Chapter 13

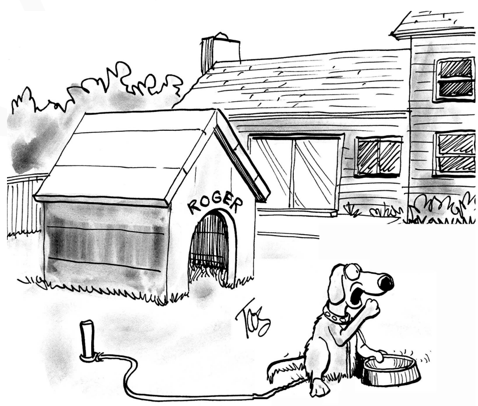
Beyond Electrification

Although electrification will be the cornerstone of a transition to a clean economy, it cannot be the whole story. There are many activities that are too difficult and expensive to electrify. There are also human emissions unrelated to energy generation. We therefore now move beyond electricity.

Activities that are difficult to electrify fall largely into two types.

The first type are activities that require the high-energy density of fossil fuels. For example, commercial air travel is based on kerosene, which is both light and dense.

The second type are activities that require high temperatures, such as making steel and cement. (Some also require carbon.) Fossil fuels are very efficient at making heat, in contrast to movement or electricity, where fossil fuels are very inefficient.



Hey, you in the house! I don't run on batteries, you know!

We now look at some other sources of greenhouse gas emissions and possible ways of dealing with them beyond electricity.

1 Hydrogen

Hydrogen is the most similar clean alternative to fossil fuels. Unlike fossil fuels, though, its combustion produces no CO_2, just water.

Table 1. Energy Densities

	Hydrogen	Gasoline	Kerosene	NatGas	Batteries
By Weight	33	12	12	13	0.25
By Volume	0.25	0.94	1.06	0.82	nc

Source: RMI.

Table 1 shows that the comparative energy density of hydrogen depends on whether it is measured by weight or volume. Hydrogen is really light. Its energy density *by weight* is nearly three times that of gasoline and natural gas, and approximately 100 times that of lithium-ion batteries. Unfortunately, even when it is compressed into a liquid, its energy density *by volume* is only about one-third of natural gas.[1]

Hydrogen Production

There is no natural source of hydrogen on Earth. Hydrogen is always bound with other molecules, usually water, and, therefore, must be produced. *Brown hydrogen* and *gray hydrogen* are created from fossil fuels. Because they come from dirty processes, they offer no advantages over fossil fuels. Their future is limited, and so we do not consider them further.

Blue hydrogen comes from splitting natural gas into hydrogen and CO_2, but its production is combined with carbon capture and sequestration. However, there is no “blue police” that checks to confirm whether a producer has really incurred the voluntary extra expense. Producers that lie and claim to be blue can always underprice their peers. Blue hydrogen is still very expensive and there is little chance that the cost will come down dramatically.[2]

[1] Hydrogen could also be converted into methane (i.e., natural gas), which could then be converted into alcohol fuel.

[2] Scientists have just discovered that it is possible to convert methane into hydrogen without making CO_2 in the first place. The question is whether this is commercially viable.

Table 2. Hydrogen Cost in 2020-$ per MWh

Fuel	Cost Per Kg	As Primary E 2021	As Primary E 2050e	To Electricity 2021	To Electricity 2050e
Hydrogen					
Brown (From Gas)	$1	$27		$70	
Blue (With Capture)	$3	$85		$210	
Green (Electrolysis)	$5	$136		$340	
Optimistic	$1 in 2050		$27		$70
Skeptical	$2 in 2050		$56		$140
Natural Gas		$20	$20	$50	$50

Source: The Economist, 2021/10/09 and IRENA, 2012. Cost estimates are approximate. Primary energy is at the source of production or wellhead. Further conversion to electricity assumes 40% efficiency.

Green hydrogen cuts out polluting fossil fuels entirely. It creates hydrogen by splitting water molecules via electrolysis. For clean hydrogen to replace fossil fuels, green hydrogen is the way forward. However, to be widely adopted, green hydrogen needs to be not much more expensive than blue hydrogen or even natural gas.

Table 2 shows that green hydrogen currently costs about 7 to 8 times as much as natural gas. The reason is that 65% of its cost comes from electricity, which is still relatively expensive. Most of the remaining 35% is the cost of purchasing, operating, and maintaining the electrolysers. However, note that *even if electricity were free*, hydrogen would still cost 2 to 3 times as much as natural gas.

Both costs will drop and so the gap will narrow — the question is by how much. Green hydrogen proponents believe that the cost can be brought down to $27 per MWh. This would make green hydrogen broadly economically competitive with natural gas — *if* natural gas suffered a CO_2 tax that doubled its cost.[3] This was part of the broad reasoning by the Biden administration,

[3] Airlines and shipping are highly competitive industries and fuel is a key cost. Their margins are typically under 10%. No airline could survive flying on hydrogen if its competitors could still fly on kerosene.

when it succeeded in getting Congress to pass the (misnamed) Inflation Reduction Act of 2022. The included subsidies reduced the net cost of hydrogen production to near zero. However, these subsidies will slowly phase out by 2032. We hope the green hydrogen proponents will be proven right and the skeptics (us among them) wrong.

Hydrogen Uses

➤ Transportation

Batteries cannot store large amounts of energy in small volumes and weights. Thus, the chemical nature of hydrogen energy make it a potential replacement for oil-based fuels for off-grid transportation, as in shipping[4] and airplanes.

The remaining engineering problem is compressing and storing the hydrogen. Due to hydrogen's density characteristics, hydrogen aircraft will be lighter (good) but require more fuel tank space (bad). The tanks also need to be stronger and cooler to keep the hydrogen from expanding. To be efficient, hydrogen aircraft will need to be redesigned.

Airbus is optimistic that it can solve the engineering problems. The "only" remaining problem is that green hydrogen costs many times more than kerosene — and flying is a hyper competitive industry in which every penny of fuel cost counts.

However, even if it were cheap, hydrogen would still face a large competitive hurdle when there is access to the electricity grid. As Figure 3 illustrates, for cars, batteries lose only 5% to charge and another 20% to move the car. In contrast, hydrogen has a net efficiency of only 30%. By the time hydrogen moves the car, nearly 80% of the original energy has already been lost. The idea of powering cars with hydrogen-combustion engines is even crazier, with a loss of over 85% of the original energy.

Thus, we believe that, regardless of the electricity generation price, hydrogen will likely never be competitive with batteries in light-vehicle transportation. The same holds true for modest-capacity electricity applications, in which the user can recharge the batteries from the grid at will. In the case of 18-wheelers, the jury is still out because weight and charging times are important, too. Hydrogen's future there will depend primarily on future

[4] There already is one hydrogen-powered pilot ship.

Figure 3. Vehicle Efficiency

		Electric Batteries	Hydrogen Fuel Cell	Conventional Combustion
Well To Tank	Clean Electricity	100%	100%	100%
	Electrolysis	100%	70%	70%
	CO_2 Capture	100%	70%	44%
	Fuel Production	95%	52%	44%
Tank To Wheel	AC/DC Inversion	90%	52%	44%
	Battery Charge	86%	52%	44%
	H2 to Electricity	86%	26%	44%
	DC/AC Inversion	81%	25%	44%
	Engine Efficiency	73%	22%	13%
	Final Efficiency	73%	22%	13%

Source: WTT (LBST, IEA, Worldbank, TTW, T&E calculations), via Zachary Shahan, Clean Technica. Conventional Combustion is a "power to liquid sustainable" gasoline-like way of fueling standard vehicles.

innovations in battery technology. Overall, hydrogen's main role will likely be in off-grid applications — but there are plenty of them.

anecdote

Saudi Arabia is placing a big bet on the future of hydrogen. The Saudis are building a $5 billion electrolysis plant powered entirely by sun and wind that will be among the world's biggest green hydrogen makers when it opens in the planned megacity of Neom in 2025. The Saudis have plans to become a global hydrogen exporter — which may make sense given how expensive it would be to build transmission cables to send their cheap solar power to major markets.

➤ Electricity Storage

Can hydrogen be used for electricity storage? Compared to batteries, the cost of hydrogen storage is low. A cool big sturdy tank will do. Thus, any excess solar and wind electricity during peak generation could be diverted for electrolysis into storage tanks.

However, the problem for hydrogen as short-term modest-capacity electricity storage is still the same: the alternative of batteries. The electron-based technology of batteries is more efficient than the chemical-conversion-based technology of hydrogen. Utility-scale batteries can return about 85% of the energy used to charge them. Hydrogen can only reach about 35% efficiency, because 30% of the electrical energy is lost in the production (electrolysis) and another 35% is lost in the turbine or fuel cell used to generate electricity.

Batteries are already much cheaper for low- to medium-capacity storage needs. Yet if future utility-scale batteries cannot solve the capacity problem — i.e., with giant-tub batteries full of electrolytes and a couple of anode/cathode sticks, rather than the volatile small lithium battery packs — then hydrogen could play a "last resort" and large-capacity storage role that covers grid needs after the (daily or weekly) batteries have been exhausted. Hydrogen might also be used for long-term seasonal storage.

➤ Industrial Heat

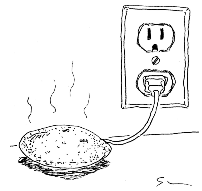
Hydrogen has also been proposed as an alternative to fossil fuels for producing industrial high heat. The production of steel and cement alone accounts for about 15% of total CO_2e emissions. The question is whether it will ever make economic sense to start with electricity and make hydrogen to burn for heat, rather than using the electricity directly and avoiding the conversion loss. Further research should resolve this issue in the near future.

➤ Fertilizer

Hydrogen is already used today for the production of industrial ammonia, the main ingredient in artificial fertilizers. Without them, agricultural productivity would plummet, and the planet could not sustain 8 billion people. This demand for hydrogen is almost certain to increase as population grows.

2 Industrial Heat

Fossil fuels are not particularly efficient when they are used to create electricity or kinetic energy, because most of their primary energy is lost in the conversion. However, they are supremely efficient when they are burned for heat. This feature makes them economically difficult to replace in heating applications.



Almost Done

Steel and Cement

The two most prolific consumers of high heat from fossil fuels are steel production and cement production, accounting for about 7% and 8% of the world's 51 $GtCO_2e$ emissions, respectively.[5] Cement is primarily a building material. Steel is also used in building, but plays a role in many industrial activities, too. Bill Gates believes that by 2060 the world's building stock will double — mostly in India, China, and Nigeria. More cement and steel will be needed for infrastructure.

Again, we believe that the dream of reducing steel and cement emission through linked CO_2 sequestration offsets is naïve. Sequestration would add about 20% to the cost of steel and about 100% to the cost of cement.[6] There is no reason why any steel producer would want to incur the expense; little reason why India, China, and Nigeria would want to hamstring their producers for the greater global good; and no police that could easily confirm that a producer has really paid the cost. Worldwide competition in steel would probably bankrupt the most compliant steel producers. Domestic competition in cement would probably do the same for compliant cement factories if competition could get away without sequestration.

This situation leaves the world with essentially two ways to reduce the emissions of these two key processes.

The first way is using cleaner energy to create the necessary high-intensity production heat. Although electricity can create high heat via electric arc

[5] Glass and Aluminum also use a lot of energy in their creation. Aluminum already uses primarily electricity, though.

[6] Besides, if it is worthwhile to sequester CO_2, why should other firms not do so, too, regardless of what they produce? The only reason to link production with sequestration is if it is a lot cheaper to sequester CO_2 at the plant than elsewhere.

technology, the economic case for clean energy will be tougher, because fossil fuels do not suffer the conversion handicap that they do when it comes to electricity generation. Thus, heat will be among the last applications to be taken over by electricity. Nevertheless, with solar power falling below $35/MWh and to $15/MWh by mid-century, and marginal costs for DC power (rather than grid-synchronized AC power) perhaps then as low as $5-10/MWh, heat reservoirs for steel production could become cost-competitive *while* the sun shines.

Nuclear reactors would seem almost ideal for high heat generation, but this would raise a host of other proliferation and safety problems. Right now, nuclear power is not even on the drawing board for industrial high-heat applications.

Finally, as mentioned in the last section, there is green hydrogen. However, when competing with direct use of electricity, hydrogen has to overcome the energy loss involved in its production. Electric arc technology seems more viable.

The second approach is to invent cleaner processes or materials. Many promising technologies have been suggested for producing cement in a more efficient way. Making cement not only pollutes because it needs high heat, but also the required "clinker" production itself releases CO_2. (The two parts are about equally responsible for CO_2 emissions.) Fortunately, some cement innovators have been heavily funded by Venture Capital (VC). Fly ash cement mixes have a good chance to be both stronger *and* better than traditional cement. It's not clear yet whether VC technology can revolutionize cement production for the global benefit, but the capitalists are already betting on it.

There are some possibilities that almost seem too good to be true. Forms of hemp (not the stuff you smoke) produce materials that are stronger than steel. They can be used as direct substitutes or mixed in with cement. We first had to do a double-take to make sure that the source was not the Hemp Council of America, but reputable outlets like the New York Times. It is indeed the case that, like wood, hemp could be a clean next-generation composite building material.

3 Agriculture

The world's 8 billion people need to be fed. And farming emits plenty of GHGs, not just CO_2, but also methane and nitrous oxide. In Chapter 2, we mentioned that methane is about 33 times more potent and nitrous oxide is about 265 times more potent than C02. Because of these large multiples, agriculture was responsible for about 7 $GtCO_2$ of our 51 $GtCO_2$ in 2019, which was about 14% of total human GHG emissions.

Worse, the human population is expected to reach approximately 10 billion by 2100. Worse again, it is getting richer — and rich people not only consume more food but also like to consume more meat and dairy whose production emits more GHGs than crops. Some scientific forecasters suggest that agriculture could contribute 0.7°C to global warming by 2060. Agricultural emissions are a serious problem.

Interestingly, economists of the past (Thomas Malthus in the 1840s, Paul R. Ehrlich in the 1970s) thought that agricultural production on Earth would limit human population. This turned out to be vastly pessimistic.[7] Simply put, it looks as if humanity will be able to produce more food than it will consume for the indefinite future.

Crops and Nitrogen

Plants need nitrogen in order to grow. There is plenty of nitrogen in the air, but gaseous nitrogen is useless to most plants. Instead, plants mostly rely on bacterial processes that "fixate" the air nitrogen into compounds that plants can then use.

Lack of nitrogen is a primary constraint to plant growth. This is where the aforementioned fertilizers come in — concentrated nitrogen in plant-consumable form. Traditional natural fertilizers are shit (i.e., manure) — from almost any kind of animal living on Earth. Synthetic fertilizers are cheaper even than manure. Without them, the world could probably feed only half as many people as it does today.

We have already discussed the CO_2 released in the production of synthetic fertilizer, but there is a bigger problem. Only about half of the nitrogen in

[7] We can thank the chemist Fritz Haber, whose first claim to fame was the artificial fertilizers mentioned above. Unfortunately, his second claim to fame was his work on then already-banned poison-gas warfare.

agricultural fertilizers is taken up by the targeted plants. The rest runs off, eventually causing unwanted local pollution elsewhere (e.g., algae blooms in lakes and oceans) or escapes into the air in the form of nitrous oxide (NOx) created by microbes. As we noted in Chapter 2 — nitrous oxide warming potential is 200-300 times higher than CO_2.

From a social perspective, fertilizers are overused by farmers — and again not just in the OECD. What can be done to discourage it?

We can dismiss the most obvious one — an appeal to the social conscience of farmers. Appeals will indeed resonate with a few, but not with the many. If appeals could solve the problem, they would have already done so.

The first realistic solution is the next obvious one: make it in farmers' interest to reduce fertilizer use, preferably by taxation. Equally obvious is why this approach is difficult to implement. Farmers are among the most powerful voting groups in every country on earth. The only hope is to offer them more carrot than stick: paying farmers to compensate them for higher taxes on fertilizers. (Another complication is that few farmers are progressive global climate activists. Instead, most tend to instinctively dislike government intervention.)

The second solution is less obvious: technology.

All farmed crops and animals today have been genetically engineered by humans for thousands of years. Scientists can just do it faster now in the lab than through selective breeding. They can now engineer plants that require less nitrogen or that can fixate some nitrogen themselves (mostly with the aid of symbiotic bacteria). Moreover, such plants cannot only reduce the need for fertilizers but also for herbicides and insecticides.[8] It is also impossible to distinguish between a plant that has been engineered with the latest CRISPR/Cas9 technique (which only cuts out a part of existing genomes and does not insert any new genes) and a plant that has naturally undergone the same kind of mutation and lost a gene. This is because there is no difference.[9]

Unfortunately, this is where science and environmentalism often collide. The "natural foods" movement — especially in Europe — seems to detest all

[8]Fertilizers, herbicides, and even insecticides as were in use 150 years ago before chemistry improved, are allowed in organic farming. Many of these substances are highly toxic.

[9]Disclosure: One of us has invested in a startup that works with CRISPR/Cas9, e.g., to reengineer coffee in order to avoid the toxic decaffeinating process.

genetically modified organisms (GMOs). Indiscriminate resistance to progress in food technology is — apologies for the strong phrase — stupid and harmful for crops and farm animals, for producers and consumers, for wild fauna and flora, and for the world in general. Genetic engineering is a powerful tool. It could even allow growing plants in the desert again and without the need for fertilizers. Like all powerful tools, genetic engineering can be used for good or evil. Of course, it requires good regulation in the common interest.[10] Properly shepherded, better plants and animals for humans could be *much* better for farmers, consumers, and the environment.

It is not an important distinction whether a food is engineered, conventionally farmed, or organic. (In many cases, this is not ascertainable.) It is sad that we have to point out that natural foods does not mean what many consumers think it means. First, natural foods can be treated with "natural" but permitted fertilizers, herbicides, and pesticides. These can be *more* toxic than those used in conventionally grown foods. It is not possible to grow appealing fruits and vegetables without them. Second, "natural" does not mean healthy. Cherries, apricots, plums, and peaches contain cyanide. If we warned naïve consumers with mandatory signs that they contain cyanide, they would probably no longer sell.

A cyanide label on cherries would be counterproductive. Of course, other food warnings are not. A little natural mushroom named Amanita phalloides, which looks like many edible mushrooms, when mixed into your food practically guarantees the need for a liver transplant. A food prohibition — and not a warning that says "all natural" — is obviously warranted. Experts need to set smart default food standards, not knee-jerk ones, to guide the public at large. There is even a simple standard here: if the overwhelming majority of experts are willing to eat the food themselves and feed it to their children, then it is probably safe for the general public. It should not carry a general health warning or non-organic sign.

[10] It is a problem that very few companies have now monopolized the seed market. The Top-10 now control 67% of the world seed market! This has raised prices and made farmers badly suspicious of their products. It is a good question whether seeds should be patentable at all.

The third solution is reducing demand by reducing the human population. But as we have said before, the means by which population might be managed, other than through economic development, is beyond the scope of this book.

sidenote

> Scientists are beginning to figure out how to make starch from CO_2 and hydrogen on an industrial scale — essentially mimicking the same process that plants use to make starch. Our grandchildren may no longer need 40% of the world's land for farming.

Rice and Methane

The world's largest food crop by calories consumed is rice. More than 3.5 billion people count on rice to provide 20% of their daily calories. Rice is typically grown in flooded fields, not because rice needs it, but because rice is indifferent to it. Weeds, on the other hand, do not survive standing water. The problem is that flooded fields emit huge amounts of methane. Rice fields contribute about 1.5% to global warming.

The problems and solutions largely mimic those of other crops.

The first solution is to charge farmers for flooding their fields. For the same reason that farmers are unlikely to be taxed for fertilizer use, this will likely not happen. The second solution is to genetically reengineer rice to require less water and compete better against weeds even in unflooded fields. The third solution is to reduce the human demand for rice. The most realistic and best choice for the planet is technology — if only environmentalists could be convinced not to poison the minds of consumers by insisting on "all natural" rice varieties grown the old-fashioned way.

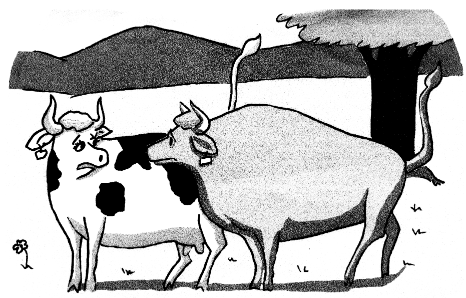
Cows, Meat, and Methane

History suggests that as the rest of the world becomes wealthier, it will gravitate towards consuming more meat and dairy. It would be great both for the world and consumers if this trend were to reverse, but it's just naïve to believe that this is likely to happen out of concern for climate change.

Globally, approximately one billion cattle are raised for meat and dairy products. These cows produce annually about 2 $GtCO_2e$, or about 4% of all global emissions, through a process called "enteric fermentation." Bacteria inside cows' stomachs break down the cellulose in grass and plants and ferment it. Methane is a byproduct, which the cow then belches out. Meat may account for as much as 60% of all GHGs from food production. If the entire supply chain is counted, meat and dairy are responsible for as much as 7 $GtCO_2e$.

The problems and solutions for animals largely mimic those for crops. The first solution is to tax cows, meat, and dairy. However, ranchers are not going to take this easily.

The second solution is again technology — finding a way to produce better foods with fewer cows and cow emissions. One approach, taken by Beyond Meat and the Impossible Burger (as well as some laboratory R&D startups), is to produce plant-based meat substitutes. It's still too expensive and not fully equivalent in texture and taste, but U.S. consumers have started to take to it. The next step will be a lab-grown steak.



Before I say yes to a date...tell me, do you contribute to global warming very often?

Rather than replacing cows, it is also possible to make them more efficient — that is, to reduce their methane production. When treated with the (reasonably cheap) compound 3-nitrooxypropanol, cows' methane emissions fall by about 30%. Unfortunately, the drug must be given daily — an expensive and impractical procedure for free-grazing cows. More preliminary research suggests that Asparagopsis, an edible warm-water seaweed grown in Australia, contains a compound called Bromoform. In trials as a food additive, Asparagopsis reduced cows' methane emissions by 80-98% when comprising as little as 2-3% of the diet (though cattle growth also slows a little and the long-term effects are still uncertain.). Unfortunately, cows don't like it. Thus, it does not work for free-grazing cows with a choice, which accounts for most cows' lifetimes. Nevertheless, it is worth investigating Asparagopsis. With some government subsidies for use, it could reduce humanity's cow-methane problem. The final and possibly best solution may however be to breed cows that belch out less methane. Estimates are that this could reduce emissions by about one quarter — and it would work for both free-grazing and feed-lot cows.

Need we state the third solution — reducing the size of the human population — again? Of course, climate-conscious consumers could just decide to eat less meat and dairy, which would have the same effect. Unfortunately, we have little faith in individualized solutions. If they worked, obesity would not be a problem in America.

anecdote

And now for an entirely innovative solution to climate-change: potty training cows! Really not an April's Fool joke, either. Here is a Video.

anecdote

The New York Times reports that some French green politicians have finally found the problem and it is French men. "If you want to resolve the climate crisis, you have to reduce meat consumption, and that's not going to happen so long as masculinity is constructed around meat."

Food Waste

You could help save the environment by eating it all here

Ironically, another meaningful source of methane emissions is food that is thrown away. Rotting food produces methane with a warming impact equal to 3.3 $GtCO_2e$ (out of 51 $GtCO_2e$ total worldwide GHG emissions). Bill Gates reports that in Europe, industrialized parts of Asia, and sub-Saharan Africa, more than 20 percent of food is simply thrown away, allowed to rot, or otherwise wasted. In the United States, it's 40 percent.

The ideal voluntary solution is behavior change — better logistics, more careful shopping, and preparation of food. But to sound like a broken record, we doubt that this will happen. It hasn't yet.

Raising food prices with taxes would help, but such a suggestion would probably be rejected by just about everyone, not just by the poor who would be hardest-hit.

Once again, technology looks like the best hope. The challenge is always figuring out how to do it economically. Not enough landfills are outfitted with methane capture equipment. Better government incentives could improve adoption. Smart bins could help people track how much food is wasted. Saving food can help the poor and the climate at the same time. Technology can also alter foods so that they spoil more slowly or release less methane when decomposing. Small-scale solutions will not change global warming but can nevertheless be cost-effective for local adopters.

Soil Tilling Practices

Some estimates are that soils remove about 10 $GtCO_2e$ per year, mostly in dry and cold environments. Estimates are that better cropland management could sequester an additional 1-1.5 $GtCO_2$ per year for about 20-40 years. The main improvement would have to come from tilling. Tilling involves turning over the first 6 to 10 inches of soil before planting new crops. This practice blends surface crop residues, animal manure, and weeds deep into the soil. It also aerates and warms the soil.

However, tilling exposes carbon buried in the soil to oxygen, allowing microbes to convert it to Methane and CO_2. The alternative is no-till farming. By keeping excess oxygen out of the soil and away from microbes, no-till farming keeps the carbon that builds up when plants die and decompose below ground.[11] The process becomes planting in the spring, spraying with *more* herbicide than in ordinary farming, and applying fertilizer dropped on the surface or injected in a slot.

With regard to no-till farming, the same three alternatives that we have routinely discussed apply. One could hope that a voluntary approach would work, but don't hold your breath. Conceptually, it might be possible to tax tilling, but it makes little practical sense. If it hurt their bottom lines, farmers would oppose it and other people would not care, paying it little mind.

Once again the best possible alternative would be to research methods of making fields equally productive and profitable but without widespread tilling. There is active sustainable agriculture research in early stages.

[11] Tilling also does some long-term harm for farming. Tillage also loosens and removes any plant matter covering the soil, leaving soil bare. Bare soil, especially soil that is deficient in organic matter, is more likely to be eroded by wind and water. Untilled soil resembles a sponge, held together by different soil particles and channels created by roots and soil organisms. When the soil is tilled, its structure becomes less able to absorb and infiltrate water and nutrients.

Ethanol

And while we are discussing agriculture, the United States should stop subsidizing Ethanol fuels immediately. These subsidies amount to as much as $100 billion per year. They live on largely because Iowa is an early primary electoral state. They were never green. It takes more than 1 gallon of fossil fuel to make 1 gallon of Ethanol fuel. When the Ethanol is burned, it releases CO2. (And Ethanol is actually harmful as an additive in combustion engines, too.)

4 More Methane Problems

Agriculture is not the only important source of potent global-warming methane. Methane comes primarily from four sources: (1) natural ones (decay of organic materials in the absence of oxygen); (2) agriculture (especially cows and rice fields); (3) landfills; and (4) oil & gas operations.

We have already discussed (1) and (2). In this section, we discuss (3) and (4).

Figure 4 shows the location of the four different types of emitters in the lower 48 states. Agriculture has low emissions per acre but covers almost the entire U.S. territory. Still, there are a few hot spots: California, the Texas panhandle, the corn belt, the Mississippi Valley (Oklahoma), and North Carolina. Oil & gas operations are more concentrated. There is one belt of emitters running a diagonal line from Texas to Wyoming, another smaller one from West Virginia to Pennsylvania, and smaller ones on the east coast and California. Landfills are near population centers and less important than agriculture and oil & gas.

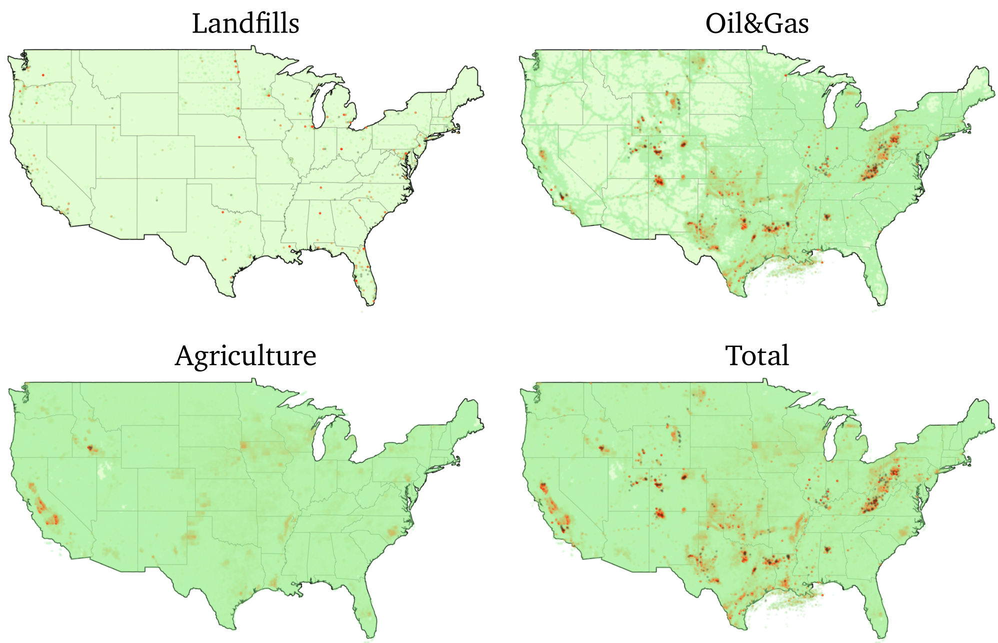
Landfills

Most landfill content is organic matter: food scraps, yard trimmings, junk wood, wastepaper. Their decomposition produces biogas, a roughly equal blend of carbon dioxide and methane accompanied by a smattering of other gases. As a result, landfills are a significant source of emissions, releasing 12% of the world's methane total — about 1 $GtCO_2e$.

The good news is that these emissions are localized, and we know where they are. Even better, the methane can be captured. The technology is relatively simple. Dispersed, perforated tubes are sent down into a landfill's depths to collect gas, which is piped to a central collection area where it can be vented or flared. It can also be compressed and purified for use as fuel in generators and garbage trucks, or mixed into the natural gas supply. (Although burning methane produces CO_2, the residual CO_2 is negligibly small.)

Oil and Gas Operations

Figure 4. 2012 US Methane Emissions



Note: Darker colors mean more methane emissions. Landfills contribute only near some cities. Oil & gas operations are prominent in California, and along a belt from Texas to Wyoming, and around Pennsylvania. (1) Landfills are mostly near cities; (2) Oil & gas is located near reservoirs; (3) Agriculture is spread across the entire continent; (4) the net total is "everywhere plus hotspots."

Source: Maasakkers et al., 2012, EPA. The scale is the same in all four plots.

The second most important emitter of methane are oil & gas wells. Some emitters are operating wells that simply allow too much leakage for no good reason, often to their own economic disadvantage. Others are more deliberate. The EPA estimates that there are 3 million abandoned leaking wells in the United States alone, and a further three million in Canada. (Furthermore, abandoned coal mines can also leak large amounts of methane.)

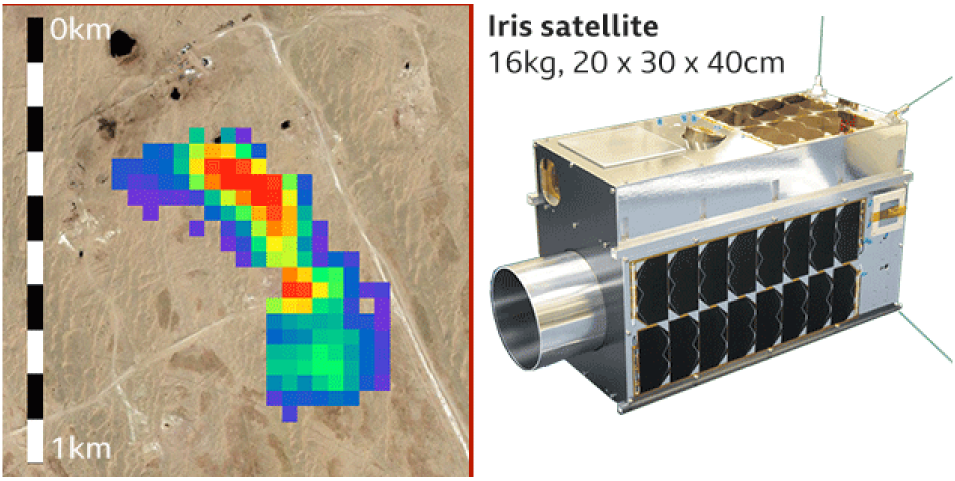
It costs about 2% of a fossil-fuel well's revenues (not profit) to plug it at the end of its life. Flaring is often cheaper, but many abandoned wells are not even flared. Walking away is always cheaper, and this is what many drillers have done for over a century. For many of these wells, even the owners themselves no longer exist. If the company is too big to walk away, it can always sell the well near the end of its life and "focus on more lucrative projects." Indeed, the five worst methane emitters in the United States today are not the oil & gas giants, but fairly small drillers now owned by private equity firms and legally insulated from liability by clever organizational structures.

Some wells can leak for decades or even centuries and pollute the groundwater. Others stop by themselves after a while. Remarkably, some estimates attribute 65% of all U.S. leak emissions to just 10 "super-emitters"![12] Fortunately, super-emitters can be easily identified. This is good news. We can plug or flare them immediately. The cost of doing so is insignificant, especially in light of the co-pollution that these leaks generate. For the broader set, there is large variability in how much it costs to plug or flare a well. For many, it is socially worthwhile (even from a local co-pollution perspective without global climate concerns); for others, it is not. Clearly, the U. S. government should have collected and set aside the cost of plugging wells at the end of their lives, but it did not do so — and it is still not doing so. This is the worst kind of subsidy imaginable to the fossil-fuel industry. Fortunately, it is a relatively easy fix. With proper policies and proper incentives, it should be possible to quickly reduce the amount of methane produced from these sources.

Understanding of methane emissions has improved greatly in the last decade. The European Copernicus Programme has launched a series of "sentinel" satellites that can measure concentrations in real-time. Even cheaper micro-satellites (Claire and Iris, see Figure 5) are now coming online, allowing private companies to monitor local or worldwide GHG emissions. Before the

[12]There is some disagreement here. A study by JPL and Arizona Universities suggested much smaller numbers for superemitters.

Figure 5. Turkmenistan Methane Emitter Spotted by Iris



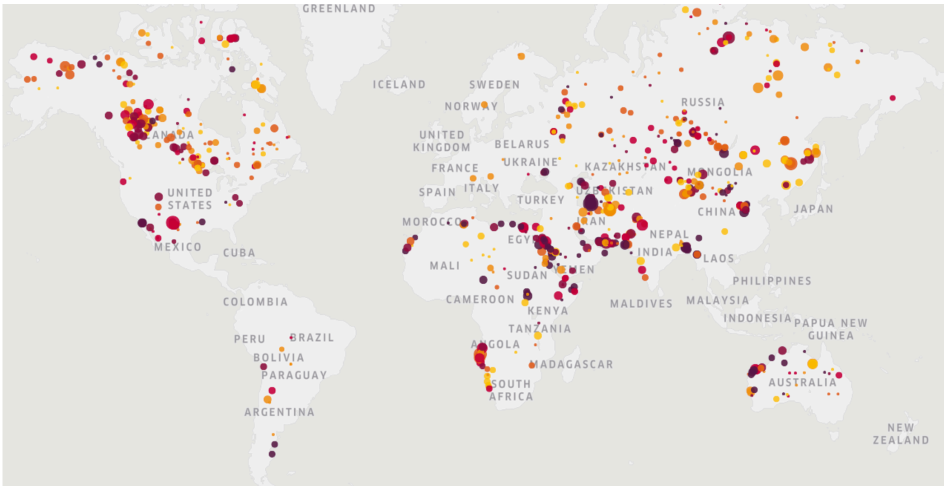
Source: GHGSat / Bing Aerial, via BBC

introduction of these satellites, the world had no idea how much methane was leaked outside the United States and Canada. And many of these sources are short-term temporary flares that are vented (without burning) by facilities in the US and Russia. Unless there is a satellite working 24/7, these flares would never have been noticed. Moreover, having verifiable satellite data that can detect emissions within a radius as small as a square mile will also make it possible to locate polluters quickly and to institute an effective stick-and-carrot program to reduce their emissions.

Figure 6 graphs the most important human point emitters of Methane. Do you remember the analogy about a "peeing section in the swimming pool" (from Chapter 5)? Even if the United States mitigates all its major methane leaks (and it probably should do so immediately if only to reduce local copollution), it is not enough to solve the problem, much less make a global difference. There are still many other methane leaks elsewhere in the world. Canadian abandoned wells alone are large enough to overwhelm anything the United States might do.[13] So are Saudi Arabia's, Iran's, Australia's, and Russia's, etc. Turkmenistan contributes more to global warming by letting

[13]These particularly problematic wells are ironically located in the area that would have been fed by the Keystone pipeline project.

Figure 6. Copernicus Methane Sentinel Sat Images of Large Emitters



Source: ESA Copernicus Sentinel, Methane Emissions, Global Map 2019.

methane escape "accidentally" than all the carbon emissions of the United Kingdom *combined*!

Unlike the Paris CO_2 climate treaty, which we believe has little chance to curb CO_2 (Chapter 7), methane super-emitter mitigation should be negotiable. The costs of methane mitigation are reasonably well-dispersed and low relative to the mitigation benefits (including local benefits), plus compliance has become much easier to measure. It will not require dramatic sacrifices, and the potential benefits are large. COP policy-makers — please do your jobs!

5 Construction and Efficiency

Building construction emits GHGs, but so does living in buildings. There are some obvious changes — and remarkably, many of them pay for themselves over time. However, despite the long-run benefits, they typically require upfront payments. This can be a hindrance for poorer people and poorer countries. It may not be an option if it prevents the residents from spending money on the food and health care necessary to stay alive.

Better Insulation

Better insulation often seems like a "no brainer." Insulation is cheap and can reduce average home heating and cooling costs by around 30% even in warm climates such as Australia and New Zealand. The cost of installing insulation there pays for itself in around 3-5 years through reduced energy bills. Upfront investment in insulation is more effective than other green investments. It is a once-only cost that lasts for the life of the building (typically 50-70 years) and requires no further maintenance.

This leads to the obvious question as to why not all people don't automatically buy more insulation. Even middle-class people in developed countries often fail to properly insulate their homes. One reason may be that they fail to appreciate the benefits. Here a nudge from the government could help. Just as labeling the nutritional value of foods helps people manage their diets, providing consistent information regarding the benefits of insulation could help residents make better economic decisions for themselves and for the environment.

Thermal Energy Storage

A storage heater or heat bank is an electrical heater that stores thermal energy when electricity is available at lower cost, and releases it when heat is required but electricity is expensive. Alternatively, solar storage heaters are designed to store solar energy as heat, to be released during the night or other periods when it is required, often making it more cost-effective than selling surplus electricity to the grid and buying it back at night. Storage heaters are usually used in conjunction with a two-tariff electricity meter, which records separately the electricity used during the off-peak period so that it can be billed at a lower rate. In most countries, storage heaters are only economical (compared to other forms of heating) when used with such special tariffs. Once such tariffs become standard, thermal energy storage and clean intermittent sources will complement one another.

Furthermore, the same process can be used in reverse to providing cooling. Thermal storage cooling solutions are a cost-effective and reliable option for cooling offices, schools, hospitals, malls, and other buildings. By producing low process fluid temperature during off-peak times, this environmentally friendly cooling solution reduces energy consumption and greenhouse gas emissions. Once again, the future of this technology depends on the rational pricing of electricity from intermittent sources of generation.

Heat Pumps

Because furnaces convert 95% of the energy in natural gas to useful heat, it may seem as if there is no better way to make heat — but that deduction is surprisingly incorrect. Heat pumps do not have to create heat — they just move it around (often into the ground). (The principle is similar to that of a refrigerator.)

Thus, for every kilowatt hour of power drawn from the electric grid, a heat pump can transfer three kilowatt hours of heat energy from the outside of the house to the inside for a total heat output of four kilowatt hours. The effective efficiency of the heat pump is 400% compared to 95% for the gas furnace.

Heat pumps do have limitations. They only work in moderate climates and have modestly shorter lifespans than furnaces. If it gets too cold outside it becomes difficult for the pump to provide energy to the interior at comfortable temperatures. For this reason, leading heating companies are now selling dual fuel systems that switch between heat sources depending on the outdoor temperature and home heating needs. These systems are not only environmentally beneficial, but they are also economical in that they are the lowest-cost source of heating. It is a perfect example of how technology improvement can play a key role in reducing emissions.

However, system-wide analyses can show that heat pumps may not be helpful everywhere. They work on demand. If the demand occurs when people come back home — say, around 6pm to 9pm — it puts additional ramp-up-and-down load onto the grid. In this case, a more old fashioned system (e.g., a water heater or floor heater) that uses and thereby stores heat around 1-3pm, when electricity is free in much of the world, could be cheaper and better from a systems-wide perspective.

Conclusion

This chapter has broadened the perspective beyond electricity as a solution to greenhouse gas emissions. It has described some of the more important sources of GHG emissions and opportunities for reducing them. There is no great common theme here, because the activities are so diverse — except perhaps that the key will have to be more research, technology, and deployment.

Further Readings

Books

- A summary of various opportunities and payoffs related to the reduction of methane emissions.
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- Garrison, Cassandra, 2021, Concrete makers face heavy lift on climate pledges, Reuters, on cement/concrete efforts to reduce CO_2.
- Hanley, Steve, There's more to lowering atmospheric carbon dioxide levels than driving electric cars. Decarbonizing the cement and steel industries will be equally as important. Clean Technica, 2020/09/14.
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- Shahan. Zachary, This Stunning Chart Shows Why Battery Electric Vehicles Win, Clean Technica, 2020/06/10.
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- The tab on Agriculture has a good list of problems and solutions.
- The Foods That Reverse Climate Change by the BBC.