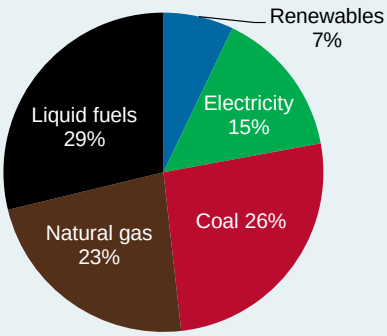
[1] Decarbonizing the industrial sector

So far, de-carbonization has been achieved primarily via renewable electricity generation; de-carbonization of industrial and transport energy use has been much slower. Last year, we discussed de-carbonization of transport through electric vehicles. This year, we look at de-carbonization of the industrial sector, which is the largest global user of energy. This would require **two distinct steps**: substitution of electricity for direct thermal heat and pressure, and much greater renewable penetration on the grid. Some background:

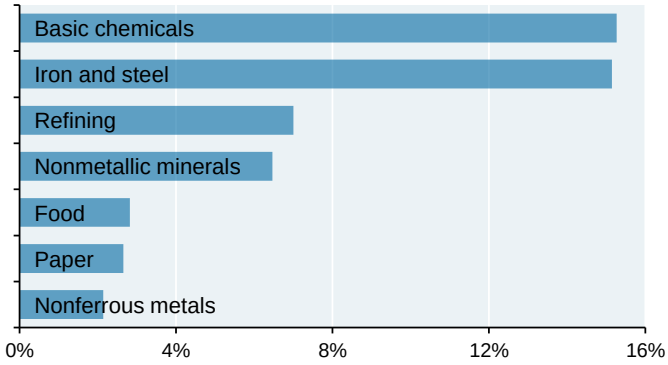
- The industrial sector uses fossil fuels for oil refining and the manufacture of chemicals, iron, steel, paper and food, which collectively form the backbone of modern society. Fossil fuels are used as raw material inputs, and to supply high-temperature heat and pressure (see tables and next page for examples)
- Only 15% of industrial energy use is derived from electricity; the rest is mostly direct fossil fuel use for heat and pressure. **Why isn't electricity used more widely?** It's *feasible* for things like paper, glass, cement and non-ferrous metals[6]. However, as shown in the 3rd chart, the cost of electricity for industrial users is **3x-5x higher per unit of energy** than natural gas. Such a switch would also require large capacity investments in new power generation. Even if such costs were borne, in countries like Germany and China, coal represents such a large share of electricity generation that substituting electricity for natural gas could currently *increase* emissions rather than reduce them

Industrial sector: electricity only 15% of energy use
Global industrial sector energy consumption by source, %



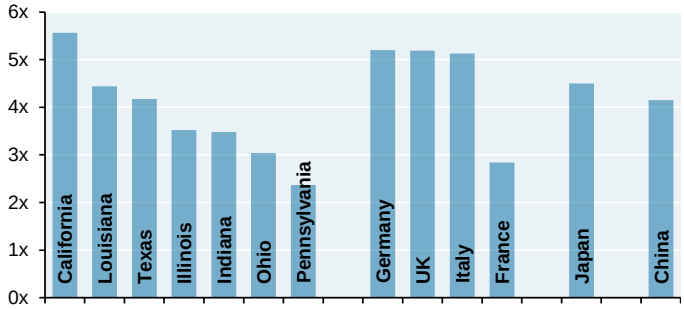
Source: Energy Information Administration. 2017.

Global industrial sector energy consumption by product
% of total



Source: Energy Information Administration, JPMAM. 2016.

Electricity is 3x-5x more expensive than natural gas
Ratio of electricity price to natural gas price for industrial users per MJ of energy



Source: EIA, Eurostat, IAEE, CEIC, IFPEN, JPMAM. 2018. The 7 US states shown are the largest industrial users of US primary energy.

Industrial use of fossil fuels as raw materials

Metallurgical coke	→	Pig (cast) iron smelting (carbon source), which eventually becomes steel
Methane	→	Synthesis of ammonia (hydrogen source), mostly used for fertilizing crops
Methane, naphtha and ethane	→	Synthesis of plastics (sources of monomers)
Heavy petroleum products	→	Production of carbon black (rubber filler), used in tires & other industrial products

Industrial use of fossil fuels to generate process heat

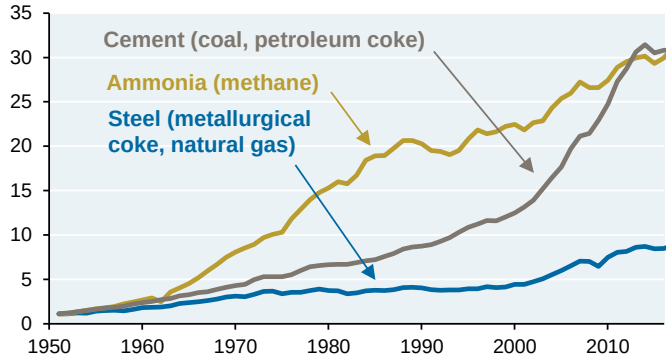
Construction materials (cement, bricks, tiles, glass, kiln-dried timber)
Production of petrochemicals, synthesis of plastics, food/beverage
Smelting of iron ores in blast furnaces

[6] A theoretical 2018 paper from the Wupperstal Institute in Germany estimated that **in the absence of cost considerations**, 100% of German industrial steam use could be replaced with electricity, and that 25% of industrial fuel use could be displaced with electricity as well.

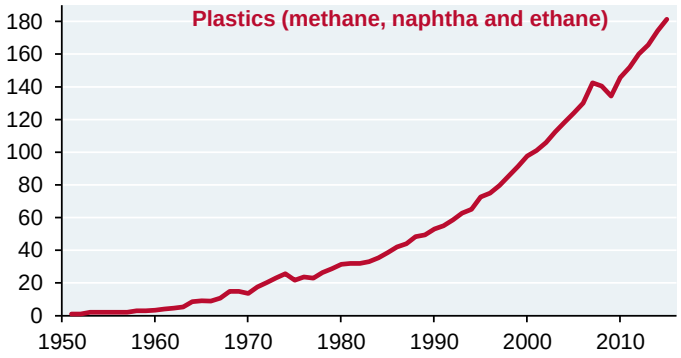
Here's some history on the four industrial pillars of modern society: cement, steel, ammonia and plastics. While their production growth has slowed in the last 2 years due slower growth in China, the IEA expects consumption of all 4 to rise by 2050 (cement by 12%, steel by 30%, ammonia by 60% and plastics by 150%). On the importance of ammonia: only half of the world's population could be sustained without it, given its critical role in the food supply as an input into fertilizer[7].

The 4 industrial pillars of modern society and their primary carbon-based inputs

Production index, 1950 = 1



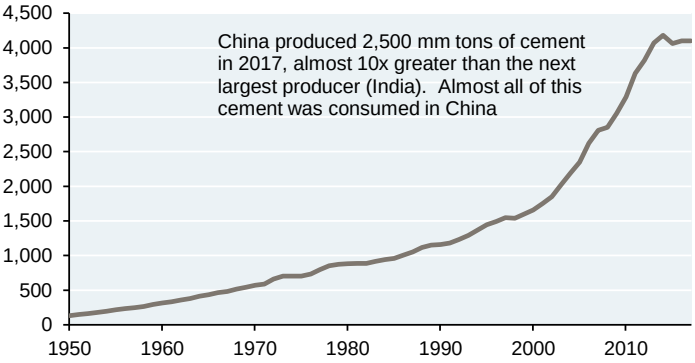
Production index, 1950 = 1



Source: US Geological Survey, Science Advances, World Steel Association. 2018.

Cement

Million tonnes



Source: US Geological Survey. 2018.

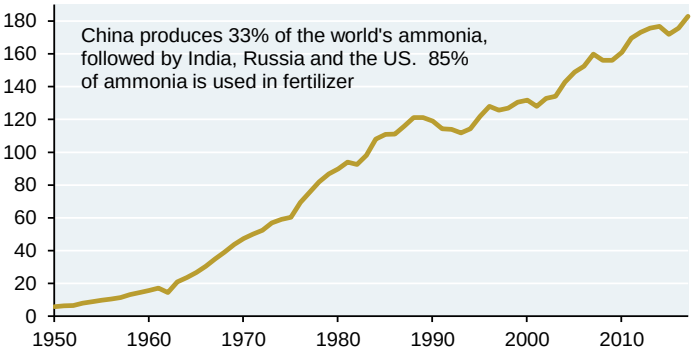
Steel

Million tonnes

Source: World Steel Association. 2018.

Ammonia

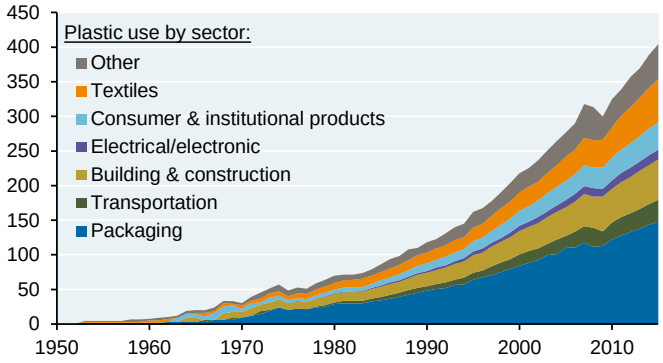
Million tonnes



Source: US Geological Survey. 2018.

Plastics

Million tonnes

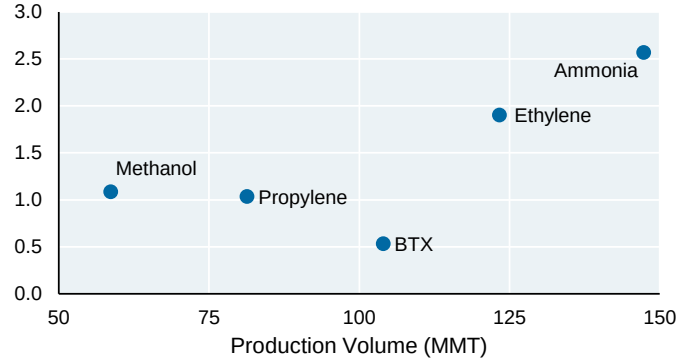


Source: Science Advances. 2017.

[7] Between 40% and 70% of ammonia (reactive nitrogen) applied in fertilizer is **lost** globally due to leaching, erosion or de-nitrification. Minimizing usage losses is just as important to de-carbonization goals as fuel substitution or other changes in the ammonia production process.

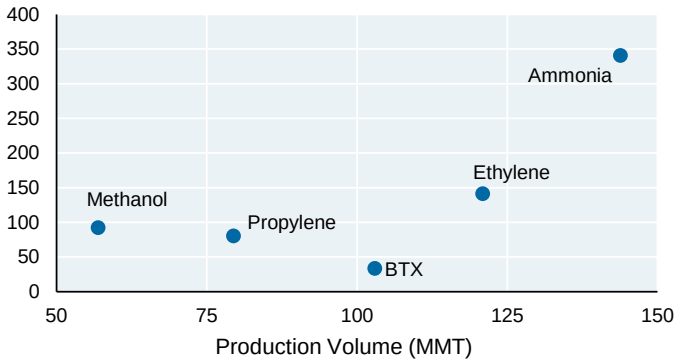
The production of **ammonia** and other chemical compounds requires a lot of energy, and creates a lot of greenhouse gas emissions (GHG), making them interesting candidates for de-carbonization.

Energy consumption and production for major chemicals
Consumption, exajoules



Source: Schiffer and Manthiram. 2018.

GHG emissions and production for major chemicals
GHG Emissions (MMT CO_2-equivalent)



Source: Schiffer and Manthiram. 2018.

Ammonia is produced via a **thermochemical** reaction which combines nitrogen and hydrogen. Its carbon intensity results from production of these inputs: nitrogen separation from air consumes large amounts of electrical power, and hydrogen production from methane[8] consumes energy as process heat, and also emits CO_2. Additional carbon intensity results from ammonia synthesis itself, which requires temperatures of ~450°C and ~200 bars of pressure.

Energy scientists have been examining an alternative: an **electrochemical** reaction that uses nitrogen and water as inputs, and relies on electricity rather than pressure to drive the reaction. This approach could reduce GHG emissions, since hydrogen would be obtained from water rather than from steam reformation of methane, and since electricity (powered by co-located renewables) could function as the energy source needed for the reaction. Other benefits: lower temperatures at which the chemical reaction could take place, and generation of oxygen as an output rather than carbon dioxide. **The problem: scientists are still searching for the best choice of materials for the necessary anode and cathode**. Some experiments show promising results, but there's a big gap between lab-scale research and industrial processes; viability at scale is a key consideration.

The bottom line: partial electrification of heat and pressure is feasible but very expensive compared to the cost of direct fossil fuel use, and would require substantial investment in new renewable generation capacity in order to reduce emissions. Electrochemical production of chemical compounds like ammonia is promising, but still on the drawing board; and any new methods would need to be used in China to have much of an impact. For Green New Deal advocates: de-carbonizing industrial energy use is more easily said than done.

[8] Hydrogen could also be obtained through electrolysis of water, but...

- **Only 4% of hydrogen was produced via electrolysis in 2016** (IRENA); the rest came from steam reformation or gasification of fossil fuels. Primary obstacle: the high cost of electrolysis
- A 2017 paper (International Journal of Hydrogen Energy) cited hydrogen costs that were 5x higher when obtained via electrolysis compared to steam reformation of natural gas, assuming 10 cents per kWh for industrial electricity
- A separate 2018 paper cited the need for another 75% decline in electrolyzer capital costs to $100 per kW and electricity costs of 1-2 cents per kWh in order for electrolysis to be cheaper than steam methane reforming as a means of obtaining hydrogen
- There are demonstration plants in Europe/Japan using renewables to source hydrogen via electrolysis and provide heat/pressure for the reaction. It remains to be seen how their capital/operating costs compare to existing plants

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