A Global Climate Strategy

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How to resolve climate change at the lowest cost

1. The Climate Solution

This chapter summarizes how to resolve climate change at the lowest cost.

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.

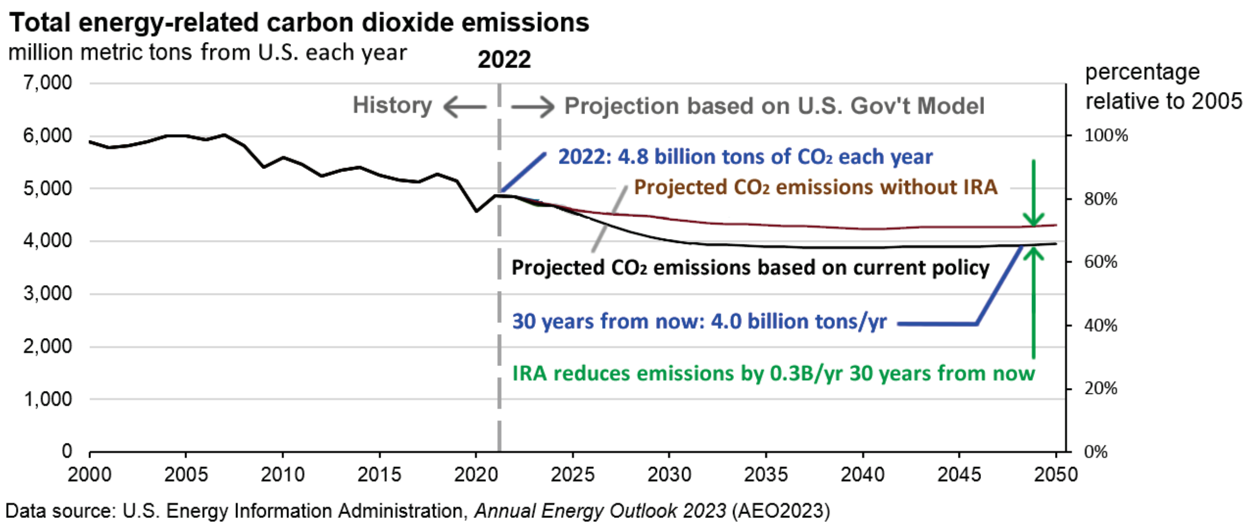


Figure 1.1: U.S. government's official projection of CO_2 emissions from the U.S. over the next 30 years in units of billions of tons each year.

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.

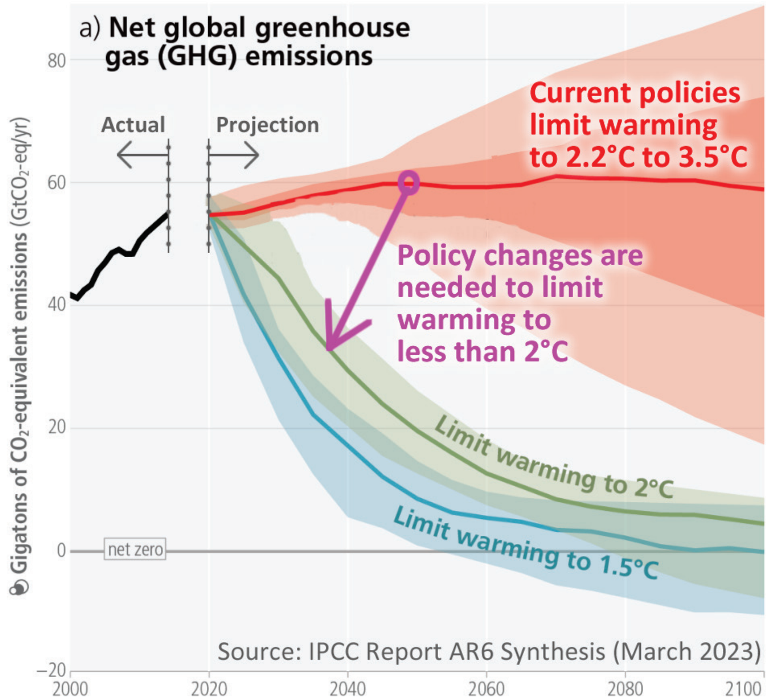


Figure 1.2: Impact of global CO_2 emissions over the next 30 years on planetary warming.

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. 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.

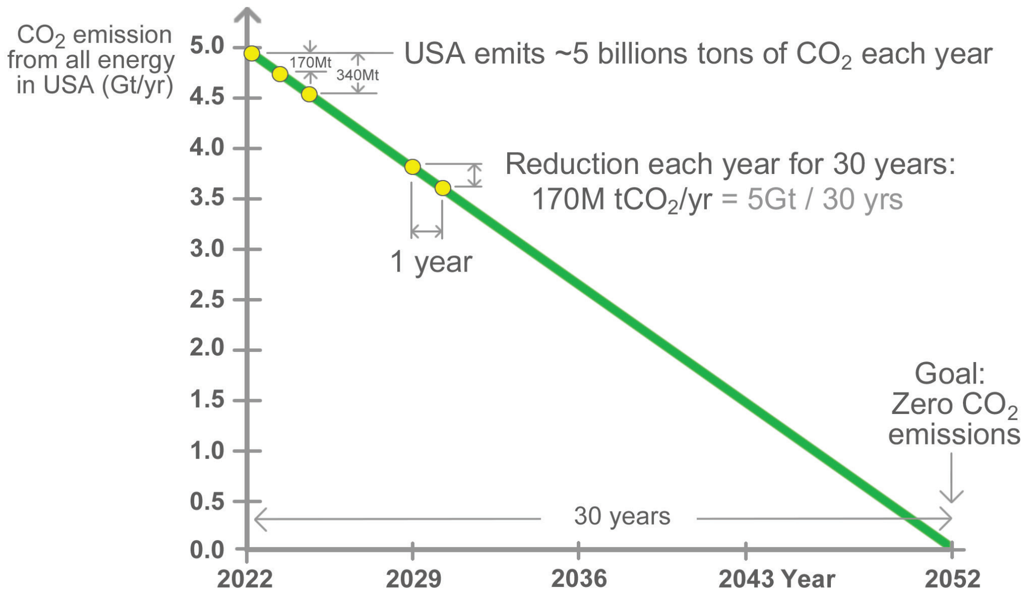


Figure 2.1: Theoretical U.S. decarbonization over 30 years at a constant rate.

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 ($/mt$CO_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. < $50/mt$CO_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 ~$80/mt$CO_2$ when replacing heat made with coal.

Decarbonizing electrical power generation (e.g. building solar farms and wind farms) typically costs $10 to $50/mt$CO_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.

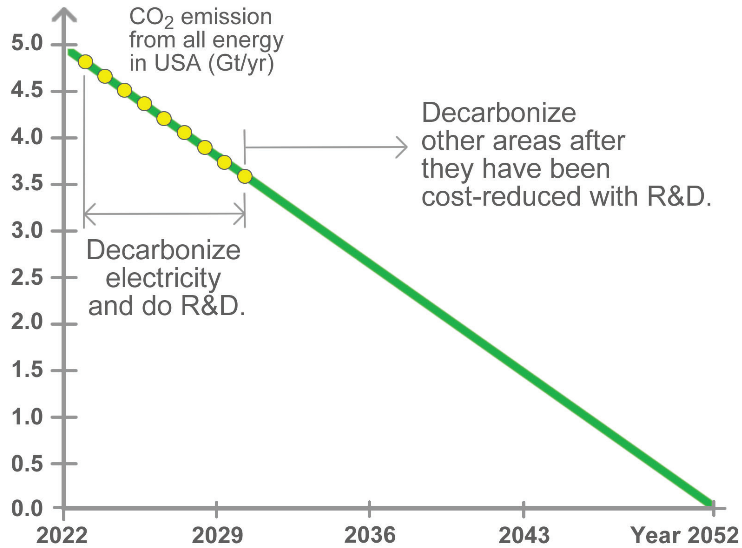


Figure 2.2: Two Phase Decarbonization Strategy.

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 2.3: 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 $10/mt$CO_2$ projects first, followed by $13/mt$CO_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 human activity 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

3. 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.

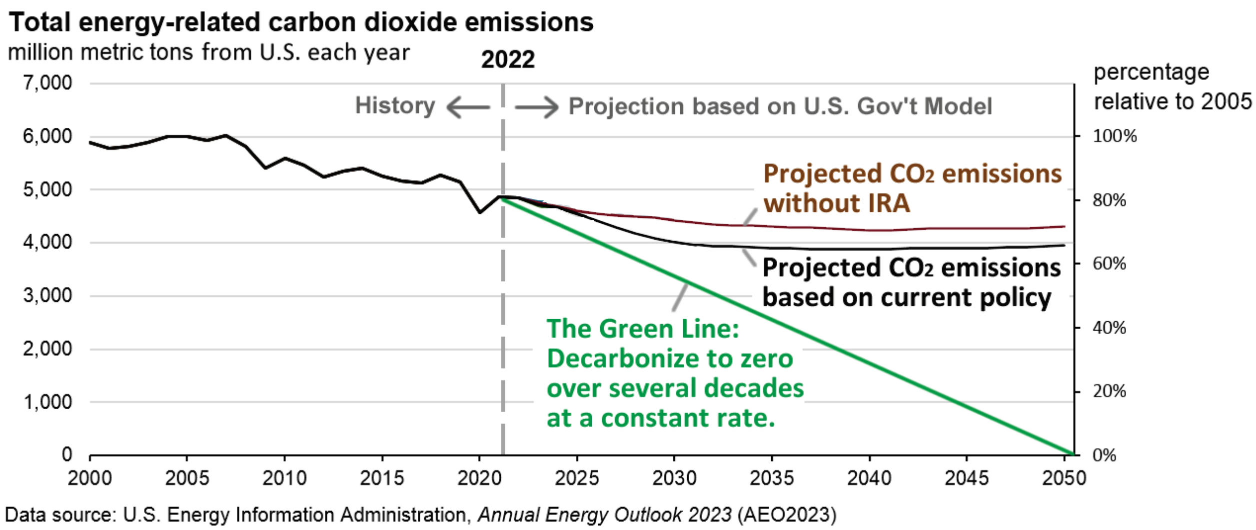


Figure 3.1: U.S. government's official projection of CO_2 emissions from the U.S. over the next 30 years in units of billions of tons each year

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.

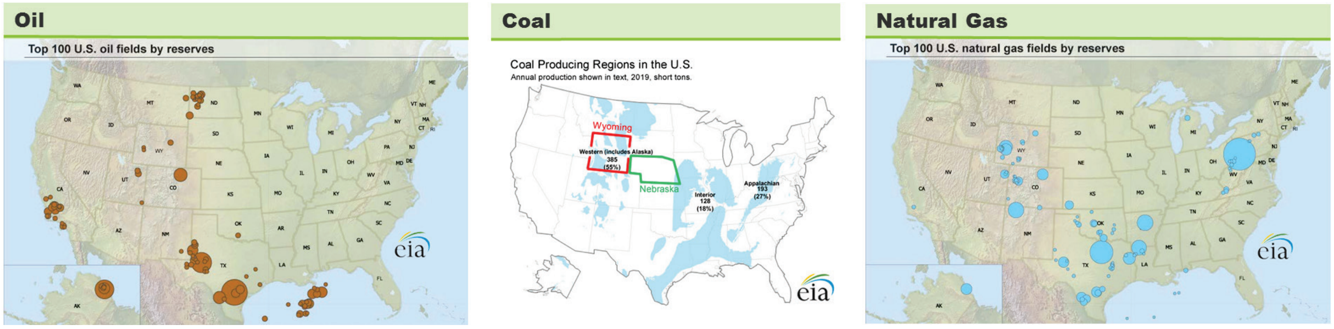


Figure 3.2: U.S. suppliers of oil, coal and natural gas.

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.

4. 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 4.1: 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

Decarbonization Laboratory Article References

[1] *How do we Accelerate the Development of Nuclear Fusion Power?*

[2] *What Might a $10B Fusion R&D Initiative Look Like?*

[3] *When will Fusion Power be Available Commercially?*

[4] *How do we Make Nuclear Fission Power Safer*

[5] *High-Temperature Green Manufacturing at Lowest Cost*

[6] *The Economics of Cheap Green Heat*

[7] *The Economics of Cheap Green Fuel*

[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

5. 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.

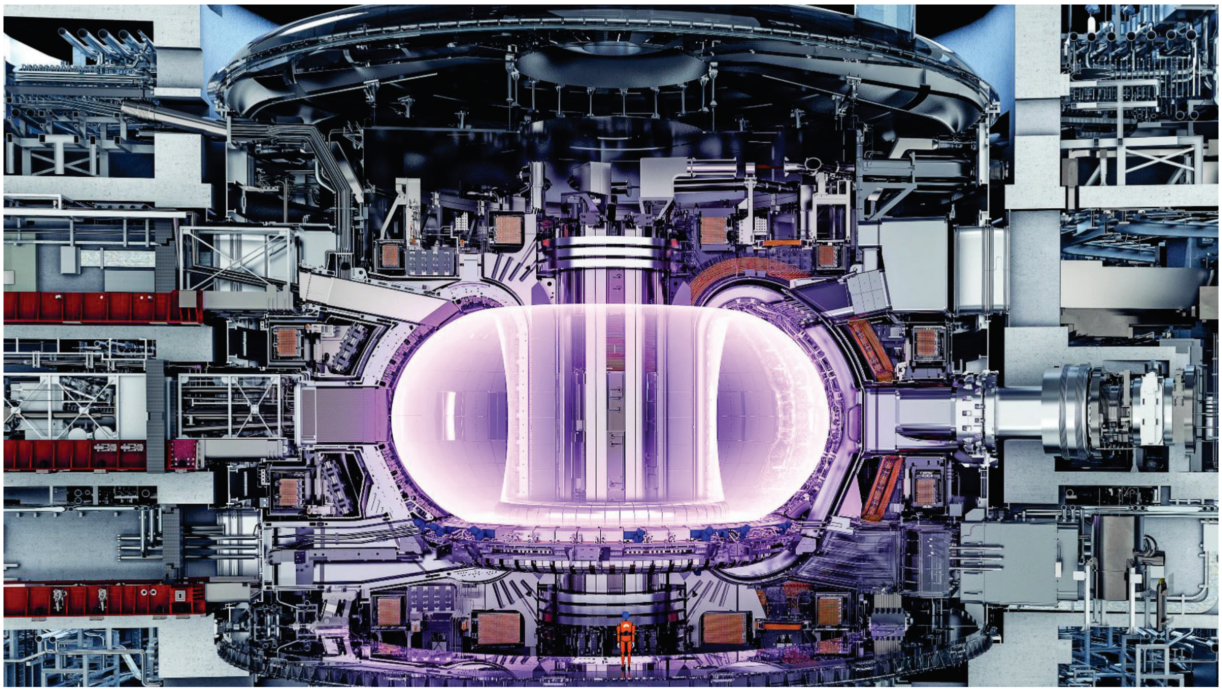


Figure 5.1: Nuclear fusion power station (illustration).

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.

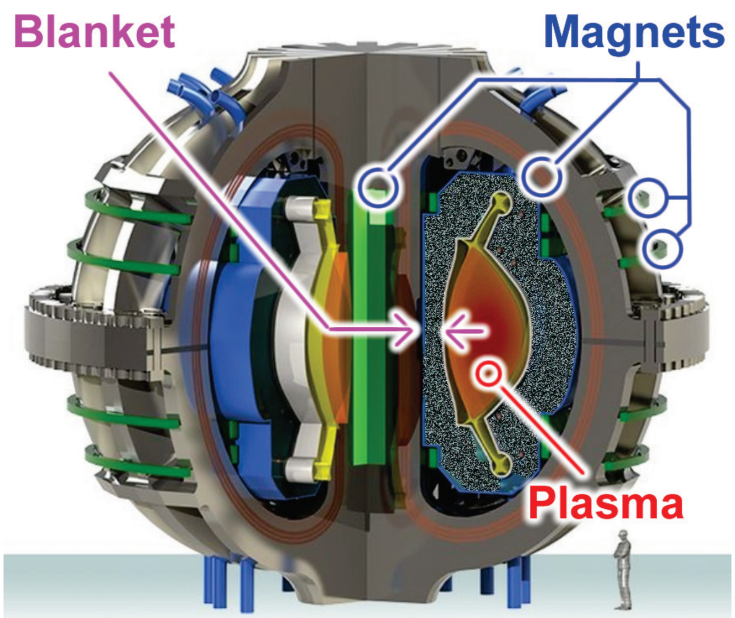


Figure 5.2: Plasma is surrounded by a reactor "blanket" which removes heat and absorbs neutron radiation.

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.

6. 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 6.1: 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.

7. 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 the cost of green manufacturing, this might be a good time to explore new transportation systems, an example of which is illustrated below.

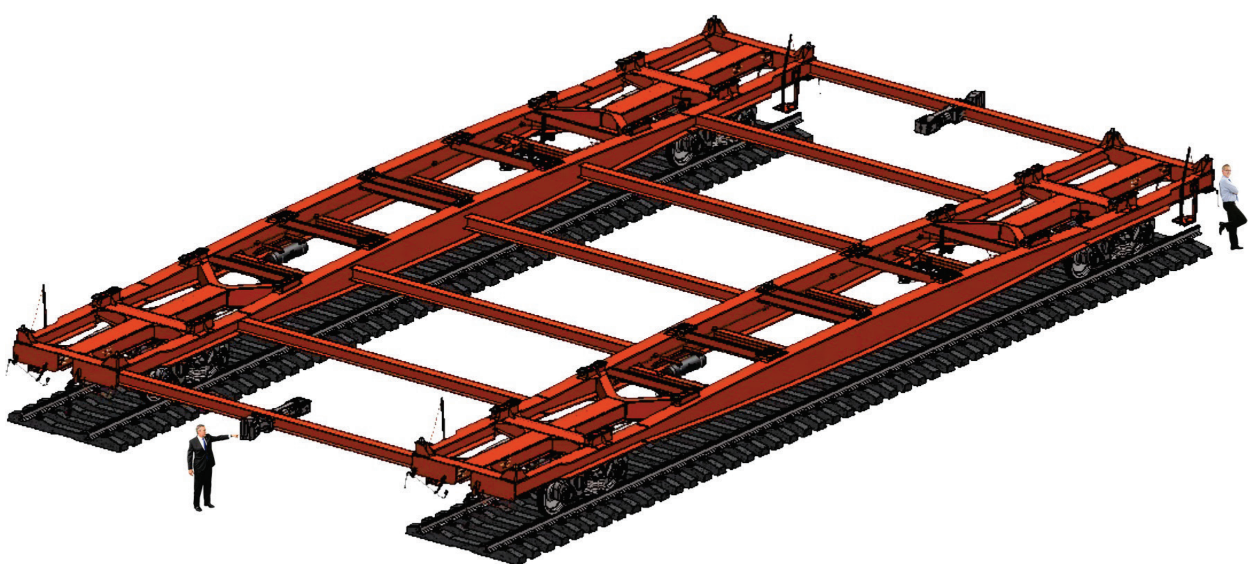


Figure 24.2: Super-sized 12 x 24m railcar (concept illustration by Weinreb).

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.

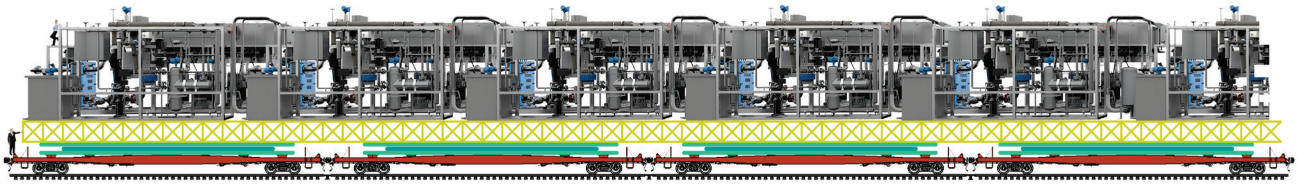


Figure 24.3: Large platform of equipment transported on long straight truss (concept illustration by Weinreb).

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.

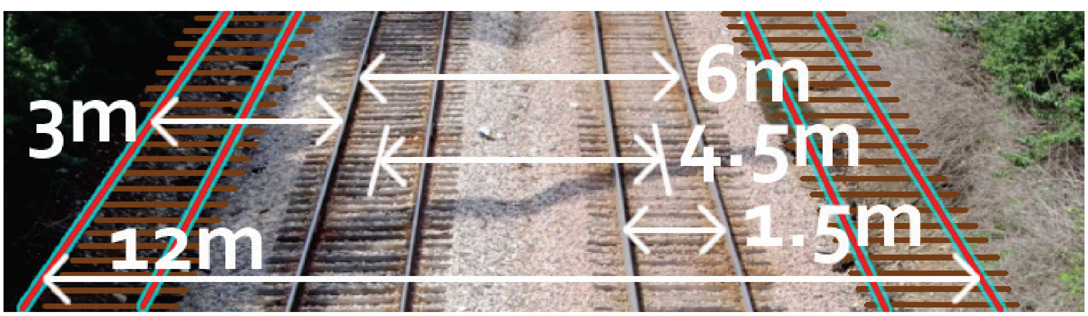


Figure 24.4: Traditional rail co-located with extra-wide rail.

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.

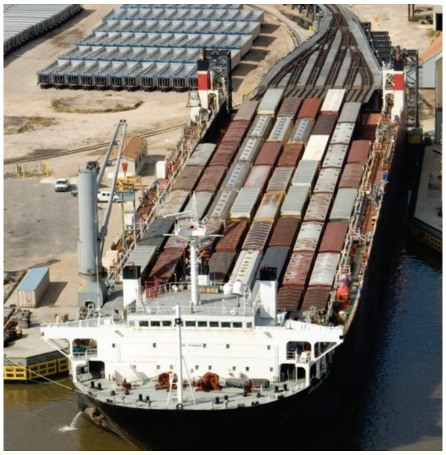


Figure 24.5: Railcars transported by ship.

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.

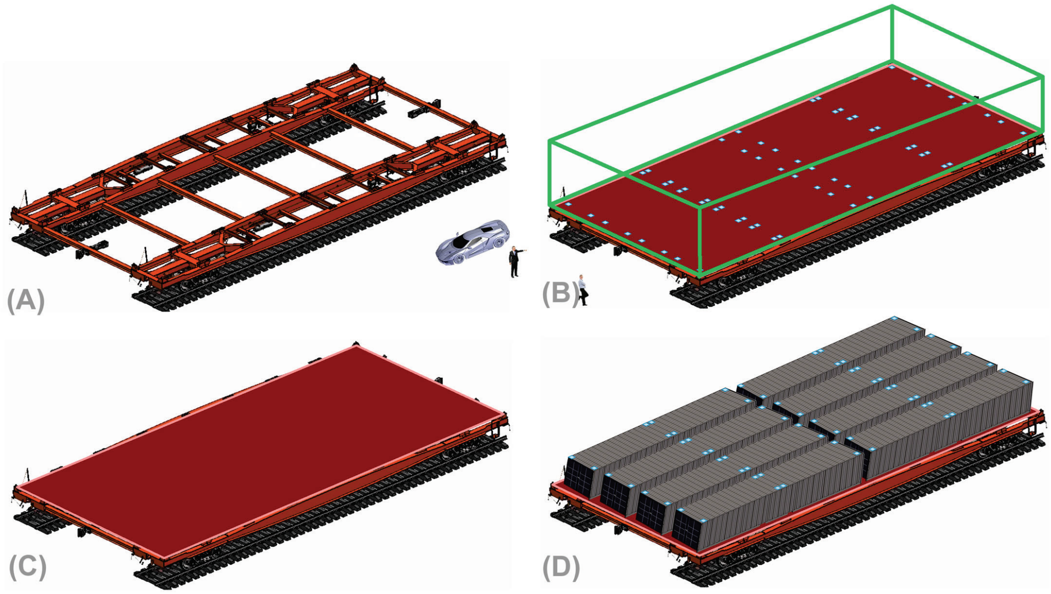


Figure 24.6: Super-sized railcar supports standard-sized containers (concept illustration by Weinreb).

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.

8. 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.

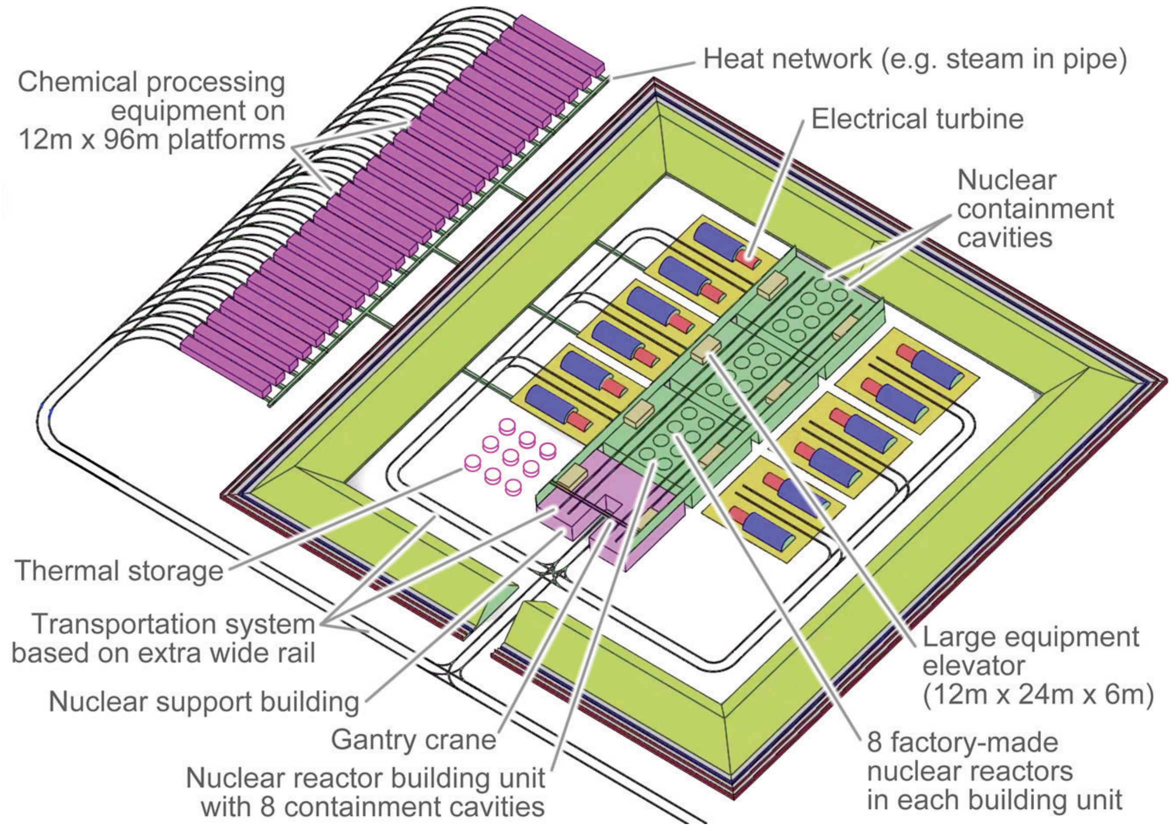
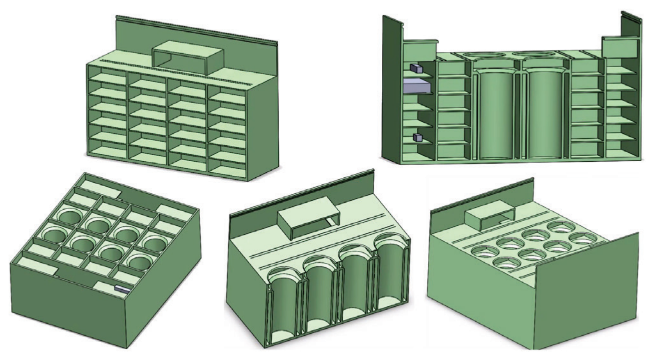


Figure 8.1: High-temperature standardized green manufacturing site (concept illustration by Weinreb).

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*.



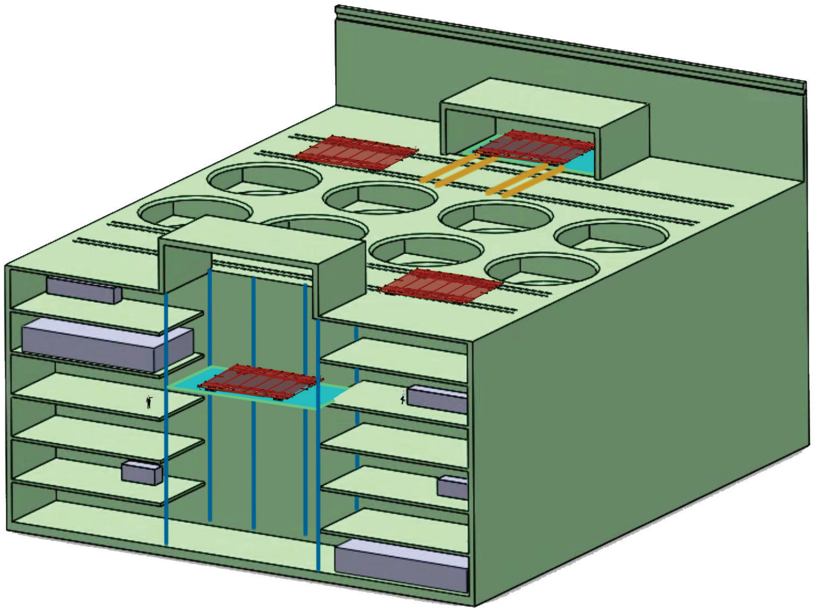


Figure 8.2: Building contains factory-made nuclear reactor equipment transported via extra-wide rail (concept by Weinreb).

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 and concentrated solar.
- 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

In theory, we can decrease the cost of high-temperature green manufacturing with more R&D. However, this might require a visionary leader within in a government or a foundation who is willing to explore large next-generation systems.

9. 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 = $h \times \pi \times r^2$ = 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)*.

10. 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.

11. 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.

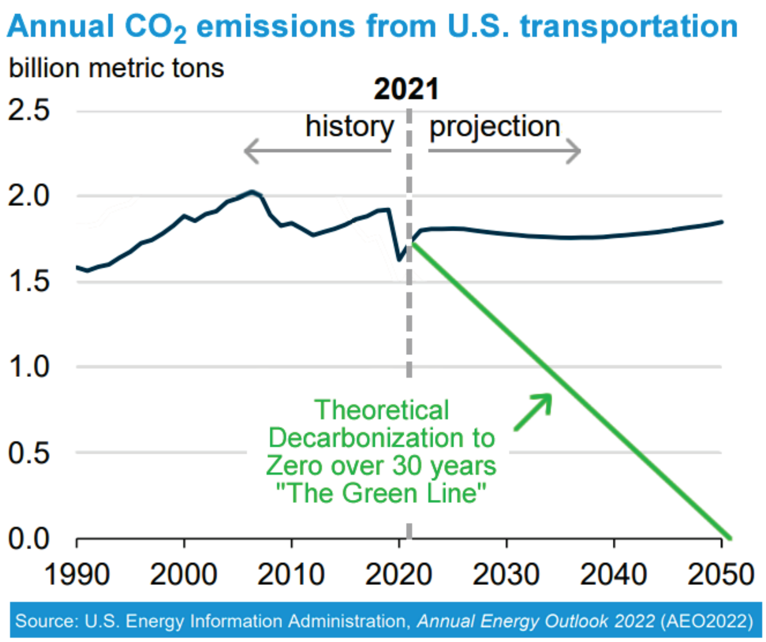


Figure 11.1: Projected annual CO_2 emissions from U.S. transportation.

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 11.2: 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.

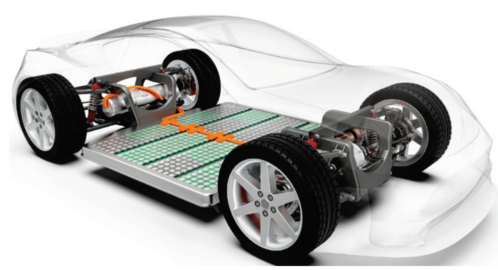
The greatest challenge with fast charging cannot be seen. It is electricity. The typical 50kWh EV battery consumes 100kW of power when charging in 30 minutes (100kW x 0.5h). This is the same amount of power drawn by 80 U.S. homes on average. In other words, supporting large amounts of power is expensive,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

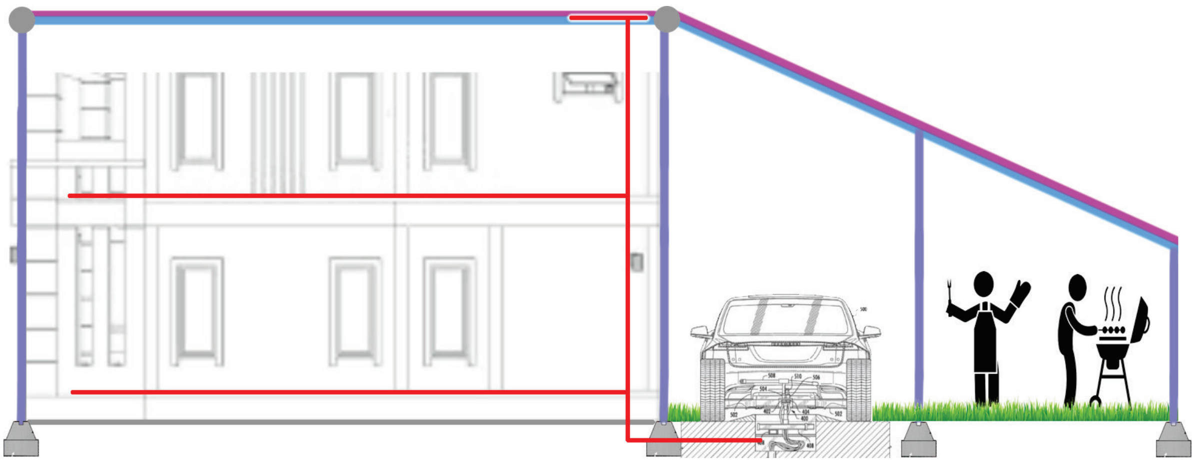


Figure 26.4: EV batteries in swap chamber power homes at night (concept illustration by Weinreb).

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.

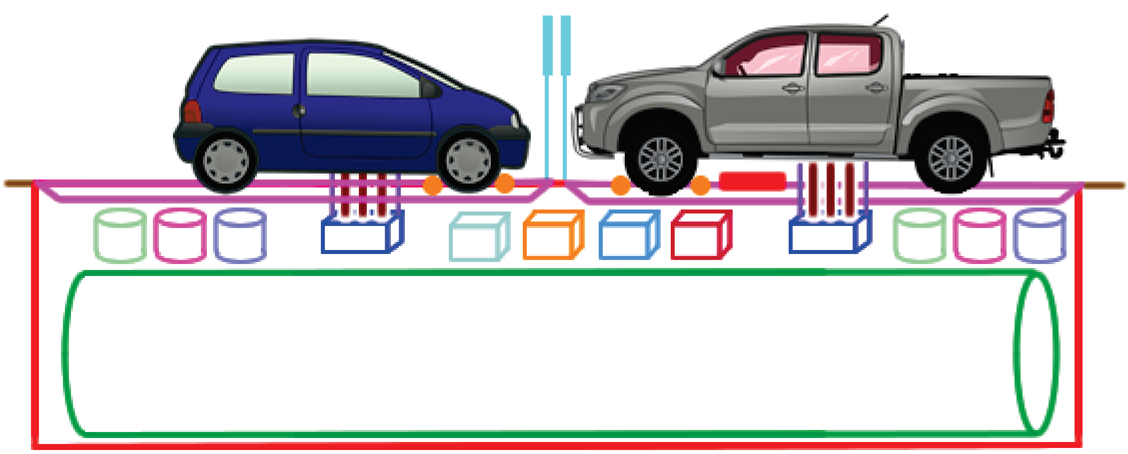


Figure 26.5: Automated refueling (concept illustration by Weinreb)

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.

12. Acknowledgments

Document History

This document draws its inspiration from a book entitled *A Plan to Save the Planet* by Glenn Weinreb.

For a free PDF file of this book, visit www.APlanToSaveThePlanet.org/pdf

For a TEDx video summary, search “KIJsu2n5j1w” at YouTube.

For YouTube videos by Weinreb, see www.YouTube.com/@GlobalClimateSolutions

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