufacturing goes far beyond the concepts of "sustainability" that have been employed to date. Sustainability (i.e., what is and what is not sustainable, how much effort is sufficient, etc.) in the textiles industry remains highly contested (Greco & De Cock, 2021; Henninger et al., 2016). In the clothing industry, many manufacturers are keen to emphasize their sustainability credentials for customer loyalty reasons (Jung et al., 2020), but unfortunately this is mostly marketing without substance (Wren, 2022). This is not to say that efforts by industry to date are without merit; nevertheless, emissions produced from textiles manufacturing continue to rise (G. Peters et al., 2021) rather than to decline or begin to approach zero. Net zero is a challenge that will require actions beyond marketing, labeling, and incremental improvements to products. Merely switching to green energy and materials as inputs does not overcome emissions associated with end-of-life disposal.

Achieving net-zero textiles would upend existing business models for a large portion of the global supply chain, representing a key pain point for the transition. A net-zero system requires fundamental changes: different production methods, new business models, new consumer behaviors, and policy measures to create and support markets needed at all stages of the value chain (Manickam & Duraisamy, 2019; Manshoven et al., 2019). For clothing, the main product category produced using textiles, a shift to higher-quality garments with longer lifetimes and greater durability is critical (Nature Climate Change, 2018; Niinimäki et al., 2020). Many of the implementation challenges discussed earlier for plastics manufacturing (see chapter 1) also apply to textiles. Textiles and clothing are a large and profitable industry; the fashion industry itself is responsible for an estimated 2% of global GDP (Shirvanimoghaddam et al., 2020). So far, the industry has not been required to bear the costs of pollution from its products. Taxing pollution may be highly disruptive to the industry.

CHAPTER 3
AUTOMOTIVE MANUFACTURING

3.1 Key Conclusions

A net-zero automotive industry needs not only to carry out its manufacturing operations without emissions but also to create products that are low emitting. A shift from internal combustion engine vehicles to electric drivetrain vehicles is the most direct way to achieve this goal for most markets and applications.

Vehicles are complex, manufactured products with lengthy supply chains. Significant emissions occur in the upstream supply chain before any automotive assembly begins.

Pain point: Decarbonizing vehicle manufacturing requires decarbonizing the mining of input materials and the production of steel, aluminum, plastics, glass and battery packs.

Pain point: A transition to net zero in automotive assembly plants will rely on low-carbon electricity for supplying most processes and the use of hydrogen or other net-zero, synthetic fuels to supply heat for high-temperature processes.

Pain point: Stimulating action on a timeline to meet the mitigation aims of the Paris Agreement is likely to need regulatory intervention. Industry alone is unable to make the necessary changes to make net-zero auto manufacturing a reality. Wide-ranging changes to infrastructure – such as decarbonizing the electricity network and creating the infrastructure needed to supply hydrogen at sufficient scale – almost certainly will require government assistance.

Opportunity: The outlook for achieving net-zero, end-of-life disposal of vehicles and material circularity is quite favorable compared to the outlook for other sectors. In principle, nearly all parts of a vehicle can be recycled if the right infrastructure and incentives are provided, and if the vehicle is designed with end-of-life disposal in mind.

Opportunity: Many major auto manufacturers have already demonstrated a limited degree of interest in producing net-zero vehicles.

3.2 Overview of Emissions from Auto Manufacturing

Automotive production creates long-lived capital assets. Automotive manufacturing is a global industry producing ground transport vehicles for passengers, freight, industrial, military, and agricultural applications. Passenger cars are the largest single component of this industry. Over the last two decades, between 60 million and 92 million cars have been sold every year (IEA, 2020a). Depending on their design, the driving conditions experienced, and the distances traveled, vehicles can have long lifespans, often in the region of 8-12 years and even longer in some markets (15+ years). An estimated 1.3 billion vehicles were thought to be in use in 2021, with the overwhelming majority of these (~99%) using internal combustion engines (EIA, 2021). Electric vehicles represent a rapidly emerging market segment; around 9% of all new cars sold in 2021 were electric, and sales of cars that run on fossil fuels are now stagnant or falling (Paoli & Gül, 2022).

The auto industry represents a huge contribution to global emissions. The life-cycle emissions from cars produced by the top 12 largest auto manufacturers are estimated to be in the region of 4.3 Gt-CO2e (gigatonnes of CO2 equivalent), representing 9% of global emissions (Greenpeace, 2019). The emissions associated with producing and disposing of a typical vehicle (depending on size and weight) are between 6-10 tCO2e (tonnes of CO2 equivalent) (Helms et al., 2016). These estimates exclude the additional emissions from the energy used during its life cycle; these emissions depend on how much the vehicle is driven. For illustrative purposes, cars that run on gasoline or diesel fuel emit around 150-200 g CO2e per kilometer traveled (Helms et al., 2016); thus, a car that travels 150,000-200,000 kilometers can potentially generate 22-40 tCO2e over its lifespan.

While their production and use are currently not emission free, switching to the production and use of electric vehicles will nevertheless be a critical means of meeting net-zero transportation requirements. It is difficult to make generalizations about the emissions associated with manufacturing the batteries for electric vehicles; different vehicles have different sized battery packs and also use different battery chemistries (Ellingsen et al., 2017; J. F. Peters et al., 2017). However, the production of most electric vehicles has a larger emission footprint than the production of fossil fuel-powered vehicles. Moreover, the emissions associated with making the battery packs alone can sometimes be greater the emissions associated with manufacturing all of the other parts of the vehicle combined (Agora Verkehrswende, 2019). In many countries where electricity itself predominantly comes from fossil fuels, emissions from driving electric vehicle are broadly comparable to those from cars that run on fossil fuels (Helms et al., 2016; Kawamoto et al., 2019). Electric vehicles, however, unlike fossil fueled cars, have the potential to produce very low emissions while in use if their power comes from zero-carbon electricity, which is why rapid electrification of the fleet is central to the decarbonization strategy of every major economy in the world (e.g., the US (US Department of State & US Executive Office of the President, 2021), the EU (European Commission, 2019), China (National People's Congress, 2021), Japan (METI, 2021), Germany (BMUV, 2016), the UK (HM Government, 2021), France (Ministry of the Ecological Transition, 2020), Canada (CCI, 2021), and Italy (MISE, 2020)).

Emissions arise during multiple stages **(i-v)** during a vehicle's life cycle:

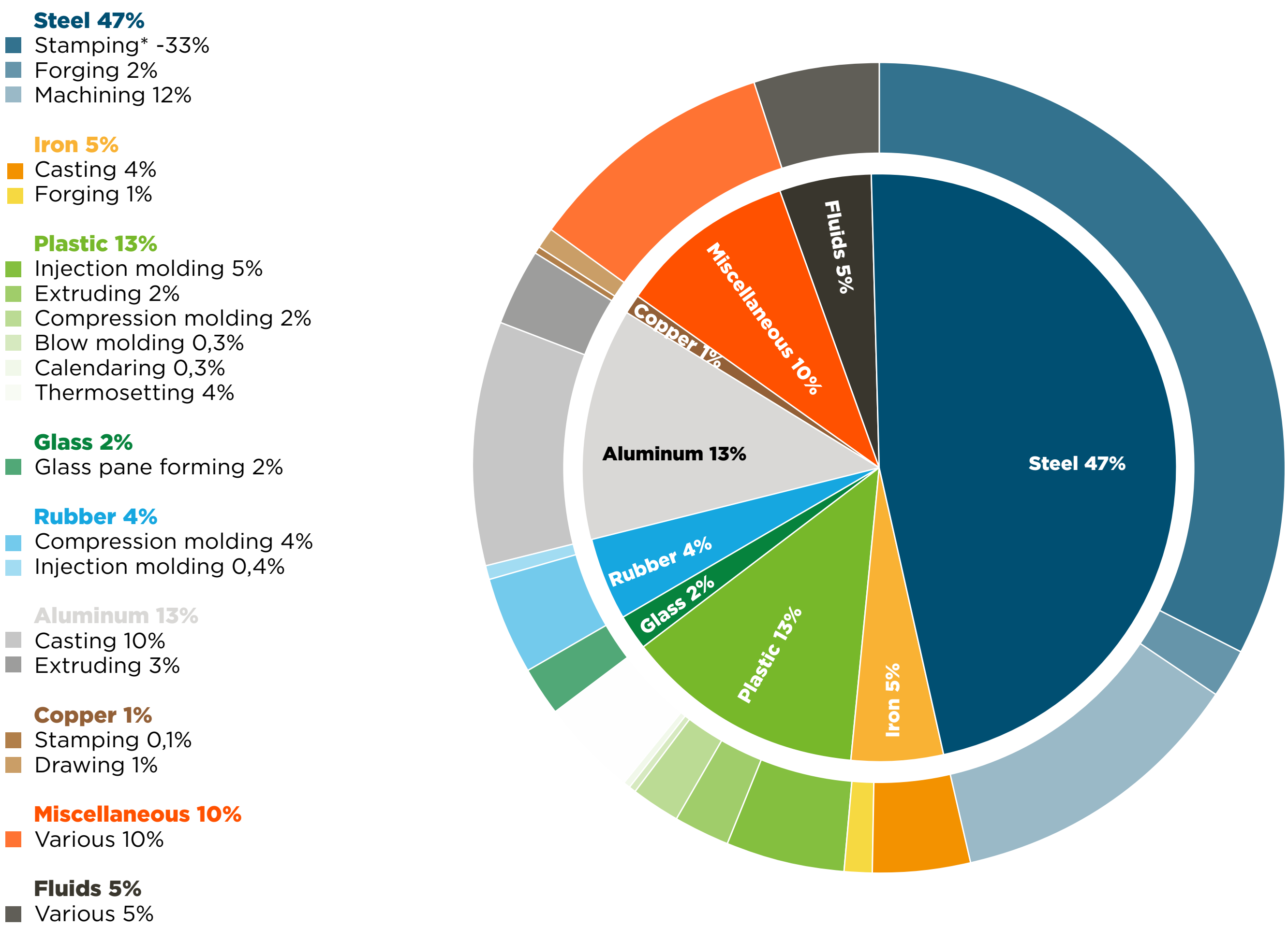
i. Upstream resource extraction

Automobiles are complex products manufactured from a variety of inputs, nearly all of which have already been processed upstream from base raw materials. As a result of their material inputs, upstream emissions for auto manufacturing are tied to energy use in the oil extraction, mining, and petrochemical industries. In passenger cars, for example, the materials consist of mainly steel, aluminum, plastics and rubber. Glass for windows is also important, as are technical textiles. Electric vehicles also have large batteries for motive power. While all cars are different in terms of body shape and size, a "typical" fossil fuel-powered car might be said to incorporate 900 kilograms of steel (World Steel Association, 2021), 160 kilograms of aluminum (Ducker, 2020), and 150 kilograms of plastics (Tullo, 2017). Electric vehicles are often heavier than similar market-segment models that run on fossil fuels, and in an effort to save weight they are often manufactured with more aluminum in their structure (~290 kg) (Ducker, 2020). The weight of batteries in electric vehicles varies by model and the designed maximum driving range, but a high-performance luxury vehicle might have batteries onboard that weigh as much as 700 kilograms (Nicoletti et al., 2020). Steel, aluminum and battery manufacturing are all energy- and emission-intensive processes.

ii. Component production and vehicle assembly

A large part of vehicle manufacturing is metalworking to create the vehicle body. Vehicles are also comprised of complex manufactured products that have already undergone significant conversion from raw materials. For example, tires, airbags, seatbelts, and computers need to be assembled into the vehicle. This assembly itself requires a complex series of energy-consuming processes. Emissions from energy use arise from electricity required to run lighting, motors, pumps, fans, welding gear, painting and body coating equipment, metal presses, and precision robotics. Process heat is also required for a large range of processes like molding plastics, hot rolling, forging and casting metals, and pickling steel to remove oxides. The balance of primary energy sources in a typical plant (for illustrative purposes) might be 56% electricity and 44% fossil fuels (Giampieri et al., 2020). Figure 3.1 from work by Sato and Nakata (Sato & Nakata, 2020) gives an overview of the material composition of an example vehicle, a 2011 Honda Accord, and the principal processes used in its fabrication.

Figure 3.1: Materials and Processes for an Example Vehicle, 2011 Honda Accord (Sato & Nakata, 2020)



iii. Transport to market

Three-quarters of all cars sold in the world today are produced in China, the US, the EU, India, and Japan (IEA, 2020a). While final auto production tends to be close to target markets (Sturgeon et al., 2008, 2009), the value chains for vehicle components may be regional or global, with the energy for freight transport mostly provided by fossil fuel sources.

iv. Vehicle use

Vehicles create emissions as they are used. A vehicle that uses an internal combustion engine powered by fossil fuels directly releases GHGs to atmosphere. An electric vehicle uses electricity to charge its batteries; today, and in most countries, this electricity is typically generated from sources that also produce emissions..

v. End-of-life disposal

As noted previously, most vehicles are mainly steel and aluminum by weight. Both steel and aluminum have excellent potential for recycling, with recovery rates of 91%-93% already found in markets with mature recycling infrastructure for vehicles; these markets include the United States or Japan (Kelly & Apelian, 2016; Ohno et al., 2015). The main reason why 100% of metals are not recycled is because of contamination during the sorting and reclamation process, but ongoing research aims to improve both the quality and the amount of aluminum (Capuzzi & Timelli, 2018) and steel (K. E. Daehn et al., 2017; Sawyer, 2016; Yellishetty et al., 2011) that can be recovered. The remaining waste fractions from automotive waste typically wind up in landfills. End-of-life disposal for plastics and textiles have been discussed in chapters 1 and 2. Lead-acid batteries for starting internal combustion engines are already widely recycled, with rates close to 99%. By contrast, and as a result of a lack of regulation or clear directives, most electric vehicle traction batteries today are simply sent to landfills (Mayyas et al., 2019). A typical automotive battery is 15% organic chemicals and 7% plastics (which may release GHGs to atmosphere as they degrade), with the remainder a mixture of heavy metals that can be highly toxic health hazards (Ordoñez et al., 2016; Winslow et al., 2018).

3.3 Decarbonization Options for Auto Manufacturing

Options for reducing the emission footprint from automotive vehicles at each stage (i-v) in the product life cycle are discussed here:

i. Upstream resource extraction

Upstream considerations for plastics and textiles have been discussed in chapters 1 and 2. The major remaining upstream emissions arise from mining operations that extract iron ore (used to produce steel), bauxite (used to produce aluminum), and lithium and cobalt (used for battery production). Steel manufacturing, aluminum manufacturing, glass manufacturing, and battery manufacturing from these raw materials are important additional sources of emissions.

a) Mining raw materials

Every mining operation has different energy requirements, but electricity is generally the largest of these, and it is usually supplied by fossil fuels. A combination of renewable electricity, battery storage, and electrolytic hydrogen may be required to decarbonize mine operations (Igogo et al., 2021).

b) Steel production

Pathways for producing net-zero steel are on the cusp of technological viability at scale (i.e., this decade). Key technologies for the 2020s include directly reducing iron using natural gas based syngas (and capturing and sequestering the emissions), directly reducing iron using green hydrogen, or making steel from recycled scrap using zero carbon electricity (Bataille, Stiebert, et al., 2021; IEA, 2020b, 2021f; Mission Possible Partnership, 2021; van Sluisveld et al., 2021; Yu et al., 2021).

c) Aluminum production

Net-zero aluminum manufacturing is possible by replacing high-carbon sources of electricity used for smelting with net-zero electricity and reactive carbon anodes with inert anodes (Gomilšek et al., 2020; IEA, 2021a; Nature, 2018).

d) Glass production

Most emissions (~75%) from a typical glass manufacturing site are from high-temperature heat from fossil fuels used for melting raw materials, with the remainder of the emissions from electricity used elsewhere in the plant (Griffin et al., 2021). Glass melting happens at extremely high temperatures (above 1500°C) (Furszyfer Del Rio et al., 2022), so fuel switching to net-zero fuels (such as green hydrogen) that can supply these temperatures will be critical for this industry.

e) Battery pack production

State-of-the-art battery production generally relies on a mixture of electricity and fossil fuels for processes such as electrode coating, drying, and cell pack assembly – all of which are processes that can be electrified with zero-carbon electricity if such a grid is made available (Aichberger & Jungmeier, 2020; Degen & Schütte, 2022).

ii. Component production and vehicle assembly

Like many industrial sectors, vehicle manufacturing depends on the production and assembly of components that in themselves involve a variety of complex processes that use significant amounts of electricity and fossil fuels for high-temperature process heat. In turn, the main pathways for achieving net-zero vehicle manufacturing will be similar to the pathways other industrial sectors must use; these pathways depend on energy efficiency, electrification of as many processes as possible with zero-carbon grid electricity, and the use of green hydrogen for high-temperature process heat (Bataille et al., 2018; Bataille, Nilsson, et al., 2021; Rissman et al., 2020). Manufacturer decisions around product design for vehicles are also extremely important. For example, one of the most important ways to reduce energy use is to cut down on the mass of the vehicle itself (Czerwinski, 2021; Kacar et al., 2018; Shaffer et al., 2021). Another important decision is the choice of drivetrain (i.e., liquid fuels or electricity). Internal combustion engine vehicles cannot easily be decarbonized due to the challenges associated with replacing automotive gasoline and diesel with biogenically derived synthetics or ethanol (essentially because of limited land use and potential conflict with food production, see (Bonsch et al., 2016; Goldemberg, 2008; Slade et al., 2014)). This means that electric vehicles should be the main focus for automotive manufacturers going forward.

iii. Transport to market

Freight-transport elements of the automotive supply chain (both finished products and intermediate components) need to be electrified or powered by net-zero liquid or gaseous synthetic fuels. Technological solutions have been scoped for decarbonizing road freight (Meyer, 2020), rail (IEA, 2019), aircraft (Bauen et al., 2020; IEA, 2021c; Viswanathan & Knapp, 2019), and shipping (Bouman et al., 2017; Mallouppas & Yfantis, 2021).

iv. Vehicle use

Electric vehicles rely on a decarbonized grid to provide a pathway to climate neutrality. This entails replacing unabated fossil fuel generation with renewable power sources, nuclear power, and/or enabling carbon capture and storage for fossil fuel emissions (IEA, 2021f). Lighter-weight vehicles with the same batteries and drivetrains will travel farther, so lighter-weight vehicles should continue also to be a focus for manufacturers (Soo et al., 2017).

v. End-of-life disposal

As noted earlier, the technical pathways for recycling most of the steel and aluminum (90%+) used in vehicles already exists and continues to improve over time. This is a question of ensuring that the required infrastructure and market incentives are in place at the necessary scale. Plastics and textiles provide a separate set of challenges for end-of-life disposal, as discussed in chapters 1 and 2. Batteries pose a challenge but one for which clear solutions are available. Lead-acid batteries and the nickel-metal-hydride batteries that are common in hybrid electric vehicles are already widely recycled with high rates of material recovery (Gaines, 2014). Infrastructure and standardized processes (clear labeling for different chemistries, for example) for handling large battery packs from electric vehicles need to be developed at scale, which may need a regulatory intervention to start in some markets (Mayyas et al., 2019). The recycling process itself (especially if aimed at recovering pure metals rather than whole batteries or components for reuse) is often energy intensive (Ciez & Whitacre, 2019; Fujita et al., 2021) and must be transitioned to using zero-carbon energy sources. Finally, manufacturers can play an important role in improving the recyclability of vehicles during the design process, both by selecting materials that can be easily recycled and structuring the components of the vehicle so that they can be easily disassembled for reuse as spare parts, or separated into individual recycling streams (i.e., using standard circular-economy principles (Aguilar Esteva et al., 2021; Baars et al., 2021; He et al., 2021)). This applies particularly to battery packs (C. Bauer, Burkhardt, et al., 2022; Harper et al., 2019) but also to other structural components such as windshields and wheel rims (McAuley, 2003; Nakano & Shibahara, 2017; Soo et al., 2017).

3.4 Implementation Strategy

Achieving net-zero automotive manufacturing requires coordinated action across multiple domains including but not limited to industrial policy, transport policy, urban planning, and power-grid planning. The technological capability to decarbonize most of the automotive value chain already exists, but the market and regulatory incentives do not. Achieving zero emissions from vehicle use requires coordinated action between auto manufacturers and policymakers in several key domains and may also require institutional strengthening to enable investment to be directed where it is needed (Mielke & Steudle, 2018). Some examples: neither the zero-emission production of vehicles nor zero-emission use of vehicles can be achieved without a power grid that is itself net zero. Electric vehicle use is unlikely to become widespread unless cities, regions, and countries (on their own or with industry) plan for networks of public charging stations that are fast and widely available. Industry cannot move with confidence to invest in new designs unless they are confident of robust markets for their products.

Manufacturers have some degree of buy-in to investing in net-zero vehicles, but rapid adoption will need sustained policy support and regulation. At the time of writing (early 2023), all major auto manufacturers have brought, or are about to bring, electric drivetrain vehicles to market; at the same time, most are also still making and selling vehicles powered by internal combustion engines that run on fossil fuels. Even with low fuel prices, electric vehicle technology is likely to continue to improve, reach parity with, and eventually surpass the performance of vehicles that run on fossil fuels (Kapustin & Grushevenko, 2020). Nevertheless, a complete transition to electricity on a timeline to achieve the net-zero targets that can in turn achieve the goals of the Paris Agreement needs regulatory pressure (IEA, 2021d; Rietmann & Lieven, 2019). Automakers have historically fought against almost every single health or environmental regulation, including emissions (Chowkwanyun, 2019; Farrauto et al., 2019), vehicle efficiency standards (Penna & Geels, 2012), air bags, and seat belts (Sperling et al., 2004). There is no reason to believe that things will be different in a regulatory environment to bring about a net-zero vehicle fleet. Policymakers must consider the whole value chain and the life cycle of vehicles, which may mean going beyond simply mandating that drivetrains are electric. Regulatory actions may need to require other actions; for example, regulations could encourage the production of lighter-weight vehicles by employing taxes based on weight (Shaffer et al., 2021).

Both upstream inputs to auto manufacturing and the downstream disposal of vehicles need additional research and policy support. For upstream inputs (e.g., steel, aluminum, plastic, glass) for auto manufacturing to achieve net-zero standards, markets need transparent and uniform standards and procedures to account for emissions. These are not yet widely established. For example, many auto manufacturers are keen to start using “green steel” in their cars (Muslemani et al., 2022), but a standardized definition of green steel that can be adopted as part of product standards and labeling regulations or in trade negotiations does not yet exist (Muslemani et al., 2021). The big picture for downstream disposal is that it is technically already possible to recycle almost an entire vehicle (~90% (D’Adamo et al., 2020)); however, the economic and market incentives for full recycling, and for the vehicles themselves to be designed in a way that would enable near total recycling (i.e., near 100%) still need to be established through regulation (Khodier et al., 2018; Vermeulen et al., 2011; Weidenkaff et al., 2021).

CHAPTER 4 FISHERIES

4.1 Key Conclusions

Creating a net-zero fisheries sector requires regulatory and market interventions to incentivize technological change, at both the national level (e.g., for fisheries, fish farms, feed production, fish processing, energy supply, and cold-chain/refrigeration) and the international level (e.g., for fishing activities in international waters, and long-distance transport).

Pain point: The large-scale provision of net-zero electricity and low-carbon, synthetic fuels (such as green hydrogen, ammonia, or synthetic hydrocarbons and alcohols) will be required to decarbonize feed-pellet production, shipbuilding, fishing-vessel powertrains, fish farms, fish-processing plants, powertrains for long-distance cargo vessels, and ship-recycling segments of the seafood value chain.

Pain point: Moving forward will require national road-mapping exercises to understand the baseline conditions of the fishing fleet and seafood-farming sectors, and to chart pathways in line with national decarbonization plans.

Pain point: Achieving net-zero fisheries will require coordination among a wide range of parties governing and setting out policies for shipping and maritime activities; energy supply; and agricultural, food, and industrial sectors. This represents a steep, international policy-coordination challenge across multiple national boundaries and jurisdictions.

Pain point: Downstream disposal of fishing vessels requires creating a more circular economy and, due to the international nature of the shipbreaking and recycling businesses, strong coordination at the global level.

4.2 Overview of Emissions from Fisheries

The fishing industry is an energy- and emissions-intensive sector that is powered almost entirely by fossil fuels. In the modern era, the global fishing fleet is primarily made up of industrial vessels (A. Sala et al., 2022). As of 2020, an estimated 4.1 million vessels were in operation, two-thirds of them operating in Asia (FAO, 2022). Fishing craft are powered almost exclusively by fossil fuels, mostly marine diesel and fuel oil (Flammini et al., 2022). Fuel use accounts for around 60% of the cost of operating a fishing fleet (Tyedmers et al., 2005). Demand for seafood is increasing, as growing population and rising incomes globally have driven greater demand for animal proteins (Tilman & Clark, 2014); fish supplied per capita has roughly tripled since 1950 (Béné et al., 2015). Wild-capture fisheries supply around 90 million-95 million tonnes of fish per year; this is just under half of the global total (FAO, 2022).

Aquaculture (seafood farming) is a fast-growing sector that is also emissions intensive. As demand for seafood continues to rise, aquaculture (fish farming) has become one of the fastest growing food- production sectors in the world (Anderson et al., 2017; Gentry et al., 2017). Aquaculture offers one potential pathway for increased production of food from the oceans in the future (Costello et al., 2020), although this may need to overcome socio-ecological constraints such as concerns over marine pollution (Costa-Pierce & Chopin, 2021; Farmery et al., 2021).

The rise of seafood farming has occurred as overfishing of wild stocks has become a major food security challenge and a threat to ocean ecosystems in a number of regions, notably in the tropics (Cabral et al., 2019; Coll et al., 2008; Link & Watson, 2019). Wild-capture fisheries in many regions have risked extracting more stocks than is viable to sustain marine animal populations (Costello et al., 2016), and total global production from fisheries has essentially plateaued since the 1990s.

Aquaculture offers one potential pathway for increased production of food from the oceans in the future (Costello et al., 2020), though ecological concerns have been raised about, for example, marine pollution (Costa-Pierce & Chopin, 2021; Farmery et al., 2021). Pollution from aquaculture includes organic waste accumulating in sediments, nitrogen leakage from uneaten fish feed, and the release of antibiotics and other chemicals into the marine environment (Miranda et al., 2018; Reverter et al., 2020; Wu, 1995).

Aquaculture statistics show current production levels of around 100 million tonnes of seafood per year (FAO, 2022).[3] It is difficult to generalize an emissions footprint for aquaculture because there is such variability in farming and transporting different species in different parts of the world for different markets (Jones et al., 2022; Poore & Nemecek, 2018). However, in broad terms, GHG emissions from aquaculture are similar in overall magnitude to most terrestrial animal farming and some wild-capture fishing (M. J. MacLeod et al., 2020; Tilman & Clark, 2014).

Emissions from both aquaculture and wild-capture fishing are growing rapidly. The rapid rise in the amount of fish being consumed and the increased reliance on fossil fuel-powered vessels led emissions from the global fishing sector to quadruple over the period from 1950 to 2016 (Greer et al., 2019). Direct emissions from wild-capture fishing are overwhelmingly the result of fossil fuel use (Parker & Tyedmers, 2015), and are estimated to represent around 200 million tonnes of CO_2 equivalent GHGs ($MtCO_2e$)

3 The edible portions of many farmed species (e.g., crustaceans and mollusks) are less than their full weight. Thus, some research contends that aquaculture provides far lower amounts of edible food, perhaps only half as much as the 100 million tonne estimate (Costa-Pierce & Chopin, 2021; Edwards et al., 2019).

annually, around 0.6% of global emissions.[4] Aquaculture is also a rapidly growing source of emissions (Yuan et al., 2019); estimates indicate that it generates 250 Mt CO_2e/year (M. J. MacLeod et al., 2020), a level that represents roughly 0.5% of global emissions.

Growing demand, technological shifts, and climate change are driving emissions from the fishing sector progressively higher over time. Data on fishing activities and the related energy use and emissions are often difficult to obtain and verify. The Food and Agriculture Organization of the United Nations (FAO) notes that around 40% of countries that have fishing fleets do not report data to the FAO (FAO, 2022). The accuracy of reported statistics is often contested (Pauly & Zeller, 2017b; Ye et al., 2017). Many reports fail to distinguish fisheries data from other agricultural data (Flammini et al., 2022); some data submissions are believed to have been manufactured or altered for political purposes (Moutopoulos & Koutsikopoulos, 2014; Pauly & Zeller, 2017a). With these caveats, the best estimates from the academic literature are that around half of all emissions from fishing are produced by just five countries: the US, China, Japan, Indonesia, and Vietnam (Parker et al., 2018). As a general trend, emissions are believed to be increasing, not only because of increased demand for fish, but also because vessels are making longer trips as fish habitats have shifted due to climate change (Madin & Macreadie, 2015). Aquaculture activities are also expanding into deeper waters (Gentry et al., 2017), a trend that may increase energy use and emissions generated by longer travel routes to and from farming operation.

Fisheries can be thought of as a value chain comprising both wild-catch and aquaculture components that deliver seafood to markets, with emissions arise during the following distinct stages (i-v):

i. Upstream inputs

Both wild capture and aquaculture make use of marine vessels of various sizes, ranging from small inland or littoral (coastal) watercraft 4 meters or 5 meters in length to large industrial-scale ships of more than 100 meters in length. China (41%-45%), South Korea (30%) and Japan (20%) are the largest global players in shipbuilding (OECD, 2022b). By weight, mass-manufactured ships are largely comprised of steel, aluminum alloys, and plastic composites (Chalmers, 1988; Molland, 2008). The manufacturing of steel, aluminum, and plastic inputs used in shipbuilding are all emissions-intensive processes that are part of the total greenhouse gas (GHG) footprint of the industry. Shipbuilding itself also is an energy- and emissions-intensive enterprise that involves significant metalworking (e.g., cutting blasting, welding, coating, painting) and moving heavy components into place using cranes and other specialized equipment (Mandal, 2017; Vakili et al., 2021; Vakili, Schönborn, et al., 2022). Electricity is also typically used to produce large volumes of gases (such as oxygen and acetylene) for welding directly on site (Hadžić et al., 2018). Aquaculture, unlike wild-capture fishing, makes use of manufactured feed as a food source for the target species being harvested. Fish and other marine animals (e.g., crustaceans) are fed with high-protein pellets, often called aquafeeds, which are made from by-products of wild-catch fishing (fish meal and fish oil), plant-based proteins (soy, corn), or livestock production by-products (meat, bone meal) (Hua et al., 2019). The upstream agricultural, manufacturing, and transporting of feed pellets for aquaculture farms are a significant source of GHGs

4 It is possible that indirect emissions from fishing mean that this figure is far higher. Some recent work argues that disturbances to the seabed from fishing activities that drag heavy nets across the ocean floor ("bottom trawling") causes CO2 that was previously held in the sediment itself to dissolve in water and, in turn, to release GHGs to atmosphere. This may mean that fishing-related emissions could potentially be in the range of 600-1500 Mt CO2e, with the upper end of this range comparable to the emissions generated by the entire global aviation sector (E. Sala et al., 2021).

(Bujas et al., 2022); for many species these processes can account for between 57%-70% of the total emissions footprint of the seafood (Gephart et al., 2021; M. J. MacLeod et al., 2020).

ii. Operational phases

Wild-capture fishing and aquaculture both require marine vessels to travel to and from the locations where fish are to be caught or harvested. Wild-capture fishing typically involves the most travel. Research suggests that the energy consumption of ships depends on a number of factors such as the structure and size of the vessel, the engine design and condition, the type of fishing gear and equipment (such as lines and nets for catching the fish), the movement pattern of the vessel during fishing, the distance traveled, and the type of species and migration routes of the fish targeted (Basurko et al., 2013; Parker & Tyedmers, 2015; A. Sala et al., 2022). Wild-capture fishing operations typically send their catch directly onward to processing and packaging facilities directly from the landing dock. Aquaculture operations feature a number of additional emissions sources besides ship transport of marine life to and from the farm site. These include emissions from energy used for lighting, air conditioning, water-circulation pumps, aeration systems (to oxygenate water), and automatic feeding machines (Troell et al., 2004). The energy supplied for aquaculture processes typically comes from grid electricity for land-based farms and for diesel generation for ocean-based farms, with inputs of up to 3 kWh/kg of food produced (Vo et al., 2021).

iii. Processing and Packaging

With the exception of the very largest "factory ships" that incorporate a degree of fish processing during wild-capture operations (Kose, 2010), both wild-capture fishing and aquaculture typically process and package their products in land-based facilities. Fish "processing" involves a sequence of activities like stunning, grading, removing slime, scaling, washing, de-heading, gutting, cutting of fins, slicing into steaks, filleting, and separating meat from the bone. All of these activities require a variety of specialized equipment, usually electrically powered devices, though some steps are occasionally performed by hand by skilled manual laborers (Ghaly et al., 2013; Quijera et al., 2014; Thrane et al., 2009). Depending on the final product, additional processing such as curing, drying, salting, and smoking (typically at temperatures between 70°C-100°C) might also be required (Horner, 1997). Packaging processes include canning, chilling, and freezing, all depending on the final product (Hall, 2010a, 2010b). Significant energy use at this stage in the value chain results from powering mechanical equipment, driving pumps and motors, generating steam, heating water, producing ice, and refrigerating the product (Boziaris, 2013). Refrigeration accounts for almost 70% of the energy demand of a typical fish-processing plant (Nordtvedt & Widell, 2020).

iv. Transport to market

Wild-capture fisheries and aquaculture both produce seafood that must be processed and packaged for transportation to markets. Depending on the destination market, seafood might travel by road, rail, air, sea, or a combination of these. An estimated 40% of seafood products are globally traded (Parker et al., 2018), traveling many thousands of kilometers (Gephart et al., 2016; Watson et al., 2015, 2017). Depending on the product (e.g., dried, canned, chilled, frozen), seafood may need to be refrigerated to different temperatures; fresh fish is typically stored at 0°C -4°C, while frozen fish is typically stored at -18°C (Alasalvar & Quantick, 1997). Emissions at this stage of the value chain arise from the fuels used for transportation and the energy used for refrigeration and freezing.

v. Ship disposal

Ship disposal involves dismantling marine vessels used for cargo transport or fishing activities at the end of their useful lives and the reuse or reprocessing of their materials into useful forms. Dismantling a ship is essentially the reverse process to ship construction (covered in the first item (i) of this list), with largely the same direct energy and emissions considerations. The energy requirements for primary raw material extraction in shipbuilding are roughly the same as the energy needs of reprocessing for ship disposal. The steel and aluminum materials used to construct most vessels are materials with excellent recycling potential. In principle, both aluminum and steel can be fully recycled, but in practice, however, contamination of the metals during the sorting and reclaiming processes lead to recycling levels below 100%. Nevertheless, in theory, it is possible to come very close to full recycling. In the case of road vehicles, markets in Japan and the United States have shown that it is possible to recover 91%-93% of these metals and to process them for reuse (Kelly & Apelian, 2016; Ohno et al., 2015). Despite this potential, more than 80% of global shipping materials (by weight) are scrapped in a typical year in India, Pakistan, and Bangladesh, with Turkey and China being other significant global players in the scrappage market (UNCTAD, 2021). The recycled materials are then used domestically or globally traded.

4.3 Decarbonization Options for Fisheries

Options for reducing the emissions footprint from fisheries at each stage (i-v) in the product life cycle are discussed here:

i. Upstream inputs

Both wild-capture fishing and aquaculture make use of ships. Decarbonizing upstream manufacturing inputs to shipbuilding requires specific interventions in mining raw materials (Igogo et al., 2021), steel manufacturing (Bataille, Stiebert, et al., 2021; IEA, 2020b, 2021f; Mission Possible Partnership, 2021; van Sluisveld et al., 2021; Yu et al., 2021), aluminum production (Gomilšek et al., 2020; IEA, 2021a; Nature, 2018), and plastics (see chapter 1 for further details). The energy for fabricating ship components and assembling them into finished vessels would need to be provided from zero-carbon sources to achieve net-zero ships (Vakili, Ölçer, et al., 2022; Vakili, Schönborn, et al., 2022). Upstream agricultural emissions are an additional major contributor to the GHG footprint of aquaculture operations. Decarbonizing the production of the feed will involve changes to upstream agricultural processes such as using zero-emission electricity to power farm operations and using other carbon sinks to balance GHGs emissions from nitrogen fertilizer production and use (Hedayati et al., 2019; M. MacLeod et al., 2015). Aquaculture itself has the potential to provide or contribute to various types of carbon sinks, such as using shells from cultivated bivalves (e.g., clams, oysters, mussels) or seaweed to sequester carbon but these are not techniques that have necessarily been proven yet at scale (Jones et al., 2022).

ii. Operational phases

A number of interventions can reduce emissions during the operational phases of wild-capture fishing and aquaculture harvesting.

a) Operational changes

Decisions about what species to target for capture and/or to cultivate are important determinants of emissions intensities. The fundamental nutrient requirements, habitats, and migration patterns differ by species. Both wild-capture fishing and aquaculture involve a degree of discards and losses, which in some fisheries are estimated as high as 25% (Béné et al., 2015). Implementing best practices to prevent fish being lost or dumped and to reduce waste would contribute to reducing the emissions associated with production. In wild-capture fishing, emissions can be reduced through behavioral changes such as reducing vessel speeds, optimizing fishing locations and times for fish (Abernethy et al., 2010), and selecting the correct type of fishing gear (line and net type) to the fish type targeted (Basurko et al., 2013); such measures can make a large difference in emissions (Bastardie et al., 2022).

b) Retrofitting existing ships

The energy performance of existing vessels can be improved to make better use of their fuel and to reduce emissions per unit of production. Existing vessels can be made more efficient through the use of shipboard energy-management systems to optimize, for example, refrigeration and engine performance (Basurko et al., 2013).

c) New ship designs

In the long term it will be necessary to develop vessels with improved hull shapes (Barreiro et al., 2022; Lindstad et al., 2022) and propulsion systems that do not rely on fossil fuels. Alternative propulsion systems include using net-zero electricity via batteries (Jeong et al., 2020), high-technology sails (Lindstad et al., 2022), fuel cells (Baldi et al., 2020; Horvath et al., 2018), or internal combustion engines running on biofuels (Kesieme et al., 2019), methanol (Helgason et al., 2020; Korberg et al., 2021), hydrogen (Atilhan et al., 2021; Bicer & Dincer, 2018), ammonia (Al-Aboosi et al., 2021; Zincir, 2022), and hybrid fuels (Karvounis et al., 2022; Mäkitie et al., 2022; Pan et al., 2014). Using liquefied natural gas (LNG), which is also a fossil fuel, has been studied as an alternative that could potentially generate lower emissions levels than marine diesel oil (Balcombe et al., 2021; Schinas & Butler, 2016; Sharafian et al., 2019) but LNG is not a net-zero solution for shipping (Balcombe et al., 2019; Fun-sang Cepeda et al., 2019).

d) Aquaculture operations

To reduce emissions overall, aquaculture must reduce the emissions that stem from both feed production (discussed above in section 4.2 of this chapter) and feed waste. A typical aquaculture facility produces a large amount of waste as large amounts of feed are often released but are not eaten (Ballester-Moltó et al., 2017). To optimize the amount and timing of food release and to reduce waste, the industry may be able to employ precision monitoring and automation using cameras, sensors, and artificial intelligence (Føre et al., 2018). In the long term, additional savings may be achieved by improving the feed conversion ratio to optimize the amount of feed required per kilogram of seafood produced by changing feed composition (Hua et al., 2019) or using genetic engineering (Besson et al., 2016).

e) Aquaculture energy supply

Aquaculture operations largely use grid electricity where they are inland or close to shore, and diesel fuels when offshore. Large-scale decarbonization of grid electricity and replacement of diesel fuels with zero-emissions alternatives will be required to bring aquaculture operations in line with net-zero aspirations. A number of existing studies have investigated the integration of renewable energy with aquaculture operations (Bujas et al., 2022; Scroggins et al., 2022; Vo et al., 2021), including floating solar (Pringle et al., 2017) and wave energy generators (Garavelli et al., 2022) for sites that are far offshore. Very remote locations may also need to supplement their energy-supply systems with batteries and/or a form of low-carbon fuel supply such as green hydrogen (Jebsen, 2021).

iii. Processing and Packaging

Most processes in a typical fish-processing plant are either powered by electricity or are suitable for electrification. In many existing plants the heat for steam generation (for sterilization) and drying is often provided by combustion of fossil fuels (Boziaris, 2013), but the temperatures involved are relatively low and can now comfortably be provided with commercially available industrial heat pumps (Arpagaus et al., 2018) or technologies such as high-temperature solar thermal (Quijera et al., 2014). Depending on local resources and conditions, decarbonization of the electricity supply can be achieved either using grid-supplied net-zero electricity, on-site renewables, low-carbon fuels, or a combination of all of these (Alzahrani et al., 2019, 2020, 2022).

iv. Transport to market

Transporting seafood to market will require technological change to decarbonize cargo modes such as road freight (Meyer, 2020), rail (IEA, 2019), aircraft (Bauen et al., 2020; IEA, 2021c; Viswanathan & Knapp, 2019), and shipping (Bouman et al., 2017; Mallouppas & Yfantis, 2021). Maritime vessels handle 80% of global trade (by volume) (Walsh et al., 2019). The technological options for reducing emissions from long-distance shipping are similar to those for fishing vessels (discussed in item (ii)(b) and (ii)(c)). Options include optimizing hull design and power and propulsion systems; using alternative fuels and energy sources; and changing operations to maximize efficiency (e.g., matching speed to sea conditions) (Bouman et al., 2017; Jimenez et al., 2022).

v. Ship disposal

The technological potential exists to recycle nearly all of the steel and aluminum used in ships. Ship recycling is an industry in which the main players act as both customers (who bid for and buy end-of-life ships) and sellers (who sell scrapped materials and equipment). In addition, the main shipping-industry players participate in related industries, such as the scrap-steel industry. In an open and globally traded market, the value of scrap steel is the major driver of recycling activities (Sornn-Friese et al., 2021). Reconfiguring the business ecosystem for ships to achieve a more circular economy will likely require a global effort to coordinate and regulate activities under the umbrella of the main ship classification societies (e.g., Lloyd's Register, the American Bureau of Shipping, Nippon Kaiji Kyokai) and will need to involve the countries where most shipbreaking occurs (India, Pakistan, Bangladesh, Turkey, and China) and the International Maritime Organization (IMO) (Milios et al., 2019). Moving ahead will require support for the reuse and remanufacturing of refurbished equipment and products, the creation of technical performance standards for second-life parts and equipment to qualify for shipping insurance, and segmentation of the scrap market by alloy and contamination levels to help make various grades of recycled steel available for different end uses in ship construction.

4.4 Implementation Strategy

Achieving net-zero fisheries requires regulatory and market interventions to incentivize technological change, at both the national level (fisheries, fish farms, feed production, fish processing, energy supply, and cold chain/refrigeration) and international level (fishing activities in international waters, and long-distance transport). The long asset lifetime of marine vessels and port infrastructure (Bullock et al., 2022), usually measured in decades, means that price competition and technological competition alone may not be enough to bring about changes fast enough to meet the goals of the Paris Agreement. International collaboration between trading nations, regulation, subsidies, and the use of market-based instruments (e.g., environmental taxes, carbon offsets, carbon credit-trading systems) will be required to incentivize important technological shifts (Cullinane & Yang, 2022; Lagouvardou et al., 2020; Psaraftis, 2012; Psaraftis & Kontovas, 2020). Shipping practices and shipping vessels (both for carrying seafood and all other kinds of traded cargo) are essentially regulated internationally through the IMO and various national classification societies whose data are used as the basis for critical activities such as providing shipping insurance. Regulations and standards for fishing vessels and seafood farming are controlled by individual countries within their territorial waters and through various regional fisheries-management bodies in international waters.

The large-scale provision of net-zero electricity and low-carbon, synthetic fuels (such as green hydrogen, ammonia, or a net-zero version of diesel) will be required to decarbonize many key aspects of the industry – feed-pellet production, shipbuilding, fishing vessels, fish farms, fish-processing plants, long-distance cargo vessels, and ship-recycling segments of the seafood value chain. The energy-supply technologies to decarbonize most of the fisheries value chain already exist, but the market and regulatory incentives to deploy these at scale are not in place. Such incentives will need to be designed into policy. Clean electricity is a prerequisite for the energy supply for feed-pellet production, shipbuilding, ship recycling, and fish processing; infrastructure for providing both clean electricity and synthetic zero-emission fuels will be required to decarbonize fishing vessels, fish farms, and cargo transport.

National road-mapping exercises are needed to understand the baseline condition of the fishing fleet and seafood-farming sectors and to chart a course toward zero emissions in line with national decarbonization plans. Data on fishing and aquaculture activities are often sparse or highly aggregated with other economic activities, which can make policy design challenging. At the national level, government departments and industry associations will need to first establish an inventory of existing assets, such as the extent and quality of the fishing fleet. A phased transition toward zero-carbon fisheries can then be created, taking into account country-specific conditions (technological, societal, economic and regulatory) and species-specific considerations. Areas that merit exploration include the impact of non-technical measures, such as intentional choices about which species to farm or fish; the prospects for retrofitting existing farms and fishing vessels to reduce waste and use the best available practices and technologies; the use of drop-in fuels that can offer incremental emission reductions and work with existing vessels and port infrastructure, such as biodiesel (Sevim & Zincir, 2022); and the timescales for introducing alternative fuels and ship designs. Green hydrogen and green ammonia are considered frontrunners for fuels to replace marine diesel oil, with LNG seen as a short-term option (Gray et al., 2021; Inal et al., 2022; McKinlay et al., 2021; Moshiul et al., 2022). Vessels powered by hydrogen are under construction in several markets such as Norway, France, and South Korea, and these should soon enter service; for example, Hyundai is designing hydrogen-powered fishing vessels (Nazir et al., 2020). Synthetic fuels made from renewable electricity are expected to become cost competitive with conventional marine diesel oil during the 2030s (Horvath et al., 2018).

Achieving net-zero fisheries will require coordination among parties responsible for setting agricultural and industrial policy, governing shipping and maritime activities, regulating the energy-supply sector – along with dedicated support for business. The energy and emissions components of the fisheries value chain often do not neatly fall into the structure of existing government departments. For example, one department might regulate ship design and safety, another might address agricultural policy and standards, yet another might manage ocean and coastal environmental issues, and yet another set energy policies. Intergovernmental coordination and agreement will therefore be essential to set and sustain a cohesive policy mix and direction over time. Large parts of the fishing industry in many countries often include many small- and medium-sized companies that may not have internal resources for planning and undertaking large-scale changes to business operations or investing in relevant research and development; thus, these businesses will likely need government support, both through provision of information and through financing. For example, research in Norway, a major fishing power, suggests larger and more established players are attempting early adoption of low-carbon fuels for marine transport, with comparatively younger and smaller businesses lagging behind (Mäkitie et al., 2022).

Downstream disposal of fishing vessels requires creating a more circular economy, which will require strong coordination at the global level because of the international nature of shipbreaking and ship-recycling operations. Bringing greater circularity to the end-of-life issues will require a globally coordinated effort between the IMO and national shipping classification societies. The governments of the major shipbreaking nations – India, Pakistan, Bangladesh, Turkey, and China – will be important in ushering in such changes.

2

COUNTRY ANALYSIS

CHAPTER 5 COLOMBIA

5.1 Key Conclusions

Decarbonizing plastics, textiles, auto manufacturing, and fisheries in Colombia requires an overarching net-zero industrial strategy.

Pain point: To create net-zero industries will require creating a zero-emission power grid, and providing access to imported or domestically produced synthetic fuels such as green hydrogen and green ammonia.

Pain point: Government policy and direction are almost certainly needed to provide access to low-carbon fuels and low-carbon sources of electricity to meet Paris Agreement commitments and timeframes.

Opportunity: Colombia has submitted a net-zero strategy to the United Nations, and is already aligning key economic, industrial strategy and energy policy documents such as the national development plan (*Plan Nacional de Desarrollo 2022-2026*), the reindustrialization strategy (*Política de Reindustrialización*) and the national energy plan (*Plan Energético Nacional (PEN) 2020 – 2050*), within this overarching framework. As a result, it is already possible to begin the process of developing strategic net-zero roadmaps for individual industrial sectors.

Opportunity: Colombia has begun to expand regional electricity access, and to improve grid transmission between its regions to move electricity from areas with abundant renewable-energy resources to areas that are demand centers.

Opportunity: Colombia is already a regional leader in thinking about circular economy and domestic production of “green” hydrogen fuel from renewable resources, two key building blocks of a net-zero industrial roadmap.

Opportunity: Colombia may wish to explore the concept of creating GHG-neutral industrial clusters to share critical infrastructures such as CCS, hydrogen, and ammonia. This may be an opportunity to create opportunities in economically depressed regions of the country.

5.2 Overview

Exploring options for placing the Colombian plastics, textiles, auto manufacturing and fisheries industries on a pathway to net-zero emissions is the objective of this report. The plastics, textiles, auto manufacturing, and fisheries industries are a significant part of the Colombian economy, together responsible for 8% of export activity (OEC, 2022). Colombia has recognized the multiple threats emerging from climate change by recognizing the Paris Agreement in domestic law (Congreso de la República de Colombia, 2017) and submitting targets to the UNFCC as part of the official Colombian Nationally Determined Contribution (NDC), which signals the intention to achieve significant reductions in emissions by 2030 (República de Colombia, 2020) and net-zero aims by 2050 (Gobierno de Colombia, 2021). Both the 2022-2026 National Development Plan (DNP, 2023) and the forthcoming Reindustrialization Policy (MINCIT, 2023) argue explicitly for industrial decarbonization and a green energy transition. Climate risks for Colombia include the loss of coastal territories to sea-level rise (Nevermann et al., 2022), increased hydropower variability, and vulnerability of the electricity system to dry periods (Arango-Aramburo et al., 2019; Restrepo-Trujillo et al., 2020), water scarcity (Molina & Bernhofer, 2019; Ríos Hernández et al., 2022), and declines in agricultural productivity (Ospina Noreña et al., 2017; Quiroz et al., 2018).

Key questions for Colombia's aim to decarbonize industrial activity concern the availability of low-carbon electricity and the changing role of the fossil fuel industry. Most of Colombia's electricity (70%-86% over the 2016-2020 period) in recent years has been generated from 17 GW of installed hydropower (UPME, 2020) but the system has been recognized as being increasingly vulnerable in dry years (Arango-Aramburo et al., 2019; Henao et al., 2020). Accordingly, Colombia has set out plans to expand and diversify its electricity system using non-hydro renewables in the latest national energy plan *(Plan Energético Nacional (PEN) 2020 – 2050*) (UPME, 2019a).

Colombia is the largest producer of coal in South America (EIA, 2022) and a major producer of oil and gas, with resource extraction for export being an important historical contributor to the country's human and economic development (Strambo & González Espinosa, 2020; Viviana & Castillo, 2019). Energy policy must thus consider the changing role of fossil fuels globally and domestically. Indeed, the Colombian fossil fuel sector risks entering a period of decline. A large fraction of Colombian natural gas is actually already being reinjected into oilfields to boost production, and some studies suggest that domestic resources have peaked, with Colombia likely to become a net overall importer of fossil fuels by the end of the decade (Chavez-Rodriguez et al., 2018). In a future net-zero world there is also a strong possibility that Colombian coal mining for export could become a less attractive business proposition as markets move decisively away from importing coal (Oei & Mendelevitch, 2019; Weber & Cabras, 2021). For example, in key export markets, such as the EU, the drive for increased energy security in the wake of the Russia-Ukraine war may result in increased coal use in the near term, only to see the reliance on imported coal eliminated from the EU energy system in the longer term. Figure 5.1 shows that coal and coke currently account for around 15% of Colombian exports ($4.8 billion), with crude and refined petroleum products representing 28% ($9 billion) (OEC, 2022). The main export markets for Colombian products (see Figure 5.2) are the United States (30%, $9.6 billion), the EU (13%, $4.1 billion), and China (9%, $2.8 billion). A net-zero future provides a range of opportunities for the Colombian fossil fuel industry to redeploy its significant industrial and human capital to provide much-needed services and products for the energy transition, as discussed in greater detail in chapters 5.7 and 5.8.

Figure 5.1: Colombian Exports to Rest of World, 2020, HS4 Coding (Colors Correspond to Different HS4 Trade Code Groups) (OEC, 2022)

Total: $32.2B

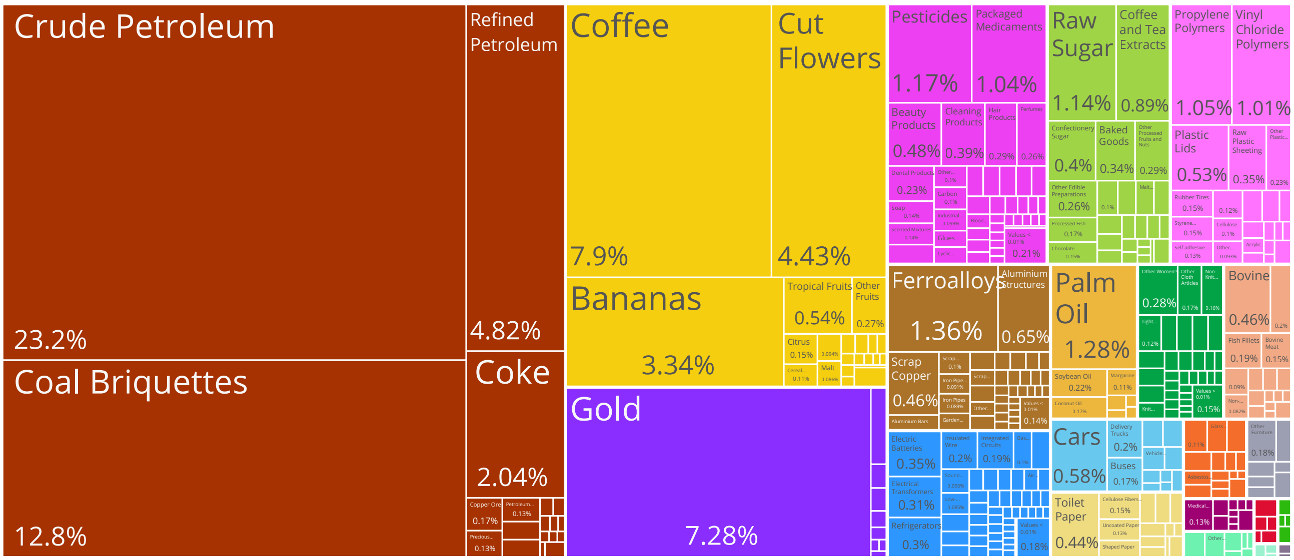
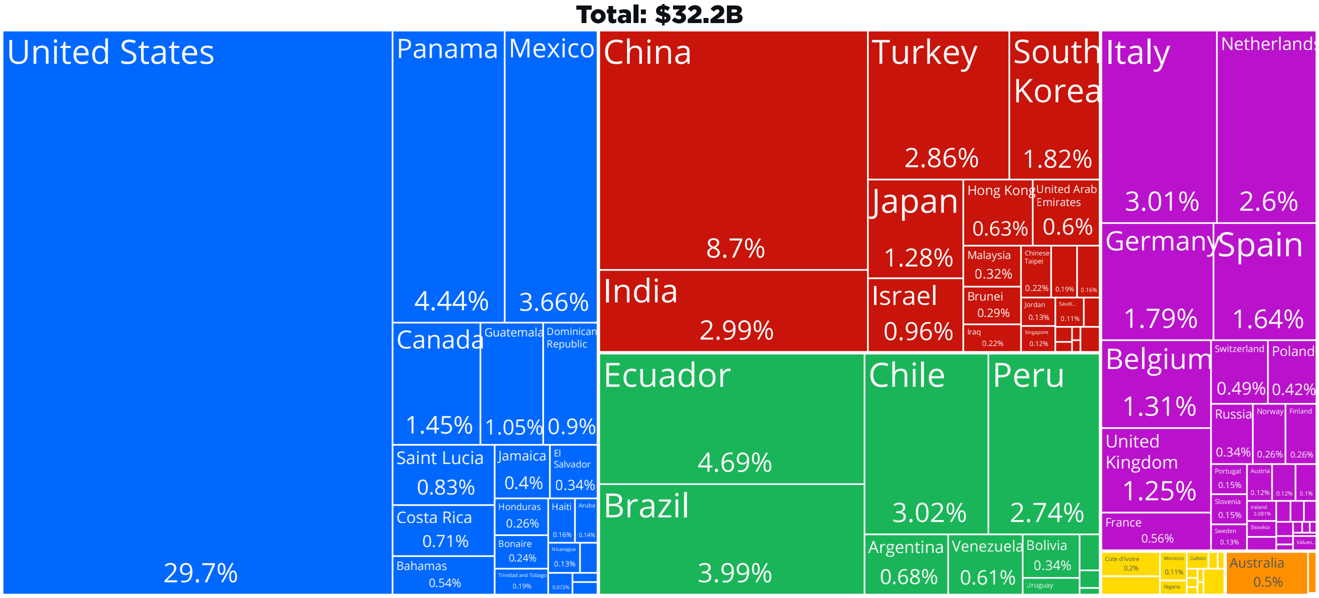


Figure 5.2: Colombian Exports to Rest of World, 2020, Percent by Country (OEC, 2022)

Total: $32.2B



5.3 Decarbonization of Plastics in Colombia

Market Overview

Plastics and synthetic rubbers accounted for $1.42 billion of Colombian exports in 2020, or about 4.4% of the total (OEC, 2022). Bulk polymers (propylene and vinyl chloride combined) represent a large fraction (47%) of total exports; finished plastic products are also significant, particularly plastic sheeting (13%) and plastic lids (8%) (see Figure 5.3). Nearly all (90%) of Colombia's plastic products are exported regionally to South and North America with comparatively few goods being shipped longer distances to Europe or Asia. Brazil stands out as being a particularly large market for Colombian plastics; it is the destination for 29% ($409 million) of plastics exports, most of which are bulk polymers (vinyl chloride, propylene and styrene) in raw forms that are likely used in Brazilian industries for manufacturing finished products.

Figure 5.3: Colombian Exports of Plastics and Rubbers, 2020, Percent by HS4 Category (OEC, 2022)

Total: $1.42B

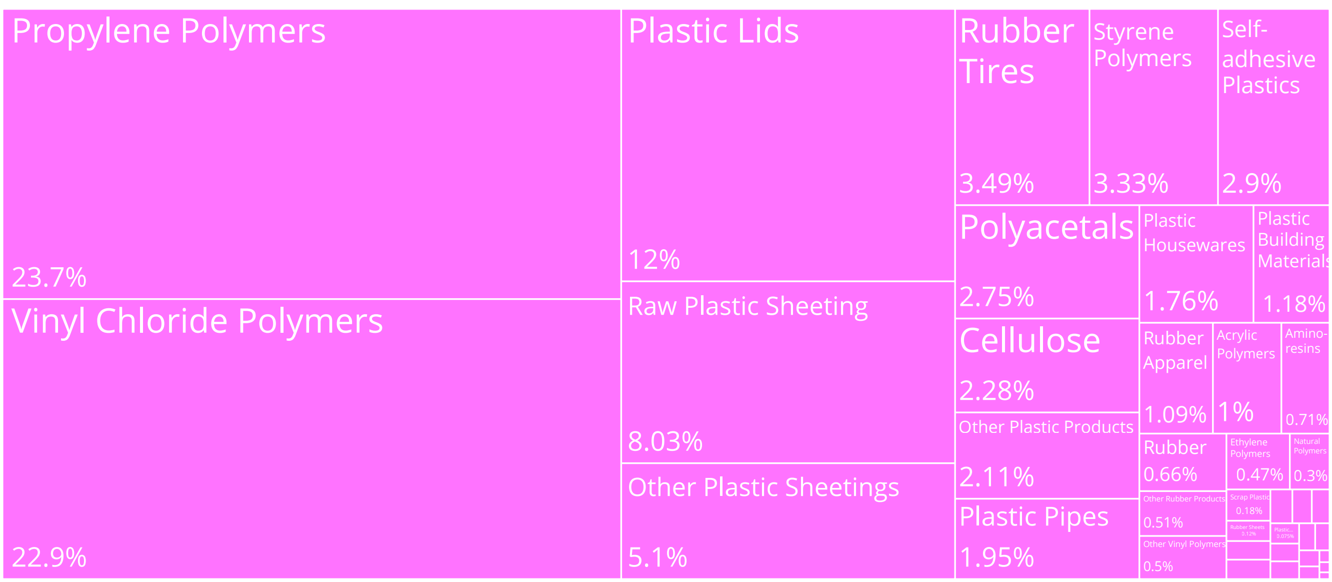
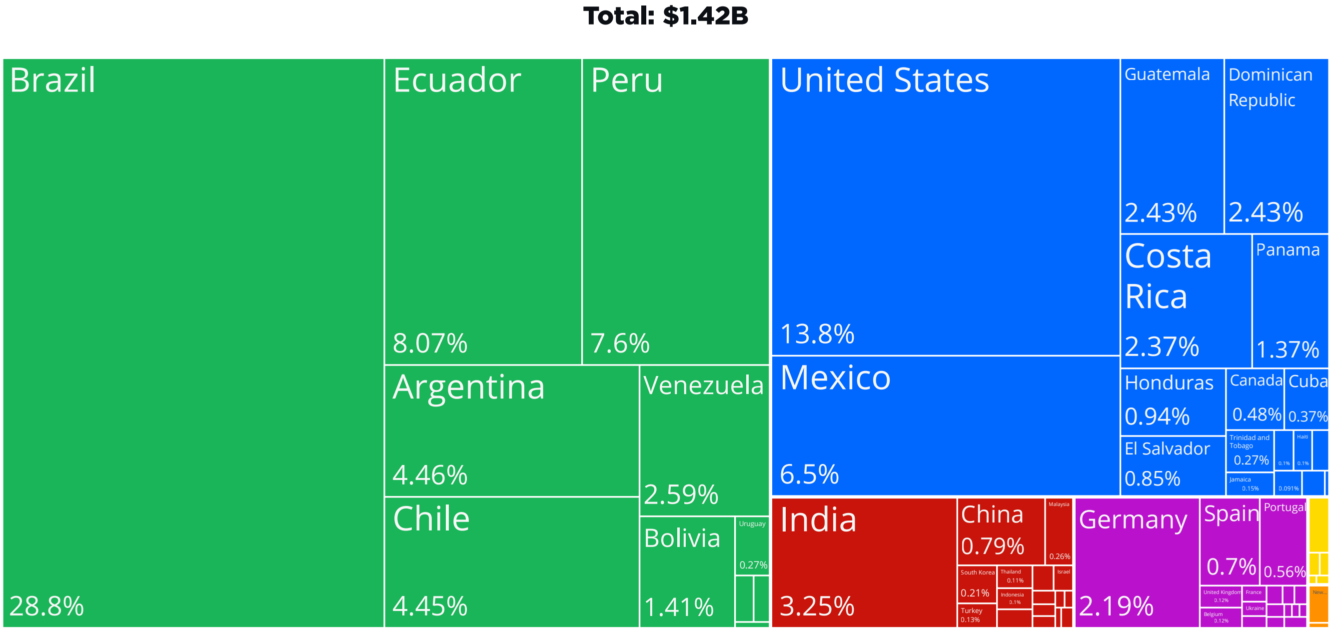


Figure 5.4: Colombian Exports of Plastics and Rubbers, 2020, Percent by Destination (OEC, 2022)



Technological Opportunities

Opportunities for reducing emissions from the plastics sector exist throughout the value chain (see chapter 1 for further detail). To address emissions from raw materials, the key approach for plastics is to replace fossil fuel-based feedstocks with biomass (Negri & Ligthart, 2021; Saygin & Gielen, 2021; Scott et al., 2020; Zheng & Suh, 2019), air-captured carbon dioxide (Lange, 2021; Palm et al., 2016; Palm & Svensson Myrin, 2018), or recycled carbon from waste (Carus et al., 2020; Moretti et al., 2020). Addressing the manufacturing of resin and finished products will require a supply of electricity and heat from carbon-free sources such as a zero-emission electricity grid (Tullo, 2021) and low-emission fuels such as green hydrogen or green ammonia (Arnaiz del Pozo & Cloete, 2022; C. Bauer, Treyer, et al., 2022). Decarbonizing the transport of raw materials and finished products would require using electricity or synthetic fuels for the freight-transport sector (i.e., road (Meyer, 2020), rail (IEA, 2019; Rungskunroch et al., 2021), aviation (Bauen et al., 2020; IEA, 2021c; Schäfer et al., 2019), and shipping (Bouman et al., 2017; IEA, 2021e; Mallouppas & Yfantis, 2021)). Net-zero, end-of-life disposal for plastics will need infrastructure and appropriate incentives so that that all plastics that remain in use can be recycled. Ultimately this may require novel polymer chemistries and (Gandini, 2008; Hatti-Kaul et al., 2020) and products designed for recycling (K. Daehn et al., 2022); in the meantime collecting and processing of existing plastic waste, much of which is simply discarded into the environment, must improve (CEIL, 2019; Lau et al., 2020).

Existing Policies

In recent years Colombia has focused on a number of policies for limiting the environmental damage from plastic waste. Colombia implemented a waste-management directive in 2018 aimed at preventing open dumping of packaging materials (Ministerio de Ambiente y Desarrollo Sostenible, 2018). Producers must submit data to the government department responsible for environmental licensing, the *Autoridad Nacional de Licencias Ambientales* (ANLA), and undergo periodic audits. There are also ongoing efforts to reduce the use of single-use plastics through various incentive/penalty structures (DNP, 2018; Ministerio de Ambiente y Desarrollo Sostenible, 2019) and to completely ban single-use plastics in Colombia's Caribbean islands (Congreso de la República de Colombia, 2019).

Colombia is also a regional leader in circular-economy thinking and policies, having established a national circular-economy strategy that creates a platform for industrial and consumer products to move toward closed loops of material flows (Ministerio de Ambiente y Desarrollo Sostenible & Ministerio de Comercio, 2019). An important, related policy document with direct relevance for the plastics sector is the Colombian national plan for sustainable management of single-use plastics (Ministerio de Ambiente y Desarrollo Sostenible, 2021). The plan builds on previous policies but also goes beyond waste management to promote eco-design principles for reusability and recyclability of containers, sustainable public procurement, and new incentives such as tax credits to facilitate and encourage adoption.

5.4 Decarbonization of Textiles in Colombia

Market Overview

Colombian textiles, footwear, headwear, and animal hides in 2020 were valued at $709 million, representing 2.2% of all exports (OEC, 2022). These goods include both finished products (e.g., clothing, luggage, household furnishings, and other soft goods) and intermediate products (e.g., bulk fabrics and yarns) (see Figure 5.5). Most export trade (88%) is within the Americas, with the United States being the single largest and most important market (39%) (see Figure 5.6).

Figure 5.5: Colombian Exports of Textiles, Footwear and Headwear, Animal Hides, 2020, by HS4 Category (OEC, 2022)

Total: $709M

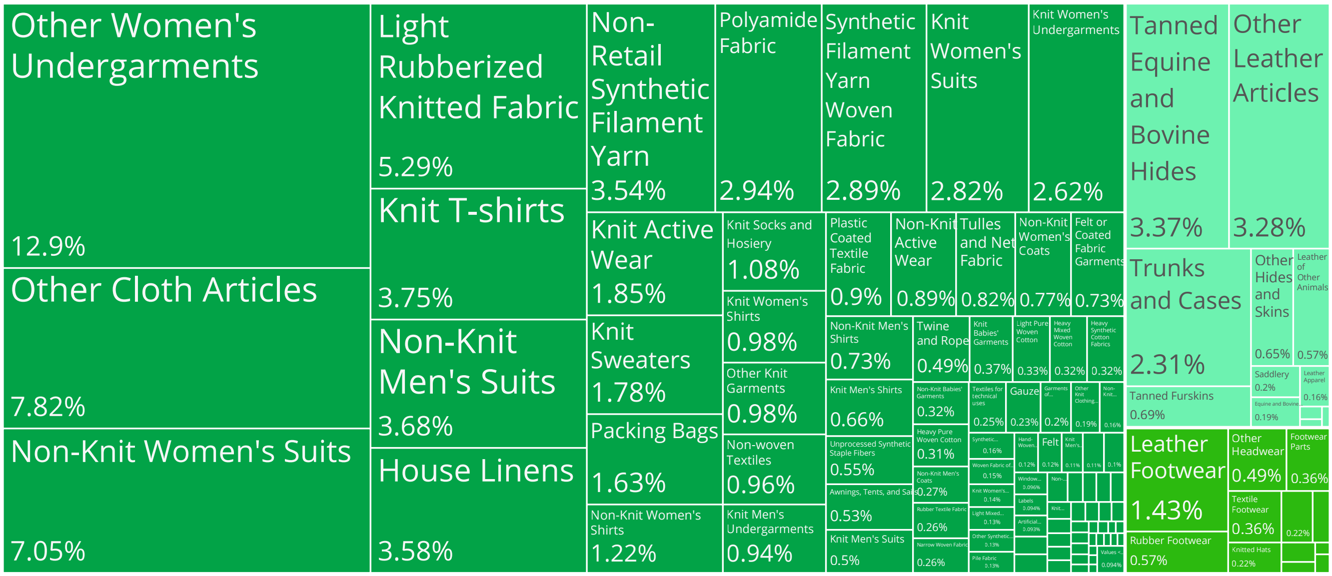
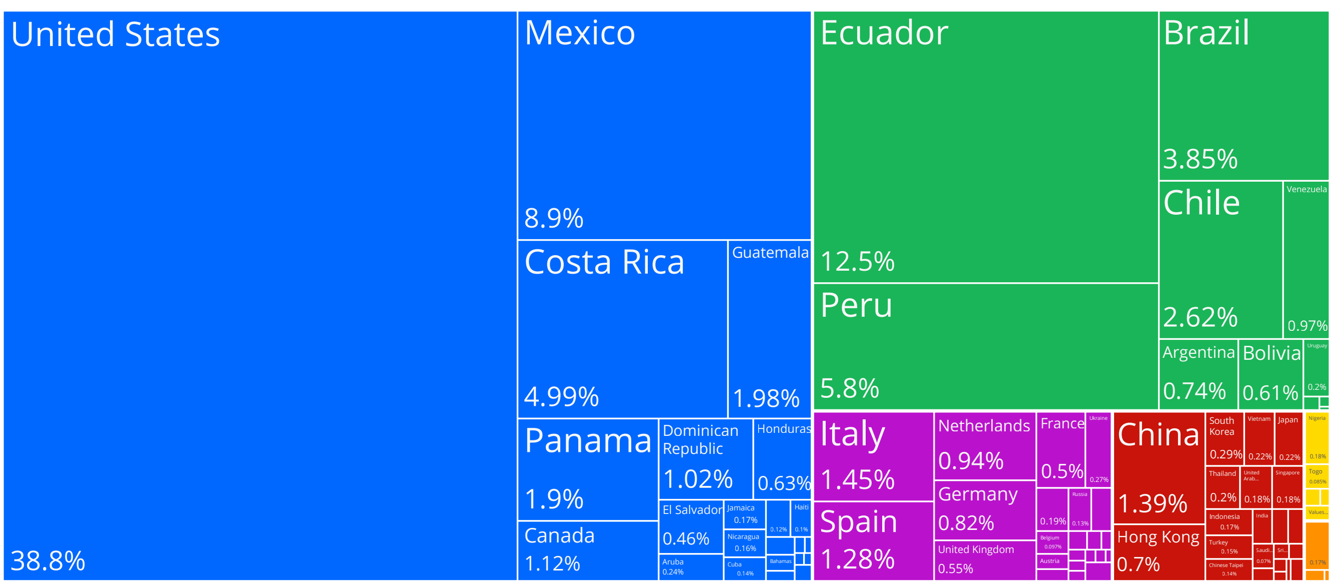


Figure 5.6: Colombian Exports of Textiles, Footwear, Headwear, and Animal Hides, 2020, Percent by Destination (OEC, 2022)

Total: $709M



Technological Opportunities

Opportunities for reducing emissions from Colombian textiles exist in the full value chain of upstream resources, fiber and finished product manufacturing, transport, and end-of-life stages (see chapter 2 for greater detail). As synthetic fibers are essentially plastics, the discussion on technological opportunities for plastics decarbonization (see chapter 1) is relevant for textiles. For natural fibers, which are an important component of Colombian exports (vegetable fibers, cotton, animal hides) decarbonizing agricultural emissions is an important aspect. Direct energy use in agricultural vehicles, irrigation pumps, and other harvesting and processing equipment should be electrified with net-zero electricity and/or replaced with equipment using zero-carbon fuels to the fullest extent possible (Hedayati et al., 2019). Potassium and phosphorous fertilizer inputs should ideally be sourced from net-zero mining operations (Ouikhalfan et al., 2022); net-zero production of nitrogen-based fertilizers requires green ammonia (Armijo & Philibert, 2020; Chehade & Dincer, 2021; IEA, 2021b). Agricultural decarbonization also requires actions to balance emission sources and carbon sinks through land-use changes (Harwatt et al., 2020; Reay, 2020) or carbon capture and storage (Hanna et al., 2021). This is because plants do not absorb 100% of the fertilizer applied, leading to emissions of nitrous oxide, a powerful greenhouse gas (Gregorich et al., 2015).

It is already technologically possible to electrify all the major processes involved in textile manufacturing, including high-temperature heat at up to 160°C (Arpagaus et al., 2018). Thus, the main pathway for achieving net-zero in this part of the value chain will be to convert processes to use electricity, alongside large-scale reduction in the emissions from the power grid. Transport of finished products to market will also require decarbonizing the transport modes employed (e.g., road freight, aircraft, railways, shipping) by using electricity or synthetic, zero-emissions fuels (Kaack et al., 2018). At the end-of-life disposal stage, the same strategies discussed for plastics (see chapter 1) are highly relevant for textiles. This is because two-thirds of textiles are plastics (Palacios-Mateo et al., 2021) and because blends of plastic and natural fibers (e.g., cotton and polyester) are increasingly common. The main avenue for achieving net-zero end-of-life disposal of textiles will be achieving material circularity through improved recycling and adoption of circular-economy principles (Ellen MacArthur Foundation, 2017a; McKinsey & Company, 2022; Shirvanimoghaddam et al., 2020; Wojciechowska, 2021). Encouraging a shift in the production of higher-quality garments with longer lifetimes and greater durability is also critical (Nature Climate Change, 2018; Niinimäki et al., 2020).

Existing Policies

Reducing emissions from the garment-manufacturing industry or closing the associated material loops are not addressed specifically in Colombia's national circular-economy strategy, but many of the cross-cutting principles highlighted in that document could apply directly to textiles production (Ministerio de Ambiente y Desarrollo Sostenible & Ministerio de Comercio, 2019). Primary research on sustainability in the Colombian textiles industry continues, examining consumer preferences (Mogollón Murcia & Parra Hermida, 2020), eco-design (Dotor Robayo, 2020), and case studies of firms implementing circular-economy practices (Arévalo Campos & Méndez Navarro, 2022). Improving the overall quality of Colombian textile products, with sustainability and "slow fashion" principles as major value-added factors, is viewed as a potential response to increased competition from Asia (Jarpa & Halog, 2021). Researchers have noted that Colombia has unique cultural and artisanal traditions that have the potential to dovetail well with a slow-fashion ethos to garment production and export (Cordoba, 2018; Spehar, 2021).

5.5 Decarbonization of Auto Manufacturing in Colombia

Market Overview

Auto-manufacturing exports in Colombia are worth $345 million, representing around 1.1% of total exports (OEC, 2022). Exports from the broader transportation sector (including aircraft) are dominated by auto-manufacturing for cars (42%), buses (13%), and delivery trucks (14%) (see Figure 5.7). Nearly all (98%) exports go to countries in North and South America (see Figure 5.8), with exports to neighbors in South America accounting for nearly three-quarters (73%) of all exported goods in the sector. Ecuador (36%), Chile (21%) and Mexico (18%) are the three most important destination markets for the Colombian auto industry. Colombian-manufactured delivery trucks and cars are the main components of exports to Ecuador. Chile imports mainly Colombian-made buses, and Mexico's imports are overwhelmingly (>90%) cars.

Figure 5.7: Colombian Exports of Transportation Products, 2020, By HS4 Category (OEC, 2022)

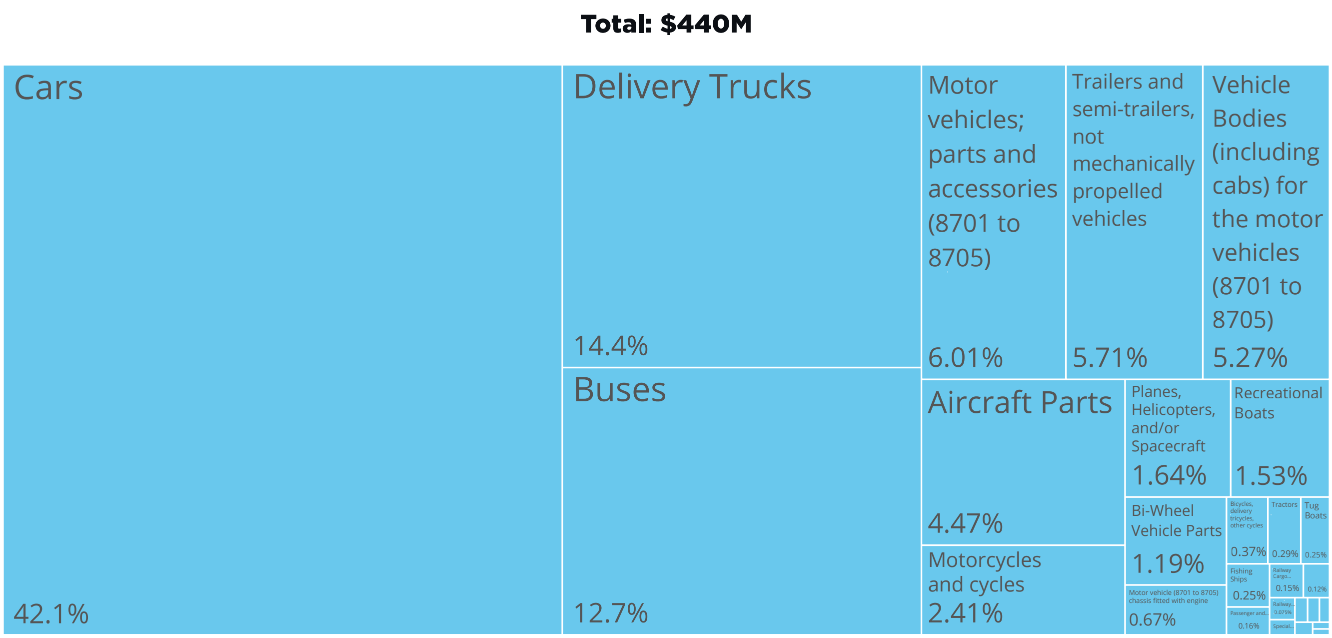
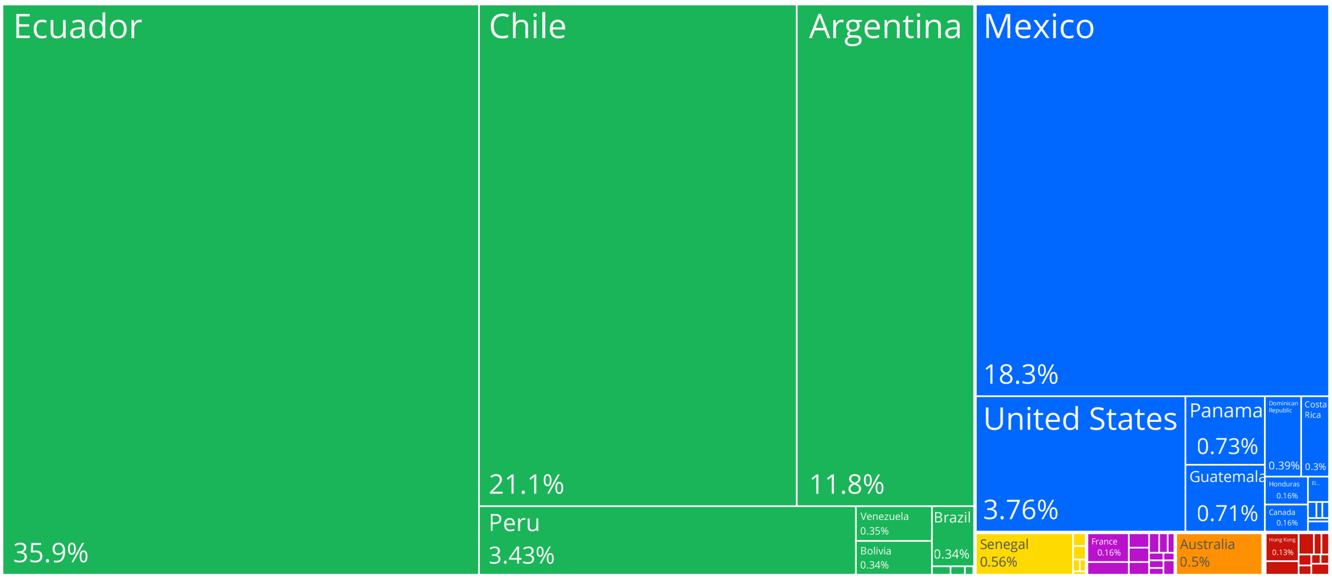


Figure 5.8: Colombian Exports of Cars, Delivery Trucks, Work Trucks, Motorcycles, Various Vehicle Parts Categories, 2020, By Destination (OEC, 2022)

Total: $375M



Technological Opportunities

Achieving net zero in auto manufacturing requires change throughout the value chain (see chapter 3 for further detail). A wide range of upstream inputs must achieve carbon neutrality; these include mining (Igogo et al., 2021), steel (Bataille, Stiebert, et al., 2021; IEA, 2020b, 2021f; Mission Possible Partnership, 2021; van Sluisveld et al., 2021; Yu et al., 2021), aluminum production (Gomilšek et al., 2020; IEA, 2021a; Nature, 2018), glass manufacturing (Furszyfer Del Rio et al., 2022; Griffin et al., 2021), and the production of battery packs (Aichberger & Jungmeier, 2020; Degen & Schütte, 2022). Achieving net zero on the vehicle-production line itself will require energy efficiency, the electrification of as many processes as possible with zero-carbon grid electricity, and the use of green hydrogen for high-temperature-process heat (Bataille et al., 2018; Bataille, Nilsson, et al., 2021; Rissman et al., 2020). Switching to lighter-weight vehicles (Czerwinski, 2021; Kacar et al., 2018; Shaffer et al., 2021) and producing electric vehicles rather than fossil fuel-powered vehicles (Crabtree, 2019; Kawamoto et al., 2019; Rietmann et al., 2020) are other important issues that must be addressed to reduce emissions of the vehicles themselves.

Freight-transport elements of the automotive supply chain (both finished products and intermediate components) need to be electrified or powered by net-zero liquid or gaseous, synthetic fuels for road freight (Meyer, 2020), rail (IEA, 2019), aircraft (Bauen et al., 2020; IEA, 2021c; Viswanathan & Knapp, 2019), and ships (Bouman et al., 2017; Mallouppas & Yfantis, 2021). End-of-life disposal for vehicles must be reimagined to drive toward circular material flows. In principle nearly all parts of a vehicle can be recycled but there must be alignment of the design of the vehicles, the infrastructure for recycling, and the appropriate market incentives. Manufacturers can play an important role in improving the recyclability of vehicles during the design process, both by selecting materials that can be easily recycled and by structuring the components to be easily disassembled for reuse as spare parts or separated into individual recycling streams (i.e., adopting standard circular-economy principles (Aguilar Esteva et al., 2021; Baars et al., 2021; He et al., 2021)). This applies particularly to battery packs (C. Bauer, Burkhardt, et al., 2022; Harper et al., 2019) but also to other structural components, such as windshields and wheel rims (McAuley, 2003; Nakano & Shibahara, 2017; Soo et al., 2017).

Existing Policies

Colombia does not yet have an integrated policy program that covers the decarbonization of the entire automotive supply chain and the automotive sector. However, work is underway on various areas that could form key components of such a strategy. For example, Colombia has explored a number of climate-mitigation scenarios for the energy and mining sectors, with some of these showing the use of renewable energy in mining operations (Ministerio de Minas y Energía, 2018a). The national circular-economy strategy directly addresses the reuse and recycling of vehicle tires as an important material flow (Ministerio de Minas y Energía, 2018a).

5.6 Decarbonization of Fisheries in Colombia

Market Overview

The Colombian seafood industry represents a small fraction of the economy; in 2020, fish and crustaceans accounted for around $209 million exports, roughly 0.7% of total export activity. The two largest market segments (see Figure 5.9) are prepared fish fillets and other forms of processed fish. Colombia exports its seafood products mostly to North America, with the US and Canada taking roughly half of all trade in 2020 (see Figure 5.10), and with remaining trade split almost evenly between the EU and neighboring countries in South America (Chile, Ecuador, Bolivia, Peru).

Figure 5.9: Colombian Exports of Animal Products and Foodstuffs, 2020, by HS4 Category (OEC, 2022)

Total: $1.92B

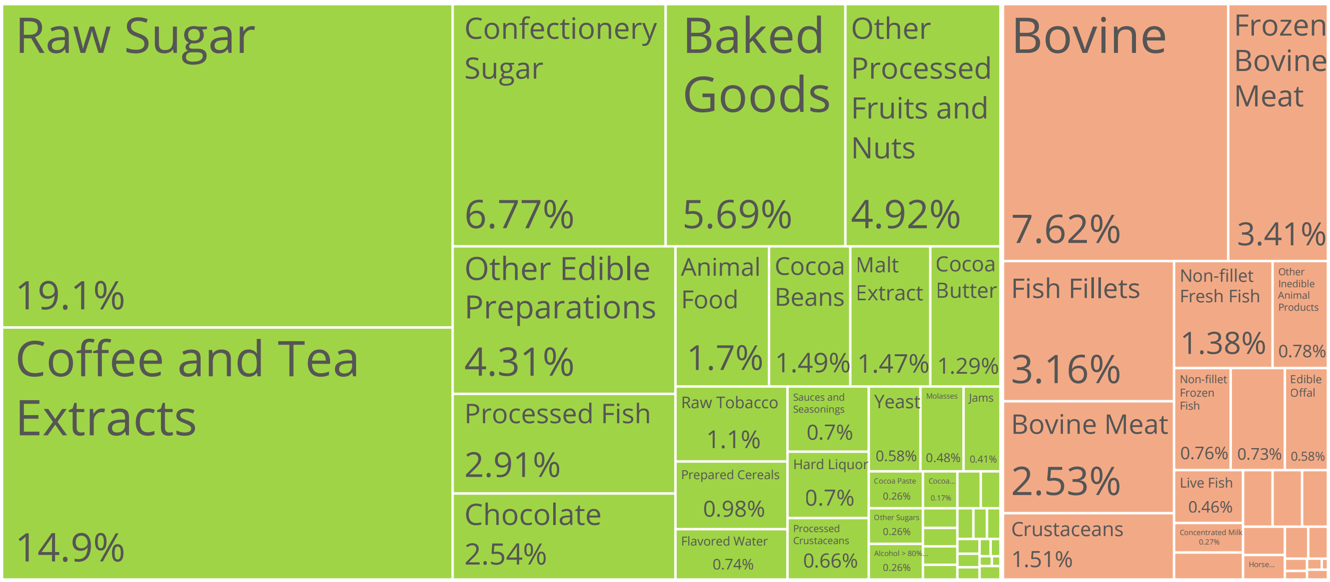
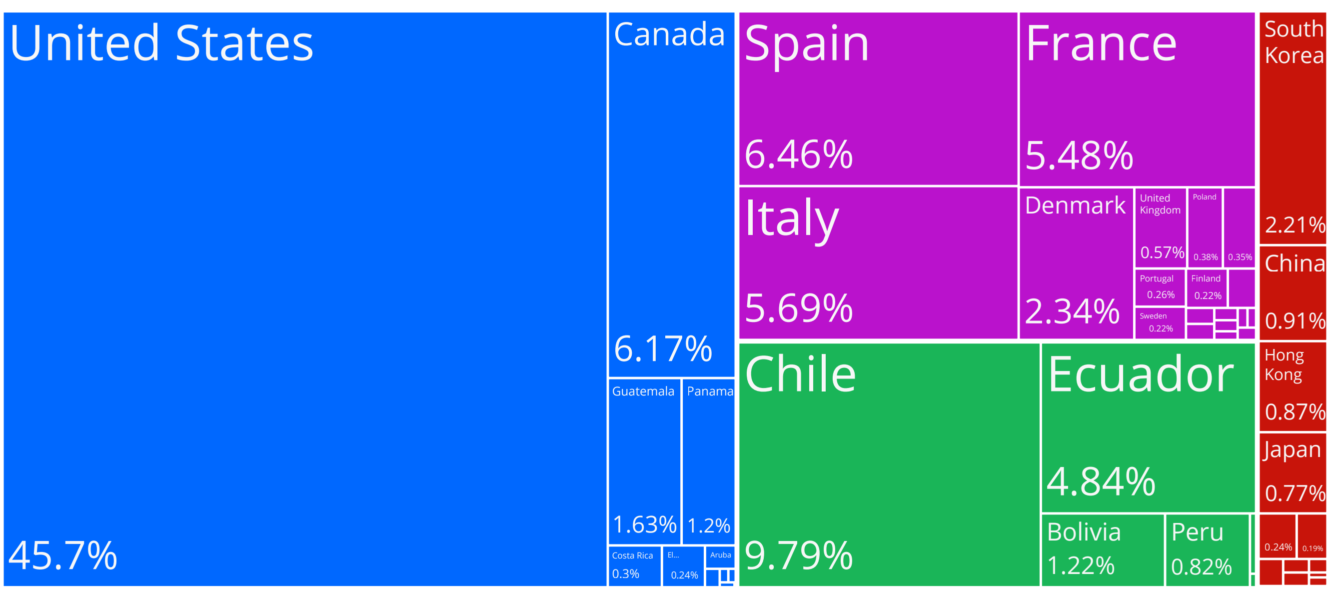


Figure 5.10: Colombian Exports of Live Fish, Non-fillet Fresh Fish, Non-fillet Frozen Fish, Fish Fillets, Dried Salted Smoked and Brined Fish, Crustaceans, Mollusks, Processed Fish, and Processed Crustaceans, 2020, by Destination (OEC, 2022)

Total: $209M



Technological Opportunities

Achieving decarbonization in this sector requires carbon neutrality throughout the value chain of the sector – from the energy used in producing upstream raw materials for vessels and feedstocks, the use of marine vessels, the transportation of products to market, and recycling of vessels at the end of their useful lives (see chapter 4 for further details) (Mallouppas & Yfantis, 2021; Vakili, Ölçer, et al., 2022). Carbon neutrality is required in the agricultural input chain that produces feed for seafood farms (Jones et al., 2022), for the fuels and electricity that powers the processing and packaging of seafood (Alzahrani et al., 2020; Scroggins et al., 2022), and for transportation of the finished products to market (Psaraftis & Kontovas, 2020). As ships and port infrastructure have long asset lifetimes measured in decades (Bullock et al., 2022), there is considerable inertia in the established system, which heavily depends on fossil fuels. Price competition and innovation alone will almost certainly not achieve the extensive changes needed in time to meet Paris Agreement targets (i.e., by 2050 and 2070); deliberate market creation and regulations will be needed to incentivize and mandate technological change (Cullinane & Yang, 2022; Lagouvardou et al., 2020).

Decarbonization of fisheries will require long-term policy planning and investments in innovation to identify the composition and condition of national fishing fleets and the associated seafood-farming sectors, and to chart a course toward zero emissions in line with national decarbonization objectives. Planning for changes needed in this sector cannot be undertaken in isolation from the rest of the economy. Support from other sectors such as agriculture, electricity and fuel supply are essential for decarbonizing fisheries. Moving forward thus will require deep coordination between national agencies that are responsible for agriculture and aquaculture (i.e., seafood farming), maritime law, ecosystem management, and the technical regulations governing marine vessels. Because fishing and the transport of seafood cross international boundaries, coordination of national decarbonization activities will also need to be aligned with international bodies such as the shipping "certification societies" (e.g., Lloyd's Register, American Bureau of Shipping, Nippon Kaiji Kyokai), which insure cargo vessels as they travel across borders, and the International Maritime Organization (IMO) (Milios et al., 2019). Almost all global ship deconstruction and recycling occurs in just five markets: India, Pakistan, Bangladesh, Turkey, and China (UNCTAD, 2021); thus, direct involvement with the governments of those countries will be required to enable a more circular economy for shipping vessels.

Existing Policies

A set of mutually reinforcing Colombian laws govern the principles behind the conservation and sustainable use of aquatic resources, the registration and operation of aquaculture farms, and the technical and administrative requirements for operating fishing vessels in Colombian waters. Responsibilities are shared between several government agencies: the Ministry of Agriculture and Rural Development (*Ministerio de Agricultura y Desarrollo Rural* (MADR)), which integrates agricultural (including fisheries) and economic development policy with national objectives; the, Ministry of Environment and Sustainable Development (*Ministerio de Ambiente y Desarrollo Sostenible* (MADS)), which directs land and resource use policy to spatially order and balance extractive and conservation activities; and the National Aquaculture and Fisheries Authority (*Autoridad Nacional de Acuicultura y Pesca* (AUNAP)), which carries out primary research and manages fishing licenses and permits with a view to ensuring sustainable fish stocks are maintained. Inter-agency fragmentation and conflicts of interest occasionally have resulted in a lack of both coherence and consistency in key areas of fisheries policy (OECD, 2016). At the time of writing (early 2023) no specific policies or regulations in Colombia target the reduction of greenhouse gas emissions from the fishing or aquaculture industry.

5.7 Toward Net-zero Plastics, Textiles, Auto Manufacturing, and Fisheries in Colombia

The technological options for reducing emissions from the plastics, textiles, auto-manufacturing, and fisheries sectors in Colombia share a number of common strategic elements. Cross-cutting strategies for industrial decarbonization that are consistent across the literature (Bataille et al., 2018; Bataille, Nilsson, et al., 2021; Lechtenböhmer et al., 2016; Rissman et al., 2020; Thiel & Stark, 2021) include:

i. Material efficiency and energy-efficient processes

ii. Electrification of process energy wherever possible

iii. Fuel switching to synthetic, low-emission fuels where electrification is not possible

iv. Carbon capture and storage where necessary

v. Material circularity and recycling

vi. Carbon dioxide removal

Material Efficiency and Energy-efficient Processes

Energy efficiency and material efficiency are important components of an overall net-zero industrial roadmap; such components ensure that waste in the processing of material inputs is minimized. Eliminating waste makes changing production processes to use clean energy sources cheaper and therefore easier to achieve. This will be true across a range of industries, including the plastics, textiles, automotive-manufacturing and fisheries sectors that form core focus of this report. Industrial energy efficiency in Colombia is directly addressed by a program under the Energy and Mining Planning Unit of the Colombian Ministry of Mines and Energy (*Unidad de Planeación Minero Energética* (UPME)); its Program for the Rational and Efficient Use of Energy (PROURE), is updated roughly every five years and sets specific sectoral targets and actions. For example, the 2010-2015 plan aimed to save 11% of final energy consumption in industry through actions such as replacing inefficient electric motors, optimizing boiler operational cycles, and promoting energy-efficient lighting (Ministerio de Minas y Energía, 2010). The 2017-2022 plan identified areas for significant improvement nationally across all industries; these included improved power quality and best practices in direct electrical heating, optimizing refrigeration through better matching of equipment to loads, automatic lighting controls and improved daylighting, and the replacement of inefficient and partially loaded electric motors (UPME, 2016). In addition, the plan explored measures for improving the efficiency of industries that relied on high-temperature heating (e.g., for glass, cement, ceramics, and metals); measures included heat recovery, improved operations and maintenance, and process changes such as moving to fluidized bed boilers from conventional boilers or preheating water with solar energy (UPME, 2016). The latest 2022-2030 plan builds on both previous strategy documents, including similar recommendations, and adding measures such as drop-in replacements for refrigerants with high global warming potential, heat recovery in refrigeration systems, smarter controls for all heating and cooling systems, and metering and submetering of end-use energy demand throughout the production chain (UPME, 2022).

Electrification

The electrification of industry with a largely fossil fuel-free grid plays a role in nearly all deep decarbonization scenarios, with Colombia being no exception (Bataille et al., 2020). General principles for decarbonizing electricity supply include planning for long-term clean electrification; creating roadmaps; making low-cost financing for generation, transmission and distribution available; setting performance standards (e.g., for GHG intensity); fast-tracking permits and approvals for construction of energy infrastructure; and setting in motion a managed phasing-out process for residual fossil fuel generation (Fazekas et al., 2022). Net-zero modeling exercises for Colombia show that the carbon intensity of power generation to supply the grid must fall by 98% by 2050 – with solar energy, hydropower, and natural gas with carbon capture and storage all potentially playing a role (Delgado et al., 2020). Achieving net-zero industry in Colombia (including in the plastics, textiles, auto-manufacturing and fisheries sectors) would require nearly 100% of electricity supplied for production to come from non-fossil fuel energy sources.

Colombia already has significant renewable-energy resources in the form of hydropower (UPME, 2020); the potential for non-hydro renewables such as wind and solar energy is also strong (Galvís-Villamizar et al., 2022; Henao et al., 2020; Moreno Rocha et al., 2022; Rueda-Bayona et al., 2019). Colombia already has plans in place (*Plan Energético Nacional (PEN) 2020 – 2050*) to diversify the energy mix away from an over-reliance on hydropower by using other renewable resources – an approach that aligns both resilience and climate-mitigation perspectives (UPME, 2019a). At present, however, most existing non-hydropower renewable generators are found in parts of the Colombian electricity system that are not interconnected with the national transmission grid, such as is the case in the Caribbean islands (Rodríguez-Urrego & Rodríguez-Urrego, 2018). Large-scale deployment of non-hydropower renewables on the main continent is still in the early stages with the first long-term contracts for renewable energy having been auctioned in 2019 (Moreno & Larrahondo, 2020). Better transmission infrastructure is needed for those regions with the highest potential to supply renewable energy (such as the Guajira Peninsula) to be able to adequately supply major demand centers such as Bogotá, Medellín, and Cali. Improvements to transmission and distribution infrastructure have been made a priority (UPME, 2021), alongside efforts to provide universal electricity access (UPME, 2019b).

Synthetic Low-GHG Fuels

At the time of writing (early 2023), not all industrial processes found in plastics and auto manufacturing are straightforward to electrify. While heat pumps can now easily supply temperatures of 150 ºC from widely available commercial products (Arpagaus et al., 2018), going above this temperature is likely to require technologies that are expected to be at the scale of laboratory bench or early prototype scale for the rest of the 2020s; going to temperatures above say, 1000 ºC, may not be practical with electricity alone. This means that net-zero industry will require synthetic zero-GHG fuels that can be combusted to provide high-temperature heat.

Past Colombian policies aimed at stimulating non-fossil fuel production have explored the potential for a domestic biofuels industry (Castiblanco et al., 2015; Colmenares-Quintero et al., 2020). Bioenergy has the potential to play a contributing role in achieving domestic climate ambition in Colombia (OECD, 2022a; Younis et al., 2021), but it may prove difficult to scale. Creating export market opportunities for biofuels may be difficult. Strong expansion of biofuels policy in Colombia may also be a political gamble (Palacio-Ciro & Vasco-Correa, 2020) due to sensitivities around food security (Martínez-Jaramillo et al., 2019), competition with land for food production, and an often negative public perception of large-scale land ownership by agribusiness (Potter, 2020; Valbuena Latorre & Badillo Sarmiento, 2022).

Leading alternative candidates to replace fossil fuels like coal and natural gas for high-temperature industrial processes include hydrogen and ammonia. Both could be produced overseas and imported to Colombia, but they could also be produced domestically. Colombia has both the geography and industrial base for producing low-cost electricity from renewable energy, a key input to so-called green hydrogen and ammonia (Muñoz-Fernández et al., 2022; Ullman & Kittner, 2022), and could also potentially produce so-called blue hydrogen from the coal industry if suitable carbon capture infrastructure were in place (Domínguez et al., 2022).[5] Colombia already has an existing mature petrochemical industry with the workforce and local knowledge to produce and export liquid fuels. A shift from production of fossil fuels to production of synthetic, green fuels could provide an excellent opportunity for the industry to reinvent itself as domestic oil and gas reserves dwindle toward the end of this decade (Chavez-Rodriguez et al., 2018). Future export market applications for green hydrogen and green ammonia include industrial heat (Philibert, 2017; Saygin & Gielen, 2021), marine transport fuels (Al-Aboosi et al., 2021; McKinlay et al., 2021; Zincir, 2022), fertilizer production (Faria, 2021) and power generation (Cesaro et al., 2021; Valera-Medina et al., 2018). Colombia

5 Colors are used to distinguish different hydrogen production and emissions impacts. Green hydrogen refers to technologies to split water by electrolysis, powered by renewable electricity, producing only hydrogen and oxygen. Blue hydrogen refers to technologies to split natural gas into hydrogen and carbon dioxide that is captured and stored (Noussan et al., 2020).

has already launched a national hydrogen roadmap, which aims to lay the foundation for both domestic use and export opportunities, and it has a near-term goal of installing between 1-3GW of electrolyzer capacity by 2030 (Ministerio de Minas y Energía, 2021a).

Carbon Capture and Storage

Deep decarbonization scenarios for Colombia have included the theoretical use of carbon capture and storage (CCS) as a means of not only offsetting the fraction of remaining emissions that cannot easily be eliminated (e.g., agricultural emissions associated with nitrogen fertilizer) but also as a means of creating net-negative emissions overall (Bataille et al., 2020; Calderón et al., 2016; Delgado et al., 2020; Younis et al., 2021). Direct applications in the Colombian plastics, textiles, automotive-manufacturing and fisheries sectors are not a prerequisite for achieving net zero but CCS may play an important role in mitigating upstream emissions from agriculture and mining (Igogo et al., 2021). CCS technology has been explored in the Colombian Ministry of Mining and Energy's most recent and most ambitious mitigation scenario for the mining and energy sectors (Ministerio de Minas y Energía, 2018b, 2021b). Favorable geology for long-term storage of CO2 underground exists in several regions, such as the Llanos basin and along the Magdalena River valley (de Carvalho Nunes & de Medeiros Costa, 2021; Mariño-Martínez & Moreno-Reyes, 2018), and research is underway to geographically match potential CCS users with CCS storage sites and thus identify spatial clusters for future development (Duarte et al., 2022; E. Yáñez et al., 2020; É. Yáñez et al., 2022).

Material Circularity and Recycling

As discussed in the individual sections covering plastics, textiles automotive-manufacturing and fisheries sectors, improved material circularity is critical for achieving net-zero emissions from end-of-life disposal. Much has already been written about circular-economy principles in relation to several of these sectors; for example, work has addressed plastics (Barrowclough & Birkbeck, 2022; Ellen MacArthur Foundation, 2017b; Lange, 2021; World Economic Forum et al., 2016), textiles (Ellen MacArthur Foundation, 2017a; McKinsey & Company, 2022; Shirvanimoghaddam et al., 2020; Wojciechowska, 2021), and automotive manufacturing (Czerwinski, 2021; He et al., 2021; Khodier et al., 2018). In broad terms, implementation requires large-scale improvements in the provision of infrastructure for collecting and processing end-of-life products, the creation of strong incentives to discourage sending waste to landfills and dumping waste in the natural environment; and upstream changes to product design and materials either through regulation or in consultation with industry to avoid the creation of products that cannot be recycled.

As noted in earlier sections, Colombia is a regional leader in circular-economy thinking and policy development (Calderón Márquez & Rutkowski, 2020; van Hoof & Saer, 2022). The national circular-economy strategy identifies "industrial materials and consumer products" as a priority material-flow category with its own set of indicators and targets (Ministerio de Ambiente y Desarrollo Sostenible & Ministerio de Comercio, 2019). The strategy has also been used as a springboard for documents that target sectors and individual products, such as single-use plastics (Ministerio de Ambiente y Desarrollo Sostenible, 2021). With such an existing track record, there exists an opportunity for the Ministry of Environment and Sustainable Development (*Ministerio de Ambiente y Desarrollo Sostenible*) to use its intellectual capacity to target other products and sectors (such as textiles and the automotive industry) with the same level of care and attention to detail. The research community also has a role to play. Research has identified business sectors and firms in which circular processes already exist in the Colombian economy; these studied area include aluminum and steel structures (Torres-Guevara et al., 2021) and concrete (Maury-Ramírez et al., 2022) in the construction sector. It is likely that existing formal or informal networks also already exist to handle automotive and textile products in their end-of-life phase. A starting point therefore would be to map and analyze these processes to quantify their flows and assess the potential for policy interventions.

Carbon Dioxide Removal (CDR)

Even with very deep reductions in emissions there are likely to be residual emissions in Colombia that cannot be easily abated directly, such as such as nitrous oxide emissions from the use of nitrogen fertilizer in agricultural production (Lim et al., 2021), whether for food or energy crop cultivation, or for textile crops like cotton. For example, existing work on very deep decarbonization pathways for Colombia has considered a 90% reduction in emissions; the remaining 10% still needs to be handled to achieve net zero. Nature-based solutions seek to remove residual emissions by expanding natural carbon sinks such as forests (Busch et al., 2019), while technical solutions include scrubbing carbon dioxide directly from the air, although this remains a technology that is still in its infancy (Erans et al., 2022; Hanna et al., 2021; McQueen et al., 2021) Reducing emissions from deforestation is an important component of Colombia's national strategy for meeting its climate-mitigation target (Gobierno de Colombia, 2021; IDEAM et al., 2021; Samaniego et al., 2021).

5.8 Conclusions

At the time of writing (early 2023), efforts to decarbonize the plastics, textiles, automotive manufacturing, and fisheries value chains in Colombia were in their very earliest stages. Achieving net-zero industrial production will require large-scale policy and investment decisions at levels well above those under the control of individual businesses, manufacturing sites and industrial sectors. The creation of a low-emission power grid and the ability to import or create synthetic low-GHG fuels such as green hydrogen and green ammonia are prerequisites for net-zero industry. The strategic direction to aim to achieve net-zero goals has been set by both top-level congressional legislation (Congreso de la República de Colombia, 2017) and planning from major government departments (DNP, 2023; MINCIT, 2023; UPME, 2019a).

Colombia is already developing the building blocks in policy terms for a net-zero industrial base, and it is a regional first mover in material-circularity thinking and in initiating a national hydrogen strategy roadmap. Colombia has also already submitted a net-zero strategy to the United Nations, and, within this overarching framework, it is possible to develop strategic net-zero roadmaps for individual sectors. These are encouraging first steps, and they provide the overarching framework within which to construct a Colombian strategy for achieving net-zero industrial production. There is the potential to accelerate policy development in this area with deeper collaboration between three key ministries: the Ministry of Commerce, Industry and Tourism (*Ministerio de Comercio, Industria y Turismo (MinComercio)*), the Ministry of Mines and Energy (*Ministerio de Minas y Energía (MinMinas)*), and the Ministry of Environment and Sustainable Development (*Ministerio de Ambiente y Desarrollo Sostenible (MinAmbiente)*).

Colombia also has an existing and well-developed oil-and-gas industry that likely has the human capital and institutional knowledge to pivot to produce synthetic, low-GHG fuels and/or to play a role in providing infrastructure for carbon capture and storage for other industries; this sector could perhaps be brought into the conversation in the early stages of policy development.

A key element for consideration is spatiality. As there are synergies between the production of synthetic fuels, access to carbon capture pipelines, and economies of scale associated with sharing such infrastructure, the spatial co-location of green industries is often thought of as a key strategy in roadmaps toward the development of net-zero manufacturing. For example, net-zero industrial clusters are central to the EU and UK industrial decarbonization strategies (BEIS, 2021; Merten et al., 2020). Such clustering has the potential to reinforce existing regional inequalities if all the best infrastructure and opportunities are concentrated in existing, highly developed, and affluent regions, but this approach could also be viewed as an opportunity to spread national wealth more evenly across the country through the establishment of new industrial hubs.

Now is the time for Colombia to embrace innovation and foresight in building upon its commendable foundations in energy and environmental policy. By intensifying cross-sectoral collaboration, allocating resources judiciously, and cultivating inclusive growth strategies, Colombia can emerge as a leader in the global race toward net-zero industries, ensuring a sustainable and prosperous future for its citizens.

CHAPTER 6 ECUADOR

6.1 Key Conclusions

Decarbonizing plastics, textiles, auto manufacturing, and fisheries in Ecuador is a concept in the very early stages of development.

Pain point: Achieving net-zero industrial production requires decision-making by the national government about policies and investments concerning national strategic infrastructure.

Pain point: Critical supporting infrastructure for net-zero industrial activity is required. The country must build a very low-emissions power grid and provide infrastructure for producing and/or importing low-GHG, synthetic fuels, such as green hydrogen and ammonia.

Pain point: Ecuador has submitted proposals for decarbonization to the United Nations Framework Convention on Climate Change (UNFCCC) but has yet to set a net-zero target or to outline a national roadmap for achieving net zero and enshrining targets into law; these steps are prerequisites for creating the necessary conditions for a net-zero industrial transition.

Opportunity: Ecuador already has a robust set of energy and environmental policies that have delivered in building major, transformative infrastructure projects (e.g., hydropower development). The institutional framework for developing a net-zero industrial strategy is arguably already in place.

Opportunity: Ecuador is in a strong position to develop a low-emission power grid for industry owing to its abundant renewable-energy resources.

Opportunity: Ecuador has an extensive oil-and-gas sector that likely has the human capital and institutional knowledge to pivot to produce synthetic, low-GHG fuels for industry and/or to play a role in providing infrastructure for carbon capture and storage (CCS) for other industries.

Opportunity: Ecuador may wish to explore the concept of creating GHG-neutral industrial clusters to share critical infrastructure such as CCS, green hydrogen, and green ammonia.

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6.2 Overview

This report considers how the Ecuadorian plastics, textiles, auto manufacturing and fisheries industries can be placed on a track to achieve net-zero emissions. Ecuador has an extensive energy-policy framework, with multiple overlapping policies that are aimed at ensuring energy access and leveraging the country's abundant hydropower and fossil resources for economic development. Ecuador also has high-level climate-mitigation and climate-adaptation drivers that serve as a backdrop to this activity. On the international stage, Ecuador has engaged in the Paris Agreement process and is an active participant in the UNFCCC process, submitting its original Nationally Determined Contribution (NDC) in 2019 (República del Ecuador, 2019). At the time of writing (early 2023), Ecuador has yet to submit an updated net-zero-aligned climate-mitigation strategy to the UNFCCC. A net-zero industrial strategy would align well with the overall direction of Ecuador's climate-mitigation policy.

Achieving net zero by transitioning the energy system away from the use of fossil fuels is viewed as the main means of avoiding future climate damages (IPCC, 2022). The future climate change risks for Ecuador are potentially acute and destabilizing, particularly in terms of the impacts of rainfall patterns and water resources and supplies. Risks include changing rainfall patterns (Chimborazo & Vuille, 2021), more intense floods and droughts (Campozano et al., 2020), instability of water resources (for example, in Quito) (Chevallier et al., 2011). If such risks materialize, they would almost certainly have negative consequences on agricultural yields, food security (Macías Barberán et al., 2019; Ovalle-Rivera et al., 2015; Quiroz et al., 2018; Ray et al., 2019), and natural biodiversity (Báez et al., 2016; Eguiguren-Velepucha et al., 2016; Iturralde-Pólit et al., 2017). Changes in the amount and variability of precipitation could negatively impact Ecuador's national electricity system if the design of existing hydrological dams proves to be inadequate to new conditions (Herbozo et al., 2022); this could lead to reduced hydropower generation in dry years (Carvajal & Li, 2019). Heat waves, particularly in the coastal and Amazon regions (Montenegro et al., 2022), will present health risks for agricultural and other outdoor workers (Harari Arjona et al., 2016) and may drive a need to rethink the design of buildings (Palme & Lobato, 2017).

Ecuadorian exports in 2020 totaled close to $21 billion, with the largest single category being crude petroleum (24%, $4.94 billion), bananas (19%, $3.83 billion), crustaceans (19%, $3.83 billion), processed fish (6%, $1.19 billion), and cut flowers (4%, $835 million). Figure 6.1 provides a detailed breakdown of Ecuadorian exports by type. Figure 6.2 provides a visualization of the destinations for Ecuador's exported goods. Key export relationships are with the US (23%, $4.6 billion), the EU (17%, $3.49 billion) and China (14%, $2.94 billion). Taken together, the plastics, textiles auto manufacturing and fisheries industries in Ecuador represent a significant part of industrial activity (62% of export value) and span a range of upstream raw materials, energy carriers, and routes to market. Exploring pathways for taking plastics, textiles, auto manufacturing and fisheries to net-zero-emissions levels may also offer valuable insights into efforts to decarbonize Ecuadorian industries in a more general sense in a way that aligns with Paris Agreement objectives.

Figure 6.1: Ecuadorian Exports to the Rest of World, 2020, HS4 Coding (Colors Correspond to Different HS4 Trade Code Groups) (OEC, 2022)

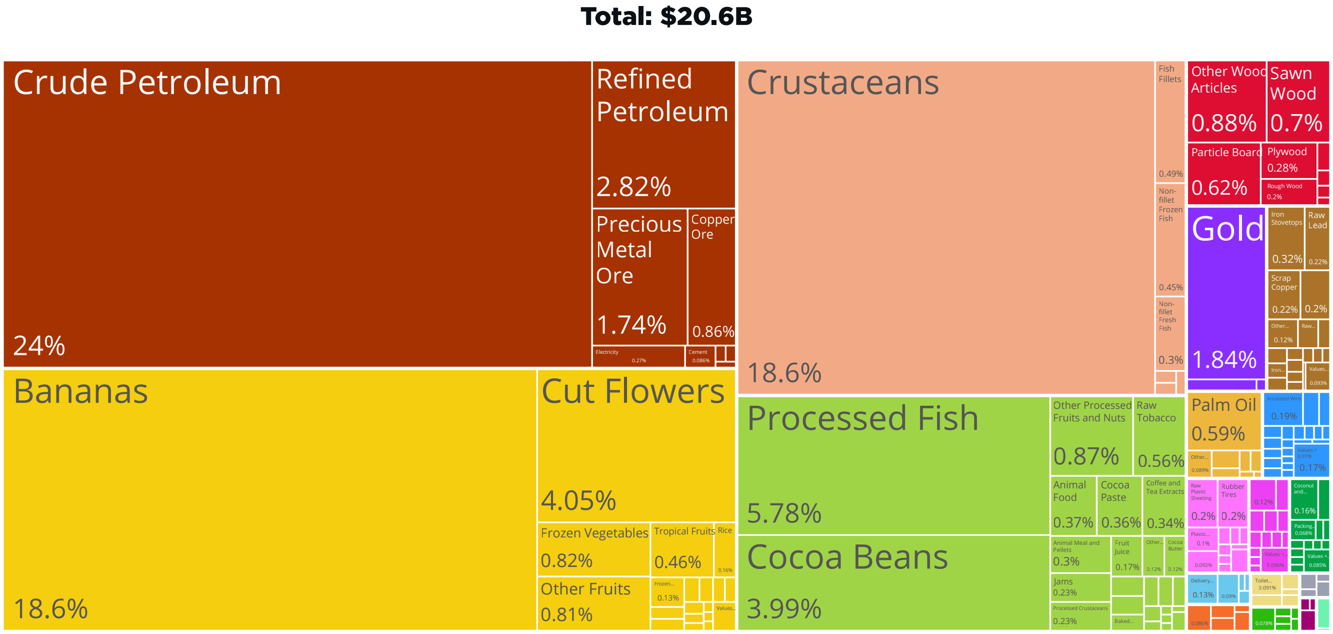
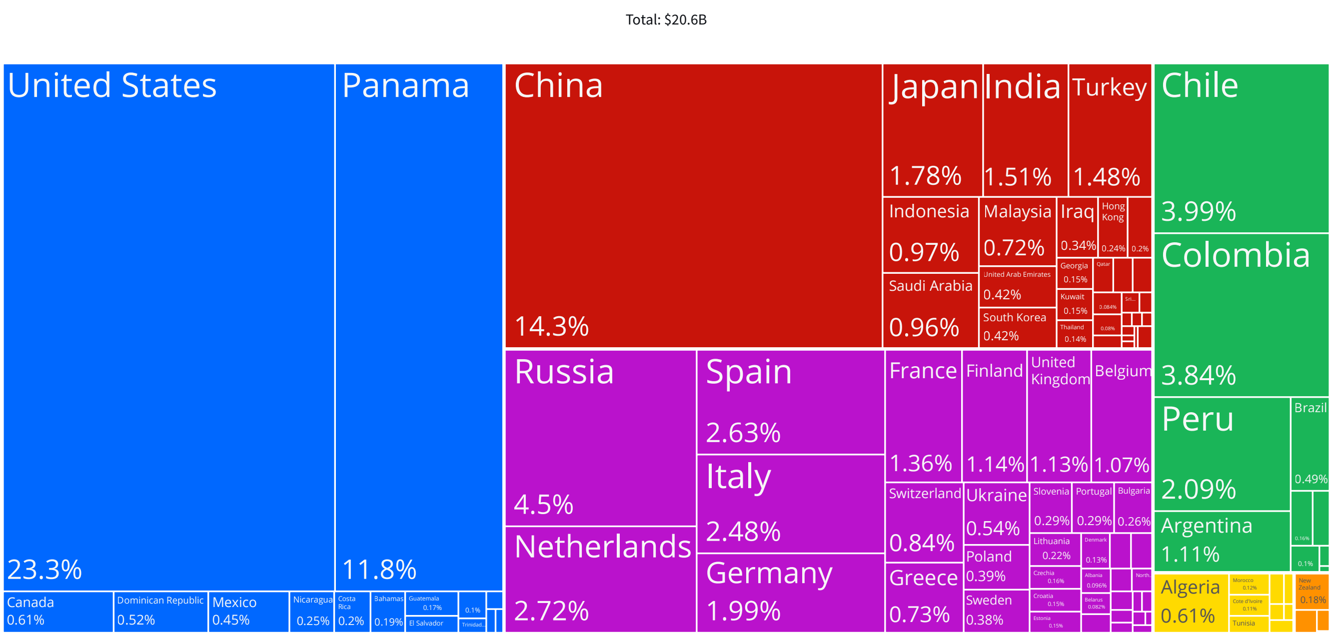


Figure 6.2: Ecuadorian Exports to the Rest of World, 2020, Percent by Country (OEC, 2022)



6.3 Decarbonization of Plastics in Ecuador

Market Overview

Plastics and synthetic rubbers comprised just over 0.75% of Ecuadorian exports in 2020, with a total value $161 million (OEC, 2022). The largest categories of exported goods (see Figure 6.3) are raw plastic sheeting (26%), rubber tires (26%), plastic lids (13%), and polyacetals (12%), a type of bulk polymer used in engineered products that need a high level of stiffness and toughness (e.g., for automobiles and machine parts) (Fan & Njuguna, 2016). The top three export markets for domestically produced plastics and rubbers (see Figure 6.4) are Ecuador's immediate neighbors Colombia (27%) and Peru (15%), and the United States (20%). The vast majority of exports (over 90%) are to countries in North and South America.

Figure 6.3: Ecuadorian Exports of Plastics and Rubbers, 2020, Percent by HS4 Category (OEC, 2022)

Total: $161M

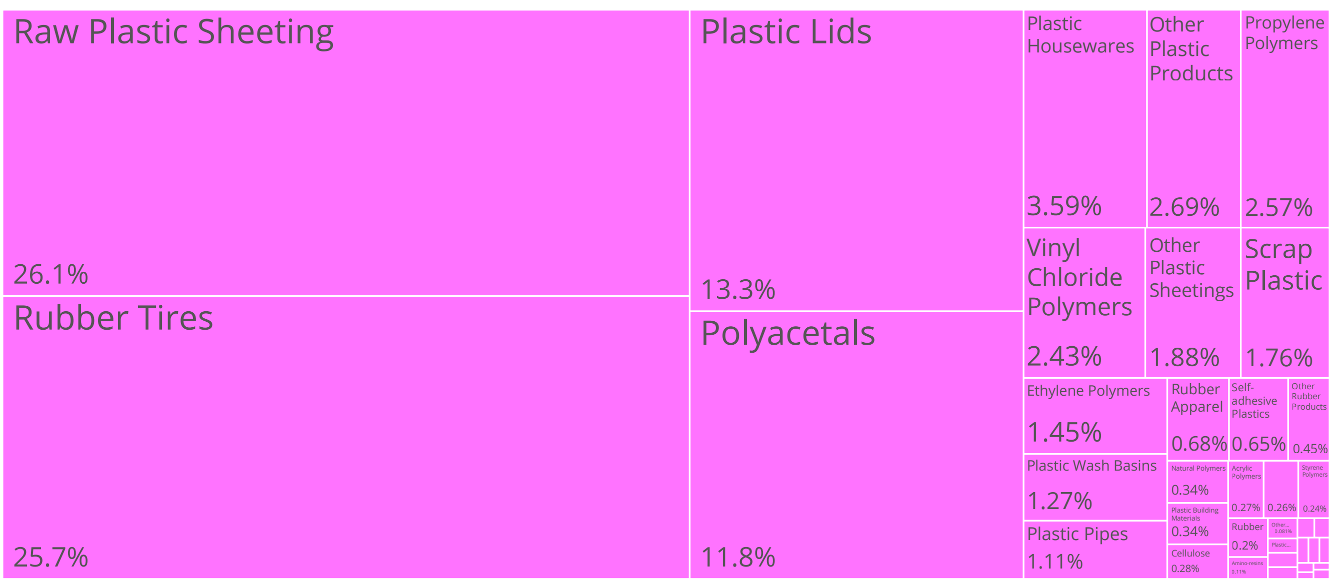
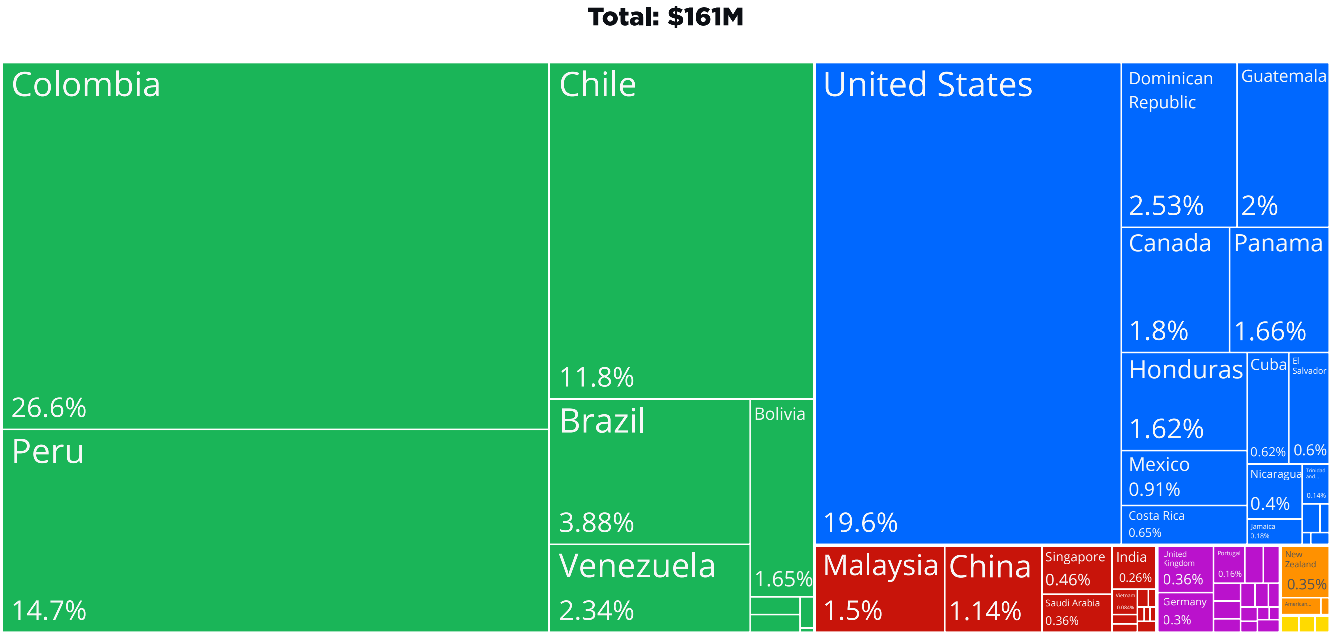


Figure 6.4: Ecuadorian Exports of Plastics and Rubbers, 2020, Percent by Destination (OEC, 2022)



Technological Opportunities

Opportunities for reducing emissions from the plastics sector exist throughout the value chain (for a detailed overview see chaper 1). The key approach for plastics to address emissions from raw materials is to explore replacing fossil fuel-based feedstocks with biomass (Negri & Ligthart, 2021; Saygin & Gielen, 2021; Scott et al., 2020; Zheng & Suh, 2019), air-captured carbon dioxide (Lange, 2021; Palm et al., 2016; Palm & Svensson Myrin, 2018), or recycled carbon from waste (Carus et al., 2020; Moretti et al., 2020). To address the resin and finished product-manufacturing issues requires supplies of electricity and heat from carbon-free sources; this requires a zero-emission electricity grid (Tullo, 2021) and low-emission fuels, such as green hydrogen or green ammonia (Arnaiz del Pozo & Cloete, 2022; C. Bauer, Treyer, et al., 2022). Transport of raw materials and finished products also need a decarbonized freight-transport sector (i.e., road (Meyer, 2020), rail (IEA, 2019; Rungskunroch et al., 2021), aviation (Bauen et al., 2020; IEA, 2021c; Schäfer et al., 2019), and shipping (Bouman et al., 2017; IEA, 2021e; Mallouppas & Yfantis, 2021)). Net-zero, end-of-life disposal for plastics will need infrastructure and appropriate incentives put in place so that that all plastics that remain in use can be recycled. Ultimately this may require novel polymer chemistries and (Gandini, 2008; Hatti-Kaul et al., 2020) and products designed for recycling (K. Daehn et al., 2022); in the meantime much work is needed to collect and process existing plastic waste, most of which is simply discarded (CEIL, 2019; Lau et al., 2020).

Existing Policies

Existing Ecuadorian policies have focused on raising awareness of the importance of preventing uncontrolled plastic waste disposal into the natural environment (e.g., the "*Plásticos en el mar… NO MÁS!*" (Plastics in the Sea… NO MORE!) campaign (IPIAP, 2018)) and placing selective bans on single-use plastics where alternatives are available (e.g., in Galapagos and Quito (MAATE, 2018)). The Ecuadorian government has also successfully implemented a rebate scheme on PET plastic bottles that has resulted in one of the highest PET recycling rates in Latin America and the Caribbean (Brooks et al., 2020). The Ecuadorian government is not only targeting plastic pollution but has also demonstrated a willingness to contemplate policies that lead to the substitution of plastics where feasible with other materials. Such an approach would open the door to policies encouraging more circular material flows. Circular-economy concepts already have some traction in Ecuador, and collaborative activity with the EU is actively investigating areas such as the progressive replacement of plastics (EEAS, 2021). Ecuador has also passed new circular-economy legislation (the *Ley Orgánica de Economía Circular Inclusiva* (Asamblea Nacional, 2021)), which sets the stage to enable prioritized reuse and recovery of different categories of waste; the legislation includes measures to create a registry of waste-management providers, establish a providers' certification system, and put in place data collection and reporting requirements. Taken together, these existing policies could serve as a useful entry point for a broader national dialogue on further greening the plastics value chain in Ecuador by addressing upstream manufacturing and transportation of plastics and the end-of-life disposal practices, including discarding of plastic wastes in the natural environment (Brooks et al., 2020; Kaza et al., 2018; Zambrano-Monserrate & Alejandra Ruano, 2020). There is a long road to travel in terms of translating policy aspirations into implementation.

6.4 Decarbonization of Textiles in Ecuador

Market Overview

In 2020, exports of Ecuadorian textiles, footwear, headwear, and animal hides in 2020 accounted for $152 million in revenue, representing 0.72% of total export revenues (OEC, 2022). The key market segments (see Figure 6.5) that account for more than half of all exports in these categories are coconut and vegetable fibers (22%), waterproof footwear (11%), woven cotton (10%) packing bags (10%), and tanned animal hides (8%). At the same time, Ecuador imports $814 million worth of goods in these same categories (OEC, 2022), with the balance skewed toward more synthetic and finished products. Ecuador exports its textiles and textile products to a broad range of markets (see Figure 6.6), with 47% going to South America, 24% to Asia, 16% to North America, and 12% to Europe. China and Hong Kong are the largest markets for Ecuadorian animal hides (80%). Colombia and Peru are the largest markets for footwear and headwear (61%).

Figure 6.5: Ecuadorian Exports of Textiles, Footwear, Headwear, and Animal Hides, 2020, by HS4 Category (OEC, 2022)

Total: $152M

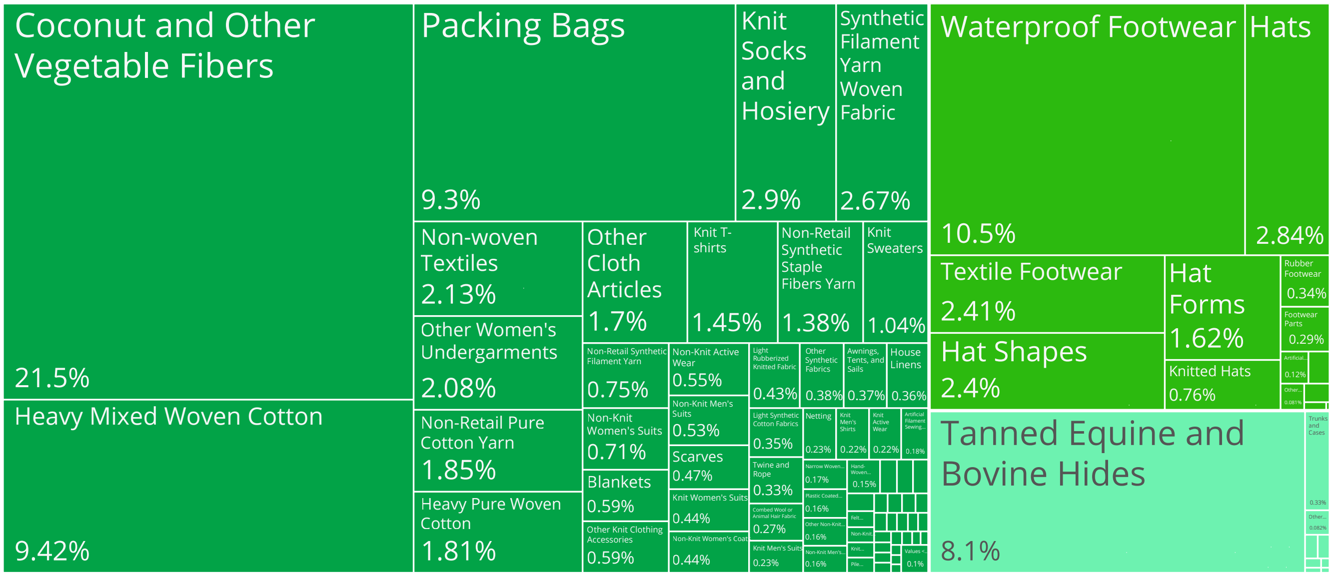
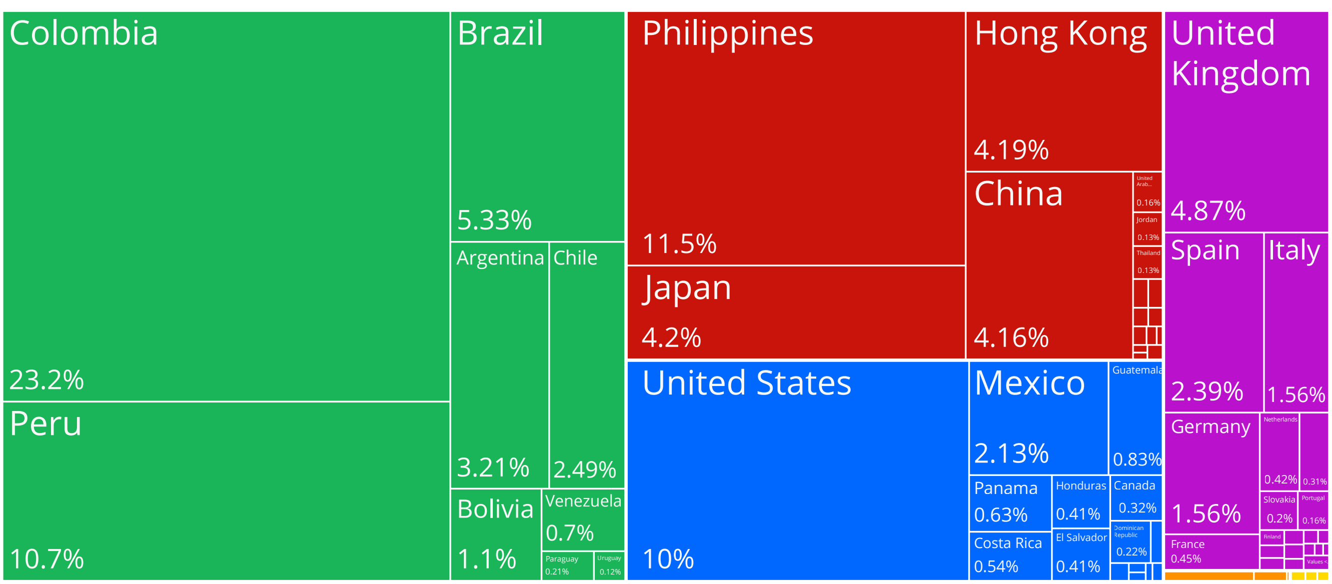


Figure 6.6: Ecuadorian Exports of Textiles, Footwear, Headwear, and Animal Hides, 2020, Percent by Destination (OEC, 2022)

Total: $152M



Technological Opportunities

Opportunities for reducing emissions from Ecuadorian textiles exist in all stages, from upstream procurement of resources to end-of-life disposal (see chapter 2 for details on textiles and chapter 1 for details on plastics decarbonization, which applies to synthetic fabrics, which are made from plastics). For natural fibers, which are an important component of Ecuadorian exports (vegetable fibers, cotton, and animal hides), to reach net zero, associated agricultural processes must be decarbonized. Agricultural vehicles, irrigation pumps, and other harvesting and processing equipment should be powered by net-zero electricity and/or zero-carbon fuels to the fullest extent possible (Hedayati et al., 2019). Potassium and phosphorous fertilizer inputs should ideally be sourced from net-zero mining operations (Ouikhalfan et al., 2022); net-zero production of nitrogen-based fertilizers requires green ammonia (Armijo & Philibert, 2020; Chehade & Dincer, 2021; IEA, 2021b). Agricultural decarbonization also requires a strategy to balance emission sources and carbon sinks through, for example, land-use change (Harwatt et al., 2020; Reay, 2020) or carbon capture and storage (Hanna et al., 2021). Such an approach is needed because not all fertilizer applied to plants is absorbed at a rate of 100% during cultivation, and the unabsorbed nitrogen leads to emissions of nitrous oxide, another powerful greenhouse gas (Gregorich et al., 2015).

Processing raw materials into fibers and finished products is a major aspect of the Ecuadorian textiles sector. It is already technologically possible for all the major processes involved in textile manufacturing (including high-temperature heat at up to 160°C (Arpagaus et al., 2018)) to be directly electrified electrothermally, or indirectly with an industrial heat pump. Thus, the main pathway for achieving net zero in this part of the value chain will be to convert processes that are currently directly combusting fossil fuels (e.g. heat supply for dyeing) to use electricity, and to reduce emissions from the power grid itself. Transport of finished products to market will also require decarbonizing transport modes (e.g., road freight, aircraft, railways, shipping) by using electricity or synthetic, zero-emission fuels (Kaack et al., 2018). With two-thirds of textiles made of plastics (Palacios-Mateo et al., 2021) and blends of plastic and natural fibers (e.g., cotton and polyester) increasingly common, end-of-life disposal strategies are similar to those of the plastics industry (see chapter 1). The main avenue for achieving net-zero, end-of-life disposal of textiles will be achieving material circularity through improved recycling and adoption of circular-economy principles (Ellen MacArthur Foundation, 2017a; McKinsey & Company, 2022; Shirvanimoghaddam et al., 2020; Wojciechowska, 2021). A shift in the production to higher-quality garments with longer lifetimes and greater durability is also critical (Nature Climate Change, 2018; Niinimäki et al., 2020); such a shift has begun in some textiles operations in Ecuador (e.g., the Ecuadorian slow-fashion company Remu Apparel (Pohlmann & Muñoz-Valencia, 2021)).

Existing Policies

Large-scale policy measures to put the national textile industry on a net-zero pathway have not yet been adopted in Ecuador; however, business associations and the government are discussing related subjects, such as cleaner production. In 2019 the main textile industry association body, *Asociación de Industriales Textiles del Ecuador* (AITE), began to discuss plans to create a joint Clean Production Center that would provide both advice and financing on energy efficiency in textiles manufacturing (AITE, 2019). The textiles and fashion industry has also recently been part an effort to identify key actors and map opportunities in the sector through the "cluster initiatives" program of the *Ministerio de Producción, Comercio Exterior, Inversiones y Pesca* (Ministry of Production, Foreign Trade, Investment and Fisheries (MPCEIP). As the vast majority (85%) of Ecuadorian textile companies have fewer than 200 employees and annual sales volumes under $5 million (Sigcha et al., 2021) viable strategies must address the small scale and dispersed nature of actors in the sector; different policies will likely be needed to address both large and small businesses. Digital technologies and digital-transformation policies may help firms collect needed data and comply with any reporting requirements; small firms may have limited additional resources to dedicate to these tasks.

6.5 Decarbonization of Auto Manufacturing in Ecuador

Market Overview

The Ecuadorian automotive market is heavily protected, with high import duties for many types of vehicles. The largest auto manufacturing plant in Ecuador is the *Ómnibus BB (OBB) Transportes* S.A. factory in Quito, which produces trucks and passenger cars under license from General Motors. Ecuador imports significantly more vehicles than it exports ($1.14 billion imports vs. $29 million exports) (OEC, 2022). Delivery trucks, cars, work trucks, motorcycles, and various vehicle parts account for only 0.14% of total exports. The most significant export product category is delivery trucks (see Figure 6.7), and the main export market for road vehicles in general is Columbia, which accounts for 93% of exports (see Figure 6.8).

Figure 6.7: Ecuadorian Exports of Transportation Products, 2020, by HS4 Category (OEC, 2022)

Total: $54.9M

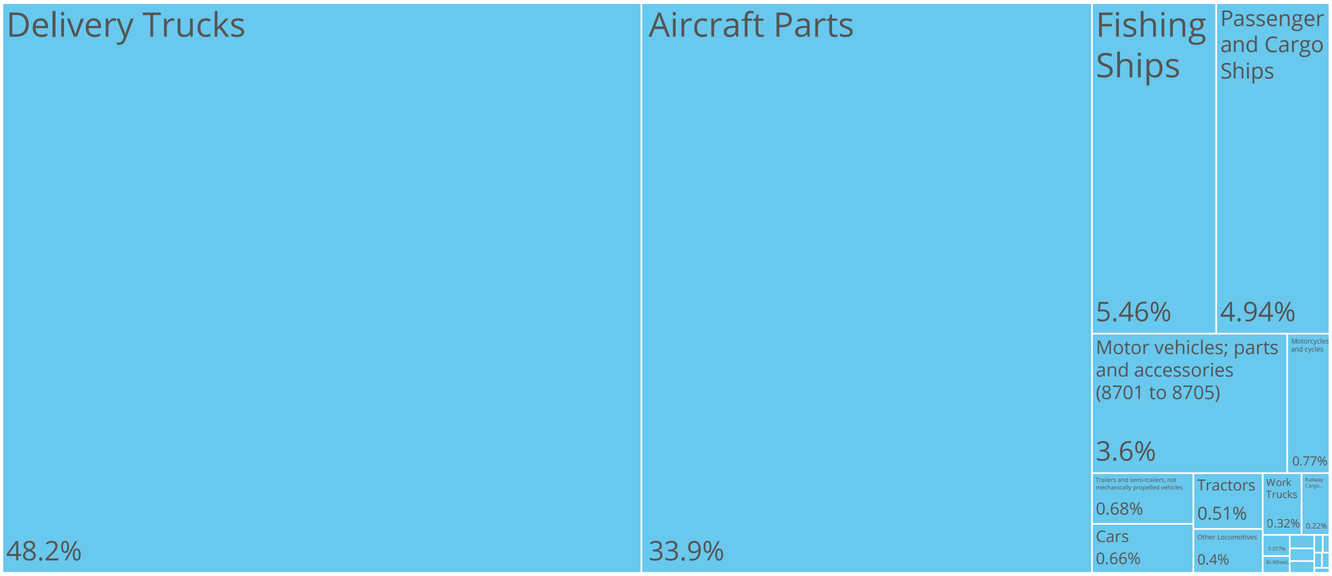


Figure 6.8: Ecuadorian Exports of Cars, Delivery Trucks, Work Trucks, Motorcycles, Various Vehicle Parts Categories, 2020, by Destination (OEC, 2022)

Total: $29.5M

Technological Opportunities

Achieving net-zero emissions in auto manufacturing requires the wide range of upstream inputs used also reach the net-zero aim (see chapter 3 for further detail). This means net-zero transformation of mining operations (Igogo et al., 2021), and processes to manufacture steel (Bataille, Stiebert, et al., 2021; IEA, 2020b, 2021f; Mission Possible Partnership, 2021; van Sluisveld et al., 2021; Yu et al., 2021), aluminum (Gomilšek et al., 2020; IEA, 2021a; Nature, 2018), glass (Furszyfer Del Rio et al., 2022; Griffin et al., 2021), and battery packs (Aichberger & Jungmeier, 2020; Degen & Schütte, 2022). Achieving net zero on the vehicle production line will require energy efficiency, the electrification of as many processes as possible by using electricity from a zero-carbon grid and hydrogen for high-temperature process heat (Bataille et al., 2018; Bataille, Nilsson, et al., 2021; Rissman et al., 2020). Switching to lighter-weight vehicles (Czerwinski, 2021; Kacar et al., 2018; Shaffer et al., 2021) and producing electric vehicles rather than fossil fuel-powered vehicles (Crabtree, 2019; Kawamoto et al., 2019; Rietmann et al., 2020) are other important opportunities for reducing emissions.

Freight-transport elements of the automotive supply chain (both finished products and intermediate components) need to be electrified or powered by net-zero liquid or gaseous synthetic fuels for transportation by road freight (Meyer, 2020), rail (IEA, 2019), aircraft (Bauen et al., 2020; IEA, 2021c; Viswanathan & Knapp, 2019), and ships (Bouman et al., 2017; Mallouppas & Yfantis, 2021). Finally, end-of-life disposal for vehicles should be reimagined to drive toward circular material flows. In principle nearly all parts of a vehicle can be recycled but the design of the vehicles, the infrastructure for recycling, and the appropriate market incentives would need to be aligned. Manufacturers can play an important role in improving the recyclability of vehicles during the design process, both by selecting materials that can be easily recycled and by structuring the components of the vehicle so that they can be easily disassembled for reuse as spare parts or separated into individual recycling streams (i.e., using standard circular-economy principles (Aguilar Esteva et al., 2021; Baars et al., 2021; He et al., 2021)). This applies particularly to battery packs (C. Bauer, Burkhardt, et al., 2022; Harper et al., 2019) and other structural components such as windshields and wheel rims (McAuley, 2003; Nakano & Shibahara, 2017; Soo et al., 2017).

Existing Policies

Ecuador's national electromobility strategy has progressive targets for the number of electric vehicles in circulation by 2025, 2030 and 2040 (Hinicio et al., 2021). Existing energy-efficiency legislation also mandates that new vehicles used for public transport in mainland Ecuador should be electric beginning in 2025 (Asamblea Nacional, 2019) (Galapagos is considered on a case-by-case basis). At minimum, a local industry for maintenance, battery reuse and recycling of all possible components should be encouraged to help build Ecuador's share of the global electric vehicle value chain.

6.6 Decarbonization of Fisheries in Ecuador

Market Overview

The Ecuadorian seafood industry represents a large fraction of the economy and is many orders of magnitude larger than the size of the plastics, textiles and automotive industries combined. Fish, crustaceans, and mollusks (all either fresh or prepared) accounted for just over $5.3 billion in exports in 2020, representing around 26% of total export activity. Two key market segments – fresh crustaceans (55%) and processed fish (17%) – account for more than half of all exports in the overall animal products and foodstuffs category (see Figure 6.9). Ecuador exports its seafood products to a broad range of markets, with the largest destinations by volume being China (~36%), the EU (~32%), and the United States (~20%) (see Figure 6.10).

Figure 6.9: Ecuadorian Exports of Animal Products and Foodstuffs, 2020, by HS4 Category (OEC, 2022)

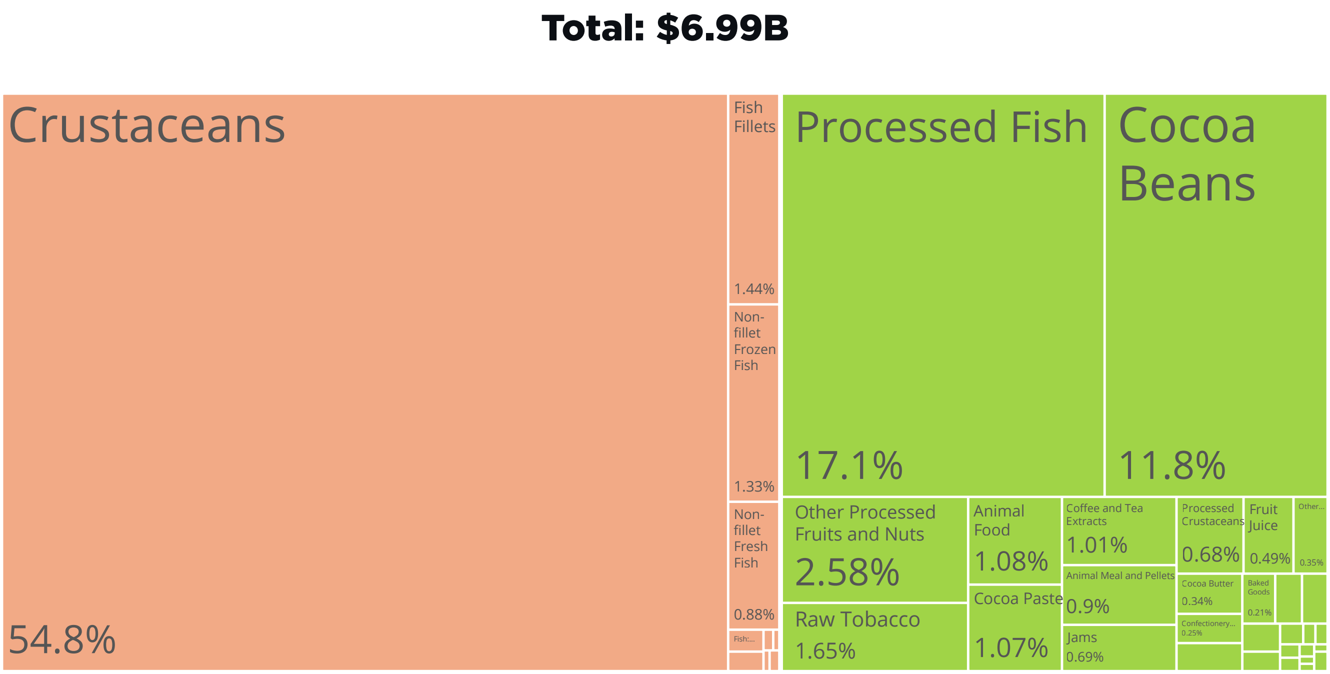
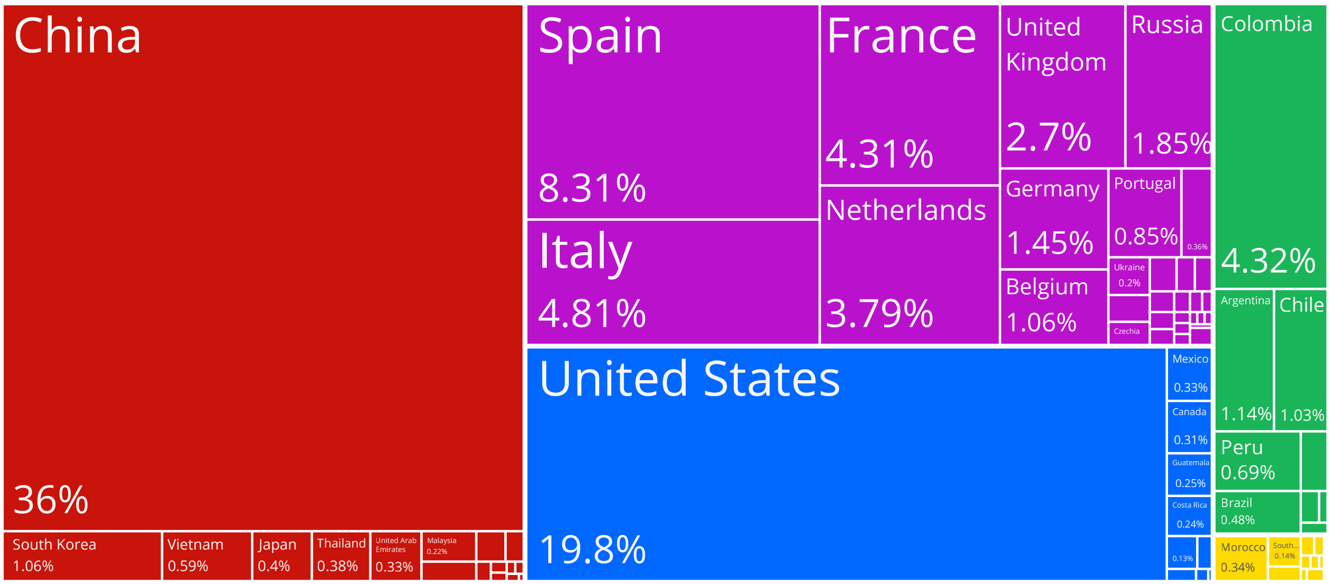


Figure 6.10: Ecuadorian Exports of Live Fish, Non-fillet Fresh Fish, Non-fillet Frozen Fish, Fish Fillets, Dried Salted Smoked and Brined Fish, Crustaceans, Mollusks, Processed Fish and Processed Crustaceans, 2020, by Destination (OEC, 2022)

Total: $5.34B



Technological Opportunities

Achieving decarbonization in fisheries requires carbon neutrality to be achieved throughout the value chain of the sector (see chapter 4 for further detail). This includes addressing the upstream raw material processes and energy inputs for building vessels, reducing emissions from marine vessels used in fishing and cargo transportation, and then recycling component parts of vessels when they reach their end-of-life phases (Mallouppas & Yfantis, 2021; Vakili, Ölçer, et al., 2022). Carbon neutrality is also required for the agricultural input chain that produces feed for seafood farms (Jones et al., 2022), for the fuels and electricity that power the processing and packaging of seafood (Alzahrani et al., 2020; Scroggins et al., 2022), and for the transportation of the finished products to market (Psaraftis & Kontovas, 2020). As ships and port infrastructure have long asset lifetimes, measured in decades (Bullock et al., 2022), there is considerable inertia in the established system that depends heavily on fossil fuels. Changing this on a timeline to meet Paris Agreement targets is unlikely to occur solely through price competition and innovation alone, and almost certainly will require deliberate market creation and regulations to bring about technological change (Cullinane & Yang, 2022; Lagouvardou et al., 2020).

Decarbonization of fisheries will require long-term policy planning and investments in innovation to identify the composition and condition of national fishing fleets and the associated seafood-farming sectors, and to chart a course toward zero-emissions in line with national decarbonization objectives. Planning for this sector cannot be undertaken in isolation from the rest of the economy because change for fisheries depends on changes in electricity sources, types and use of fuels, and agricultural processes. Deep coordination among national agencies that are responsible for agriculture and aquaculture (i.e., seafood farming), maritime law, ecosystem management, and the technical regulations governing marine vessels will be required. Because fishing and the transportation of seafood cross international boundaries, coordination of national decarbonization activities will also need to be aligned with international bodies such as the shipping "certification societies" that insure cargo vessels as they travel across borders (e.g., Lloyd's Register, the American Bureau of Shipping, Nippon Kaiji Kyokai) and the International Maritime Organization (IMO) (Milios et al., 2019). Almost all global ship deconstruction and recycling occurs in only five markets: India, Pakistan, Bangladesh, Turkey, and China (UNCTAD, 2021); thus, direct involvement with the governments of those nations is needed to enable a more circular economy for shipping vessels.

Existing Policies

The existing policy framework for fisheries in Ecuador is focused mainly on management and conservation of the country's aquatic resources (i.e., to prevent overfishing and ecosystem degradation). At the time of writing (early 2023), Ecuador does not yet have a focus on decarbonizing the fisheries sector in line with an overarching national climate action plan; nevertheless, the institutions and regulatory architecture to start such a process are arguably in place. For example, Ecuador has a research-driven executive agency dedicated to fisheries management and technology transfer in the form of the *Instituto Nacional de Pesca* (National Fisheries Institute, (INP)). The INP is closely aligned with the *Ministerio de Producción Comercio Exterior, Inversiones y Pesca* (Ministry of Production, Foreign Trade, Investment and Fisheries) (MPCEIP), which maintains a full licensing and registration database on the Ecuadorian fishing fleet. Thes database can be used to understand the age and condition of vessels. Moreover, the Ministry has the remit to promote and develop the fisheries industry in a sustainable manner.

6.7 Toward Net-zero Plastics, Textiles Auto Manufacturing and Fisheries in Ecuador

Decarbonization pathways for Ecuador's plastics, textiles, auto manufacturing and fisheries sectors share a number of common strategic elements, which are also important for achieving net-zero across a range of other industries. Cross-cutting strategies for industrial decarbonization that are consistent across the literature (Bataille et al., 2018; Bataille, Nilsson, et al., 2021; Lechtenböhmer et al., 2016; Rissman et al., 2020) and include:

i. Material efficiency and energy-efficient processes

ii. Electrification of process energy wherever possible

iii. Fuel switching to synthetic low-emissions fuels where electrification is not possible

iv. Carbon capture and storage where necessary

v. Material circularity and recycling

vi. Carbon dioxide removal

Material Efficiency and Energy-efficient Processes

Material efficiency and energy efficiency play important roles in net-zero industry by reducing total energy requirements to create the same products. This in turn makes all subsequent parts of the transition easier to achieve. More efficient processes have the potential to usher in large emissions reductions. For example, it is estimated that 26% of steel and 41% of aluminum become scrap during the production of products from the basic materials (Milford et al., 2011). While the scrap is then diverted and remelted so that it can be ultimately made into useful products, the remelting itself is a significant energy sink. It is estimated that energy use could be reduced by between 6% to 17% through techniques to reduce process scrap in these industries. Product-design optimization has similar potential for large material savings. For example, analysis has shown that many metal-based products could be made around 30% lighter without sacrificing performance (Carruth et al., 2011).

Energy efficiency in industry is addressed specifically by Ecuador's National Energy Efficiency Plan (PLANEE) (MEER, 2017). The main action items in the plan are the promotion of cogeneration systems (i.e., combined heat and power), the identification and replacement of inefficient equipment (e.g., pumps, motors, boilers) and the development of energy service businesses that can participate in an efficiency services market. One study suggests that cogeneration could improve the energy efficiency of Ecuadorian industries by up to 40% (Pelaez-Samaniego et al., 2020). Implementation of these action items has met with only partial success to date. The main barriers to industrial energy efficiency in Ecuador have been assessed as price subsidies for electricity (which weakens the case for efficiency measures as energy prices are artificially depressed), and challenges obtaining financing, stemming from complex procurement processes and a lack of confidence that some contracts will be enforced (USAID, 2020, 2021).

Electrification

A critical strategy for emissions reductions and achieving net-zero for virtually all industries in Ecuador is the electrification of production processes wherever possible using decarbonized electricity. Ecuador benefits from an abundance of renewable-energy resources, of which hydropower is the most well developed. Hydropower has expanded significantly since 2007 (Ponce-Jara et al., 2018). Hydropower is now the single largest component of Ecuadorian power generating capacity at 62%, with fossil power plants at 36%, and the remainder is a mixture of non-hydropower renewables (MERNNR, 2020).

Achieving net zero in the industrial sector will require Ecuador to generate nearly all power from fossil fuel-free sources. To date Ecuador has successfully deployed hydropower at scale, but has so far had some difficulty attracting international investment to construct wind and solar power plants (USAID, 2020). Future hurdles to overcome include improving transmission capacity to handle increased flows of energy on the system, especially when integrating variable renewable-energy sources, and diversifying the generation mix away from hydropower while also reducing grid emissions to very low levels. Reducing reliance on hydropower would help to hedge against the risk posed by highly variable rainfall patterns forecast under future climate scenarios that could reduce hydropower generation (Carvajal et al., 2019; Carvajal & Li, 2019; Ramirez et al., 2020).

Ecuador is arguably in a strong position to deliver on a strategy that requires electrification of industrial processes. In brief, the Ministry of Energy and Non-Renewable Natural Resources (Ministerio de Energía y Recursos Naturales no Renovables (MERNNR[6]) oversees the Ecuadorian energy system. The Agency for Regulation and Control of Electricity (Agencia de Regulación y Control de Electricidad (ARCONEL)) is the state electricity regulator. The National Centre of Energy Control of the Republic of Ecuador (Centro Nacional de Control de Energía de la República del Ecuador (CENACE)) operates the transmission system and wholesale power market. These three agencies have powers that derive from the most recent revision to the Ecuadorian Constitution (Asamblea Constituyente, 2008), which includes specific clauses establishing state ownership and responsibility for provision of electricity to citizens (Article 314), renewable energy and energy efficiency (Article 413), and the adoption of climate change mitigation measures (Article 414). The latest national Electricity Master Plan (PME) (MERNNR, 2020) aims to add an additional ~7 GW of generation capacity by 2027, with supporting transmission-system upgrades.

A 2022 Inter-American Development Bank report, "Achieving Net-zero Prosperity: How Government Can Unlock 15 Essential Transformations" (Fazekas et al., 2022), provides detail on government actions needed to remove barriers on a sectoral level and pursue pathways to lower emissions across the economy. For decarbonizing and growing electricity supply, it suggests five key steps: i) working with utilities to establish electricity-system decarbonization and growth plans to support clean electrification; ii) helping utilities acquire and deploy low-cost capital to pay for clean power generation and necessary transmission; iii) expanding clean power generation by setting standards for renewable portfolios and grid GHG intensity using reverse auctions or feed-in tariffs; iv) easing siting approvals, especially for transmission; and v) phasing out coal, heavy oil, and, eventually, natural gas power plants. The phase-out of such fossil fuels will require careful consideration of local workforce and community transition plans, and support will be needed for communities whose economies depend on mining and producing fossil fuels.

6 Formerly the Ministry of Elecricity and Renewable Energy (*Ministerio de Electricidad y Energía Renovable* (MEER)).

Synthetic, Low-GHG Fuels

Innovations in heat-pump technology over the last decade (Arpagaus et al., 2018) for delivering heat at very high temperatures (up to 150 ºC commercially, and potentially higher) now mean that decarbonizing textiles can likely be achieved with electricity. However, plastics manufacturing (e.g., thermal cracking and injection molding) and upstream inputs to auto manufacturing (e.g., steel, glass, etc.) are likely to require heat inputs that can only be achieved through fuel combustion or electrothermal equipment that puts too high an instantaneous load on the gird. This does not mean that those fuels must be fossil fuels. Green hydrogen is a leading candidate for replacing fossil energy in industrial heat delivery, and while this fuel could be imported in future, the potential for local production is also strong. This is because Ecuador has significant renewable-energy resources that can provide low-cost electricity, a critical input in making green (i.e., low-GHG) hydrogen and green ammonia. Moreover, Ecuador's existing, mature domestic oil-and-gas industry has the technology base, the human capital, and the institutional knowledge to produce and export liquid fuels. With forecasts indicating that the country's dwindling oil reserves are likely to lead Ecuador to become a net oil importer by the late 2020s (Chavez-Rodriguez et al., 2018; Espinoza et al., 2019), a pivot by the local oil-and-gas industry to producing synthetic, renewable fuels might be particularly attractive and strategic.

Though the main policy literature from the Ecuadorian government has largely focused on electricity provision rather than synthetic fuels, regional studies from the Ecuadorian research community have begun to explore the issue. Assessments of biofuel potential in Ecuador have been mostly negative, due to the prospects for competition between biofuels and other important land uses (Ortega-Pacheco et al., 2019), especially food crop cultivation (Arcentales & Silva, 2019; Pazmiño & Arranz, 2015). Hydrogen has been assessed in a more promising light. Country-scale analyses estimate that low-cost electrolytic (i.e., green) hydrogen from renewable hydropower should be possible in Ecuador at costs below 2-3 $/kg (Pelaez-Samaniego et al., 2014; Posso et al., 2015). Pathways have also examined the potential for hydrogen production from agricultural and forestry residues (Posso et al., 2020). Other studies have considered hydrogen for the transport and buildings sectors (Posso et al., 2016; Posso Rivera & Sánchez Quezada, 2014) but not for industrial purposes. We suggest that this is an area that would benefit from further investigation. For example, the German government strategy (BMWI, 2020) may offer useful insights to explore how to achieve industrial decarbonization of high-temperature heat with hydrogen. At the time of writing (early 2023) the Inter-American Development Bank (IDB) has funded an ongoing project exploring the development of a green-hydrogen roadmap for Ecuador (IDB, 2021) but it has yet to be published in full.

Carbon Capture and Storage

Achieving net-zero aims for textiles, plastics, auto manufacturing, and fisheries sectors is not expected to require large-scale carbon capture in the product-manufacturing phases of the value chain. Carbon capture and storage may make sense in certain applications; for example, it may be useful for ethylene plastic production, which often involves separating CO_2. Carbon capture and storage may play a role in upstream raw material extraction in mining (Igogo et al., 2021) and steel production (Fischedick et al., 2014), but advances and investments in hydrogen reduction at present make applications in steel production less likely at present (Vogl et al., 2021). Carbon capture and storage at scale would require large-scale investment in CO_2 pipelines and suitable geological storage sites (such as depleted oil fields or saline aquifers) for long-term underground sequestration of CO_2. An example of a large-scale carbon capture infrastructure project provided by government to enable low-carbon industrial growth is the Alberta Carbon Trunk Line (ACTL), a 240-kilometer pipeline in Canada that connects major industrial facilities to carbon-storage sites (Cole & Itani, 2013). As a result of these investments, the region is now becoming a hub for low-carbon-fuel manufacturing (blue ammonia, blue hydrogen) for both domestic use and export to Asia (Air Products, 2021; Itochu, 2022). Recent Ecuadorian analysis on pathways to achieving deep decarbonization has shown the potential for carbon capture technologies to play a strong role for direct use in industry and as a means of decarbonizing the power sector or achieving negative emissions (Villamar et al., 2021). There may therefore be a case for exploring the future role of Ecuador's oil-and-gas sector as an important actor in developing carbon capture and storage. This could offer a way to help the country develop such an industry and to help the sector find new, viable pathways; the sector itself is expected to begin to decline later this decade, as noted in Chavez-Rodriguez et al. (Chavez-Rodriguez et al., 2018) and Espinoza et al. (Espinoza et al., 2019).

Material Circularity and Recycling

Improved material circularity is the main avenue for achieving net-zero emissions in the end-of-life disposal phase in the life cycle of plastic, textiles, and automotive products (including the vessels and equipment used in fisheries). Much has been written about circular-economy principles in relation to a number of these sectors (e.g., plastics (Barrowclough & Birkbeck, 2022; Ellen MacArthur Foundation, 2017b; Lange, 2021; World Economic Forum et al., 2016), textiles (Ellen MacArthur Foundation, 2017a; McKinsey & Company, 2022; Shirvanimoghaddam et al., 2020; Wojciechowska, 2021), and automotive manufacturing (Czerwinski, 2021; He et al., 2021; Khodier et al., 2018)). In broad terms, implementation requires large-scale improvements in the provision of infrastructure for collecting and processing end-of-life products; the creation of strong incentives to discourage both sending waste to landfills and dumping waste in the natural environment; and upstream changes to product design and materials, either through regulations or in consultation with industry to avoid the creation of products that cannot be recycled.

Carbon Dioxide Removal (CDR)

Very deep decarbonization of the Ecuadorian economy is still likely to result in a degree of residual emissions that cannot be eliminated directly through either technological change in industrial processes or the provision of large-scale clean-energy infrastructure. One example is the production of nitrous oxide emissions from the use of nitrogen fertilizer in agricultural production (Lim et al., 2021). Analysis on deep decarbonization pathways for Ecuador to date has considered a range of scenarios, with the most ambitious exploring how emissions can fall by around 75% on 2015 levels by 2050 (Villamar et al., 2021). Achieving net-zero means that the remaining 25% of the emissions that remain, even in this most ambitious scenario, will still need to be addressed. One avenue to achieve this would be to use nature-based solutions, which seek to remove residual emissions by expanding natural carbon sinks such as forests (Busch et al., 2019). Such an approach links with the strategy that Ecuador has proposed for reducing emissions through the NDC submitted to the UNFCCC (República del Ecuador, 2019); this correspondence highlighted the reduction of emissions from deforestation as a key part of its wider strategy. Technical measures – such as scrubbing carbon dioxide directly from the air using direct air capture technologies – have also been proposed as alternatives to natural carbon sinks, but involve technologies that is still in the earliest stages of development (Erans et al., 2022; Hanna et al., 2021; McQueen et al., 2021).

6.8 Conclusions

An enormous transformation of virtually all sectors of the economy and many individual behaviors is necessary to create the supporting conditions for human development in a state of improved equilibrium with the natural world – concepts that are central to the Ecuadorian Constitution (Asamblea Constituyente, 2008). At the time of writing (early 2023), Ecuador has submitted proposals for decarbonization to the UNFCCC but has yet to set a net-zero target, or to outline a national roadmap to achieve net-zero goals through its policies and laws. Such steps are prerequisites for creating the conditions for a net-zero industrial transition.

Efforts to decarbonize the plastics, textiles, auto manufacturing, and fisheries value chains in Ecuador are in the nascent stages of conceptual development. Achieving net-zero industrial production in these and virtually all industries in Ecuador will require large-scale policy and investment decisions that go beyond the reach of any individual manufacturing plants or any single industrial sector. The prerequisites for net-zero industries are a low-emission power grid and the ability to import or create synthetic, low-GHG fuels, such as green hydrogen and green ammonia. Ecuador arguably has a strong track record of delivering on major infrastructure projects (notably hydropower, as described in (Ponce-Jara et al., 2018)).

Ecuador's abundant renewable-energy resources put it in a strong position to continue to develop a low-emission power grid for industry. To date, however, Ecuador has faced challenges attracting foreign investment for wind and solar power projects (USAID, 2020, 2021). Ecuador has an extensive oil-and-gas sector, which likely has the human capital and institutional knowledge to pivot to produce synthetic, low-GHG fuels for industry, and/or to play a role in providing infrastructure for carbon capture and storage for other industries. The fundamental knowledge and technological skills required for the extraction, refining, safe handling, and transport for petrochemicals translate very well to those needed in processes involved in producing and using low-carbon, synthetic fuels such as biodiesel, green ammonia, and green hydrogen. The spatial co-location of green industries is often thought of as a key strategy in roadmaps to develop net-zero manufacturing because of the synergies between the production of synthetic fuels, access to carbon-capture pipelines, and economies of scale associated with sharing such infrastructure. Net-zero industrial clusters are for example, central to the EU and UK industrial decarbonization strategies (BEIS, 2021; Merten et al., 2020).

It is imperative for Ecuador's leaders to demonstrate visionary leadership and proactive engagement in formulating and implementing comprehensive strategies for industrial decarbonization. As the global community accelerates towards a net-zero future, Ecuador must seize this pivotal moment to harness its innate resources and capabilities, thereby contributing to and benefiting from the global transformation, instead of being relegated to the sidelines of progress.

CHAPTER 7
PERU

7.1 Key Conclusions

Peru is in the early stages of developing a net-zero transition strategy for the economy as a whole.

Pain point: Peru has submitted proposals for decarbonization to the UNFCCC but does not yet have a net-zero target or a national roadmap to pursue carbon neutrality. Achieving carbon neutrality requires transformational changes to the power grid to provide and transport net-zero sources of electricity for the country; thus, an integrated policy drive to set and pursue net-zero aims across the whole country and to legislate targets and timelines will be required to set the stage to plan for a net-zero transition for industry.

Pain point: Even without the net-zero strategy in place, it is apparent that Peruvian efforts on decarbonization of energy supply will almost certainly require an updated national energy strategy from the Ministry of Energy and Mining (MINEM), which may require tighter coordination with the Ministry of Environment (MINAM). The existing national energy plan, which covers the 2014-2025 period, may need to explicitly consider new challenges that have arisen since it was drafted to address near-term energy and resource scarcity and national economic fallout from the COVID-19 pandemic.

Pain point: Any industrial decarbonization policy for plastics, textiles, auto-manufacturing and fisheries sectors would need to be integrated in a cohesive way with the overall net-zero strategy for the country.

Pain point: Achieving material circularity in Peru appears to be challenging. The most important near-term actions in this area are taking steps to formalize waste collection and prevent uncontrolled disposal in open dumps.

Pain point: State intervention will be required to develop green energy resources in a timely manner, and state intervention will be needed to adapt the existing electricity market structure.

Opportunity: Peru has abundant renewable-energy resources for supplying low-carbon industrial activity.

Opportunity: Peru has already begun the process of establishing a framework for green hydrogen projects to be built in the country. This is a potential, critical element of a net-zero industrial system.

7.2 Overview

This report explores the potential for Peru to place its plastics, textiles auto-manufacturing and fisheries sectors on a pathway to net-zero emissions within the context of Peru's existing climate policy framework. Peru faces a number of climate risks, and the breadth and scope of the national response has begun to reflect this. Risks include disruption to key economic activities such as copper, gold, and zinc mining from periods of intense rainfall (Gonzalez et al., 2019), and negative impacts on agricultural production from periods of water scarcity, increasing variability of water resources, and rising temperatures (Ovalle-Rivera et al., 2015; Quiroz et al., 2018; Tambet & Stopnitzky, 2021). Forecasts indicate that Peru is likely to experience more flooding (Bergmann, 2021), with the retreat of glaciers possibly driving both increased flood risks from atypical melting (Huggel et al., 2020) and reduced availability of water resources from their shrinking over the long term (Chevallier et al., 2011; Mark et al., 2017; Oesterling, 2015). The elevated temperatures forecast pose human health challenges to all Peruvians, who may face increasing risks of food insecurity, heat stress, and exposure to infectious diseases (Carrillo-Larco et al., 2022; Nicholas et al., 2021; USAID, 2017).

Peru has recognized these parallel threats to security and prosperity, and it has responded by commencing the development of an integrated climate policy framework with the objective of building consensus between government departments and major civil society groups. In 2018, Peru passed what is to date its most significant piece of climate legislation: the Framework Law on Climate Change (MINAM, 2018). The framework aims to align climate policy in Peru with economic and social-development goals, commits to Peruvian participation in the UNFCCC (i.e., Paris Agreement) processes, and designates the Ministry of the Environment (*Ministerio del Ambiente* (MINAM)) as the main national authority on climate policy. The official Peruvian Nationally Determined Contribution (NDC) to the Paris Agreement targets a 30% reduction in emissions by 2030, but also notes that Peru is in the process of developing a comprehensive national climate strategy with a 2050 time horizon (Gobierno del Perú, 2020a) and will be updating the NDC to include actions required to achieve carbon neutrality (i.e., net zero). At the time of writing (early 2023), the national net-zero strategy for Peru[7] was being constructed by the MINAM with inter-departmental participation from all major government ministries and a broad range of civil society groups through the CNCC.[8] An independent evaluation of Peru's prospects for achieving net zero by 2050 by the Inter-American Development Bank (Quirós-Tortós et al., 2021) concluded that such a transformation is not only possible but is also likely to be an excellent investment for Peru, offering an opportunity for the country to achieve climate-mitigation and adaptation goals while also improving productivity, incomes, and human health.

Important questions for Peru to consider as part of any discission on decarbonizing industry will be the availability of renewable electricity and the future role of fossil fuels. Hydropower (55.2%) and natural gas (36.9%) are the two main sources of electricity, with wind (3%) and solar (1.5%) having relatively minor roles (MINEM, 2019). Electrification is low across most sectors and end-use demands (residential, 21.8%; industrial, 26.5%; transport, 0.1%). This implies a need for large-scale expansion of renewable energy supply. Peru has stated the ambition to incrementally raise the share of renewable electricity in the system over time, and to improve energy access.

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7 This is provisionally titled the "*Estrategia Nacional ante el Cambio Climático al 2050* (ENCC)", the "National Strategy Against Climate Change to 2050" (see: https://www.gob.pe/institucion/minam/campa%C3%B1as/3453-estrategia-nacional-ante-el-cambio-climatico-al-2050)

8 *Comisión Nacional sobre el Cambio Climático (CNCC),* National Commission on Climate Change (see: https://www.gob.pe/institucion/minam/campa%C3%B1as/5064-cmision-nacional-sobre-el-cambio-climatico)

Peru has economic specialties in mining, manufacturing, and agricultural production. Total exports from Peru in 2020 were valued at $40.5 billion; the main products are raw copper ore (23%, $9.23 billion), gold (16%, $6.4 billion), refined copper (4%, $1.8 billion), petroleum gas (3.5%, $1.41 billion), and animal feed (3%, $1.19 billion) (see Figure 7.1). The main export destinations (by value of exports to a given destination) are China (28%, $11.3 billion), the US (16%, $6.4 billion), the EU (13%, $5.2 billion), South Korea (7%, 2.7 billion), Canada (6% $2.4 billion), and Japan (5%, $1.9 billion) (see Figure 7.2). Taken together, the plastics, textiles, auto-manufacturing and fisheries sectors generate 8% of export activity (OEC, 2022).

Figure 7.1: Peruvian Exports to the Rest of World, 2020, HS4 Coding (Colors Correspond to Different HS4 Trade Code Groups) (OEC, 2022)

Total: $40.5B

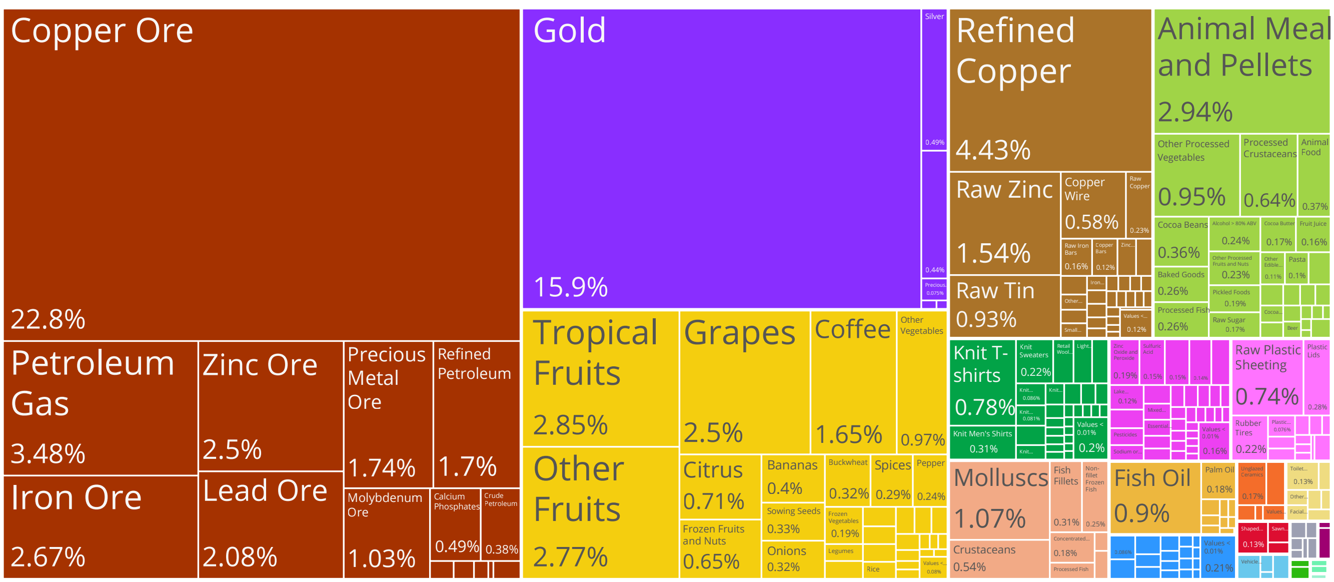
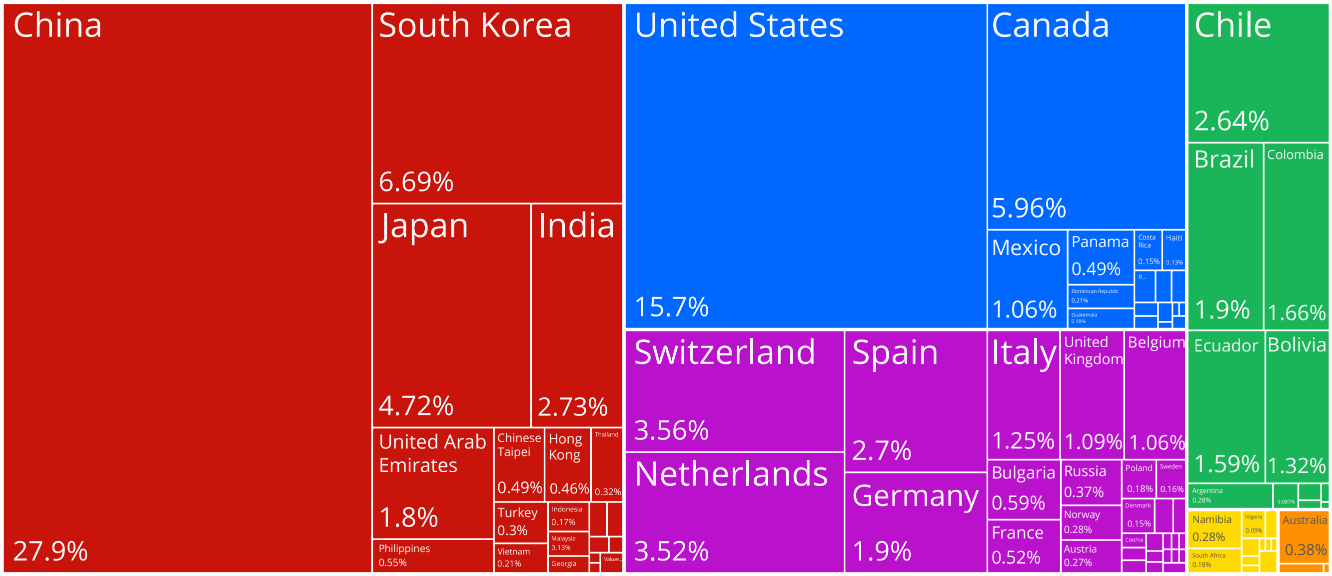


Figure 7.2: Peruvian Exports to Rest of World, 2020, Percent by Country (OEC, 2022)

Total: $40.5B



7.3 Decarbonization of Plastics in Peru

Market Overview

In 2020, exports of plastics and synthetic rubbers were valued at $656 million, around 1.6% of total exports (OEC, 2022). Finished products, particularly plastic sheeting (46%), plastic lids (17%) and rubber tires (13%) are the main export items (see Figure 7.3). Nearly all exports (96%) are to North and South America with the US, Mexico, Chile, and Colombia being the most important markets (see Figure 7.4).

Figure 7.3: Peruvian Exports of Plastics and Rubbers, 2020, Percent by HS4 Category (OEC, 2022)

Total: $656M

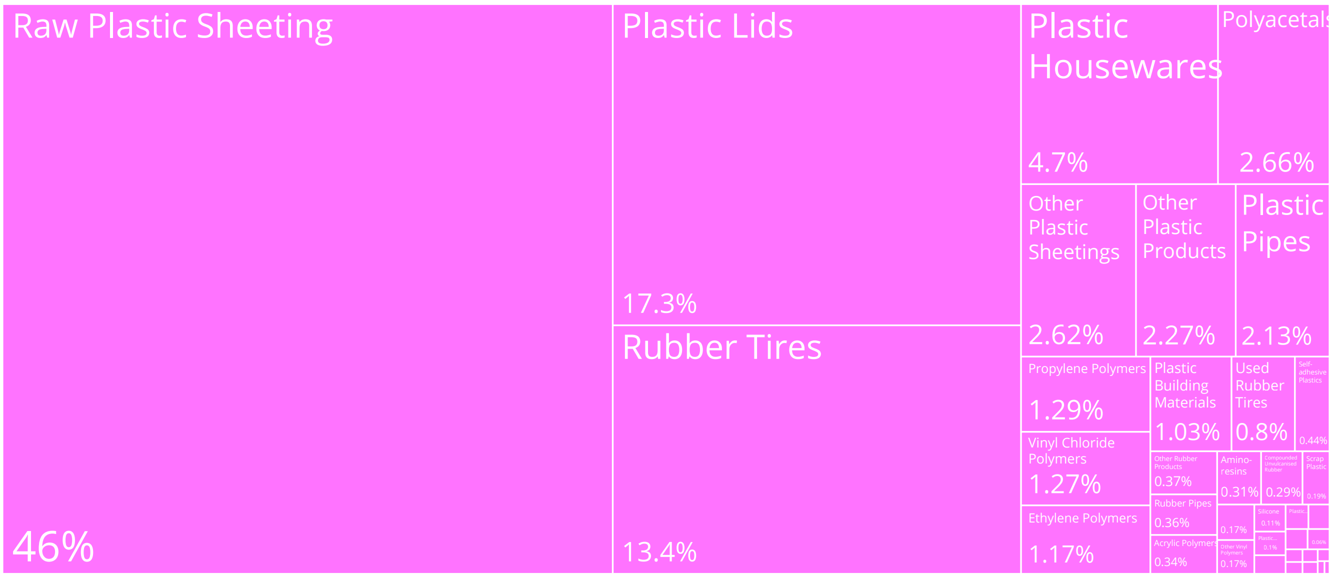
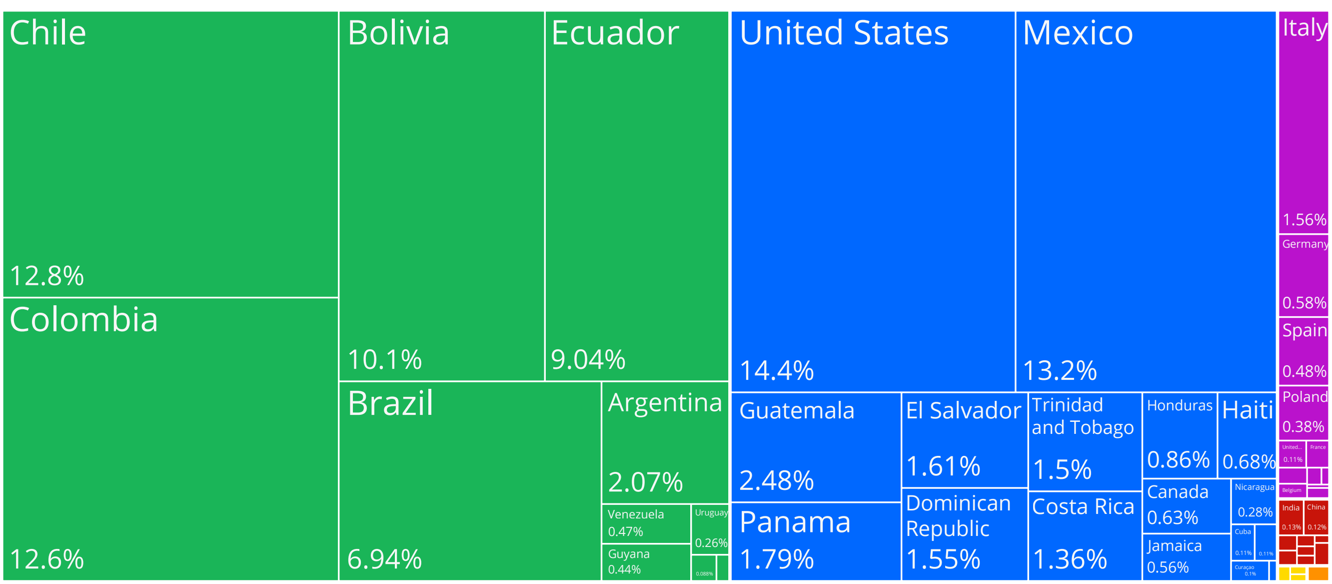


Figure 7.4: Peruvian Exports of Plastics and Rubbers, 2020, Percent by Destination (OEC, 2022)

Total: $656M



Technological Opportunities

A detailed overview of decarbonization options for the plastics sector can be found in chapter 1. Opportunities for reducing emissions from the plastics sector exist throughout the value chain. From a raw materials perspective, the key approach for plastics is to explore replacing fossil fuel feedstocks with biomass (Negri & Ligthart, 2021; Saygin & Gielen, 2021; Scott et al., 2020; Zheng & Suh, 2019), air-captured carbon dioxide (Lange, 2021; Palm et al., 2016; Palm & Svensson Myrin, 2018), or recycled carbon from waste (Carus et al., 2020; Moretti et al., 2020). From a resin and finished product-manufacturing perspective, electricity and heat need to be supplied from carbon-free sources such as a zero-emission electricity grid (Tullo, 2021) and low-emission fuels such as hydrogen or ammonia (Arnaiz del Pozo & Cloete, 2022; C. Bauer, Treyer, et al., 2022). Transport of raw materials and finished products would need to require that the freight-transport sector is also decarbonized with electricity or synthetic fuels (i.e., road (Meyer, 2020), rail (IEA, 2019; Rungskunroch et al., 2021), aviation (Bauen et al., 2020; IEA, 2021c; Schäfer et al., 2019), shipping (Bouman et al., 2017; IEA, 2021e; Mallouppas & Yfantis, 2021)). Finally, net-zero end-of-life disposal for plastics will need infrastructure and appropriate incentives put in place so that all plastics that remain in use can be recycled. Ultimately this may require novel polymer chemistries and (Gandini, 2008; Hatti-Kaul et al., 2020) and products to be designed for recycling (K. Daehn et al., 2022), but in the meantime there is a lot of work to be done to simply collect and process existing plastic waste, much of which already is simply discarded into the environment (CEIL, 2019; Lau et al., 2020).

Existing Policies

Peru has recently begun to enact policies for limiting the environmental impacts of plastic waste, such as effectively banning and/or imposing additional costs for the use of certain single-use plastic items (Alvarez-Risco et al., 2020; Congreso de la República, 2018; MINAM, 2019a, 2019b) and imposing fines on businesses that fail to comply (Rondon-Jara et al., 2021). These are positive early steps. Research suggests the potential for major improvements in the handling of end-of-life disposal for plastics in general in Peru and a need to restructure technical and legal regulations to financially incentivize recycling in general (Torres & Cornejo, 2016). Peru has signaled the intention to move toward a more circular economy in recent publications such as the Roadmap toward a Circular Economy in the Industry Sector[9] (Gobierno del Perú, 2020b) and the National Competitiveness and Productivity Plan[10] (MEF, 2019). The former makes some provision for MINAM to explore technological adaptation to find substitute materials for disposable plastics, but it is clear that exact details are to be filled out over the five-year implementation horizon.

9 In Spanish: "Hoja de Ruta hacia una Economía Circular en el Sector Industria"

10 In Spanish "Plan Nacional de Competitividad y Productividad (PNCP)"

7.4 Decarbonization of Textiles in Peru

Market Overview

Peruvian textiles, footwear and headwear, and animal hides in 2020 comprised 2.7% of exports, valued at $1.08bn (OEC, 2022). Finished items of clothing like t-shirts, shirts, sweaters etc. account for more than half of this trade, with bulk fabrics and yarns also being significant (see Figure 7.5). The main export destination for Peruvian textiles is the United States (51%), with the EU (10%) being the second largest market (see Figure 7.6).

Figure 7.5: Peruvian Exports of Textiles, Footwear and Headwear, Animal Hides, 2020, Percent by HS4 Category (OEC, 2022)

Total: $1.08B

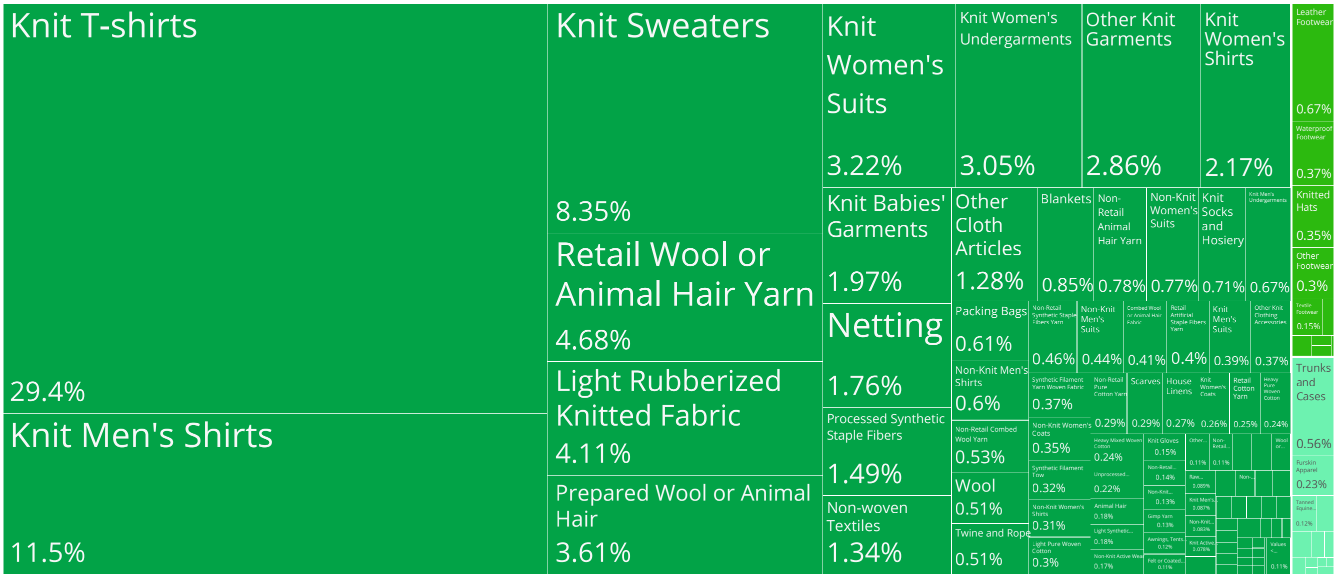
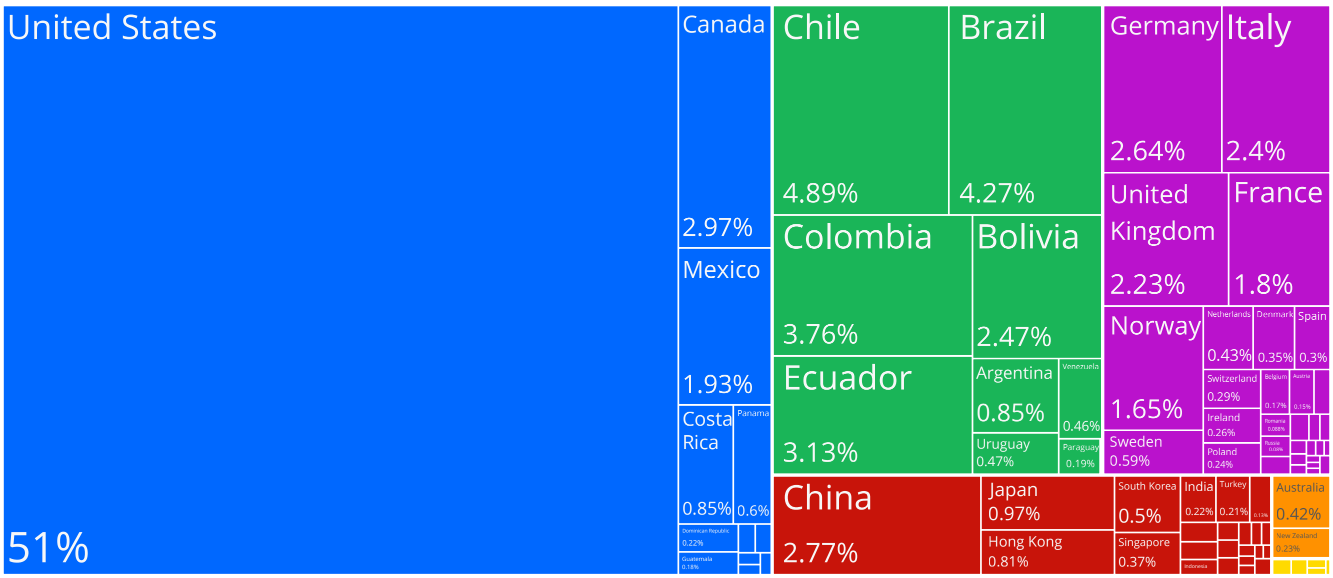


Figure 7.6: Peruvian Exports of Textiles, Footwear and Headwear, Animal Hides, 2020, Percent by Destination (OEC, 2022)

Total: $1.08B



Technological Opportunities

Reducing emissions from Peruvian textiles will entail addressing emissions throughout the life cycle of the industry – in the upstream resources, fiber and finished product manufacturing, transport, and end-of-life stages (see chapter 2 for further details). Because synthetic fibers are essentially plastics, the discussion on plastics decarbonization (see chapter 1) is relevant for textiles. For natural fibers (e.g., vegetable fibers, cotton, and animal hides), which are an important component of Peruvian exports, decarbonizing will require reducing agricultural emissions. Direct energy use by agricultural vehicles, irrigation pumps, and harvesting and processing equipment should be electrified with net-zero electricity and/or replaced with zero-carbon fuels to the fullest extent possible (Hedayati et al., 2019). Potassium and phosphorous fertilizer inputs should ideally be sourced from net-zero mining operations (Ouikhalfan et al., 2022). Net-zero production of nitrogen-based fertilizers requires green ammonia (Armijo & Philibert, 2020; Chehade & Dincer, 2021; IEA, 2021b). Agricultural decarbonization also requires balancing of emission sources and carbon sinks through land-use changes (Harwatt et al., 2020; Reay, 2020) and/or carbon capture and storage (Hanna et al., 2021). Action is needed because fertilizer applied to plants is not fully absorbed, leading to emissions of nitrous oxide, itself is a powerful greenhouse gas (Gregorich et al., 2015).

It is already technologically possible to electrify all the major processes involved in textile manufacturing, including high-temperature heat at up to 160°C (Arpagaus et al., 2018); thus, the main pathway for achieving net-zero in this part of the value chain will be to convert processes to use electricity from a zero-emissions power grid. Transport of finished products to market will also require that the transport modes employed (e.g., road freight, aircraft, railways, shipping) are decarbonized using electricity or synthetic, zero-emissions fuels (Kaack et al., 2018). At the end-of-life disposal stage, the same strategies discussed for plastics (see chapter 1) are highly relevant for textiles because two-thirds of textiles are plastics (Palacios-Mateo et al., 2021), and blends of plastic and natural fibers (e.g., cotton and polyester) are increasingly common. The main avenue for achieving net-zero, end-of-life disposal of textiles will be through achieving material circularity by improving recycling and the adoption of circular-economy principles (Ellen MacArthur Foundation, 2017a; McKinsey & Company, 2022; Shirvanimoghaddam et al., 2020; Wojciechowska, 2021). Encouraging a shift to produce higher-quality garments with longer lifetimes and greater durability is also critical (Nature Climate Change, 2018; Niinimäki et al., 2020).

Existing Policies

Targeting emissions reductions from the textiles and garment production industries does not yet appear specifically in existing Peruvian government work on its circular-economy strategy (other than as part of manufacturing in general). It is likely that the strategy is at the early stages of development and will need to identify sector-specific actions and targets going forward. Improving the overall quality of Peruvian textile products, with sustainability and "slow fashion" principles as major value-added factors, is viewed as a potential response to increased competition from Asia (Jarpa & Halog, 2021).

7.5 Decarbonization of Auto Manufacturing in Peru

Market Overview

Auto manufacturing exports in Peru are worth $60 million, representing 0.15% of total exports (OEC, 2022). Exports of transportation products are dominated by automotive ground vehicles, but they also include aircraft and sea-going vessels (see Figure 7.7). The most significant export categories for ground vehicles are motor vehicle parts and accessories (45%), of which 75% are sent to the US; buses (17%), which are sent mainly to Chile, Ecuador, and Bolivia; and special-purpose motor vehicles and cars (12%), which mainly go to Chile.

Figure 7.7: Peruvian Exports of Transportation Products, 2020, by HS4 Category (OEC, 2022)

Total: $71.2M

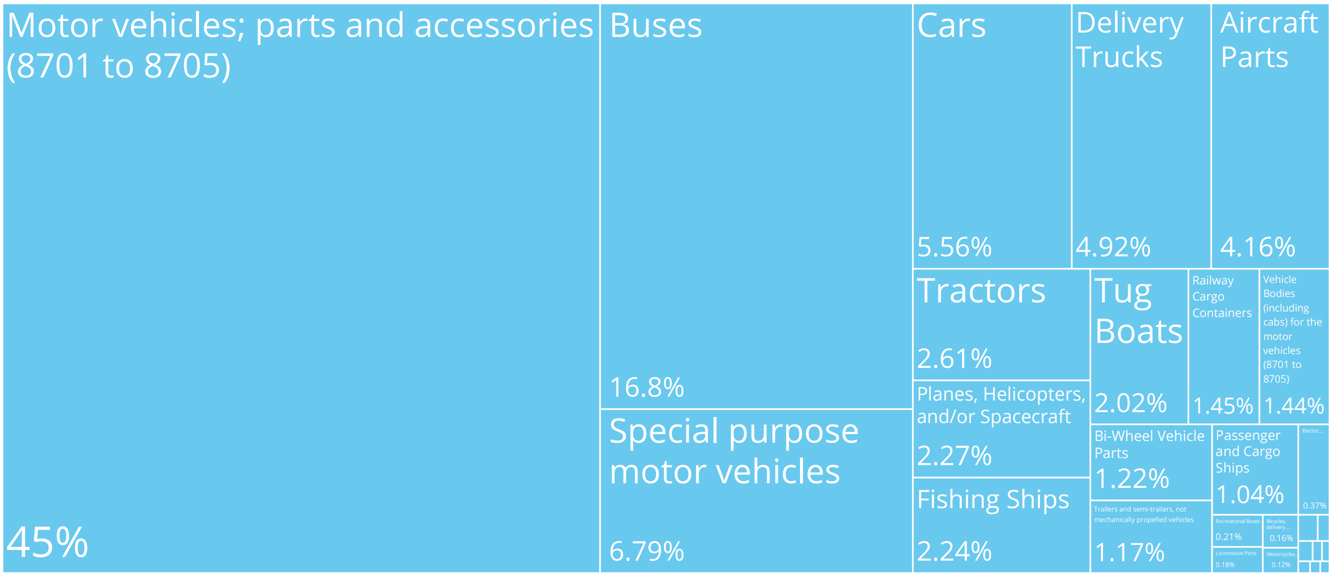
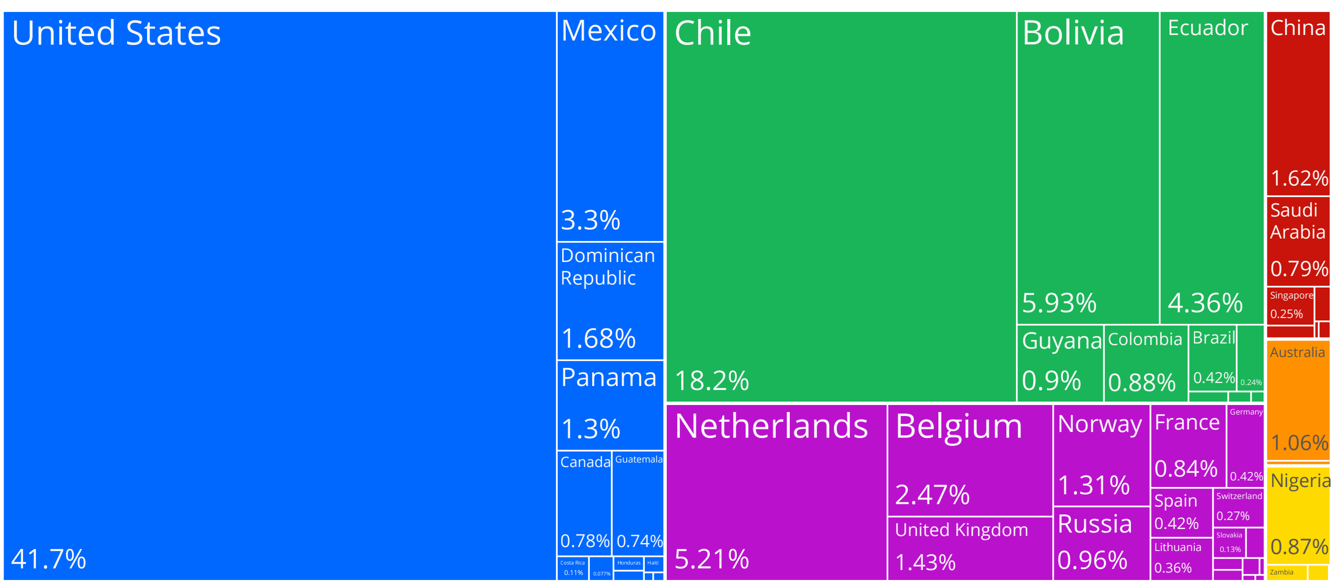


Figure 7.8: Peruvian Exports of Cars, Delivery Trucks, Work Trucks, Motorcycles, Various Vehicle Parts Categories, 2020, by Destination (OEC, 2022)

Total: $60.1M



Technological Opportunities

To achieve net zero in the automotive industry will require addressing emissions that occur throughout the supply chain and life of vehicles, including in producing the upstream input materials and component parts, manufacturing the vehicles, driving the vehicles, and disposing of the component parts at the end of the vehicle's life cycle (see chapter 3 for details). Emissions must be reduced for upstream steps including mining (Igogo et al., 2021); and for producing steel (Bataille, Stiebert, et al., 2021; IEA, 2020b, 2021f; Mission Possible Partnership, 2021; van Sluisveld et al., 2021; Yu et al., 2021), aluminum (Gomilšek et al., 2020; IEA, 2021a; Nature, 2018), glass (Furszyfer Del Rio et al., 2022; Griffin et al., 2021), and battery packs (Aichberger & Jungmeier, 2020; Degen & Schütte, 2022). Achieving net zero on the vehicle production line will require energy efficiency, the electrification of as many processes as possible with zero-carbon grid electricity, and the use of green hydrogen for high-temperature-process heat (Bataille et al., 2018; Bataille, Nilsson, et al., 2021; Rissman et al., 2020). Switching to lighter-weight vehicles (Czerwinski, 2021; Kacar et al., 2018; Shaffer et al., 2021) and producing electric vehicles rather than vehicles powered by fossil fuels (Crabtree, 2019; Kawamoto et al., 2019; Rietmann et al., 2020) are other important opportunities for reducing emissions.

Freight-transport elements of the automotive supply chain (both finished products and intermediate components) need to be electrified or powered by net-zero liquid or gaseous synthetic fuels for road freight (Meyer, 2020), rail (IEA, 2019), aircraft (Bauen et al., 2020; IEA, 2021c; Viswanathan & Knapp, 2019), and ships (Bouman et al., 2017; Mallouppas & Yfantis, 2021). End-of-life disposal for vehicles should be reimagined to drive toward circular material flows. In principle nearly all parts of a vehicle can be recycled but to make this happen in practice alignment is needed on vehicle design, recycling infrastructure, and appropriate market incentives. Manufacturers can play an important role in improving the recyclability of vehicles during the design process, both by selecting materials that can be easily recycled and by structuring the components of the vehicle so that they can be easily disassembled to reuse as spare parts, or separated into individual recycling streams (i.e., using standard circular-economy principles) (Aguilar Esteva et al., 2021; Baars et al., 2021; He et al., 2021). This applies particularly to battery packs (C. Bauer, Burkhardt, et al., 2022; Harper et al., 2019) but also to other structural components such as windshields and wheel rims. (McAuley, 2003; Nakano & Shibahara, 2017; Soo et al., 2017).

Existing Policies

Peruvian industrial policy does not yet focus on decarbonization of automotive manufacturing, presumably because it contributes a small share to the national economy. However, mining is one of Peru's most critical industries both in terms of production and as a source of tax revenues for the state; mining is a key upstream activity that feeds into the global production of automotive products and marine vessels (e.g., through the supply of iron and copper ores for making steel and wiring). Incremental decarbonization of the mining sector will need to become an explicit policy position with long-term durability if Peru is to achieve its stated climate ambitions to become a net-zero economy by the 2050s.

7.6 Decarbonization of Fisheries in Peru

Market Overview

The Peruvian seafood industry is a small fraction of the economy. In 2020 crustaceans and mollusks (all either fresh or prepared) accounting for just over $1.3 billion of exports, equivalent to around 3% of total export activity. The largest seafood export segments (see Figure 7.9) are crustaceans (~11%, if fresh and processed are aggregated together), mollusks (10%), and fish (~9% across all fresh/prepared categories). Peru exports its seafood products to every continent (see Figure 7.10), with the largest destinations by volume being the EU, followed by the US, and South Korea.

Figure 7.9: Peruvian Exports of Animal Products and Foodstuffs, 2020, by HS4 Category (OEC, 2022)

Total: $4.16B

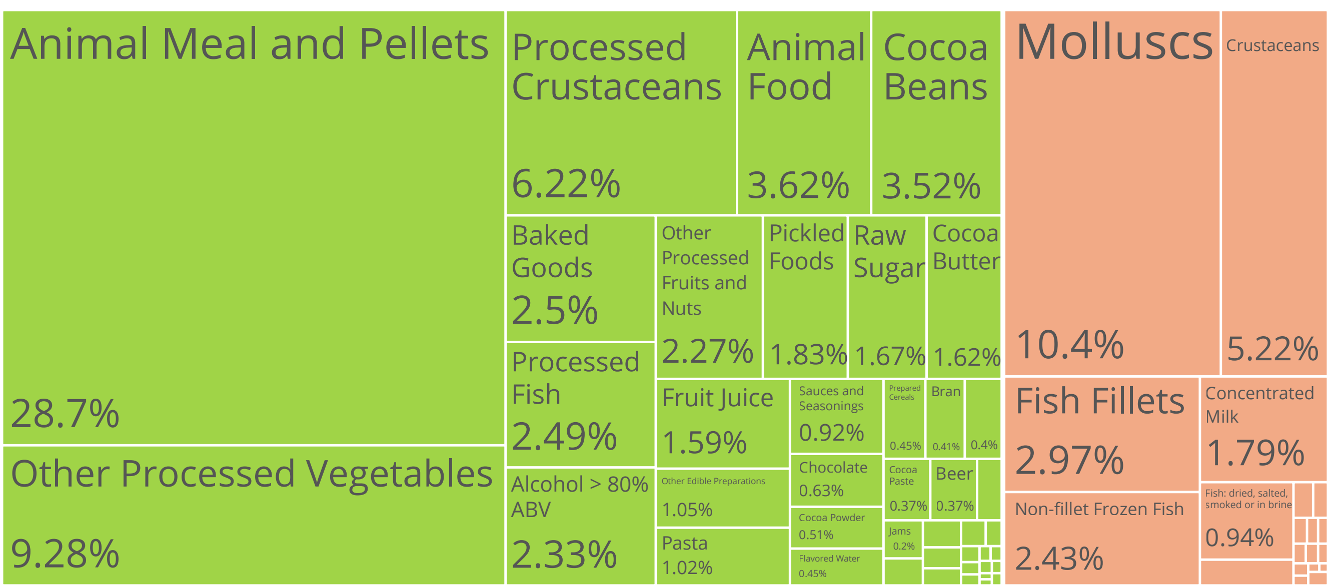
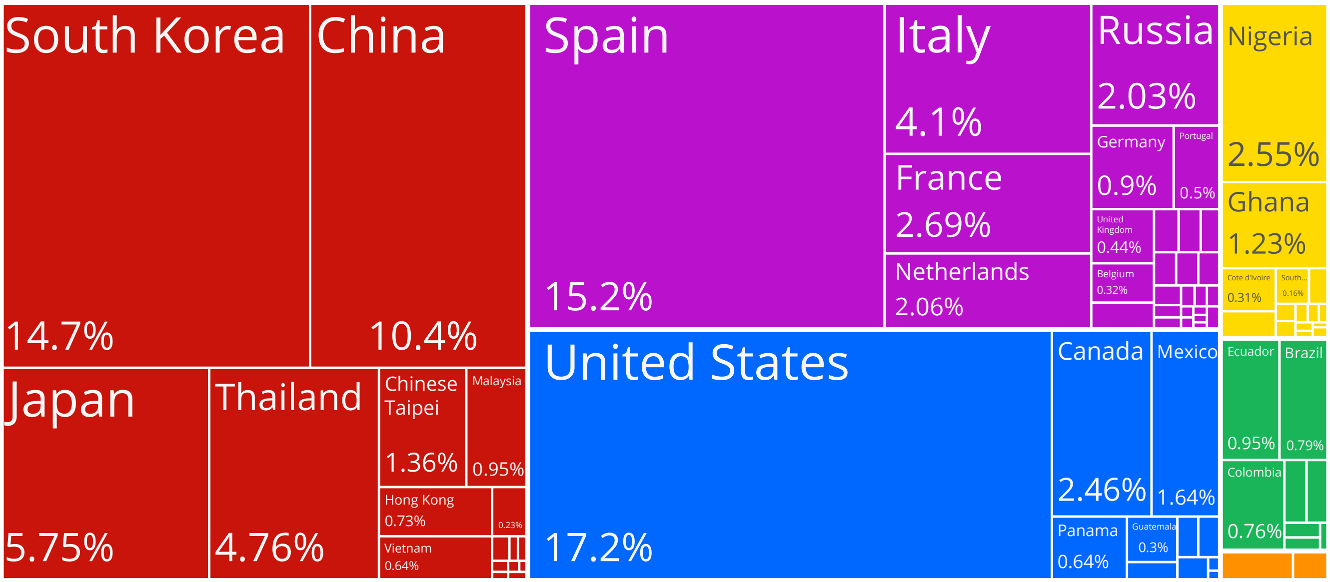


Figure 7.10: Peruvian Exports of Live Fish, Non-fillet Fresh Fish, Non-fillet Frozen Fish, Fish Fillets, Dried Salted Smoked and Brined Fish, Crustaceans, Mollusks, Processed Fish and Processed Crustaceans, 2020, by Destination (OEC, 2022)

Total: $1.29B



Technological Opportunities

Decarbonization in the fisheries sector requires carbon neutrality to be throughout the value chain of the sector. Emissions must be reduced in producing upstream, input materials and feed for vessels and farmed fish; in operating fishing vessels, transporting products, and dealing with marine vessels at the end of their useful lives (Mallouppas & Yfantis, 2021; Vakili, Ölçer, et al., 2022). Carbon neutrality is required in the agricultural input chain that produces feed for seafood farms (Jones et al., 2022) and for the fuels and electricity to power the processing and packaging of seafood (Alzahrani et al., 2020; Scroggins et al., 2022), and to transport the finished products to market (Psaraftis & Kontovas, 2020). As ships and port infrastructure have long asset lifetimes measured in decades (Bullock et al., 2022), there is considerable inertia in the established system, which depends heavily on fossil fuels. Price competition and innovation alone are unlikely to lead to the transformational changes needed to help meet the Paris Agreement aims by 2050 and 2070. Deliberate market creation and regulations will almost certainly be needed to incentivize and require technological change (Cullinane & Yang, 2022; Lagouvardou et al., 2020).

Decarbonization of fisheries will require long-term policy planning and investments in innovation to identify the composition and condition of national fishing fleets and the associated seafood-farming sectors, and to chart a course toward zero emissions in line with national decarbonization objectives. Support from other sectors such as agriculture, and electricity and fuel supply are essential for decarbonizing fisheries. Thus, planning for this sector cannot be undertaken in isolation from the rest of the economy. Deep coordination between national agencies that are responsible for agriculture and aquaculture (i.e., seafood farming), maritime law, ecosystem management, and the technical regulations governing marine vessels will be required. As fishing and the transport of seafood cross international boundaries, coordination of national decarbonization activities will also need to be aligned with international bodies such as the shipping "certification societies" (e.g., Lloyd's Register, American Bureau of Shipping, and Nippon Kaiji Kyokai), which insure cargo vessels as they travel across borders, and with the International Maritime Organization (IMO) (Milios et al., 2019). Almost all global ship deconstruction and recycling occurs in just five markets: India, Pakistan, Bangladesh, Turkey, and China (UNCTAD, 2021); direct involvement with the governments of those countries is needed to enable a more circular economy for shipping vessels.

Existing Policies

The main legislation addressing reduction of greenhouse gas emissions from wild-capture fishing and aquaculture in Peru is *Decreto Supremo No. 02-2019-PRODUCE* (Gobierno del Perú, 2019). This requires all wild fishing and aquaculture license holders to develop environmental management plans that include measures to address GHG emissions. At the time of writing (early 2023), no single institution in Peru is responsible for overall regulation, management, and transformation of the fisheries and aquaculture sectors in line with national targets or objectives. For example, the Ministry of Production (*Ministerio de la Producción* (PRODUCE)) manages fishing stocks, and inspects and issues licenses to the commercial fishing fleet; and the Ministry of the Environment (*Ministerio del Ambiente* (MINAM)) has overall responsibility for marine and freshwater ecosystem protection and the sustainable development of the country's natural resources. Peruvian fisheries policy arguably suffers from institutional fragmentation. There are no less than eight different government agencies, each with their own policies and independent multi-year strategic planning processes. For both marine and inland waters there is a general lack of coordination or policymaking that takes into account national or regional economic, social, and environmental objectives (OECD, 2017). This has made joined-up decision-making in this sector very difficult. Reforms are required if an agency or set of agencies with the institutional legitimacy is to create and operationalize an integrated policy framework for the decarbonization of fisheries and aquaculture.

7.7 Toward Net-zero Plastics, Textiles, Auto Manufacturing and Fisheries in Peru

The technological options for reducing emissions from the plastics, textiles, auto-manufacturing, and fisheries sectors in Peru share a number of common strategic elements. Cross-cutting strategies for industrial decarbonization that are consistent across the literature (Bataille et al., 2018; Bataille, Nilsson, et al., 2021; Lechtenböhmer et al., 2016; Rissman et al., 2020; Thiel & Stark, 2021) include:

i. Material efficiency and energy-efficient processes

ii. Electrification of process energy wherever possible

iii. Fuel switching to synthetic, low-emission fuels where electrification is not possible

iv. Carbon capture and storage where necessary

v. Material circularity and recycling

vi. Carbon dioxide removal

Material Efficiency and Energy-efficient Processes

Using available energy and material resources in an efficient manner is a critical starting position for a net-zero industrial strategy. Minimizing waste during production makes the task of providing infrastructure to decarbonize energy and material inputs less costly. Industrial energy efficiency in Peru is addressed by the Ministry of Energy and Mines (*Ministerio de Energía y Minas* (MINEM)) in its 2009 energy-use strategy (MINEM, 2009). The main target for industry in this document was to modernize 60% of industrial boilers. It is unclear whether this target was achieved or whether a replacement strategy document is under development. Energy-efficiency goals and targets for end-use demand sectors (which would encompass industry) are notably absent from MINEM's national energy plan (MINEM, 2014), and any future revisions should ideally include specific, measurable, and actionable targets. A peer assessment of the Peruvian policy landscape by the Asia Pacific Energy Research Centre found that, despite some past successes, the overall potential for energy efficiency in Peru remains largely untapped, and that engagement between industry and the executive on the subject is lacking (APERC, 2020).

Electrification

In line with worldwide assessments of technological and economic pathways toward net-zero, achieving deep decarbonization of Peruvian industry would require a large-scale expansion of clean grid electricity. For Peru to achieving net-zero industry (including in the plastics, textiles, auto-manufacturing, and fisheries sectors) will require that nearly 100% of electricity supplied for production comes from energy sources that are not fossil fuels. General principles for decarbonizing electricity supply include planning for long-term clean electrification, creating roadmaps; making low-cost financing available for generation, transmission, and distribution; setting performance standards (e.g., GHG intensity); fast-tracking permits and approvals for construction of energy infrastructure; and setting in motion a managed phasing-out process for residual fossil fuel generation (Fazekas et al., 2022).

Peru's potential to generate renewable energy is very high, but such potential is underutilized (IRENA, 2014). For example, based purely on solar resources and geographical constraints (i.e., the grid would also need to be reinforced accordingly) estimates suggest that Peru could generate from solar power alone roughly 10 times the electricity that it produces today (NREL, 2019). However, the Peruvian roadmap for scaling up renewable energy is unclear, and renewable-energy project auctions that were intended to be held annually have been stalled since 2016. MINEM has not updated its strategic energy plan (MINEM, 2014) in nearly a decade; the lag suggests an absence of tight coordination between environmental policy objectives and energy-policy goals. Only around 70% of the population in rural areas has access to electricity, and so a large-scale rural electrification plan is central to government plans for improving economic opportunities and livelihoods (MINEM, 2020). A large challenge identified for Peru has been limited access to finance for renewable-energy projects and climate finance in general, and unaddressed needs for additional support in the technological development and innovation space (Umweltbundesamt, 2018). Tighter coordination across government and the involvement of different agencies would be useful steps to help close this gap. For example, one near-term action for the Ministry of Economy and Finance (*Ministerio de Economía y Finanzas* (MEF)), would be to identify investment opportunities and promote them. To undertake this, MEF could use the skills and expertise held within *ProInversion*, a state-funded, specialized, technical agency that is part of the Peruvian Ministry of Economy and Finance and is intended to serve as a key vehicle for encouraging private investment in the Peruvian economy.

Synthetic, Low-GHG Fuels

Various industrial processes such as steel manufacturing, cement production, glass production, and chemical refining require elevated temperatures. Creating bulk polymers in the plastics industry and the dyeing textile fabrics are other examples. Commercially available electric heat pumps can already supply temperatures up to 150 °C but higher temperatures are likely to be a challenge until the 2030s (Arpagaus et al., 2018). Decarbonizing industry therefore requires synthetic, low-emission fuels to provide heat from combustion.

Efforts to develop biofuels in Peru have had mixed results to date (Pacheco Canales, 2019); historically such efforts have been met with concerns about impacts on forests, water availability, and overall food security (Tejada & Rist, 2018; Urteaga-Crovetto & Segura-Urrunaga, 2021). Efforts to control deforestation in Peru have led to higher food prices (Ugarte et al., 2021), amplifying such concerns. Thus, it appears that large-scale cultivation of bioenergy crops may be challenging to combine with efforts to preserve forest carbon sinks under Peru's national decarbonization strategy (Gobierno del Perú, 2020a).

The leading candidates for replacing fossil fuels in industry include green hydrogen and green ammonia, both of which could be manufactured domestically in Peru. In an encouraging first step, MINEM recently signed an agreement with *H2 Perú*, an industry association representing various energy and chemical engineering firms, to collaborate and promote technology development for green-hydrogen projects (MINEM, 2022). The first pilot project that has been proposed is a 160 MW electrolyzer producing 55 tonnes/day of hydrogen, using Siemens equipment, with the objective of producing green hydrogen, methanol or ammonia for export to Asia and the West Coast of the US (H2 Perú, 2022). Green ammonia and green hydrogen are also considered to be the leading contenders for replacing fossil fuels in power generation (Cesaro et al., 2021; Valera-Medina et al., 2018) and marine shipping (Al-Aboosi et al., 2021; Inal et al., 2022). Ammonia is already in high demand globally as a key input for agricultural fertilizer (Faria, 2021). This means that developing a robust Peruvian hydrogen industry could help decarbonize domestic production, offer export market opportunities, and increase energy security from reduced reliance on imported fossil fuels. Hydrogen and ammonia production represents an opportunity for the domestic natural gas industry to diversify its activities; such an approach could become particularly important because Peru is likely to become a net importer of natural gas in the mid-2030s (Chavez-Rodriguez et al., 2018; Leung & Jenkins, 2014).

Carbon Capture and Storage

Technologies for artificial sequestration of CO_2 such as direct air capture technologies (Erans et al., 2022; Hanna et al., 2021; McQueen et al., 2021) do not yet appear in the Peruvian policy literature. Researchers in Peru have, however, already performed assessments of likely storage reservoirs for long-term geological storage of captured carbon dioxide (Carlotto et al., 2022).

Material Circularity and Recycling

Waste management remains a major challenge for Peru. Informal disposal dominates, as suggested by a recent assessment that documented 29 registered landfills and 1,400 open dumps (Ziegler-Rodriguez et al., 2019). Estimates indicate that only 3% of households recycle their waste (Lavanda Reyes, 2021). There has been decade-long effort by the Ministry of the Environment (MINAM) to overcome these issues and transition to a waste-management system with separation at the source and controlled collection in sanitary landfills (MINAM, 2021a, 2021b). At the same time, recycling as a means of recovering materials for reuse is increasing every year in Peru, albeit mostly through informal channels (De-La-Torre-Jave et al., 2022), and researchers have begun to engage with businesses to understand what factors might motivate circular-economy-compatible behaviors (Alvarez-Risco et al., 2021). The Peruvian government has begun to bring the concept of more circular material flows into environmental and economic policymaking through publications such as the Roadmap toward a Circular Economy in the Industry Sector (*Hoja de Ruta hacia una Economía Circular en el Sector Industria*) (Gobierno del Perú, 2020b) and the National Competitiveness and Productivity Plan (*Plan Nacional de Competitividad y Productividad*) (MEF, 2019).

Carbon Dioxide Removal (CDR)

To bring Peruvian emissions to a carbon-neutral state for its industries and across the entire economy will likely require steps to remove carbon dioxide from the atmosphere. Nature-based approaches offers a means of offsetting the fraction of emissions that cannot be easily eliminated, such as nitrous oxide emissions from the use of nitrogen fertilizer in agricultural production (Lim et al., 2021) for cultivation of food and textile crops. Peru's Nationally Determined Contribution to the Paris Agreement (Gobierno del Perú, 2020a) relies on natural carbon capture through rainforest protection and management as a key means of taking the country's GHG emissions closer to zero by 2050 (Ugarte et al., 2021). There is also the potential to increase carbon sinks through reforestation; such an approach will require taking steps to address improper accounting of such sinks and damage to forests from, for example, fires and disease (Lefebvre et al., 2021).

7.8 Conclusions

Peru is a country in the early stages of developing a net-zero transition strategy that can align with other critical national objectives such as rural electrification, economic diversification, and poverty alleviation. At the time of writing (early 2023), a national roadmap for achieving carbon neutrality by 2050 has yet to be published. Any future industrial decarbonization strategy will need to fit within the overall contours of the forthcoming plan (to be produced by the Ministry of Environment (MINAM)). Peru has a number of advantages in terms of both its natural resources and its location. It has the potential to generate abundant solar and wind power. Its ports on the Pacific Rim provide export routes to major economies in North America and Asia. It is not clear whether these are being leveraged to the extent possible to achieve greater development aims.

Even without the net-zero strategy being in place, it is apparent that large increases in the availability of low-carbon electricity through the national grid system will be required to make net-zero industrial activity possible in Peru. This may well require state intervention in the existing electricity market structure to accelerate the rollout of renewables and increase generation capacity, which has been lagging behind targets in recent years. The last national energy plan was published in 2014 – nearly a decade ago. The absence of an updated, overarching energy roadmap from the Ministry of Energy and Mining (MINEM) has left an implementation gap between energy, environmental, and economic policies. This can only be closed through tighter inter-departmental coordination. To achieve a transition of the magnitude needed will require all those working in government ministries and departments on energy, mining, environmental, economic and finance issues to work closely together.

Low-carbon, synthetic fuels are also a prerequisite for net-zero industrial activities. They are particularly important for manufacturing industries that require high-temperature-process heat, which is needed for producing plastics, refining petrochemicals, and producing key, upstream inputs (such as steel and glass) for auto manufacturing. A promising early first step in this area has been an agreement between MINEM and the Peruvian Hydrogen Association (H2 Peru) to promote green-hydrogen projects (MINEM, 2022). In addition, Peru has begun the process of injecting circular-economy thinking into its more recent strategy documents; nevertheless, achieving material circularity will be difficult unless the performance of the waste-collection system can be improved to prevent uncontrolled disposal in open dumps, which are still the main method of end-of-life disposal for discarded products.

To fulfill its potential and make substantial progress towards a net-zero industrial future, Peru's leadership must take bold and decisive actions. Building upon the country's natural advantages and historical initiatives, it is essential to revamp energy policies, foster inter-departmental synergies, and invest in new infrastructure. By doing so, Peru can harmonize economic growth with environmental stewardship for the well-being of its citizens.

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