A Plan to Save the Planet

By Glenn Weinreb

*How to resolve climate change
at the lowest cost*

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PART ONE:
THE CLIMATE SOLUTION

1.   The Climate Solution

This book presents a realistic *plan* to resolve climate change at the lowest cost. We define "realistic" as observing political, economic, and technical principles (which will be discussed later). Also, this is open-source, which means others can copy and modify the original files for free.

The world currently burns coal, natural gas, and oil-based products to generate electricity, push vehicles, heat buildings, and fabricate materials. Unfortunately, the exhaust contains carbon dioxide (CO_2), a greenhouse gas that warms the planet. A little warming is ok; however, harmful amounts of warming are expected this century.

In theory, carbon-based fuels could be replaced with energy created at solar farms, wind farms, hydro-electric dams, and nuclear power plants. However, replacement is not occurring fast enough. For example, the U.S. government projects U.S. CO_2 emissions to decrease from 4.8 billion tons in 2022 to 4.0 billion tons in 2052. This is a 20% reduction over 30 years, and is far short of our planet's needs.
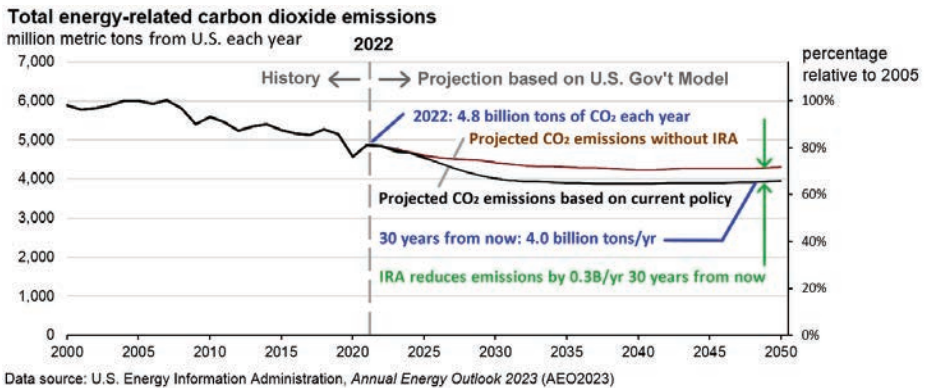
Figure 1.1: U.S. government's official projection of CO_2 emissions from the U.S. over the next 30 years in units of billions of tons each year.

As one can see from the above graph, President Biden's $391B Inflation Reduction Act (IRA) caused the 2052 expectation to drop from 4.3 to 4.0 billion tons a year. In other words, the IRA did little.

The U.S. government does not have a plan to reduce CO_2 significantly, and when it spends money on climate, it is often not effective. This is due to

several reasons that include: (a) the hi-jacking of climate (i.e. organizations use climate to make money), (b) a lack of websites that model cost and impact of policy *before* it is enacted, and (c) government leaders often delegate to entities that do not have the physical ability to reduce CO_2 at the lowest cost and at large scales.
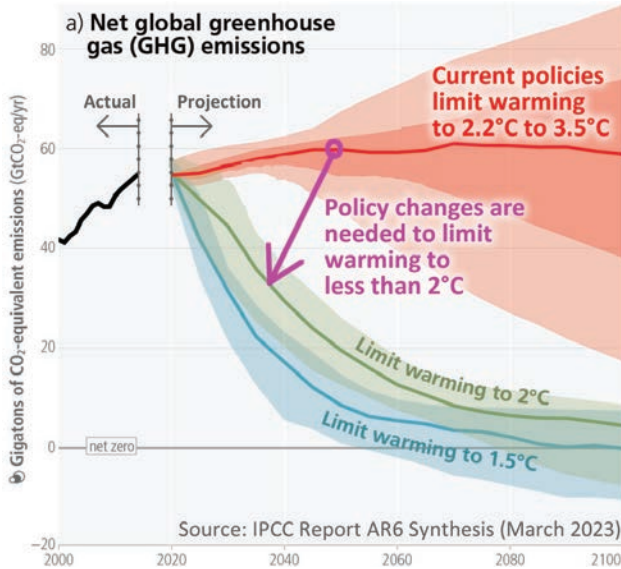
Figure 1.2: Impact of global CO_2 emissions over next 80 years.

The Intergovernmental Panel on Climate Change (IPCC) 6th Report expects current national policies to facilitate warming between 2.2°C and 3.5°C, as illustrated above. This would lead to catastrophic amounts of sea level rise, damage from storms, and increased food costs due to drier land. In other words, nations need to change their current policies to avert disaster.

What is the Lowest-Cost Solution?

This begs the question, "What is the lowest cost way to make these policy changes and what would it cost?" One can look at U.S. gov't cost data and do a little math to see this would probably entail building solar farms and wind farms at a rate that is approximately 4-times greater than current construction levels. In the U.S. this would cost approximately $20 per person per year in year #1, $40 in year #2, $60 in year #3, etc. In the typical case, this would pay the mortgage on new solar farms and new wind farms, minus the cost of carbon-based fuels that were not burned due to being

replaced with green electricity. Ultimately, these costs would appear as an increase in the cost of goods and services.

The Prisoner's Dilemma Problem

Companies, cities and states are not likely to spend significant amounts of money to reduce CO_2 since they do not benefit. In other words, they can reduce emissions to zero and the world will still emit CO_2 and cause them harm. This is referred to as a "prisoner's dilemma problem."

Therefore, decarbonization to zero over a reasonable duration, is not likely to occur unless required by law. And this law does not exist. This begs the question, "How does one structure an effective climate law that has majority support?"

U.S. Climate Politics

States that import natural gas and coal benefit from decarbonization in two ways: (a) they gain green jobs while carbon jobs are lost elsewhere, and (b) their costs decrease when the price of fuel decreases due to less consumption. The opposite is true for states that produce natural gas or coal. They are hurt by decarbonization due to loosing carbon jobs, and lower fuel price entails less revenue. Therefore, one can expect carbon producers, which is approximately one-third of the U.S. states, to not support significant decarbonization legislation.

According to survey, 40% of Republicans and 95% of Democrats are concerned about climate and want to decarbonize. We can do some math to see that approximately half of Americans want to decarbonize and are from states that do not produce natural gas or coal. In other words, we are close to majority support for significant decarbonization legislation.

This would need to meet the satisfaction of Republicans and Democrats who want to decarbonize. Republicans typically require two things: (a) lowest cost, and (b) minimal federal involvement. And Democrats typically require one thing: government engineers at EIA need to score the proposed initiative as reducing CO_2 significantly over a reasonable period of time.

What Might a Real Climate Law Look Like?

A federal law that meets that meets the above requirements might: (a) do more R&D, and (b) require states to reduce CO_2 emissions by 1/N each year

relative to today. The later would cause emissions to decrease to zero over N years. For example, to decarbonize over 30 years, one would set N to 30 and reduce today's emissions $1/30^{th}$ each year (i.e. "30 Year Climate Law").

Part (a) of this law uses R&D to decrease the cost of new green infrastructure. This infrastructure is likely to cost 100 trillion dollars globally over several decades. Therefore, spending billions of dollars to reduce this is reasonable. Yet what might one develop that is not already being worked on? And what might one develop that would have a big impact? One could work on these questions within a business plan for more R&D. This could be reviewed and reworked to the satisfaction of the various participants. Also, researchers could potentially be paid approximately $10K each to develop proposals for R&D referenced in the plan. For example, 50 proposals might cost $500K total.

Part (b) of this law (e.g. $1/30^{th}$ reduction) would probably require a website that models cost and impact. In other words, a website that calculates how much CO_2 is reduced, and cost per ton of CO_2, for each decarbonization initiative. Already some of this is done by the U.S. government's NEMS model. However, it needs a website user interface to be more useful.

Reasonable Next Steps

To move lowest cost decarbonization forward, universities, foundations, and non-profits can do several things:

- Develop websites that calculate the cost and impact of proposed laws.
- Hire researchers to write proposals for large R&D initiatives that are currently not being worked on and could potentially have a significant impact. These could be placed into an open-source business plan for a new R&D laboratory that tackles climate change at the lowest cost.
- Produce materials that explain politically feasible lowest cost decarbonization. For example, produce a documentary film called "The Climate Solution." Documentaries typically explore Problems. This instead would focus on the Solution.

In summary, climate is a 100 trillion dollar problem and we need to think about how to spend billions of additional R&D dollars to save trillions; think about how to create better tools for lawmakers; and think about how to better educate the public on how to tackle climate at the lowest cost.

2.   A Quickly Changing Planet is a Bad Planet

This chapter is a brief summary of climate physics.

Electricity in a Nutshell

A watt (W) is a unit of electrical power, and a watt flowing over a period of time is a unit of energy. For example, one thousand watts flowing for one hour is a kilowatt-hour (1 kWh), and one trillion watts flowing for one hour is a terawatt-hour (1 TWh).

Total electricity consumption during 2021 was 8,500 TWh in China, 4,200 TWh in the U.S., and 1,700 TWh in India. The typical U.S. home consumes 10,000 kWh of electricity each year at an average cost of 14¢ per kilowatt-hour (EIA, May 2021). This is the retail price, and it includes the cost of generation and distribution. Alternatively, the wholesale price refers to a large quantity at the front gate of a power generation facility.

"Green" electricity does not emit CO_2 and is primarily generated by solar panels, wind farms, hydroelectric dams, and nuclear power plants. This typically costs 3¢ to 6¢ per kWh wholesale. Alternatively, carbon-based electricity is generated by burning coal or natural gas at a typical wholesale cost of 2¢ to 4¢ per kWh. Consumers often receive a blend of green and carbon-based electricity. For example, if 20% is 4¢ green electricity, and 80% is 3¢ natural gas based electricity, the blend would cost 3.2¢ per kWh ((20% x 4¢) + (80% x 3¢)).

Power company engineers are tasked with providing electricity at lowest cost, independent of CO_2. They do this unless given further instructions from government or customers who can request greener electricity, even if it cost more.

CO_2 in a Nutshell

Quantities of carbon dioxide gas (CO_2) are defined by their weight. For example, one metric ton (1 $mtCO_2$) and one billion metric tons (1 $GtCO_2$) both refer to CO_2 quantities. For reference, one metric ton is 1000 kilograms (2,204LBs) and one short ton is 2,000Lbs (907kg).

The typical U.S. gas car emits 4.6 metric tons of CO_2 each year (4.6mtCO$_2$/yr). And the typical U.S. home emits 4.1 metric tons each year due to electricity consumption (4.1mtCO$_2$/yr).

In most countries, the lowest cost way to make electricity is to burn coal, and this emits 1kg (2.2LBs) of CO_2 for each kWh of electricity. Alternatively, one can burn natural gas, and emit 0.4kg (0.9LBs) of CO_2 per kWh.

Annual CO_2 emissions are 10 billion tons from China, 5 billion tons from America, and 2.5 billion tons from India. Approximately one-third is due to making electricity with natural gas and coal, one-third from pushing vehicles with gasoline and diesel fuel, and one-third from making heat within factories and buildings with natural gas and coal. Worldwide, CO_2 emissions keep going up, as shown below.

CO2 emissions by fuel type, World
Annual carbon dioxide (CO₂) emissions from different fuel types, measured in tonnes per year.

Source: Global Carbon Project   OurWorldInData.org/co2-and-other-greenhouse-gas-emissions/ • CC BY
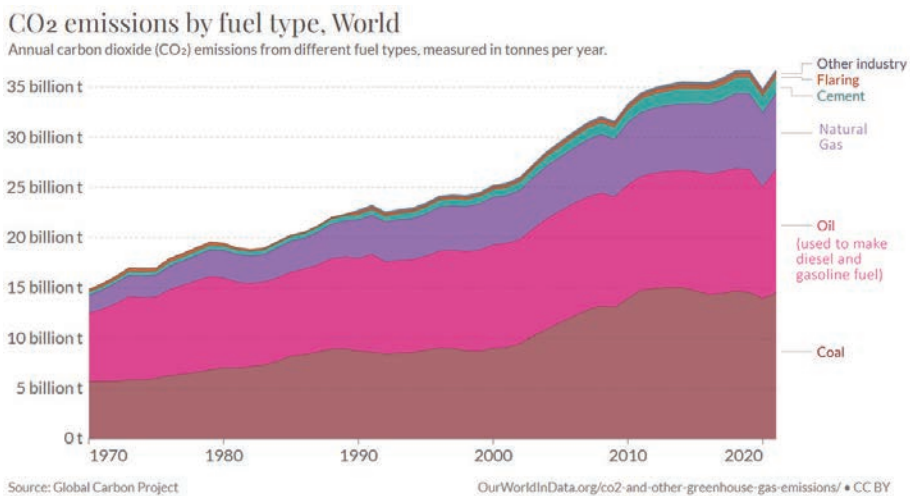
Figure 2.1: Global CO₂ emissions over the last 50 years.

The Problem with CO₂

The Earth is an 8,000 mile (13K km) diameter sphere covered by a 60 miles (100 km) thick atmosphere. Incoming radiation from the sun passes through the atmosphere as it travels toward land. And outgoing radiation from the land travels in the opposite direction toward outer space.

The Earth gets warmer if outgoing radiation decreases, or incoming radiation increases. And radiation decreases if it bumps into molecules in the atmosphere that deflect. Also, the type of outgoing radiation is

different than the type of incoming radiation. The outgoing type deflects more easily.

Scientists approximately 100 years ago placed different gases and different types of radiation into desk-sized laboratory chambers and measured deflection. They observed some molecules and some types of radiation deflect more than others. For example, greenhouse gases such as CO_2 and CH_4 (methane) deflect more than the typical air molecule.

When a photon travels through the atmosphere, it passes approximately 300,000,000 air molecules *each meter* as it travels 100,000 meters. The photon only needs to bump into one molecule along its path to deflect. For this reason, a relatively small amount of CO_2 can have an impact.

The Food Problem

Additional heat causes land to dry out. And dryer soil often produces less food. When people do not have enough food, they typically move to areas with more food. And this can lead to overcrowding, shortages, and high prices. The wealthy buy what they need when prices are high, while the poor struggle. And this can lead to social unrest, more police, and gated communities. We are observing some of this already, in part due to climate change. However, it is unclear when, where and how it will get worse.

Migration does not necessarily need to be a problem. If the rate of adding food production and housing is greater than the rate of adding population, then shortages and high prices are less likely.

The Tipping Points Problem

Another problem with CO_2 is the possibility that a not well-understood positive feedback loop will make the situation worse than expected. For example, thawing permafrost could potentially release greenhouse gas methane more than expected. And this could lead to more warming and more thawing.

The Sea Level Rise Problem

Eventually our civilization will stop putting CO_2 into the atmosphere and the planet will stop warming. However, after we stop emitting CO_2, the additional temperature will hover for thousands of years as the CO_2 slowly falls back to earth, and the temperature slowly reverts back to its original level.

As the elevated temperature hovers for thousands of years, it will slowly melt a 2000 meter-thick slab of ice on Antarctica (i.e. the South Pole). And this will cause the sea to rise and cover coastal cities. Sea level is expected to rise slowly. Perhaps one to two meters every 100 years. However, after 30 to 300 years, this will be a problem for many coastal areas.

A *Quickly Changing* Planet is a Bad Planet

In theory, civilization can move to areas that are more suitable. However, this entails a race between a changing planet, and the builders of metropolitan areas. If the planet changes faster than the civilization can build, there will be suffering.

The degree of suffering is likely to be proportional to the rate of planet changing, not the absolute amount. For example, if it takes 1000 years to flood coastal cities, and each building lasts 100 years, then new buildings would probably not be built in areas that are flooded in their lifetime.

In summary, a quickly changing planet is a bad planet.

3.   Climate is a 100 Trillion Dollar Problem

Tackling climate change entails transitioning from a carbon-based economy to one that does not emit CO_2. This is referred to as "decarbonization," and it entails building new infrastructure that is likely to cost the world approximately 100 trillion dollars over several decades. Approximately one-third for electrical power generation, one-third for cars, and one-third for factories.

> ~$30T - Solar farms, wind farms, hydroelectric dams, more grid
> ~$30T - 1.5 billion cars x $20K per car
> ~$40T - New factories and agriculture that do not emit CO_2

How Much Energy Do We Need?

Each year the world produces 583 exajoules (EJ) of heat energy, and if this were fed into a 35% efficient turbine, 56,000 TWh/yr of electricity would be produced.

We know how much electricity is produced by large facilities like the Hoover dam in Nevada. Therefore, we can divide 56,000 TWh/yr by their annual production to calculate roughly how many facilities one would need to match global energy production.

Figure 3.1: Large sources of green electricity.

For example, 56,000 TWh/yr corresponds to 17,200 Hoover Dams, 22,700 London Arrays, 44,200 Topaz Solar Farms, and 22-times the world's nuclear fission reactors.

# of sites	TWh/yr	Site	Description
17,171	3.3	Hoover Dam	Large dam in Nevada
44,200	1.3	Topas Solar Farm	Solar farm in California
22,666	2.5	London Array	175 windmills in water, near London, UK
22	2,553	All Nuclear Reactor	Power generated by all fission reactors

Figure 14.2: Number of select facilities needed to replace the world's energy consumption.

What Does a $27 Trillion Dollar Solar Farm Look Like?

The Topaz solar farm produces 0.55GW of electricity, and solar farms cost $1.12-per-watt at today's prices (NREL, 2022, CAPEX). Therefore 44,200 would cost 27 trillion dollars in total ($1.12 x 0.55GW x 44,200).

This might seem excessive, and it is. Also, it works economically, kind of. The money would be borrowed from banks and bonds. And the facility would repay the loans with the ~2 trillion dollars' worth of electricity that is produced each year (0.55GW x 44,200 x 2,180 kWh/Wh/yr x 0.001 kWh/Wh x $0.037/kWh). In other words, consumers would not pay $27 trillion and instead would pay the difference in the cost of green electricity and carbon based electricity.

Topaz's panels sit on approximately 4 square miles, therefore 44,200 facilities would consume 176K square miles (44,200 x 4). The state of Texas is 268K square miles; therefore, this would fit nicely in 65% of Texas (176K / 268K).

Solar power is intermittent; therefore, coating Texas with solar would not be a direct replacement for carbon-based sources that are available 24x7. And we are combining consumers of heat with consumers of electricity, which differ in multiple ways. Also we are not taking into consideration GDP growth. And this would need to be spread out globally, not jammed into Texas. In other words, this analysis is only an approximation. However, it does provide a rough idea of how much green energy construction is needed globally over several decades.

Easy at First and More Difficult Later

Initially, solar, wind, and hydro projects are built in the most favorable conditions. However, as one builds, conditions often become less favorable, and costs increase. Hydroelectric dams prefer sloped land with

running water. Wind farms prefer windy land away from people or windy shallow water close to shore. And solar farms prefer cheap, cleared, sunny land not far from cities. In other words, decarbonization is likely to be easier at first and more difficult later.

Material Fabrication Needs to be Decarbonized Too

Thousands of solar farms, wind farms, and hydroelectric dams would consume significant amounts of metal and cement. Fabricating these materials with carbon-based fuels would cause CO_2 emissions to increase. Therefore, material fabrication needs to be decarbonized too. In theory, the lowest cost way to do this is with nuclear reactors in China. More about that later.

Infrastructure Is Paid for with Borrowed Money

Most infrastructure is paid for with money borrowed from banks and bonds. Later, these are repaid with revenue generated by the infrastructure. For example, a bank loan might initially fund solar farm construction, while later electricity revenue repays the loan over 30 years.

Economically, decarbonization is like a nation buying one new house each year, where the house represents all green infrastructure built that year. The nation ends up with one "house" after year #1, two after year #2, etc.

Also, each house has a mortgage. Therefore, the nation pays one mortgage after year #1, two mortgages after year #2, etc. These mortgage payments show up as an increase in the costs of goods and services. And one can calculate this increase in units of dollars-per-person-per-year. If one decarbonizes in lowest-cost order, each house is more expensive than the previous.

Can We Afford $100T?

Gross Domestic Product (GDP) worldwide is $96T per year. If we assume inflation and growth are zero, to simplify, GDP over 30 years would be $2,880T ($96T x 30yrs). Subsequently, $100T of infrastructure, built over 30 years, would consume 3.5% of GDP ($100T / $2,880T).

We are looking at bonds and bank loans paying for green infrastructure instead of it paying for carbon-based infrastructure. For example, we are looking at building wind farms in water, instead of building oil drilling

platforms in water. Unfortunately, in many cases, green infrastructure costs more. For example, we need more windmills than oil drilling platforms.

Harm from a warmer planet is costly too. For example, damage from sea level rise, damage from storms, and damage from dryer land are all costly. Fortunately, the cost of decarbonization is less than the cost of a warmer planet. However, decarbonization costs are immediate, and many warmer planet costs are several decades away.

How Smart Are We?

In many cases, a population favors itself over its future self. Yet to what extent? As evidence of climate change increases, support for decarbonization also increases. According to a survey, 67% of Americans want to decarbonize. This suggests significant steps will be taken this decade. However, will we be smart and decarbonize at the lowest cost? In many cases, this does not occur for a variety of reasons, which we explore in later chapters.

How Do We Spend Billions of Dollars to Save Trillions?

In theory, one can reduce the cost of green infrastructure with more R&D. Nevertheless, it is unclear what and where to develop. Subsequently, we should be asking top scientists and engineers the following question:

How might we spend additional hundreds of billions of dollars on R&D, over approximately a decade, to save trillions of dollars on green infrastructure?

4. Everyone's CO_2 Is Your CO_2

We will now explore how one might economically justify spending their own money to reduce someone else's CO_2.

A Rising Sea Hits Landfill First

Much of Boston, Massachusetts, USA, was permanently covered by water in 1630. Then, over hundreds of years, it was filled in by engineers who added only enough material to meet their needs, as illustrated below left in light green. Also, according to the U.S. National Oceanic and Atmospheric Administration (NOAA), the sea will be 1.6m (5ft) higher 65 to 200 years from now. And this will cover Boston's landfill, as illustrated below right in light blue.
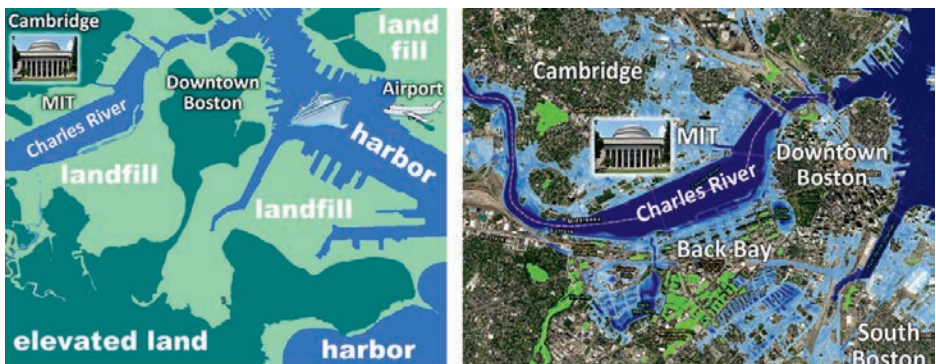
Figure 4.1: Locations of the land-fill in Boston, MA, USA.

For details on other U.S. cities, visit NOAA's Sea Level Rise Viewer and enter an address at the top, and a sea level increase at the lower-left.

One might consider building a seawall, perhaps similar to the one in the movie *Blade Runner 2049*. However, a rising underground water table would eventually cause water to seep into basements and below-ground infrastructure, even if a seawall were in place.

Decarbonize Others to Help Yourself

The state of Massachusetts (MA) emits $1/500^{th}$ of the world's CO_2. Therefore, if MA reduced emissions to zero, the world's $499/500^{th}$ would still harm MA with a rising sea.

MA can put money into R&D or brute-force decarbonization. An example of R&D would be to develop a website that identifies the lowest cost method for others to decarbonize and how to justify it economically. An example of brute-force decarbonization would be to place solar panels on the roof of the Boston Public Library.

If MA compares the amount of CO_2 reduced globally per dollar spent with each of these, building a trusted website would probably do better. In other words, if MA had a fixed budget to minimize sea level rise in Boston 200 years from now, using their brains might do more than their muscles.

Everyone's CO_2 Is Your CO_2

Currently, nations and regions within nations are looking at decreasing their own CO_2. An alternative approach is for each to consider everyone else's CO_2 to be their CO_2 since it affects them. Below are several ways one can reduce CO_2 in faraway places.

- Build websites that: (a) calculate the lowest cost way to decarbonize, (b) identify cases where decarbonization causes one to save money, and (c) identify coalitions of fuel importers who can save money by lowering fuel prices via decarbonization.

- Fund R&D that requires developed technology to be given away for free to increase utilization and decrease global decarbonization costs.

- Build transparent factories that others can copy for free to reduce the manufacturing costs of green products.

The latter two suggestions help foreign manufacturers and, therefore, might not be popular with some lawmakers. However, if one looks at the amount of CO_2 reduced per dollar spent, they might find these appealing.

Several foundations have expressed an interest in spending billions of dollars to tackle climate change. They tend not to favor one nation over another. Therefore, they are in a unique position to fully maximize CO_2 reduction per R&D dollar. They can do this by: (a) tasking panels of the smartest and most experienced in the world with R&D objectives, (b) providing them with ample funding, (c) requiring produced materials to be open source, (d) monitoring money flow, and (e) adjusting as needed.

5.   Tackling Climate the Right Way

Reducing CO_2 "the right way" involves doing so at the lowest cost and at large scales.

Decarbonization Scale and Cost

Current CO_2 emissions from the U.S. are approximately 5 billion tons a year, and many Americans want to reduce significantly over several decades. The below theoretical CO_2 vs. time graph shows what this would look like if it occurred at a constant rate over 30 years.
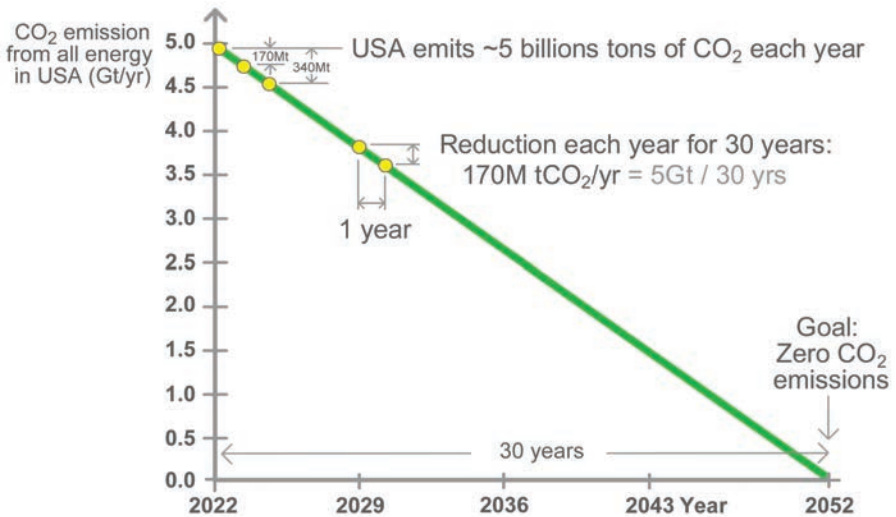
Figure 5.1: Theoretical U.S. decarbonization over 30 years at a constant rate.

When implementing the above Green Line, one must contend with two important parameters: Decarbonization Cost and Decarbonization Scale.

Decarbonization Cost refers to the amount of money required to reduce CO_2 and is typically measured in dollars per metric ton of CO_2 reduced ($/mtCO_2$).

Decarbonization Scale, on the other hand, refers to the amount of CO_2 emissions that are reduced each year. For example, if the goal is to eliminate the U.S. 5 billion ton per year emissions over a 30 year period,

then one would need to reduce by ~170 million tons each year on average. This is because 5 billion divided by 30 years is ~170 million.

Three Areas that Need Decarbonizing

There are roughly three areas that need decarbonizing: (a) electrical power generation, (b) fabrication of materials and chemicals, and (c) transportation. Electricity can be decarbonized now at large scales and low costs; whereas other areas have a scale problem, a cost problem, or both. And one can improve the other areas with R&D *while* decarbonizing electricity.

Electrical Power Generation is Ready to Decarbonize at Large Scales and Low Costs

In the near future there is only one way to reduce CO_2 emissions at low cost (e.g. < $50/mtCO_2$), large scales (e.g. 170M ton/yr reduction in the U.S.) and with government oversite. This is to enact laws that require power companies to decarbonize electrical power generation. These companies typically do this by building new solar farms, new wind farms and new hydroelectric dams. And this causes less natural gas and less coal to be burned for electricity.

Already the state of California requires their power company to decarbonize power generation by approximately 3% each year. For example, if 50% of their electricity is green today, then 53% would be green after one year, 56% after two years, etc. If this was implemented at the federal level and increased to a rate of 6% each year, it would be possible to reduce emissions by approximately 170 million tons each year for approximately 9 years, and do the Green Line at the lowest cost.

Transportation is Not Ready to Decarbonize at Large Scales and Low Costs

The U.S. currently makes approximately 1 million EVs each year and each EV reduces CO_2 approximately 3.5 tons a year. This reduces CO_2 emissions by 3.5 million tons each year (1M x 3.5mt) and is far short of the 170 million needed to get to zero over several decades. In other words, we currently have a Scale problem with transportation. One might look at

increasing production; however, this would entail trying to keep the cost of rare materials down as increased consumption makes them more rare.

According to the U.S. Government, the average EV cost $0.47/mile, the average gas car cost $0.30/mile, the average EV emissions is $179gCO_2$/mile (grams of CO_2 emissions per mile), and the average gas car emissions is $425gCO_2$/mile. One can do a little math to calculate decarbonization cost of $691 per metric ton of CO_2 reduced (($0.47 - $0.30) / ((0.425 - 0.179) / 1000)). In other words, transportation currently has a Decarbonization Cost problem.

Heat Driven Manufacturing is Not Ready to Decarbonize at Large Scales and Low Costs

Many manufacturing processes use high-temperature heat to make chemicals (e.g. hydrogen, ammonia) and to make materials (e.g. plastics, metals, ceramics, glass, cement).

One can replace heat made by burning coal or natural gas with heat made with green electricity. However, as discussed in the CCS chapter, this cost ~$140 per metric ton of CO_2 reduced when replacing heat made with natural gas, and ~$80/mtCO_2$ when replacing heat made with coal.

Decarbonizing electrical power generation (e.g. building solar farms and wind farms) typically costs $10 to $50/mtCO_2$. In other words, if one is paying money to reduce CO_2 in the near future, they would probably favor decarbonizing electrical power generation over heat driven manufacturing since it costs less. And after electrical power generation is decarbonized, society is likely to tackle material and chemical fabrication at large scales.

Tracking Systems Are Needed

If we had a market for green cement (i.e. made without emitting CO_2) and non-green cement, then "entrepreneurs" would move the lower cost non-green cement to a green cement warehouse (at 3am). Economists refer to this as "shuffle". In other words, it is easier to claim a product is green, than to actually make a green product. To deal with this, one would need an international system that tracks the production, transportation, storage and consumption of materials and chemicals. This system does not exist; however, in theory, it could be developed. Electricity does not have this

problem since electrical power meters and anti-tamper laws are already in place.

Two Phase Decarbonization Strategy

If the U.S. wanted to reduce 170M tons each year over 30 years at the lowest cost, it would end up with two decarbonization phases. Phase I would be approximately 9 years and would be achieved mostly with electrical power decarbonization. And the following 21 year Phase II would involve other areas that are more costly. To better prepare for Phase II, one could do more R&D during Phase I.
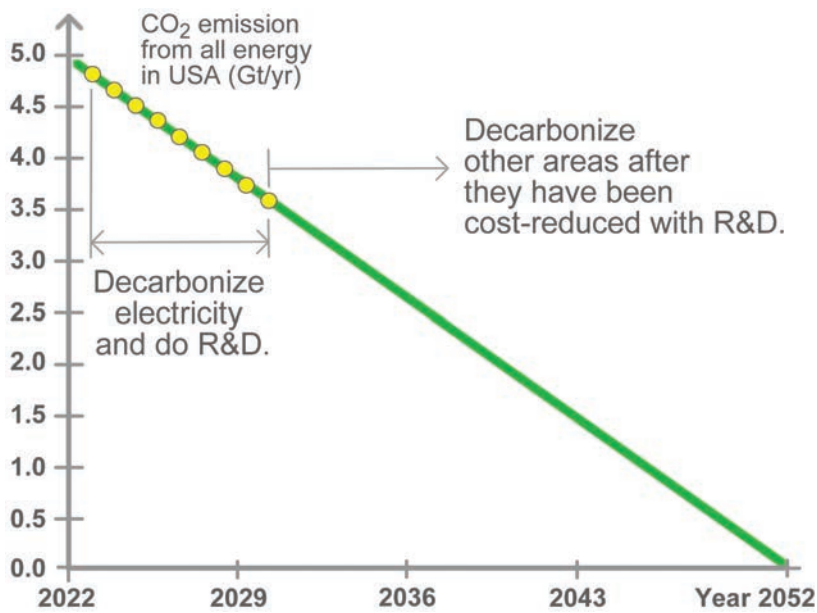
Figure 5.2: Two Phase Decarbonization Strategy.

What Does this Cost?

Yet how much would this cost the consumer? The answer is complicated since required decarbonization would result in reducing the consumption of natural gas, and this would cause the price of this fuel to decrease. And savings from lower fuel costs would offset the cost of building more solar farms and wind farms. Yet to what extent?

To get an accurate assessment one would need government engineers to calculate the impact of specific decarbonization legislation on fuel price. In

theory, lawmakers can request this; however, government engineers' ability to satisfy requests is limited by their time. For an example of what a request might look like, visit www.APlanToSaveThePlanet.org/study

If one does *not* model the impact on fuel price and one decarbonizes at $40-per-ton of CO_2 reduced, for example, then 170M tons would cost the U.S. $7B in year #1 (170Mt x $40), 340M tons would cost $14B in year #2, 510M tons would cost $21B in year #3, etc. This would cost each U.S. citizen $20 in year #1 ($7Bt / 330M population), $40 in year #2, $60 in year #3, etc. In the typical case, this would pay the mortgage on new solar farms and new wind farms, minus the cost of carbon-based fuel that was not burned due to being replaced with green electricity. Ultimately, these costs would appear as an increase in the cost of goods and services.

	Year 1	Year 2	Year 3
Cost/Person/Yr	$20	$40	$60
CO_2 Reduced	170M tons	340M tons	510M tons

Figure 5.3: Decarbonization cost per person per year.

Decarbonize in Lowest Cost Order

In theory, one can tackle climate change in the lowest cost order. For example, tackle $10/mtCO_2$ projects first, followed by $13/mtCO_2$, etc. If one uses the fruit analogy, this entails consuming the lowest hanging fruit first, followed by the layer above.

Evidence of climate change increases each year; therefore, tolerance of decarbonization costs are also likely to increase. To decarbonize, costs need to stay below tolerance of costs as one goes through time. For this reason, decarbonizing in lowest cost order might be required by the public.

There are not enough Democrats from U.S. states who benefit economically from decarbonization; therefore, a real climate law would need support from Republicans concerned about climate.

Republicans only support lowest cost decarbonization. For example, they oppose gov't intervention that promotes: (a) residential solar, (b) electric cars, and (c) restrictions on oil drilling. These reduce CO_2, yet not at lowest

cost. In effect, Republicans require lowest cost order; and their support is required to form a majority.

What does a Real Climate Law Look Like?

A federal law that decarbonizes in lowest cost order might consists of three main provisions:

1. CO_2 emissions from <u>human activity</u> are *required* to decrease to zero, over 30 years, at a constant rate, at the lowest cost, and in lowest cost order (i.e. follow the Green Line).

2. U.S. electricity is *required* to decarbonize at 6% per year, over a period of 9 years, at lowest cost. For example, 38% of electricity is made without emitting CO_2 today, 44% after year #1, 50% after year #2, etc. In other words, power companies are required to build more solar farms, more wind farms, etc.

3. A new R&D laboratory is set up to further reduce decarbonization costs.

Political Support

As of this writing, political support for a real climate law does not exist. However, as evidence of climate change increases each year, it is likely significant climate legislation will appear some time this decade.

Planet Saving Websites

Suppose a region is considering decarbonizing X% of electricity each year over a period of Y years. To assess impact, one would need to calculate: (a) lowest cost approach, (b) amount of CO_2 reduced, (c) cost per ton of CO_2 reduced, (d) cost per person per year, (e) savings due to lower fuel price, (f) number of jobs gained and lost, and their locations.

Currently, this information is not easily obtained. Therefore, a website is needed that calculates the above parameters after the user specifies X, Y, and region.

Doing detailed modeling for all nations, regions, and metropolitan areas worldwide might cost many millions of dollars. However, without this website, lowest-cost global decarbonization might be impossible.

What to Do If Your Competitor's Factory Costs Zero Dollars

Reports often compare the cost of a green product with its carbon-based counterpart when both production factories are built from scratch. However, this typically does not occur when decarbonizing. Instead, the carbon-based factory is already built and paid for. And we would like the new green factory to cost less than the incremental cost of operating the old factory. In most cases, new green fails economically against existing carbon. This is one reason why economists' CO_2 predictions are so dour.

In theory, new laws could require decarbonization, with additional costs passed onto consumers. The public is not comfortable with these at this time; however, it is likely they will appear this decade due to increasing evidence of climate change. To prepare for that day, one can do R&D to reduce decarbonization costs via automation and standardization, both in factories and at heat-driven industrial processing sites.

Multiple R&D Moonshots

A "moonshot" refers to a large R&D initiative that is implemented over a relatively short period of time. In theory, multiple moonshots could be done to reduce decarbonization costs. They would probably focus on areas that are currently not being worked on, and have potential for significant impact.

One might proceed with the following steps for each initiative: (a) establish goal, (b) write several page summary, (c) pay researchers approximately $10K each to write proposals to implement that described in summary, (d) spend several million dollars on initial R&D, and (e) proceed with more proposals and more money if project appears economically and technical viable.

A foundation, government or wealthy individual might set up a $500K fund that supports 50 proposals, for example. Also, they might require proposals be open-source, which means they would appear publically for anyone to use for free, to reduce further dependence on authors.

New green infrastructure is likely to cost 100 trillion dollars globally over several decades. Therefore, spending additional billions of dollars on R&D, to save trillions, is reasonable.

Always Begin with Plan

Plan writing forces one to break a problem down into component parts, put together a solution for each, and make sure each solution is feasible. With climate change, this entails putting together an economic strategy, a political strategy, and a technical strategy. Economic strategy involves decarbonizing at the lowest cost. Political strategy involves groups that have at least 51% political support who benefit from lowest-cost decarbonization. And technical strategy involves reducing decarbonization costs with more R&D.

The world has not had a plan to tackle climate change in the past, and this has led to wasted time and money.

Business schools and engineering schools teach "Always begin with a plan".

We should apply this to climate change.

You Can Save the Planet Too!

Governments, foundations and researchers can develop plans to save the planet too. To make this easier, this book's original Microsoft Word file, spreadsheets, and illustrations are available to copy and modify for free at www.APlanToSaveThePlanet.org/open

If a plan involves more R&D, it might include a business plan for a new laboratory. For an example, visit www.APlanToSaveThePlanet.org/lab

If a plan involves a new federal law, it might include a one page summary and another document that explains why this is the easiest way to solve the problem. For an example, see www.APlanToSaveThePlanet.org/da202x

If a plan involves a website that calculates the cost and impact of decarbonize policy, it might include an open-source proposal to develop this tool. For an example, see www.APlanToSaveThePlanet.org/study

6.   Tackling Climate the Wrong Way

Tackling climate change "the wrong way" involves doing so at high costs, low scales, and without broad political support.

Past U.S. Decarbonization Efforts Have Been Deficient

The amount of U.S. green electricity as a percentage of total increased from 35% to 37% over the last 5 years. In other words, U.S. electricity is decarbonizing at a rate of 0.5% each year ((37.6% - 35.4%) / 4yrs). Alternatively, if the U.S. fully decarbonized its electricity over 10 years, for example, this increase would need to be 6% each year ((100% - 38%) / 10yrs)). Other countries, like China, are similar.

Future U.S. Decarbonization Efforts are Expected to be Deficient

The U.S. Energy Information Administration (EIA) is an organization within the U.S. government that studies energy and CO_2 emissions. They expect CO_2 emissions over the next 30 years to remain approximately constant, as shown in the graph below. In other words, according to the U.S. government, the U.S. is not reducing CO_2 emissions to zero. Other countries are similar.

Total energy-related carbon dioxide emissions
million metric tons from U.S. each year   **2022**

History ⟵ ⟶ Projection based on U.S. Gov't Model

percentage relative to 2005

Projected CO_2 emissions without IRA

Projected CO_2 emissions based on current policy

The Green Line: Decarbonize to zero over several decades at a constant rate.

Data source: U.S. Energy Information Administration, *Annual Energy Outlook 2023* (AEO2023)

Figure 6.1: U.S. government's official projection of CO_2 emissions from the U.S. over the next 30 years in units of billions of tons each year

The reader may have seen decarbonization scenarios that show CO_2 emissions dropping to zero over several decades. These show what would happen if decarbonization did occur, an example of which is the Green Line

in the previous graph. Projections, on the other hand, are based on existing laws and observed behavior.

Decarbonization does Not Occur Unless Required by Law

If a consumer has a choice between buying a product that emits CO_2, and buying a product that does not, they often ignore CO_2 and select the lower cost option. Many people consider their own CO_2 to be insignificant, and prefer the world's other inhabitants buy green and pay more. This is observed behavior, and is consistent with economic theory. Subsequently, to do the Green Line, decarbonization would need to be required by law.

The Prisoners Dilemma Problem

A person, city, state or nation can decarbonize to zero while CO_2 emissions from the rest of the world causes them harm. In other words, eliminating one's own CO_2 has close to no impact. Subsequently, many people are not inclined to incur additional decarbonization costs. Economists refer to this as a "prisoner's dilemma" problem.

The trade deficit between the U.S. and China is an example of prisoner's dilemma. Americans complain about the deficit while buying Chinese made products at Walmart. In response, U.S. manufacturers occasionally promote "Made in USA". However, this is largely ignored. In other words, consumers favor lowest cost since one person buying American-made has close to no impact.

The Rising Global GDP Problem

If 100% of global infrastructure was replaced over 30 years at a constant rate, for example, then 3.3% would be replaced each year (100% / 30yrs). Global gross domestic product (GDP) increases approximately 3% each year. Therefore, to keep up with GDP growth and decarbonization, one would need to build green at a rate of 6.3%/yr (3% + 3.3%). This is not happening, and this is one reason why global CO_2 emissions are increasing.

Carbon Offsets, Not Really

Many companies want to report they emit little or no CO_2. To do this, they pay organizations to supposedly reduce CO_2 emissions, to offset their own emissions. These are referred to as "carbon offsets", and they often sell for $3 to $5 per metric ton of CO_2 reduced.

Unfortunately, there are many offset schemes that are economically invalid, scientifically invalid, or fraudulent. For example, if someone is paid to not do tree farming on one parcel of land, to supposedly reduce CO_2, tree farming will be done elsewhere. This is due to lumber production being set by demand. In other words, if one parcel of land is blocked, the home builder will get his 2x4 boards from a different parcel of land.

Some schemes supposedly reduce CO_2 by planting trees. However, this only works if the trees and their offspring persists for thousands of years at no additional cost, which is often unlikely.

Capital needs to flow to where it is needed most. Therefore, government should consider shutting down schemes with inaccurate claims.

Corporate Social Responsibility, Not Really

Some companies buy carbon offsets that match their own CO_2 emissions. This is referred to as "net zero," and it is often done to appear more socially responsible. Also, these companies must decide if they want to pay more, and be at real net zero, or pay less and be at less than net zero. For example, a company that emits 10 million tons of CO_2 each year could buy $15-per-ton real offsets for $150M each year, or $3-per-ton fraudulent offsets for $30M. In both cases, they report net zero. However, in the latter case, their profit is $120M higher.

Replace Carbon, Do Not Block Carbon

Environmentalists sometimes advocate restricting the production of carbon-based fuels. For example, they might advocate reducing the number of drilling permits for natural gas. At first glance, this might seem reasonable. However, it does not reduce CO_2 at the lowest cost. Instead, it leads to fuel shortages, high fuel prices, inflation, high-interest rates, and increased risk of recession.

To decarbonize at the lowest cost, one must build a solar farm or a wind farm *before* reducing the output of the nearby carbon-based power plant. In other words, replace carbon, do not block carbon.

Block vs. Replace

Now, let's compare block with replace. Suppose we block carbon and create an oil shortage that causes the price to increase by $10 per barrel.

The U.S. consumes 7.2B barrels each year; therefore, this would cost $72B each year.

Alternatively, one could use the $72B to build solar farms. They cost approximately $1.12-per-watt (CAPEX, NREL, 2022). Therefore, one could build 64GW of solar with $72B ($1.12 x 64GW). Over a year, they typically produce 2,334 watt-hours of electricity for each watt of capacity. Therefore, this would produce 149 TWh of electricity each year (64GW x 2,334).

When one replaces 1 TWh of natural gas based electricity with green electricity, CO_2 emissions decrease by 0.41 million tons. Therefore, this would reduce CO_2 by 61 million tons each year (149 TWh x 0.41 $MtCO_2$).

One can typically sell electricity wholesale for approximately $0.03/kWh. Therefore, this solar farm would produce 4.5 billion dollars of revenue each year for 30 years ($0.03 x 149e12 x 0.001). What would you prefer?

a)   Pay $72B with little benefit.
b)   Pay $72B to reduce CO_2 by 61Mt/yr and receive $4.5B/yr for 30 years.

Creating a shortage that increases price is almost always a terrible way to solve a problem.

Subsidizes Are Not Efficient

Consumers typically disfavor green products because they cost more. However, in theory, government can change this by paying a portion. This is referred to as a "subsidy" and it is typically implemented with a percentage of electricity revenue or percentage of equipment cost that are offset with a tax credit.

The goal is to cross over a tipping point where the subsidized green product costs less than the carbon-based product. This works fine in theory; however, prices of both green and carbon-based products typically vary over time and place. For example, the price of natural gas in the U.S. varied between 2¢ and 4¢/kWh between 2017 and 2021 (i.e. fuel cost per kWh of electricity) and was 20% more in California than nearby Utah.

Due to these fluctuations, fixed subsidies are often not helpful, or are too helpful. For example, if the green premium starts at +1.5¢ (i.e. difference between green product and carbon-based product), then lowering it to

+0.5¢ with a 1¢ subsidy still does not make the green product cheaper. Or if the green premium starts at +0.5¢, then lowering it to -0.5¢ with a 1¢ subsidy wastes public money.

Subsidizing electricity is tricky since natural gas consumption decreases when it is replaced by renewables. And this causes its price to decrease, which causes the green premium to increase, which leads to an ineffective subsidy. In other words, if the subsidy is working, it will eventually stop working.

Taxes Are Not Efficient

Taxes designed to change behavior are often inefficient. For example, a 0.1¢ tax on non-green electricity (per kWh) will not reduce much CO_2 if the green premium is 1¢ (i.e. the subsidized price is still 0.9¢ away from the tipping point). However, the market is forced to incur an additional 0.1¢ expense, which ultimately leads to a high decarbonization cost.

Required Electricity Decarbonization is the Lowest Cost Approach

Instead of subsidies or carbon taxes, one can require power companies to obtain more green electricity each year. This avoids the above-stated problems, and power company engineers can implement at the lowest cost. Already, many U.S. states have green electricity requirements. They are commonly referred to as "Renewable Portfolio Standards" (RPS). However, they are not federal and are often undersized relative to what is needed.

Our *Economic* Decarbonization Strategy Is Flawed

The current economic decarbonization strategy is to encourage individuals, companies, cities, and states to reduce CO_2 emissions. At first glance, this might seem reasonable. However, it is flawed since these entities rarely have the physical ability to do this at the lowest cost. This is like asking a city mayor to build a car from scratch in the local shop. Can he do it? Yes. However, it might cost him 100 times more than factory mass production. Instead, the mayor should let the automobile industry handle mass production in the same way we should let power companies decarbonize at massive sales and at lowest costs.

Here's another example. Imagine trying to place 20 solar panels onto a million different homes. One would incur project overhead cost a million

times (e.g. customer acquisition, system design, permitting, inspection, etc.). Alternatively, if one installs 20 million panels at a large solar farm, they would not see overhead every 20 panels. This is why solar farm cost-per-unit-electricity is approximately 3-times less than residential solar.

Decarbonization Politics

There are two kinds of regions -- those that produce and export carbon-based fuels, and those that import fuels. One might think of these as *fuel exporters* and *fuel importers*.

In many cases, regions that produce a fuel will not politically support eliminating it.

Fuel *exporters* are hurt by decarbonization. However, the opposite is true for *importers*. They benefit in two ways:

1. Local green jobs are created when nearby wind and solar farms are constructed. This occurs while carbon jobs are lost elsewhere.

2. Money is saved when decarbonization causes fuel prices to decrease, due to less fuel consumption, due to decarbonization.

Fuel Producing Regions in the U.S.

The maps below indicate where fuels are produced in the U.S. Two-thirds of U.S. states do not produce natural gas or coal. In other words, more than half of U.S. lawmakers are not likely to resist significant electricity decarbonization.
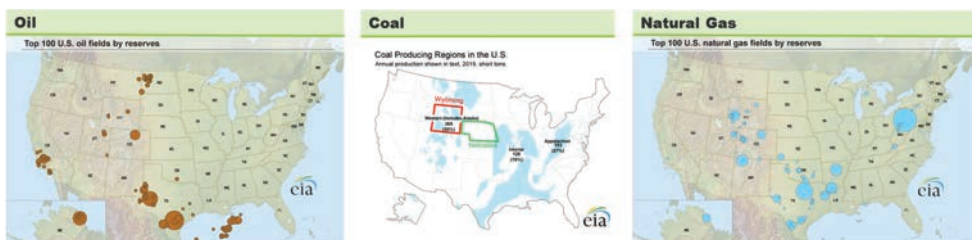

Figure 6.2: U.S. suppliers of oil, coal and natural gas.

Our *Political* Decarbonization Strategy Is Flawed

Existing decarbonization legislation in the U.S. was drafted by a political coalition of environmentalist, labor unions, domestic manufacturers, and

the automobile industry. At first glance, this might seem reasonable. However, it is fundamentally flawed since labor and manufacturers must focus on their own financial interests, not getting to zero at the lowest cost.

Alternatively, to decarbonize electricity at the lowest cost, one would need a coalition of lawmakers that benefit from exactly that, lowest-cost electricity decarbonization. This is not labor or auto. Instead, this would be the two-thirds of the U.S. states that import natural gas and coal.

The Hi-Jacking of Climate

Many organizations use climate to make money. For example, domestic manufacturers have encouraged government to subsidize the making of solar panels in the U.S. Unfortunately, making panels in the U.S. instead of China does not reduce CO_2. Ironically, many provisions within climate legislation do not reduce CO_2, or do not do so at the lowest cost. And instead they implement protectionism (i.e. favor domestic manufacturers over foreign).

Lawmakers Need to Be Better Informed

To fix the climate problem, federal lawmakers need to realize three things:

a)   Lawmakers need to lead (e.g. require electricity decarbonization and more R&D) instead of delegate to cities, states, companies, and domestic manufacturers.

b)   In order to gain the support of Republicans concerned about climate, decarbonization legislation must rely on R&D and on markets (e.g. builders of solar farms and wind farms compete with each other to drive down costs).

c)   Majority support is likely to come from regions that import carbon-based fuels.

7.   Decarbonize Electricity First

This chapter looks at the impact of decarbonizing 6% of U.S. electricity each year over 9 years.

How Much Would This Cost?

Currently, 38.4% of U.S. electricity is made without emitting CO_2 and if this were to increase 6% each year over 9 years, then 92% would be green in year #10 (38.4% + 6% x 9yrs).

The U.S. produces 4,100TWh of electricity each year and if 6% of this were decarbonized each year, then approximately 246TWh of coal and natural gas based electricity would be replaced with solar, wind, hydro and nuclear each year (4,100 x 6%).

Currently, 38% of U.S. electricity is made with natural gas, and 22% is made with coal. If 246TWh/yr were divided by these proportions, then 157TWh of natural gas and 89TWh of coal would be replaced with green electricity each year. Subsequently, CO_2 would decrease 65Mt/yr due to burning less natural gas, and decrease 90Mt/yr due to burning less coal (millions of metric tons per year). Total CO_2 reduction would be 154Mt/yr (65 + 90) and this would satisfy 90% of the 170Mt/yr requirement (154 / 170).

If half of the carbon-based electricity were decarbonized by constructing solar farms and half by constructing wind farms, for example, then 53GW of solar would be constructed each year, and 32GW of wind would be constructed each year. This is approximately 4-times more than the average between 2016 and 2021. The solar TWh-to-GW ratio is different than the wind ratio, since the wind blows more than the sun shines.

If decarbonization costs increased from $10/mtCO_2$ to $50/mtCO_2$ over a 9 year period (cost to reduce CO_2 by one metric ton), for example, then the cost of residential electricity would increase $1 per-person-per-year in year #1.

Sounds too good to be true? Total cost for year #1 would be $1.54B (154Mt x $10/mtCO_2$), total electricity cost-per-person-per-year would be $5 ($1.54B / 330M population), and *residential* electricity cost-per-person-per-year would be $1 ($5 x 20%). We apply 20% since 1/5th of all electricity is residential.

The table below shows what this looks like for the first four years. This analysis assumes inflation and GDP growth are zero to make this easier to follow.

		Year #1	Year #2	Year #3	Year #4
Decarbonization Cost	$/mtCO$_2$	$10	$15	$20	$25
% U.S. Electricity Decarbonized	%	44%	50%	56%	62%
Decarbonization "Mortgages"	$B/yr	$1.5	$1.5	$1.5	$1.5
US NREL, LCOE, 2022, Class 4	"		$2.3	$2.3	$2.3
	"			$3.1	$3.1
	"				$3.9
Total cost	$B/yr	$1.5	$3.9	$6.9	$10.8
Total cost for residential electricity (20%)	$B/yr	$0.3	$0.8	$1.4	$2.2
Cost of residential electricity per person	$/yr	$0.9	$2.3	$4.2	$6.5

Table 1: Calculated electricity decarbonization costs.

If one did not decarbonize in the lowest cost order and instead incurred $50/mtCO$_2$ costs in year #1, then the total electricity cost-per-person-per-year in year #1 would be $25 instead of $5.

Getting it done at the Lowest Cost

About 30% of all U.S. CO$_2$ emissions are from making electricity and 70% are from burning carbon-based fuels to produce heat and force within vehicles, factories and buildings. If one wanted to decarbonize all energy over 30 years at the lowest cost, one might first focus on electricity, and decarbonize other areas after they had been cost-reduced via R&D. In other words, spend as little money as possible each year, over 30 years, while reducing CO$_2$ emissions by $1/30^{th}$ of today's emissions each year.

A strategy like this would result in constructing significantly more solar farms and wind farms. Yet how does one do that?

What Drives Solar/Wind Farm Construction?

The number of solar farms and wind farms built each year is primarily determined by the following factors:

i. **Government Requirements:** Legislation that requires power companies to generate more green electricity each year (e.g. RPS).

ii. **Government Subsidies**: Legislation that provides government money to help pay for green electricity to reduce its effective price (e.g. ITC).

iii. **Cost of Green Electricity:** Cost to generate green electricity (¢/kWh).

iv. **Cost of Carbon Fuel:** Cost of natural gas and coal fuel that are burned to produce carbon-based electricity (¢/kWh).

v. **Green Consumerism:** The number of consumers willing to pay more for green products.

In the above list, (i) and (ii) are controlled by lawmakers, (iii) improves each year due to technology and production advancements, (iv) varies up and down due to external factors, and (v) increases as climate change harm becomes more obvious.

Increase Solar Farm and Wind Farm Construction

To increase the rate of electricity decarbonization, one would need more of the above listed items. For example, U.S. federal *subsidies* on green electricity are approximately 1¢/kWh as of April 2023, and if these doubled, the affect would be significant. In another example, Massachusetts *requires* 35% of its electricity to be green by 2030. Other states are similar. However, these targets need to be significantly larger.

Climate Change Policy Options

Policy options can reduce decarbonization costs. Below are several examples.

- Establish a government office with authority to amend electricity purchase agreements between electricity customers and carbon-based power plants. This would help large customers to more easily replace carbon-based electricity with green electricity.

- Establish a government office with authority to *replace* existing power transmission lines with larger lines on a wider tract of land. For details, see the "Automate the Construction of Power Transmission Towers" chapter.

- Set up a green energy production zone program where communities voluntarily join to increase economic activity. In these zones, land-owners have the right to build solar farms and wind farms, a government office has the authority to demand right of way for new power transmission lines, etc.

Decarbonization Anxiety

Required decarbonization is scary is two ways:

Cost Anxiety: It is reasonable to be afraid of decarbonization costs, especially when nations rarely decarbonize at the lowest cost. For this reason, decarbonization law that requires lowest cost, and websites that calculate costs, are important.

Carbon Industry Anxiety: It is reasonable for regions with many carbon-based industries to be afraid of the social and economic pain associated with downsizing. One should not expect political support from these regions when tackling climate change at large scales.

8.   Do We Need a Decarbonization R&D Laboratory?

The U.S. government currently operates dozens of national laboratories, an example of which is the Jet Propulsion Laboratory (JPL) in California. They develop gadgets that explore outer space with a $3B/yr budget.

Figure 8.1: Jet Propulsion Laboratory in California, USA.

In theory, the U.S. government could do something similar with climate change by setting up a new national laboratory that develops gadgets that reduce decarbonization costs.

Foundations could also set up laboratories. For example, Bill could set up a Gates Decarbonization Laboratory, and Elon could set up a Musk Decarbonization Laboratory. And these could collaborate with Joe's U.S. National Decarbonization Laboratory.

What Do Labs Do?

Some laboratories develop large systems, whereas others focus on supporting research via grants. For example, JPL focuses on developing large systems such as the Mars rover, and the National Renewable Energy Laboratory (NREL) is active in supporting research grants.

The typical grant process is as follows: (a) announce funding opportunity, (b) collect proposals, (c) review, (d) select, and (e) manage awardees.

Foundations, Companies, and Universities

Companies and universities who receive money for R&D often prioritize their own financial interests over reducing CO_2. For example, they typically do not share developed materials unless they are required to do so. This is because transparency often detracts from: (a) filing patents, (b) developing proprietary products, and (c) raising money for companies and labs.

A decarbonization laboratory, on the other hand, might be tasked with solving the climate change problem, and not with making money. And to do this, they might require developed materials be placed onto the internet, open source. This would maximize the utilization of developed technology worldwide, maximize candid review, maximize the development of interconnection standards, and minimize inaccurate claims.

Organizational Structure

Laboratories typically divide responsibility among multiple divisions, and divisions typically divide responsibility among multiple groups. A lab could have any number of divisions and any number of groups, and these could be added or subtracted at any time.

Panels of individuals typically allocate money from a general fund to divisions and to groups. And staff are typically encouraged to raise money from external sources via proposals.

Some laboratories have many employees at one site, whereas others funnel money toward other organizations. For example, a laboratory that accelerates the development of fusion power might pass money to scientists at the world's 10 fusion research organizations who are already familiar with fusion.

Reduce Waste Due to Project Bias

Governments and foundations occasionally fund projects that are not technically feasible or are not economically viable. This is often due to developers who claim everything is OK when it is not, to raise money, to pay people.

To defend against "project bias", a lab could potentially task the best and brightest engineers and scientists in the nation to oversee multiple projects, and reasonably throttle money up or down, to each, over time.

Laboratory Divisions

Below are examples of divisions within a laboratory.

Commercial Fusion Moonshot: Achieve commercial fusion within 10 years. Funding is directed by the world's top fusion scientists and flows toward top people at existing fusion research institutions.[1, 2, 3, 25]

Fission Moonshot: Dramatically increase the production of nuclear fission reactors over the next 10 years in a manner that meets the satisfaction of the public.[4, 5, 6, 7, 24]

High-Temperature Manufacturing: Develop next-generation high-temperature green manufacturing sites, standards, and supporting transportation infrastructure.[4, 5, 6, 7, 26]

Custom Solar Skin: Develop machines that fabricate, install and maintain custom pieces of PV solar that wrap building roof and wall surfaces.[8, 31]

Solar Sub-Assembly Development: Develop standardized modular solar sub-assembles that stack within a shipping container and are assembled under robotic control.[9, 32]

Solar Panel Installation Automation: Automate the placing of traditional solar panels on buildings.[9]

Solar Farm Automation: Develop next generation automated solar farms that consume significantly less metal, concrete, and glass.[10, 33]

The National Solar Farm: Develop an automated software system that supports ownership of solar panels on a solar farm.[29]

Ammonia Transportation: Do paper-only design of a global well-to-wheels ammonia based transportation system. This entails exploring ammonia-based fuel cells, ammonia tanks, automated refueling mechanisms, and citywide ammonia monitoring and service.[11, 27, 28]

Hydrogen Transportation: Similar to the above yet hydrogen (H_2) instead of ammonia (NH_3).[11, 27, 28]

Electric Vehicle Cost Reduction: Reduce the cost of electric vehicles (EVs) to the extent required to make them cost less than gasoline and diesel powered vehicles. This includes improving EV battery longevity 2-fold (i.e. to beyond the lifespan of the vehicle), exploring dynamic battery warranty, and exploring mandated diagnostic battery reporting.[12, 13, 15, 28]

Swappable EV Battery: Develop a standardized swappable EV battery system, to the point of simple prototypes.[14, 28]

HVAC Command and Control: Develop software and standards that connect HVAC equipment in all buildings to regional computers. Support a national strategy that decarbonizes building heat at lowest cost.[16, 35]

Building Automation: Develop software, devices, and standards that automate buildings.[16, 17, 18, 19, 36]

Carbon Capture and Sequestration (CCS): Develop software, standards, systems, and models that support the eventual unfolding of CCS.[20, 30]

Power Line Transmission Automation and Commoditization: Reduce cost of electrical power transmission lines via automation and standardization.[21, 34]

Decarbonization Policy Making Tools: Maintain websites that calculate the lowest cost way for regions to decarbonize given policy options.[22, 23, 37]

Conclusion

Developing large systems is often avoided for a variety of reasons; however, one can explore with a relatively small budget. And one can require open-source to avoid placing the entire system onto the shoulders of one organization.

Business schools teach that the best productivity comes from well-funded teams of outstanding individuals who are surrounded by minimal bureaucracy. Organizations that apply this principle tend to be more successful.

For an open-source (i.e. free) decarbonization laboratory business plan, visit www.APlanToSaveThePlanet.org/lab

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[8] *How to Cover Buildings with Solar Skins*

[9] *Why Spend $1B on Solar Installation R&D?*

[10] *Mechanizing PV Solar on Land*

[11] *How to Decarbonize Transportation*

[12] *The Little Secret of Electric Vehicles*

[13] *Car Costs and CO2 are Complicated*

[14] *Are We Ready For a Swappable EV Battery?*

[15] *How to Improve Gas Mileage 25% to 50%*

[16] *How to Decarbonize the Heating of Buildings at Lowest Cost*

[17] *Using processors and software to make buildings smarter*

[18] *Standards Are Needed to Thermally Cover Windows*

[19] *Standards Are Needed to Fully Control Air in Buildings*

[20] *What is our Long Term CCS Strategy?*

[21] *How to Reduce the Cost of Electrical Power Transmission*

[22] *Develop Your Own Decarbonization Plan*

[23] *A Framework to Tackle Climate Change*

Decarbonization Laboratory Chapter References

[24] "Are We Ready for a Fission Moonshot?" chapter

[25] "Are We Ready for a Fusion Moonshot?" chapter

[26] "Develop Next Generation Industrial Processing Systems" chapter

[27] "The Economics of Green Fuel" chapter

[28] "Develop Cheap Green Cars" chapter

[29] "Develop a National Solar Farm" chapter

[30] "Carbon, Capture and Sequestration" chapter

[31] "Cover Buildings with Solar Skin" chapter

[32] "Automate Solar on Buildings" chapter

[33] "Mechanize Solar on Soil" chapter

[34] "Automate the Construction of Power Transmission Towers"

[35] "Decarbonize the Heating of Buildings" chapter

[36] "Develop Next Generation Buildings" chapter

[37] "Save the Planet with a Website" chapter

9. Are We Ready for a *Fusion* Moonshot?

There are two types of nuclear power: fission and fusion. Traditional nuclear power plants generate electricity with uranium via fission. However, this is not popular due to meltdown risk, nuclear waste, nuclear bomb proliferation risk, and cost. Fusion, on the other hand, does not have these issues; however, it is still in development. Typical fusion systems maintain a hot plasma in a donut-shaped reactor called a tokamak, as illustrated below.
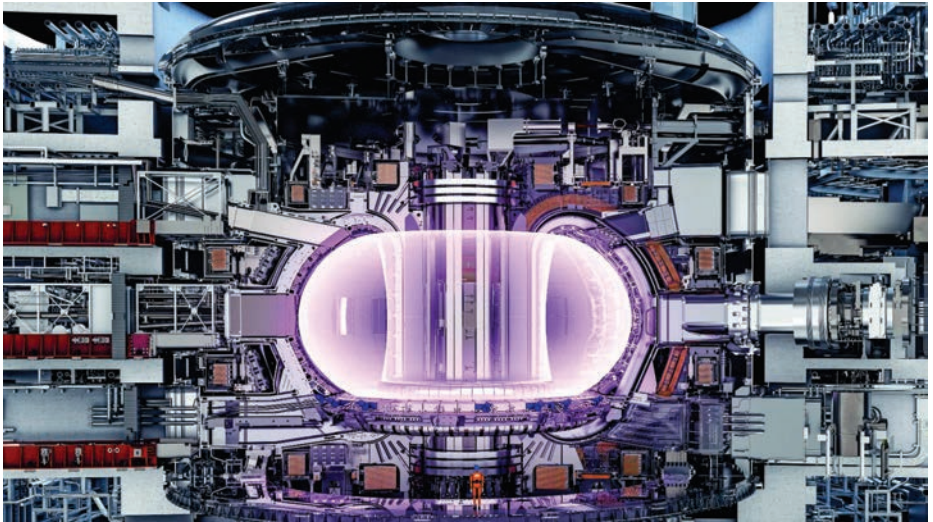
Figure 9.1: Nuclear fusion power station (illustration).

The First Moonshot

In 1961, President Kennedy stated he wanted a man on the moon by the end of the decade. In response, a program was set up and funded. In theory, a government leader could do the same with nuclear fusion power. For example, they could state that commercial fusion must be operational within 10 years. This might seem unrealistic. However, notice how many "gadgets" the U.S. designed and manufactured between 1939 and 1945.

Commercial Fusion Moonshot

"Commercial fusion" refers to generating electricity at a cost comparable to electricity made with natural gas or coal. This requires the fusion reactor to run for long durations, without failure, and at a low cost.

A "moonshot" refers to a large R&D initiative that is implemented over a relatively short period of time. One might define "fusion moonshot" as:

*Achieve **commercial** fusion within 10 years.*

Fusion Milestones

There are three fusion milestones that have not yet been met:

- Generate significant amounts of heat, expected ~2025.
- Generate electricity for less than a day, expected ~2035.
- Generate electricity commercially at low cost, expected ~2045 without moonshot.

Heat is Probably Not the Problem

Reports in national media suggest current fusion reactors do not produce sufficient heat. This is true. However, heat increases when one increases the strength of the magnets, and stronger magnets were recently developed at MIT. These will be installed into a test reactor soon, and MIT hopes to demonstrate sufficient heat in 2025. In other words, heat is probably not the problem.

So what is the problem? Below are several.

Challenge #1: Reactor Build Time

Fusion test reactors typically take many years to build, and this is probably the greatest obstacle to commercial fusion. To move rapidly, one might need hundreds, or even thousands of engineers in places like China who can build and test quickly.

What does Elon Musk do after one of his rockets fails in spectacular fashion? He repeats. And after dozens of cycles, a working system emerges. To get commercial fusion working quickly, a similar approach might be needed.

Challenge #2: Component Longevity

To produce electricity at a low cost, a commercial fusion reactor would need to run for long durations without failure. To ensure longevity, engineers could run individual components in test fixtures at maximum power, or more, to see how and when they break, and then improve as needed. This might sound easy; however, doing this with many components takes time and requires many engineers. And if a delicate component, such as a magnet, fails prematurely on a regular basis, a remedy might not be quick or easy.

Challenge #3: Disposable Plasma Confinement Chamber

The heat from a fusion reactor core needs to be moved outward, to create steam, to press on turbine fan blades, to produce electricity. The easiest way to do this is to pump fluids, such as molten lead or molten salt, toward the hot plasma, and then outward.
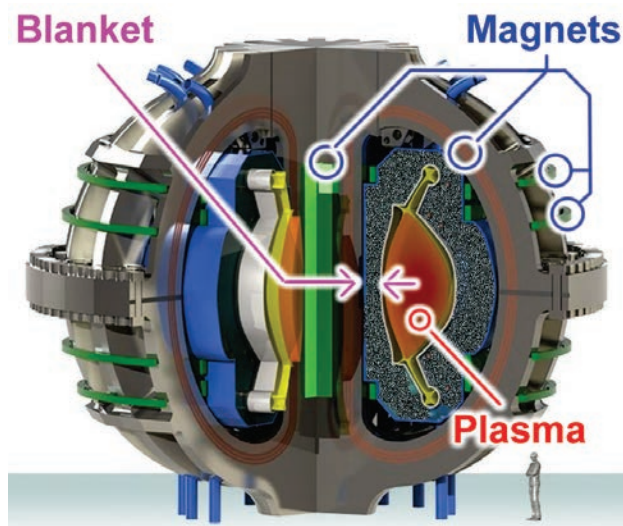
Figure 9.2: Plasma is surrounded by a reactor "blanket" which removes heat and absorbs neutron radiation.

Neutron radiation from hot plasma weakens surrounding metal for about one meter of penetration depth. Consequently, the plasma confinement chamber would need to be replaced approximately once a year. This chamber is labeled "blanket" in the above illustration. In other words, one might need to fabricate 50 of these chambers over a 50-year period. And

fabricating these at low cost would probably require automation and molded processes. For example, an industrial robot might weld together molded metal panels affixed to a jig on a rotating table.

It is not difficult for a team of engineers, or even one engineer, to design the mechanics of how a fusion reactor fits together. Also, multiple teams could create multiple designs that are later selected or merged after being reviewed. However, it is not clear how to identify the best design. And after committing to one design, it might take many years to build and test.

To help verify designs, one could build prototypes *quickly* that are 1 to $10m^3$ in size. These might not include magnets, and might not maintain the plasma. However, they could verify assembly of molded panels via industrial robots, verify pumping of fluids at high pressure, verify moving heat, and verify replacing internal components via industrial robots.

To Plan or Not To Plan?

There are two ways to manage a large development initiative. The traditional method is to develop a plan, get it funded, and implement. Alternatively, one can set goals, assemble a top team, give them authority, provide funding, and get out of their way. The traditional method works well if one knows what needs to be done. Unfortunately, commercial fusion is not well understood.

Achieve Commercial Fusion as Soon as Possible

ITER is a $25B fusion reactor development program based in France. Their reactor was designed 20 years ago and is currently obsolete due to advances over the last two decades. If ITER had been driven by a goal instead of a plan, it would probably be further along. An example goal might be, "achieve commercial fusion as soon as possible given $1B/yr."

How Might a Foundation Accelerate Fusion Development?

If a philanthropic foundation wanted to accelerate the development of fusion power with $100M, for example, how might it proceed? Below is one possible approach.

- Establish a blue ribbon panel with 5 to 15 of the world's top fusion scientists and engineers.

- Establish a goal, such as "achieve commercial fusion within 10 years."

- Set up a management team, possibly within a foundation or institution, that manages the initiative. More specifically, they oversee contracts, purchase orders, invoices, and money.

- The blue ribbon panel determines how to spend money, and the management team is instructed to provide them with maximum support. In other words, power is placed in the hands of the panel and not the management team. And cash is put into the hands of the management team, not the panel.

- All scientists and engineers who receive money are required to make produced materials open source (e.g. spreadsheets, designs, simulations, and test data). Subsequently, anyone can view, copy, modify and use it in any way; at no cost. Materials are placed on the internet, and anyone is welcome to review, rework, or improve. Transparency improves productivity since problems are identified more quickly.

- Scientists and engineers at the world's top 10 fusion research organizations are invited to participate. Many are motivated since they receive money in return for work, and they can use produced materials.

- The initiative produces multiple paper-only reactor designs, simulations, simple prototypes of components, and proposals for more work. However, the initiative does not produce an actual physical reactor. For that, one would need more money.

How Is This Different?

After the typical fusion R&D initiative commits to one design and begins construction, money and talent focus on building the test reactor instead of more design. Also, most fusion research programs focus on the first two milestones (i.e. more heat, remove heat) as opposed to commercial fusion (i.e. low cost, reliable, serviceable, automated assembly). Therefore, an initiative that focuses on design-only, open source, cost reduction, component longevity, and automated fabrication/maintenance would be different from existing fusion development initiatives.

When to Profit?

If the above initiative ultimately led to a commercial fusion reactor, its design could potentially be licensed for manufacture. Licensing revenue could then be fed back to the organizations that designed it. The world's fusion organizations know this. Therefore, they might be inclined to convert an open-source initiative to proprietary. For example, top people might stop contributing to open source when it is 90% complete, and do the last 10% as proprietary. In other words, a philanthropic foundation might get this started open source. However, ultimately, the financial interests of governments, investors, companies, and fusion research institutions might cause them to lose interest in open source when close to complete (which would be okay).

Getting Started with $100M

Why would this initiative not be funded originally by commercial investors? That is already happening; however, those efforts are not expected to produce commercial fusion before 2040.

Why would this initiative not be funded originally by government? That is already happening too. However, national interests and emphasis on plan are not expected to produce commercial fusion any time soon.

To accelerate fusion development, one might initially need a sponsor who is *not* looking for a return on investment, requires transparency, is willing to give power to top people, and encourages participation across national boundaries.

10. Are We Ready for a *Fission* Moonshot?

As noted previously, fission is the traditional form of nuclear power and it is not popular due to meltdown risk, nuclear waste, nuclear bomb proliferation risk, and high cost. In theory, it could be improved. However, could it be improved to the extent required by the pubic? One could explore this question within a fission moonshot initiative, perhaps defined as:

> *Dramatically increase the production of nuclear fission reactors over the next 10 years in a manner that meets the satisfaction of the public.*

How do we Resolve Meltdown Risk?

Resolving meltdown risk is relatively easy. Some nuclear fuels do not melt when not cooled. This is due to additives to the nuclear fuel that cause energy production to decrease when fuel temperature exceeds normal operation. This is referred to as "negative temperature coefficient fuel".

Figure 10.1: Illustration of U.K. Hinkley Point C nuclear power station.

What is the World's Safest Nuclear Fission Reactor?

If one wants to build reactors quickly, they would need to start with an existing commercial reactor, and then copy, or improve and then copy. One would not have time to start from scratch, or work with an experimental design.

To meet the satisfaction of the public, one would need to copy one of the safest nuclear reactors in the world, such as China's HTR-PM. Its fuel has the negative temperature coefficient feature, and its coolant is non-

radioactive helium gas. Subsequently, if coolant escapes, radiation does not enter the atmosphere. And if coolant disappears, the reactor does not melt down. Also, its containment chamber does not contain water, which means internal pressure from steam cannot rupture the chamber. Its fuel is considered safe since it does not react with air or water, and does not make them radioactive.

A variation of HTR-PM is HTR-PM600. This produces $0.66GW_e$ of power and if this was used to decarbonized 30% of U.S. electricity over 15 years, for example, one would need to build 16 of these each year for 15 years (($500GW_e$ x 30% / $0.6GW_e$) / 15yrs).

Cost Reduction via Commoditization

Currently, the cost of nuclear power in the U.S. and Europe is high due to designing, building and certifying one reactor at a time. Alternatively, building many identical systems would cost less.

Reduce Waste and Reduce Bomb Risk with Thorium Fuel

Initially, one might work with uranium-based fuel. However, one might also look at a developing machines that make thorium fuel. Thorium has less nuclear bomb proliferation risk and less nuclear waste.

The Four Pillars of Green Electricity

The primary ways of generating electricity without emitting CO_2 are solar farms, wind farms, hydroelectric dams, and nuclear fission power. Each of these involves challenges. For example, wind farms need windy land away from people, solar farms need cleared sunny land, and hydroelectric dams need sloped land with running water. Also, the output from wind farms and from solar farms is often deficient due to little wind or sun. And one must contend with "not in my backyard" (NIMBY), which is when communities resist nearby construction. Fission power also has challenges. However, a fission moonshot might be able to resolve these to the extent required by the public. To begin, one could establish a goal, pay for proposals that pursue that goal, and then fund those proposals. Initial development could be funded at almost any level since it cost little to do paper-only designs, calculate costs, and write more proposals.

11. Save the Planet with a Website

The petroleum industry favors handing "red meat" to Climate activists. In other words, enact ineffective decarbonization legislation so that Climate activists fight less. This only works if journalists and lawmakers fail to understand the costs and impact of proposed legislation. Unfortunately, this is exactly what happens since it is not well documented. This might seem absurd, because it is. However, this can be fixed, as we discuss in this chapter.

Calculating Cost and Impact of Proposed Climate Law

To calculate the effect of U.S. decarbonization legislation, one typically needs help from engineers at the U.S. Energy Information Administration (EIA) and the U.S. National Renewable Energy Laboratory (NREL). In theory, U.S. lawmakers can request a graph that shows projected U.S. CO_2 emissions, with and without a government initiative. The difference between the two is the effect of the initiative. A theoretical example is shown below.
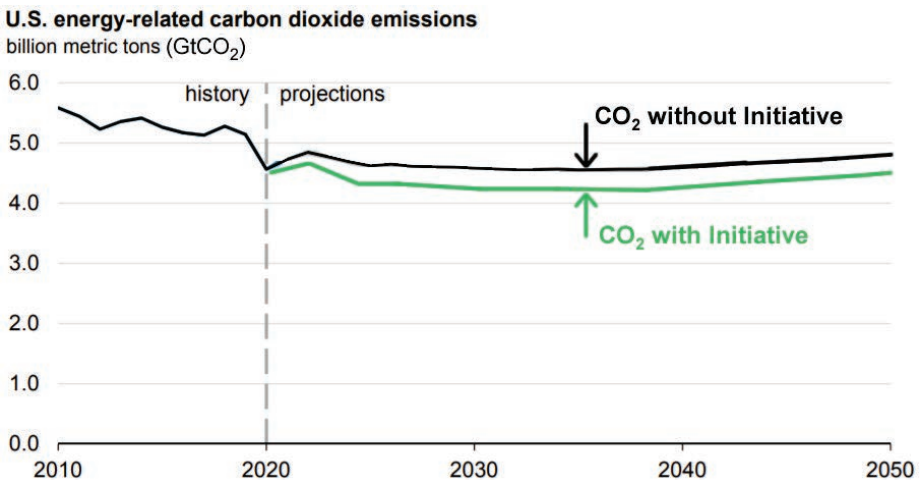
Figure 11.1: Conceptual projection of CO_2 emissions, with and without a decarbonization initiative.

The *difference* between the two plots is the amount of CO_2 reduced each year due to the initiative (e.g. $GtCO_2$/yr). And one can divide this difference by the cost of the initiative ($/yr) to calculate the cost to reduce emissions

by one metric ton of CO_2 ($/mtCO_2$). Also, one can divide cost ($/yr) by population to calculate cost-per-person-per-year ($/person/yr).

One can calculate cost and impact of many different initiatives. For example, "What happens when 5% of electricity is required to decarbonize each year?" Or 3% each year? In theory, multiple reports could identify how to get to zero at lowest cost.

Change the Climate with a Website

A website could potentially analyze different policies in different countries. For example, it could look at what happens when electricity is required to decarbonize at X percent-per-year at lowest cost, over Y years, in country Z. Anyone with a web browser could then specify X, Y, and Z and instantly see cost and impact.

A website could also support individual states and metropolitan areas. For example, state and city officials might want to see the cost and impact of different amounts of required decarbonization.

Calculation models already exist. For example, the U.S. government has a model called "NEMS", and it can be downloaded for free. However, website user interface, support for user input, support for different regions is lacking.

Trust is Required

Many models are not trusted and are subsequently ignored. However, much can be done to elicit trust. This includes: (a) building on top of existing models that are already trusted by government, (b) collaborating with government engineers, (c) requiring materials be made open source, (d) paying scientists to review models, (e) requiring reviews be made public, and (f) paying others to copy and improve.

Developing a trusted system might cost 10-times more than developing an ignored system.

Some Regions Make Money by Decarbonizing

Modeling different cities and regions is important since some make money by decarbonizing, and these need to be identified. For example, pipes that carry natural gas into the city of Boston, MA, USA are too small. And this

has created a regional natural gas shortage, which has increased the price of natural gas and electricity. If Boston decarbonized electricity, the local price of natural gas and electricity would decrease.

States that import carbon-based fuels would probably benefit from lower fuel prices, and are therefore more inclined to support the Green Line. The same is true with nations that import fuel. For this reason, it would be helpful to have websites that identifies cities, regions and nations that economically benefit from decarbonization. They would then be more inclined to decarbonize locally, and to form coalitions that support decarbonization.

Planet Saving Website

Below is an illustration of a website that calculates the cost and impact of a user defined climate strategy. This is not a real website, only a concept.

Figure 11.2: Conceptual illustration of website that calculates impact of decarbonization policy.

One might begin by modeling green electricity subsidies (e.g. subsidize green electricity by X ¢/kWh) and green electricity requirements (e.g. electricity is required to decarbonize at Y %/yr). And calculate cost of initiative, cost-per-person, CO_2 reduced, decarbonization cost ($/mtCO$_2$), natural gas price, coal price, savings-per-person due to cheaper fuel, number of carbon jobs-lost, number of green jobs-added, and locations of lost and added jobs.

The Green Line would be more feasible if voters had a better sense of cost-per-person and lawmakers had a better sense of how jobs-gained offset jobs-lost. Or in the case of regions that import fuel, how job-gained are local, and jobs-lost are elsewhere.

Creating databases, models, and simulations for many regions worldwide and many policy options would require hundreds or thousands of engineers. This might seem excessive. However, the alternative is to encourage people, companies and regions to decarbonize. And, as discussed previously, these entities rarely have the ability to do so at lowest cost. In other words, it is probably less costly to accurately model lowest-cost decarbonization, and have these models drive policy, than to operate blindly and pay more.

Also, high-cost decarbonization puts us at risk of paralysis due to fatigue, before achieving significant results.

12. Save the Planet with Money

Nations, foundations and individuals have expressed an interest in using their money to save the planet. However, what, where, and how to spend is often unclear. This chapter offers a few suggestions.

Build Planet Saving Website ($100K to $100M)

If one is looking to save the planet for $100K to $100M, consider building tools that calculate the cost and impact of proposed decarbonization laws. If interested, contact a university with a sustainability program, or a climate software company such as Energy Innovations. For details, see www.APlanToSaveThePlanet.org/study

Publish Planet Saving Book ($100K to $3M)

If one wants to spend several million dollars to save the planet, consider hiring a university to publish a plan for how to get to zero emissions. For example, MIT professors could potentially publish "MIT's Plan to Save the Planet". For free open-source materials used to create this book, see www.APlanToSaveThePlanet.org/open

Explore Large R&D Initiatives ($10K to $1M)

Hire researchers to write proposals for large R&D initiatives that are currently not being worked on, and could potentially have a significant impact. These could then be placed into an open-source business plan for a new R&D laboratory that tackles climate change at the lowest cost. Fifty proposals that cost $10K each would cost $500K total, for example.

Set up Decarbonization Laboratory ($10M to $10B)

Set up a decarbonization R&D laboratory. This could have almost any number of divisions, and each could potentially be funded to almost any level. For an example open-source laboratory business plan, see www.APlanToSaveThePlanet.org/lab

Produce "Climate Solution" Film ($300K to $10M)

Produce a documentary film, perhaps called "The Climate Solution", which explores politically feasible lowest cost decarbonization. Documentaries typically look at Problems. This instead would focus on The Solution.

PART TWO:
THE CLIMATE WAR

13. The Climate War

The fossil fuel industry and their suppliers support many people. However, they are not a majority and the majority of U.S. citizens want to decarbonize according to survey. Ultimately, we are looking at a political fight between "Carbon" and "Climate". They are both in an existential crisis. They are both fighting for their lives.

The primary participants on the climate battlefield are as follows.

Climate:	People concerned about climate change
Carbon:	Fossil fuel industry and their suppliers
Labor:	Labor unions and their workers.
Green Republicans:	Republicans who want to decarbonize

U.S. Climate Politics

National media often portray the climate war as a fight between those who want to decarbonize and those who do not. However, this is an oversimplification. The truth is more nuanced and is summarized as follows.

- Carbon interests spend significantly more money on lobbying and makes more political donations than Climate. The Sierra Club and their friends are small relative to an industry.

- An industry's political activity is backed by a profit model. In other words, they spend one dollar on lobbying and political donations, and get back more than one dollar in benefit. Climate's model is different. Their benefit is to someone else, far into the future. And they are not supported by an industry's revenue stream.

- Climate is not politically strong enough to fight Carbon by themselves. Therefore, they typically elicit help from Labor, who requires protectionism in return for their support. This leads to provisions that favor U.S. manufacturers over lower cost imports. Ironically, these increase CO_2 emissions when they increase decarbonization costs.

- According to a survey, 60% of Republican voters do not want to decarbonize. Therefore, Green Republican lawmakers cannot be too

vocal about their views. And they are a small group relative to the Democrats. For these reasons, they are rarely recognized.

- Republicans are not opposed to green electricity. For example, red states North Carolina ([47%](#)) and Arizona (45%) each produce more green electricity as a percentage of total than blue states Florida (16%), Nevada (23%), and Massachusetts (29%). The values in parenthesis refer to the percentage of electricity in each state that is generated without emitting CO_2.

- Politically liberal coalitions have formed most climate legislation. Subsequently, it contains many fiscally liberal provisions, and these are not accepted by fiscally conservative Republicans. For example, Green Republicans often do not support decarbonization measures that cost more than $50/mtCO_2$.

- Lawmakers from regions that produce coal or natural gas are not likely to support the Green Line due to the social and economic pain it would bring to many of their employers.

- Approximately two-thirds of the U.S. states do not produce natural gas and do not produce coal. Instead, they import fuel, and they benefit from low fuel prices. A coalition of Democrats and Green Republicans from these states could potentially decarbonize electricity at less than $50/mtCO_2$.

- Republicans and Democrats often do not get along. However, simple legislation is sometimes feasible when based on a common goal, and both sides are given veto power over each provision.

Carbon Blocks Decarbonization with Money

The five largest petroleum companies together spend [$200M](#) each year on lobbying to block decarbonization. Green organizations, like the Sierra Club, do not have this kind of money. And non-green Republicans who vote against climate remedies, for a variety of reasons, do not spend money to block Climate.

What does $200M buy? [Carbon wants Climate to believe](#) they are decarbonizing when they are not, to get them to fight less. To do this,

some climate remedies are enacted; however, they are watered down relative to what is needed. In the end, decarbonization is mild.

Figure 13.1: A portion of an oil refinery's vast revenue is often used to protect their financial interests.

Climate is a Small Monkey

Industries are politically powerful due to their vast wealth and large numbers of employees. Employees and their friends vote, while employees and their employers make political donations. To connect the dots, lobbyists suggest to lawmakers that donations and votes are contingent on support for specific measures.

Each industry is a political gorilla, while other groups metaphorically are small monkeys. The fossil fuel industry ("Carbon"), labor unions ("Labor"), automobile manufacturers ("Auto"), and groups of factories ("Manufacturing") are examples of political gorillas. And a group of non-profits that encourage decarbonization ("Climate") is the small monkey.

In theory, a monkey can jump on a gorilla's back and ride forward. However, in practice, the gorilla typically receives most of the benefit, while the monkey gets the crumbs.

The Alliance between Climate and Labor

To get IRA to pass, Climate put together an alliance with Labor. For this reason, much of the IRA helps Labor and ignores CO_2. For example, one provision cancels the $7.5K subsidy on electric vehicles made outside North America. Ironically, this *increases* CO_2 emissions since it blocks low cost EVs from entering the U.S.

Cheap Green Car

One can buy a small EV in China with a 250-mile range for $15K, an example of which is pictured below. If these were allowed into the U.S. with a $7K subsidy, final price would be $8K. And this would cause more families with two cars to consider having one gas muscle car and one light electric. Normally, Americans favor more car for more money. However, an $8K price would cause some to reconsider.

Figure 13.2: EV Dolphin (Atto 2) manufactured by China's BYD in 2021.

Protectionism

Many nations protect their domestic manufacturers from foreign-made goods. They do this with import tariffs, government subsidies for domestically manufactured goods, and regulations that block imports. These practices are commonly referred to as "protectionism". They reduce trade deficits, help domestic manufacturers, and help domestic Labor.

However, they also increase prices, increase inflation, increase interest rates, increase the risk of recession, hurt domestic consumers, and do not reduce CO_2.

The U.S. implemented little protectionism over the last several decades, and this made it easier for Americans to shop. However, the Trump administration increased protectionism with more import tariffs, and the Biden administration increased it with legislation like the IRA.

Protectionism is a form of trade warfare where a nation demands more access to foreign markets, in return for increased access to their own markets. In other words, nations occasionally agree to protect less with respect to each other.

Arrangements are codified in what are called Free Trade Agreements (FTA). As of 2022, the U.S. had FTA arrangements with 20 countries. This included Canada, Mexico, Korea, and Australia. However, it did not include China, Japan, India, and European countries.

Figure 13.3: Ships often carry hundreds of millions of dollars' worth of cargo, which effectively transfers wealth from one country to another.

The Chinese block many imports into China with regulations. And they often copy products designed by others. This drives the Americans crazy. In response, the IRA links electric vehicle subsidies to these practices. For example, EVs made with Chinese battery components will not receive U.S.

government subsidies, unless the Chinese soften their business practices, which is unlikely.

Figure 13.4: Relations between the U.S. and China are often tense.

The Easiest Way to Decarbonize Transportation

The easiest way to decarbonize U.S. transportation is to pick on a different industry to protect. However, this is not likely since Climate's political power is small relative to the combined strength of Carbon, Labor and Auto. If we use the monkey analogy, this would be like one small monkey overpowering several gorillas.

Figure 13.5: Industrial robots assemble automobiles at low-cost.

14. Carbon is Fighting for Their Lives

To better understand what is happening, one needs to take a break from Climate and explore Carbon.

The Unbearable Pain of Decarbonization

Decarbonization, by definition, would have a devastating impact on the fossil fuel industries, and their suppliers.

We are looking at replacing coal, natural gas and oil with green energy. Less consumption of carbon-based fuels would lead to excess fuel supply, which would lead to lower fuel prices. The combination of less quantity and less revenue-per-unit would have a devastating impact on the entire fuel supply chain. This includes exploration, extraction, refining, storage and distribution. In other words, decarbonization would cause companies involved in carbon, and their suppliers, to downsize.

Even the threat of fuel price collapse is enough to cause carbon companies to shudder. This is because they have lived it. They have lived through periods of low fuel prices and high. And they know low entails significantly less money in their pockets.

Also, if government enacted significant decarbonization legislation, Carbon's ability to borrow money would decrease immediately. For example, banks would reduce loans to build offshore drilling platforms, fearing those loans would not be repaid. And banks instead would lend to builders of solar farms and wind farms since long term demand for their product would be more likely.

Transferable Carbon Skills

If a petroleum company were a broadly defined energy company instead of a narrowly defined petroleum company, they might be able to maintain their revenue while the world moved from carbon. However, in most cases, petroleum companies do not have the equipment and expertise to compete against solar and land-based wind farm construction companies.

Petroleum companies do have some transferable skills. For example, carbon, capture and sequestration (CCS) is similar to natural gas extraction, processing and distribution. And offshore windmills are slightly similar to

offshore drilling platforms and their associated underwater infrastructure. However, CCS and offshore windmills are expensive relative to other decarbonization options, and are therefore in less demand at large scales.

Some laid-off oil workers might find themselves working at a wind farm, closer to home, and with better pay. However, many carbon workers would not see better jobs.

Our Changing World

Let's take a break from Carbon and talk about manufacturing.

Boston Dynamics recently demonstrated robots with dance moves more complex than the repetitive tasks performed by most factory workers. These robots are currently manufactured in low volumes and at high costs. In other words, they would cost much less if mass produced.
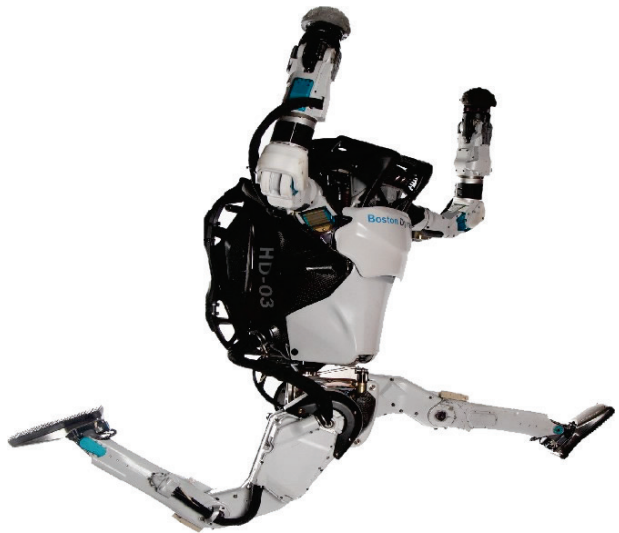
Imagine a $2K robot that operates for 5 years, works 160 hours a week, moves 3 times faster than a human, and has cameras that inspect more accurately. Now, compare this with a human factory worker making $10K a year. It will soon cost 10 to 100-times less to assemble by robot than human.

It was painful for many U.S. factory workers when they were replaced by international workers several decades ago. And it will be painful for many international workers when robots eventually replace them.

Our world is constantly changing. And this results in crisis for some, and opportunity for others. Energy is changing too, and its transformation will probably be as seismic as that experienced by manufacturing.

15. Fight Carbon with Regions That Do Not Produce It

We will now explore how some regions economically benefit from decarbonization. This is important since they are the ones that are likely to support real climate law. Decarbonization can be divided into three broad areas:

- **Electricity**: Generate electricity with solar farms, wind farms, hydroelectric dams and nuclear power plants; instead of generating electricity by burning coal or natural gas.

- **Transportation**: Power vehicles with green electricity, green hydrogen, or green ammonia; instead of gasoline or diesel fuel.

- **Heat**: Make heat in buildings and factories with green electricity or green hydrogen; instead of burning natural gas or coal.

Decarbonizing electricity tends to cost little, whereas decarbonizing transportation and decarbonizing heat tend to be expensive. Therefore, if one wants to reduce $1/30^{th}$ of emissions each year at lowest cost, they might first focus on electricity *while* reducing the cost of transportation and heat decarbonization via R&D.

Fight Carbon with Lower Fuel Prices

In some cases, decarbonizing electricity can save customers money even if the green electricity initially cost a little more than the carbon-based electricity.

The price of carbon-based electricity is largely determined by the price of natural gas and coal fuel. And fuel prices often decrease when fuel consumption decreases.

Let's look at an example to see how this might work. Let's assume a region starts out by generating 100% of its electricity with 3¢ (per kWh) natural gas, and 20% is replaced with 4¢ green electricity. Let's also assume that less natural gas consumption leads to price decreasing from 3¢ to 2¢. The resulting blended electricity ends up costing 2.4¢, which is less than the

original 3¢ ((20% x 4¢) + (80% x 2¢)). In other words, in some cases, one can save money when moving to greener electricity.

Fight Carbon with Regions that Import Coal

Coal is produced in a relatively small region within the U.S., as shown below in light blue.
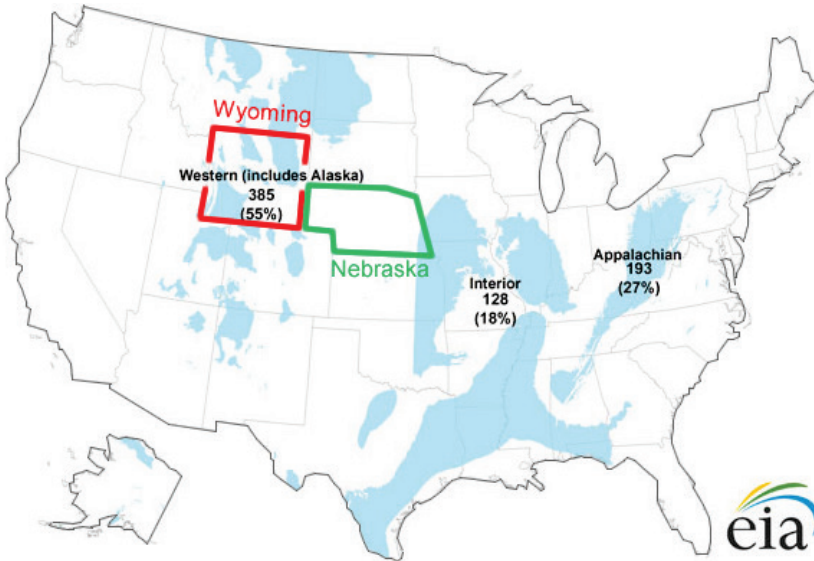
Figure 15.1: Sources of coal in the U.S.

Coal employs about 50K people in the U.S. and therefore has political power at the federal level, and at the local level within regions that produce it. However, coal does not have political power at the local level in non-producing regions (shown above in white). Subsequently, non-producers who consume coal *benefit* from a lower coal price. They also gain jobs if they replace coal-based electricity with green jobs. In other words, in many regions, decarbonizing coal results in green jobs being added locally while carbon jobs are lost elsewhere. And coal *importers* do not fear coal price collapse since it allows them to save money.

Wyoming, shown above in red, is an example of a coal exporter and neighboring Nebraska, show above in green, is an example of a coal importer. Wyoming employs 5K coal workers and Nebraska employs none. Therefore, Nebraska might be inclined to support decarbonizing coal, while Wyoming opposes it.

One can apply this logic to entire countries that import coal.

A website is needed that identifies cities, regions, and entire nations that save money and create local jobs when coal-based electricity is replaced with green electricity.

Fight Carbon with Regions that Import Natural Gas

One can apply the same logic to natural gas. Regions that import natural gas can potentially benefit from replacing natural gas based electricity with green electricity. The map below shows reserves of natural gas in the U.S. As one can see, many regions are importers of natural gas.
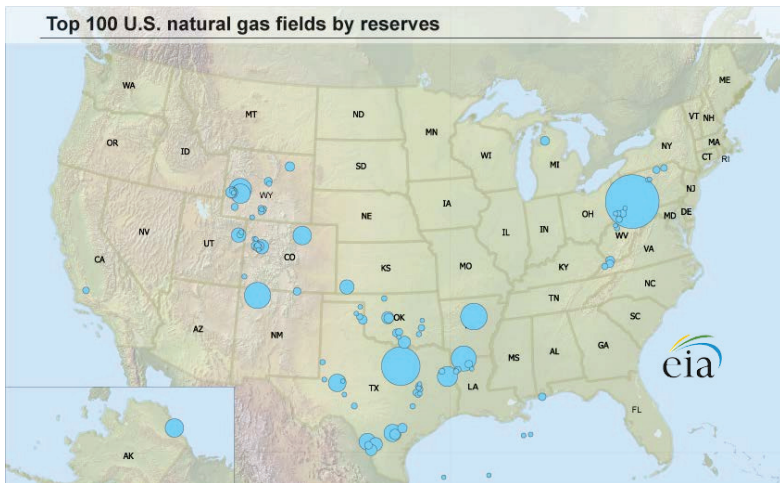
Figure 15.2: Locations of natural gas in the U.S.

U.S. Energy Politics

The U.S. produces approximately 1 trillion cubic meters of natural gas each year. This comes from approximately 25% of the states. This includes AK, AR, CO, LA, NM, ND, OH, OK, PA, TX, WV, and WY.

The U.S. also produces approximately 0.7 billion tons of coal each year. This also comes from approximately 25% of the states. This includes AL, CO, IL, IN, KY, ND, PA, TX, UT, VA, WV, and WY.

The following states control approximately two-thirds of the U.S. congress and they do *not* produce coal and do *not* produce natural gas: AZ, CA, CT, DE, FL, GA, HI, ID, IA, KS, ME, MD, MA, MI, MN, MS, MO, MT, NE, NV, NH, NJ, NY, NC, OR, RI, SC, SD, TN, VT, WA, and WI.

Do not Fight Oil while Fighting Coal and Natural Gas

If legislation focuses exclusively on decarbonizing electricity, it only needs to contend with natural gas and coal interests. And if it adds transportation, it also needs to contend with oil interests. Approximately 50% of the U.S. states produce oil, coal, or natural gas. And approximately 36% of the U.S. states produce coal or natural gas. Therefore, it is politically easier to tackle electricity today, and chew on transportation tomorrow. Also, this makes sense from an economic and technical perspective, since decarbonizing transportation entails getting the lifetime costs of electric vehicles to be less than that of gas cars. After this is achieved, markets would decarbonize transportation. And lower EV costs can be achieved with less protectionism, or a battery that lasts twice as long. Both are worth $10K to $20K, which is more than the current $7.5K subsidy on top of costly U.S. production. For details, see the "Cheap Green Car" chapter.

Consider Buying Coal

There are approximately 50K coal jobs in the U.S. and if this decreased to zero over 20 years, it would decrease 2,500 jobs each year (50K / 20). If states were awarded $100K for each lost coal job, to help them cope with their loss, this would cost $250M each year over 20 years (2,500 * $100K). In other words, each U.S. citizen might be able to pay $0.76 each year in return for decarbonization support ($250M / 330M population). Or, if this was not sufficient, pay coal workers $1M to walk away from their jobs, at an annual cost of $7.60 from each U.S. citizen over 20 years ($0.76 x 10).

Approximately 1 billion tons of CO_2 are emitted from the U.S. each year due to burning coal and if this decreased $1/20^{th}$ each year, CO_2 emissions would decrease 50M tons each year (1Gt / 20 years). One needs a 170M tonne per year reduction to do the Green Line. Therefore, this would constitute 30% of what is needed (50M / 170M). Or one might consider doubling this rate and do 60% of the Green Line each year at an annual cost of $15.20 from each U.S. citizen over 10 years.

In summary, consider buying coal.

16. Fight Carbon with Better Friends

The U.S. government passed the Inflation Reduction Act (IRA) in August of 2022, and several of its provisions reduce CO_2. The centerpiece entails a seven year extension of the ~1¢/kWh green electricity subsidy. This is implemented with tax credits that use government money to reduce the effective price of green electricity. This subsidy had been in place since 2006 and was scheduled to end in 2025. However, the IRA extended it to 2032, and also gave the U.S. Secretary of Energy the authority to extend it further to 2050. The IRA's extension does not affect green electricity from facilities built before 2026. However, it will reduce the effective cost of green electricity from facilities built after 2025.

The below Feb 2022 graph from EIA shows the number of solar farms and wind farms that are expected to be built each year over the next 30 years. This graph was published before the IRA was passed, and therefore does not reflect its impact. The height of each bar above the zero line reflects the amount of power generation built each year. Solar farms are shown in yellow, wind farms are shown in green, and natural gas based power plants are shown in light blue.
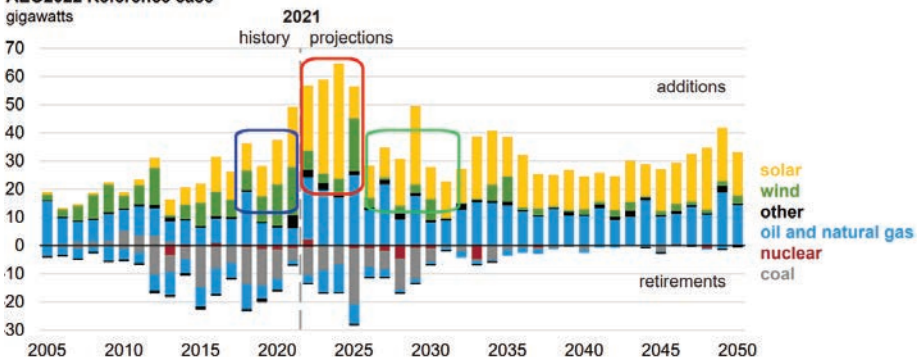
Figure 16.1: Projection of U.S. solar farm and wind farm construction each year over the next 30 years.

The above graph shows solar farm and wind farm construction decreasing after 2025 due to the expected expiration of the 1¢/kWh subsidy (i.e. the

area circled in green is less than the area circled in red). However, with the IRA's extension, this 2025 decrease is instead expected to occur sometime between 2032 and 2050.

The graph also shows green electricity construction *increasing* around 2021 (i.e. the area circled in red is larger than the area circled in blue). This was due to an increase in the cost of natural gas and coal fuel in 2021, and not from a subsidy increase. This fuel price increase made green electricity more affordable relative to carbon-based electricity. In many cases, fuel prices have a greater impact than subsidies, as discussed in later chapters.

As noted previously, the U.S. decarbonized electricity at 0.5% per year between 2017 and 2021, and the 1¢/kWh green electricity subsidy was in place during that time. This decarbonization rate is lower than what is needed; therefore, do not expect this subsidy by itself to solve the climate problem.

Can the Inflation Reduction Act be Improved?

If the entire 700 page IRA was replaced with the following sentence, more CO_2 would be reduced: *U.S. electricity is required to decarbonize at 6% each year over 9 years, at lowest cost.*

To improve the IRA, one might elicit help from fiscal conservatives who want to decarbonize. However, unlike Labor, fiscal conservatives are not fond of subsidies for U.S. companies. Therefore, if one gains support from some fiscal conservatives with fewer subsidies, they might lose support from other lawmakers who are close to Labor.

If subsidies were reduced to the extent required by Green Republicans, and the number of solar farm and wind farm workers were increased, then Labor might stay engaged. However, Labor is not looking for any job, or many jobs. They are looking for well-paying jobs.

Consider Buying Labor

In theory, one could increase wages at solar farms and wind farms in return for Labor's support of the Green Line. This could be done by several techniques, such as requiring workers be paid a prevailing wage.

Let's run the numbers to see how much this might cost the typical U.S. homeowner. Let's assume each house consumes 10,000 kWh of electricity

each year, 30% comes from solar farms, solar operations cost 1¢/kWh, 40% of this is labor, and worker compensation is increased 50% to get Labor's support. According to the math, this would cost each U.S. homeowner $6 per year (10,000 x 30% x 1¢ x 40% x 50%).

Labor Should Welcome Decarbonization

The IRA tries to soften the blow from declining oil jobs by creating new green jobs. It does this with subsidizes to U.S. factories that make solar panels and EV batteries. However, making solar panels in the U.S. instead of China does not reduce CO_2. Instead, government money would be more effective if it created jobs by increasing the number of solar farms and wind farms constructed each year. Workers are needed to build and maintain these facilities, and to build supporting power transmission lines.

To decarbonize at the lowest cost *and* meet the satisfaction of Labor, architects of climate legislation need to identify lowest-cost decarbonization projects (i.e. low $/mtCO_2$), and make sure new jobs receive a prevailing wage. To help with this, a website is needed that calculates job-gained and wages given different policy options. In other words, to keep Labor engaged, we need detailed reports on new jobs.

If it is Not Working for Both Sides, it is Not Working

There is a saying in politics, "If it is not working for both sides, it is not working". And this probably applies to Green Republicans and Democrats with climate change. Both want to decarbonize. However, if one tries to decarbonize without the other's support, provisions are likely to be watered down, and implementation is likely to be impeded. In other words, it is probably in both sides best interest to provide the opposing

side with veto power over each provision, and trust EIA to accurately score each initiative.

Decarbonizing the Easiest Way Possible

The easiest way to decarbonize the U.S. is probably to: (a) require increasing amounts of green electricity, (b) have consumers pay the additional cost, (c) let power company engineers get it done at lowest cost, (d) reduce subsidies to garner support from Green Republicans, (e) buy Labor, (f) buy Coal and (g) work with a coalition of lawmakers from regions that import carbon-based fuels.

Perhaps the Little Climate Monkey needs a New Girl?

As we discussed previously, the Climate Monkey has been dating the Labor Gorilla for several years now. And it is possible she is not good for him. She stays out all night with Auto executives and this is hell on his nerves.

Perhaps he would be better off with a new girl, such as Green Republicans? Perhaps she would let him have that cheap EV from China he has always wanted? Or perhaps he could date *both* Labor and Green Republicans, and keep them both calm with sweeteners?

In either case, the possibility of fuel price collapse would cause their Carbon Gorilla friend to go bananas.

In summary, resolving climate change is a tricky political puzzle.

17. Fight Carbon with Food

A homeowner might compare the cost of decarbonization with the cost of a warmer planet, and only be inclined to decarbonize if the warmer planet cost more.

Electricity Decarbonization cost-per-house

Already 40% of U.S. electricity is made without emitting CO_2. And if this increased to 100% using green electricity that cost 2¢/kWh more, for example, the additional cost per house would be $120 each year (2¢ x 60% x 10,000 kWh/house/yr). This assumes the price of carbon fuel remains unchanged.

Climate's First Harm

Now let's look which warmer planet cost first exceeds $120/year/house. One might think of this as *climate's first harm*. It is probably not sea level rise since that is expected later. And it is probably not more severe storms, since the odds of one's house being hit by a costly storm are low. We are already observing less water in rivers and reservoirs, in part due to climate change. And food prices are up, in part due to less water. Therefore, higher food costs might be climate's first harm. The canary in the climate coal mine.

Fight Carbon with Food

Warmer air leads to dryer land, dryer land leads to less food, and less food leads to higher food prices. And as mentioned previously, requiring decarbonization typically leads to higher electricity prices, at least initially.

In theory, a website could compare decarbonization costs with additional food costs, in a dryer world. And it could identify ways to spend money today, to reduce food costs tomorrow.

Let's look at an example to see how this might work. The average U.S. house spends $5,200 each year at the supermarket and if this increased by 20% due to dryer land, for example, additional cost would be $1,040 ($5,200 x 20%). Obviously, this is significantly more than the $120 per house to decarbonize electricity.

Water Shortages are Not Always Due to Climate

We sometimes see less water in rivers and reservoirs; however, this is not always due to climate change. For example, an increase in upstream agricultural production will likely lead to less water downstream. And more upstream farming could be caused by a variety of things, such as population growth. In other words, it is difficult to calculate how much climate change affects food prices. And if calculations are not done in an unbiased manner, they are likely to be ignored. To elicit trust, one can do a variety of things, as discussed in the "Save the Planet with Websites" chapter.

18. Fight Carbon with Better Information

Journalists often ignore decarbonization costs and ignore decarbonization scales when discussing climate solutions. Below are several examples.

Example #1: Electricity Vehicles

Approximately 2.8M EVs and Plug-in EVs were sold in the U.S. between 2010 and 2022. Each reduces CO_2 by approximately 3.6 tons a year; therefore, the total CO_2 reduction is 10 million tons each year (2.8M x 3.6t). The U.S. emits approximately 5 billion tons of CO_2 each year. Therefore, EV production over the last 12 years has only reduced it by 1/500th (10Mt / 5Gt).

The total cost of EV lifetime ownership has been thousands of dollars more than gas cars, partly due to replacement battery costs. If one divides this additional cost by the amount of CO_2 reduced, one can see hundreds of dollars for each ton of CO_2 reduced. This is much higher than many other decarbonization options.

Example #2: Green Electricity

According to NREL, U.S. electricity costs are ~3¢/kWh with solar farms and land-based wind farms, ~5¢/kWh with solar panels on commercial buildings, ~6¢/kWh with offshore wind farms, and ~9¢/kWh with solar panels on homes. In other words, some sources are cheap, and others are less so. These costs tend to decrease over time, but their ratios change little since the more costly sources are also more difficult to implement.

Consumers rarely buy a product at a high price when they can get it for less. Therefore, higher-cost options are less likely to scale up appreciably.

Misdirection to Make Money

Groups and individuals sometimes provide incorrect or incomplete information to make money. This includes: (a) companies that sell products or services, (b) special interest groups with agendas, (c) professors who promote research to increase funding, (d) shareholders who talk the talk to increase share price, and (e) entrepreneurs who raise capital. These biases

sometimes affect reports in national media, published papers, websites, and books.

Where Does One Go for Good Information?

The U.S. Energy Information Administration (EIA) and the U.S. National Renewable Energy Laboratory (NREL) are tasked with providing unbiased and accurate information. EIA's annual energy and emissions reports, NREL's data on electricity, and NREL's data on vehicles are all good sources of information. Almost all of the numerical data in this book was derived from these sources.

Prior to writing this book, Weinreb published 30 articles on climate solutions for decarbonization engineers. They need accurate and unbiased information to do their work, and therefore rely heavily on EIA and NREL.

19. China is at Climate's Center

China is at the center of the climate issue for multiple reasons: (a) they emit more CO_2 than any other nation in part due to making things for others, (b) their mass production of solar and wind power equipment has reduced green electricity costs significantly, (c) they developed HTR-PM, the safest nuclear reactor in the world, (d) they have built more nuclear reactors in the last five years than any other nation, (e) their nuclear reactors are likely to become the lowest cost way to decarbonize high-temperature manufacturing, (f) they are likely to become the largest supplier of equipment that makes green energy, and (g) they are likely to drive down the cost of decarbonization more than any other nation via factory mass production.

China Is Decarbonizing at the Pace of a Snail

China's CO_2 emissions keep going up, as shown below. This is in part due to their gross domestic product, which increases approximately 6% each year.

Figure 19.1: Annual CO_2 emissions from China.

In China, the amount of green electricity as a percentage of total increased from 29% to 32% over the last 6 years. In other words, China's electricity is decarbonizing at a rate of 0.7% each year ((32.6% - 28.9%) / 5yrs).

Alternatively, if China fully decarbonized its electricity over 10 years, for example, this increase would be 7% each year ((100% - 32%) / 10yrs)). China is decarbonizing electricity at the pace of a snail. And the U.S. is <u>not doing better</u>.

What Might Cause China to Decarbonize More Quickly?

As noted previously, warmer air leads to dryer land, dryer land leads to less food, and less food leads to higher food prices. Spending money today on greener electricity, in theory, could save money tomorrow in multiple ways, including lower food costs. There is a saying, "The key to a man's heart is his stomach." Perhaps this applies to climate change?

China experienced <u>severe droughts</u> in 2022, leading to low water levels in rivers and lakes. It is possible food shortages in China will worsen, partly due to climate change, and lead to more decarbonization. However, it is unclear when and to what extent this might occur.

Figure 19.2: Dried-up canal in a rural village on Lantau Island, Hong Kong, China.

California in the U.S. spends more money on decarbonization than any other U.S. state, in part due to daily images on TV showing low water levels in California reservoirs. Perhaps similar images on China's TV will have a similar effect.

PART THREE:
CLIMATE ECONOMICS

20. Green Electricity in the U.S.

The U.S. generates 22% of its electricity from coal, and 38% from natural gas. If these were replaced with green electricity (e.g. solar, wind, hydro), CO_2 emissions from all sources (e.g. cars, factories, electricity) in the U.S. would decrease approximately by 30% (1.5Gt / 5Gt).

Currently, 38% of U.S. electricity is already "green." This includes 19% from nuclear, 9% from wind, 6% from hydroelectric dams, and 4% from solar. However, if one looks at select states, they will see a different picture, as shown in the table below.

Region	Total GREEN	Nuclear	Hydro	Small + Utility Solar	Wind	Utility Solar	Small Solar
USA Total	38.4%	18.9%	6.3%	4.0%	9.2%	2.8%	1.2%
California (D)	50.2%	8.3%	7.4%	26.6%	7.9%	17.4%	9.2%
Texas (R)	32.6%	8.3%	0.2%	3.4%	20.7%	2.9%	0.5%
North Carolina (R)	46.9%	32.9%	5.8%	7.9%	0.4%	7.5%	0.4%
Florida (D)	16.0%	11.5%	0.1%	4.5%	0.0%	3.7%	0.8%
Nevada (D)	23.4%	0.0%	4.5%	18.0%	0.8%	15.8%	2.3%
Arizona (R)	44.8%	29.3%	5.4%	8.7%	1.5%	6.1%	2.6%
Massachusetts (D)	28.6%	0.0%	4.2%	23.3%	1.0%	9.2%	14.2%
New York (D)	54.3%	24.9%	22.3%	3.6%	3.4%	1.0%	2.7%
New Mexico (D)	36.8%	0.0%	0.5%	6.0%	30.3%	4.9%	1.1%

Figure 20.1: Electricity generation as a percentage of total electricity (Source: U.S. EIA 2021).

"Utility solar" typically refers to solar farms with greater than 1-megawatt capacity (≥ 1MW), and "small solar" typically refers to solar panels on buildings.

California is evenly balanced among solar, wind, hydro, and nuclear. They are also considering replacing their nuclear power with solar and wind power, which is feasible, to an extent. On the other hand, Massachusetts shut down its nuclear power plants without replacement and is, therefore, less green than average. In general, states strong in nuclear are also more green.

Texas and New Mexico rely heavily on wind power due to an ample wind supply far from buildings. New York relies heavily on hydroelectric power due to hydroelectric dams in Canada and Niagara Falls. Nevada and

California rely heavily on solar farms due to an ample supply of cleared, sunny unused land.

Approximately 70% of utility-scale solar power in the U.S. is generated by six states. Three of them lean to the political left (e.g. CA, FL, NV) and three lean to the political right (i.e. TX, NC, AZ). In other words, solar is popular with both the political left and right.

Figure 20.2: Solar farm and wind farm.

When homeowners generate their own electricity via solar panels, they are often compensated at the retail electricity generation plus distribution price. Subsequently, there is more incentive to install residential solar in states with high electricity prices. For example, Massachusetts and California residential electricity is approximately 60% higher than the national average (e.g. 23¢/kWh vs. 14¢/kWh, May 2021). This has driven Massachusetts residential solar to 14% of state electricity and driven California residential solar to 9% of state electricity. Both of these are high relative to the national average of 1.2%.

Local lawmakers can increase carbon-based electricity prices via a variety of techniques, such as creating a regional natural gas shortage by not

building pipes that carry natural gas. Some might consider this a good way to decarbonize. However, it is costly relative to other techniques. The lowest cost way to decarbonize is to require power companies to buy increasing amounts of green electricity and pass additional costs onto consumers. In other words, builders of solar farms and wind farms compete with each other to drive down costs.

U.S. Electricity Expansion During 2022

The below map shows *new* utility scale (≥ 1MW) power generation facilities that are expected to be completed in the U.S. between May 2022 and April 2023. The area of each circle is proportional to power output. Yellow refers to solar farms, green refers to wind farms, and tan refers to natural gas based power plants.

Figure 6.1.C. Utility-Scale Generating Units Planned to Come Online from May 2022 to April 2023
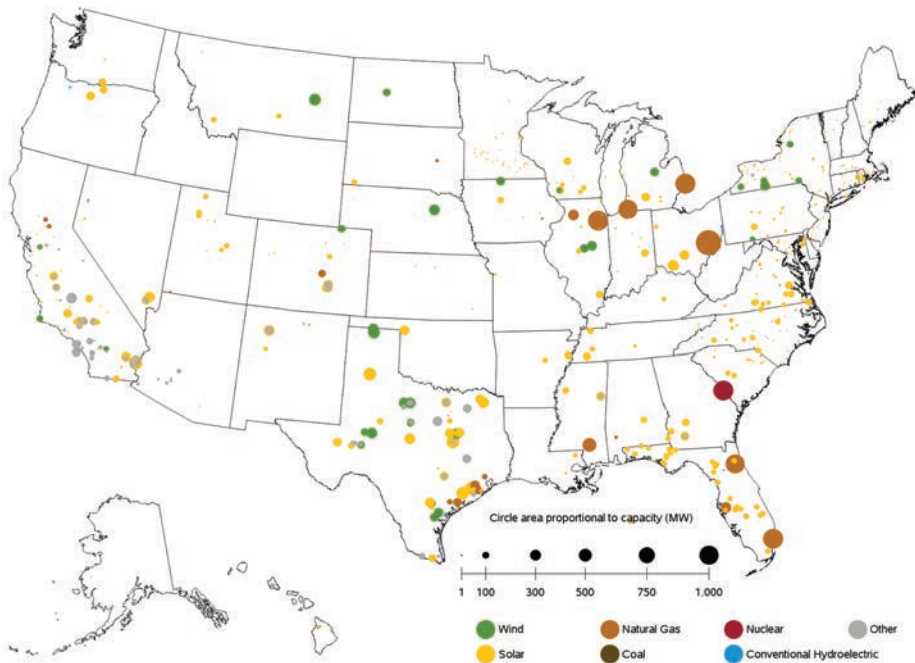
Figure 20.3: New utility scale (≥ 1MW) power generation facilities expected to be completed between May 2022 and April 2023.

Green Electricity Saturation

Green electricity saturation occurs when one discards electricity due to having enough. In other words, if electricity from solar, wind, hydro, *and* nuclear exceeds what is needed, the most costly source is typically asked to reduce output.

California is currently bumping into saturation, in part due to significant solar and wind capacity. In other words, California sometimes discards electricity from solar and wind farms when both sunny and windy, and when total electricity consumption is low.

Discarding some electricity is okay since it is often less costly to over-build solar or wind power with occasional discarding than to add battery storage.

One might reach saturation with a relatively small amount of additional solar if already significantly covered by wind/hydro/nuclear. Alternatively, one might be able to construct many solar farms before reaching saturation if only lightly covered by wind/hydro/nuclear.

Consumption Varies Throughout the Day, Week, and Year

The graphs below show how the consumption of electricity in the U.S. varies throughout the day, week and year. Consumption is lower at night and when outdoor temperatures require little heating or air conditioning (e.g. 75°F/24°C). Over a year, U.S. electricity consumption ranges between 320GW and 680GW; and averages 470GW.
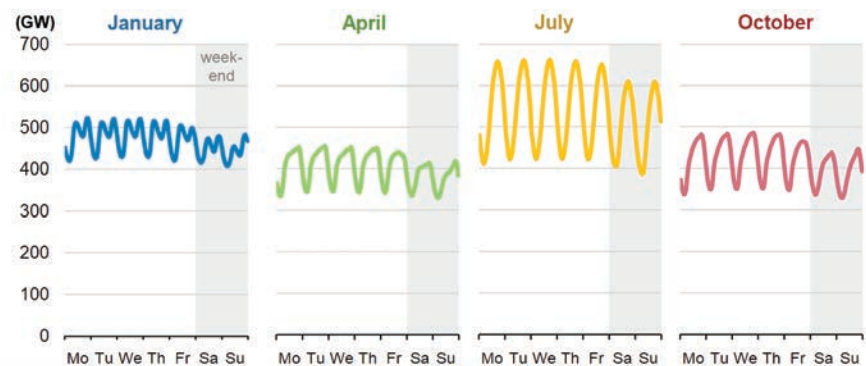
Source: U.S. Energy Information Administration, *U.S. Hourly Electric Grid Monitor*
Note: Data shown represent the average aggregate U.S. hourly load (Eastern Standard Time) by day of the week for the months indicated between 2015 and 2019.

Figure 20.4: U.S. electricity consumption during selected months.

Bumping Into Saturation

U.S green electricity *production* capacity is 410GW when solar power and wind power are at maximum levels. This includes 95GW from nuclear, 80GW from hydro, 98GW from solar, and 137GW from wind.

Alternatively, *consumption* at midday, during the spring and fall, is 450GW. In other words, the U.S. is close to saturation in the spring and fall, when solar and wind power are at maximum. However, the U.S. rarely meets all of these conditions at the same time.

Region	Electricity Consumption (GW)				Maximum Electricity Production (GW)				
	Summer Min Load	Summer Max Load	Spring Min Load	Spring Max Load	Total GREEN	Nuclear	Hydro	Small + Utility Solar	Wind
USA Total	420	650	350	450	410	95	80	98	137
California (D)	28	48	25	33	38	2	10	19	6
Texas (R)	37	63	29	40	52	5	1	11	36

Figure 20.5: Minimum and maximum U.S. consumption in spring and summer, and maximum green electricity production, in gigawatt units (Source: EIA Feb 2020).

If one looks at different regions, they are likely to see a different picture. For example, California and Texas are already bumping into saturation. California *consumption* at midday during the spring is 33GW, and maximum green electricity *production* is 38GW. Alternatively, Texas consumption at midday during the spring is 40GW, and maximum green electricity production is 52GW. This might seem encouraging. However, it is rare for wind to be at maximum, while sunny, while HVAC is off.

Figure 20.6: Windfarms in Texas occasionally discard electricity.
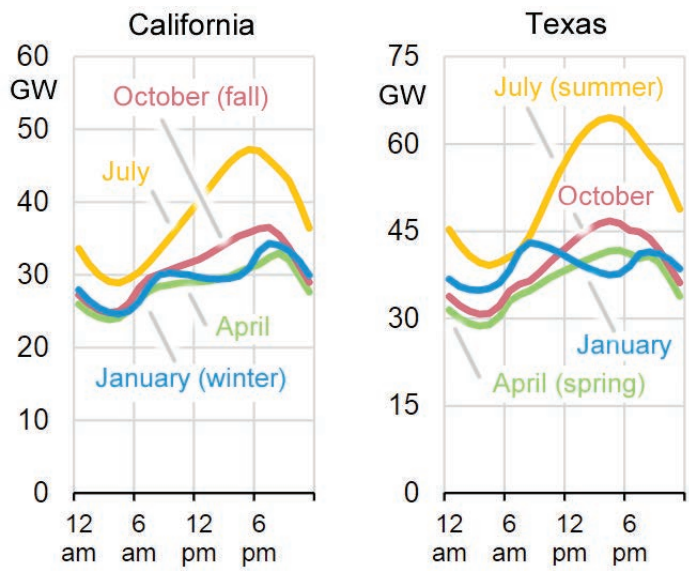
Figure 20.7: Total electricity consumption over a 24-hour period in California and Texas (Source: EIA Feb 2020).

Some Saturation Is OK

Saturation might seem wasteful; however, it is not as bad as it sounds. Let's look at an example case to gain a better understanding. We begin by assuming electricity from solar is 40% of the total, and 30% of solar power is discarded 25% of the time. The average U.S. home consumes 10,000 kWh a year, and if solar wholesale electricity generation costs 3¢/kWh, then discarding in this manner would cost $9 per-house-per-year ($0.03 x 10,000 x 40% x 30% x 25%).

Figure 20.8: Carbon-based electricity is not generated when renewables are in saturation.

A Day in the Year 2050

The graphs below show expected sources of electricity over a 24-hour cycle in the year 2050, in three U.S. regions. Solar power is shown in yellow, wind power is shown in green, hydroelectric power is shown in dark blue, nuclear power is shown in dark red, natural gas based electricity is shown in light blue, and coal-based electricity is shown in gray.

The West is expected to rely heavily on solar, wind, and hydro; with little storage. California is expected to rely mostly on solar and battery storage. And the Southeast is expected to rely mostly on solar, nuclear, and natural gas.
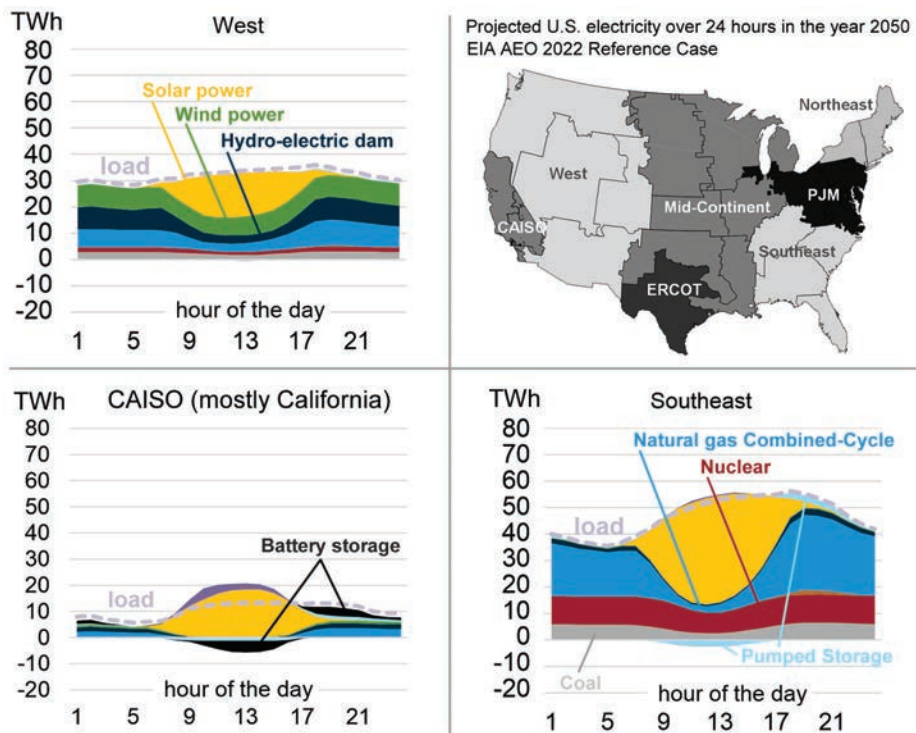
Figure 20.9: Projected sources of electricity over a 24 hour cycle in the year 2050 (Source: EIA Outlook 2022).

U.S. 30-Year Projection

The following graph is the official U.S. government projection for U.S. electricity over the next 30 years, based on economic and market behavior.
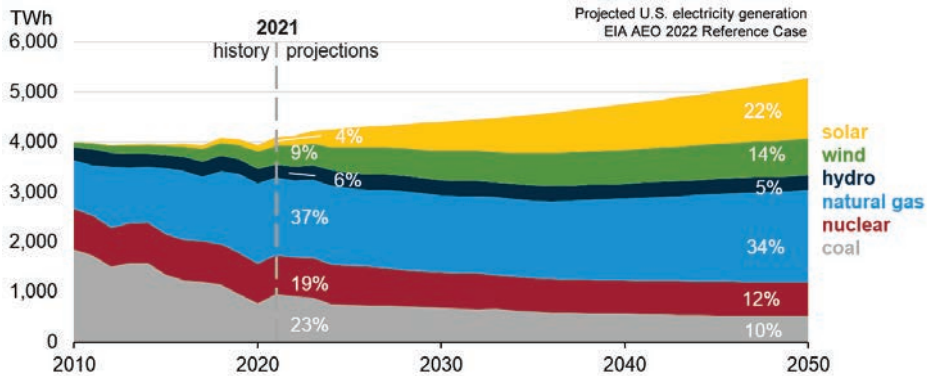
Figure 20.10: Projected U.S. electricity generation over the next 30 years (Source: EIA Outlook Feb 2022).

As one can see, electricity from natural gas is not expected to change significantly, and electricity from coal is expected to decrease approximately 2-fold. This is another way of saying significant decarbonization does not occur unless required by law, and this law does not exist.

Conclusion

Each region in the U.S. is looking at decarbonizing differently due to different resources and priorities. Solar and wind power are low cost. However, they are also intermittent, and this leads to multiple challenges. Decarbonization costs-per-person-per-year are often affordable, even with some saturation and some battery storage.

21. The Economics of Green Electricity

Reports often compare the cost of electricity from a new solar farm or a new wind farm, with the cost of electricity from a *new* natural gas or coal-fired power plant. However, this is not what happens. Instead, the carbon plant has already been built and paid for, and it burns less fuel when its electricity is *replaced* with intermittent green electricity. Also, the carbon plant is needed when the sun goes down or the wind stops blowing.

The Green Premium

Electricity made without emitting CO_2 is typically referred to as "green electricity." Example sources are solar farms, wind farms, hydroelectric dams, and nuclear power plants. Alternatively, carbon-based electricity is typically made by burning natural gas or coal.

The difference in the cost of the green option (which does not emit CO_2) and the carbon-based option is referred to as the "green premium." For example, if electricity from a solar farm costs 4¢/kWh and the natural gas fuel it replaces costs 3¢/kWh, the green premium would be approximately 1¢/kWh.

In some cases, 0.1 to 1¢/kWh is added to the cost of the carbon-based fuel to cover additional expenses (i.e. variable costs).

The green premium for solar and wind farms is typically between -1¢/kWh and +3¢/kWh. Negative values refer to green electricity that costs less than the natural gas or coal fuel it replaces. This is rare; however, it does occasionally occur due to fuel shortages that increase fuel prices.

The U.S. Southwest is Sunny and the Middle is Windy

The cost of fuel varies over time and place. Also, the cost of electricity from wind and solar power varies depending on the region since some are sunnier and others are windier. For example, the U.S. South West is often sunny, and the middle part of the U.S. is often windy. For details, one can refer to a Solar Map or a Wind Map, examples of which are shown below.

Figure 21.1: Average sunshine in units of heat energy-per-square-meter-per-day for a surface that constantly faces the sun.
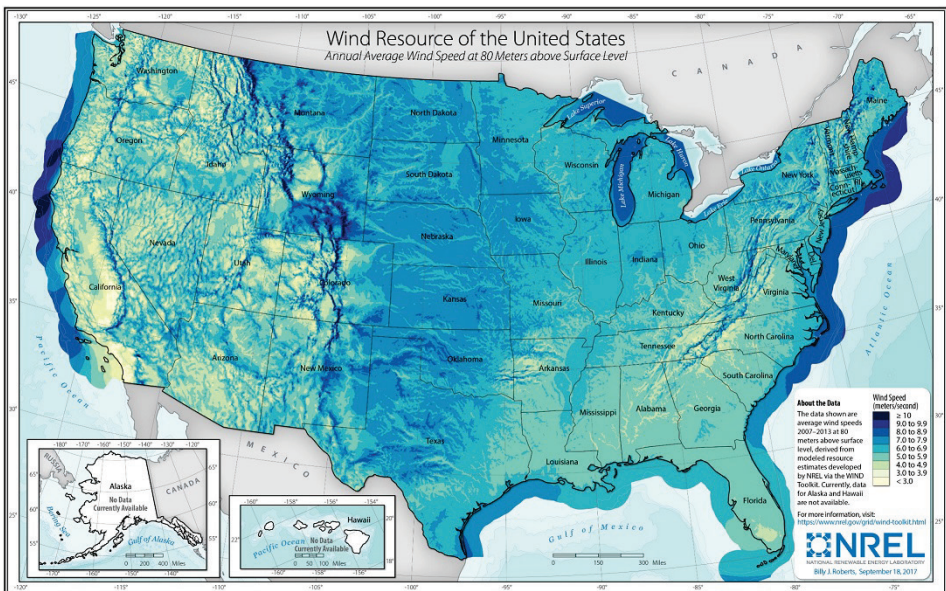
Figure 21.2: Average wind velocity at 80m above land in units of meters-per-second.

Green Premium Math

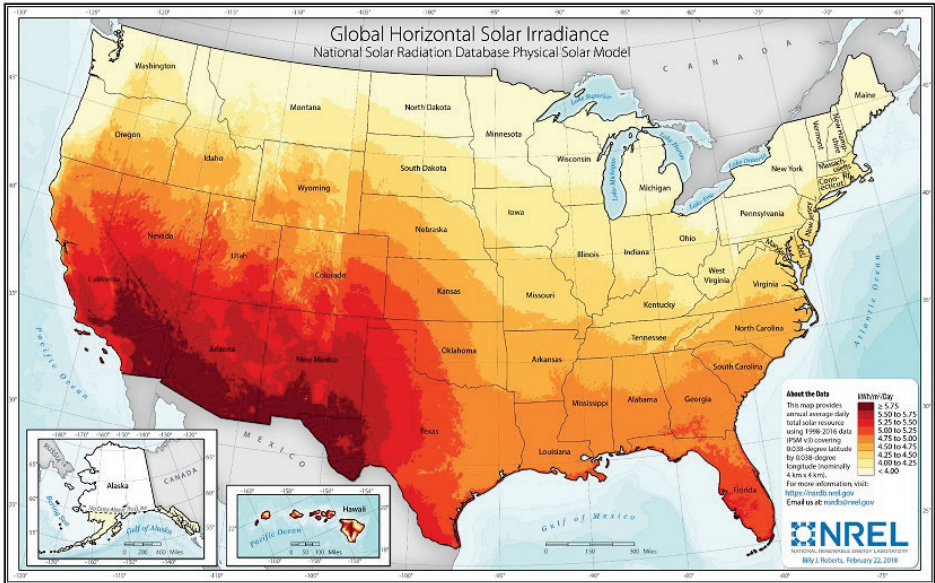The tables below show the cost of electricity from solar farms in green-color and the cost of carbon-based fuel in red-color. One subtracts a red-colored value from a green-colored value to calculate the approximate green premium. As one can see, the cost of electricity is less in sunny regions (i.e. more kWh/m^2/day).

Solar Farm Electricity Cost[1]

Resource Class	Heat Energy (kWh/m^2/Day)	Mean AC Capacity Factor	U.S. Area (sq. km)	2022 NREL LCOE Cost $0.01/kWh
1	> 5.75	33%	216,551	3.3¢
2	5.5–5.75	32%	349,894	3.4¢
3	5.25–5.5	30%	372,764	3.5¢
4	5–5.25	29%	497,444	3.7¢
5	4.75–5	27%	779,720	3.9¢
6	4.5–4.75	26%	870,218	4.1¢
7	4.25–4.5	25%	727,918	4.2¢
8	4–4.25	23%	828,438	4.4¢
9	3.75–4	22%	794,496	4.6¢
10	< 3.75	20%	163,120	5.0¢

Cost of Natural Gas fuel used to Generate Electricity[2]

($0.01/kWh)	2017	2018	2019	2020	2021
USA avg	2.6¢	2.8¢	2.2¢	1.9¢	3.9¢
Calif.	2.8¢	3.5¢	2.9¢	2.5¢	4.2¢
Utah	2.6¢	2.4¢	2.4¢	2.0¢	3.5¢

Cost of Coal fuel used to Generate Electricity[3]

($0.01/kWh)	2017	2018	2019	2020
USA avg	2.2¢	2.2¢	2.2¢	2.0¢

1) US, wholesale, no tax credits, includes $0.005/kWh for power wires., US NREL 2022, https://atb.nrel.gov/electricity/2022/index
2) US, wholesale, power plant already built, 44% eff. elect. gen., https://www.eia.gov/dnav/ng/ng_sum_lsum_dcu_SCA_a.htm
3) US, wholesale, coal delivered to power sector, EIA 2022, https://www.eia.gov/energyexplained/coal/prices-and-outlook.php

Figure 21.3: Cost of electricity from solar farms and carbon sources in units of U.S. cents per kilowatt hour (¢/kWh).

Also, one can do this with wind power via the tables below.

Wind Farm Electricity Cost[1]

Resource Class	Wind Speed Range (m/s)	2022 NREL LCOE Cost $0.01/kWh
1	> 9.0	3.2¢
2	8.8 - 9.0	3.4¢
3	8.6 - 8.8	3.5¢
4	8.4 - 8.6	3.5¢
5	8.1 - 8.4	3.6¢
6	7.6 - 8.1	3.8¢
7	7.1 - 7.6	4.1¢
8	6.5 - 7.1	4.6¢
9	5.9 - 6.5	5.4¢
10	0 - 5.9	8.1¢

Cost of Natural Gas fuel used to Generate Electricity[2]

($0.01/kWh)	2017	2018	2019	2020	2021
USA avg	2.6¢	2.8¢	2.2¢	1.9¢	3.9¢
Calif.	2.8¢	3.5¢	2.9¢	2.5¢	4.2¢
Utah	2.6¢	2.4¢	2.4¢	2.0¢	3.5¢

Cost of Coal fuel used to Generate Electricity[3]

($0.01/kWh)	2017	2018	2019	2020
USA avg	2.2¢	2.2¢	2.2¢	2.0¢

1) US, wholesale, no tax credits, includes $0.005/kWh for power wires., NREL 2022, https://atb.nrel.gov/electricity/2022/index
2) US, wholesale, power plant already built, 44% eff. elect. gen., https://www.eia.gov/dnav/ng/ng_sum_lsum_dcu_SCA_a.htm
3) US, wholesale, coal delivered to power sector, EIA 2022, https://www.eia.gov/energyexplained/coal/prices-and-outlook.php

Figure 21.4: Cost of electricity from wind farms and carbon sources.

The above green-colored values reflect the *wholesale* cost to generate electricity. When calculating green premiums, one can ignore *residential retail* prices since a difference can be calculated by subtracting two wholesale values. For reference, U.S. *residential retail* is typically 7¢/kWh for generation and 7¢/kWh for distribution (May 2021 EIA).

Figure 21.5: Wind farms typically generate electricity at a low cost.

Many nations use subsidies to lower the green premium. For example, the U.S. government subsidizes green electricity by approximately 1¢/kWh as of April 2023. This is helpful; however, subsidized green electricity still costs more than carbon-based sources when natural gas and coal fuel prices are low. The green-colored values in the above tables do not include subsidies.

If Texas is windy and Oklahoma is not, more power wires from Texas windmills to Oklahoma cities would be helpful. The cost of adding more wires typically ranges between 0.1¢ and 1¢/kWh. The green-colored values in the above tables include 0.5¢/kWh for more power wires.

In summary, green premiums in the U.S. typically vary between -1¢/kWh and +3¢/kWh when replacing coal or natural gas based electricity with solar or wind power.

Electricity Economics

The revenue at a carbon-based power plant is the sum of the following components: (a) fuel cost, (b) mortgage on the original construction, (c) fixed expenses that do not change when output power changes, (d) variable expenses proportional to output power, and (e) profit to the

owner. When a carbon-based facility reduces output power due to being replaced by green electricity, savings are mostly from lower fuel costs.

Consumers typically see an increase in the cost of goods and services when electricity prices increase. This is due to competition that pushes the price of goods and services down to approximately 8% more than costs. In other words, a company's profit is 8% of revenue, on average.

If the cost of wholesale electricity increased, one's residential electric bill would increase, as well as the cost of goods and services that consume electricity. Residential electricity is approximately 20% of all electricity.

Figure 21.6: Power plants burn natural gas to produce electricity.

Decarbonization Is Often Driven by Price, Not by Government

In many cases, CO_2 is reduced to save money, and not to reduce CO_2. For example, between 2005 and 2019, U.S. CO_2 emissions decreased by 0.86 billion tons (0.86GtCO$_2$/yr). One might think this was intentional. However, 70% of this was due to replacing coal with lower-cost natural gas. In another example, wind and solar farm construction surged in 2022, driven by high natural gas and coal prices.

Historically, markets have affected CO_2 more than government intervention.

Decarbonization Math ($/mtCO₂)

When replacing *coal-based* electricity with green electricity, the decarbonization cost is approximately $10 per metric ton of CO_2 avoided per 1¢/kWh of green premium.

Alternatively, when replacing *natural gas based* electricity with green electricity, the decarbonization cost is approximately $24 per metric ton of CO_2 avoided per 1¢/kWh of green premium.

For example, if green electricity costs 1.5¢/kWh more than the natural gas fuel it replaces, the decarbonization cost is approximately $36/mtCO₂ ($24 x 1.5¢ / 1¢). Or if green electricity costs 2.5¢/kWh more than the *coal* fuel it replaces, the decarbonization cost is approximately $25/mtCO₂ ($10 x 2.5¢ / 1¢).

Coal often costs less than natural gas; however, coal's CO_2 emissions are greater. Therefore, the cost to avoid a ton of CO_2 is often less when replacing coal, as shown in the below table.

Fuel Replaced	Decarboniza tion Cost ($/mtCO₂)	Green Premium ($/kWh)	Green Premium (¢/kWh)
Coal	$5	$0.005	0.5¢
	$10	$0.010	1¢
	$20	$0.020	2¢
	$30	$0.030	3¢
	$40	$0.040	4¢
Natural Gas	$12	$0.005	0.5¢
	$24	$0.010	1¢
	$48	$0.020	2¢
	$73	$0.030	3¢

Figure 21.7: Decarbonization cost ($/mtCO₂) is proportional to green premium ($/kWh).

22. The Economics of Green Heat

Decarbonizing electrical power generation can be done by building more solar, wind and hydro. However, high-temperature manufacturing still needs to be decarbonized. This entails making chemicals (e.g. hydrogen, ammonia) and making materials (e.g. plastics, metals, ceramics, glass, cement).

When creating high temperatures without emitting CO_2, the lowest-cost option is to use heat directly from a nuclear fission reactor. Unfortunately, the alternatives tend to be expensive (e.g. solar, wind, and hydro). Co-locating fission and manufacturing is currently not being done. However, if one is looking for lowest-cost high-temperature green manufacturing, this is probably it.

Nations averse to nuclear will probably import before building reactors at home. In other words, they will probably use solar, wind, and hydro to decarbonize their electricity; and use someone else's nuclear power to obtain green materials at the lowest cost.

Figure 22.1: Heat is often moved by pumping steam within pipes

China Is Comfortable with Nuclear Power

The amount of electricity produced by nuclear fission power in China doubles every 5 years, as shown below. China builds more nuclear reactors each year than any other nation and will probably be the first to export cheap green materials made directly with nuclear reactor heat. They are motivated to do this since it enables them to gain wealth via export.

Reference: World Nuclear News, 24 February 2020.
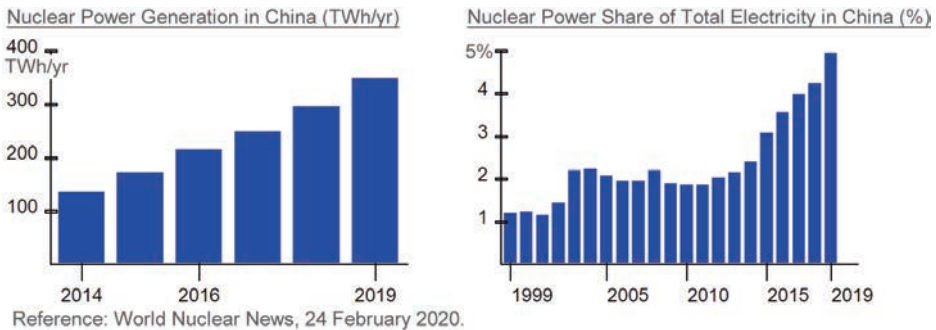
Figure 22.2: Nuclear power in China (Source: Wikipedia)

Does the U.S. or Europe Want to Compete in Green Heat?

Nuclear reactors in the U.S. and Europe cost three times more than that in China ($6K vs $2K/kW$_e$). If the U.S or Europe wanted to be more competitive, they could: (a) reduce the cost of fission via standardization, commoditization, and automated site construction, (b) improve fission with more R&D, and (c) accelerate fusion development with more money.

Heat Weights and Measures

Heat is often represented in units of gigajoules (GJ), and the cost of heat is often represented in units of dollars-per-gigajoule ($/GJ). Natural gas is typically priced in units of dollars per 1000 cubic feet ($/mcf), and coal in units of dollars per metric ton ($/mt).

How Much Does Heat Cost?

The two main sources of *carbon-based* heat are natural gas and coal:

- Heat typically costs $3 to $6/GJ when burning $3 to $6/mcf natural gas.
- Heat typically costs $1.5 to $6/GJ when burning $33 to $132/mt coal.

Sources of *green* heat include heat directly from a nuclear reactor and renewables (e.g. solar, wind, hydro):

- Heat direct from a nuclear reactor in China costs approximately $4/GJ and is similar to the cost of burning natural gas. Chinese reactors are often built one at a time. However, if manufactured in larger quantities, their costs would be less.
- High-temperature heat costs $8 to $16/GJ when created with 3¢ to 6¢/kWh green electricity via a direct heating element.

Heat Costs Are Mostly Driven by Fuel Costs

The following tables show the approximate cost of heat from burning natural gas and coal as a function of fuel cost. Also shown is the cost of heat from electricity as a function of electricity cost. As one can see, generating heat with electricity is often not competitive with burning natural gas or coal. The prices shown here are typical for large industrial customers.

	Cost Of Heat	Cost of Fuel	
Burn Natural Gas	Heat ($/GJ)	Heat $/mmbtu	Gas $/mcf
(1.03MMbtu/mcf)	$3.00	$3.17	$3.20
	$4.00	$4.22	$4.26
	$5.00	$5.28	$5.33
	$6.00	$6.34	$6.39

	Heat ($/GJ)	Heat $/mmbtu	Coal $/ short ton	Coal $/ metric ton
Burn Coal				
(21MMbtu/tonne)	$1.50	$1.59	$30	$33
	$3.00	$3.17	$60	$66
	$4.51	$4.76	$90	$99
	$6.01	$6.34	$120	$132
	$8.01	$8.46	$160	$176
	$10.68	$11.28	$213	$235

	Heat ($/GJ)	Electricity ($/kWh)	Electricity (¢/kWh)
Electricity to Heat			
(heating element)	$8.31	$0.03	3¢
	$11.08	$0.04	4¢
	$13.85	$0.05	5¢
	$16.62	$0.06	6¢

Figure 22.3: Cost of heat when burning natural gas, burning coal, and converting electricity directly to heat.

Low Utilization Is Expensive

It is costly to underutilize expensive factory equipment; therefore, a persistent energy source, such as a nuclear reactor, is often desired. Unfortunately, solar farms only provide significant power approximately 25% of the time, and wind farms only provide significant power approximately 40% of the time.

Figure 22.4: Industrial equipment is expensive and, therefore, prefers to operate 24 x 7.

Conclusion

In conclusion, high-temperate nuclear reactors in China are the lowest cost sources of green heat in the world. Therefore, nations averse to nuclear power in the future might not be competitive when making green chemicals and green materials.

23. The Economics of Green Fuel

A fuel is a compound that is typically used to (a) store energy, (b) transport energy, (c) produce heat via burning, (d) produce force via expansion, and (e) produce electricity via a fuel cell device. Examples of fuels are coal, gasoline, and natural gas.

To decarbonize, one needs fuels that do not emit CO_2 when made *and* when consumed. When fuels are *made* without emitting CO_2 they are referred to as "green." Making *green* fuels typically requires a green source of electricity (e.g. solar, wind, hydro, or nuclear) and/or a green source of heat (e.g. nuclear).

Co-Locate Nuclear Fission and Manufacturing

One can transfer heat from a nuclear reactor to a heat-driven process less than 1000 meters away via a pipe that carries a hot gas or a hot liquid such as molten salt. One can then use this heat to make things such as hydrogen, ammonia, chemicals, and materials. Co-locating nuclear reactors with manufacturing is typically not done; however, this might change due to cost. In other words, a nation that co-locates fission with green hydrogen and green ammonia production might dominate these markets due to lower costs. An illustration of this is shown below.
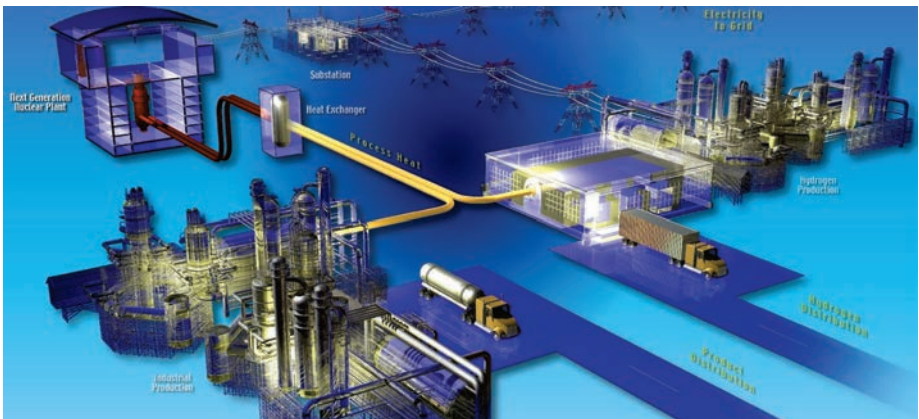
Figure 23.1: Illustration of nuclear reactor co-located with high-temperature manufacturing (Source: Idaho National Laboratory).

Why Hydrogen and Ammonia Are Important

A hydrocarbon is a type of fuel that only contains hydrogen (H) and carbon (C) atoms. Examples are oil, gasoline, and natural gas. When these burn, their carbon atoms bond with oxygen (O) from the atmosphere and form CO_2, a greenhouse gas. Subsequently, if one wants something that burns and does not emit CO_2, one needs a compound that does not contain carbon (C), such as hydrogen gas (H_2) or liquid ammonia (NH_3).

An "energy carrier" is a substance that transports energy from one place to another. The four big carriers of green energy are green electricity, piped green hydrogen gas, green liquid ammonia, and green heat in a pipe (e.g. steam or molten salt). To produce green energy carriers, one needs an energy source that does not emit CO_2, such as wind, solar, hydro, or nuclear power.

Hydrogen gas moves easily in a pipe, provided one has a pipe. However, it does not transport easily in a vehicle. Nor does it store easily due to its 700 atm pressure (10,000 psi) when compressed as a gas in a tank at room temperature, or its -253°C (-423°F) temperature when a liquid not under pressure. Electricity in large quantities does not store easily either. Therefore, if one wants low-cost green storage or low-cost transportation via truck, train, or ship, one might be looking at tanked liquid ammonia.

Ammonia is NH_3, which means it has three hydrogen atoms and one nitrogen atom. Adding and subtracting nitrogen atoms to and from hydrogen consumes energy and costs money. However, it is sometimes worth the effort due to easier storage and easier transportation.

Ammonia can be: (a) burned directly after being mixed with something more flammable, (b) turned into hydrogen after removing its nitrogen atom, or (c) pushed into an ammonia fuel cell to make electricity.

Liquid ammonia in a tank needs to be refrigerated to -33°C (-27°F) if under no pressure, or pressurized to 10 atm pressure (150 psi) if at room temperature. This is cumbersome; however, the world has much experience with ammonia since it is used to make fertilizer.

Figure 23.3: A rail tank car being filled with liquid ammonia.

Examples of green energy sources, carriers, and storage are as follows:

Green Energy *Sources:* Solar panels, hydroelectric dams, windmills, and nuclear power plants.

Green Energy *Carriers:* Green electricity traveling in a wire, green heat traveling as steam in a pipe, green hydrogen gas traveling in a pipe, and green liquid ammonia traveling in a pipe.

Green Energy *Storage:* Green liquid ammonia in a tank, green electricity in a battery, and hot molten salt in a tank.

Lowest Cost Green Hydrogen and Ammonia

If one converts one gigawatt (1 GW$_h$) of hot heat to hydrogen via a 56% efficient low-cost process (e.g. sulfur-iodine via nuclear reactor heat), one will get 0.56GW of cheap hydrogen. Alternatively, if one converts heat to electricity with a 42% efficient electrical turbine and converts electricity to hydrogen with a costly ~80% efficient process, they will get 0.33GW of costly hydrogen (42% x 80%). In other words, when making hydrogen, hot green heat (e.g. nuclear reactor) costs less than hot electricity (e.g. high-temperature electrolysis via nuclear reactor), and hot electricity costs less than cold electricity (e.g. low-temperature electrolysis via solar/wind/hydro).

After making hydrogen (H_2), one can add a nitrogen atom to make ammonia (NH_3) and then transport it to any location. Later, the ammonia

can be converted to hydrogen by removing the nitrogen atom, or the ammonia can be fed into an ammonia fuel cell to produce electricity.

Nuclear reactors in China cost three times less than nuclear reactors in the U.S. or Europe. Therefore, the lowest-cost way to make green hydrogen and green ammonia is probably a chemical process driven by heat from a nuclear reactor in China.

Figure 23.4: Nuclear power plant.

Why Is Lowest Cost Important?

Costs are important since consumers buy the lowest cost product, independent of where it is made or how it is made. In other words, if the lowest cost is made with China nuclear, consumers will buy it, even if they do not like China and do not like nuclear. This is consistent with economic theory and observed behavior.

A high-temperature fission reactor might produce 700°C; however, many processes need higher temperatures. For example, curing cement requires ~1400°C. The lowest-cost way to go higher is probably to pre-heat to 700°C with direct nuclear reactor heat and then go higher by burning green hydrogen.

Advanced reactors, such as HTR-PM in China, have uranium-based nuclear fuel that reduces energy output when nuclear fuel temperature exceeds normal operation, to the extent required to avoid melting when not cooled. In other words, newer and more advanced nuclear fission reactors are safer than older reactors.

Fuel Costs

Energy is often represented in units of gigajoules (GJ), and energy costs are often represented in units of dollars-per-gigajoule ($/GJ). Fuels can be converted to heat by burning (i.e. "combustion"). Therefore, one can think of their cost as the number of dollars needed to produce one gigajoule of heat when they are burned.

The upper third of the following table shows typical wholesale costs of existing carbon-based fuels. We are working with pre-COVID prices since they were more stable.

Type	Fuel	$/GJ	Cost	Conditions
Carbon-Based Fuel, USA, 2019	Gasoline	$16.38	$2.12/gal	USA, Wholesale, 2019, Pre-COVID
	Diesel	$14.37	$2.1/gal	"
	Ethanol	$25.76	$2.34/gal	"
	Crude Oil	$8.97	$1.25/gal	"
	Heating Oil	$12.75	$1.8/gal	"
	Natural Gas	$3.19	$3.4/mcf	"
	Coal, Anthracite	$2.09	$57/ton	"
	Electricity from Natural Gas	$11.11	$0.04/kWh	Electricity made with natural gas, USA, 2019
Green Energy Inside China	Green Heat, China, Nuclear*	$3.99	$4.21/mmbtu	Made with HTR-PM nuclear reactor ($2400/kW) in China, consumed ≤ 1000 meters from reactor
	Green Hydrogen, China, Nuclear*	$8.93	$1.26/kg	Made w/ HTR-PM nuclear reactor in China, delivered to China via pipe, sulfur-iodine (56%, $500/kW)
	Green Electricity, China, Nuclear*	$9.51	$0.034/kWh	Made w/ HTR-PM nuclear reactor in China, 24 x 365, 42% efficient turbine
Green Energy Outside China	Green Ammonia, Any Location*	$15.24	$0.66/gal	Made w/ HTR-PM nuclear reactor in China, delivered to any location via ship, Haber-Bosch (65%, $300/kW)
	Green Hydrogen, Any Location*	$18.29	$2.58/kg	Ammonia made w/ HTR-PM reactor in China, shipped to any location, and then converted to hydrogen.
	Green Electricity, Solar/Wind	$10.46	$0.038/kWh	PV Solar (25% availability) or land-based wind power (40% availablity).

*Still in development, cost is estimate

Figure 23.5: Estimated cost of select fuels in units of wholesale dollars-per-gigajoule (Calculations by Weinreb).

The middle third of the table estimates the cost of green energy made with nuclear fission power in China. This includes heat directly from the reactor, green hydrogen made by the reactor, and green ammonia made by the reactor. Manufacturing via direct nuclear reactor heat is still in development; therefore, these costs are estimated.

The lower third of the table estimates costs after green ammonia has been transported from China to any location. As discussed previously, ammonia can be consumed directly, converted to hydrogen, or converted to electricity. Also shown is the typical cost of electricity made by solar, wind, or hydroelectric power.

Fuel Reflections

Below are several comments based on the above data.

- The cost of heat directly from a nuclear reactor in China is similar to the cost of heat from burning natural gas or coal.

- Burning piped green hydrogen gas in China is not competitive with burning natural gas or coal in China.

- Green hydrogen gas outside China, made with green ammonia from China, is not competitive with burning gas or coal outside China.

- Green ammonia from China could be used to make electricity at any location via several different methods; however, this is not competitive with electricity from solar, wind, or hydroelectric power.

- Outside China, the cost of gasoline is similar to the cost of green ammonia made with China's nuclear reactors. Moreover, ammonia fuel cells that convert ammonia to electricity are typically twice as efficient as gasoline internal combustion engines. Therefore, green ammonia made in China could potentially compete with gasoline and diesel fuel outside of China. For details, see *How to Decarbonize Transportation (Power Electronics, Oct 2021)*.

Conclusion

In the future, green hydrogen gas and green liquid ammonia will probably be as important as today's natural gas and oil. Nuclear reactors are the lowest-cost way to make these green fuels. Therefore, nations will probably either: (a) import green fuel or (b) make green fuel locally after improving nuclear fission safety and reducing its cost.

PART FOUR:
15 R&D MOONSHOTS

- **Fusion**
- **Fission**
- **Cheap Green Car**
- **Building Automation**
- **National Solar/Wind Farm**
- **Custom Solar Skin**
- **Solar on Land**
- **Solar on Buildings**
- **Automated Power Tower**
- **Super-sized Transportation**
- **Next Generation Processing**
- **Earth Camera**
- **Direct Air Capture (DAC)**
- **Carbon, Capture & Seq (CCS)**
- **Decarbonization Planning**

24. Develop Super-Sized Transportation Systems

The photograph below shows industrial processing equipment that was built in a factory-like shipyard and placed onto a floating platform. This costs less than assembling in the field, especially if the factory is in Asia and the field is in Europe or the U.S.

Figure 24.1: Ship-mounted industrial processing equipment.

Next Generation Industrial Processing Transportation

Currently, there is no way to move ship-sized industrial processing equipment from a factory to a site. However, if we are looking for R&D to reduce green manufacturing costs, this might be a good time to explore new transportation systems, an example of which is illustrated below.
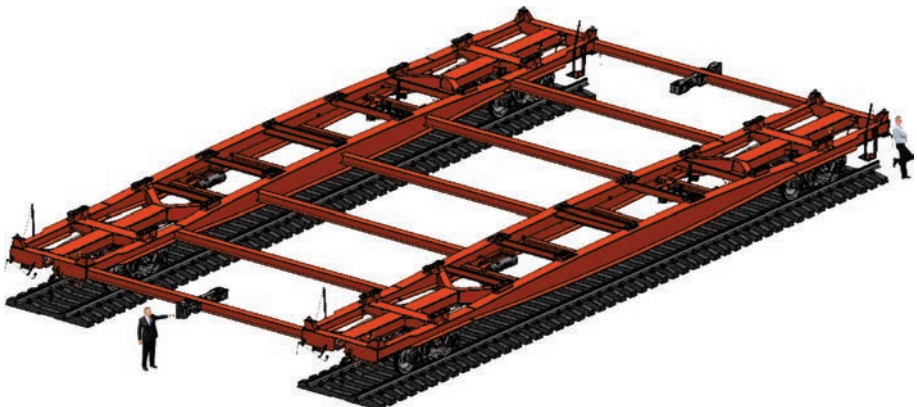
Figure 24.2: Super-sized 12 x 24m railcar (concept illustration by Weinreb).

Moving Large Platforms of Equipment from Factory to Site

The equipment on the ship in the above photograph is larger than one super-sized railcar. Therefore, engineers might place a truss on top of multiple rail cars, as illustrated below. In this concept, jacks between railcars and truss keep truss straight as train bends side-to-side and up-and-down. To get a sense of size, note the person in the lower-left corner.

Figure 24.3: Large platform of equipment transported on long straight truss (concept illustration by Weinreb).

Super-Sized Rail

In this concept, 12m by 24m railcars are mounted on double tracks 12m apart. These roll from a factory or shipyard to a dock at the water's edge, to a ship, to a dock near the site, and then to a site. The distance between the factory and the dock, and from the dock to the site, might be less than 10km (16miles) since this involves special track.

In some cases, one might rip up short segments of existing track and rebuild with a total of four tracks, two for existing trains, and two for extra-wide railcars, as illustrated below. Alternatively, one might have two tracks instead of four and use the same track for both local and wide traffic. However, this would require both sets to use the same rail gauge.

Figure 24.4: Traditional rail co-located with extra-wide rail.

Rolling between ship and shore is not new, as shown below. Ballast tanks align the height of a ship to the height of a shore.

Figure 24.5: Railcars transported by ship.

The illustrations below show how one might: (i) transport eight standard-sized containers on one railcar, (ii) transport 2-wide, 3-wide or 4-wide containers, (iii) transport bulk material such as iron ore in a bin, and (iv) transport equipment on a flat steel plate.
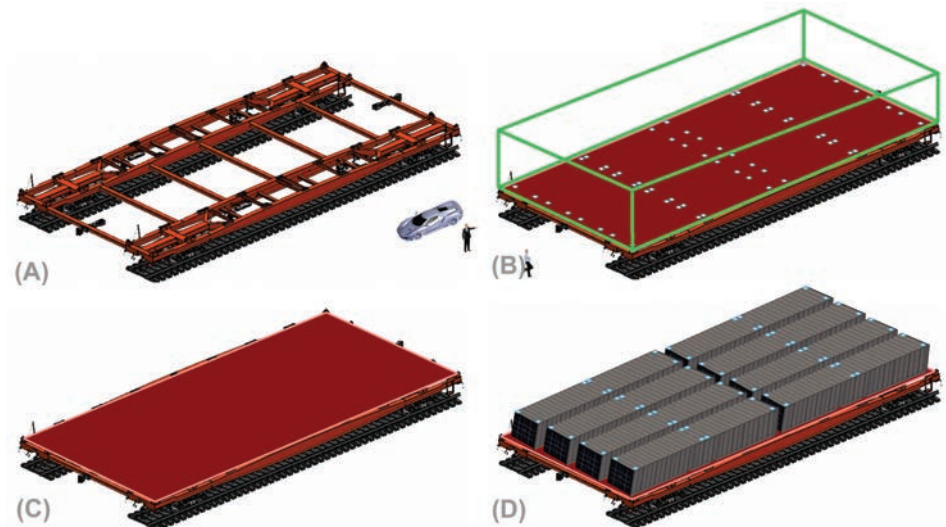
Figure 24.6: Super-sized railcar supports standard-sized containers (concept illustration by Weinreb).

A new transportation system that moves large and heavy objects would probably have a significant impact on industrial site design, manufacturing strategy, and total site cost. Also, it would cost little to do an initial paper-only design since rail, ship, and crane technology already exists.

25. Develop Next Generation Industrial Processing Systems

This chapter discusses how one might reduce the cost of high-temperature green manufacturing. This includes making green chemicals (e.g. hydrogen, ammonia) and making green materials (e.g. plastics, metals, ceramics, glass, cement).

Green Manufacturing at the Lowest Cost

As discussed previously, the lowest cost way to do high-temperature green manufacturing is probably to pump a hot working fluid from a nuclear fission reactor to nearby industrial processes, as illustrated in the previous chapter's first figure. This is not being done today; however, it might be done in the future.

The cost-per-gigajoule of green hydrogen made with a nuclear reactor would probably be 2 to 3-times higher than the cost-per-gigajoule of direct heat from the reactor. Therefore, nearby heat-driven industrial processes might utilize direct reactor heat, while faraway processes on the same continent might utilize piped green hydrogen gas.

Nuclear power is 3-times less costly in China than in the U.S. and Europe. And China is building nuclear reactors at a fast pace; therefore, the above concept would most likely appear first in China. However, an R&D laboratory outside of China might be inclined to work on nuclear heat-based manufacturing, to reduce global CO_2 emissions.

Standardized Green Site

If we extend the super-sized transportation concept further, the platforms eventually plug into a site, as shown below. In this concept illustration, multiple nuclear reactors provide heat (center) to 25 platforms of equipment (upper-left corner). Each platform might be on the order of 12m x 96m. Standards define how platforms communicate, connect mechanically and connect electrically. Site-wide efficiency is maximized by capturing unused heat and redirecting it to make electricity, make chemicals, and increase the temperature of thermal storage. Theoretically,

green heat sources include fission power, fusion power, concentrated solar (CS), and green electricity.
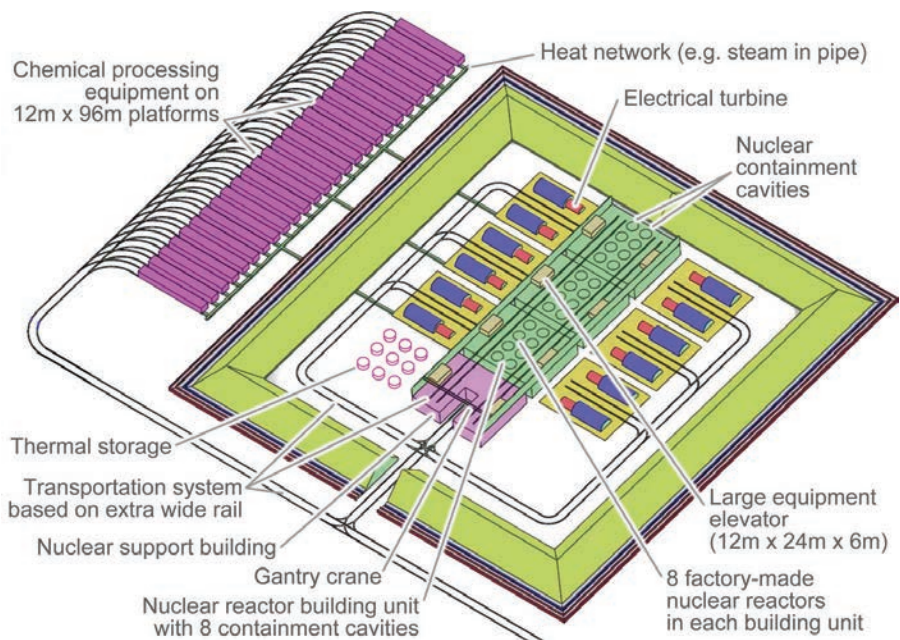
Figure 25.1: High-temperature standardized green manufacturing site (concept illustration by Weinreb).

Factory-Made Nuclear Reactors

Nuclear power in the U.S. and Europe is costly. However, if nuclear reactor equipment was mass-produced in a factory, it would cost less, especially if the factory was offshore.

If one extends the super-sized railcar concept further, one might envision a building that houses factory-made nuclear reactors that are transported by large railcar, as illustrated below. For details, see *How to Reduce the Cost of Nuclear Fission Power*.
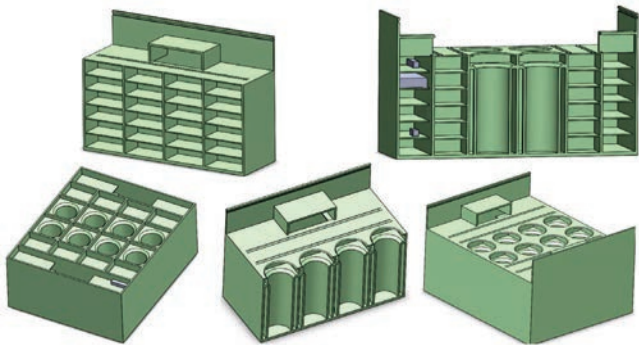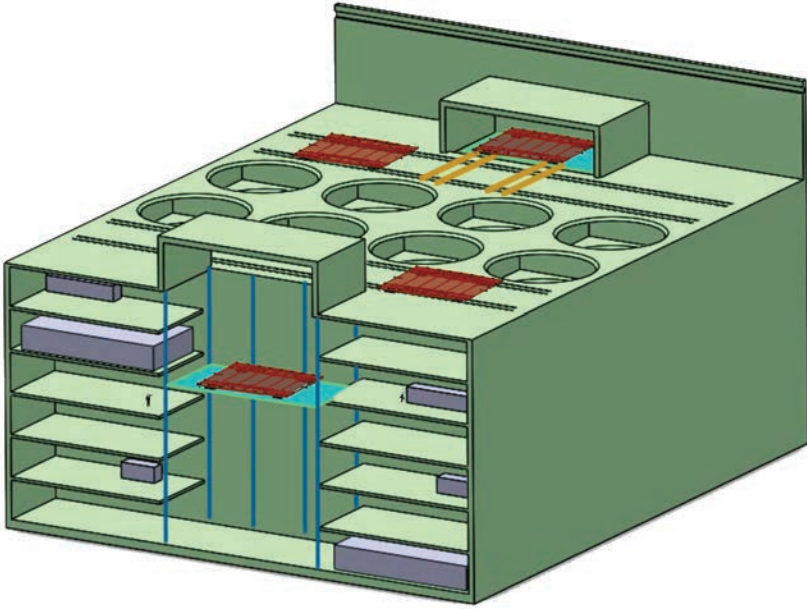
Figure 25.2: Building contains factory-made nuclear reactor equipment transported via extra-wide rail (concept by Weinreb).

Balancing Load and Recovering Waste Heat

If a nuclear reactor is used to make green electricity, make green hydrogen gas, and power heat-driven industrial processes, then tanks of molten salt could potentially help to balance loads. For example, if electricity demand was low, reactor heat could be stored in tanks of molten salt and used later when electricity demand was especially high.

Many industrial processes produce waste heat that is lost to the atmosphere. One would prefer to use it in some way; however, it is rarely at a convenient temperature and power level. For example, curing cement might need 1400°C at 10MJ/sec, while waste heat after generating electricity might be different. Tanks of molten salt could potentially help to synchronize multiple processes when using waste heat.

To reduce the cost of molten salt storage tanks, engineers could explore: (a) placing extra-wide rail next to tanks, (b) fabricating tank components in factories and transporting via extra-wide rail, and (c) automating tank assembly via machines mounted on extra-wide railcars.

How Might R&D Push This Forward?

Investment capital would probably consider the above concepts "too big," "too much risk," and "too many moving parts." The truth is, they are. If one component is missing, revenue is zero. How might R&D push this forward? Below is one possible approach.

- A government or foundation budgets $10M to $100M to develop next-generation high-temperature green manufacturing sites, standards, and supporting transportation infrastructure.

- The initiative supports multiple paper-only designs, simulations, simple prototypes of components, and proposals for more work. However, an actual site is not built. For that, one needs more money.

- Heat sources include nuclear fission, nuclear fusion, concentrated solar (CS), and green electricity.

- Engineers explore new transportation systems that move large platforms of industrial equipment between factory and site.

- Standards are developed that define how equipment connects mechanically, electrically, and in software.

- All scientists and engineers who receive money are required to make produced materials open source (e.g. software, designs, simulations, etc). Subsequently, anyone can view, copy, and modify at no cost.

- Transparency and open source are required since this is too big for one organization to build themselves. And companies typically cannot afford to develop interconnection standards used mostly by others.

Conclusion

Moving this forward might require a visionary leader who is willing to spend money on large next-generation systems. Someone like Elon Musk would be good. However, he is busy trying to leave the planet.

26. Develop Cheap Green Cars

U.S. government engineers at EIA expect CO_2 emissions from U.S. transportation to remain approximately constant over the next 30 years, as shown below. In other words, according to the U.S. government, the U.S. is not decarbonizing transportation.

Annual CO_2 emissions from U.S. transportation
billion metric tons
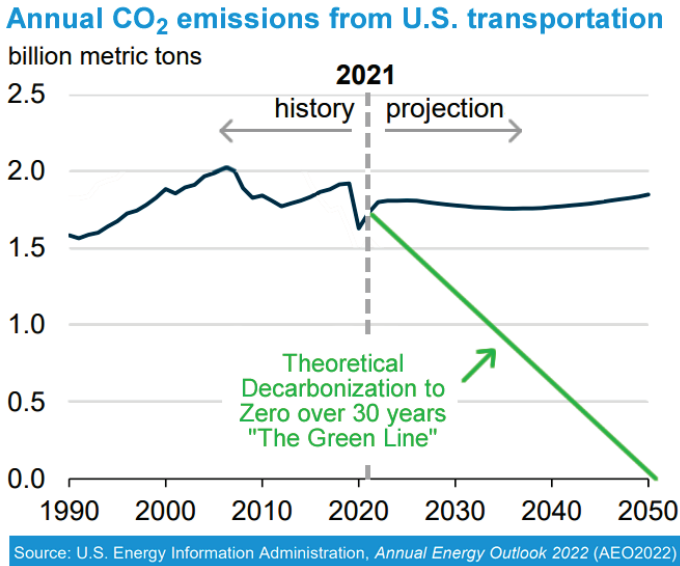
Figure 26.1: Projected annual CO_2 emissions from U.S. transportation.

As noted previously, consumers go green if required by law, or if the green option costs less. And EIA does not expect either with transportation. This is partly due to challenges involving: (a) rare earth materials, (b) fast-charging, and (c) grid decarbonization.

Decarbonizing Transportation for Real

A green line in the above graph shows what it would look like to decarbonize transportation at a constant rate over 30 years. To do this line, at least one of the following would need to occur: (i) reduce the cost of green cars to below that of gas cars via more R&D, more productive EV manufacturing, or more government subsidies, (ii) enact laws that require consumers buy green cars even if they cost more, or (iii) enact laws that allow cheap EVs to enter domestic markets. Also, if transportation is powered by electricity, the grid needs to be decarbonized too.

U.S. Transportation Politics

In 2010 the U.S. set up a program to reduce the effective cost of electric vehicles by contributing approximately $7.5K to each EV sold. For example, if the EV sells for $40K, the U.S. federal government pays $7.5K via reduced tax, and the buyer pays $32.5K. As one can see from the previous graph, this had little impact between 2010 and 2021. In other words, to decarbonize transportation for real, significantly more government intervention is needed. And this would probably require a coalition of lawmakers from regions that do not produce oil and do not manufacture gasoline-powered cars. In the U.S., there are not enough Democrats from these regions to form a majority. Therefore, one would probably need support from Green Republicans. And they would probably require a lowest cost approach.

Real Transportation Decarbonization via More R&D

There are 1,500,000,000 gas cars (1.5 billion) in the world, and if these were replaced with $20K cars that did not emit CO_2, the total cost would be 30 trillion dollars (1.5B x $20K). In theory, this justifies spending billions of additional dollars on R&D to make green cars cost less than gas cars.

Consider HEV for Quick Improvement

If one is looking to reduce CO_2 emissions quickly without spending money, consider government intervention that encourages gasoline and diesel-powered cars to include a tiny electric motor that improves fuel mileage by approximately 30%. This adds ~$1.5K to the initial price of the car; however, this additional cost is paid back within one to three years due to savings at the gas station.

Gas cars with tiny electric motors are referred to as "Hybrid Electric Vehicles" (HEV) and are often misunderstood due to having a name similar to "Plugin Hybrid Electric Vehicle" (PHEV). The plug-in cost ~$12K more than the gas car and has a large electric motor that enables it to run exclusively on electricity for 15 to 50 miles. Alternatively, the non-plugin HEV has a regular-sized gasoline engine. And it has a tiny electric motor and a tiny battery that recovers energy while braking and pushes the car while coasting. Most of the time, cars do not accelerate, and a tiny electric motor (e.g. 20hp) can maintain a constant speed.

In theory, government could require this tiny electric motor be added to gasoline engines in the next generation of each car. Car generations typically lasts 5 years. Or it could require improved gasoline mileage, which can be achieved with this additional hardware. For details, see *How to Improve Gas Mileage 25% to 50%* *(Power Electronics, Aug 2022)*.

Car Lifetime Costs

A vehicle's lifetime cost is the sum of the following components: (a) initial vehicle cost, (b) replacement battery cost, (c) repair cost, and (d) gasoline or electricity fuel cost. The typical car lasts 200K miles; therefore, one can divide lifetime cost by 200K miles to calculate the average cost-per-mile over a lifetime.

Most EV batteries are warrantied for 100K miles; therefore, one can expect to replace the battery at least once during a vehicle's 200K mile lifetime (100K x 2). Batteries typically cost $15K, and it is not clear how their costs will change over time since battery materials might become rarer and more costly as consumption increases.

EVs Cost less than Gas Cars When Gasoline Is Expensive

If the price of gasoline is high and the price of electricity is low, the lifetime cost of an EV could potentially be less than that of a gas car. Gasoline prices surged in 2022, and this caused EV sales to also surge. However, gasoline is not expected to stay high forever, as noted by EIA's graph at the beginning of this chapter.

It is easy to think the next 30 years will be similar to this year, and fuel prices will not change appreciably. However, government economists do not see it that way. Instead, they expect fuel prices to decrease when fuel production increases, or economic activity decreases.

The table below calculates the lifetime cost for both the Hyundai Kona electric vehicle and the same model with a gasoline engine. Also, it makes this comparison with different gasoline and electricity prices. As one can see, the EV costs less than the gasoline car when gasoline prices are high. For details, see *Car Costs and CO2 are Complicated* *(Power Electronics, Sept 2022)*.

Gas Cost ($/gal)	Electricity Cost ($/kWh)	Kona Gas Car Lifetime $	Kona EV Lifetime ($)	Difference ($)	EV Cost Less with 100K mi battery?	EV Cost Less with 200K mi battery?
$2.00	$ 0.10	$35,408	$52,681	$17,274	no	no
$3.00	$ 0.10	$41,562	$52,681	$11,120	no	yes
$4.00	$ 0.10	$47,715	$52,681	$4,966	no	yes
$5.00	$ 0.10	$53,869	$52,681	-$1,188	yes	yes
$6.00	$ 0.10	$60,023	$52,681	-$7,342	yes	yes
$7.00	$ 0.10	$66,177	$52,681	-$13,496	yes	yes
$2.00	$ 0.20	$35,408	$57,642	$22,235	no	no
$3.00	$ 0.20	$41,562	$57,642	$16,081	no	no
$4.00	$ 0.20	$47,715	$57,642	$9,927	no	yes
$5.00	$ 0.20	$53,869	$57,642	$3,773	no	yes
$6.00	$ 0.20	$60,023	$57,642	-$2,381	yes	yes
$7.00	$ 0.20	$66,177	$57,642	-$8,534	yes	yes
$2.00	$ 0.30	$35,408	$62,604	$27,196	no	no
$3.00	$ 0.30	$41,562	$62,604	$21,042	no	no
$4.00	$ 0.30	$47,715	$62,604	$14,888	no	no
$5.00	$ 0.30	$53,869	$62,604	$8,734	no	yes
$6.00	$ 0.30	$60,023	$62,604	$2,581	no	yes
$7.00	$ 0.30	$66,177	$62,604	-$3,573	yes	yes

* Conditions: 200K lifetime miles, $13K battery replacement cost, $23K gas car cost, $34K EV cost.

Figure 26.2: Lifetime cost comparison of gas vs. EV, with different gasoline and electricity prices (calculations by Weinreb).

Double the Lifetime of the EV Battery

Normally, EV batteries are warrantied for 100K miles and are replaced once during a vehicle's 200K mile lifetime. If battery longevity was instead twice as long, and replacement did not occur, EV lifetime costs would decrease significantly.

The second to the last column in the above table assumes the typical 100K mile battery is replaced once, and the last column assumes a 200K mile battery is not replaced. As of this writing, 200K mile batteries do not exist. As one can see, doubling battery longevity via R&D causes EVs to cost less than gas cars in the typical fuel price case. In other words, the easiest way to decarbonize transportation is probably to double the longevity of the battery. For details, see *The Little Secret of Electric Vehicles*.

Battery Fundamentals

There are different types of EV batteries, and one can characterize each type with several parameters. These include: (a) cost per unit energy, (b)

amount of energy stored per unit weight, (c) number of charge/discharge cycles over battery lifetime, and (d) fastest charging speed.

Shorter range helps one avoid difficult to obtain materials, such as cobalt. For example, the low-range Lithium Iron Phosphate (LFP) battery is cheaper than the Nickel Manganese Cobalt (NMC) battery, since LFP avoids cobalt. Sodium-ion batteries also trade range for cost by avoiding rare materials.

If one decreases energy stored per weight by a factor of two, and decreases the fastest charging speed by a factor of 16, then battery-system costs are likely to decrease by a factor of three or more. For example, a battery-system that supports a 125-mile (200km) range and an 8-hour fastest charging speed is likely to cost significantly less than a 250-mile (400km) system that supports 30-minute charging.

There are several reasons for this cost reduction, including a 16-fold decrease in power while charging (i.e. reduce size of charging hardware 16-fold), a 16-fold decrease in heat generated while charging, and a lower-cost battery chemistry.

Half the Car for Half the Money ("Cheap Green Car")

Currently, low-range EVs (e.g. ≤ 125 miles) are sold in the U.S. for $30K (e.g. MINI Electric Cooper) and are sold in China for $12K. These do not sell well in the U.S. since Americans are not comfortable paying $30K for half a car. However, they might pay $15K for half a car. At the right price, U.S. families with two cars might consider having one powerful car and one light electric. And individuals who rarely drive long distances might consider owning a light electric and borrowing more car as needed.

In theory, a nation could define a new automobile class, perhaps called the "Light Electric," and allow low-cost models to enter domestic markets. For example, it might have ≤ 125-mile range, ≥ 8 hours to fully charge, and ≤ 85 mph maximum speed. Alternatively, one might allow all automobile classes to enter domestic markets; however, lawmakers might consider that too disruptive. To push cheap green car forward, one would probably need a coalition of lawmakers from regions that do not produce cars or gasoline.

Can China's Cheap Green Car Slip Into the U.S.?

In theory, U.S. auto makers could rebrand China's 250-mile range BYD Dolphin EV. This sells for $15K retail in China and one can calculate the U.S. retail price required to maintain U.S. auto manufacturer and U.S. dealer gross profit. For example, if U.S. manufacturer gross profit per gas car is $5K, U.S. dealer gross profit is $4K, and China EV wholesale cost is $11K, then buyer's price would be $20K ($5K + $4K + $11K). This might seem promising; however, getting this to work politically and economically involves challenges:

- U.S. dealers and U.S. manufacturers might consider this acceptable. However, auto workers would have a different opinion. How easy would it be for them to find similar or better jobs? And how might government help them transition, to the satisfaction of the workers?

- Is it possible for the U.S. to decarbonize transportation via Chinese manufacturing while maintaining low levels of national unemployment via more jobs at solar farms and wind farms?

- How many Americans would pay $20K for a small EV with a 250-mile range?

- Would this EV's cost-per-mile be less than that of the comparable gasoline car?

Answering these questions and turning this into policy would probably require a model with a website user interface, and this does not exist. However, for relatively small money, it could be developed.

The Charging Problem

In the past, what did you see while glancing at fast charging stations? Did you see cars charging? In many cases, charging stations are underutilized.

The equipment cost-per-charge is determined by the equipment cost divided by the number of charges. Therefore, the cost-per-charge is high

when the number of charges is low. This causes fast charging to typically cost three times more than slow charging at home. This, along with charging inconvenience, causes EV owners to rarely fast charge.

The greatest challenge with fast charging cannot be seen. It is electricity. The typical 50kWh EV battery consumes 100kW of power when charging in 30 minutes (100kW x 0.5h). This is the same amount of power drawn by 80 U.S. homes on average. In other words, supporting large amounts of power is expensive, especially if the hardware is underutilized.

Charging stations are often located at shopping malls and hotels since they have plenty of power for air conditioning. This power can be redirected when the air conditioning is off. However, one still needs expensive electronics to convert grid AC power to battery DC power. And to reduce cost, this gear is often undersized. This leads to longer charging times, especially when multiple cars are charging at the same time. And this leads to more range anxiety since drivers often do not know how long it will take to charge since it depends on who else is charging, and air conditioning.

Swappable Battery

There is one way to resolve all of the problems alluded to in this chapter. It is a standardized plug-in swappable EV battery. Currently, the world has mechanical and electrical standards that define batteries, and these enable us to power many products at a low cost.

In theory, one could have a standardized car battery that looks similar to the Tesla EV battery, yet is used by multiple manufacturers. The standard would define the mechanics (e.g., height, length, and width), electrical connections, and communication between battery and car. This is not a new idea. For a video that discusses this, search "2-xwyscsvts" at YouTube.

Currently, proprietary batteries are built into EVs and are charged periodically. Alternatively, one could have a standard plug-in battery, wherein all cars use the same form, and swap with a fresh battery in less than one minute. Car owners would pay for electricity consumed and wear on the battery. And they
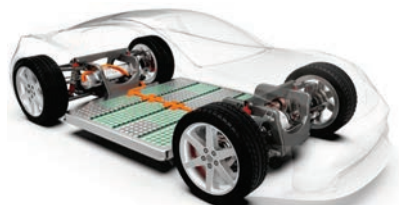
would pay less when using lower-range lower-cost batteries. Cavities would be dug out at key locations, and a mechanism that charges, stores, and swaps would be dropped in. Cars would position themselves over the mechanism and swap.

Those who drive less than 100 miles (160 km) per day could swap in a low-cost, low-range battery and charge at night. Cost reduction would occur because lower-range batteries use fewer rare Earth materials. For long trips, one could swap in a costly high-range battery or swap more often. Swapping would also reduce costs via commoditization since multiple battery manufacturers would compete and drive down price.

Homes could install swap chambers in their driveway with multiple batteries, as illustrated below. These could be charged by solar panels during the day, power the house at night, and swap with cars as needed.
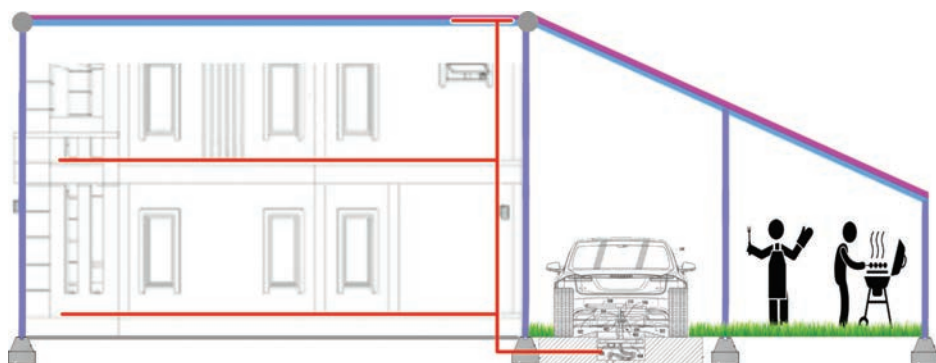
Figure 26.4: EV batteries in swap chamber power homes at night (concept illustration by Weinreb).

The downside is that swap would require a massive effort by automakers who would need to design vehicles around a swappable battery and construct new factories to make those vehicles. And the world would need to install millions of swap chambers at great cost.

To move this forward, a government or foundation could spend $10M to $100M to develop an open-source standardized swappable battery system to the point of simple prototypes. For details, see *Are we Ready for a Swappable EV Battery? (Power Electronics, Aug 2022).*

Ammonia Based Transportation

In theory, vehicles could be powered by liquid ammonia. However, making this work economically and technically would probably require billions of dollars of R&D. The car is the tip of the iceberg since the entire fuel supply chain is what determines the total cost. The entire system would need to be economically competitive with gasoline-based transportation in order for it to be accepted globally. This is theoretically possible via (a) green ammonia made with nuclear reactors in regions that are receptive to nuclear power, (b) fuel cells in vehicles that convert ammonia to electricity for motors, (c) automated refueling infrastructure that supports transferring multiple chemicals into and out of the vehicle, and (d) emergency response systems that handle ammonia failures.
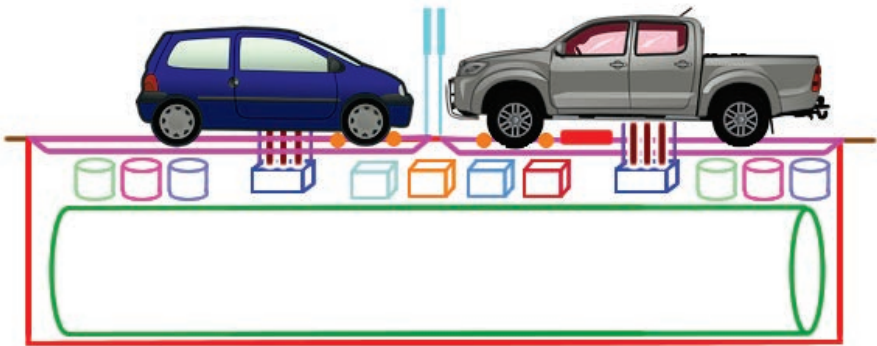
Figure 26.5: Automated refueling (concept illustration by Weinreb)

As discussed in the previous "Economics of Green Fuel" chapter, ammonia made with nuclear reactors in China is likely to cost approximately $15 per gigajoule of energy, and gasoline often costs more. And fuel cells are typically more efficient than internal combustion engines. In other words, ammonia-based transportation, cheaper than gas, is theoretically possible.

This might seem complicated, and it is. Also, battery-powered EVs is just as complicated, if not more so. Battery-powered EVs need to deal with decarbonizing the grid, the cost of rare earth materials as consumption increases, charging station economic viability, reducing EV costs below that of gasoline-based transportation, and providing convenience comparable to gasoline. And, as noted at the beginning of this chapter, engineers at EIA do not expect these challenges to be overcome.

In theory, a division within a decarbonization laboratory could be tasked with designing a global system that powers transportation with ammonia at the lowest cost and cheaper than gasoline. With a relatively small budget, one could do paper-only designs and build simple prototypes. For details, see *How to Decarbonize Transportation* *(Power Electronics, 2021)*.

Hydrogen Based Transportation

One could also have a division within a decarbonization laboratory that does the same with hydrogen gas based transportation.

If a country like China created hydrogen with nuclear reactors and fed the hydrogen into a pipe network within Asia they could power factories, heat buildings, and power vehicles. The hydrogen (H_2) would probably cost half as much as ammonia (NH_3) since adding and subtracting nitrogen atoms (N) to and from hydrogen (H) costs money.

Unfortunately, hydrogen has several disadvantages: (a) it probably requires a pipe network to be economically viable, (b) pipes do not easily cross oceans, (c) storing hydrogen in tanks is expensive, and (d) making hydrogen with renewables (e.g. solar, wind, hydro) tends to be expensive.

Consumers buy the lowest-cost product. Therefore, engineers who design a global ammonia or hydrogen-based transportation system would need to identify the lowest-cost approach in order for their work to be relevant.

Transportation R&D

One can decarbonize via brute-force or via R&D. The latter typically costs less. However, it is often not clear what, where, and how to develop. A decarbonization laboratory with a transportation division could potentially be helpful. Groups within the division might include: (a) design global well-to-wheels lowest-cost ammonia-based transportation system, (b) same but with hydrogen, (c) develop a swappable battery standard, (d) increase battery longevity to beyond the lifespan of the car ("kill the replacement battery"), (e) explore light electric vehicle category ("half the car for half the money"), and (f) explore requiring small electric motors in gasoline-based cars.

27. Develop a National Solar Farm

Approximately 3% of U.S. electricity is generated by solar farms, and this only increases by 0.5% each year. Unfortunately, this growth rate would need to be much higher if one wanted to decarbonize the U.S. within a reasonable period. Yet how might one increase this rate? Would it help to automate solar farm financing, construction, and maintenance with software?

This chapter explores these questions and discusses a potential concept which we refer to as the "National Solar Farm System" (NSFS). This does not exist. However, it could exist, perhaps after one to three years of software development. In summary, the NSFS oversees solar farm owners, investors, and customers.

- **Owners** build and maintain solar farms.
- **Investors** pay for solar farm construction in return for a portion of electricity revenue.
- **Customers** buy electricity generated by solar farms.

Participation in NSFS would be optional. In other words, solar farm owners would either operate traditionally or within NSFS.

Figure 27.1: Large solar farm.

Solar Bonds

When a government builds a highway for automobiles, it typically: (a) issues bonds to fund construction, (b) uses toll revenue to pay bond holders, and (c) allows bonds to be traded. The value of a bond is typically the sum of its expected future payments, discounted by inflation. A national solar farm system would be similar. The initial bond would pay for solar farm construction, electricity revenue would support dividend payments to bond-holders, and bonds could be traded.

Figure 27.2: Illustration of solar bond. This is not a real product.

Individuals would register at a website, transfer money to their account, buy solar capacity within the system, receive money based on electricity sales, and sell solar capacity with the click of a mouse.

Each share would be referred to as a "solar bond," and each bond might be economically equivalent to a 300W solar panel. If this were the case, each bond would sell for approximately $336 due to typical solar farm parts and labor cost of $1.12-per-watt ($1.12 x 300W).

Financial Requirements

To get this to work economically, the system would need to meet the following requirements:

- The rate of return to investors would need to be similar to or greater than that offered by traditional bonds for the same level of risk. In other words, investors would not participate if solar bonds were not competitive with other investment opportunities.

- Electricity would need to be priced at its cost plus a reasonable profit to the solar farm owner. Otherwise, if the electricity price were too high, electricity customers would seek alternatives. And if too low, solar farm owners would not participate.

Tension between Investors and Customers

The green option often costs more than the carbon-based option. Therefore, to decarbonize, government subsidies need to close the gap, or new laws need to require customers to buy green and pay a higher price. As noted previously, the price difference between the green option and the carbon option is commonly referred to as the "green premium."

Both investors and electricity customers need to be kept happy; otherwise, neither will participate. A dollar saved by the electricity customer is approximately one dollar less received by the investor. Therefore, to get this to work economically, competition among solar farm owners would need to drive down costs and drive down electricity price, and investors would need to see a competitive return on their investment.

Risk Is as Important as Price

What is the probability that a solar farm owner buys junky hardware, promises a low price due to lower costs, and has the hardware fail prematurely? The result would be reduced dividends to investors due to less electricity revenue. Yet, more importantly, other investors would see this and be less likely to participate in future NSFS projects.

What is the probability that a farm owner promises a low electricity price to be competitive and uses money from future projects to pay for past projects? This is referred to as "Ponzi Scheme."

Unfortunately, the probability of these problems is high unless a mechanism is in place that blocks each. Suppose one has a market with 100 suppliers, and 10 of them are Ponzi or favor junk, either wittingly or unwittingly. These 10 are more likely to win contracts due to quoting lower prices or quoting higher returns to investors. In some markets, the honest and competent engineer finishes last. In other words, the risk of Ponzi and the risk of junk need to be controlled.

Transparency Enables One to Control Risk

The enemy of Ponzi and the enemy of junk is transparency. If all information is disclosed, risk and returns can be calculated more accurately.

There are two types of transparency, technical and economic. Technical entails publicly reporting solar farm design, lists of components, amount of electricity produced, solar panel efficiency vs. time, and technical failures. Economic transparency entails publicly reporting equipment costs, maintenance costs, and electricity revenue.

To get the NSFS to work economically, at large scales, it might need to be transparent. In other words, designs with known performance might need to be made public, so that they can be easily copied and improved.

The probability that an investment fails is referred to as "risk." And if one can reduce risk, one can reduce the rate of return demanded by investors and therefore reduce the price paid by electricity customers. In other words, risk is somewhat proportional to electricity price. If risk goes down, electricity price goes down too. Also, transparency reduces risk. Therefore, transparency reduces electricity price.

Some solar farm owners might be uncomfortable with transparency and avoid NSFS. However, others might find it acceptable, especially if they can copy what works, have it perform as expected, and easily access capital.

Investors might favor NSFS over traditional options due to transparency and additional oversite. However, NSFS would be unpopular if it did not function properly for a variety of reasons, such as buggy software.

Solar Farms within the System

The NSFS oversees multiple solar farms, each of which has an owner and one or more customers. Before a solar farm is built, the owner would submit an application that includes a technical plan and an economic plan. The technical plan would include the technical design and list of components. And the economic plan would include expected equipment costs, maintenance costs, etc. Owners could copy proposals from existing solar farms or expand existing farms. The NSFS organization would estimate risk, estimate the cost of capital, and introduce electricity

customers to farm owners. Projects would not be funded unless the owner had a customer that agreed to an electricity price.

The NSFS organization would take care of financing by selling bonds through an automated system. To diversify risk, multiple solar farms would be put together into one bond issue. In other words, a bond-holder might own a small piece of dozens of solar farms. Subsequently, if one farm failed, consequences would be minimized. The NSFS computer would keep track of revenue from each farm and calculate who gets what.

The Solar Commissioner

The system would be overseen by a Solar Commissioner whose first priority would be to represent the interests of the government, second priority would be to represent the interests of investors, and third priority would be to represent the interests of electricity customers.

As mentioned previously, government wants a decent number of solar farms constructed each year, investors want to maximize their return on investment (for a given level of risk), electricity customers want to minimize price, and solar farm owners want to maximize profit.

The NSFS would oversee the following kind of process:

1. Government sets the minimum amount of solar farm capacity built each year.

2. Commissioner sets investment rate-of-return, for a given level of risk, sufficient to the raise money needed for step #1.

3. Commissioner gathers proposals from potential owners to build solar farms.

4. Commissioner estimates a variety of parameters, such as risk and investor rate-of-return, for each proposal.

5. Commissioner helps establish electricity purchase agreements between solar farm owners and wholesale electricity customers.

6. Commissioner sells solar bonds to pay for new construction.

7. The NSFS computers monitor performance, failures, electricity generated, and revenue.

Calculating expected risk (i.e. probability of economic failure) and expected rate-of-return (i.e. dividend as a percentage of initial investment) requires computers, software, and past data. This is complicated and would therefore need to be handled by an office that reports to the commissioner. If the actual rate of return was less than expected, future investors would be less likely to participate. In other words, calculating accurately would be crucial.

Wind Too

A sister system for wind farms could be built as well. In theory, an automated National **Wind** Farm System (N**W**FS) could be overseen by a Wind Commissioner who sells Wind Bonds.

Figure 27.3: Utility-scale wind farm.

Setting Size

The majority of people want to resolve climate change. Subsequently, new laws that require decarbonization will probably appear this decade. It is likely these would increase solar farm and wind farm construction. For example, if government wanted to decarbonize 6% of all electricity each year, and 1% is already being decarbonized by building traditional solar farms and 1% is already being decarbonized by building traditional wind farms, the government might want the NSFS and NWFS combined to contribute at least 4%. In other words, electricity customers might be required to buy more green electricity each year, and the NSFS/NWFS organizations would need to raise money accordingly.

Junk Is a Serious Problem

Let's take a break from economics and talk about electronics. Hardware devices that convert one type of electricity to another type are typically rated for a maximum amount of electrical power. In many cases, a device will not perform long at advertised power. However, manufacturers are compelled to claim high power ratings to be competitive. Subsequently, solar farm owners might be misled into buying hardware that fails prematurely. And this might decrease dividend payments to bond-holders.

The Commissioner Must Block Junk

Electricity customers would want contracts with lower-priced farms. Therefore, owners would be under pressure to keep costs down. However, not too low as to buy junk that fails prematurely. This includes electronics, solar panels, frames that hold panels, underground conduits, and wiring harnesses.

Electricity customers might be inclined to accept contracts with junk since they only pay for electricity received and are not adversely affected by reduced output, reduced profit to the owner, and reduced dividends to investors.

Investors have no way of evaluating when owners should spend money and when they should economize. Therefore, the Commissioner would need to block junk on their behalf and protect the entire NSFS system. To do this, the commissioner would need an office of engineers who understand solar farm construction and use past data to estimate future technical and economic performance.

Let's Run the Numbers

If 2% of U.S. electricity were decarbonized each year via the NSFS, it would need to oversee 35GW of solar power construction each year. If the capacity of each solar farm were 0.5GW, for example, 71 farms would be built each year, where each is approximately 3 x 3 km (2 x 2 miles) in size.

Typical equipment costs are $1.12-per-watt (CAPEX, NREL 2022); therefore, investors would need to put in $39B/yr (35GW x $1.12). Typical electricity costs are 3.7¢/kWh (LCOE, NREL 2022 Class 4, no tax credits, 0.5¢/kWh for power wires). Therefore, revenue would need to be at least $3B/yr to cover costs ($.037 x 35GW x 0.001 x 2334Wh/W/yr). The investment rate

of return would depend on several factors, such as profit to owner and electricity price. For details, see the below analysis.

Decarbonization	2.0%	%/yr	% US total electricity decarbonized ea yr
	4,120	TWh/yr	Total electricity consumption, 2021 US EIA
	82	TWh/yr El	Electricity decarbonized each year
	187	TWh/yr Ht	Heat avoided from burning natural gas
Solar Farm	35	GW	Capacity of each solar farm
	$3.0	$B/yr	Electricity cost per year, LCOE, NREL 2022
	34	MtCO$_2$/yr	CO$_2$ reduced per year (gas not burned)
	$39.5	$B/yr	Solar farm initial equipment cost
Multiple Solar Farms	0.50	GW	Size of each solar farm
	71	count	Number of solar farms
	10	sq km	Square kilometers per solar farm
Solar Farm Costs	$1.120	$/Watt	Solar farm inital cost, CAPEX, NREL 2022
	$0.037	$/kWh El	Electricity cost, LCOE, NREL 2022 Class 4,
			no tax credits, $0.005/kWh power wires
	2,334	kWh/kW	Annual production, NREL 2022 Class 4
Natural Gas Power	$4.00	$/mcf	Cost of natural gas, wholesale, typ. price
	0.000413	mtCO$_2$/kWh el	CO$_2$ emissions from electricity, metric ton
	$3.75	$/GJ	Internal energy within natural gas
	$0.014	$/kWh Ht	Cost of heat energy in natural gas
	44%	%	Efficiency of gas power plant
	$0.031	$/kWh El	Cost of natural gas per unit of electricity
Additional Cost	$0.006	$/kWh El	Additional cost green electricity
(solar instead of gas)	$0.53	$B/yr	Additional cost green electricity
	$15	$/mtCO$_2$	Decarbonization cost, $-per-m-ton-CO$_2$
	330	M	U.S. population
	$1.59	$/person/yr	Decarbonization cost-per-person-per-yr

Figure 27.4: The economics of decarbonizing 2% of U.S. electricity via 71 solar farms, each 0.5GW in size (Calculations by Weinreb).

The Residential Solar Problem

The cost of electricity from solar panels on houses is 3-times higher than that at solar farms (e.g. 2.6¢/kWh vs. 8.6¢/kWh LCOE). This is due to residential solar incurring the following overhead cost every ~20 panels: multiple quotes, contracting, mechanical design, city approval, electrical design, installation, and inspection. Incidentally, this overhead causes

fiscally conservative lawmakers to disfavor government support for residential solar.

Figure 27.5: Residential solar panel installation.

Resolving the Residential Solar Problem

In theory, the electricity billing system for residential and commercial buildings could be connected to the NSFS/NWFS system. Building owners could then invest in solar and wind farms instead of their own buildings.

For example, a homeowner might prefer to give $10K to their power company for 30 panels at a solar farm, instead of giving $10K to a solar installation company that installs 14 panels on their roof. The solar farm panels would produce 1.6-times more electricity per panel due to continuously tilting toward the sun via a motor instead of being stationary.

Solar bonds might appear on a home-owner's electric bill as an asset that pays a monthly dividend determined by solar farm electricity sales. If a homeowner bought $10K of solar bonds, their bill would probably be close to zero for approximately 20 years. Also, they could sell bonds at any time.

Carbon Offsets at Large Scales without Fraud

Investors and farm owners participate to make money, not to reduce CO_2. However, many entities are willing to pay money to reduce CO_2. These exchanges are typically referred to as "carbon offsets," and unfortunately, many are fraudulent. Alternatively, if one is looking for real offsets at large scales, the NSFS/NWFS system might be a nice option. More specifically, the system could be used to pay the green premium on someone else's electricity, and flip them off carbon. For example, if coal cost 2.5¢/kWh and

green electricity cost 4¢/kWh, a 1.5¢/kWh offset could flip the customer and reduce CO_2 at $15-per-ton ([$10](#) x (4¢ - 2.5¢)).

Who Might Develop this System?

NSFS software does not exist. However, it could be developed to the point of simple prototypes, perhaps for less than $100M.

A company might look at developing this as a proprietary system that they control. However, investors in their venture would probably consider this too much risk. If one component was missing or government regulators were not supportive, revenue would be zero.

Alternatively, a government or philanthropic organization looking to reduce CO_2 might fund development. They might consider this a relatively low-cost method to reduce CO_2 globally. However, most nations do not trust others to manage their national infrastructure. Therefore, they might require open source and control over their commissioner's office, both of which are feasible. Open-source entails placing files on the internet for anyone to copy and modify at no cost. And a philanthropic entity might be inclined to do this to reduce CO_2.

Figure 27.6: Utility-scale solar farm.

Conclusion

A transparent and automated solar farm and wind farm system could potentially reduce cost, reduce risk, and increase construction rates. And a government or foundation could probably get this started with open-source software development.

28. Carbon, Capture and Sequestration (CCS)

Carbon Capture and Sequestration (CCS) is a process by which CO_2 gas is captured and then stored or utilized. CCS is of intense interest for several reasons:

- It reduces CO_2 emissions.

- It helps to maintain the value of carbon-based infrastructure that has already been built and possibly paid for (e.g. coal-fired cement factory).

- It helps to maintain the value of underground carbon-based assets that would otherwise be unburnable due to decarbonization (e.g. coal, oil, and natural gas reserves).

- It provides a way for petroleum companies to utilize their core competencies in a decarbonized world since CCS is mechanically similar to natural gas extraction, only in reverse.

What Is Carbon Capture and Sequestration?

CCS consists of three steps: Capture, Transport, and Storage.

- **Capture** involves extracting CO_2 from a stream of gas. For example, one can extract CO_2 from the exhaust of a facility that burns natural gas to produce electricity. Before capture, approximately 10% of this exhaust is CO_2, while the rest is mostly nitrogen. Capture entails separating the CO_2 from the nitrogen.

- **Transport** typically involves moving CO_2 in pipes.

- **Storage** entails placing CO_2 underground or using it in some way. The cost of storage is often a small percentage of the total CCS cost.

The cost of extraction increases as the CO_2 in the source becomes more dilute. For example, it is easier to extract CO_2 from ethanol production with 85% CO_2 exhaust (~\$15/mtCO$_2$ extraction cost) than to extract from natural gas-fired electricity generation with 10% CO_2 exhaust (~\$60/mtCO$_2$). Even more difficult is Direct-Air-Capture (DAC), which involves extracting CO_2 from the atmosphere. Air contains 0.042% (420ppm) CO_2 and extraction costs several hundred \$/mtCO$_2$.

To store, one typically converts CO_2 gas to a liquid with ≥72 atm (1058 psi) pressure, and injects the liquid 800 meters or more below the surface. One injects to sites that already have fluids at these pressures, which indicates they can hold pressure. Existing oil and natural gas fields are often good candidates since their underground dynamics are already well understood.

When one compresses CO_2 into a liquid, volume decreases 3000-to-1, and density becomes similar to water (i.e. one cubic meter weighs approximately one metric ton). In theory, one could store a year's worth of the world's CO_2 in a 21km diameter underground cylinder that is 100m tall (34Gt/yr global CO_2 = h x π x r^2 = 100m x 3.14 x 10,400m^2).

What Limits CCS?

Currently, 40 million tons of CO_2 are processed by CCS each year worldwide (40Mt/yr). However, global CO_2 emissions are approximately 1000 times more. CCS at large scales is not limited by the availability of underground storage, nor is it limited by technology. CCS has not progressed further due to: (a) a lack of government intervention that forces markets to absorb this additional cost, (b) lower costs methods of decarbonization, and (c) lower cost methods of obtaining green heat.

CCS Must Compete with the Decarbonization of Electrical Power Generation

CCS must complete with electricity decarbonization, where the cost to reduce CO_2 is less. More specifically, the cost to reduce CO_2 when building a solar farm or wind farm is typically $10 to $50/mtCO_2$, while the cost to reduce CO_2 with CCS is typically $100 to $150/mtCO_2$. In other words, if one is paying money to reduce CO_2, they would favor decarbonizing electricity over CCS since each additional dollar goes further. And after electrical power is decarbonized, one could look at implementing CCS at large scales.

CCS Must Compete with Heat Created with Green Electricity

If one has a heat-driven industrial process that burns coal or natural gas, one might consider decarbonization via CCS. Alternatively, one might make heat with green electricity derived from a solar farm or a wind farm. Obviously the lowest cost approach would be favored. In other words, CCS ultimately needs to compete with green electricity.

Green electricity typically costs $0.035/kWh. The wholesale cost of heat from burning natural gas is approximately $3 per gigajoule (GJ) of energy ($3.40/mcf x 0.9 mcf/GJ). The wholesale cost of heat from burning coal is approximately $2 per GJ of energy ($57/ton x 0.037 GJ/ton). The cost of heat from electricity produced by a solar farm or wind farm is approximately $10/GJ ($0.035/kWh x 277 kWh/GJ). The CO_2 emissions from burning 1GJ of natural gas is approximately 0.05 metric tons. And the CO_2 emissions from burning 1GJ of coal is approximately 0.098 metric tons.

We can do a little math to calculate decarbonization cost of approximately $140 per metric ton of CO_2 reduced when replacing natural gas based heat with green electricity based heat (($10 - $3) / 0.05), and approximately $80 per metric ton of CO_2 reduced when replacing coal based heat with green electricity based heat (($10 - $2) / 0.098). In other words, when decarbonizing industrial processes that burn coal, it typically cost less to do this with green electricity than it does with CCS. However, when decarbonizing processes that burn natural gas, green electricity and CCS typically have similar decarbonization costs.

If a cost-reduced nuclear reactor is available, then direct heat from the reactor would probably cost less than CCS and green electricity. In other words, in a green new world, nations averse to nuclear might be at an economic disadvantage relative to those who are receptive.

What Would It Cost to Capture 30% of the World's CO_2?

The world currently emits approximately 34Gt/yr of CO_2. If 10Gt/yr were processed via CCS at a cost of $100-per-ton, for example, then the total cost worldwide would be $1T each year (10G x $100). If the U.S. handled 16%, cost would be $160B each year after it had been built out to the 1.6Gt/yr level. If built over 10 years, the cost would be $16B in year #1, $32B in year #2, and $160B/yr after year #10. The public is not comfortable with these numbers, and less expensive ways to reduce CO_2 exist. Therefore, R&D is needed to reduce CCS costs.

CCS Strategy

A reasonable CCS strategy assumes government intervention eventually pushes decarbonization forward in increasing cost-to-avoid-a-ton-of-CO_2

order and prepares accordingly. Preparation can be broken into several types:

- Increase R&D that reduces the cost of capture, transport, and storage.

- Build databases of potential decarbonization projects worldwide that include CCS.

- Build models that design piping networks that transport CO_2 from sources to storage.

- Build systems that track the production, distribution, and consumption of green commodities. This includes electricity, chemicals and materials.

For details, see *What is our Long Term CCS Strategy?* *(Power Electronics, Jan 2022)*.

29. Direct Air Capture (DAC)

Direct-Air-Capture (DAC) entails extracting CO_2 from atmosphere and using it or storing it in some way.

The Sea Level Rise Problem

Eventually our civilization will stop putting CO_2 into the atmosphere, perhaps 30 to 70 years from now, and the planet will stop warming. However, after we stop emitting CO_2, the additional temperature will hover for thousands of years as the CO_2 slowly falls back to earth, and the temperature slowly reverts back to its original level.

As the elevated temperature hovers, it will slowly melt a 2000 meter-thick slab of ice on Antarctica (i.e. the South Pole). And this will cause the sea to rise and cover coastal cities. Sea level is expected to rise slowly. Perhaps one to two meters every 100 years. However, after 30 to 300 years, this will be a problem for many coastal areas.

Two CO_2 Problems

In a sense, we are dealing with two CO_2 problems. One is the *immediate* impact of higher global temperatures that cause the land to become drier and cause storms to become more intense. And the other is the *long-term* problem of melting South Pole ice that causes the sea to rise one to two meters every 100 years. The first problem is addressed by reducing CO_2 emissions *now*. And the second problem is addressed with Direct Air Capture (DAC), perhaps over hundreds of years, *starting* several decades from now.

DAC Strategy

Over the next few decades DAC will not be done at large scales since extracting CO_2 from a gas that is 0.04% CO_2 (i.e. atmosphere) cost more than extracting CO_2 from a gas that is 10% CO_2 via CCS (e.g. exhaust from burning natural gas to produce electricity). And it is unlikely CCS will be done at large scales in the near future since it cost less to reduce CO_2 by building a solar farm or a wind farm. Therefore, a reasonable DAC strategy is to cost-reduce DAC with R&D, to prepare for the day when electrical power generation has been decarbonized, and atmosphere is the densest source of CO_2.

30. Cover Buildings with Solar Skin

In theory, a billion dollar-sized R&D initiative could potentially develop machines that fabricate, install and maintain custom pieces of PV solar material that wrap building roof and wall surfaces at a cost less than traditional coverings. Costing less is potentially feasible since side clapboards and roof shingles are installed by hand, and solar skin could be automated. If solar skin costs less than traditional coverings, it could be driven forward by buyers who favor paying less.

Figure 30.1: Illustration of custom PV solar skin that mounts directly onto plywood and wraps features such as windows and doors (concept illustration by Weinreb).

Custom Solar Fits Together Like a Puzzle

The typical house places drywall on internal wall surfaces and places plywood on external wall surfaces. Workers typically begin with solid 4 x 8ft (1.2 x 2.4m) panels and cut them into custom shapes that wrap windows and doors. To make this easier, architectural software generates drawings of each piece.

In theory, one could do something similar with solar material that directly attaches to external plywood. For example, one could wrap a building with

12 *custom* solar pieces, as illustrated . In this concept, pieces are outlined in green and numbered; horizontal rails that secure material to external plywood are shown in blue, and brackets that provide a watertight seal at window/door vertical edges are shown in violet.
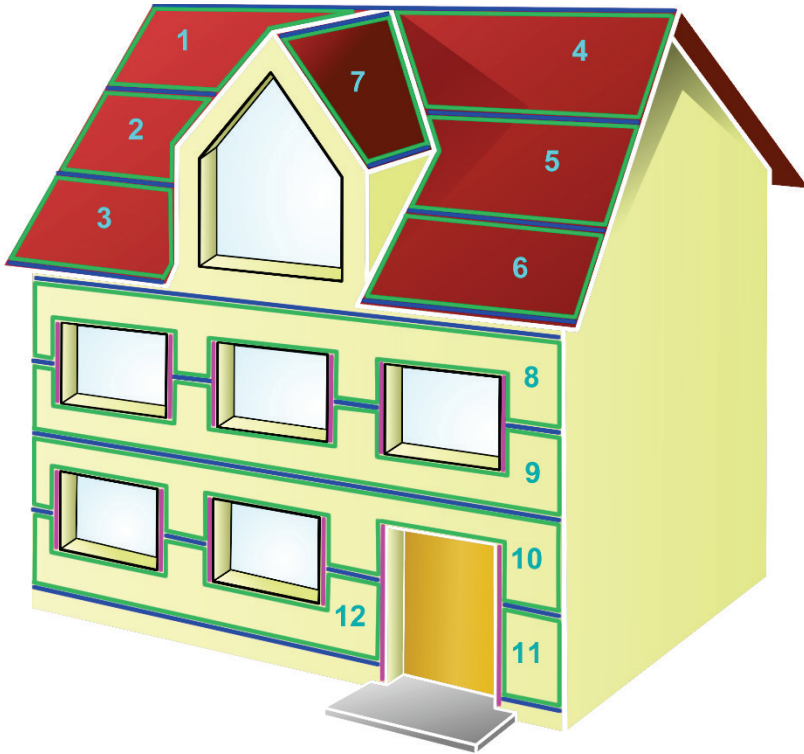
Figure 30.2: Custom pieces of solar fit together like a puzzle
(concept illustration by Weinreb).

Solar cannot be cut in the field due to internal wires; therefore, machines would be needed to fabricate custom shapes in a factory. The placement of windows and doors relative to drawings is often only accurate to ±1cm. Therefore, photography, video, or laser scanning would be needed to improve accuracy.

Newly constructed buildings might incorporate windows/doors with standardized features that mechanically interface to solar material. Alternatively, existing construction might utilize custom factory-made brackets. A building lasts much longer than PV solar; therefore, solar skin would need to support disassembly and replacement, via bolts and screws.

Horizontal Rails Secure Solar Skin to Surface

The figure below shows an example of a horizontal seam between two pieces of solar skin. This seam is illustrated above in blue. A lower rail (violet) attaches to plywood via screws, and an upper rail (light green) attaches to the lower rail via bolts. Flexible ~2mm thick PV solar material (dark blue) attaches to rails via an adhesive (yellow). An optional embedded Printed Circuit Board (PCB) (dark green) supports electronic components ~1cm tall (dark red), and a lower layer of thin sheet metal (gray) presses against plywood (brown). This provides strength and a fire barrier. Not shown is the honeycomb plastic between the lower metal layer and upper solar layer that fills empty space around PCB. Rain-water (bright red) flows across overlapped joints, and avoids plywood.
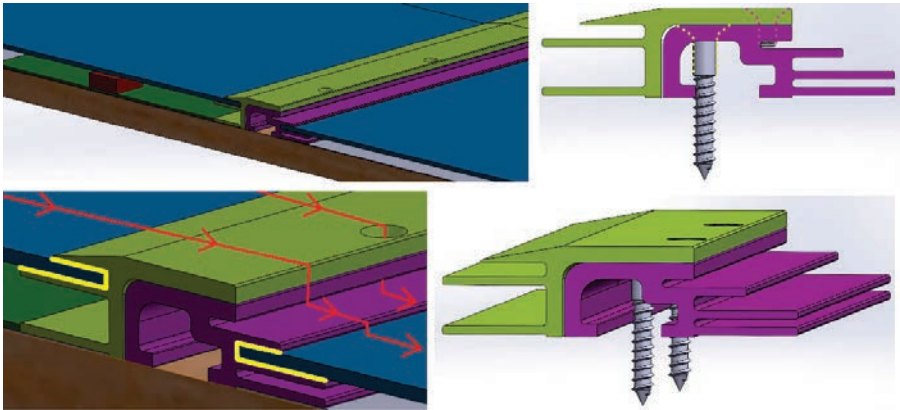
Figure 30.3: Concept illustration of horizontal rails that secure solar material with a watertight seal (Source: UMass Open-Source Solar Design Team sponsored by Manhattan 2).

Why Has This Not Been Done?

The good news is PV silicon and thin-film materials cost relatively little. And developing a mechanical system that wraps a building costs little. The bad news is developing commercial-grade machines that fabricate and install custom pieces would be expensive. Also, multiple complicated machines causes investors to consider this "too big" or "too many moving parts," which it is.

Subsequently, government or foundation funding would be needed to move this forward.

R&D Strategy

There are many ways to <u>wrap a building</u>, each of which can be characterized with several parameters: type of building, new construction or existing, roof or wall, solar material physical topology (e.g. large rollable, large flat, small flat), embedded electronics or not, 3mm flat glass or flexible plastic cover, and silicon or thin-film PV. In other words, one can specify seven parameters and then design the mechanics of a solar skin system that fits those parameters.

Designing the mechanics of a solar skin system, and constructing a one cubic meter sized prototype would cost little money. However, developing automated machines that fabricate and install could cost hundreds of millions of dollars or more.

Interconnection standards are needed to coordinate multiple companies, and in many cases, one company cannot afford to develop these. Therefore, government or foundation support would be needed.

Getting Started With a "Small" Budget

One can do paper-only designs and build simple prototypes without spending significant money. More specifically, one can:

- Design and prototype hardware that provides a water-tight seal at vertical and horizontal joints.

- Build simple prototypes with several pieces of solar material that overlap at a horizontal edge, or interface with a window vertical edge, and test with wind and water.

- Build a one cubic meter sized "house" out of plywood, wrap it with pieces of solar skin made by hand, and test it with wind and water. One can initially work with sheets of plastics (not PV material) and focus on creating a watertight system that attaches to plywood, wraps windows and doors, and supports disassembly. A one cubic meter box with one window and one door would probably be sufficient.

For more details, see *How to Cover Buildings with Solar Skins* *(Power Electronics, Feb 2022)*.

31. **Automate Solar on Buildings**

A house needs a significant amount of PV solar to be a net producer of electricity, especially when heating with electricity in a cold climate. For this reason, one might fully cover an oversized roof edge-to-edge, as illustrated below. This has a 1:1 floor-to-solar ratio (i.e. both are 185m^2).
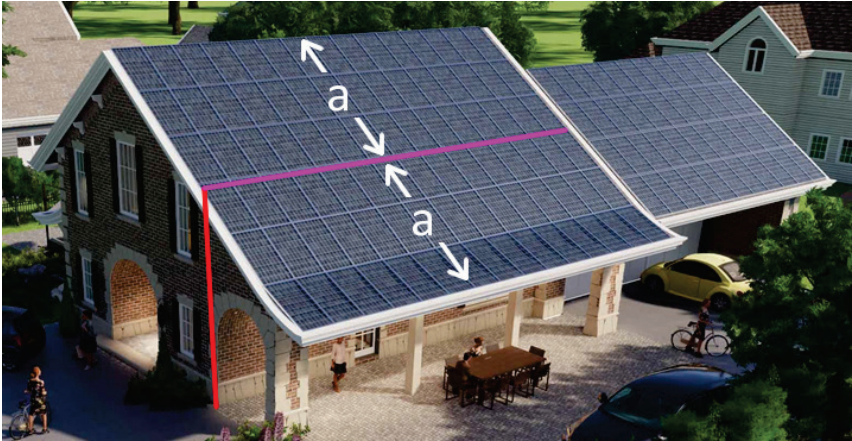
Figure 31.1: Oversized roof (concept by architect John Meyer).

If one examines the above illustration carefully, they might notice half the roof is not above the structure. In other words, the roof is oversized. Making this economically viable is a challenge since large structures similar to that shown above tend to be expensive. However, engineers might be able to make this work financially by extending a traditional roof with light factory-made framing, as illustrated below.

Figure 31.2: External framing supports solar (concept by Weinreb).

The above structures might seem unattractive. However, some homeowners might prioritize electricity revenue over aesthetics.

The local power company might comment, correctly, that solar farms on land provide electricity at a lower cost than solar panels on buildings (i.e. lower $/kWh). However, in some cases, land for solar farms is not available. And engineers can look at driving down the cost of building based solar with standardization and automated installation.

Reduce Costs with Standardized Sub-Assemblies and Machines

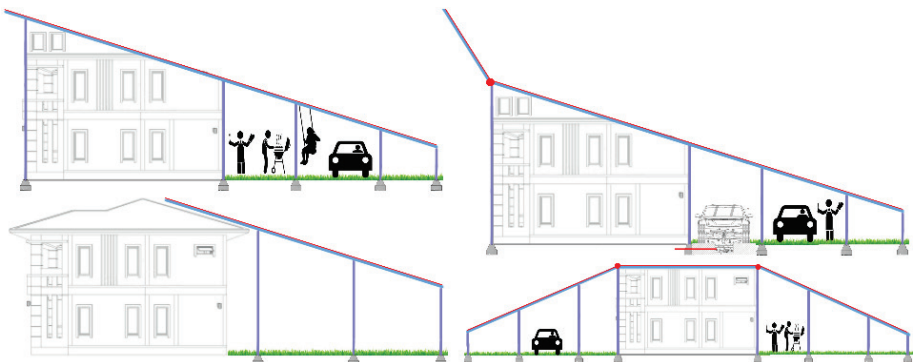To reduce the cost of solar panels mounted on metal framing, engineers can explore modular systems that support: (a) multiple factories that mass produce standardized sub-assemblies, (b) transportation systems that stack sub-assemblies in shipping containers, and (c) automated installation via custom machines. For example, each sub-assembly might consist of 36 traditional solar panels on aluminum framing. In theory, this could be used with residential buildings, commercial buildings, and parking lots.

Figure 31.3: Standardized sub-assemblies with automated assembly.

Automate Solar Installation on Buildings

The average US resident pays $2.81-per-watt to install PV solar panels on their house. However, the panels themselves only cost $0.27-per-watt wholesale in China. This means 90% of the costs are for things other than panel manufacturing ($2.54 / $2.81). Therefore, it is reasonable for governments and foundations to automate the handling of traditional solar panels (not sub-assemblies and not custom shapes). This includes installation, maintenance, repair, customer acquisition, quotation, contracting, permitting, and design. For details, see *Why Spend $1B on Solar Installation R&D? (Power Electronics, Nov 2021).*

32. Mechanize Solar on Soil

Agricultural farms were maintained by hand for thousands of years until they were mechanized with farm equipment. Today, we maintain solar farms mostly by hand, but in theory, they could be mechanized too. The world is looking at spending trillions of dollars on solar farms. Therefore, it is reasonable to spend billions of dollars to automate, to reduce cost. Obviously, one would first spend small money and verify feasibility, before spending big money. It is unlikely that a company would do the initial design since they would consider this too big. However, governments and foundations might be inclined to develop a next-generation solar farm that uses machines to install, maintain, clean, and mass-produce solar material.
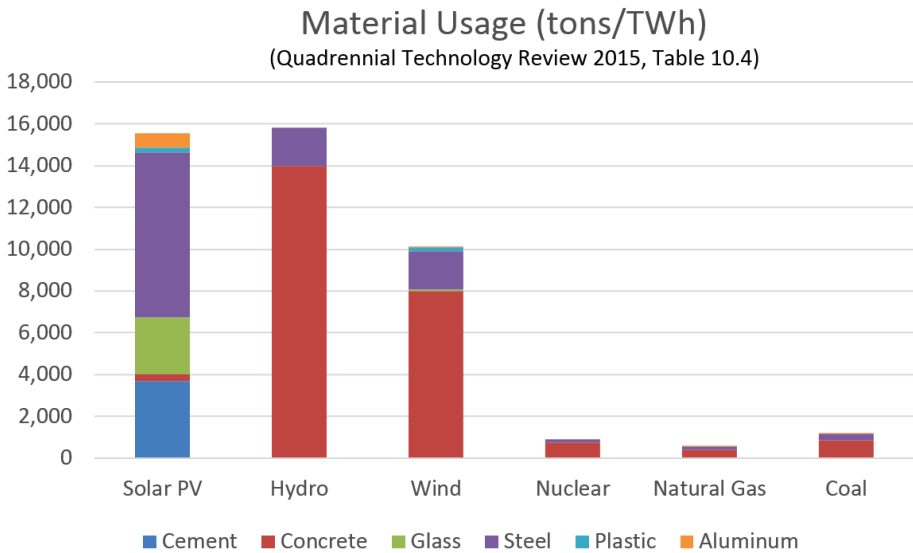
Figure 32.1: Amount of material used to build a facility that generates electricity.

The Materials Problem

This graph shows how much material is used by the traditional methods of generating electricity. Materials primarily include steel, concrete, and glass. PV solar farms use as much material as hydroelectric dams in terms of weight per unit of lifetime electricity generated. This is a lot, and we would

like to reduce, to reduce the cost of solar, and to reduce CO_2 emitted when making materials.

Silicon solar cells are typically covered with 3.2mm (0.125") thick tempered glass to protect against hailstones and wind. Wind applies tremendous force. For example, 100mph wind presses 220kg per-square-meter against a surface. In other words, protecting silicon for 30 years requires significant amounts of material.
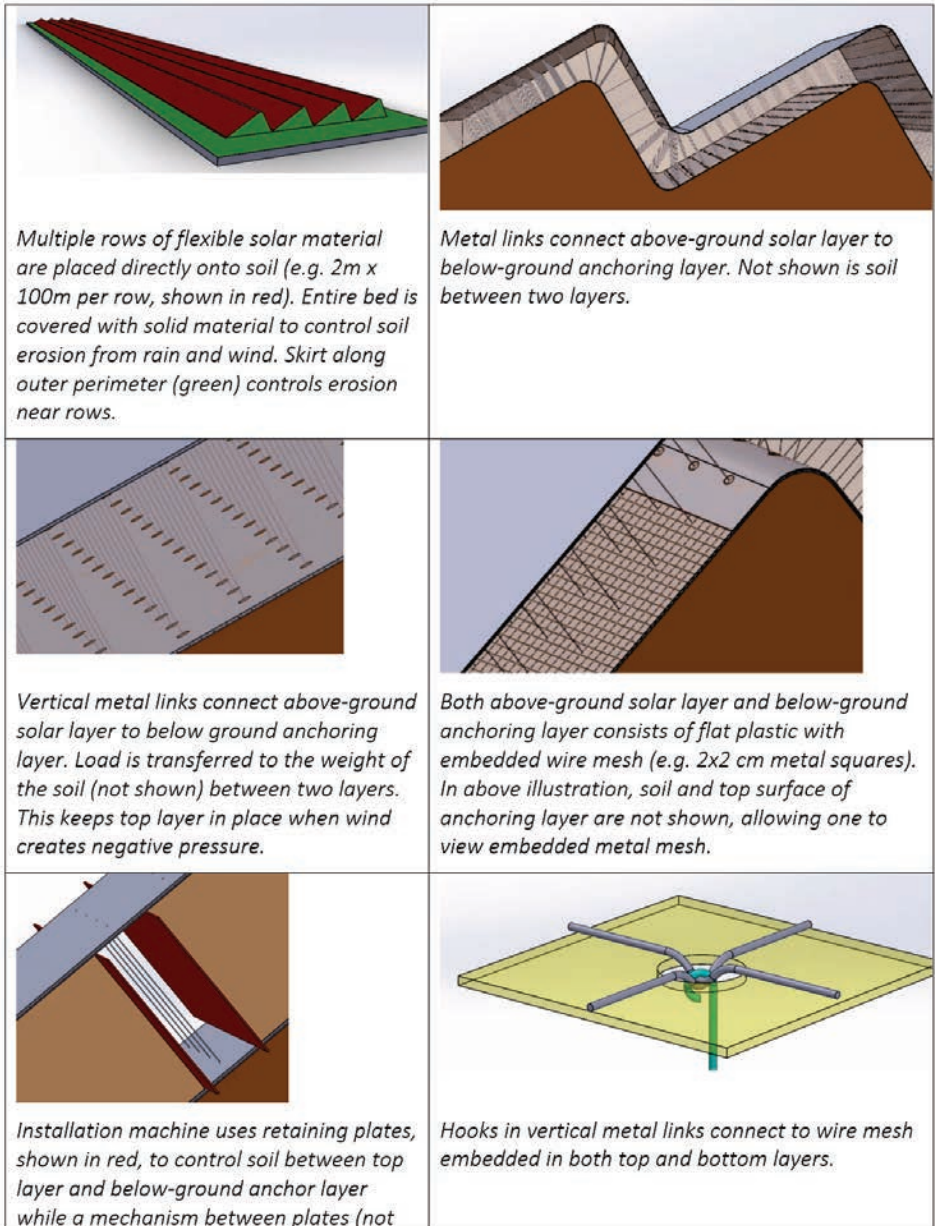
Solar Direct to Soil

Solar farms typically mount silicon solar cells 1.5m (4.5ft) above ground. Alternatively, one might unroll flexible thin-film ~2mm (0.1") thick solar material directly onto soil in a manner similar to unrolling a 2m x 100m (6 x 300ft) carpet onto a surface. Prior to installation, the land would be shaped with earth-moving equipment under computer control.

Initially, this might seem like a bad idea. However, there are good reasons for going to ground, such as significantly less material usage. Engineers could explore various techniques for overcoming challenges such as soil erosion, upward pressure due to wind, and keeping solar material clean.

Traditional PV solar farms use aluminum and glass to resist wind loads. Alternatively, direct-to-soil would use soil for rigidity and use thin-film conversion material instead of silicon solar cells. Thin-film is typically rollable, resistant to hailstones, and does not need 3.2mm (0.12") thick protective flat tempered glass. It also has less conversion efficiency and more efficiency degradation per year, which means one needs more land for the same energy output. However, if one has an infinite supply of land, they might focus on cost-per-watt as opposed to cost-per-square meter of land.

The above-ground layer might be similar to flat flexible plastic with an embedded steel wire mesh. To hold in place, installation machinery might install a parallel layer of material underground, perhaps 50cm (20") below the top above-ground layer. The above-ground layer might connect to the underground anchoring layer via metal links. The following pictures illustrate this concept.

Multiple rows of flexible solar material are placed directly onto soil (e.g. 2m x 100m per row, shown in red). Entire bed is covered with solid material to control soil erosion from rain and wind. Skirt along outer perimeter (green) controls erosion near rows.	Metal links connect above-ground solar layer to below-ground anchoring layer. Not shown is soil between two layers.
Vertical metal links connect above-ground solar layer to below ground anchoring layer. Load is transferred to the weight of the soil (not shown) between two layers. This keeps top layer in place when wind creates negative pressure.	Both above-ground solar layer and below-ground anchoring layer consists of flat plastic with embedded wire mesh (e.g. 2x2 cm metal squares). In above illustration, soil and top surface of anchoring layer are not shown, allowing one to view embedded metal mesh.
Installation machine uses retaining plates, shown in red, to control soil between top layer and below-ground anchor layer while a mechanism between plates (not	Hooks in vertical metal links connect to wire mesh embedded in both top and bottom layers.

Figure 32.2: Thin-film solar direct to soil (concept by Weinreb).

Some regions would be more feasible than others. For example, deserts with 3cm (1") rain per month, and dense soil, might be most suitable. Engineers would need 30-year simulations and wind tunnel testing to ensure that soil movement due to wind and rain is acceptable.

Currently, silicon-based solar panels are mass-produced and cost less than thin-film. However, direct-to-soil uses less metal, glass, and concrete; and thin-film PV is easier to fabricate than silicon solar cells. Therefore, direct-to-soil thin-film would probably cost less if mass-produced. Also, it would consume significantly less material and emit less CO_2 due to less material fabrication.

Machines that shape land might look similar to earth-moving equipment, and machines that clean might look similar to agricultural sprinklers yet with less water, examples are which are pictured below.

Figure 32.3: Earth-moving vehicles and agricultural sprinkler system.

Further Reading

For details on how this might work, see the following articles published in Power Electronics in 2021.

- *Mechanizing PV Solar on Land*
- *Turning Deserts into Factories*
- *How to Solve the Climate Change Problem with Solar Farms*

33. Automate the Construction of Power Transmission Towers

It is easier to transport coal or natural gas fuel to a power generation plant near a city, than to generate electricity faraway and move the electricity on power wires. However, placing power sources next to consumers is sometimes not convenient when working with solar farms, wind farms, and hydroelectric dams. For example, Colorado might rely on local wind farms when windy in Colorado, and rely on faraway solar farms in Arizona when sunny in Arizona. Or Colorado might rely on wind farms in faraway Texas when calm in Colorado and windy in Texas. In other words, decarbonization requires significantly more long-distance power wires.

Upgrading Power Lines

Obtaining land for *new* power wires is sometimes "complicated". Therefore, a government office with authority to rebuild existing power wires on a wider tract of land would be helpful. If one replaces three 2.5cm diameter cables with eight 5cm diameter cables and increases voltage 5-fold, power transmitted increases 50-fold, for example (5^2 x 5cm / 2.5cm). This requires removing existing towers, increasing land tract width, and building new towers.

Figure 33.1: Traditional power cables (left) and jumbo-sized ultra-high-voltage cables (right).

Get Ready For Jumbo-Sized Power Transmission

Jumbo-sized power transmission (pictured above right) requires stronger towers, taller towers, and sophisticated ultra-high-voltage electronics. Currently, jumbo is only prevalent in China. However, this will probably change when other nations make more use of distant sources of green electricity.

The state of New York typically requires 40GW of power, and each jumbo-sized line typically carries 8GW. Therefore, powering the entire state would require 5 jumbos (40GW / 8GW). However, solar and wind sources are intermittent. Therefore, more lines would be needed to support variable sources.

Automate Power Transmission Tower Assembly

Expanding the grid will cost trillions of dollars worldwide over several decades. Therefore, it is reasonable to spend billions of additional dollars on R&D, to reduce this cost. For example, one might explore machines that automate the building of power towers using industrial robots mounted on trucks, as illustrated below. For details, see *How to Reduce the Cost of Electrical Power Transmission* *(Power Electronics, Sept 2021)*.
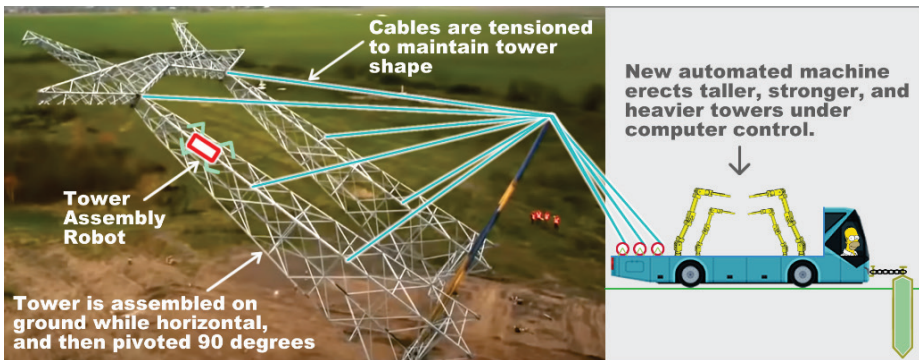
Figure 33.2: Machine automates the assembly of power transmission towers (concept illustration by Weinreb).

34. Decarbonize the Heating of Buildings

Many buildings are heated by burning natural gas in a furnace. This heats metal fins within a duct, which heats air that circulates throughout the building. Alternatively, one can install a system that creates heat using electricity.

There are two primary ways to produce heat with electricity. One is a heat pump, and the other is a simple electrical heating element. The heat pump is 2 to 4 times more efficient than the heating element. For example, one can feed 1 watt into a heat pump and get 4 watts of heat; or feed 1 watt into a simple heating element and get 1 watt of heat. One can get more out of the heat pump since it moves heat from one place to another instead of creating it. When heating a building, heat pumps move heat from outside the building to inside. And this causes outdoor air to become colder. Heat pumps are already inside air conditioners. Therefore, they can be used to heat buildings, to an extent, with little additional equipment cost.

In most cases, the electricity that feeds a heat pump is made by burning natural gas or coal at a power plant, and this facility emits CO_2. One might prefer "green" electricity, made without emitting CO_2. However, additional green electricity for buildings is often not available.

A building's energy cost often increases when it switches from a natural gas furnace to a heat pump, especially when outdoor temperatures are very cold. This is due to the fact that a heat pump's efficiency decreases when outdoor temperatures decrease.

Gas Furnace vs. Electric Heat Pump

Buildings typically obtain heat from a gas furnace or an electric heat pump, and it is impossible to generalize which of these costs less or emits less CO_2. This is due to multiple factors that vary over time and place. For example, the efficiency of a heat pump is a function of outside air temperature. And the spot price of both natural gas and electricity vary throughout the day and between regions.

Unfortunately, the size of the heat pump needed for a very cold day tends to be larger than that needed for a hot summer day. For example, the typical air conditioner on a 38°C summer day moves heat 14°C (38°C to 24°C), and the typical heating system on a -18°C winter day moves heat 42°C (-18°C to 24°C). The latter is 3-times further and therefore requires a much larger and more costly heat pump. To reduce the need for costly heat pumps, one can operate a gas furnace and a heat pump concurrently on very cold days.

National HVAC Communications and Control

There are many ways to decarbonize building heat. However, to get this done at the lowest cost, one would probably need standardized communications between HVAC equipment, regional computers, and national computers. This currently does not exist; however, it could be developed. For details, see *How to Decarbonize the Heating of Buildings at Lowest Cost* *(Power Electronics, June 2022)*.

Thermal Storage

Thermal storage typically entails placing a tank of water in a building, heating or cooling it with cheap or green energy, and then using it later when energy is less cheap or less green. For example, if a wind farm at 3 am is discarding electricity due to being in saturation (e.g. no natural gas is being burned to produce grid electricity), then one might store heat or cold in a tank and use it later when green electricity is not available. This would only be done at large scales if thermal storage $/mtCO_2$ decarbonization costs were competitive with other decarbonization options.

Reduce Cost of Installing Ground Source

Underground soil is typically at a ~14°C (58°F) temperature, and if one embeds pipes into that soil and circulates water through those pipes, they can get water at that temperature. If one circulates this water through a heat pump, they can reduce electricity consumption approximately 2-fold when heating and cooling. This technique is referred to as a "ground source heat pump" (GSHP), and it has two disadvantages. It consumes land, and installing underground piping is costly (e.g. $20K per house). Therefore, engineers should consider reducing this cost with automated installation machines.

35. Develop Next Generation Buildings

To fully automate buildings, one would need to place a microprocessor chip in every device and connect all devices with reliable communication. Devices include things like light switches, light sockets, HVAC equipment, appliances, motorized dampers in ducts, fans in ducts, motorized valves in radiators, thermal storage tanks, motors that move thermal covers over windows, occupancy sensors, temperature sensors, and fire detectors.

This would enable one to control the temperature of each room, move heat from one room to another, move heat between rooms and thermal storage, and move heat between rooms and underground soil. As noted previously, one can run pipes underground to get approximately 14°C (58°F), and this can be used to significantly reduce HVAC energy consumption.

Open Source Operating System

To ensure coordination, all devices would probably need to run the same operating system. Companies and countries would only accept this if it were open source (i.e. no one owns it). An example is BuildingBus, developed by Weinreb in 2021. He has developed approximately 30 automation and control systems over the last 43 years.

Reliable Communication

When one turns on a physical wall light switch, the communication between the switch and the ceiling bulb is operational ≥ 99.999% of the time ("5 nine's"). It's a subtle point that gets little attention yet is important. Occupants do not accept less reliability from common building infrastructure. It's worth noting that wireless and power-line communication are significantly less reliable, with failure rates on the order of 1%. To get 99.999% reliability within a building, one would probably need to include a communications data wire in power cables embedded in walls. The additional cost of this wire would be small.

Light and Heavy Devices

One might divide devices into two categories: Light and Heavy. Light might consume less than 20W of power, while heavy devices consume more.

Light might include things like light bulbs, light switches, sensors, and small motors. And Heavy might include things like 110/220 V_{AC} power outlets, HVAC equipment, large appliances, and large motors. Most devices in a building are Light and, therefore, could be powered by smaller cables with lower voltages and fewer safety requirements. In other words, a building might have a network of light devices powered by 48 V_{DC} and one communications wire. And it might have another network of Heavy devices powered by 110/220 V_{AC} and two data wires. The Heavy devices might route thick power wires in metal conduit, whereas the Light devices might use smaller cables without conduit.

Plug-and-Play Standards are Needed

To support plug-and-play connectivity, one would need to develop interconnection standards that define how devices connect electrically, mechanically, and with data communications.

Before proposing a standard, one must develop, prototype, test, and debug the system. And this might cost tens of millions of dollars, assuming the money is controlled by talented engineers, and open source is required by the funding source.

Companies cannot afford this, and governments rarely provide this kind of leadership. Therefore, a foundation would probably be needed to move this forward. The Gates Foundation would be uniquely suited since Bill Gates has experience developing operating systems and interconnection standards (e.g. UPnP).

Further Reading

- *Using processors and software to make buildings smarter*
- *Standards Are Needed to Thermally Cover Windows*
- *Standards are Needed to Fully Control Air in Buildings*
- *How to Decarbonize the Heating of Buildings at Lowest Cost*
- *Manhattan 2 Open-Source Smart Building Development*
- *Manhattan 2 Open-Source Window Thermal Cover Development*
- *Manhattan 2 Open-Source Fan/Damper Development*

Epilogue

Those concerned about climate change might feel like they are stuck in a bad dream. Like being chased in the forest at 3am and unable to break free. The threat is obvious, yet little is being done. What is happening? Below is a brief summary.

- Decarbonization to zero emissions will not occur unless required by law, and this law does not exist.

- Moving this law forward would require a political coalition that benefits. For example, states that import carbon-based fuels benefit from decarbonization in two ways: (a) they gain local green jobs while carbon jobs are lost elsewhere, and (b) they save money when decarbonization causes fuel price to drop, due to less consumption.

- Past decarbonization efforts have been mild. Alternatively, to get to zero over several decades, the world would need to do massive construction at unprecedented scales. This might sound expensive; however, infrastructure is typically paid for with borrowed money. And loans are repaid with revenue generated by the infrastructure.

- Individuals, companies, cities and states are often encouraged to reduce CO_2. However, they rarely have the physical ability to do so at low cost. This is mostly due to overhead costs at each "small" project.

- Power companies can decarbonize electricity at massive scales and at low costs. However, this will not occur unless required by law.

- The fossil fuel industries and their friends oppose decarbonization legislation by spending money on lobbyists and donations. However, the largest obstacle seems to be the failure of government leaders to realize they are led by domestic manufacturers who are focused on their own financial interests, not getting to zero at the lowest cost.

- To fix this, we need: (a) websites that calculate the cost and impact of proposed decarbonization law, (b) more resources that explain how to tackle climate change at the lowest cost, and (c) multiple R&D moonshots.

Final Note from Author

This book might seem critical of manufacturing and petroleum engineers; however, it is not my intent to be negative. I have worked extensively with these engineers for forty years and for the most part, they are good people, they are smart, they care about their planet, and they want prosperity for all. Also, they must keep costs down to compete. And, if government requires their competitors to incur an additional expense, they can afford it too.

Power Company engineers know how to decarbonize, yet will not proceed without a mandate from government. And government engineers know how to set up a mandate, yet will not proceed without instructions from government leaders.

Government leaders are surrounded by domestic manufacturers (my friends) who state "let me fix this". However, these companies are focused on their own financial interests, not getting to zero at the lowest cost.

To resolve climate change, government leaders need to consider: (a) laws that require decarbonization at the lowest cost, and (b) large R&D initiatives that are likely to have a significant impact.

Author Biography

Glenn Weinreb is the Director of the Manhattan 2 Project, a non-profit that does research on how to resolve climate change at the lowest cost and in a way that is politically feasible.

Weinreb founded GW Instruments in the 1980's while a student at MIT. This company designs and manufactures products that automate factories and research laboratories. And over forty years, almost every day, he interacted with manufacturing engineers and research scientists at thousands of different organizations.

One morning in 2019 Weinreb awoke with an epiphany. He felt his job was meaningless, and he wanted to do something different. He was tired of chasing money as an entrepreneur, and he instead wanted to help the planet. He thought about how his background was unique and gave him a different perspective on energy, manufacturing and R&D. So he formed The Manhattan 2 Project with some friends. And between 2019 and 2022 he sponsored and managed 25 university R&D students, and published 30 articles on climate change solutions.

For a TEDx talk that summarizes this book in 10 minutes, search "KIJsu2n5j1w" at YouTube. And for a CBS news segment that discusses some of Glenn's work, search "sesL3id7hba" at YouTube.

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