DE-CARBONIZING THE MANUFACTURING SECTOR:

A SERIES OF INDUSTRIAL REPORTS

By: Raj Mehta

FEATURES:

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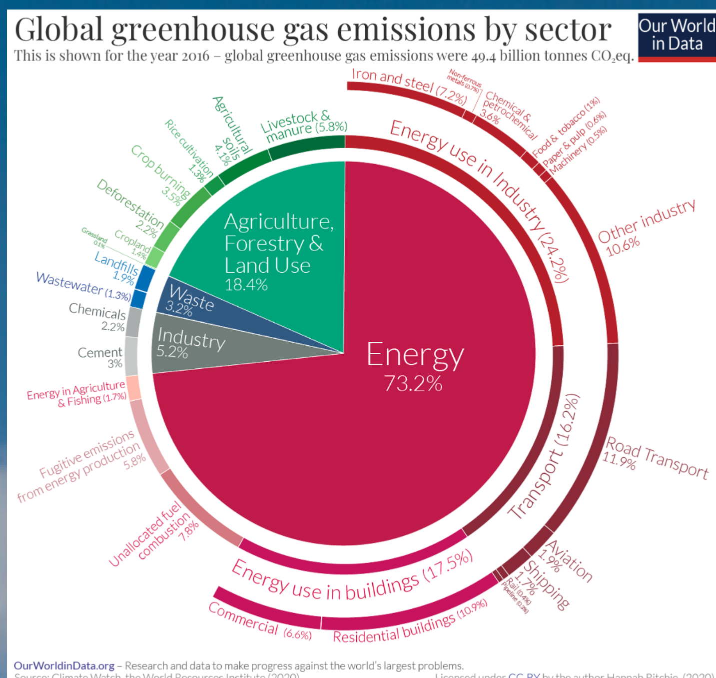
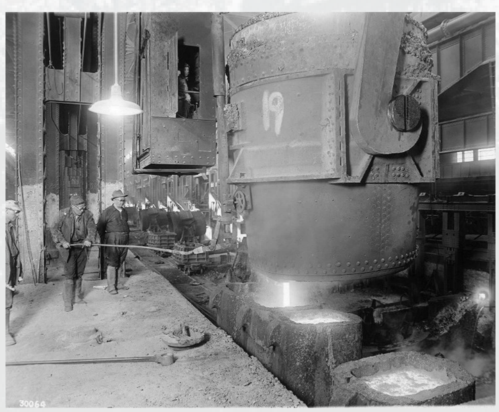


Introduction

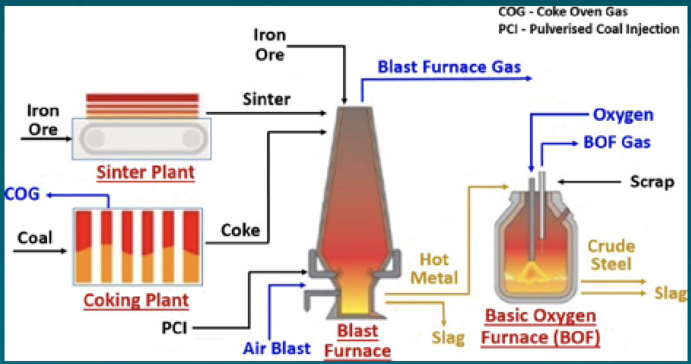
First off, we will begin with one of the foremost sectors within heavy industry: iron and steel production. The energy requirement for manufacturing steel is the single largest contributor to the release of CO2, composing around 30% of industrial emissions and over 7% of total global Carbon emissions.

History

Current processes involved with iron purification and steel casting have a longstanding historical presence. The first high-intensity furnaces used for melting and welding iron were developed over 2 millennia ago in China during the Han Dynasty (31 AD). This ancient approach utilized an extensive system of waterwheels, connective rods, and piston bellows to produce the requisite high-pressure air needed to fuel the melting process and raise the rate of combustion. This iron melting process then spread globally to Europe through trade and cultural exposure with East Asia during the Middle Ages, where the process was further developed. Given the highly volatile and divisive political situation in Europe, there grew an increased demand for iron in arms and cannon production, thereby initiating the current process of charcoal-powered blast furnaces. Innovations such as



Homestead Steel Works (1914)



Representation of of a Typical Smelting Process

replacing charcoal with coke (purified coal) as well as the hot blast technique where waste Carbon Monoxide (CO) gas was reused and burnt to create higher-temperature furnaces increased iron capacity and fuel efficiency. These advances thereby proved monumental in the large-scale industrialization of the process by the time of the Industrial Revolution in the early 1800s.

Current Manufacturing Processes

Interestingly, although technology has evolved in the last two centuries, the key approach to the steel-making process has remained the same. At present-day, 70% of the world's steel is still developed through the traditional route involving blast furnaces for iron melting and basic oxygen furnaces for steel production.Modern blast furnaces continue to use materials such as:

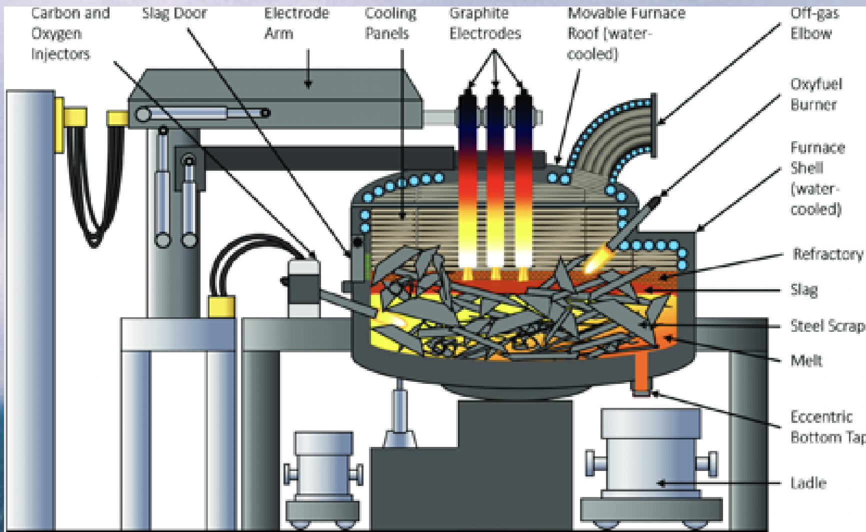
- Coke: the result of heating coal in an environment of close to 1800°F for around 24 hours until it becomes almost pure carbon
- Limestone: natural geographic byproduct
- Steel scrap & Iron Ore: former represents recycled or reused steel while the latter is represented by various types of naturally-present rocks with varying chemical elements including iron

Melting these raw materials and extracting their iron elements involve a complex chemical conversion process:

1. First, Coke is prepared and CO is introduced through Coke as it reacts with excess Carbon from ores
2. CO is the main reducing agent that also attracts Oxygen atoms out from ore, helping to purify the materials
3. Further pretreatment is performed to desulfurize and dephosphorize the iron base
4. Remaining rocky material of ore is combined with limestone in the furnace to produce a waste by-product known as "slag"
5. Slag and molten iron are removed separately through different tap holes at the bottom of the furnace

Now that the molten iron has been extracted from the furnace, the final part of the process is converting molten pig iron into steel through a basic oxygen furnace:

1. A water-cooled ladle containing high-purity oxygen is introduced into the molten iron mixture
2. The ladle delivers high-purity oxygen at supersonic speeds, which reacts with the outlying carbon present in the steel
3. This raises the temperature to over 1700°C producing Carbon Monoxide and Carbon Dioxide gases as byproducts
4. Other unwanted elements are also removed through further introduction of fluxes (processed chemical cleaning agents)
5. This creates both pure steel and a waste byproduct (slag), which are removed separately with further alloy materials being added to the steel to form specific properties



Graphic of Electric Arc Furnace (EAF) Technology

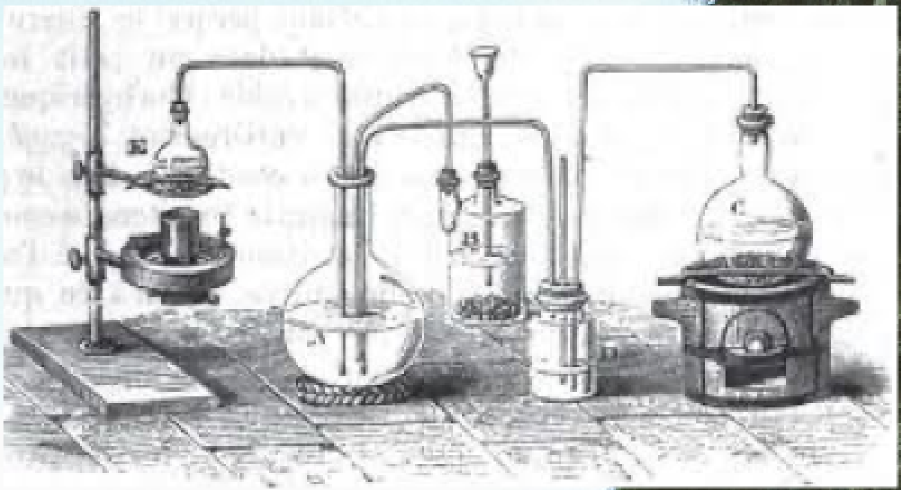
Current Impact

Both of the above processes have a very obvious environmental footprint. There are heavy investments of Carbon required to fuel the furnaces and there are various Carbon-heavy gases in the form of CO and CO2 that arise from the processes. Additionally, the slag material that is composed as an aggregate of the byproducts of these chemical reactions has no straightforward disposal process and is often dumped into natural sites. Thus, the current steel-making process is unsustainable and poses clear environmental concerns we must tackle.

Present-Day Solutions

There are currently several ideas on how the steelmaking industry can improve its environmental impact. Great news for the industry is that steel is one of the strongest and most easily-recyclable materials in the world at a 98% rate. Thus, many steel companies have begun to reduce their usage of iron ore now replaced with filtered steel scraps that are simpler to process. Additionally, besides resourcing of raw materials, new technology is being developed to replace the heat-intensive blast furnaces traditionally used in steel making. Electric ARC furnaces are one of the major innovations that replace Coke with electricity as the power source of the melting reaction. The furnace depends on an electric current being run between two highly-charged electrodes, which radiates enough heat to melt iron scraps. Then, hydrogen is introduced as the main reducing agent to purify the compound in a mostly-iron based steel product. This approach is becoming more common in many American and European steel facilities, with further economic incentives required to push the approach into other regions of the globe. The main concern comes back to the bigger picture of electricity generation and making our power grids fully renewable.

Petrochemicals



Journal sketches of Henri Victor Regnault - founder of polyvinyl chloride aka PVC (1835)

Introduction

Next, we will move to another high-impact heavy industry sector: petrochemicals. Similar to iron and steel production, the energy requirement for manufacturing petrochemicals requires high levels of CO2, composing 20% of industrial emissions and 4% of global emissions.

History

Although the large-scale commercialization of petrochemicals occurred recently, the products themselves have a longstanding historical presence dating back thousands of years ago. Originally, farmers in Ancient Egypt took advantage of products such as ethylene to stimulate plant ripening and bitumen for construction material in building the pyramids. This use of ethylene and other chemicals on a small-scale basis continued naturally before synthetic development began in the early 1800s. By this time, scientific discoveries of synthetic plastics and rubbers (exs: polyvinyl chloride and styrene-butadiene rubber) mostly came out by accident in the labs of individual European chemists. Around this time, petroleum and natural gas reserves were also being discovered through rock mining in different parts of the world. More in-depth experiments continued within American and European research labs, and the potential of petroleum was realized for the development of high-density oils and chemical products important for commercial use. Oil refineries began to appear in larger numbers, and the field became consolidated amongst a select few industrialists such as John Rockefeller. From there, the industry grew in coordination with other innovations at the time such as the large-scale adoption of electricity, automobile manufacturing, and consumer plastic use. As the population of the world has grown and more oil reserves have been discovered in the Middle East and South America, the industry has become a powerhouse with the demand for oil and plastic products only increasing.

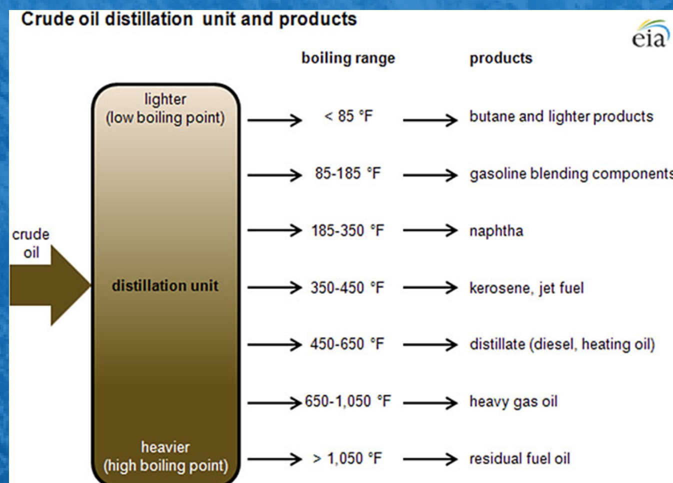
Current Manufacturing Processes

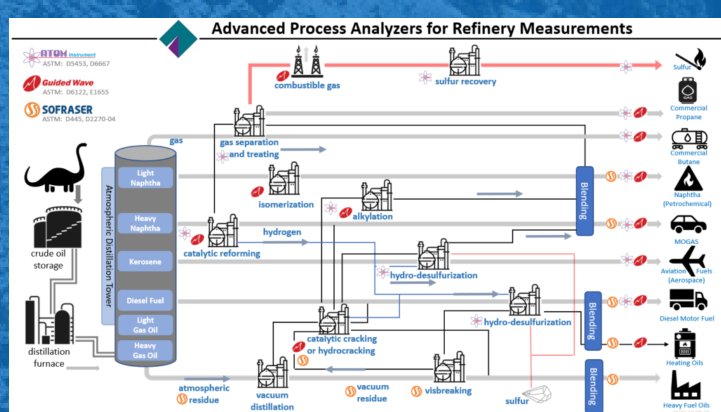
The main operations of chemical development within the industry involves a series of distillations, filtrations, and separations that thoroughly break down petroleum. Crude oil is unrefined petroleum, and it contains a wide mixture of hydrocarbon molecules that exhibit varying properties. There are different types of machines and furnaces that are used to refine petroleum, but the general step-by-step process is similar throughout all refineries:

- Separation
- Conversion
- Treatment

Starting off, crude oil is separated into distinct molecular compounds through a boiling process taking advantage of their differing chemical properties:

1. Crude oil is introduced into the refinery
2. The oil is transferred through various furnaces and distillation units, where it begins to separate into heavier and lighter "fractions" (hydrocarbon compounds)
3. Different compounds have varying boiling points up to around 1050°F, which allows for an efficient separation process
4. Lighter products such as gasoline and butane vaporize because of lower boiling points and recondense at the top of the mixture
5. On the other hand, mid-range products such as jet fuel and kerosene as well as heavier products such as residual fuel oil settle closer to the bottom as liquids





Given that crude oil has now been refined, conversion is the intermediate step where heavier compounds are "cracked" or processed into more desirable lighter compounds:

1. Different components from the distillation chambers are filtered out with the heavier components being kept isolated in streams
2. From here, these heavier products are then "cracked" through varying processes to break down longer hydrocarbons into smaller constituents
3. There are 3 main types of conversion processes: thermal cracking (intense heat), hydrocracking (intense pressure + hydrogen), and catalytic cracking (chemical catalyst)
4. Given that much of "cracking" is catalytic, the used catalysts have to regenerate by burning off small forms of carbon that have accumulated from reuse, also creating heat
5. After cracking, smaller molecules are formed that make up lighter compounds such as gasoline, distillate, and propane
6. 6.These molecules are then further processed and desulfurized in fractionators to create fuel gas for sale such as methane or ethane and different forms of intermediate gasoline

The final aspect of the process is the treatment stage where the finishing touches occur:

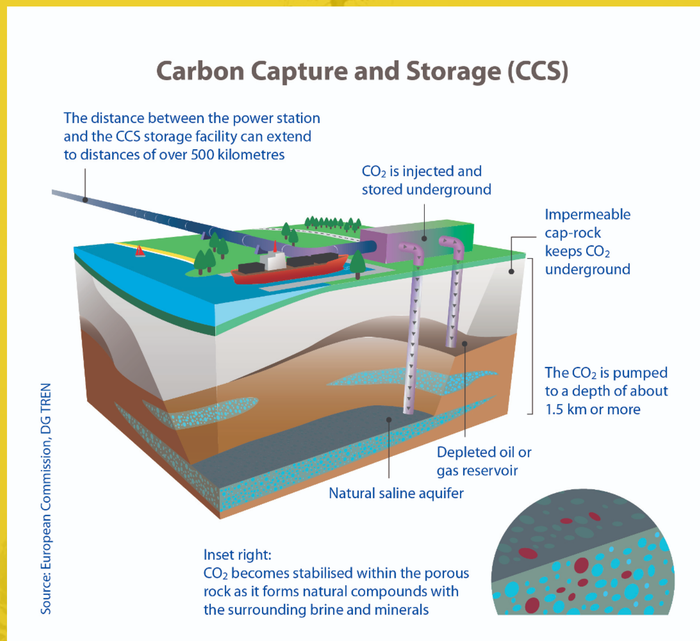
1. Technicians and chemical engineers combine different streams of products from the conversion process to develop finished gasoline
2. Various factors such as octane level and vapor pressure are then taken account of, dividing the gasoline into different blends

Current Impact

The three processes described above detail just how complex and demanding petroleum is to truly break down. Given the high-heat and pressure intensities necessary to undergo refinement, the petrochemical industry is a major culprit in environmental harm. Naturally, extracting petrochemicals through invasive techniques such as fracking can disturb natural geographic formations, and any oil accidents or spills can permanently damage local ecosystems including both habitats and species development. Additionally, the burning of petroleum and oils can release toxic substances such as ash,

Present-Day Solutions

Given how many different ways petrochemicals harm the environment, there are a broad range of efforts and solutions required to truly curb the industry's impact. The leading approach involves mitigating the industry's carbon emissions through CCUS aka Carbon Capture, Utilization, and Storage.



This approach involves literally capturing or trapping CO2 emanating from industrial pipelines, transporting the gas in a compressed form, and either utilizing the gas or storing it within deep geological formations underground. After the success of early projects, CCUS is gaining new momentum around the world with hundreds of new facilities planned for opening. In addition to carbon capture techniques, many scientists have also been working on improving refinement processes through more efficient and less heat-intensive membranes. This is still an ongoing effort, but there have been successful ventures and startups formed such as MIT-based Via Separations which is developing a highly-flexible graphene oxide membrane that facilitates molecular separation with low energy requirements. Besides scientific and technological developments, many environmentalists agree that new policies and guidelines are also necessary to address product disposal issues especially regarding plastics. On this note, stronger waste management infrastructures and recycling systems are vital to address these interrelated environmental issues.

Aviation + Shipping

Introduction

Finally, the last high-intensity sector we will focus on is the aviation and shipping industry. In total, the energy and fuel combustion requirements for product shipping across both transport mechanisms represents close to 3% of global Carbon emissions with aviation transport composing a hefty 2%.

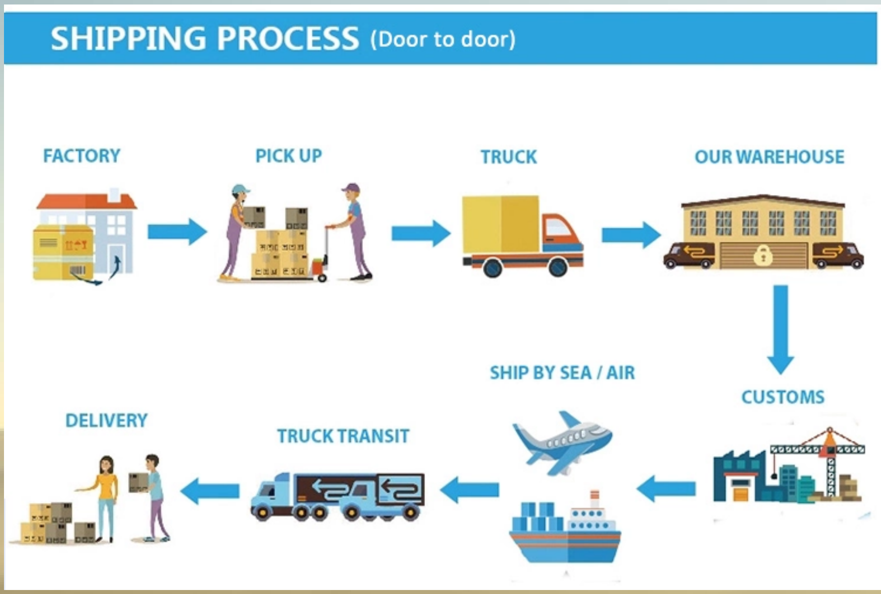
Ancient Spanish merchant ship (13th century)

Cessna Airmaster (late 1930s - U.S.)

History

Unlike the classic paradoxical "chicken vs egg" debate on what came first, shipping was a clear predecessor to aviation from a historical scope of cargo transit systems. Several thousand years prior, horses were domesticated and wheeled vehicles had been developed, meaning horse-drawn carriages were the first official transportation mechanism for shipping cargo. Eventually, as societies began to grow and interact across large distances, ships and rafts then became the predominant method to transport goods and materials between regions. Improved naval engineering and new steam engines led to the development of steamboats in the late 18th century with canals developed for easier transportation. Thereafter, cross-continental mechanisms such as railroads, station wagons, and eventually automobiles by the late 19th century promoted shipping across land.

At last, the most recent development in shipping systems has been the aviation industry. In 1903, the Wright Brothers made history as aircraft connoisseurs performing the first powerful, controlled, and sustained airplane flight on a three-axis scale. From here on, aircrafts began to transport more people and cargo as designs grew more reliable, larger, and advanced through the World Wars. With such a large quantity of pilots present by the mid-century, lighter aircrafts were built and new commercial jets were also constructed to hold large quantities of people and cargo. This was made possible by the use of gas turbines, composite material airframes, and solid-state electronics. At present-day, aviation is one of the main international material transit mechanisms in conjunction with cargo ships. Most of the largest delivery companies such as FedEx and Maersk use intermodal transport involving intertwining aviation, shipping, and railroad systems to support cargo delivery.



Current Processes

Aviation and shipping involve straightforward and specified methods for loading, transporting, and discharging cargo. Both require very important planning processes to coordinate activities between local cargo owners, packaging companies, and either aircrafts or ships.

Using air freight is the quickest manner to transfer freight at a domestic or international level:

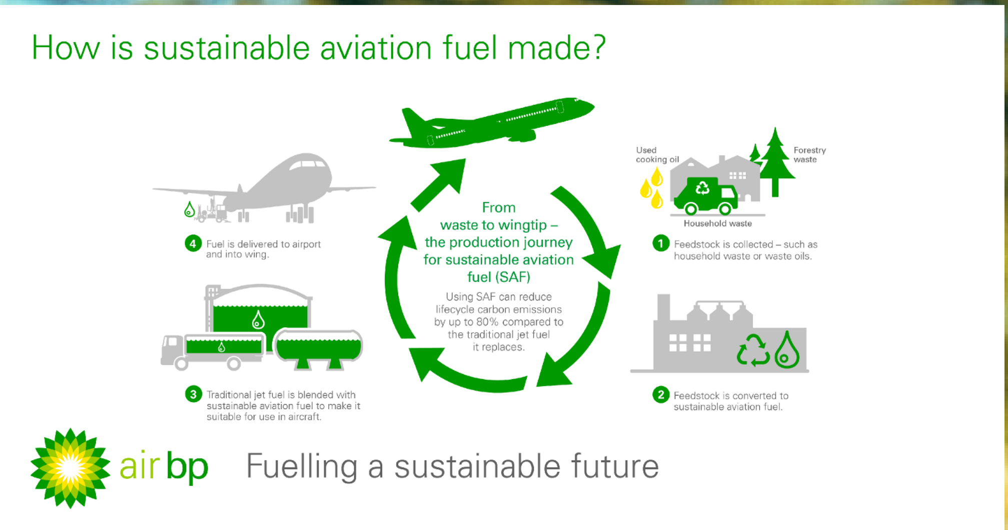
1. First, the shipment is prepared for export and transportation through specific packaging
2. The chargeable weight is taken account of detailing the volumetric weight of the cargo container
3. Bookings are arranged with the air freight forwarder to set up the flight pickup
4. A drafted airway bill is prepared with cargo details, shipper and destination information, as well as flight schedules
5. Next, the cargo is transported to a local Warehouse Terminal to await flight arrival
6. The cargo is then inspected by specific customs officials who check for any anomalies in weight, measurements, or description from the airway bill
7. Finally, as soon as the flight arrives, the shipment is loaded into the airplane fuselage with a ULD (Unit-Load Device) where it is transported to its final destination

On the other hand, the shipping industry is a more affordable manner to transport cargo with larger capacities offered:

1. The process begins when an importer (consignee) orders goods from a supplier (consignor), where the buyers will provide suppliers with an order summary
2. A freight forwarder is then contracted to manage transportation of the goods with a commercial invoice produced
3. The forwarder then begins to arrange export with certain documents such as packing lists, certificates of origin, and manufacturing declarations required for customs
4. Next, the supplier books the export shipment and the goods are loaded onto the freight ship within intermodal shipping containers
5. Finally, the last step is cargo processing through customs to confirm shipment aspects, and upon clearance, the shipment is transported to its final destination

Current Impact

The aviation and shipping industries have become the key methods through which much international cargo is transported across regions. However, considering the long distances that are traveled, both industries have gained a notable ecological footprint. The shipping and aviation industries emit high levels of greenhouse gases including CO_2 through the burning of nonrenewable oil sources. There are additional claims of noise pollution regarding aircrafts as well as marine pollution from waste spills off ships which further define both sectors' negative impacts.



Present-Day Solutions

Therefore, aviation and shipping are two key industries that must also see changes in operations to become more sustainable. Within both, many advancements have been made in base material durability, engine performance, and traffic systems that have improved fuel efficiency by over 80% since the 1950s. However, the next steps for these industries go beyond just fuel efficiency to the actual material used as the fuel source. Traditionally, airplanes and ships have relied on petroleum-based heavy oils whose combustion creates high quantities of greenhouse gases such as CO2. However, newer more-sustainable fuel alternatives are currently in development. Initially, electric-powered engines were the primary source in consideration, but there are both technical challenges and concerns about producing enough renewable electricity to supply both industries' capacity needs. The most feasible alternative thereafter is developing SAFs (sustainable alternative fuels) generally through biological engineering. Within shipping, fuel cells are the most promising especially for hydrogen-derived compounds such as ammonia which are energy-efficient, cheap to store, and require little space. However, the two major shortcomings are the toxicity of ammonia and the difficulty to produce hydrogen in a fully renewable manner; currently only 0.1% of all hydrogen is produced without any fossil fuel base. Within aviation, there are numerous biofuels with promising results to replace current jet oils, many of which utilize renewable biomass or microbial-based hydrocarbons as feedstocks. The current drawback that scientists are working to address are both research costs and capital needed to produce SAFs on a global scale.

Sources

Iron/Steel

1. American Iron & Steel Institute: Industry Data (https://www.steel.org/industry-data/)
2. Keel Ovens: How Steel is Made (https://www.keenovens.com/articles/steel-furnance.htm)
3. Australian Steel Institute: Recent Sustainability Developments in the Iron & Steel Industry (https://www.steel.org.au/ASI/media/Australian-Steel-Institute /PDFs/Pages-from-steel-Australia-Autumn-2021pages28-29.pdf)
4. American Institute of Steel Construction: Structural Steel - The Premier Green Construction Material (https://www.aisc.org/why-steel/sustainability/)

Petrochemicals

1. Syntor: The History of Petrochemicals (https://www.syntor.co.uk/petrochemical-history/)
2. Offshore Technology: The History of the Oil and Gas Industry from 347 AD to today (https://www.offshore-technology.com/comment/history-oil-gas/)
3. US Energy Information Administration (EIA): Oil and Energy Products Explained (https://www.eia.gov/energyexplained/oil-and-petroleum-products/refining-crude-oil-the-refining-process.php)
4. Sciencing: The Harmful Effects of Petrochemicals on the Environment (https://sciencing.com/environmental-impacts-mining-drilling-19199.html)
5. International Energy Agency: The Future of Petrochemicals (https://www.iea.org/reports/the-future-of-petrochemicals)

Aviation & Shipping

1. Street Directory: History of Trade (https://www.streetdirectory.com/travel_guide/141653/trading/history_of_trade.html)
2. Freight Waves: Flashback Friday - the history of air freight (https://www.freightwaves.com/news/flashback-friday-the-history-of-air-freight)
3. Ice International Cargo Express: How the Shipping Process Works Step-by-Step (https://www.icecargo.com.au/shipping-process-2/)
4. European Environment Agency: Aviation and Shipping in the Spotlight (https://www.eea.europa.eu/signals/signals-2016/articles/aviation-and-shipping-in-the-spotlight)