YourName Climate Lab Business Plan

By Dr. X Y

Bifurcation

Example

Table of Contents

1. Executive Summary

This is a business plan for a new R&D laboratory that tackles the climate problem.

We begin with a question:

> *If a new lab was set up,*
> *what might it do that is not already being done,*
> *and has the potential for significant impact?*

The following video explores the answer, and is a summary of this business plan.

> **Do We Need a New Climate R&D Laboratory? (CS12)**
> https://www.youtube.com/watch?v=mIMFC6OM7RY

The Planet is Changing too Fast

We primarily have two climate problems. One is global warming from carbon dioxide, and the other is global warming from tipping points.

We can solve the carbon dioxide problem by replacing fossil fuel with green energy. However, this will probably not solve the tipping point problem. We seem to be tipping too fast. Therefore, we probably need to reflect a tiny percentage of sunlight back into outer space. There are several ways to do this, one of which is to inject sulfur, into the atmosphere, above where airplanes typically fly.

Sulfur is contained within coal and oil, and is therefore commonly emitted upon combustion. In theory, we can filter it out before combustion, move the harvested sulfur to an airplane, and emit it at a high altitude, instead of a low altitude. High altitude sulfur stays aloft for a year or two, while low altitude sulfur typically stays aloft for several days. Therefore, changing the emissions site reduces the temperature of the planet, while not increasing total sulfur emissions. The latter point is important, since sulfur is harmful to people, plants and oceans.

Increasing atmosphere reflectivity is a new field and there are many things we don't know. We don't know what to inject, when, where and how. And we don't have an accurate assessment of cost, and adverse side effects. To resolve unknowns, the proposed Lab does R&D. This includes developing better instrumentation for measuring atmospheric reflectivity, developing equipment that injects small amounts of material for field experiments, and developing equipment that injects large amounts of material for full scale operations.

Decarbonization

Approximately one-third of carbon dioxide emissions are from electrical power generation, one-third from material and chemical production, and one-third from transportation. And a small percentage is due to natural gas based building heat.

The Lab works on all of these. This includes commercial fusion (Chapter 3), improved fission (Chapter 4), tracking systems for materials and chemicals (Chapter 9), and standards for automating buildings (Chapter 19).

Resolving Climate at Lowest Cost

The following question is of profound importance, yet rarely discussed:

> *If we resolved climate change at the lowest cost to society,*
> *what would we do physically,*
> *and how much would it cost?*

The Lab approaches the climate problem from this perspective, as summarized in the following video:

> **How Much Does it Cost to Fix the Climate Problem? (CS11)**
> https://www.youtube.com/watch?v=Q0TyImEEk9I

Communicating with the Public

The Lab explains the planet problem to the public with two websites. One focuses on climate science, while the other focuses on carbon dioxide policy. For details, see the following videos.

> **How to Resolve Climate Tipping Points (CS9)**
> https://www.youtube.com/watch?v=x6wE6AOVPxw

> **Policy Tools are Needed to Tackle Climate Change (CS8)**
> https://www.youtube.com/watch?v=gwPMe29F8Ag

Mission

The Lab's mission is to:

> **Save the planet from climate change**

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.

In 1940 MIT President Karl Compton mobilized his resources to tackle the war problem in Europe. More specifically, he set up a laboratory to develop radar and other microwave technology. Some historians credit this with helping to win World War II.

Fast forward to today, 84 years later, and we have MIT President Sally Kornbluth exploring how to mobilize her resources to save the world from climate change. Like her predecessor, this involves identifying large projects that are not being done, and have the potential for significant impact. Decisions about what to work on, and how to approach each project, are of profound importance.

This business plan is the culmination of four years of research by The Manhattan 2 Project, a non-profit based in Cambridge, MA. All materials produced by this organization are open-source, and are therefore available to be used in any way for free.

2. 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 2.1: Jet Propulsion Laboratory in California, USA.

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.

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.

3. Achieve Commercial *Fusion* within Several Years

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.

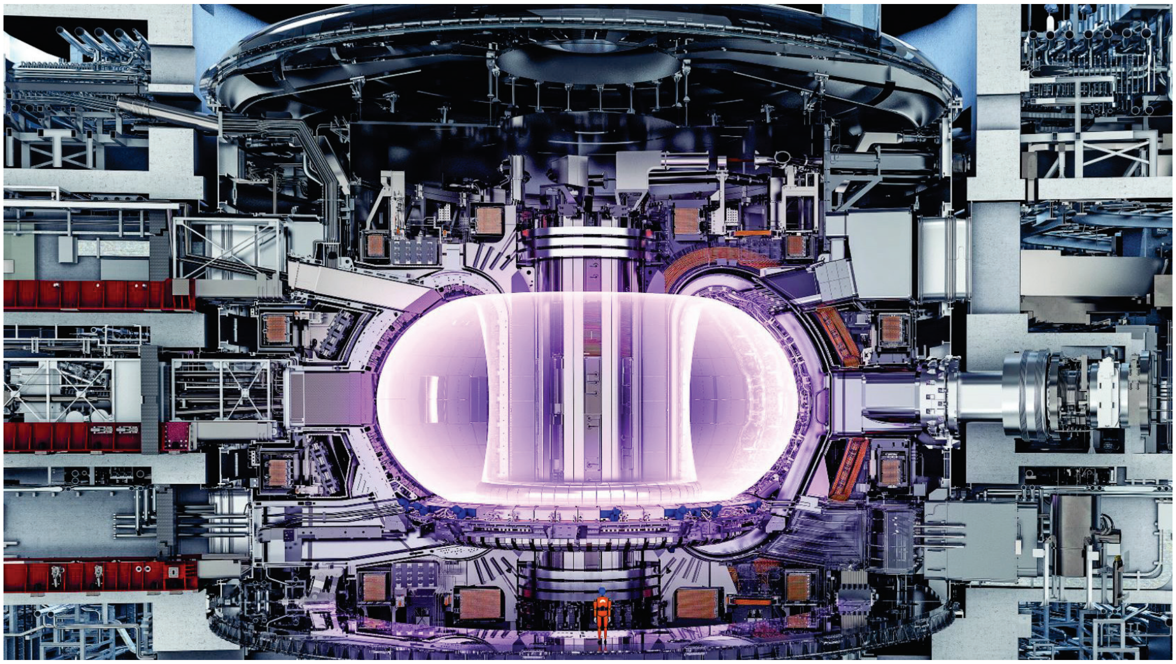


Figure 3.1: Nuclear fusion power station (illustration).

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 several 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 several years.*

The Lab's Role

The lab assumes billions of additional dollars will be available for a commercial fusion moonshot program, and gets it started with a multimillion dollar proposal writing and design fund, overseen by the world's top scientists.

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. 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: Unobtainium

Metals are corroded by molten salt, and made brittle by helium. Unfortunately, this presents a major obstacle to achieving commercial fusion.

Challenge #4: 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.

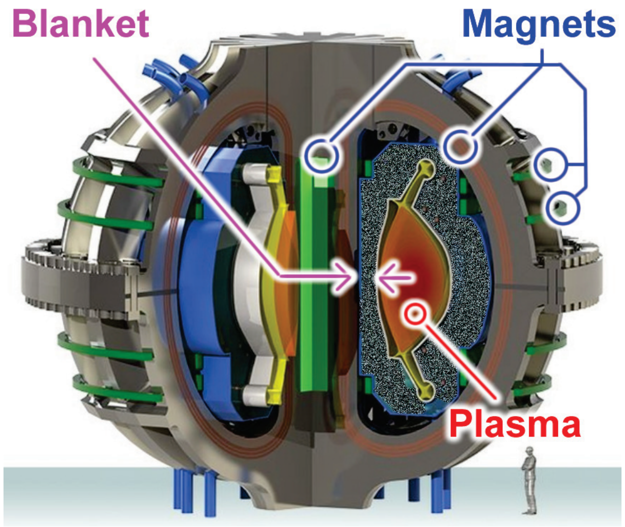


Figure 3.2: Plasma is surrounded by a reactor "blanket" which removes heat and absorbs neutron radiation.

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.

Challenge #5: Remove Heat

The fusion machine generates two types of heat, both of which need to be removed. One is from photons that radiate against the internal surface of the donut-shaped confinement chamber. And the other is from neutrons that penetrate beyond that surface and heat the blanket. Penetration occurs for about a meter; however, most heating occurs within the first 20cm. The main purpose of the blanket is to capture this heat and move it outward, as illustrated in the figure below.

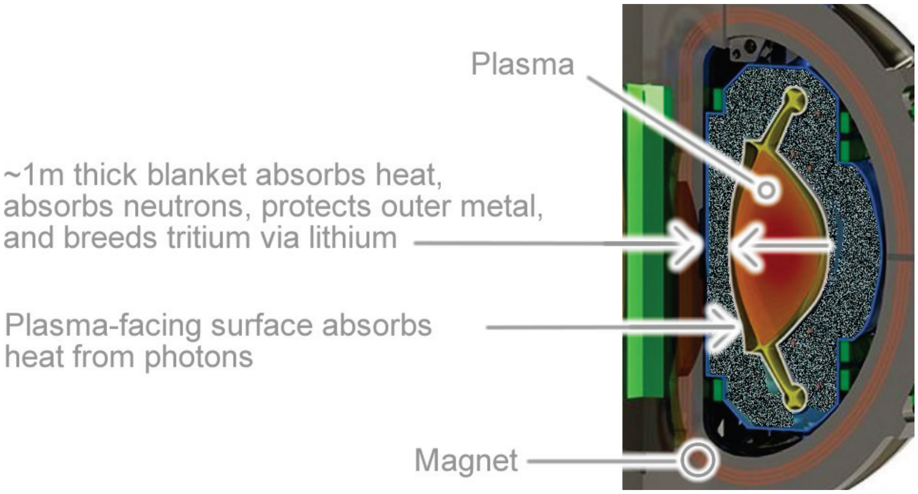


Figure 3.3. Blanket absorbs neutrons, moves heat outward, protects external structure from neutron damage, and makes more tritium via lithium.

Typical fusion internal surface heating is 1 megawatt of power per square meter ($1MW/m^2$). This is challenging, especially in the presence of strong magnetic fields and neutron radiation. For reference, a sunbather incurs $0.001MW/m^2$ of surfacing heating, and a space ship re-entering the atmosphere incurs 500-times more.

Cost is somewhat proportional to toroidal volume, and most of the volumetric heat is delivered to the first 20cm of volume within the blanket. Therefore, to be economically viable, the machine must move approximately $20MW/m^3$ of energy *into* this volume via neutrons, and move it *out* via flowing liquid. The average American home consumes ~0.001MW of electricity; therefore, this is like moving 20,000 homes worth of electricity into a cubic-meter via radiation, and then moving it out via flowing liquid.

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.”

Further Reading

- When will Fusion Power be Available Commercially?
- What Might a $10B Fusion R&D Initiative Look Like?
- What would it take to get Commercial Fusion running this decade?

4. Improve Nuclear *Fission*

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 with a fission R&D initiative, perhaps driven by the following goal:

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

The Lab's Role

The Lab assumes billions of dollars will be available for a fission moonshot program, and gets it started with a multimillion dollar proposal writing and design fund, overseen by the world's top scientists.

This includes developing a program that makes safe reactors quickly by copying an extra-safe, currently operating, commercial reactor. More specifically, the Lab (a) selects an existing reactor to commoditize, (b) sets up a manufacturing license that enables responsible parties to utilize the design at a reasonable cost, (c) improves the design to the satisfaction of U.S. and European regulators, (d) has the design certified in both the U.S. and Europe, and (e) builds one unit as quickly as possible. The latter step is probably implemented in China since they can build quickly.

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 4.1: 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.

National Fission Strategy

To meet the satisfaction of the public one must contend with: (a) meltdown risk, (b) nuclear waste, (c) nuclear bomb proliferation risk, and (d) high cost. To address the first three concerns, a nation could establish stricter safety standards for both new and existing reactors. Otherwise, in many cases, new reactors are not likely to be built and existing reactors are likely to be shut down. Below is an example safety standard:

- Loss of coolant does not result in a meltdown via negative temperature coefficient fuel.
- Nuclear fuel does not react with air or water and does not make them radioactive.
- The reactor does not produce waste that lasts longer than *X* years.
- Fuel is proliferation resistant.
- Existing reactors are *rebuilt* by the year 20xx to meet a new safety standard or shut down.

The Lab suggests a safety standard that meets the satisfaction of the public. It does this by exploring the various options, conducting focus groups, and interviewing lawmakers. Ultimately, this might evolve into a national fission strategy.

5. The Climate Problem

There are multiple components to global warming, each of which are shown below.

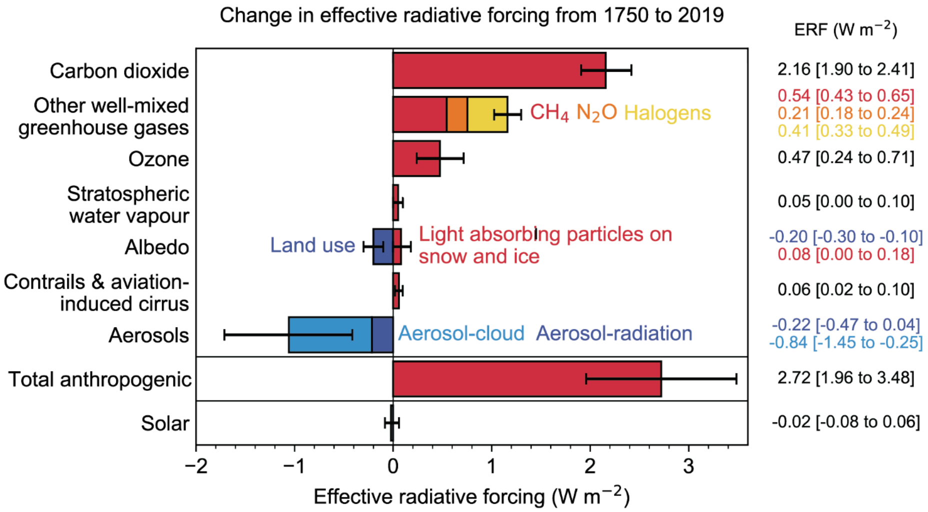
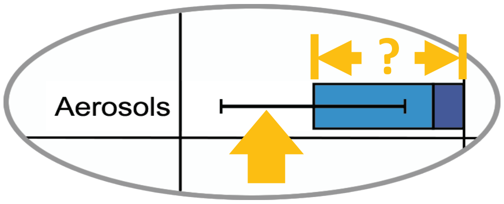


Figure 5.1: Global warming components. Source: IPCC AR6, Figure 7.6.

Some components increase global warming, whereas others decrease global warming (shown above in blue). These combine, to get total warming, which is the same as observed warming.



One of the components is global cooling, which is caused by sunlight reflecting off of particles and droplets in the atmosphere. In some cases, this is caused by air pollution. What is fascinating about this component is the error bars. These tell us that climate scientists do not know if this is a little, or a lot. Unfortunately, the difference between these two is profound.

If planet cooling is large, then climate models say significant changes will occur to our planet over the next 30 years. Otherwise, if planet cooling is small, climate models tell us changes will occur more slowly. IPCC reports that appear on the desks of national leaders, are based on models that assume cooling is moderate, and changes will occur more slowly. However, these models are not consistent with actual measurements.

For example, satellites measure global warming in the atmosphere verses time, as shown below.

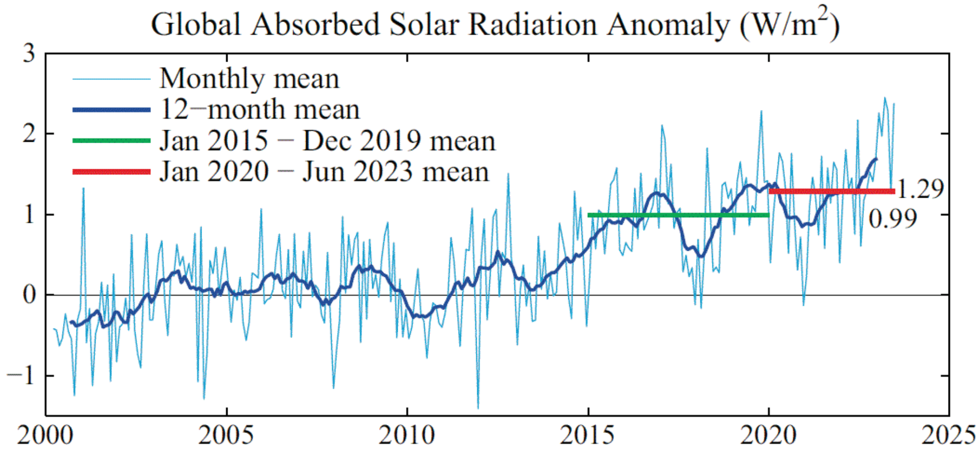


Figure 5.2: Global absorbed solar radiation (W/m^2) relative to mean of first 120 months of CERES data. Source: Global Warming in the Pipeline, Hansen et al., 2023.

They see one “blanket” around the planet, due to 150 years of carbon dioxide and methane emissions. And they see a 2nd blanket, of comparable size, appear over the last 10 years. This 2nd blanket is not explained by carbon dioxide, methane, or tipping points. This might seem crazy, yet this is seen by satellites, and this was the focus of *Global Warming in the Pipeline*.

This was one of the most important climate papers published in 2023. Author James Hansen was the director of the NASA Goddard Institute for Space Studies, for 32 years, and is considered to be one of the world's top climate scientist. According to Hansen, the leading explanation for this 2nd blanket is the world reduced air pollution, starting about 10 years ago. And this caused less sunlight to reflect back into outer space. In other words, less air pollution, leads to less reflected sunlight, which leads to less cooling and more warming. It turns out, reflecting just 1/400th of sunlight has a big impact.

Our 2nd blanket is also seen by global temperature measurements. More specifically, global temperature increased 0.18°C per decade between 1970 and 2010, and this rate seems to have increased 50% to 100% over the last 10 years.

In other words, global warming is accelerating, due to less air pollution and tipping points. And the climate problem has probably been understated by most climate scientists because they do not know how much sunlight reflects off air pollution.

Author's note: I apologize if this chapter sounds crazy.

6. Stratospheric Aerosol Injection

We can solve the carbon dioxide problem by replacing fossil fuel with green energy. However, this will probably not solve the tipping point problem. We seem to be tipping too fast. Therefore, we probably need to reflect a tiny percentage of sunlight back into outer space. There are several ways to do this, one of which is to inject sulfur, into the atmosphere, above where airplanes typically fly.

Sulfur is contained within coal and oil, and is therefore commonly emitted upon combustion. In theory, we can filter it out before combustion, move the harvested sulfur to an airplane, and emit it at a high altitude, instead of a low altitude. High altitude sulfur stays aloft for a year or two, while low altitude sulfur typically stays aloft for several days. Therefore, changing the emissions site reduces the temperature of the planet, while *not* increasing total sulfur emissions. The latter point is important, since sulfur is harmful to people, plants and oceans.

The Lab's Role

Increasing reflectivity is a new field and there are many things we don't know. We don't know what to inject, when, where and how. And we don't have an accurate assessment of cost, and adverse side effects. To resolve unknowns, the proposed Lab does R&D. This includes developing better instrumentation for measuring atmospheric reflectivity, developing equipment that injects small amounts of material for field experiments, and developing equipment that injects large amounts of material for full scale operations.

Further Reading

- Geoengineering Earth’s climate future: Straight talk with Wake Smith
- Solar geoengineering could start soon if it starts small, By David W. Keith & Wake Smith
- The cost of stratospheric aerosol injection through 2100
- Pandora's Toolbox: The Hopes and Hazards of Climate Intervention
- How Much Does it Cost to Fix the Climate Problem? (CS11 Video)
- Do We Need a New Climate R&D Laboratory? (CS12 Video)

7. Planet Dashboard Website

In order to survive climate change, the public needs to understand the problem, and the solution. To communicate this, the proposed Lab maintains a planet dashboard. This would be a website that explains what is expected to happen to the planet, each year, over the next few hundred years. It does this with graphs that show expected global temperature increase, sea level rise, food production decrease, planet cooling needed to block an insane sequence of events, and amount of money lost due to global warming. In other words, the planet problem is summarized with several graphs.

Also, the user can drill down and see components that make up each graph. For example, global temperature increase is the sum of temperature increase from carbon dioxide, temperature increase from melting sea ice, temperature increase from thawing permafrost, etc. Component graphs are helpful since they would illustrate what is expected to happen when, where, and to what extent. And this would help the public understand, the expected, sequence, of events.

Each event is typically associated with a tipping point. These are activated by heat. And after being activated, they create more heat. In other words, they activate each other, and are therefore like dominos. For example, melting North Pole sea ice is expected to cause snow on Greenland to melt, which will reduce ocean currents, which will decrease moisture in soil, which will reduce food production. More specifically, a recent study predicts the amount of global land, suitable for growing corn and wheat, to decrease 2-fold, by the year 2055.

This begs an important question:

> *How much does it cost to block the first tipping point?*

The planet dashboard calculates this, and plots this cost as a function of time. And this enables the website user to compare the cost of cooling the planet, with the cost of *not* cooling the planet.

The website's graphs are generated by climate models. These are confusing; therefore, they are selected by top scientists, and the website user selects a scientist, not a model. For example, one website user might trust the leader of the IPCC, while another user trusts the leader of NOAA.

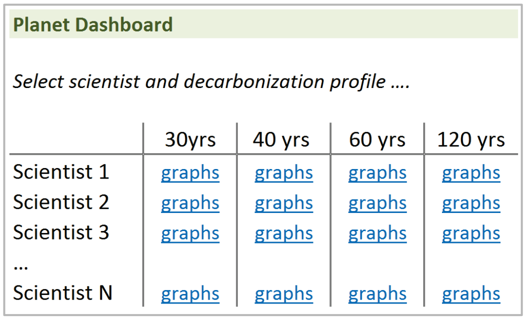
The website user must also specify how many years they expect our society to emit carbon dioxide. Many economists expect this to be over 100 years, while climate activists prefer less than 40 years.

After the user selects a climate scientist, and a decarbonization profile, the graphs appear. These are important, since they help the public better understand the climate problem. And they illustrate how, when and why we might block tipping points.

For details, see the following videos.

How to Resolve Climate Tipping Points (CS9)
https://www.youtube.com/watch?v=x6wE6AOVPxw

Do We Need a New Climate R&D Laboratory? (CS12)
https://www.youtube.com/watch?v=mIMFC6OM7RY



Planet Dashboard

Select scientist and decarbonization profile ….

	30yrs	40 yrs	60 yrs	120 yrs
Scientist 1	graphs	graphs	graphs	graphs
Scientist 2	graphs	graphs	graphs	graphs
Scientist 3	graphs	graphs	graphs	graphs
…				
Scientist N	graphs	graphs	graphs	graphs

8. Climate Plan Website

It is unlikely lawmakers would support major changes to their economy without a detailed climate plan. These plans do not exists; however, they could be generated with a little software and existing economic models.

The proposed Lab remedies this with a website that creates a plan after the user specifies a climate strategy. For example, the website user might want to "Decarbonize nation Z, over X years, at lowest cost, in lowest cost order, with additional costs passed onto consumers."

The website would then produce a climate plan, which would be a list of initiatives that are implemented each year, over the next few decades. For each initiative, the following would be estimated: cost ($), carbon dioxide reduced ($mtCO_2$), and cost per ton of carbon dioxide reduced ($\$/mtCO_2$). This might seem like artificial intelligence; however, economists have methods for producing this information without AI.

The Lab's Climate Plan website would support multiple nations, since everyone needs to decarbonize, not just one nation.

Climate Costs

The Lab's Climate Plan website answers the following question:

How much does it cost to fix the Climate Problem?

An example answer is shown in the following table.

	Year 1	Year 2	Year 3	…	Year 10	…	Year 20	…	Year 30
Planet Cooling R&D	$5	$5	$5	…	$5	…	$5	…	$5
Planet Cooling Op.				…	$27	…	$27	…	$27
Green Premium	$10	$20	$30	…	$142	…	$445	…	$727
More R&D	$30	$30	$30	…	$30	…	$30	…	$30
TOTAL	$45	$55	$67	…	$204	…	$507	…	$789

Figure 8.1: Estimated decarbonization costs in units of dollars-per-American-per-Year.

All numbers are in units of dollars cost per American per year. Europeans would see similar numbers. These costs would show up as an increase in the cost of goods and services, in addition to money spent by government. Costs are divided into three categories: planet cooling, additional cost for green products, and more R&D. The above table assumes decarbonization occurs over 30 years, at a constant rate. And it assumes decarbonization green premium costs start out at $20 dollars per ton of carbon dioxide reduced, and increase, over 30 years, to $80 dollars per ton.

The left part of the table looks at Years 1, 2, and 3. While the right part of the table looks at Years 10, 20, and 30. One might think of these as the "early years" and the "later years". The early years are relatively easy, since green premium costs are proportional to the amount of carbon dioxide reduced, and initially this is small.

For details on climate plan website, and climate costs, see the following videos:

Policy Tools are Needed to Tackle Climate Change (CS8)
https://www.youtube.com/watch?v=gwPMe29F8Ag

How Much Does it Cost to Fix the Climate Problem? (CS11)
https://www.youtube.com/watch?v=Q0TyImEEk9I

Do We Need a New Climate R&D Laboratory? (CS12)
https://www.youtube.com/watch?v=mIMFC6OM7RY

Further Reading

- Proposal to Develop On-line Climate Policy Making Tools

9. Material and Chemical Decarbonization

Approximately one-third of carbon dioxide emissions are from electrical power generation, one-third from material and chemical production, and one-third from transportation.

The Lab develops systems that use capitalism to decarbonize the production of chemicals and materials, at lowest cost and at large scales. It does this by developing tracking systems and master distributors, as described in the following video.

How to Decarbonize the Making of Materials & Chemicals (CS10)
https://www.youtube.com/watch?v=nqGALLC-R1k

10. 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 (~$15/mt$CO_2$ extraction cost) than to extract from natural gas-fired electricity generation with 10% CO_2 exhaust (~$60/mt$CO_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 $/mt$CO_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 $CO_2 = h \times \pi \times r^2 = 100m \times 3.14 \times 10{,}400m^2$).

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.

The Lab's Role

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:

- Do 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.

Further Reading

- What is our Long Term CCS Strategy?

11. 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. Unfortunately, the sea is expected to rise geometrically. More specifically, we can expect a small amount of sea level rise over the next 30 years, and multiple meters between 2050 and 2150.

DAC Challenges

For the above stated reasons, there is interest in DAC. However, DAC will probably never see large scale implementation due to lower cost options. These are summarized as follows.

- Extracting CO_2 from a gas that is 0.04% CO_2 cost more than extracting from a gas that is 10% CO_2. In other words, it cost more to extract from atmosphere via DAC (e.g. ~\$1000/mtCO_2), than to extract from fossil fuel combustion exhaust via CCS (e.g. ~\$100/mtCO_2).
- Solar farms and wind farms (e.g. ~\$20/mtCO_2) cost less than DAC (e.g. ~\$1000/mtCO_2).
- Stratospheric Aerosol Injection (SAI) cost less than DAC.

The Lab's Role

Even with these economic challenges, the Lab studies how to reduce DAC costs.

Further Reading

- What is our Long Term CCS Strategy?

12. Super-Sized Transportation

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 12.1: Ship-mounted chemical 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.

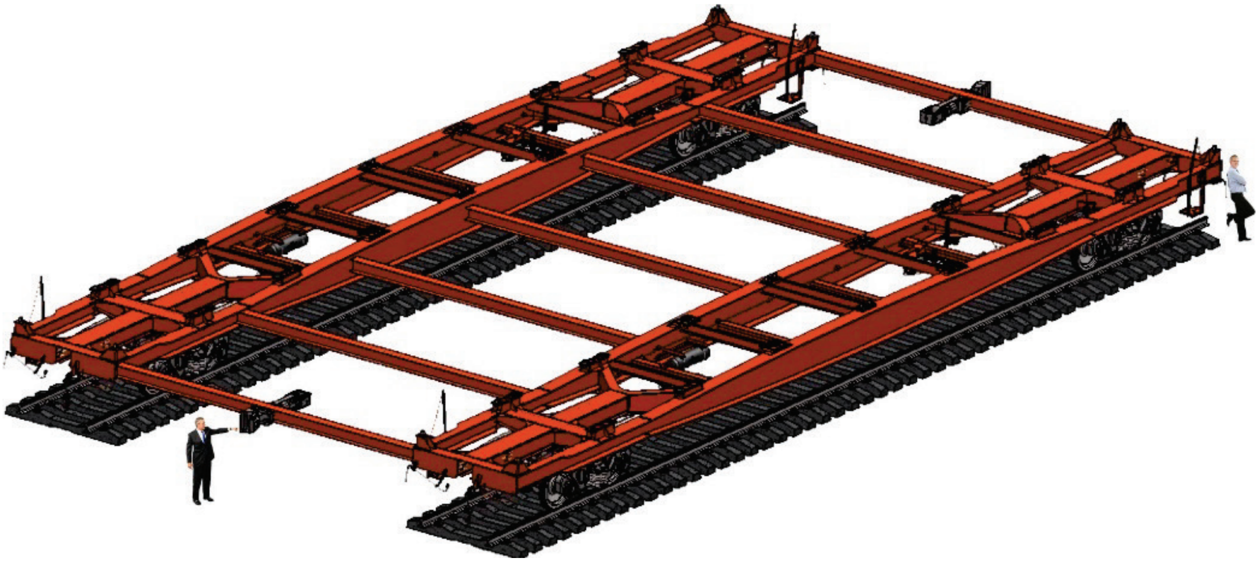


Figure 12.2: Super-sized 12 x 24m railcar (concept illustration by Weinreb)

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.

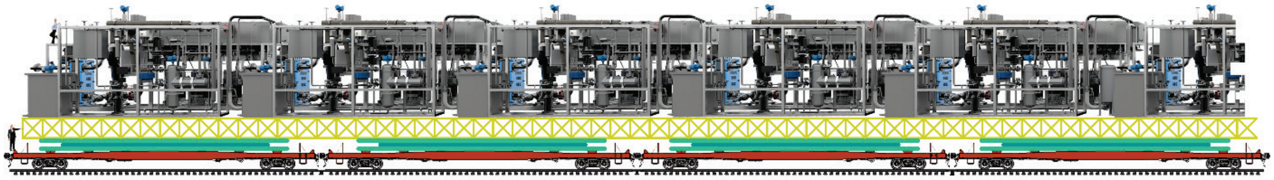


Figure 12.3: Large platform of equipment transported on long straight truss (concept illustration by Weinreb).

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.

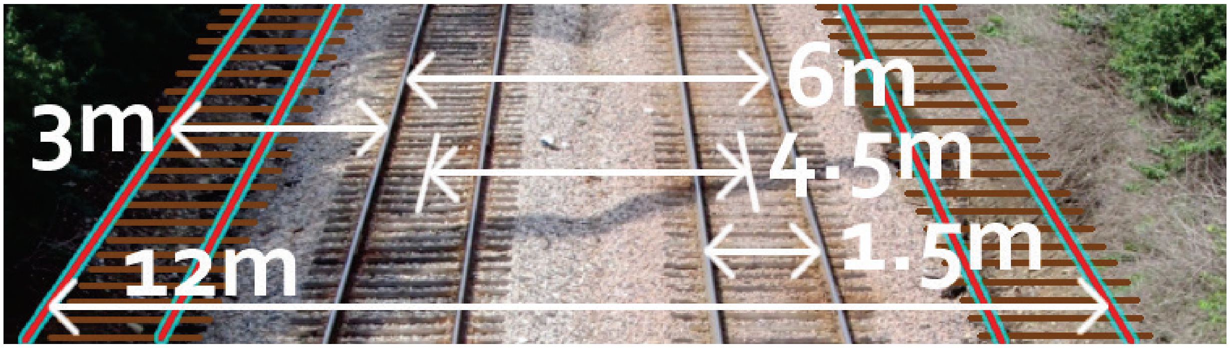


Figure 12.4: Traditional rail co-located with extra-wide rail.

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

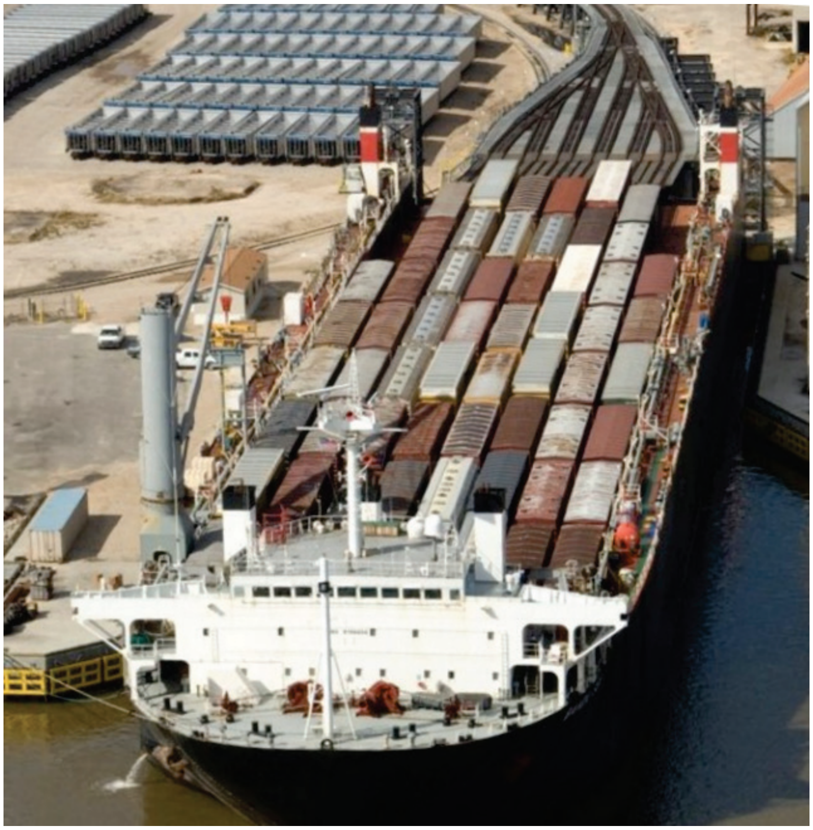


Figure 12.5: Railcars transported by ship.

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.

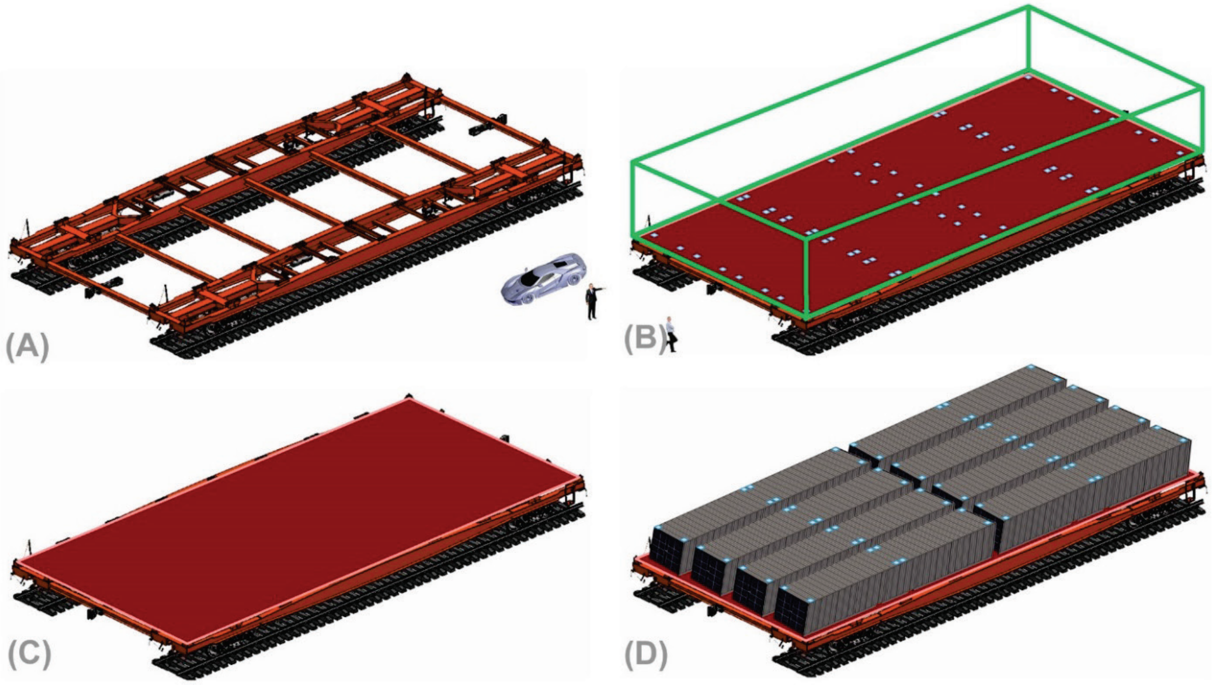


Figure 12.6: Super-sized railcar supports standard-sized containers (concept illustration by Weinreb).

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.

The Lab's Role

The Lab develops standardized systems that move large and heavy platforms of industrial processing equipment from a factory or shipyard to a distant site. This includes the following:

- Design super-sized railcars and interconnection standards.
- Design rigid platforms that are mounted on multiple railcars. These do not bend while the underlying train moves left-to-right and up-and-down. These enable one to maintain rigidity while moving large platforms of equipment.
- Explore methods of moving portable platforms of industrial processing equipment between a ship and shore. This includes roll-on/roll-off and crane.
- Develops standards that define how components within a global system coordinate. For example, if one moves X tons of size H x W x L from point A to B, the system checks if these parameters are supported along the entire path.

13. Next Generation Industrial Processing

The Lab develops next generation methods for making green chemicals (e.g. hydrogen, ammonia) and making green materials (e.g. plastics, metals, ceramics, glass, cement).

Green Manufacturing at the Lowest Cost

A nuclear reactor in China can make green heat (i.e. zero CO_2 emissions) for approximately $4 per gigajoule (GJ). If one converts wholesale $0.035/kWh green electricity from a solar farm or wind farm to heat, then cost works out to $10 per GJ ($0.035/kWh x 277kWh/GJ). In other words, nations that accept nuclear power might be more competitive in a green new world.

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 below. This is not being done today; however, it might be done in the future, driven by capitalism (i.e. nations that co-locate nuclear reactors and industrial processes might be more competitive).

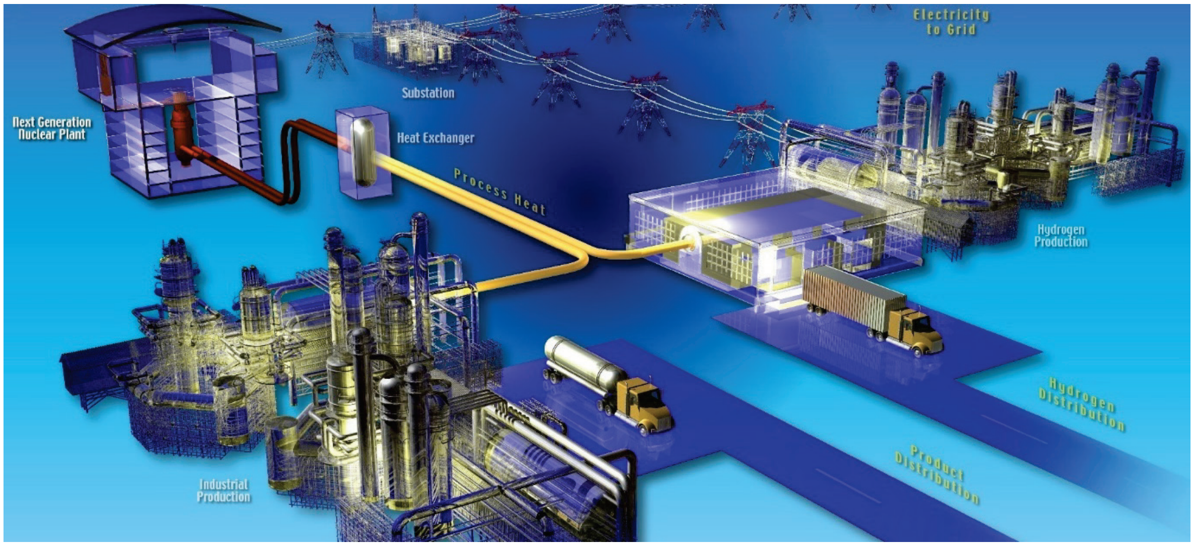


Figure 13.1: Illustration of nuclear reactor co-located with high-temperature manufacturing (Source: Idaho National Laboratory).

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 might 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.

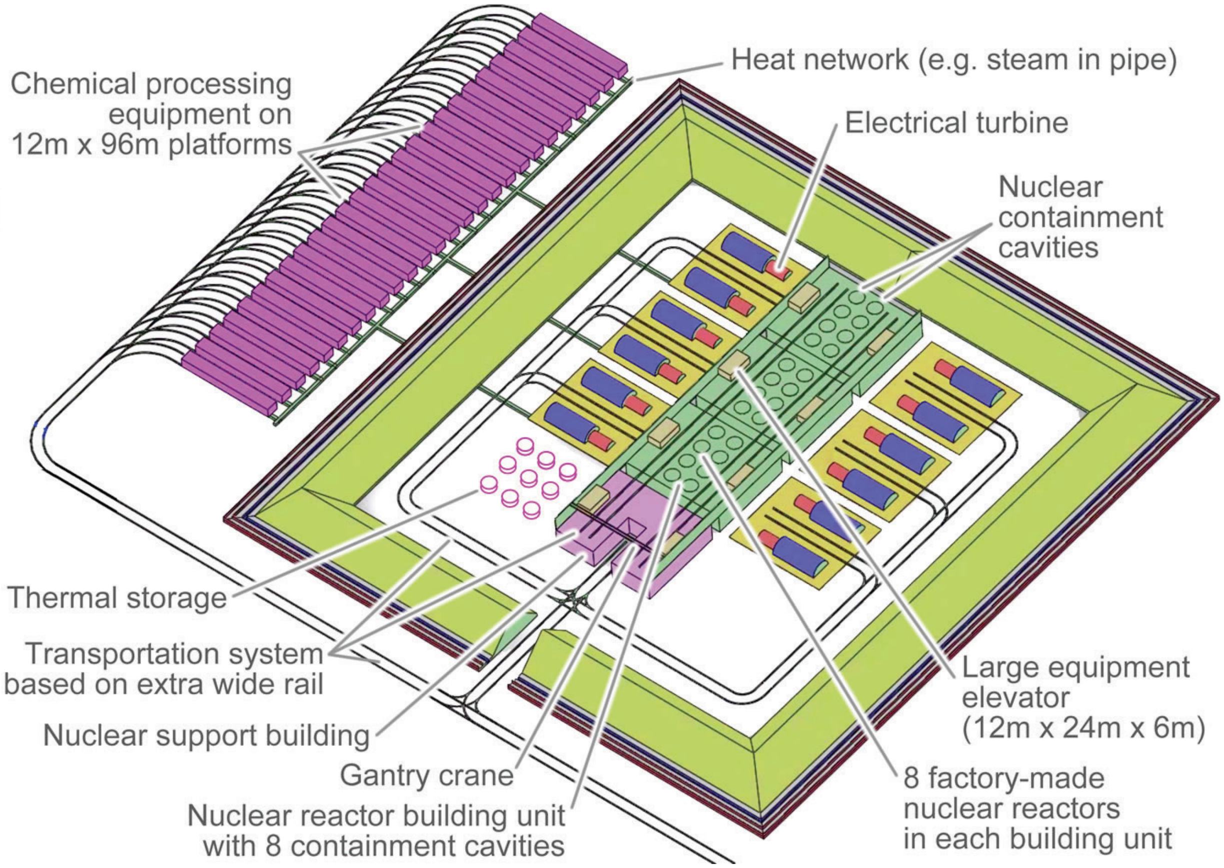


Figure 13.2: High-temperature standardized green manufacturing site (concept illustration by Weinreb).

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.

The Lab's Role

The Lab develop next-generation high-temperature green manufacturing sites, standards, and supporting transportation infrastructure. This includes the following:

- Write software that calculates the lowest cost way to decarbonize industrial processing globally using automated systems. This includes simulating how, when and where these sites might be built given different driving forces such as government requirements, subsidies and carbon taxes. This helps to determine where to place supporting infrastructure such as docks, rail, and a green hydrogen pipe networks.
- Develop mechanical and software standards that define how portable platforms of industrial processing equipment rest on foundations and interface with heat sources (e.g. steam or molten salt pipe network).
- Develop systems and standards that coordinate site-wide industrial processing in real-time. For example, heat is moved to molten salt storage instead of electrical power generation when demand for electricity decreases.
- Develop automated systems that build molten salt storage tanks. This includes working with supplies and equipment on nearby ships and super-sized railcars.
- Develop automated systems that prepare sites with earth moving equipment (e.g. excavate to bedrock). This includes working with supplies and equipment on ships and railcars.
- Develop automated systems that store, transport, prepare and dispense concrete. For example, bins of material and processing equipment reside on nearby ships, rail cars and trucks.
- Develop automated systems that store, transport, prepare and install reinforcing bar (“rebar”).

Further Reading

- A Plan to Save the Planet, Chapter 22, “The Economics of Green Heat”
- A Plan to Save the Planet, Chapter 23, “The Economics of Green Fuel”

14. Custom Solar Skin on Buildings

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

Figure 14.1: Illustration of custom PV solar skin that mounts directly onto plywood and wraps features such as windows and doors (concept illustration by Weinreb).

Custom Solar Fits Together Like a Puzzle

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

In theory, one could do something similar with solar material that directly attaches to external plywood. For example, one could wrap a building with 12 *custom* solar pieces, as illustrated below. In this concept, pieces are outlined in green and numbered; horizontal rails that secure material to external plywood are shown in blue, and brackets that provide a watertight seal at window/door vertical edges are shown in violet.

Figure 14.2: Custom pieces of solar fit together like a puzzle (concept illustration by Weinreb).

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

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

Horizontal Rails Secure Solar Skin to Surface

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

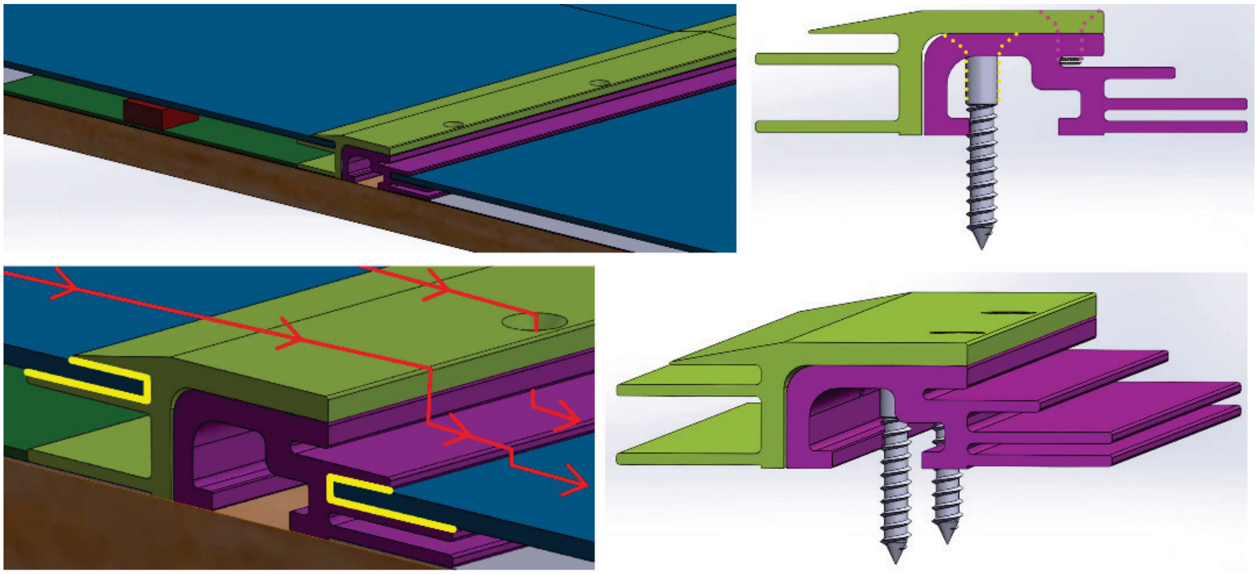


Figure 14.3: Concept illustration of horizontal rails that secure solar material with a watertight seal (Source: UMass Open-Source Solar Design Team sponsored by Manhattan 2).

Why Has This Not Been Done?

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

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

R&D Strategy

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

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

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

Getting Started With a "Small" Budget

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

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

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

The Lab's Role

The lab develops custom solar skins for buildings. This includes the following:

- Develop a standardized custom thin-film solar skin system for newly constructed plywood walls.
- Similar to above yet existing plywood wall.
- Similar to above yet newly constructed plywood roof.
- Similar to above yet existing plywood roof.
- Develop machines that install custom solar skin.
- Develop machines that fabricate custom solar skin.

Further Reading

- How to Cover Buildings with Solar Skins

15. Develop Standardized Solar Subassemblies

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

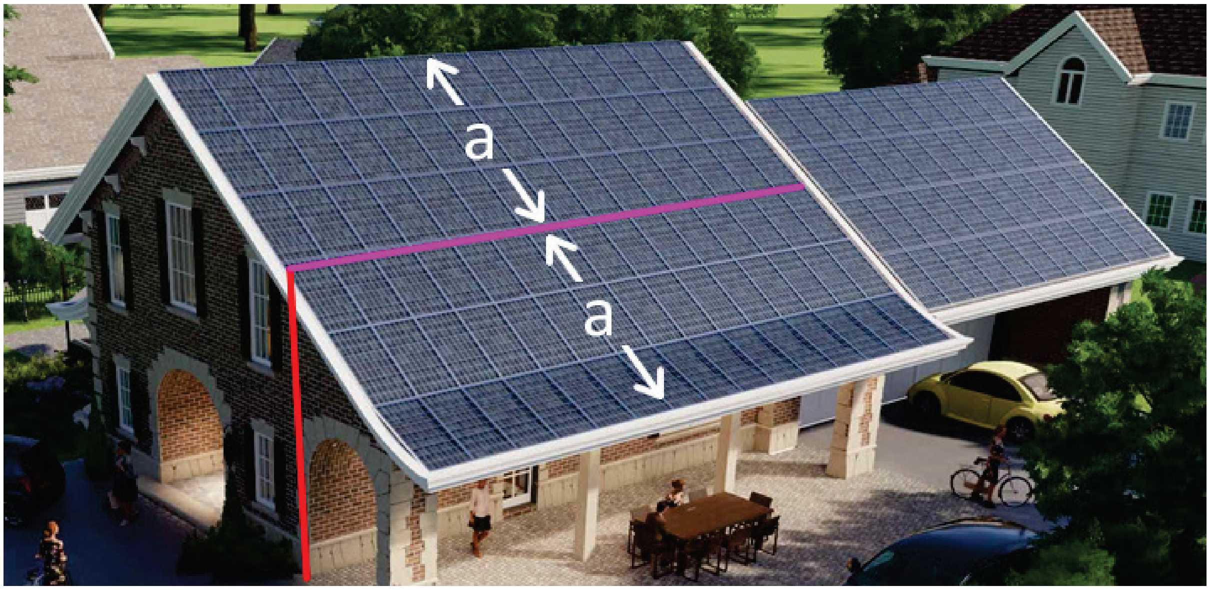


Figure 15.1: Oversized roof supports significantly more solar than a typical residential solar installation (concept by architect John Meyer).

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

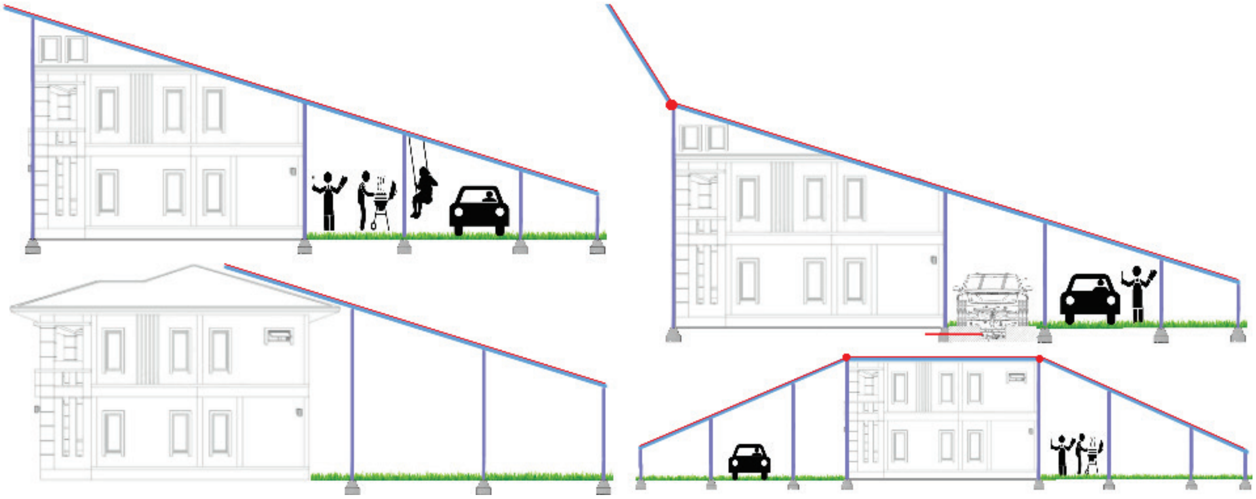


Figure 15.2: External metal framing supports large amounts of solar (concept illustration by Weinreb).

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

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

Reduce Costs with Standardized Sub-Assemblies and Machines

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

Figure 15.3. Standardized sub-assemblies with automated assembly (concept illustration by Weinreb).

The Lab's Role

The Lab develops standards that define sub-assemblies of solar panels held together with metal framing. It also explores and develops machines that automate installation. This includes the following:

- Develop a standard that defines semi-custom sub-assemblies that are characterized by three parameters: length in whole meters, width in whole meters, and number of tilt axes (0, 1 or 2). Maximum length might be 13 meters and maximum width might be 2 meters since this is the largest size supported by standard shipping containers. For example, an architect might use three segments sized at 10 x 2m, 10 x 2m and 10 x 1m to cover a 10 x 5m roof. A factory would fabricate the three semi-custom segments and one would transport to site via a specialized shipping container that holds multiple segments of varying size. A specialized robotic handler might dangle from a crane or articulating arm and move segments from shipping container to roof. Tilt helps to: (a) point toward the sun, (b) move snow off panels, and (c) direct panels away from hailstones.

- Develop supporting hardware and installation machines for above subassemblies.
- Same as above, yet commercial buildings.
- Same as above, yet parking lots.
- Same as above, yet solar farms.

16. Automate the Installation of Standardized Solar Panels on Buildings

The average US resident pays $2.81-per-watt to install PV solar panels on their house. However, the panels themselves only cost $0.27-per-watt wholesale in China. This means 90% of the costs are for things other than panel manufacturing ($2.54 / $2.81). These other things include installation, design and customer acquisition.

The world currently spends $3.4T/yr on electrical power generation and distribution, which works out to $100T if spent over 30 years ($3.4T x 30). Decarbonization entails replacing much of this with solar, wind, hydro, and nuclear power. Some of this would be implemented with solar panels on buildings. If 5% was solar on buildings ($5T) and automation reduced this by 30%, for example, then automation would save $1,500B. Therefore, it is reasonable for governments and foundations to automate the handling of traditional solar panels. This does not involve sub-assemblies or custom shapes described in previous chapters.

The Lab's Role

The Lab develops systems that automate the installation of traditional solar panels on buildings. This includes installation, maintenance, repair, customer acquisition, quotation, contracting, permitting, and design.

Further Reading

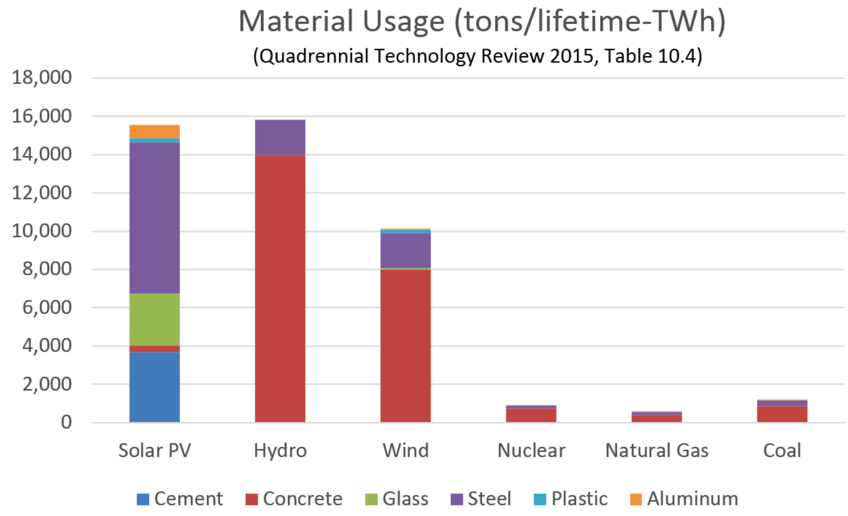
- Why Spend $1B on Solar Installation R&D?

17. Mechanized Solar on Soil

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

The Materials Problem

This graph shows how much material is used by the traditional methods of generating electricity. Materials primarily include steel, concrete, and glass. PV solar farms use as much material as hydroelectric dams in terms of weight per unit of lifetime electricity generated. This is a lot, and we would like to reduce, to reduce the cost of solar, and to reduce CO_2 emitted when making materials.



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

Solar Direct to Soil

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

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

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

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

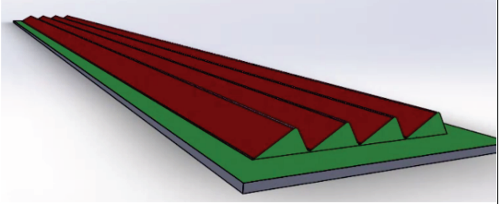
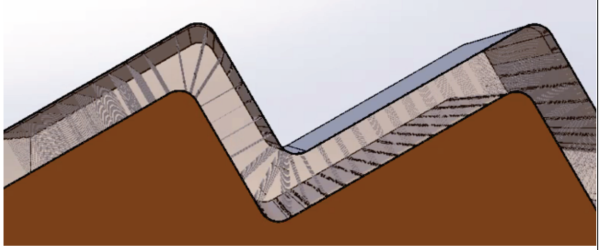
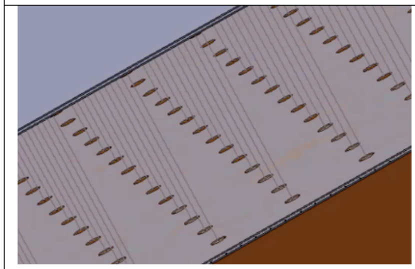
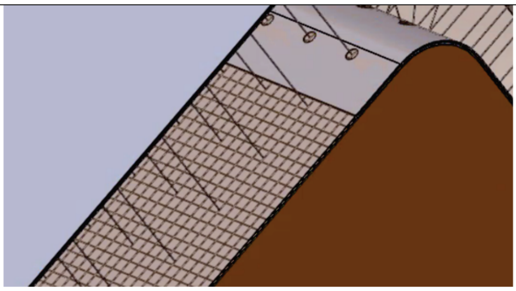
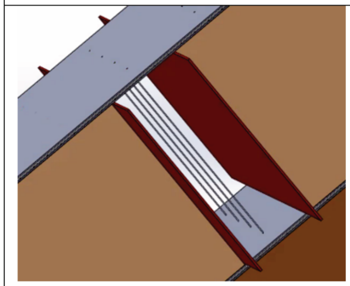
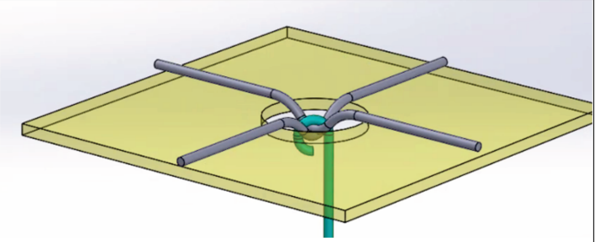
 *Multiple rows of flexible solar material are placed directly onto soil (e.g. 2m x 100m per row, shown in red). Entire bed is covered with solid material to control soil erosion from rain and wind. Skirt along outer perimeter (green) controls erosion near rows.*	 *Metal links connect above-ground solar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

Figure 17.1. Thin-film solar direct to soil (concept illustration by Weinreb).

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

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

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

Figure 17.2. Earth-moving vehicles and agricultural sprinkler system.

The Lab's Role

The Lab explores placing solar material directly onto soil. This includes the following:

- Explore the impact of wind (e.g. 100mph during storm) and what to do about it (e.g. underground anchoring layer holds above-ground material in place).
- Explore the impact of rain water (e.g. mixes with sediment and turns to mud) and water management (e.g. dispose in-place, or flow to pond).
- Explore the impact of debris (e.g. sediment blown by wind) and what to do about it (e.g. remove with machines that clean material).
- Explore the mechanics of solar material placed directly onto soil.
- Explore site preparation with earth moving machines under computer control.
- Develop machines that fabricate large rolls of solar material.
- Develop machines that install solar material.
- Develop machines that clean solar material.

Further Reading

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

18. Automate the Construction of Power Transmission Towers

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

Upgrading Power Lines

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

Figure 18.1: Traditional power cables (left) and jumbo-sized ultra-high-voltage cables (right).

Get Ready For Jumbo-Sized Power Transmission

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

The state of New York typically requires 40GW of power, and each jumbo-sized line typically carries 8GW. Therefore, powering the entire state would require 5 jumbos (40GW / 8GW).

However, solar and wind sources are intermittent. Therefore, more lines would be needed to support variable sources.

Automate Power Transmission Tower Assembly

Expanding the grid will cost trillions of dollars worldwide over several decades. Therefore, it is reasonable to spend billions of additional dollars on R&D, to reduce this cost. For example, one might explore machines that automate the building of power towers using industrial robots mounted on trucks, as illustrated below.

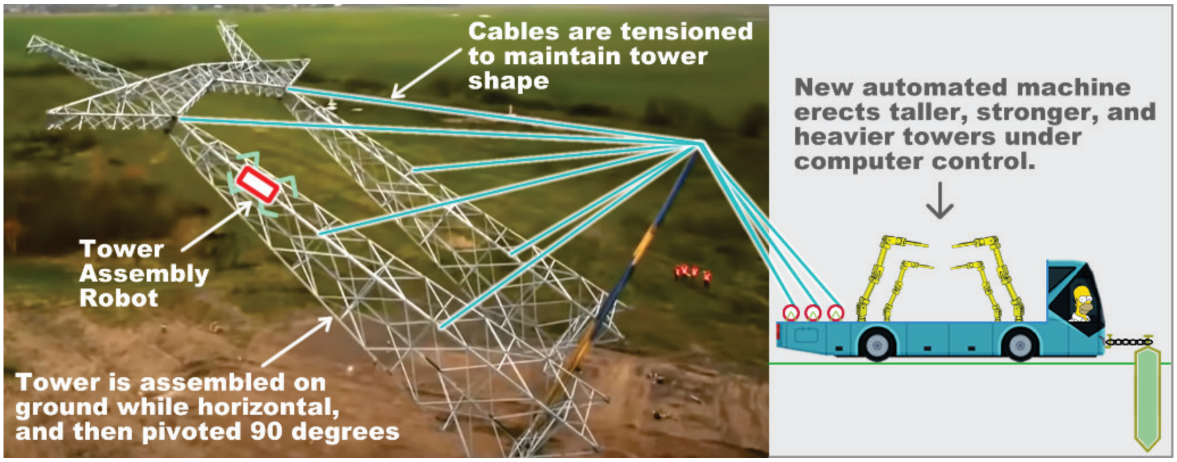


Figure 18.2: Machine automates the assembly of power transmission towers (concept illustration by Weinreb).

The Lab's Role

The Lab explores automating the construction of power transmission lines. This includes the following:

- Develop machines that automate the assembly of towers while they rest on the ground in a horizontal orientation.
- Develop machines that pivot towers from a horizontal position to a vertical position.
- Develop machines that automate the construction of foundations.
- Explore replacement of segments of existing power lines with larger cables on a wider track of land. For example, one might replace an existing 40km segment with 50 new towers by constructing new foundations and horizontal towers while legacy equipment operates. And then have multiple teams erect many towers quickly.

Further Reading

- How to Reduce the Cost of Electrical Power Transmission

19. Develop Next Generation Buildings

To fully automate buildings, one would need to place a microprocessor chip in every device and connect all devices with reliable communication. Devices include things like light switches, light sockets, HVAC equipment, appliances, motorized dampers in ducts, fans in ducts, motorized valves in radiators, thermal storage tanks, motors that move thermal covers over windows, occupancy sensors, temperature sensors, and fire detectors.

This would enable one to control the temperature of each room, move heat from one room to another, move heat between rooms and thermal storage, and move heat between rooms and underground soil. As noted previously, one can run pipes underground to get approximately 14°C (58°F), and this can be used to significantly reduce HVAC energy consumption.

Open Source Operating System

To ensure coordination, all devices would probably need to run the same operating system. Companies and countries would only accept this if it were open source (i.e. no one owns it). An example is BuildingBus, developed by Weinreb in 2021. He has developed approximately 30 automation and control systems over the last 45 years.

Reliable Communication

When one turns on a physical wall light switch, the communication between the switch and the ceiling bulb is operational ≥ 99.999% of the time (“5 nine's”). It’s a subtle point that gets little attention yet is important. Occupants do not accept less reliability from common building infrastructure. It’s worth noting that wireless and power-line communication are significantly less reliable, with failure rates on the order of 1%. To get 99.999% reliability within a building, one would probably need to include a communications data wire in power cables embedded in walls. The additional cost of this wire would be small.

Light and Heavy Devices

One might divide devices into two categories: Light and Heavy. Light might consume less than 20W of power, while heavy devices consume more. Light might include things like light bulbs, light switches, sensors, and small motors. And Heavy might include things like 110/220 V_{AC} power outlets, HVAC equipment, large appliances, and large motors. Most devices in a building are Light and, therefore, could be powered by smaller cables with lower voltages and fewer safety requirements. In other words, a building might have a network of light devices powered by 48 V_{DC} and one communications wire. And it might have another network of Heavy devices powered by 110/220 V_{AC} and two data wires. The Heavy devices might route thick power wires in metal conduit, whereas the Light devices might use smaller cables without conduit.

Plug-and-Play Standards are Needed

To support plug-and-play connectivity, one would need to develop interconnection standards that define how devices connect electrically, mechanically, and with data communications.

Before proposing a standard, one must develop, prototype, test, and debug the system. And this might cost tens of millions of dollars, assuming the money is controlled by talented engineers, and open source is required by the funding source.

The Lab's Role

The Lab develops standards that define how all devices in a building connect electrically, mechanically and in software. It assumes the same open source operating system is installed on each device and develops: (a) low level software that enables all devices to talk to each other, (b) medium level software that defines how these work together in a system, and (c) high level user interface software to configure, monitor, maintain, and control. All source code is made available to the public for free to elicit global acceptance.

More specifically, the Lab develops:

- An open source operating system that runs on all devices.
- User interface software for: (a) engineers who define the system in each building, (b) technicians who install and configure devices, (c) building owner, and (d) building occupants.
- Electrical standards for power cables that include data wires which provide reliable communication between devices.
- Mechanical and electrical standards that define replaceable motorized window thermal covers. These are embedded in a wall next to a window, and slide out to physically cover the window when the room is not occupied. For details, see *Standards Are Needed to Thermally Cover Windows* *(Power Electronics, Nov 2021)*.
- Standards that define replaceable fans embedded in HVAC ducts. For details, see *Standards are Needed to Fully Control Air in Buildings* *(Power Electronics, April 2022)*.
- Standards that define replaceable dampers embedded in HVAC ducts. For details, see *Standards are Needed to Fully Control Air in Buildings* *(Power Elect., April 2022)*.

Further Reading

- Using processors and software to make buildings smarter
- BuildingBus Development Guide
- Manhattan 2 Open-Source Smart Building Development
- Manhattan 2 Open-Source Window Thermal Cover Development
- Manhattan 2 Open-Source Fan/Damper Development

20. Decarbonize the Heating of Buildings

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

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

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

A building's energy cost often increases when it switches from a natural gas furnace to a heat pump, especially when outdoor temperatures are very cold. This is due to the fact that a heat pump's efficiency decreases when outdoor temperatures decrease.

Gas Furnace vs. Electric Heat Pump

Buildings typically obtain heat from a gas furnace or an electric heat pump, and it is impossible to generalize which of these costs less or emits less CO_2. This is due to multiple factors that vary over time and place. For example, the efficiency of a heat pump is a function of outside air temperature. And the spot price of both natural gas and electricity vary throughout the day and between regions.

Unfortunately, the size of the heat pump needed for a very cold day tends to be larger than that needed for a hot summer day. For example, the typical air conditioner on a 38°C summer day moves heat 14°C (38°C to 24°C), and the typical heating system on a -18°C winter day moves heat 42°C (-18°C to 24°C). The latter is 3-times further and therefore requires a much larger and more costly heat pump. To reduce the need for costly heat pumps, one can operate a gas furnace and a heat pump concurrently on very cold days.

National HVAC Communications and Control

There are many ways to decarbonize building heat. However, to get this done at the lowest cost, one would probably need standardized communications between HVAC equipment, regional computers, and national computers. This currently does not exist; however, it could be developed. For details, see *How to Decarbonize the Heating of Buildings at Lowest Cost* *(Power Electronics, June 2022)*.

Thermal Storage

Thermal storage typically entails placing a tank of water in a building, heating or cooling it with cheap or green energy, and then using it later when energy is less cheap or less green. For example, if a wind farm at 3 am is discarding electricity due to being in saturation (e.g. no natural gas is being burned to produce grid electricity), then one might store heat or cold in a tank and use it later when green electricity is not available. This would only be done at large scales if thermal storage \$/mtCO_2 decarbonization costs were competitive with other decarbonization options.

Reduce Cost of Installing Ground Source

Underground soil is typically at a ~14°C (58°F) temperature, and if one embeds pipes into that soil and circulates water through those pipes, they can get water at that temperature. If one circulates this water through a heat pump, they can reduce electricity consumption approximately 2-fold when heating and cooling. This technique is referred to as a "ground source heat pump" (GSHP), and it has two disadvantages. It consumes land, and installing underground piping is costly (e.g. \$20K per house). Therefore, engineers should consider reducing this cost with automated installation machines.

The Lab's Role

The lab develops standards and systems that reduce energy consumed by buildings. This includes the following:

- Develop standards that define how HVAC equipment communicates with regional computers. This would reduce costs and reduce CO_2 emissions. For details, click here.
- Study the cost and efficacy of government policies that reduce building CO_2 emissions. This helps to identify the lowest cost way to decarbonize building heat.
- Develop machines that automate the installation of a ground source. Engineers produce paper-only designs, cost models, and proposals for more work. Further development is done if proposed design(s) appear economically and technically feasible.
- Develop standards that define how ground source components communicate (i.e. software protocol, physical layer), connect mechanically, and connect electrically. In other words, this defines how pumps, valves, tanks, and temperature sensors plug-and-play together to manage ~14°C water within a building.
- Similar to the above, yet applies to thermal storage within a building.

21. Automated Green Energy Production Zone

Approximately 5% of U.S. electricity is generated by solar farms, and this only increases by approximately 1% each year. Unfortunately, this growth rate would need to be much higher if one wanted to decarbonize the U.S. within a reasonable period. Yet how might one increase this rate? Would it help to automate solar farm financing, construction, and maintenance with software?

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

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

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

Figure 21.1: Large solar farm.

Solar Bonds

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

Figure 21.2: Illustration of solar bond. This is not a real product.

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

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

Financial Requirements

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

- The rate of return to investors would need to be similar to or greater than that offered by traditional bonds for the same level of risk. In other words, investors would not participate if solar bonds were not competitive with other investment opportunities.
- Electricity would need to be priced at its cost plus a reasonable profit to the solar farm owner. Otherwise, if the electricity price were too high, electricity customers would seek alternatives. And if too low, solar farm owners would not participate.

Tension between Investors and Customers

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

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

Risk Is as Important as Price

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

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

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

Transparency Enables One to Control Risk

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

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

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

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

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

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

Solar Farms within the System

The NSFS oversees multiple solar farms, each of which has an owner and one or more customers. Before a solar farm is built, the owner would submit an application that includes a technical plan and an economic plan. The technical plan would include the technical design and list of components. And the economic plan would include expected equipment costs, maintenance costs, etc. Owners could copy proposals from existing solar farms or expand existing farms. The NSFS organization would estimate risk, estimate the cost of capital, and introduce electricity customers to farm owners. Projects would not be funded unless the owner had a customer that agreed to an electricity price.

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

The Solar Commissioner

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

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

The NSFS would oversee the following kind of process:

1. Government sets the minimum amount of solar farm capacity built each year.
2. Commissioner sets investment rate-of-return, for a given level of risk, sufficient to the raise money needed for step #1.
3. Commissioner gathers proposals from potential owners to build solar farms.
4. Commissioner estimates a variety of parameters, such as risk and investor rate-of-return, for each proposal.
5. Commissioner helps establish electricity purchase agreements between solar farm owners and wholesale electricity customers.
6. Commissioner sells solar bonds to pay for new construction.
7. The NSFS computers monitor performance, failures, electricity generated, and revenue.

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

Wind Too

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

Setting Size

The majority of people want to resolve climate change. Subsequently, new laws that require decarbonization will probably appear this decade. It is likely these would increase solar farm and wind farm construction. For example, if government wanted to decarbonize 6% of all electricity each year, and 1% is already being decarbonized by building traditional solar farms and 1% is already being decarbonized by building traditional wind farms, the government might want the

NSFS and NWFS combined to contribute at least 4%. In other words, electricity customers might be required to buy more green electricity each year, and the NSFS/NWFS organizations would need to raise money accordingly.

Junk Is a Serious Problem

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

The Commissioner Must Block Junk

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

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

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

Let's Run the Numbers

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

Typical equipment costs are $1.12-per-watt (CAPEX, NREL 2022); therefore, investors would need to put in $39B/yr (35GW x $1.12). Typical electricity costs are 3.7¢/kWh (LCOE, NREL 2022 Class 4, no tax credits, 0.5¢/kWh for power wires). Therefore, revenue would need to be at least $3B/yr to cover costs ($.037 x 35GW x 0.001 x 2334Wh/W/yr). The investment rate of return would depend on several factors, such as profit to owner and electricity price. For details, see the below analysis.

Decarbonization	2.0%	%/yr	% US total electricity decarbonized ea yr
	4,120	TWh/yr	Total electricity consumption, 2021 US EIA
	82	TWh/yr El	Electricity decarbonized each year
	187	TWh/yr Ht	Heat avoided from burning natural gas
Solar Farm	35	GW	Capacity of each solar farm
	$3.0	$B/yr	Electricity cost per year, LCOE, NREL 2022
	34	$MtCO_2$/yr	CO_2 reduced per year (gas not burned)
	$39.5	$B/yr	Solar farm initial equipment cost
Multiple Solar Farms	0.50	GW	Size of each solar farm
	71	count	Number of solar farms
	10	sq km	Square kilometers per solar farm
Solar Farm Costs	$1.120	$/Watt	Solar farm inital cost, CAPEX, NREL 2022
	$0.037	$/kWh El	Electricity cost, LCOE, NREL 2022 Class 4, no tax credits, $0.005/kWh power wires
	2,334	kWh/kW	Annual production, NREL 2022 Class 4
Natural Gas Power	$4.00	$/mcf	Cost of natural gas, wholesale, typ. price
	0.000413	$mtCO_2$/kWh el	CO_2 emissions from electricity, metric ton
	$3.75	$/GJ	Internal energy within natural gas
	$0.014	$/kWh Ht	Cost of heat energy in natural gas
	44%	%	Efficiency of gas power plant
	$0.031	$/kWh El	Cost of natural gas per unit of electricity
Additional Cost	$0.006	$/kWh El	Additional cost green electricity
(solar instead of gas)	$0.53	$B/yr	Additional cost green electricity
	$15	$/mtCO_2$	Decarbonization cost, $-per-m-ton-$CO_2$
	330	M	U.S. population
	$1.59	$/person/yr	Decarbonization cost-per-person-per-yr

Figure 21.3: The economics of decarbonizing 2% of U.S. electricity via 71 solar farms, each 0.5GW in size (calculations by Weinreb).

The Residential Solar Problem

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

Figure 21.4: Residential solar panel installation.

Resolving the Residential Solar Problem

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

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

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

Carbon Offsets at Large Scales without Fraud

Investors and farm owners participate to make money, not to reduce CO_2. However, many entities are willing to pay money to reduce CO_2. These exchanges are typically referred to as “carbon offsets,” and unfortunately, many are fraudulent. Alternatively, if one is looking for real offsets at large scales, the NSFS/NWFS system might be a nice option. More specifically, the system could be used to pay the green premium on someone else's electricity, and flip them off carbon. For example, if coal cost 2.5¢/kWh and green electricity cost 4¢/kWh, a 1.5¢/kWh offset could flip the customer and reduce CO_2 at $15-per-ton ($10 x (4¢ - 2.5¢)).

The Lab's Role

The Lab develops a national solar farm and national wind farm system. This includes writing software and developing standards that coordinate the various components.

22. Cheap Green Car

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.

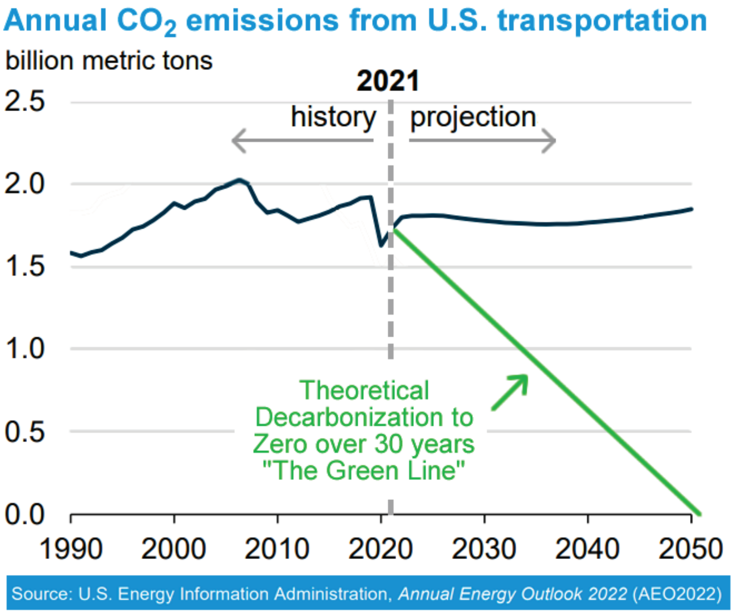


Figure 22.1: Projected annual CO_2 emissions from U.S. transportation.

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 Legislation

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. 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 CO$_2$ 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 22.2: 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 on how this might work, see *The Little Secret of Electric Vehicles* *(Power Electronics, Sept 2022)*.

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

Currently, low-range EVs (e.g. ≤ 125 miles) are sold in the U.S. for $40K (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 $40K for half a car. However, they might pay $20K 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.

Approximately 7% of US car sales in 2023 were electric. These EVs try to mimic the traditional gas car with a decent range and a fast charge capability. However, there is a market for drivers who are not driving long distances, have access to more car for long distances, are never fast charging, can easily slow charge overnight at home, and are looking for a low cost-per-mile.

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

In theory, U.S. auto makers could rebrand something like 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 per gas car, and China EV wholesale cost is $11K, then end user price would be $20K retail ($5K + $4K + $11K). This might seem promising; however, getting this to work politically and economically involves several 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?

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.

Figure 22.3 Charging stations are often 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.

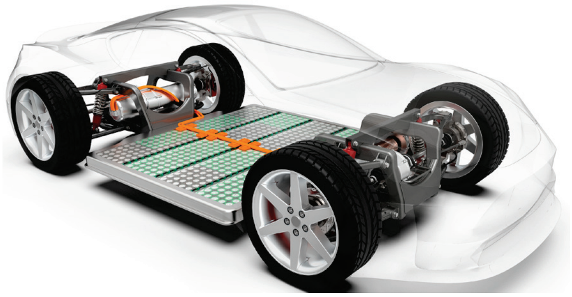
The greatest challenge with fast charging cannot be seen. It is electricity. The typical 50kWh EV battery consumes 100kW of power when charging in 30 minutes (100kW x 0.5h). This is the same amount of power drawn by 80 U.S. homes on average. In other words, supporting large amounts of power is expensive,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

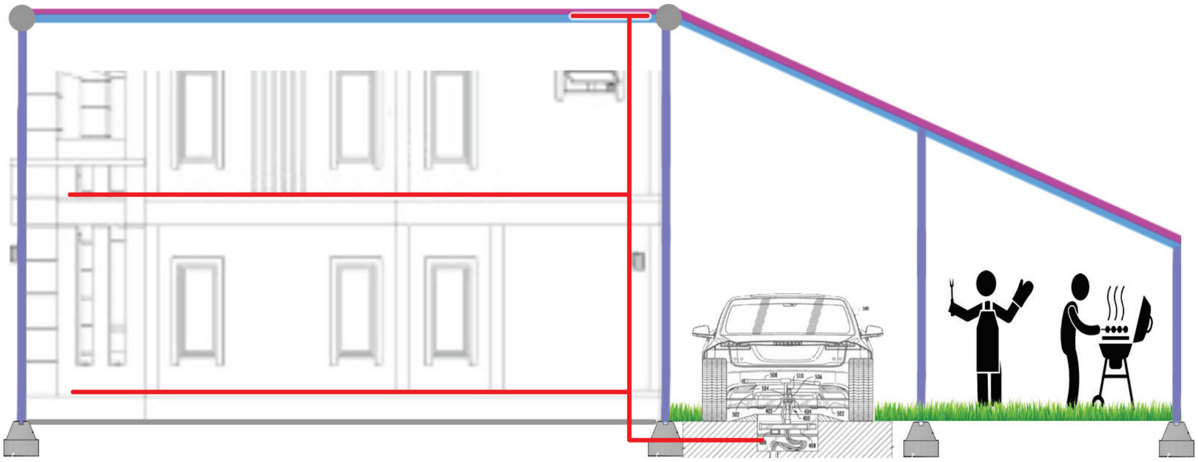


Figure 22.4: EV batteries in swap chamber power homes at night (concept illustration by Weinreb).

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. For details, see *Are we Ready for a Swappable EV Battery?* *(Power Electronics, Aug 2022)*.

The Lab's Role

The Lab reduces carbon dioxide emissions from transportation via the following initiatives:

- Explore the economic viability of a cheap green car with a slow charging speed and a low range.

- Explore requiring a small electric motor and small battery in gasoline/diesel vehicles to improve mileage at little additional cost. For details, see the previous “Consider HEV for Quick Improvement” discussion.
- Develop a model with a website user interface that calculates the cost of electronic assist hardware for each battery chemistry and its variations. The Lab reduces CO_2 worldwide; therefore, this model supports cars manufactured globally. This helps automakers throughout the world add HEV hardware to their next generation automobiles.
- Build a model that calculates the lowest cost way to design an EV given several input parameters. These include fastest charging time (e.g. 30min or 8hrs), external temperature profile (e.g. California vs. Colorado), amount battery is recharged (e.g. charge to 90% of capacity instead of 100%), battery depletion when charging begins (e.g. begin charging when 10% full instead of 0%), range (e.g. 250 miles), passenger volume (e.g. 90 cubic feet), etc. The model calculates battery-cost-per-mile and car-cost-per-mile for each battery chemistry, and its variations.

  A website user interface is included. This enables the public to easily ask the following kinds of questions: "If we reduce fastest charging time from 30min to 8hrs, how does this effect car-cost-per-mile?" One might look for EV's with a cost-per-mile less than gasoline-powered cars. However, these tend to be less convenient due to less range and more time to charge.

  The model also estimates sales price, sales volume, and profit to manufacturer (or loss). This enables the user to search for EV designs that are profitable and cost less than their gasoline-based counterparts.
- The above design tool is likely to show that EV's with similar convenience to gasoline-powered cars (i.e. significant range, fast charging) tend to be expensive. Alternatively, lower range cars that charge overnight (not at fast-charging stations) cost less and are also less convenient.

  If 90% of Americans drive less than 100 miles a day on 90% of the days, then the 10% of the people that drive long distances often would probably favor gas cars. And the 90% that rarely drive long distances might favor a cheap low range EV if charging was convenient (e.g. charge overnight at single family home) and they could borrow more car easily and at low cost. In other words, if car sharing was cheap and convenient, the lower range / lower cost EV's would be more popular.

  The Lab develops software that helps groups of drivers share cars. For example, an app could help several people who possibly know each other schedule car usage and share expenses.

  A car-sharing circle might share expenses proportional to miles driven. For example, if driver X drove 15% of the time, driver Y 5%, and driver Z 80%, then simple repairs and fuel costs might be shared in those proportions.

  In most cases, cars in a sharing circle would be borrowed from car owners who receive money in return for usage. Owners with older cars might be more inclined to lend, since they would be less concerned about potential damage. And owners concerned about misuse might be only inclined to set up a small sharing circle that consists of nearby friends and family.

In theory, multiple cars could be shared by larger groups within a neighborhood. For example, 100 people within a neighborhood might share 10 gas cars parked on the street.

One could apply this to gas cars as well as EV's. For example, one might join a nearby car-sharing circle with 10 EV's and join another car-sharing circle with 3 gas cars. Or an EV owner might lend his EV to one car-sharing circle during select times, and borrow more car as needed from another circle.

Car-sharing software and services is not new. However, it needs more automation, better coordination and a better user interface. More specifically, the Lab develops and proposes communication standards between cars and external computers. These are used to track a car's location, identify drivers, record miles driven by each driver, track repairs, track refueling events, handle financial transactions, etc.

The Lab develops software that runs on end user smartphones, external servers, a car's computer, and also a car's user interface display. The Lab builds prototypes using open-source cars and after the system is debugged, they suggest communications standards.

The automobile industry might be initially reluctant since they would prefer 100 families to buy 100 cars, one per family, instead of share a fewer number of cars. However, non-automobile manufacturing companies and standards bodies such as IEEE are likely to be supportive.

Some automakers might be initially reluctant to install car-sharing software onto their cars. However, if a few automakers are supportive and this helps them sell their cars, then the other automakers would be likely to eventually follow.

This group does not need to focus on the U.S. since the Lab reduces global CO_2. In other words, they would want their software to reduce CO_2 somewhere in the world.

Developed software is open source (i.e. free). This increases utilization by for-profit companies, rental companies, and national governments.

- Support research that increases battery lifespan, as noted in the previous “Double the Lifetime of the EV Battery” discussion.
- Develop a dynamic battery warranty system, as discussed in *The Little Secret of Electric Vehicles (Power Electronics, 2022)*.
- Explore regulations and standards that require auto-makers to display battery diagnostic reports, to effectively reduce the cost of EVs.
- Explore rebranding foreign-made low cost EV's in a way that meets the satisfaction of U.S. auto manufacturers, U.S. dealers, and U.S. Labor. It builds a model with a website user interface that helps decision-makers understand how this might work. For details, see the previous “Can China's Cheap Green Car Slip into the U.S.?” discussion.
- Model U.S. trade policy options for EV's. With each policy it calculates EV price, EV sales volume, national inflation, number of U.S. labor jobs, CO_2 emissions, etc. Reshoring (i.e. more protectionism) increases price and leads to more inflation and higher interest rates, which reduces the value of bonds and increases the risk of recession. Macro-economic parameters

are studied to more fully understand protectionism's cost to society. A website user interface is included.

- Develop a swappable EV battery standard (SEB). This includes standards that define how SEB batteries mechanically attach to vehicles and external charging systems, standards that define how SEB batteries interface to cars and charging stations, and standards that define how SEB batteries communicate with cars and how cars communicate with SEB swap stations. The Lab also develops mechanical systems that charge SEB batteries and move batteries to/from cars.
- Develop machines that automate the installation of underground infrastructure.
- Develop machines that automate the installation of underground swap and EV charging equipment. For details, see *How to Decarbonize Transportation* *(Power Electronics, 2021)*.
- Develop machines that automate the installation of underground conduit, pipes and cables. For details, see *How to Decarbonize Transportation* *(Power Electronics, 2021)*.

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

Open-Source

To the author's knowledge, the concepts discussed in this document are public knowledge and no patents are pending.

For original files, visit www.APlanToSaveThePlanet.org/open

Acknowledgments

We would like to thank Dr. Maurizio Di Paolo Emilio for editing material previously published in EETimes.com and PowerElectronicsNews.com. This document reprints some of this with the permission of publisher AspenCore.